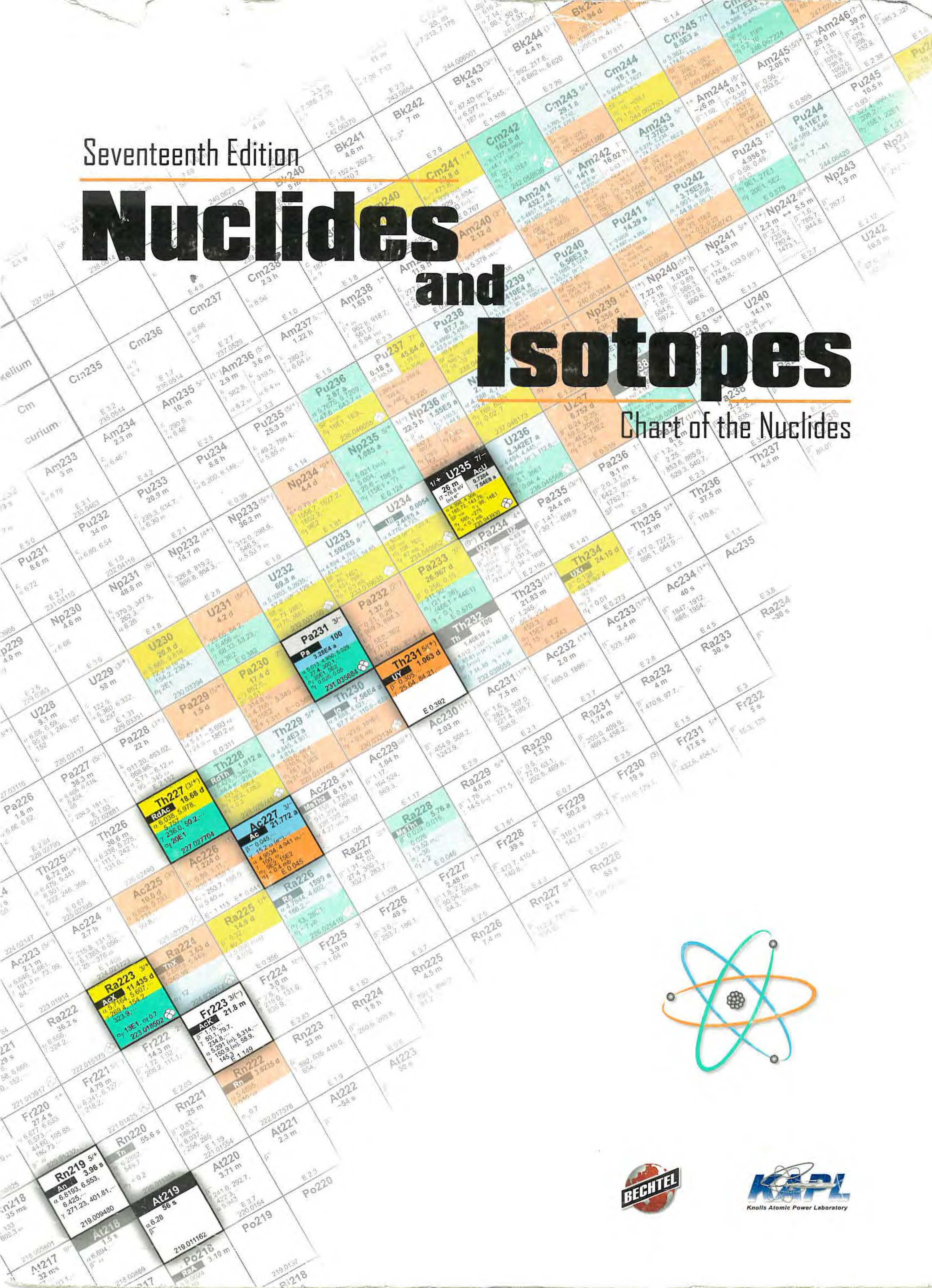
Seventeenth Edition

Nuclides and Isotopes

Chart of the Nuclides



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List of Elements by Atomic Number

Z	Symbol	Name	Naturally Occurring Isotopes*	Atomic Weight (u)**	Z	Symbol	Name	Naturally Occurring Isotopes*	Atomic Weight (u)**
1	H	hydrogen	2	1.007 94(7)	60	Nd	neodymium	7	144.242(3)
2	He	helium	2	4.002 602(2)	61	Pm	promethium		....
3	Li	lithium	2	6.941(2)	62	Sm	samarium	7	150.36(2)
4	Be	beryllium	1	9.012 182(3)	63	Eu	europium	2	151.964(1)
5	B	boron	2	10.811(7)	64	Gd	gadolinium	7	157.25(3)
6	C	carbon	2	12.0107(8)	65	Tb	terbium	1	158.925 35(2)
7	N	nitrogen	2	14.0067(2)	66	Dy	dysprosium	7	162.500(1)
8	O	oxygen	3	15.9994(3)	67	Ho	holmium	1	164.930 32(2)
9	F	fluorine	1	18.998 4032(5)	68	Er	erbium	6	167.259(3)
10	Ne	neon	3	20.1797(6)	69	Tm	thulium	1	168.934 21(2)
11	Na	sodium	1	22.989 769 28(2)	70	Yb	ytterbium	7	173.04(3)
12	Mg	magnesium	3	24.3050(6)	71	Lu	lutetium	2	174.967(1)
13	Al	aluminum	1	26.981 5386(8)	72	Hf	hafnium	6	178.49(2)
14	Si	silicon	3	28.0855(3)	73	Ta	tantalum	2	180.947 88(2)
15	P	phosphorus	1	30.973 762(2)	74	W	tungsten	5	183.84(1)
16	S	sulfur	4	32.065(5)	75	Re	rhenium	2	186.207(1)
17	Cl	chlorine	2	35.453(2)	76	Os	osmium	7	190.23(3)
18	Ar	argon	3	39.948(1)	77	Ir	iridium	2	192.217(3)
19	K	potassium	3	39.0983(1)	78	Pt	platinum	6	195.084(9)
20	Ca	calcium	6	40.078(4)	79	Au	gold	1	196.966 569(4)
21	Sc	scandium	1	44.955 912(6)	80	Hg	mercury	7	200.59(2)
22	Ti	titanium	5	47.867(1)	81	Tl	thallium	2	204.3833(2)
23	V	vanadium	2	50.9415(1)	82	Pb	lead	4	207.2(1)
24	Cr	chromium	4	51.9961(6)	83	Bi	bismuth	1	208.980 40(1)
25	Mn	manganese	1	54.938 045(5)	84	Po	polonium		....
26	Fe	iron	4	55.845(2)	85	At	astatine		....
27	Co	cobalt	1	58.933 195(5)	86	Rn	radon		....
28	Ni	nickel	5	58.6934(2)	87	Fr	francium		....
29	Cu	copper	2	63.546(3)	88	Ra	radium		....
30	Zn	zinc	5	65.409(4)	89	Ac	actinium		....
31	Ga	gallium	2	69.723(1)	90	Th	thorium	1	232.038 06(2)
32	Ge	germanium	5	72.64(1)	91	Pa	protactinium	1	231.035 88(2)
33	As	arsenic	1	74.921 60(2)	92	U	uranium	3	238.028 91(3)
34	Se	selenium	6	78.96(3)	93	Np	neptunium		....
35	Br	bromine	2	79.904(1)	94	Pu	plutonium		....
36	Kr	krypton	6	83.798(2)	95	Am	americium		....
37	Rb	rubidium	2	85.4678(3)	96	Cm	curium		....
38	Sr	strontium	4	87.62(1)	97	Bk	berkelium		....
39	Y	yttrium	1	88.905 85(2)	98	Cf	californium		....
40	Zr	zirconium	5	91.224(2)	99	Es	einsteinium		....
41	Nb	niobium	1	92.906 38(2)	100	Fm	fermium		....
42	Mo	molybdenum	7	95.94(2)	101	Md	mendelevium		....
43	Tc	technetium		....	102	No	nobelium		....
44	Ru	ruthenium	7	101.07(2)	103	Lr	lawrencium		....
45	Rh	rhodium	1	102.905 50(2)	104	Rf	rutherfordium		....
46	Pd	palladium	6	106.42(1)	105	Db	dubnium		....
47	Ag	silver	2	107.8682(2)	106	Sg	seaborgium		....
48	Cd	cadmium	8	112.411(8)	107	Bh	bohrium		....
49	In	indium	2	114.818(3)	108	Hs	hassium		....
50	Sn	tin	10	118.710(7)	109	Mt	meitnerium		....
51	Sb	antimony	2	121.760(1)	110	Ds	darmstadtium		....
52	Te	tellurium	8	127.60(3)	111	Rg	roentgenium		....
53	I	iodine	1	126.904 47(3)	112	Cn	copernicium		....
54	Xe	xenon	9	131.293(6)	113				
55	Cs	cesium	1	132.905 4519(2)	114				
56	Ba	barium	7	137.327(7)	115				
57	La	lanthanum	2	138.905 47(7)	116				
58	Ce	cerium	4	140.116(1)					
59	Pr	praseodymium	1	140.907 65(2)	118				

* The number of naturally-occurring isotopes.

** The numbers in parentheses following the atomic weights are the uncertainties in the atomic weights.

Nuclides and Isotopes

Chart of the Nuclides

Seventeenth Edition
Revised 2009

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The Elements and the Periodic Table

Introduction

Man's speculation on the composition of the universe began with the ancient Greeks. In the fifth century B.C., Democritus of Abdera believed that the world was made up of four substances—earth, water, fire, and air—and that each of these substances was formed by minute particles that were, themselves, indivisible. These particles were called *atomos*[1] from a Greek word meaning "uncut or indivisible." Qualities—coldness, hotness, wetness, and dryness—were attributed to these classical substances to give them their characteristics. Through the Middle Ages, many variations on these early idealizations were devised.

Robert Boyle gave the modern concept of an element in 1661 in his book *The Sceptical Chymist.*[2] Boyle believed that there existed elemental substances not capable of being broken down into still simpler substances. All other materials were composed of these elemental substances.

Early Developments

Boyle's definition was somewhat vague, however, and chemists of that time could not be sure that some newly developed experimental technique might break down a material previously thought to be an element.[3] Nevertheless, as chemical methods improved, approximately 40 elements were isolated by the early 1800s.

Throughout the Middle Ages, substances were designated by a variety of symbols and letters. Astronomical signs represented the metals known to the ancients: gold (sun), silver (moon), and tin (Jupiter). Two superimposed V's, one inverted, formed the symbol for glass (*vitrum* in Latin). The symbolic representations of the elements and compounds underwent major changes in the early 1800s. In 1803, John Dalton proposed a more standardized system where circles containing dots, dashes, and the initial letters of the English name of the element designated the atoms of the elements. Initially, this proposal gained some acceptance, but in 1813, the Swedish chemist, Jöns Jacob Berzelius, suggested the use of only letter symbols consisting of the first letter of the name of the element and a second letter from the body of the name.[3, 4] This system has remained in effect to the present day.

Between 1803 and 1808, John Dalton[5] made rough determinations of the relative weights of about 35 elements, choosing to make the measurements relative to hydrogen. Berzelius[6] carried out similar work on 41 elements in 1814. These studies seemed to indicate that the relative weights were largely integral numbers. Based on these results, William Prout[7] suggested in 1815 that all elements were built up from the hydrogen atom (Prout's hypothesis). As more precise determinations of the weights were made over the years, Prout's hypothesis was ultimately shown to be incorrect, though for a number of elements the values were tantalizingly close to integral values.

Following Alessandro Volta's invention[8] in 1800 of the electric pile, or battery, it was soon discovered that elements could be separated by electrolysis, that is, by passing electric currents through solutions containing compounds. In 1834, Michael Faraday[9] showed that a different characteristic weight of each element was produced per unit of charge passed. The charge-carrying species in the electrolysis experiments were called ions. Some elements, such as oxygen, were formed at the positive electrode or anode and some, such as hydrogen, were formed at the negative electrode, or cathode. Ions of the two different types were called anions (negatively charged ions) and cations (positively charged ions), respectively.

As chemical elements were isolated, they were classified according to their chemical and physical properties. Similarities and trends in these properties were noticed. In 1817, Johann W. Döbereiner[10] pointed out the similarities of several groups of three elements (triads), e.g., calcium-strontium-barium and chlorine-bromine-iodine. Several physical properties of a single member of a triad could be predicted by knowing the properties of the other two.

By the mid-1800s, approximately 60 elements had been isolated, and new techniques for identifying elements were being developed. One technique was optical spectroscopy. If the light emitted by a material heated to a high temperature was passed through a prism, that light would be broken up into a spectrum and a number of discrete wavelengths, or lines, could be observed. Robert Wilhelm Bunsen and Gustav Kirchhoff stated that every chemical element was characterized by a unique optical spectrum.[11] Bunsen and Kirchhoff[12] could detect traces of known elements and they predicted new elements could be discovered using this technique. In 1860, in an analysis of a sample of water, they observed two blue lines in the spectrum and attributed these to a new element. The element was named cesium,[13] the name being derived from the Latin word *caesius* meaning "sky blue." During the following year, they detected another element, rubidium.[14] The spectrum of rubidium consisted of two characteristic intense red lines; the name rubidium is from the Latin *rubidus* meaning "deepest red."

Mendeleev's Periodic Table

Dmitri Mendeleev began systematizing the properties of the known elements. In 1869, he published a short note[15] entitled "The Correlation between Properties of Elements and Their Atomic Weights." He devised a table in which the known elements were arranged in columns according to the magnitude of their relative atomic weights, beginning with the smallest. In this vertical form, elements in the same row showed remarkable similarities in their chemical properties, while the properties were periodic from column to column. Originally, Mendeleev called this arrangement the "natural system" but later[16] named it the "periodic system." Yet, there were problems with the arrangement. Certain pairs of elements, e.g., nickel and cobalt, iodine and tellurium, when originally arranged in order of increasing atomic weight, were out of order with their chemical properties.

The concept of valence was proposed in 1852 by the English chemist Sir Edward Frankland.[17] Most of the elements known at that time would form compounds with oxygen and hydrogen. The valence of an element was related to the number of hydrogen or oxygen atoms that would combine with the element. Hydrogen

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[1] *atomos*, from *a* (not) + *tomos* (cut).

[2] A reproduction of the 2nd Edition of *The Sceptical Chymist*, originally published in 1680, has been published by The Classics of Science Library, a Division of Gryphon Editions, 1997, New York.

[3] Isaac Asimov, *Understanding Physics, Volume III, The Electron, Proton and Neutron*, (The New American Library, Inc., New York, April 1969).

[4] A more complete description of the work of Dalton and Berzelius on chemical symbols and on mass determinations can be found in F.P. Armitage, *A History of Chemistry*, (Longmans, Green and Company, London, 1920).

[5] J. Dalton, *A New System of Chemical Philosophy*, (Manchester, 1808), p. 213.

[6] J.J. Berzelius, Ann. Phil. **3** 353 (1814).

[7] W. Prout, Ann. Phil. **6** 269 (1815).

[8] A. Volta, Phil. Trans. R. Soc. **90** 430 (1800).

[9] M. Faraday, Phil. Trans. R. Soc. **124** 77 (1834).

[10] J.W. Döbereiner, Ann. Physik **57** 435 (1817).

[11] R. Bunsen and G. Kirchhoff, Phil. Mag. **20** 89 (1860).

[12] R.W. Bunsen and G. Kirchhoff, Chem. News **2** 281 (1860).

[13] N.E. Holden, "History of the Origin of the Chemical Elements and Their Discoverers," BNL-NCS-63850-01/10-REV, Brookhaven National Laboratory, 2001. On the Internet, see http://www.nndc.bnl.gov/publications/preprints/origindc.pdf.

[14] R.W. Bunsen, Chem. News **3** 357 (1861).

[15] D. Mendeleev, Zeits. Fur Chemie **12** 405 (1869).

[16] D. Mendeleev, J. Russ. Chem. Soc. **3** 25 (1871).

[17] E. Frankland, Phil. Trans. Roy. Soc. **142** 417 (1852).

Reihen	Gruppe I – R^2O	Gruppe II – RO	Gruppe III – R^2O^3	Gruppe IV RH^4 RO^2	Gruppe V RH^3 R^2O^5	Gruppe VI RH^2 RO^3	Gruppe VII RH R^2O^7	Gruppe VIII – RO^4
1	H=1							
2	Li=7	Be=9.4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27.3	Si=28	P=31	S=32	Cl=35.5	
4	K=39	Ca=40	– =44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59 Ni=59, Cu=63
5	(Cu=63)	Zn=65	– =68	– =72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	– =100	Ru=104, Rh=104 Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Figure 1. Mendeleev's Periodic Table of 1871 (Ref. 18). The relative weights are given after the equal signs.

and oxygen combine to form water (H_2O). Hydrogen was given a valence of one and oxygen two. Nitrogen and hydrogen combine to form ammonia (NH_3); nitrogen was then assigned a valence of three. Carbon and oxygen combine to form carbon dioxide (CO_2), while carbon and hydrogen combine to form methane (CH_4); carbon was then assigned a valence of four.

In 1871, Mendeleev[18] revised his first table, arranging the elements in rows (instead of columns) in order of increasing weight. Elements that combine with the same number of hydrogen or oxygen atoms (i.e., having the same valence) were placed in the same columns. He repositioned 17 elements from the positions indicated by their weights to new positions indicated by their chemical properties. He argued that the relative weight determinations for these elements must have been in error. The newer table is shown in Figure 1. The number following the symbol of the element is the relative weight. Notice that the triads, Ca-Sr-Ba and Cl-Br-J (the symbol is now I), are located in the same columns, indicating the similarities in chemical properties.

In order to maintain the periodicity of the properties of the known elements, it was necessary for Mendeleev to leave gaps in the table. He believed these gaps must correspond to yet undiscovered elements with atomic weights of 44, 68, and 72. All three of these elements (gallium, scandium, and germanium) were discovered within the next 15 years and their properties were found to be as he had predicted.

Five elements listed in the table have question marks beside the symbols. Mendeleev was uncertain about the location of these elements in the table. One of them, diadenium (Di), was later shown not to be an element. Three of the remaining four, erbium (Er), cerium (Ce), and lanthanum (La) were moved to different locations in later versions of the periodic table (see "The Rare Earths"). The location of yttrium (Yt) has remained the same.

Three elements (copper [Cu], silver [Ag], and gold [Au]) appear in two locations in Mendeleev's table. Mendeleev was unsure as to whether these elements should be located in column one or eight—he favored column eight.

By the early 1890s, approximately 80 elements had been isolated, including uranium, thorium, and most of the elements known today through bismuth. Though some gaps remained, Mendeleev's table nicely showed the periodic nature of the properties of the known elements. When these gaps were filled, would the table be complete, or was it possible that whole families of yet undiscovered elements might exist? The latter proved to be the case. Between 1894 and 1898, the inert gases—helium, neon, argon, krypton, and xenon—were discovered.[19] As the relative weights and chemical properties of these gases were determined, a new previously unexpected column was inserted into the periodic table. Until the cause of the periodicity of the properties of the elements was understood, there could be no guarantee that still other unknown families of elements might not exist.

The Rare Earths

Certain metallic oxides such as alumina, silica, and zirconia, which were found in minerals, were called "earths."[20] These oxides were difficult to reduce and, because of this difficulty, some had been erroneously classified[21] as elements. In 1794, Johan Gadolin[22] isolated a new "earth" later named yttria from minerals found near Ytterby, a village in Sweden. A second new earth, ceria, was isolated independently by Martin H. Klaproth[23] and by Jons J. Berzelius and W. Hisinger[24] in 1803. Initially, it was believed that only a few geographically isolated mineral deposits contained these oxides, and they were therefore called the "rare earths." Over the course of the next hundred years, the two materials were found to contain sixteen new elements. In yttria, the elements scandium, yttrium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium were identified. Lanthanum, cerium, praseodymium, neodymium, samarium, and europium were found in ceria.

The location of these elements in the periodic table was uncertain. As more of these elements were isolated, their chemical properties were found to be similar and their atomic weights were closely spaced. In 1905, A. Werner[25] published a new version of the periodic table including the known rare earths and the known inert gases. This "long form" of the periodic table is shown in Figure 2. The twelve series in Mendeleev's table were combined into seven periods (rows) in Werner's table. Gaps left in periods four and five of Werner's table provided space for the rare earths in period six.

---

[18] D. Mendeleev, Annal. Der Chemie Supp. **VIII** 133 (1871).

[19] Helium was first discovered in solar observations by Pierre Jules Cesar Janssen and, independently, by Sir Norman Lockmeyer in 1868. In 1895, Sir William Ramsey discovered helium on earth in a uranium metal, clevite. Argon was discovered by Lord Raleigh and Sir William Ramsey in 1894. Neon, krypton, and xenon were discovered in 1898 by Sir William Ramsey and Morris Travers. Finally, radon was discovered by Robert Owens and Ernest Rutherford in 1899.

[20] "Earth" is an obsolete term for oxide.

[21] See James F. Spencer, *The Metals of the Rare Earths*, (Longmans, Green and Co. London, 1919), for a detailed account of the discovery of the rare earths as well as changes in the periodic table during this time.

[22] J. Gadolin, K. Svenska. Vet-Ak. Hdl. Oefv. **15** 137 (1794).

[23] M.H. Klaproth, Crell's Ann. **I** 307 (1801).

[24] J.J. Berzelius and W. Hisinger, Gehl. Ann. **2** 303 (1804); **2** 397 (1804).

[25] A. Werner, Ber. Dtsch. Chem. Ges. **38** 914 (1905).

1	H 1.008																																He 4
2	Li 7.03																										Be 9.1	B 11	C 12	N 14.04	O 16.00	Fl 19	Ne 20
3	Na 23.05																										Mg 24.36	Al 27.1	Si 28.4	P 31.0	S 32.06	Cl 35.45	A 39.9
4	K 39.14	Ca 40.1																Sc 44.1	Ti 48.1	V 51.2	Cr 52.1	Mn 55.0	Fe 55.9	Co 59.0	Ni 58.7	Cu 63.6	Zn 65.4	Ga 70	Ge 72	As 75.0	Se 79.1	Br 79.96	Kr 81.12
5	Rb 85.4	Sr 87.6																Y 89.0	Zr 90.7	Nb 94	Mo 96.0	–	Ru 101.7	Rh 103.0	Pd 106	Ag 107.9	Cd 112.4	In 114	Sn 118.5	Sb 120	Te 127.6	J 126.9	X 128
6	Cs 133	Ba 137.4	La 133	Ce 140	Nd 143.6	Pr 140.5	–	–	Sa 150.3	Eu 151.8	Gd 156	Tb 160	Ho 162	Er 166	–	Tu 171	Yb 173.0	–	–	Ta 183	W 184.4	–	Os 191	Ir 193.0	Pt 194.8	Au 197.2	Hg 200.3	Tl 204.1	Pb 206.5	Bi 208.5	–	–	–
7	–	Ra 225	Laα ?	Th 232.5	–	–	–	–	–	U 239.5	–	–	–	–	–	Ac ?	–	–	–	–	–	–	–	–	–	–	–	–	Pbα ?	Biα ?	Teα ?	–	–

Figure 2. The Long Form of the Periodic Table Published by A. Werner in 1905 (Ref. 25). The dark lines around certain pairs of elements indicate the ordering of the pair was based on chemical properties, not atomic weights.

The Electron

The conduction of electricity through rarified gases was a popular subject of study by scientists in the second half of the nineteenth century. Sir William Crookes[26] used a partially evacuated glass tube, known as a discharge tube, containing two electrodes attached to an external voltage source to carry out such investigations. Crookes observed that if the gas pressure in the discharge tube was reduced to some critical value, long bright streamers extended from the negative electrode (cathode) along the length of the tube. These streamers were called cathode rays. Transverse electric and magnetic fields could deflect the rays, and the direction in which they were deflected indicated that the charge of the particles comprising the rays was negative.

In 1897, at the Cavendish Laboratory in Cambridge, Joseph J. Thompson[27] made measurements of the charge-to-mass ratio (e/m) of the cathode-ray particles using electric and magnetic fields to deflect the beam. To be certain that the properties of the cathode rays were independent of the materials used, several measurements were carried out using different gases in the discharge tube and different electrode materials. All measurements gave the same surprisingly large value for the ratio.

Prior to Thompson's e/m measurement of the cathode rays, values of the charge-to-mass ratio for some ionized atoms had been obtained in experiments involving electrolysis of solutions. The largest ratio was obtained for an ionized hydrogen atom. (In 1920, E. Rutherford suggested the name *proton*, a Greek word meaning "first," for the ionized hydrogen atom.[28]) Thompson's e/m value for the cathode-ray particles was 1,836 times larger than that of hydrogen. Either the charge of the cathode-ray particle was much larger than that of the ionized hydrogen atom, or the particle mass was much smaller. Thompson believed the latter and that the negative charge on the particle was equal in magnitude to that of a singly ionized atom. Robert A. Millikan[29] would later confirm this in experiments carried out in 1910. The cathode-ray particles were called "electrons," a name originally suggested by the British scientist G. Stoney in 1894 for the charge of a univalent ion.[30]

Optical Spectroscopy

Anders Ångström[31] initially investigated the optical spectrum of hydrogen in 1855. In the visible region, nine lines were observed. In 1885, Johann Balmer, a Swiss mathematician, showed[32] that the wavelengths (λ) of these lines could be expressed by the formula

$$\lambda = B\frac{n^2}{n^2-4},$$

where B was a constant and n an integer that could take on values from 3 to 11. Upon learning that additional, shorter wavelength lines of this series had been observed in astronomical studies, Balmer showed that the above equation also correctly predicted the wavelengths of these newly observed lines.

Balmer's work prompted additional searches for empirical formulae that would give the wavelengths of spectral lines of other elements. Johannes Rydberg did much of this work.[33] Rydberg found it more convenient to deal with the wave number, k, and rewrote Balmer's formula as

$$k = \frac{1}{\lambda} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right), \quad n = 3, 4, 5, \ldots,$$

where R_H is the Rydberg constant for hydrogen. The value of R_H was empirically determined. (The Bohr model of the hydrogen atom would later provide an expression for the Rydberg constant in terms of fundamental physical constants.) Formulae of this type, but generally more complex, were obtained for a number of other series observed in the spectra of heavier elements.

An Early Model of the Atom

The proof of the independent existence of the electron was a starting point for theories of atomic structure. In 1910, Thompson[34] proposed one of the first models of the atom. His "plum pudding" model of internal structure depicted the atom as a homogeneous sphere of positive fluid, the "pudding," in which were imbedded the negatively charged electrons, the "plums." In this model, the electrons, which repel each other but are attracted to the positive charge, assume certain stable positions inside the atom. If an external force, e.g., the violent collisions between atoms in a hot gas, disturbed the electron distribution, the electrons would vibrate about their equilibrium positions and emit electromagnetic radiation. Thompson's model, then, provided a qualitative picture for the optical spectra of atoms. Calculations of the spectrum of radiation emitted from this model were not in quantitative agreement with experimental data. Conclusive proof of the inadequacy of this model would come in 1911 from experiments[35] carried out earlier

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[26] W. Crookes, Phil. Trans. Part I, 135 (1879), see W.F. Magie, *A Source Book in Physics*, (McGraw Hill, New York, 1935).

[27] J.J. Thompson, Phil. Mag. **44** 293 (1897).

[28] See F.W. Aston, *Mass Spectra and Isotopes, Second Edition*, (Longmans, Green & Company, NY, 1941), p. 192.

[29] R.A. Millikan, Phil. Mag. **19** 209 (1910).

[30] G.J. Stoney, Phil. Mag. **38** 418 (1894).

[31] A.J. Ångström, Phil. Mag. **9** 327 (1855).

[32] J.J. Balmer, Ann. der Physik und Chemie **25** 80 (1885). This reference is a summary of two earlier publications by Balmer on the hydrogen spectrum.

[33] J.R. Rydberg, K. Svenska Vet-Ak. Hdl. Oefv. **23** (1889).

[34] J.J. Thompson, Proc. Cambridge Phil. Soc. **15** 465 (1910).

[35] H. Geiger and E. Mardsen, Roy. Soc. Proc. **82** 495 (1909).

by two students, H. Geiger and E. Mardsen, working under Ernest Rutherford.

X-rays

In 1895, while experimenting with electric current flow in a discharge tube, Wilhelm Konrad Röentgen[36] noticed that salts of barium would fluoresce when brought near the tube. He determined that whatever caused the fluorescence in the salts originated at the point of the discharge tube where the cathode rays struck the glass wall. Apparently, some type of radiation was produced when the cathode rays impacted the end of the tube. Röentgen called this radiation X-rays, because of its unknown nature. He found the radiation to be energetic—it could pass through many layers of paper and even thin layers of metal. If metallic anodes were used in the cathode-ray tube, even more X-rays were produced; anodes made of heavy metals produced more X-rays than anodes of light metals. The X-rays traveled in straight lines and were not affected by electric or magnetic fields. They were found to ionize gases, making the gases conductors of electricity. In 1912, experiments[37] involving the scattering of X-rays from crystals indicated the rays were wave-like in character, i.e., a form of electromagnetic radiation.

Radioactivity

After the discovery of X-rays, scientists wondered if this radiation might also be emitted by certain materials that were known to be fluorescent—materials that would absorb light of a particular wavelength and then give off light of a longer wavelength. In 1896, Antoine-Henri Becquerel[38] began such studies on a uranium-containing compound, potassium uranyl sulfate. He found that after exposing this material to sunlight, radiation from the compound would penetrate paper and darken a photographic plate. More surprisingly, he found the material would darken the plate without having been exposed to sunlight. This would indicate that the material must have been emitting some type of radiation all the time. Becquerel found this radiation to be as penetrating as X-rays and capable of ionizing gases. Two years later, Marie Curie[39] observed a similar radiation emitted from compounds containing thorium.

In 1898, Marie and Pierre Curie began detailed studies consisting of standard chemical separations of the materials found in pitchblende, a uranium ore. The intensities of the radiation emitted by the separated compounds changed as a function of time. Measurements of the activities, or rates of decay, of the separated compounds were carried out. The activities were measured with an ionization chamber, first developed[40] by the Curies. In the course of these studies, the Curies isolated a new element, chemically similar to bismuth. Mme. Curie named the element polonium, in honor of her native country, Poland. In a July 1898 publication[41] announcing this discovery, the word "radio-active" was used for the first time in describing the materials in the uranium compounds. ("Radio" comes from the Latin word *radius*, meaning "ray." A radio-active material, then, is one that emits rays.) The Curies continued their studies and, in December 1898, announced the discovery of another element, which they[42] named radium, also from the Latin word *radius*. The following year, Andre Debierne, a former student of Pierre Curie, discovered a third element, actinium (from the Greek *aktis*, meaning "beam" or "ray"), in similar studies.[43]

Ernest Rutherford began studying the uranium and thorium compounds in 1898. He determined that two types of radiation were being emitted from the materials, "one that is very readily absorbed, which will be termed for convenience α radiation, and the other of a more penetrative character, which will be termed β radiation."[44] In 1899, Friedrich Giesel[45] determined that β rays were the same as cathode rays. In 1900, Paul Villard[46] identified still a third type of radiation, which was designated γ radiation. This was subsequently shown to be a form of electromagnetic radiation, like light and X-rays, only having higher energy. In 1909, Rutherford,[47] by collecting the α rays in an evacuated tube and detecting the buildup of helium, demonstrated that α particles were doubly ionized helium atoms.

Ernest Rutherford and Frederick Soddy quantitatively studied the activities of the materials chemically separated from the uranium and thorium compounds.[48] They found an exponential decay rate for the activity, A, as a function of time, t,

$$A(t) = A_0 e^{-\lambda_d t},$$

where λ_d is the disintegration constant[49] and A_0 is the initial activity. Another related constant used to characterize the materials was the half-life, $t_{1/2}$, the time needed for half of the radioactive atoms in a given sample to disintegrate:

$$t_{1/2} = \ln(2)/\lambda_d \approx 0.693/\lambda_d .$$

The various "daughter" products in the disintegrations could then be characterized by their half-lives as well as the types of radiation emitted. In 1903, Rutherford and Soddy[50] published a paper, "Radioactive Change," describing the change of an atom of one material into an atom of another material by the emission of an alpha or beta ray. An atom of uranium would spontaneously emit an alpha ray, changing into a chemically distinct atom of another material called uranium X_1. This atom would then emit a beta ray, changing into an atom of another material, called uranium X_2, and so on. A series of radioactive materials was thus generated.

Actually, three naturally-occurring radioactive decay series—the thorium, uranium, and actinium series—were being studied during this time (see Figure 15, page 27). Names were given to more than 40 radioactive "species" isolated in these series.[51] In the uranium series, there were uranium I (U_I), uranium X_1 (UX_1), uranium X_2 (UX_2), ionium (Io), radium A (RaA), radium B (RaB), and others. In the thorium series, there were mesothorium I ($MsTh_I$), mesothorium II ($MsTh_{II}$), radiothorium (RdTh), thorium X (ThX), thorium A (ThA), thorium B (ThB), and others. Between 1906 and 1907, several investigators showed that ionium, a uranium decay product, and radiothorium, a thorium decay product, when mixed with thorium, could not be separated by any chemical process. The three substances had different radioactive properties, but were chemically the same. In addition, A.S. Russell and R. Rossi[52] showed that the optical spectra of pure thorium and a mixture of thorium and ionium were indistinguishable. It would seem that these substances should occupy the same position in the periodic table. Soddy introduced the term "isotope"[53] to describe these materials.

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[36] W.K. Röentgen, Sitzber. Wurzberger Phys.-Med. Ges., Dec. 1895; Nature **53** 274 (1896).

[37] W. Freidrich, P. Knipping, and M. von Laue, Ber. Bayer. Akad. Wiss. 303 (1912).

[38] A.H. Becquerel, Compt. Rend. **122** 420 (1896); **122** 501 (1896).

[39] M. Sklodowska, C.R. Acad. Sci., Paris **126** 1101 (1898).

[40] See S. Quinn, *Marie Curie: A Life*, (Simon & Schuster, New York, NY, 1995), p. 145.

[41] P. Curie and M. Sklodowska Curie, Compt. Rend. **127** 175 (1898).

[42] P. Curie, Mme. P. Curie, and G. Bemont, Compt. Rend. **127** 1215 (1898).

[43] A. Debierne, Compt. Rend. **130** 960 (1900).

[44] E. Rutherford, Phil. Mag. **47** 109 (1899).

[45] F. Giesel, Ann. d. Phys. **69** 834 (1899).

[46] P. Villard, Compt. Rend. **130** 1178 (1900).

[47] E. Rutherford and T.D. Royds, Phil. Mag. **17** 281 (1909).

[48] E. Rutherford and F. Soddy, Phil. Mag. **4** 370 (1902); **4** 569 (1902); **5** 576 (1903).

[49] Due to the use of the symbol "λ" for wavelength previously, the subscript "d" is added when denoting the disintegration constant; this is not the standard notation.

[50] E. Rutherford and F. Soddy, Phil. Mag. **5** 576 (1903).

[51] A system for naming the radioactive "elements" was suggested by E. Rutherford but was not uniformly used. See N.R. Campbell, Nature **76** 638 (1907).

[52] A.S. Russell and R. Rossi, Proc. Roy. Soc. **87** 478 (1912).

[53] The word "isotope" is from the Greek words *isos* meaning "equal," and *topos* meaning "place," and was suggested by Soddy since isotopes occupy the same place in the periodic table of the elements. See F. Soddy, Nature **92** 399 (1913).

That a given element could exist in more than one chemically identical form would explain the large number of materials that were being observed in the studies of the radioactive decay chains. (For nuclides belonging to the three naturally-occurring radioactive decay chains, the historic symbols, UX_1, ThB, etc., are given on the Chart of the Nuclides.)

Confirmation of the existence of isotopes came in 1911 when Soddy published a comparison of the atomic weights of the stable element lead obtained from uranium- and thorium-rich ores.[54] The lead from the uranium ores had an average atomic weight slightly less than that from the thorium ores. More conclusive proof of isotopes came when J.J. Thompson[55] and Francis William Aston[56] carried out experiments consisting of passing positively charged neon ions through a magnetic field onto a photographic plate. Aston found two spots on the plate, one ten times larger than the other. He concluded that the neon atoms could have either of two weights, and that the abundance of the lighter was ten times that of the heavier. (A third isotope of neon would be discovered[57] later.) Modifying Prout's hypothesis, Aston proposed the whole number rule stating that the fractional atomic weights of elements are due to the presence of two or more isotopes, each of which has an approximately integral weight.[58]

Van den Broek[59] had suggested that the number of elementary positive charges in an atom corresponds to the ordinal number of the element in the periodic table. In 1913, Soddy[60] announced the displacement laws of radioactive decay. He proposed that the result of alpha emission (alpha particles have a +2 electric charge) from a material would be the formation of a "daughter" product that is two places to the left of the "parent" in the periodic table. Furthermore, the emission of a beta particle, having a charge of −1, would result in the formation of a "daughter" product that is one place to the right of the "parent" on the periodic table.

Rutherford's Model of the Atom

Beginning in 1906, Geiger and Mardsen,[35] working with E. Rutherford carried out a series of experiments with a beam of high-energy alpha particles bombarding a very thin metal foil, detecting the number of alphas scattered at various angles from the target. With the Thompson plum pudding model of the atom in which the positive charge was uniformly distributed throughout the atom, a sufficiently large concentration of charge would not exist in any one region of the atom to affect the alpha particles significantly. One would expect the alpha particles to pass through the material nearly undeflected. Most of the alpha particles passed straight through the foil or were scattered only slightly from their original paths. However, a small percentage was significantly deflected with some reversing their directions. This was totally unexpected. Rutherford thought, "[the experimental result] was about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."[61]

To explain these results, in 1911 Rutherford[62] postulated that the atom does not consist of a uniform sphere of positive electrification but that the positive charge is concentrated in a very small region, called the nucleus, at the center of the atom. In his dynamic planetary model, the nucleus plays the role of the sun and the electrons correspond to the individual planets of the solar system, revolving about the sun. This model, along with the classical laws of electricity and mechanics, provided an adequate explanation of alpha-particle scattering. Subsequent experiments performed on seven different scattering materials and for different alpha energies verified Rutherford's theory.

While the model satisfactorily explained the results of alpha-particle scattering, there were still questions about the stability of such an atom. Electromagnetic theory demands that an oscillating or revolving electric charge emit electromagnetic radiation. Such emission would result in the loss of energy by the emitting particle. Applied to orbital electrons, this energy loss would cause a steady contraction of the system, since the electrons would spiral into the central nucleus as their rotational energy was dissipated. This process would occur very rapidly and would directly contradict the permanent existence of atoms. In addition, if the radiation pattern produced by the atom were related to the energy radiated by the moving electron, this radiant energy would change with the radius of curvature of the electron's path. The pattern would consist of a continuous range of wavelengths. However, this is contradicted by experiments where individual, well-defined lines characterize the optical (and X-ray) spectra for a given element, not a continuous range of wavelengths.

Quantum Theory

In the early 1900s, it became obvious that not all physical phenomena could be adequately explained by the laws of classical physics. The thermal radiation spectrum emitted by a "blackbody" (a perfectly absorbing body) was one such phenomenon. A cavity inside a blackbody heated to a high temperature would contain electromagnetic radiation, generated by vibrating particles in the walls of the cavity. The distribution of the wavelengths of the radiation depended only on the temperature, not on the composition of the material.

Early attempts to explain the observed wavelength distribution failed. Theoretical predictions by Rayleigh[63] and Jeans[64] using classical statistical mechanics agreed with the experimentally measured distribution for long wavelengths, but disagreed at shorter wavelengths, approaching infinity as the wavelength became small. A comparison of the Rayleigh-Jeans predictions with experimental measurements is shown in Figure 3. In 1900, Max Planck[65] resolved this problem by making the radical assumption that the particles in the cavity wall could radiate energy only when the total energy was a multiple of some discrete amount (or quantum[66]) of energy. The energies were given by

$$E = nh\nu,$$

where n is an integer, ν is the frequency of the emitted electromagnetic radiation, and h is a constant (later named Planck's constant). With this assumption, the predicted spectrum agreed very well with experimental data.

Classical physics also failed in explaining the photoelectric effect. When light (electromagnetic radiation) is incident on a metallic surface, electrons are sometimes emitted from the metal. According to classical physics, the energy associated with an electromagnetic wave is proportional to the square of the amplitude or intensity. Accordingly, the emission of the photoelectrons should occur when the intensity of the light is sufficient to supply the

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[54] F. Soddy, Trans. Chem. Soc. **99** 72 (1911).

[55] See F.W. Aston, *Isotopes*, (Edward Arnold & Co., London, 1923), pp. 33–34.

[56] F.W. Aston, Phil. Mag. **39** 449 (1920).

[57] T.R. Hogness and H.M. Kvalnes, Phys. Rev. **32** 942 (1928).

[58] F.W. Aston, Proc. Roy. Soc. **A115** 487 (1927).

[59] A. Van den Broek, Physik. Z., **14** 32 (1913).

[60] F. Soddy, *Chemistry of the Radio-Elements*, (Longmans, Green & Co., Ltd, London, 1914).

[61] Quoted in J. Needham and W. Pagel, Ed., *Background to Modern Science*, (Cambridge University Press, 1940), p. 68.

[62] E. Rutherford, Phil. Mag. **21** 669 (1911).

[63] Lord Rayleigh, Phil. Mag. **49** 539 (1900).

[64] J.H. Jeans, Phil. Trans. A **196** 397 (1901).

[65] M. Planck, Verb. D. deut. Physik. Gesell **2** 237 (1900); Ann. Physik **4** 553 (1901).

[66] From the Latin *quantus*, meaning "how great." The word quantum, meaning "a quantity or an amount," had been used by British lawyers for several hundred years. In about 1910, scientists began using it following the work of Planck and that of Einstein, described below.

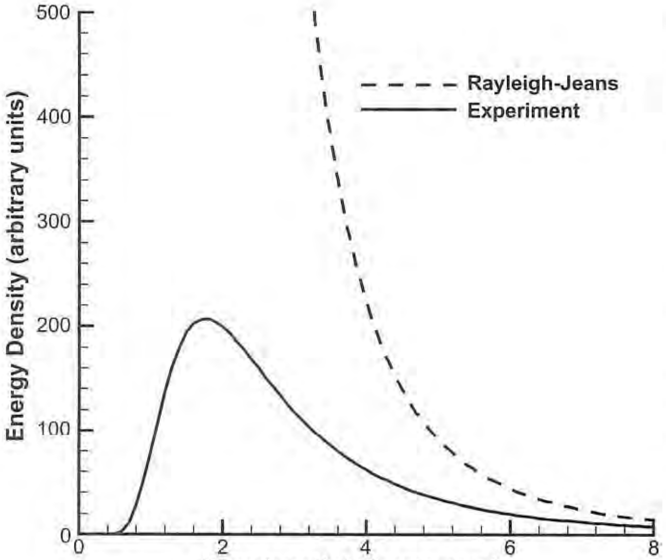

Figure 3. Comparison of the Rayleigh-Jeans Prediction for the Spectrum of Blackbody Radiation with Experimental Measurements (T = 1640 K). At long wavelengths, the theoretical predictions agree with experimental results.

necessary energy to eject the electrons. This is not the case.

Experimentally, it is found that the production of photoelectrons depends on the frequency of the incident light. Below a certain "threshold" frequency, which depends on the metal, no electrons are emitted regardless of the intensity of the light. Above this frequency, electrons are emitted and their energy is proportional to the frequency of the light. For light of a given frequency, the number of photoelectrons depends on the intensity of the light.

In 1905, Albert Einstein[67] proposed a mechanism for the emission of photoelectrons from a metal. He assumed that light has particle-like characteristics and that the energy, E, associated with these quanta was given by

$$E = h\nu,$$

where ν is the frequency of the light and h is Planck's constant. A quantum of light would interact with an electron in the metal. If the energy imparted to the electron were sufficiently large, the electron would be emitted from the metal. The maximum kinetic energy of the electron is given by

$$T_{\max} = h\left(\nu - \nu_0\right),$$

where ν_0 is a constant, the threshold frequency, characteristic of the metal. Experimental measurements confirmed the validity of this equation; higher precision measurements, made later, were used to accurately determine the value of Planck's constant.

Relativity

In the early 1900s, Einstein[68] also resolved some inconsistencies between the behavior of electromagnetic radiation and the laws of classical physics. According to his special theory of relativity, published in 1905, the mass of an object in a given frame of reference is given by

$$m = m_0\left(1-\frac{v^2}{c^2}\right)^{-1/2},$$

where m_0 is its mass when at rest, v is its velocity in the reference frame, and c is the speed of light in a vacuum. No particle with a finite rest mass can travel at $v = c$ in any reference frame, because its mass and energy would be infinite. Furthermore, mass and energy are equivalent, the total energy content of an object of mass m being given by the equation $E = mc^2$.

Beta particles emitted in radioactive decay can have velocities close enough to c that relativistic effects become important. Heavier particles of comparable energy travel much more slowly, so that their behavior is adequately described by classical physics.

Studies of X-Ray Spectra

Charles W. Barkla continued studies of Röentgen's X-rays. In 1911, he showed[69] that the energy of the X-rays emitted from a cathode-ray tube depended on the anode material. The X-ray spectra consisted of a continuous broad band of wavelengths on which groups of a few sharp, intense lines were superimposed. The "hardest" or most energetic group of lines was called the K-series, the next the L-series, then the M-series, and so on.[70]

In 1913, Henry G.J. Moseley[71] studied the K-series spectra for the elements from calcium to zinc and the following year looked at the L-series spectra for elements up to gold. Generally, as the atomic weight increased, the frequency of the X-ray lines increased, but there were irregular variations. There was, however, a regularity of the frequency as a function of the position of the element in the periodic table. If each element was assigned a number, Z, according to its position on the periodic table, Moseley found the square root of the X-ray frequency was proportional to Z − 1 for each element (see Figure 8, page 14). He reasoned that Z (now called the atomic number) must correspond to the positive charge on the nucleus. He concluded the ordering of elements in the periodic table should be based on Z, not on atomic weights.

This insight into the ordering of the elements in the periodic table was an important advance[72] and provided a new tool to scientists. The proper order of the known elements, including the rare earths, was now understood. The elements still missing from the periodic table could now be predicted with certainty. In 1913, the heaviest element known was uranium (Z = 92). Below that, seven gaps still existed, corresponding to Z = 43, 61, 72, 75, 85, 87, and 91. These were the only elements yet to be isolated. There were no more missing families of elements, as the inert gases had been earlier. Figure 4 shows the status of the periodic table at that time.

The Bohr Hydrogen Atom

Since the known stability of atomic systems could not be reconciled with classical principles of mechanics and electrodynamics, Niels Bohr, in 1913, reasoned[73] that classical physics laws must be wrong when applied to the motion of the electron in Rutherford's model of the atom. Bohr coupled Rutherford's model with quantum theory to produce the first quantum theory of atomic structure.

A body that spins about its own axis or revolves in an orbit about a central point possesses angular momentum. Bohr assumed that the electron's angular momentum was restricted to certain values (he quantized the angular momentum). Each of the values, which was described by a principal quantum number, n, would specify a particular circular orbit. An atomic system, whose electrons were in given orbits, would not emit electromagnetic radiation even

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[67] A. Einstein, Ann. Physik **17** 132 (1905).

[68] A. Einstein, Ann. Physik **17** 891 (1905).

[69] C.W. Barkla, Phil. Mag. **22** 396 (1911).

[70] *ibid.* These series had earlier been designated by the letters A, B, etc. Barkla, anticipating that additional series with both shorter and longer wavelengths probably existed, believed the designations K, L, M, etc. were preferable.

[71] H.G. J. Moseley, Phil Mag. **26** 1024 (1913); **27** 703 (1914).

[72] It was quite likely that Moseley would have been awarded the Nobel Prize for this work. However, when World War I broke out, Moseley enlisted in the Royal Engineers and on August 10, 1915 was killed by a sniper at Gallipoli. The Nobel Prize is not awarded posthumously. Of Moseley's death, Isaac Asimov wrote, "In view of what he might still have accomplished (he was only twenty-seven when he died) his death might well have been the most costly single death of the war to mankind generally." See Isaac Asimov, *Asimov's Biographical Encyclopedia of Science and Technology*, Second Revised Edition (Doubleday and Company, New York, 1982), p. 713.

[73] N. Bohr, Phil. Mag. **26** 1 (1913); **26** 476 (1913).

Period	Series	Group																
		I		II		III		IV		V		VI		VII		VIII			O
		a	b	a	b	a	b	a	b	a	b	a	b	a	b	a			b
1	1	H 1																	He 2
2	2	Li 3		Be 4			B 5		C 6		N 7		O 8		F 9				Ne 10
3	3	Na 11		Mg 12			Al 13		Si 14		P 15		S 16		Cl 17				Ar 18
4	4	K 19		Ca 20		Sc 21		Ti 22		V 23		Cr 24		Mn 25		Fe 26	Co 27	Ni 28	
	5		Cu 29		Zn 30		Ga 31		Ge 32		As 33		Se 34		Br 35				Kr 36
5	6	Rb 37		Sr 38		Y 39		Zr 40		Cb 41		Mo 42		43		Ru 44	Rh 45	Pd 46	
	7		Ag 47		Cd 48		In 49		Sn 50		Sb 51		Te 52		I 53				Xe 54
6	8	Cs 55		Ba 56		rare earths		72		Ta 73		W 74		75		Os 76	Ir 77	Pt 78	
	9		Au 79		Hg 80		Tl 81		Pb 82		Bi 83		Po 84		85				Rn 86
7	10	87		Ra 88		Ac 89		Th 90		91		U 92							

rare earths	La 57	Ce 58	Pr 59	Nd 60	61	Sm 62	Eu 63	Gd 64
	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	

Figure 4. The Short Form of the Periodic Table, ca. 1913. In the United States, the name columbium, Cb, was used for niobium, Nb (Z= 41), until 1949. In addition, by 1913, several claims as to the discovery of the element with Z = 43 had been made, but all were either proven false or never substantiated. (See Reference 13 for details.)

though the particles were accelerating. The whole atom was said to be in a stationary state. This assumption is contrary to classical electrodynamics as mentioned earlier. In Bohr's theory, electromagnetic radiation would be emitted or absorbed only when an electron changed from one allowed orbit to another allowed orbit. The energy difference between the two states would be emitted or absorbed in the form of a single quantum of radiant energy. This would produce the distinct spectral lines, described earlier, of definite frequencies, ν, related to the energy E by the relation $E = h\nu$ (already postulated by Planck and Einstein).

In Bohr's theory[74] for the hydrogen atom, the radii of the electron's circular orbits are given by

$$r = \frac{n^2\hbar^2}{m_r e^2}, \quad n = 1, 2, 3, \ldots,$$

where e is the charge on the electron, $\hbar = h/2\pi$, and m_r, the reduced mass, is given by

$$m_r = \frac{m_e M}{m_e + M},$$

where m_e is the electron mass, and M is the mass of the hydrogen nucleus. The corresponding total energy of the electron is given by

$$E = -\frac{m_r e^4}{2\hbar^2 n^2}, \quad n = 1, 2, 3, \ldots.$$

If an electron were to move from an orbit specified by the quantum number n_i to a different orbit specified by the quantum number n_f, the difference in energy of the electron would be

$$E_i - E_f = \frac{m_r e^4}{2\hbar^2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right).$$

The frequency of the light emitted (or absorbed) during this transition would be given by

$$\nu = \frac{c}{\lambda} = \frac{\left(E_i - E_f\right)}{h} = \frac{m_r e^4}{4\pi\hbar^3}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right).$$

The wave number, k, (the reciprocal of the wavelength) is given by

$$k = \frac{1}{\lambda} = \frac{m_r e^4}{\left(4\pi\hbar^3\right)c}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right).$$

The form of this equation is identical to that given by Rydberg (see "Optical Spectroscopy," page 3) for the Balmer series of lines in the hydrogen optical spectrum if $n_f = 2$ and

$$R_H = \frac{m_r e^4}{4\pi c\hbar^3}.$$

The value of R_H calculated from the above equation was found to be in good agreement with the value experimentally determined by Rydberg.[75]

Since other values of n_f are allowed in the above equation, the Bohr model predicted additional series in the optical spectrum of hydrogen. In succeeding years, four other series were observed experimentally: the Lyman[76] series in the ultraviolet region, corresponding to $n_f = 1$, and the Paschen,[77] Brackett,[78] and Pfund[79] series in the infrared region, corresponding to $n_f = 3$, 4, and 5, respectively. The Bohr model succeeded remarkably well in explaining the spectroscopic properties of the hydrogen atom.

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[74] More complete discussions of the Bohr theory of the hydrogen atom can be found in many nuclear physics textbooks, e.g. R.G. Sachs, *Nuclear Theory*, (Addison-Wesley Publishing Company, Cambridge, Mass., 1953). Bohr actually arrived at his model by a somewhat different and more general route, but he pointed out that the quantization of angular momentum in circular orbits provides a simple interpretation of it.

[75] The Rydberg constant, $R_\infty = m_e e^4/(4\pi c\hbar^3)$, is obtained from R_H as $M/m_e \to \infty$.

[76] T. Lyman, Nature **93** 241 (1914).

[77] F. Paschen, Ann. d. Phys. **27** 565 (1908).

[78] F.S. Brackett, Nature **109** 209 (1922).

[79] A.H. Pfund, J. Opt. Soc. Am. **9** 193 (1924).

Extension of the Bohr Theory

As higher resolution spectroscopic studies of hydrogen were made, it was found that spectral lines, originally believed to be single lines, actually consisted of a number of closely spaced lines. To explain this "fine structure," the quantum theory was further refined in 1916 when Arnold Sommerfeld[80] introduced an azimuthal quantum number, ℓ, where $\ell \leq n - 1$. With this modification, discrete elliptical orbits, in addition to the circular orbits, are allowed for electrons. This change permitted the Bohr model to account for detailed structure in the pattern of radiation emitted by hydrogen and other atoms.

To explain the change in the emitted radiation pattern when an atom is exposed to a magnetic field, a magnetic quantum number, m_ℓ, with permitted values from $-\ell$ to $+\ell$ was added. This quantum number designates different projections of the possible circular or elliptical orbits along the direction of the magnetic field in space.

Finally, to account for the close grouping of two or more spectral lines, George Uhlenbeck and Samuel Goudsmit[81] postulated that the electron has an intrinsic angular momentum, called spin. In a magnetic field, the spin axis can have two directions relative to the field, corresponding to the two possible values for the spin quantum number $m_s = \pm 1/2$.

For multi-electron atoms, the distribution of electrons among the allowed orbits was first studied by N. Bohr[82] and E. Stoner.[83] The orbits are determined by a set of the four quantum numbers, n, ℓ, m_ℓ, and m_s. All electrons with principal quantum number $n = 1$ are in the innermost orbit, called the K-shell.[70] Because electrons are "fermions" and obey the Pauli Exclusion Principle (see "Quantum Mechanics" below), only two electrons can occupy this shell. Both will have $\ell = 0$ and $m_\ell = 0$, but m_s can be $\pm 1/2$. For historic reasons, the integral values of the quantum number ℓ are often represented by letter symbols, i.e., s, p, d, f, g, …, corresponding to $\ell = 0$, 1, 2, 3, 4, …, respectively.[84] The innermost shell is designated the 1s shell (or subshell) corresponding to $n = 1$ and $\ell = 0$. For $n = 2$, the L-shell, two subshells are possible: the 2s and 2p. The designation of the shells and subshells, as well as the maximum number of electrons in each for up to 60 electrons, is shown in Table I.

Table I. Electron Subshells for $n = 1$–4

n	1	2	3	4
shell	**K**	**L**	**M**	**N**
ℓ	0	0, 1	0, 1, 2	0, 1, 2, 3
subshell	1s	2s, 2p	3s, 3p, 3d	4s, 4p, 4d, 4f
electrons/subshell	2	2, 6	2, 6, 10	2, 6, 10, 14
total electrons/shell	2	8	18	32

Electron Configurations

The structure of the atom predicted by the Bohr model provided a satisfactory understanding of many atomic phenomena. A neutral atom of an element has a characteristic number, Z, of net positive electronic charges in the nucleus with an equal number of electrons in the electron shells to balance the charge. Ions, the species responsible for electrical conduction in Faraday's experiments,[9] are simply atoms that have more or fewer electrons in their electron shells than positive charges in their nuclei. The net number of positive charges in the nucleus determines the elemental identity of the atom, while the difference between the number of electrons in the electron shells and the nuclear charge determines whether the atom behaves as a neutral atom, a positively charged ion (cation), or a negatively charged ion (anion).

When enough electrons are present to fill an electron shell, the atom is in a stable configuration and does not easily undergo chemical reactions. The inert gases have this electron configuration.

The similarities in chemical properties of the elements in the same column of Mendeleev's periodic table are due to the similarities in the configurations of the outer electron shells for those materials. Hydrogen, lithium, and other elements in the first column of the periodic table have only one electron in the outermost shell; beryllium, magnesium, calcium, and the other elements in the second column have two electrons in the outermost shell.

The similarity in the chemical properties of the rare earth elements was explained by the similarities in the structure of the outer electron shells for these materials. The additional orbital electrons in the elements from lanthanum to hafnium fill an inner electron shell (the 4f shell), while the outer shell structure of these elements stays almost the same.

The groups of X-ray lines, the K-series and the L-series, studied by Barkla[69] and Moseley,[71] can now be explained in terms of transitions within the shell structure of the electrons. If an electron is removed from one of the inner shells of an atom, an electron in some outer shell can fill the vacancy. The final state of the atom will be of lower energy and the atom would emit the energy difference in the form of an X-ray. The K-series of X-rays is produced by vacancies in the K-shell being filled by electrons originally in the L- or M-shell. The K_α series is due to transitions from the L subshells to the K-shell, while the K_β series arises from transitions from the M subshells to the K-shell. Similarly, the L_α and L_β series are produced by transitions from the M subshells to the L subshells.

Wave-Particle Duality

The wave nature of light had been demonstrated in experiments involving reflection, refraction, and diffraction. As mentioned earlier, Freidrich, Knipping, and von Laue[37] demonstrated the wave nature of X-rays by showing that X-rays are diffracted by crystals. Other studies, mentioned above, seemed to indicate that light also has a particle nature. In Planck's treatment of blackbody radiation, the concept of discrete amounts of energy (the energy quantum) was first introduced. Einstein then applied this concept to light in explaining the photoelectric effect.

The quantum theory states that electromagnetic radiation must be emitted or absorbed in integral multiples of these quanta. The quantization of its energy gives electromagnetic radiation some of the properties of particles and the term "photon" is used to refer to such particles of radiation. X-rays were found to have much shorter wavelengths than visible light, and correspondingly higher frequencies and energies. Visible light has wavelengths from 400 nm to 700 nm, and photon energies from 1.8 eV to 3.1 eV.[85] By comparison, the energies of K-series X-rays range from 54.3 eV for lithium to 115 keV for uranium and still higher for the transuranic elements.

In analogy with the wave-particle properties of light, Louis de Broglie[86] hypothesized in 1924 that particles might have wave properties as well. Like photons, the momentum and wavelength of particles would be related by $p = h/\lambda$. He further showed that the allowed orbits of the electrons in the Bohr model of the hydrogen atom could be defined by the condition that the circumference of

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[80] A. Sommerfeld, Ann. d. Phys. **51** 1 (1916).

[81] G.E. Uhlenbeck and S. Goudsmit, Naturwisse. **13** 953 (1925).

[82] N. Bohr, Zeit. f. Phys. **9** 1 (1922).

[83] E.C. Stoner, Phil. Mag. **48** 719 (1924).

[84] The letters s, p, d, and f are from the words "sharp," "principal," "diffuse," and "fundamental" and were originally used to describe the optical spectra of the alkali metals. The lines of the "sharp" series appear as relatively sharp lines, while the "diffuse" series lines are relatively broad, etc. see K. Kaplan, *Nuclear Physics*, (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1963), p. 138, and G. Herzberg, *Atomic Spectra and Atomic Structure*, (Dover Publications, New York, 1944), p. 86. For $\ell > 3$, the letter symbols simply follow alphabetically.

[85] The electron volt (eV) is defined as the energy necessary to raise one electron through a potential difference of 1 volt. The kiloelectron volt (keV) equals 1,000 eV and the megaelectron volt (MeV) equals 10^6 eV.

[86] L. de Broglie, Phil. Mag. **47** 446 (1924).

the electron's orbit contains an integral number of the electron's wavelengths, i.e., standing waves.[87]

In 1927, C. Davisson and G. Germer[88] showed that electrons could be diffracted by crystal lattices. Other experiments[89] also showed that when electrons passed through thin films of metal foils, the resulting diffraction patterns were similar to those obtained with X-rays. These experiments confirmed de Broglie's postulate.

Quantum Mechanics

As pointed out earlier, several phenomena could not be explained using the laws of classical physics and ad hoc assumptions were required, for example, Bohr's assumption that the orbital angular momentum of the electron was restricted to certain discrete values. A new explanation was provided by the development of quantum mechanics almost simultaneously by W. Heisenberg[90] and by E. Schrödinger.[91] Starting with de Broglie's postulate, these theories describe the motion of the de Broglie waves of a particle under the influence of an externally applied potential. The stationary states of the Bohr atom are then conceived as proper solutions of a fundamental wave equation.

In 1928, George Gamow was able to formulate a theory[92] of the alpha-decay of a radioactive nuclide in one of the first applications of quantum mechanics. The strength of the attractive force that binds the nucleons together in a nucleus decreases much more quickly with increasing distance than does the Coulomb force that causes particles with like charges to repel each other. When a positively-charged particle either approaches a nucleus from outside, or attempts to leave it from the inside, it encounters a region of space where the energy of the system is a maximum. This high-energy zone near the surface of the nucleus is now called the Coulomb barrier. Classical physics predicts that a particle that has insufficient energy to surmount the barrier at its highest point has zero probability of ever appearing on the other side. Quantum mechanics predicts that the probability of barrier penetration or "tunneling" through the barrier is small, but not zero, and becomes greater as the particle energy gets closer to the barrier height and as the barrier gets narrower. Gamow showed that alpha-radioactivity is a quantum mechanical barrier-penetration phenomenon.

In dealing with the behavior of a large number of particles, statistics are used. For example, the distribution of energies or velocities of the molecules of a gas can be described by the classical Maxwell-Boltzmann statistics. Classical statistics, however, cannot be used when dealing with the properties of large assemblies of electrons, protons, neutrons, and atomic nuclei. In quantum statistics, all particles or aggregations of particles have a net spin, which is either an integer (including zero) or half-integer. Particles with half-integer spin, including electrons and protons, obey the Pauli Exclusion Principle.[93] In general terms, this principle states that in a given system two identical particles cannot have the same set of quantum numbers. The behavior of large numbers of particles with half-integer spin is described by Fermi-Dirac statistics, and the particles are collectively called "fermions."[94] Particles with integral spin, such as photons, do not obey the Pauli principle. Instead of Fermi-Dirac statistics, they obey Bose-Einstein statistics and are collectively called "bosons." At high temperature or low densities, both the Fermi-Dirac and the Bose-Einstein behaviors converge toward classical, or Maxwell-Boltzmann statistics.

The Heisenberg Uncertainty Principle

Another result of the de Broglie hypothesis was the Heisenberg uncertainty principle.[95] Heisenberg stated that it is impossible to simultaneously determine both the position and momentum of a particle exactly. This limitation is expressed mathematically as

$$\Delta x \Delta p_x \geq \hbar.$$

Decreasing the uncertainty in the position, Δx, of the particle results in increased uncertainty in the momentum, Δp_x, of the particle, and the formula that describes the trade-off is based on Planck's constant. Similar relationships apply to certain other pairs of quantities, for example, energy and time. If the energy, E, of a particle is measured in a time interval, Δt, there will be a resulting uncertainty in the energy, ΔE, where

$$\Delta E \Delta t \geq \hbar.$$

One of the causes of the uncertainty relationship is that in measuring a property of a particle, e.g., the position, the measurement process itself disturbs the particle whose properties are being measured. The Heisenberg uncertainty principle goes beyond the observer effect and characterizes the uncertainty inherent to the mathematical quantities themselves. In other words, in quantum physics, an ideal experiment of a system is not deterministic but rather is characterized by a probability distribution. Therefore, if an experiment is repeated to measure a certain aspect of the quantum state, e.g., position, energy, or momentum, the result of the measurement will be a probability distribution. The wider the range of the distribution of results, the more "uncertain" is that aspect of the quantum state. The uncertainty principle and other aspects of quantum mechanics upended classical physics and replaced certainty with chance and probability.

Discovery of the Neutron

Through the early 1900s, the structure of the nucleus was not well understood. The lightest positively-charged particle was, presumably, the hydrogen nucleus or proton. Though scientists searched for a lighter particle, none was found. A proton-electron model had been assumed for the nucleus.[96] Nuclei of atoms heavier than hydrogen might be composed of protons and electrons, the protons supplying the bulk of the mass, while the electrons balance the electronic charge. The mass, A, of a given nucleus, expressed in units of the proton mass, would be approximately 2Z, where Z is the position of the element on the periodic table. A nucleus might then be composed of A protons and (A − Z) electrons. A neutral oxygen atom, for example, with Z = 8, would have a nucleus consisting of 16 protons and 8 electrons, and would have eight orbital electrons.

This view of the structure of the nucleus was altered with the discovery of the neutron.[97] In 1930, W. Bothe and H. Becker[98] found that a highly penetrating radiation was emitted when beryllium, boron, or lithium were bombarded by alpha particles from polonium. The radiation was not affected by magnetic fields and was not ionizing radiation. Initially, it was believed that this radiation might be high-energy gamma rays. In subsequent experiments carried out by Irene Curie and Frederic Joliot[99] in 1932, protons were

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[87] See R.B. Leighton, op. cit., p. 81.

[88] C. Davisson and L.H. Germer, Phys. Rev. **30** 705 (1927).

[89] G.P. Thomson, Proc. Roy. Soc. (London), **A117** 600 (1928); **A119** 663 (1928).

[90] W. Heisenberg, Z. Physik **33** 879 (1925).

[91] E. Schrödinger, Ann. Phys. **79** 361 (1926); **79** 489 (1926); **81** 109 (1926).

[92] G. Gamow, Z. Physik **51** 204 (1928).

[93] W. Pauli, Z. Physik **31** 765 (1925).

[94] The terms "fermion" and "boson" are contractions of the terms "Fermi-Dirac particle" and "Bose-Einstein particle." See R.D. Evans, *The Atomic Nucleus*, (McGraw Hill Book Company, New York, 1955), p. 180.

[95] W. Heisenberg, Z. Physik **43** 172 (1927).

[96] W.D. Harkins and E.D. Wilson, J. Am. Chem. Soc. **37** 1367 (1915); **37** 1383 (1915); **37** 1396 (1915).

[97] The first use of the word "neutron" has been attributed to E. Rutherford by J.L. Glasson (Phil. Mag. **42** 597 [1921]) and to W.D. Harkins (Phil. Mag. **42** 305 [1921]) by S. Glasstone, *Sourcebook on Atomic Energy*, (Van Nostrand, New York, 1950), p. 56.

[98] W. Bothe and H. Becker, Zeits. f. Phys. **66** 289 (1930).

[99] I. Curie and F. Joliot, Compt. Rend. **194** 273 (1932).

found to be produced when this radiation struck hydrogen-containing substances such as paraffin. James Chadwick[100] repeated these experiments and demonstrated[101] that the evidence from these experiments was compatible with the assumption that the radiation consisted of an uncharged particle having a mass approximately equal to that of the proton. The particle was called the neutron.

Soon after the discovery of the neutron, Heisenberg[102] suggested a neutron-proton model of the nucleus. The nucleus consists of Z protons and N neutrons. Protons and neutrons are both referred to as nucleons. The total number of nucleons in the nucleus is called the mass number, $A = N + Z$. An isotope is one of a group of two or more nuclides having the same number of protons or the same atomic number, but different numbers of neutrons. For example, natural hydrogen consists almost entirely of atoms having nuclei consisting of a single proton. However, a small amount (0.0115 percent) of deuterium (heavy hydrogen) is present in nature; the deuterium atom has a nucleus consisting of one proton and one neutron. The hydrogen and deuterium atoms both have a single orbital electron. In general, the situation becomes more complex as the heavier elements are encountered. Natural tin, which has an atomic number of $Z = 50$, consists of 10 stable isotopes of masses 112, 114, 115, 116, 117, 118, 119, 120, 122, and 124. Although the nuclei of all these isotopes have 50 protons, each contains a different number of neutrons (ranging from 62 to 74). The neutral atoms of these isotopes all have 50 orbital electrons.

The term "nuclide" refers to a species of atom characterized by the number of neutrons and protons contained in the nucleus.[103] Symbolically, a nuclide of element "X" may be represented by the elemental symbol with a subscript specifying Z and a superscript specifying A:

$$^{A}_{Z}\text{X}.$$

For example, the isotope of tin with $A = 115$ is represented as

$$^{115}_{50}\text{Sn}.$$

As mentioned above, in the study of the naturally-occurring radioactive series, more than 40 radioactive "species" were isolated. Soddy had pointed out that several of these materials were chemically identical, and with the new understanding of isotopes, the reasons were clear. The materials ionium, radiothorium, and thorium were all isotopes of thorium—^{230}Th, ^{228}Th, and ^{232}Th. RaA, AcA, and ThA were all isotopes of polonium; RaB, AcB, and ThB were all isotopes of lead. The three naturally-occurring radioactive decay series[104] are discussed in more detail on page 26.

The Positron

In his work on the relativistic quantum theory of the electron, Paul Adrien Maurice Dirac[105] first postulated the existence of an antiparticle of the electron, the positron, in 1931. The positively charged positrons would have the same mass (511 keV) and magnitude of charge as the electron and would react with electrons in matter by annihilation to produce gamma radiation. In an annihilation reaction, two 511 keV gamma rays, emitted in opposite directions, are produced, conserving momentum and energy. C.D. Anderson[106] established the existence of these particles in 1932 in studies of cloud chamber photographs of cosmic rays. This was the first indication that the universe is made up of both matter and antimatter.

Artificial Radioactivity

In 1932, after learning of the discovery of the positron, I. Curie and F. Joliot[107] re-examined experiments they had carried out earlier on the bombardment of certain elements with alpha particles from polonium sources. For some light elements, notably beryllium and aluminum, not only were neutrons emitted, but positrons were also observed. Furthermore, when the alpha source was removed, the emission of neutrons ceased but the positron emission continued, decaying with a characteristic half-life. With aluminum as the target, the half-life of the positron emission was about three minutes. For aluminum, Curie and Joliot hypothesized that the absorption of an alpha particle, ^{4}He, by aluminum, ^{27}Al, and subsequent emission of a neutron, ^{1}n, would lead to the formation of an isotope of phosphorus, ^{30}P. The phosphorus might be the source of the positron emission, decaying to ^{30}Si. While the detection of the small amounts of silicon produced in this reaction was not possible by chemical means, other chemical separations to isolate the phosphorus were devised. The positron emission followed the phosphorus in these separations, indicating the hypothesis was correct.

The isotope ^{30}P does not exist in nature. The work of Curie and Joliot showed that new isotopes could be produced through nuclear reactions, and they introduced the term "artificial radioactivity"[107] to indicate the manner in which these new isotopes were produced.

Nuclear Reactions

The initial reaction studied by Curie and Joliot can be represented by the following equation:

$$^{27}_{13}\text{Al} + ^{4}_{2}\text{He} \rightarrow ^{1}_{0}\text{n} + ^{30}_{15}\text{P}.$$

The symbols on the left represent the reacting nuclides; those on the right are the products of the reaction. Note that the superscripts on one side of the arrow balance those on the other side. The same is true for the subscripts. The balance represents the conservation of the number of protons and neutrons separately. In addition to charge and mass number, all nuclear reactions conserve momentum, angular momentum, mass-energy, and spin. A more abbreviated notation is frequently used:

$$^{27}\text{Al}(\alpha,\text{n})^{30}\text{P}.$$

In 1935, a summary of the known nuclides and the reactions used to study the nuclides was published by Giorgio Fea.[108] Included in the work was a "proton-neutron chart" showing the known isotopes of each element, whether the nuclide was stable or radioactive, and if stable, an indication of the relative abundance of the isotope. A portion of Fea's chart is shown in Figure 5. This was one of the earliest published charts of the nuclides.

Beta Decay and the Neutrino

The term "beta radiation" given to the radiation observed by Rutherford in the decay of the uranium and thorium compounds includes two types of decay: β^-, the emission of an electron from a nucleus, and β^+, the emission of a positron from a nucleus. These forms of decay differ from alpha, gamma, and X-ray emission in that the β^- and β^+ particles have continuous spectra of energies ranging from near zero up to an end-point value that is characteristic of the decaying nuclide. To account for the continuous spectrum, Wolfgang Pauli[109] suggested in 1930 that a new type of particle, the

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[100] J. Chadwick, Nature, p. 312 (1932).

[101] J. Chadwick, Proc. Roy. Soc. (London) **A136** 692 (1932).

[102] W. Heisenberg, Zeit. Phys. **78** 150 (1932).

[103] The word "nuclide" was proposed by Truman P. Kohman. See T.P. Kohman, Am. J. Phys. **15** 356 (1947).

[104] The symbols for the historic names of the nuclides belonging to each of the three naturally-occurring decay series are given in the squares for each of these nuclides on the Chart of the Nuclides.

[105] P.A.M. Dirac, Proc. Roy. Soc. **A133** 60 (1931).

[106] C.D. Anderson, Phys. Rev. **43** 491 (1933).

[107] I. Curie and F. Joliot, Compt. Rend. **194** 708 (1932).

[108] Giorgio Fea, Nuovo Cimento **2** 368 (1935).

[109] W. Pauli, unpublished letter, Dec. 4, 1930. An English translation is given in J. Steinberger, Science **259** 1872 (1993).

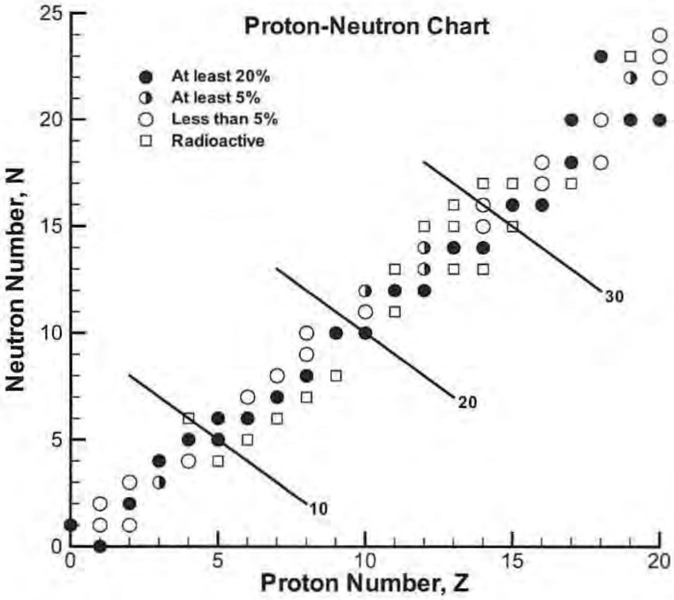

Figure 5. A Portion of the Proton-Neutron Chart Published by G. Fea in 1935 (Ref. 108). Radioactive nuclides are indicated by squares. The relative abundances of the stable nuclides are indicated by the shading of the circles as shown in the legend.

neutrino[110] (little neutral one) or its antiparticle, the antineutrino, might be emitted in beta decay. These are uncharged particles with either extremely small or zero rest mass and have extremely low probabilities of interacting with matter. The sum of the beta-particle energy and the neutrino or antineutrino energy, rather than the beta-particle energy alone, would have discrete values.

The production of antineutrinos from the beta decay of the neutron was confirmed in 1956. The detection of the products of the reaction of antineutrinos (produced from the decay of neutrons in a high flux reactor) and protons by Reines and Cowan[111] gave unmistakable evidence for the existence of the antineutrino.

For β^- decay, the process is represented by

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu},$$

or

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^- + \bar{\nu},$$

where is $\bar{\nu}$ an antineutrino. Likewise, for β^+ decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e + {}^{0}_{0}\nu,$$

or

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^+ + \nu,$$

where ν is a neutrino.

An alternative to β^+ decay, electron capture, ε, was proposed by Yukawa and Sakata[112] in 1936. Here an orbital electron from the K or L shell is captured by the nucleus and is accompanied by the emission of a neutrino.

$${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{0}\nu.$$

As in β^+ decay, the atomic number, Z, of the original nucleus is reduced by one, while the mass number, A, is unchanged. L. Alvarez[113] observed this type of decay in 1938.

Production of New Elements Using Nuclear Reactions

The realization that new nuclides could be produced through reactions with alpha particles led to the development of particle accelerators capable of producing beams of high-energy charged particles. Among these machines were the Cockcroft-Walton accelerator,[114] the Van de Graaff accelerator,[115] the cyclotron,[116] the betatron,[117] and the linear accelerator[118] (linac). Reactions induced by protons, deuterons (the deuterium, ^{2}H, nucleus), neutrons (produced using charged-particle-induced reactions), and photons were shown to lead to other radioactive products, each characterized by a half-life and certain decay products.

Nuclear reactions were used to produce the elements still missing from the periodic table below Z = 92. In 1937, the element technetium (from the Greek word *technetos* meaning "artificial") was produced[119] by bombarding a molybdenum target with deuterons. This was the first element to be produced artificially. Similarly, the element promethium was produced[120] in 1947 by bombarding a neodymium target with deuterons. No naturally-occurring (stable) isotopes of either technetium or promethium exist.

Fission

In attempts to produce transuranium elements, i.e., elements beyond uranium in the periodic table, scientists bombarded uranium targets with slow neutrons, believing the capture of a neutron by the uranium nucleus, followed by beta decay, might produce isotopes of elements with Z > 92. They expected the atomic number of the resulting nuclides to be only slightly different from that of uranium. The experiments were complicated by the difficulty in chemically separating the trace amounts of reaction products. Furthermore, choosing the proper chemical techniques for separation was difficult since the chemistry of the transuranium elements was open to speculation. Correlating the properties of the newly produced radioisotopes with those predicted for the transuranium elements proved extremely difficult. For several years, scientists were misled by the *a priori* assumption that the neutron bombardment of uranium would produce only transuranic elements.

In 1939, Hahn and Strassmann[121] showed that the products of the neutron bombardment of uranium included barium, lanthanum, and cerium, with Z = 56, 57, and 58, respectively. The presence of elements in the medium mass region was totally unexpected. Other medium mass materials—molybdenum, rubidium, antimony, and iodine—were detected in further chemical analyses. The presence of elements of intermediate mass indicated the uranium nucleus had split into fragments. L. Meitner and O. Frisch[122] proposed the use of the word "fission" to describe this process and showed that the energy associated with the fissioning of the ^{235}U nucleus was on the order of 200 MeV. (The word fission was originally used in biology to describe the way cells divide.)

The emission of neutrons during fission was soon reported by several groups of researchers.[123] The possibilities of a chain reaction with the liberation of a tremendous amount of energy became apparent. With the obvious military possibilities of nuclear energy, a secret program for the development of a fission bomb was begun in 1939 in the United States.[124]

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[110] The name "neutrino" was suggested by Enrico Fermi. See Emilio Segre, *Enrico Fermi, Physicist*, (University of Chicago Press, Chicago 1970), p. 70.

[111] F. Reines and C.L. Cowan, Jr., Nature **178** 446 (1956); Phys. Rev. **113** 273 (1959).

[112] H. Yukawa and S. Sakata, Proc. Phys. Math. Soc. Japan. **18** 128 (1936).

[113] L. Alvarez, Phys. Rev. **53** 213 (1938); **54** 486 (1938).

[114] J.D. Cockcroft and E.T.S. Walton, Proc. Royal. Soc. **A136** 619 (1932).

[115] R.J. Van de Graaff, Phys. Rev. **38** 1919 (1931).

[116] E.O. Lawrence and N.E. Edlefsen, Science **62** 376 (1930); E.O. Lawrence and M.S. Livingston, Phys. Rev. **40** 19 (1932).

[117] D.W. Kerst, Phys. Rev. **60** 47 (1941).

[118] R. Wideroe, Arch. Elektrotech. **21** 387 (1928).

[119] C. Perrier and E. Segre, Nature **140** 193 (1937).

[120] J.A. Marinsky, L.E. Glendenin, and C.D. Coryell, J. Am. Chem. Soc. **69** 2781 (1947).

[121] O. Hahn and F. Strassmann, Naturwissenschaften **27** 11 (1939).

[122] L. Meitner and O.R. Frisch, Nature **143** 239 (1939).

[123] H. von Halban, F. Joliot, and L. Kowarski, J. Phys. Rad. **10** 428 (1939); H.L. Anderson, E. Fermi, and H.B. Hanstein, Phys. Rev. **55** 797 (1939); L. Szilard and W. Zinn, Phys. Rev. **55** 799 (1939).

[124] See Richard Rhodes, *The Making of the Atomic Bomb*, (Simon and Schuster, Inc., New York, 1986).

Production of Elements with Z = 93 and 94

The elements with Z greater than 92 were produced by other nuclear reactions. In 1940, E.M. McMillan and P.H. Abelson[125] identified an isotope of element 93, ^{239}Np, produced by the capture of a neutron by ^{238}U:

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} + \gamma,$$

and

$$^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + \beta^{-} + \bar{\nu}.$$

The new nuclide, ^{239}Np, was itself radioactive, decaying by β^- emission with a half-life of 2.4 days. Since this new element was the first element beyond uranium, which was named after the planet Uranus, it was named neptunium, from Neptune, the first planet beyond Uranus.

Plutonium with Z = 94 was produced by bombarding ^{238}U with deuterons from the 60-inch cyclotron of the University of California at Berkeley by G.T. Seaborg, A.C. Wahl, and J.W. Kennedy[126] in 1941. The new element was named after the planet Pluto, following the pattern used for neptunium.

Modifications to the Periodic Table

The newly discovered elements, neptunium (Z = 93) and plutonium (Z = 94), were initially placed in the seventh row of the periodic table, following uranium (Z = 92). It was assumed that elements 95 and 96 would have chemical properties similar to those of neptunium and plutonium. Attempts were made[127] to produce these elements by bombarding ^{239}Pu with neutrons and deuterons and chemically isolating the new elements. These experiments failed.

It was suggested[128] that the elements following actinium on the periodic table should be placed in a second series, similar to the series of rare earths (which follow lanthanum). If this were the case, the chemical properties of elements 95 and 96 would be similar to actinium (Z = 89) and to the corresponding elements in the rare earths, europium (Z = 63) and gadolinium (Z = 64). With this assumption, new experiments[127] using different methods for chemically isolating the products were carried out[129] and succeeded[130] in producing isotopes of elements 95 (americium), in 1944, and 96 (curium), in 1945.

In this form of the periodic table, the rare earth series, starting with cerium (Z = 58) and ending with lutetium (Z = 71), was called the lanthanoid[131] series. The newer series[132] was located below the lanthanoids and was called the actinoid series. This new series began with thorium (Z = 90) and would ultimately end with lawrencium, Z = 103.

Recent Work

Since 1945, isotopes of twenty-one new elements have been produced. This work is summarized in "An Island of Stability for Superheavy Elements," beginning on page 34. Names have been given to sixteen of the twenty-one new elements. The known elements are listed in order of increasing atomic number and alphabetically by name in tables on the inside front cover and the last page of this book, respectively. In both lists, the atomic weights[133] (in atomic mass units, u) and the number of isotopes[134] are given for the stable and naturally-occurring radioactive elements. In the tables, the number in parentheses following the weight is the uncertainty in the last significant figures of the weight.

The proton-neutron chart published by Giorgio Fea in 1935 (Figure 5, page 11) included information on about 320 nuclides. Today, approximately 2,900 nuclides are known. The Chart of the Nuclides summarizes the properties of these nuclides; a description of the type of information included on the Chart begins on page 16.

The Periodic Table of the Elements

The Periodic Table of the Elements is shown on the inside back cover of this book. The elements are arranged in the table, first in order of increasing atomic number (the number of protons in the nucleus or the number of extra-nuclear electrons in the uncharged atom), and then in horizontal rows, called periods, and vertical columns, called groups or families. Members of each group have similar electron configurations in the outermost electron shells and, therefore, have similar physical and chemical properties. As shown in Table II, Group 1 elements are called the alkali metals, Group 2 the alkaline earth metals, Group 17 the halogens, Group 18 the noble gases, etc. In this form of the periodic table, two separate periods of elements, the lanthanoids and the actinoids, are shown outside the main table. The elements in groups 3 to 11 are sometimes called "transition metals"; yttrium and the lanthanoids are also called the "rare earth elements."

Table II. Groups/Families of Elements[135] on the Periodic Table

Group	Family
1	alkali metals or hydrogen family
2	alkaline earth metals or beryllium family
3	scandium family
4	titanium family
5	vanadium family
6	chromium family
7	manganese family
8	iron family
9	cobalt family
10	nickel family
11	copper family
12	zinc family
13	boron family
14	carbon family
15	pnictogens or nitrogen family
16	chalcogens or oxygen family
17	halogens or fluorine family
18	noble gases or helium family

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[125] E.M. McMillan and P.H. Abelson, Phys. Rev. **57** 1185 (1940).

[126] G.T. Seaborg, A.C. Wahl, and J.W. Kennedy, Phys. Rev. **69** 367 (1946). (This work was submitted for publication in 1941, but was voluntarily withheld from publication until the end of World War II because of the nature of its contents.)

[127] G.T. Seaborg and W.D. Loveland, *The Elements Beyond Uranium*, (John Wiley & Sons, Inc. New York, 1990).

[128] G.T. Seaborg, Chem. and Eng. News **23** 2190 (1945).

[129] The chemical separation and identification of these elements were extremely difficult and went on for nearly a year. During this time, one member of Seaborg's research group referred to these (yet unnamed) elements as "pandemonium" and "delirium." See M.E. Weeks and H.M. Leicester, *Discovery of the Elements*, (Mack Printing Company, Easton, Pa., 1968), p. 847.

[130] B.B. Cunningham, Metallurgical Laboratory Report CS-3312, pp. 5–6 (1945). The first public announcement of the discovery of americium and curium was made by Seaborg on the Quiz Kids radio program, November 11, 1945. See G.T. Seaborg, J. Chem. Ed. **45** 278 (1968).

[131] The International Union of Pure and Applied Chemistry (IUPAC) currently recommends the names lanthanoid and actinoid rather than lanthanide and actinide, since the suffix "-ide" normally indicates a negative ion.

[132] See Reference 127 for a discussion of changes to the periodic table during this time.

[133] As mentioned earlier, Dalton obtained masses relative to the hydrogen atom. In 1819, Berzelius published a table of masses relative to the mass of oxygen, which was taken to be 100. This system was used until the 1860s, when chemists again adopted the hydrogen scale. In 1906, this was converted back to the oxygen scale and the atomic mass unit was taken to be 1/16 of the atomic mass of oxygen. After the discovery of the oxygen isotopes, two scales were used—a chemical scale based on 1/16 of the average mass of the natural oxygen atom and a physical scale, using a mass unit equal to 1/16 of the mass of the ^{16}O atom. In 1961, a single scale based on ^{12}C, whose mass was taken to be 12.000000, was chosen.

[134] Eighty-four elements have stable or long-lived naturally-occurring isotopes. There are a total of 288 stable or long-lived naturally-occurring isotopes for which isotopic abundances are given on the Chart of the Nuclides. See "Isotopic Abundances" on page 18.

[135] N.G. Connelly, T. Bauhus, R.M. Hartshorn, and A.J. Hutton, "Nomenclature of Inorganic Chemistry, IUPAC Recommendations 2005," International Union of Pure and Applied Chemistry, 2005.

Within each square, the atomic number, the name and symbol, the relative atomic weight, and several physical and chemical properties are given for the element. The color of the name and symbol indicates the form of the element at standard temperature and pressure[136] (STP): gas (green), liquid (blue), or solid (black). Elements that do not exist in nature (artificially prepared) are shown in red. The atomic number is given in the upper left corner of the square and is the number of protons in the nucleus of the atom or the number of orbital electrons in the uncharged atom. The relative atomic weights of the naturally-occurring elements, in atomic mass units (u), are given below the symbols. The atomic mass unit is 1/12 of the mass of the ^{12}C atom in its atomic and nuclear ground state.

In the upper right corner of the square, the common oxidation states[137] of the element are given with the most common in red. For an element in a combined state (a compound), the oxidation state is the number of electrons that must be added to or subtracted from the ion to convert it to the elemental form. For example, in the compound $NiCl_2$, the oxidation state of Ni is +2, while that of chlorine is –1. While some elements have only one oxidation state (see the Group 1 and 2 elements in the Periodic Table) others can take on several values (see Groups 7, 8, and 9, for example).

Below the oxidation states, the electronegativities of the elements are given. These parameters describe, on a relative basis, the tendencies of an atom in a molecule to attract bonding electrons and are discussed in the Chemical Bonding section below.

Along the lower left side of each square, the melting and boiling points, the specific gravity, and the thermal conductivity are given for each element.

- Melting and Boiling Points. The melting and boiling points are given in degrees Celsius and are at atmospheric pressure. For some materials, e.g., carbon and arsenic, the sublimation temperature (denoted by "subl") is given instead of the boiling point. The melting and boiling points of the elements having $18 \le Z \le 90$ are shown in Figure 6. Three periods are shown on the graph: $19 \le Z \le 36$, $37 \le Z \le 54$, and $55 \le Z \le 86$. The last period includes the lanthanoids ($58 \le Z \le 71$). Similarities in the trends of the melting and boiling points for the three periods should be noted.

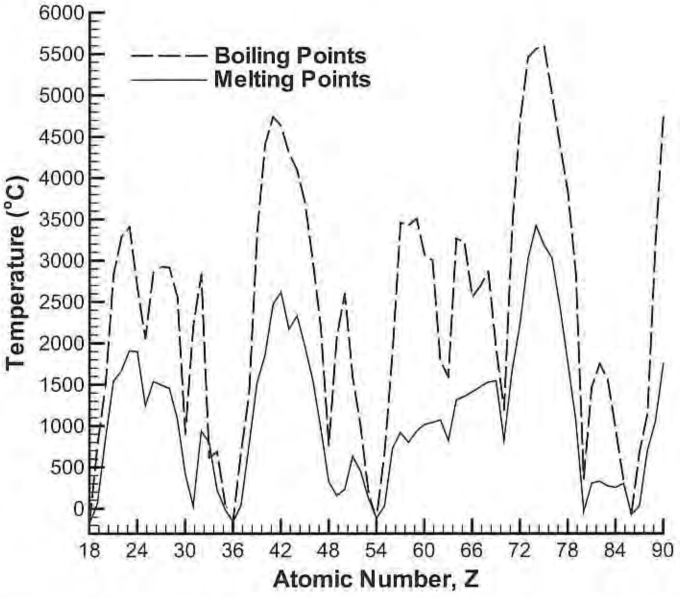

Figure 6. Melting and Boiling Points for the Elements between Z = 18 and Z = 90.

- Specific Gravity (for gases, density). For elements that are liquids or solids at standard temperature and pressure, the specific gravity is given. The specific gravity of a material is the ratio of the weight of that material to the weight of an equal volume of water. The specific gravities given on the periodic table are at 20°C. For elements that are gases at STP, the density is given in grams per liter at 0°C.
- Thermal Conductivity. The thermal conductivity[138] of a material is the rate of heat transfer by conduction through a unit thickness per unit area per unit difference of temperature and is given in units of watts per meter per Kelvin.

On the lower right side of each square, the atomic radius, the principal X-ray emission energies in keV, and the crustal abundance are given.

- Atomic Radius. The atomic radius is given in picometers (10^{-12} meters). Generally speaking, the atomic radius increases from top to bottom of a group and decreases from left to right over a period. Figure 7 is a plot of values of the atomic radii for elements with $18 \le Z \le 90$. Note the similarities in the shape of the curve going from period to period.
- Principal X-ray energies. For elements with $Z \le 62$, energies[139] of the K_α and K_β lines are given, while for $Z > 62$, the energies correspond to the L_α and L_β lines. The regular variation (observed by Moseley[71]) of the square root of the energy of these X-rays as a function of the atomic number is shown in Figure 8.
- Crustal Abundance. Geologically, the planet earth consists of three shells: the core, the mantle, and the crust. Though the crust is only about 20 km thick and contains about one percent of the total mass of the earth, this region is vitally important since it provides the raw materials required by man. The crustal abundance of each element is given in parts per million by mass.

Chemical Bonding

In the first half of the 20th century, G.N. Lewis,[140] Irving Langmuir,[141] Linus Pauling,[142] and others explained much of what

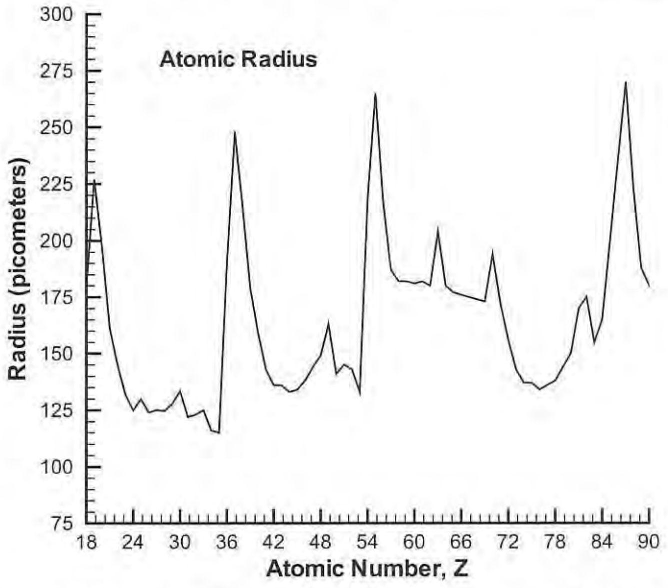

Figure 7. The Atomic Radius for the Elements between Z = 18 and Z = 90. The peaks occur at Z = 19, 37, 55, and 87, corresponding to elements in Group 1 of the Periodic Table.

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[136] "Standard Temperature and Pressure" (STP) is defined as a temperature of 0°C (273.15 K) and a pressure of 1 atmosphere (101.325 kPa).

[137] Numerical values taken from David R. Lide, Editor-in-Chief, *Handbook of Chemistry and Physics, 89th Edition, 2008–2009*, (CRC Press, Boca Raton, 2008).

[138] Numerical values taken from J. Emsley, *The Elements*, (Clarendon Press, Oxford, 1996).

[139] G.C. Johnson and G.B. White, *X-ray Emission Wavelengths and keV Tables for Nondiffractive Analysis*, ASTM Data Series, DS46 (1970).

[140] G.N. Lewis, J. Amer. Chem. Soc. **38** 762 (1916).

[141] I. Langmuir, J. Amer. Chem. Soc. **41** 868, 1543 (1919).

[142] Linus Pauling, *The Nature of the Chemical Bond, Third Edition*, (Cornell University Press, Ithaca, NY, 1960).

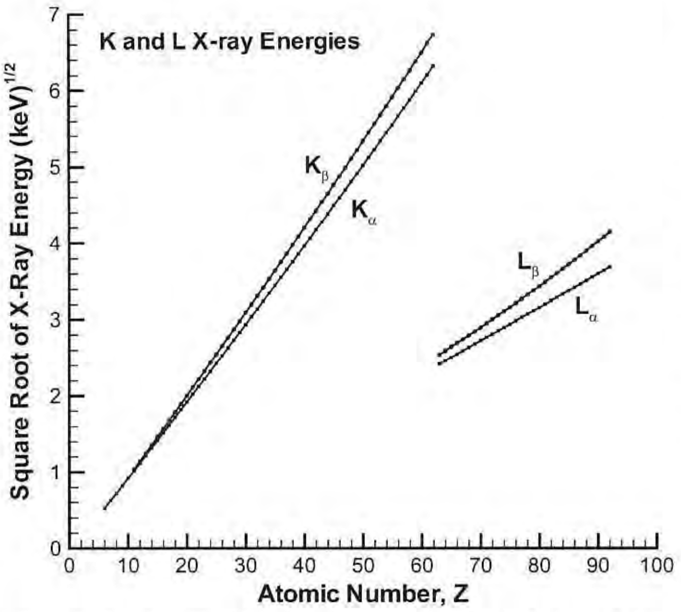

Figure 8. The K and L X-ray Energies Plotted as a Function of the Atomic Number. The regularity of the square root of the X-ray energy as a function of the position of the element in the periodic table was first observed by Henry G.J. Moseley (see "Studies of X-Ray Spectra," page 6).

had been observed about the structure and stability of chemical substances in terms of atomic theory and wave mechanics. They recognized three idealized forms of strong primary bonding and several weaker secondary interactions. To a first approximation, all forms of bonding involve only the electrons in the outer shells of the atoms, those that are most weakly bound to the nucleus. The special stability of completely-filled electron shells plays a large role in chemical bonding. The energies involved in all three primary forms of chemical bonds are on the order of one to ten electron volts per atom. The three forms of primary bonding are called ionic, covalent, and metallic. The actual bonding in many compounds is best described as a combination of the primary forms.

Electrons are transferred in ionic bonding. If only one or two electrons are in the last unfilled shell of an element, it is relatively easy for the atom to lose these electrons to another atom whose last unfilled shell has one or two vacancies. Both atoms can thus attain configurations in which the outermost electron shell is completely filled. The first of these atoms becomes a positively charged ion because of the loss of electrons, and the second becomes a negatively charged ion because of the gain of electrons. NaCl, LiF, and Fe_2O_3 are some compounds having ionic bonding. The electrostatic attraction between the ions binds them into a compound. The attraction is strongest for small ions with high charge. In idealized ionic bonding, the electron distribution around either type of ion is spherically symmetric. In ionic crystals, the relative sizes and numbers of the different types of ions largely determine their geometric arrangement. In an ionic crystal of formula A_mB_n, where $n \geq m$, the ions of element A are typically surrounded by four to eight ions of B in a lattice that resembles a three-dimensional checkerboard.

Atoms also bond to each other by sharing electrons, usually in pairs. Such covalent bonds are formed between atoms of the same element, or between pairs of elements that are not as far apart on the periodic table as the pairs that form ionic bonds. The H_2O, N_2, and O_2 molecules have this type of bonding.

Atoms usually form just enough covalent bonds to fill their unfilled shells when each shared electron is counted as if it belonged to each atom sharing it. Covalent bonds are localized in space, in that the density of electrons is greater near a line between the two atoms than elsewhere, and pairs of covalent bonds to a given atom tend to have a characteristic angle between them. In typical covalent compounds, four or fewer nearest-neighbor atoms surround each atom. Atoms of different elements share electrons unequally. The tendency to attract shared electrons is called electronegativity. Although various definitions and scales of electronegativity have been proposed, they all agree that elements that most easily form negative ions have the highest electronegativity, while elements that most easily form positive ions have the lowest. Covalent bonds between atoms with different electronegativities are called polar covalent or partially ionic bonds. They gain additional strength through their partial ionic character.

Atoms in metals are bound by electrons that are spread out through the entire solid or liquid. Like ionic bonding, and unlike covalent bonding, metallic bonding has no preferred directions. Most metallic elements crystallize in one of three simple crystal structures, in which each atom is symmetrically surrounded by eight or twelve nearest neighbors. Metals can form compounds with each other in which the bonding is mainly metallic. These intermetallic compounds exhibit a wide variety of structural types. Except for hydrogen, all the elements in columns 1–12 of the periodic table are metals (see Figure 9). Columns 13–16 include some metals, some non-metals, and several elements with intermediate properties. Al, Ga, Sn, Bi, and Po are predominantly metallic, while elements above or to the right of them have progressively fewer metallic properties. Some compounds between metals and non-metals, for example the carbides and nitrides of the metals in columns 4–6, are predominantly metallic.

While the gain or loss of a single electron is easiest for atoms with only one electron or one vacancy in an unfilled shell, multiply-charged ions are more strongly attracted to each other in a crystal lattice. For example, sodium fluoride (Na^+F^-) melts at 1,269 K and boils at 2,075 K, while magnesium oxide ($Mg^{2+}O^{2-}$), which has the same crystal structure and the same total number of electrons, melts at 3,105 K. Atoms whose unfilled shells are more nearly half-filled can form greater numbers of covalent bonds or form stronger

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac*	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	113	114	115	116		118

***Lanthanoids**	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
***Actinoids**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 9. Periodic Table of the Elements Showing the Families of the Elements.

metallic bonds than those in the outer columns of the periodic table. The trends in melting points (see Figure 6, page 13) of the elements within each row of the periodic table illustrate this effect.

Atoms that have already attained a filled outer shell by electron transfer or sharing can still participate in secondary forms of attraction. Energies of these secondary forms of attraction range from near zero to about a tenth of an electron volt per atom. One of the stronger forms of secondary attraction is called hydrogen bonding.[143] A hydrogen atom that is already covalently bonded to a highly electronegative atom (F, O, or N) in one molecule can form a hydrogen bond to an F, O, or N atom in another molecule. Hydrogen bonding is largely responsible for the high boiling point of H_2O in comparison to many other small covalent molecules.

Molecules with polar covalent bonds have non-uniform distributions of electrical charge. The more negative portion of a polar molecule will be attracted to positive ions or to the positive portions of other polar molecules.

Even nonpolar molecules and single neutral atoms are subject to secondary attractive forces. The electric field of a nearby ion or polar molecule can perturb the electron cloud of a nonpolar molecule or atom, inducing a small temporary charge redistribution that results in a weak attraction. Finally, the electron clouds of nonpolar molecules or atoms can perturb each other enough to generate weak attractive forces. The secondary attractions that affect nonpolar molecules and atoms become stronger with increasing size of their electron clouds. This trend is illustrated by the boiling points of the elements in column 18, which vaporize as single atoms, and those in column 17, which form covalently bonded diatomic molecules.

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[143] T.S. Moore and T.F. Winmill, J. Chem. Soc. **101** 1635 (1912); W.M. Latimer and W.H. Rodebush, J. Amer. Chem. Soc. **42** 1419 (1920).

Overview of the Chart of the Nuclides

Earlier Charts and Tabulations

As new nuclides were produced using techniques described in the previous section, charts and tables summarizing properties of the known nuclides were developed. One of the earliest charts was published in 1935 by Giorgio Fea[108] and a portion of that chart is shown in Figure 5 on page 11. Charts with other formats[144,145] were used by researchers to emphasize different properties or relationships between the nuclides. Emilio Segre developed a more detailed chart, similar to current charts, in 1946.[146] In Segre's chart, masses, abundances, capture cross sections, half-lives, and decay modes were given for the known nuclides. As with Fea's chart, the neutron number was used as the vertical axis and proton number as the horizontal axis.

In 1957, a trilinear chart of the nuclides was published by W.H. Sullivan.[147] A portion of the chart is shown in Figure 10. Here, each nuclide is represented by a hexagon. Within the hexagons, half-lives, spins, decay modes, thermal neutron cross sections, and other information about each nuclide were given. With this arrangement, **isobars** (nuclides having the same mass number) lie in a vertical line; **isotopes** (nuclides with the same atomic number) lie along a line inclined at 30° above the horizontal; **isotones** (nuclides with the same number of neutrons) lie along a line inclined at 30° below the horizontal; and **isodiapheres** (nuclides having the same excess number of neutrons, A − 2Z) lie on a horizontal line. Additional information about the trilinear coordinate system is given in Reference **145**. In 2005, the Radiochemistry Society published the latest version[148] of the trilinear chart.

Several other nuclide charts are currently available. These include the Karlsruhe[149] Nuclide Chart, the Strasbourg[150] Nuclide Chart, and the JAERI[151] Nuclide Chart.

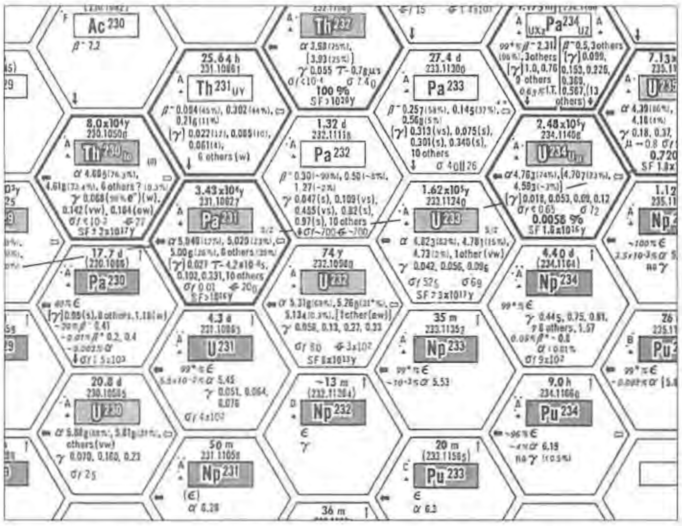

Figure 10. A Portion of the Trilinear Chart of the Nuclides Published by W.H. Sullivan (Ref. 147).

One of the first comprehensive tabulations of properties of known nuclides was published by Livingood and Seaborg in 1940.[152] This tabulation was the first edition of the Table of Isotopes. The eighth edition of this table was released in 1996, with updates in 1998 and 1999.[153] Currently, the *Isotope Explorer Version 3D*[154] is available on the Internet.

The first edition of the present *Chart of the Nuclides* was compiled by G. Friedlander and M. Perlman and published by the General Electric Company in 1946. This Chart differed from those of Fea and Segre in that the proton number was used as the vertical axis and the neutron number as the horizontal. All editions of the *Chart of the Nuclides* since then have used this layout. The current chart is the seventeenth edition of the *Chart of the Nuclides*.

At present, there are about 2900 known nuclides and 640 known isomers [see "Isomeric (Metastable) States," page 20]. Except for short-lived isomers present in decay of longer-lived parents or as part of the naturally-occurring radioactive series, only isomers with half-lives greater than about one second are included in the above count. Active nuclear research causes additions and changes in the list of nuclides. A given nuclide is included on the Chart only if the work leading to its discovery has been published in a refereed, scientific journal. Proceedings of technical conferences and the Evaluated Nuclear Structure Data Files[155] (ENSDF) at the National Nuclear Data Center are also consulted for the evaluation. Data referenced as "private communication" are not included in the Chart.

General Layout of the Chart

Information about the known nuclides, both stable and unstable, is summarized on the Chart of the Nuclides. Each nuclide occupies a square in a grid where the atomic number, Z, is plotted vertically against the number of neutrons, N, plotted horizontally. The atomic number is given at the left of each horizontal row. Each row represents one element; the gray squares indicate the known stable isotopes (and in some cases, long-lived naturally-occurring isotopes) of that element. Each vertical column shows nuclides having the same number of neutrons (isotones).

The heavily bordered square at the left side of each horizontal row gives the name, chemical symbol, elemental mass, thermal neutron absorption (disappearance) cross section, and resonance integral of the element. Each of the other occupied spaces in the row carries the chemical symbol and the mass number of the nuclide indicated. The mass number, A, is the sum of the number of neutrons, N, and the number of protons, Z, in the nucleus.

Nuclides on diagonals running from the upper left to the lower right of the Chart have the same mass numbers; these nuclides are called isobars. For example, one diagonal could connect ^{40}Ca, which has 20 protons and 20 neutrons, with ^{40}Ar, which has 18 protons and 22 neutrons. Both ^{40}Ca and ^{40}Ar have mass numbers of 40.

Heavy lines on the Chart occur for N or Z equal to 2, 8, 20, 28, 50, and 82, and for N = 126. These are the so-called "magic numbers," i.e., the numbers of neutrons or protons present when a neutron or proton shell is closed.

Colors and shading are used on the chart squares to indicate relative magnitudes of half-lives and neutron absorption properties. Four different colors—blue, green, yellow, and orange—are used for these identifications. The background color of the upper half of a square represents half-life and the background color of the lower half of a square represents the greater of the thermal neutron

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[144] See Clark Goodman, Ed., *Introduction to Pile Theory*, (Addison-Wesley Press Inc., Cambridge, Mass., 1952).

[145] D.E. Hull and W.H. Sullivan, J. Chem. Education **24** 436 (1947).

[146] Emilio Segre, *A Mind Always in Motion, The Autobiography of Emilio Segre*, (University of California Press, Berkeley, 1993), p. 190. Segre's original chart was developed at Los Alamos in 1945. An unclassified revision of the first chart was available in 1946. A third revision, carried out in 1948, is included in Reference 144.

[147] W.H. Sullivan, *Trilinear Chart of Nuclides, 2nd Edition*, (U.S. Government Printing Office, Washington, D.C., 1957).

[148] Radiochemistry Society, P.O. Box 3091, Richland, WA 99354 or www.radiochemistry.org.

[149] *Karlsruhe Chart of the Nuclides*, 7th Edition 2006, G. Pfennig, H. Klewe-Nebenius, and W. Seelmann-Eggebert.

[150] *Strasbourg Nuclide Chart 2002*, M.S. Antony, Centre de Recherches Nucleaires et Universite Louis Pasteur, Strasbourg, France.

[151] *JAERI Chart of the Nuclides 1996*. Japanese Nuclear Data Committee and Nuclear Data Center, JAERI, T. Horiguchi, T. Tachibana, and J. Katakura.

[152] J.J. Livingood and G.T. Seaborg, Rev. Mod. Phys. **12** 30 (1940).

[153] R.B. Firestone, S.Y. Frank Chu, and C.M. Baglin, *Table of Isotopes, Eighth Edition, 1998 Update*, (John Wiley and Sons, New York, 1998).

[154] This is an IP, LBNL-Lund collaboration at http://ie.lbl.gov/ensdf.

[155] Evaluated Nuclear Structure Data Files at http://www.nndc.bnl.gov.

cross section or resonance integral. When the nuclide is stable and the thermal neutron cross section is small or unknown, the entire square is shaded gray.

The gray shading is also used for unstable nuclides having lifetimes sufficiently long (> 5×10^8 years or 5E+8 years[156]) to have survived from the time the elements were formed. These naturally-occurring radioactive nuclides are highlighted by a special black band or rectangular area near the top. Other black-banded nuclides are formed through cosmogenic processes in the atmosphere (^{3}H, ^{7}Be, and ^{14}C) or are daughter products of naturally-occurring radioactive parents. The nuclides belonging to the naturally-occurring radioactive decay series are indicated by smaller black rectangles containing the symbol for the historic name, e.g., RaA, MsTh$_1$, and Io, given when these series were first investigated. White or colored squares represent artificially produced radioactive nuclides.

Certain squares, e.g., ^{60}Co, ^{115}In, and ^{116}In, are divided. Such divisions occur when a nuclide has one or more isomeric (or metastable) states. Isomers are nuclides having the same A and Z but different nuclear and radioactive properties resulting from different energy states of the same nucleus.

The known isobaric fission chains for the thermal neutron fissioning of ^{235}U, ^{233}U, and ^{239}Pu are indicated by lines drawn diagonally off the corner of the first or last nuclide for each mass number A. For a given value of A, the total cumulative yield for ^{235}U thermal neutron fission is given at the lower end of the right-most diagonal line; the total cumulative yields for ^{233}U and ^{239}Pu thermal neutron fission are given at the upper end of the left-most diagonal line, with the ^{239}Pu yields in parentheses. Nuclides that are fission products formed by the thermal neutron fission of ^{235}U are identified by small triangles or squares in the lower right corner of the squares. See page 27 for more details.

Information about the products of various nuclear reactions can be easily obtained from the Chart of the Nuclides. Figure 11 illustrates the combinations of incident (or bombarding) and emitted particles for several types of reactions and how each combination changes the target nucleus. A special type of shorthand is used on this diagram to identify the reactions. An example is (p,n) which denotes a reaction in which the nucleus absorbs a proton and emits a neutron. For this reaction, the product nucleus would have a value of N that had decreased by one:

$$N_{product} = N_{target} + N_{proton} - N_{neutron} = N_{target} + 0 - 1 = N_{target} - 1,$$

but the value of Z would have increased by one:

$$Z_{product} = Z_{target} + Z_{proton} - Z_{neutron} = Z_{target} + 1 - 0 = Z_{target} + 1.$$

On the Chart, the product nucleus is located one square to the left (N − 1) and one square above (Z + 1) the target nucleus. Note the location of the square labeled "(p,n)" relative to the "target nucleus" square in Figure 11.

For the (n,α) reaction, the target nucleus would have a value of N that had decreased by one:

$$N_{product} = N_{target} + N_{neutron} - N_{alpha} = N_{target} + 1 - 2 = N_{target} - 1,$$

and a value of Z that had decreased by two:

$$Z_{product} = Z_{target} + Z_{neutron} - Z_{alpha} = Z_{target} + 0 - 2 = Z_{target} - 2.$$

In essence, the target would have lost one neutron and two protons. The product nucleus would then be located one square to the left (N − 1) and two squares below (Z − 2) the target nucleus. Note the location of the square labeled "(n,α)" relative to the "target nucleus" square in Figure 11.

There is not enough space to indicate the one standard deviation uncertainty for the numerical values on the Chart. Therefore, the following convention has been adopted: the values given have been rounded off so that the uncertainty in the last decimal place is less than or equal to five units. For example, a cross section value of 6.78±0.08 barns would be quoted as 6.8. Similarly, a half-life value of 2,500±300 years would be quoted as 2.5E+3. If the error is estimated to be close to the limit of five units in the last figure, the value is preceded by a tilde (~). Thus, a cross section value of 2.75±0.05 barns is quoted as ~2.75. If trailing zeros are followed by a decimal point, the zeros are all significant. Otherwise, the last non-zero digit indicates the uncertainty of the value.

	(α,3n)	(α,2n) (^{3}He,n)	(α,n)	
	(p,n)	(p,γ) (d,n) (^{3}He,np)	(α,np) (t,n) (^{3}He,p)	
	(p,pn) (γ,n) (n,2n)	**Target Nucleus** (n,n)	(d,p) (n,γ) (t,np)	(t,p)
(p,α)	(n,t) (γ,np) (n,nd)	(n,d) (γ,p) (n,np)	(n,p) (t,^{3}He)	
	(n,α) (n,n^{3}He)	(n,^{3}He) (n,pd)		

Figure 11. Changes Produced by Various Reactions. See page 23 for symbol definitions.

Properties of the Nuclides Displayed on the Chart

The type of information given in each square of the Chart depends on whether the square corresponds to a chemical element, a stable nuclide, or a radioactive nuclide. Several example squares are shown in the "Guide for Using the Chart of the Nuclides" with an indication of the type of information given in each of the squares. Table III on page 18 lists the properties for which values (when known) are given for each type of square on the Chart. Each property is described in detail in Sections A–M, below.

A. Chemical Element Names and Symbols

The element names and symbols used on the Chart are those recommended by the International Union of Pure and Applied Chemistry (IUPAC). These include the new names for elements 111, roentgenium,[157] and 112, copernicium.[158] Elements above Z = 112 had not been named officially by IUPAC at the time of publication and are listed solely by atomic number.

A question mark following the nuclide symbol indicates uncertainty in the identification of the nuclide, e.g. ^{202}Pt.

B. Spins and Parities

The spin and parity of the nuclear energy level are located in the upper right corner of the square for the ground state of a nuclide and the upper left corner of the square of the isomeric state. These are depicted as J^π, where J represents the spin (either integral or half-integral) and π represents the parity (either "+" or "−"). Each neutron and proton has an intrinsic spin of ½ (in units of $\hbar$), similar

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[156] Throughout the Chart and this book, the designation E is used to mean power of ten, e.g. 5E+8 = 5×10^8.

[157] J. Cornish and G.M. Rosenblatt, Pure Appl. Chem. **76** 2101 (2004).

[158] see http://www.gsi.de/portrait/Pressemeldungen/14072009_e.html.

Table III. Types of Information Given for Elements and Nuclides on the Chart of the Nuclides[159]

Type of Square	Property	See
1. Chemical Element	a. Chemical symbol.	a. Section A
	b. Atomic weight on the ^{12}C = 12.000 000 scale.	b. Section C
	c. Chemical element name.	c. Section A
	d. Total thermal neutron absorption cross section and absorption resonance integral in barns per atom.	d. Section H
2. All Nuclides	a. Chemical symbol and mass number.	a. Section A
	b. Spins and parities of the ground and metastable states, except for even-Z even-N nuclides.	b. Section B
	c. The thermal neutron cross sections and resonance integrals for significant absorption reactions. The values of these quantities determine the background color of the lower half of the chart square.	c. Section H and I
	d. Fission products produced in the thermal neutron fission of ^{235}U, ^{233}U, and ^{239}Pu are indicated.	d. Section M
3. Stable Nuclides	a. Isotopic abundance, on an atom percent basis.	a. Section D
	b. Isotopic mass of the neutral atom, on the ^{12}C = 12.000 000 scale.	b. Section C
	c. Also see "All Nuclides."	
4. Radioactive Nuclides	a. Half-life. The magnitude of the half-life determines the background color of the upper half of the chart square.	a. Section E and F
	b. Major modes of decay and decay energies (gamma-ray energies in keV, all other particle energies and decay energies in MeV).	b. Section J
	c. An order of magnitude indication of absolute abundance of radiation emitted when less than one percent.	c. Section J
	d. Beta disintegration energies in units of MeV and/or the isotopic mass of the neutral atom on the ^{12}C = 12.000 000 scale.	d. Sections K and C
	e. Isomeric (Metastable) States.	e. Section G
	f. Long-lived radioactive nuclides and members of the naturally-occurring radioactive decay series are indicated by a black band near the top of the square.	f. Section L
	g. Also see "All Nuclides."	

to that of the electron. The nucleon spin combines with the orbital angular momentum to produce a resultant angular momentum called the nuclear spin. Since the orbital angular momentum is always zero or an integral multiple of $\hbar$, the nuclear spin (in units of $\hbar$) is always integer or half-odd-integer, depending upon whether the nucleus has an even or odd number of nucleons. For example, the spin and parity of ^{27}Al are shown on the Chart as $5/^{+}$, where the 2 in the denominator of 5/2 has been removed to improve the readability. The ground states of all even-even nuclides are known to have spin and parity 0^{+}, so 0^{+} has been omitted from the Chart squares for these nuclides. The concept of parity was introduced by the mathematical formalism of quantum theory and has no classical analogue.

The arguments for the assignment of spin and parity to nuclear states can be divided into two classes: strong arguments, such as measuring values directly, and weak arguments, such as inferring values indirectly. On the Chart, the absence of parentheses indicates spins and/or parities based on strong arguments; the presence of parentheses indicates spins and/or parities based on weak arguments. An effort has been made to not include those values inferred solely from systematics.

C. Atomic Weights and Isotopic Masses

The atomic weight of an element is defined as the ratio of the average mass of a neutral atom of an element to 1/12 of the mass of the neutral ^{12}C atom. An atomic weight can be defined for a sample of any given isotopic composition. The standard atomic weight refers to a sample of normal terrestrial isotopic composition (see "Isotopic Abundances," below). The term "relative atomic mass" is synonymous with "atomic weight."

The atomic mass unit is the unit of mass used in nuclear science and is defined as the mass of one neutral atom of ^{12}C divided by 12. Masses of nuclides are normally expressed in atomic mass units. Isotopic masses in atomic mass units (u) are given on the Chart for stable isotopes, for certain long-lived naturally-occurring radioactive isotopes, and for those nuclides where particle (alpha, proton, or neutron) decay becomes a prominent mode (> 10 percent) of decay. If the nuclide decays primarily by β^{+}, ε, or β^{-} decay, the disintegration energy is given instead. If particle decay and β^{+}, ε, or β^{-} decay are both prominent (> 10 percent) modes of decay, both the isotopic mass and the total disintegration energy are given. Isotopic masses were taken from the 2003 study of G. Audi, A.H. Wapstra, and C. Thibault.[160]

The atomic weights of the elements listed on the Chart are those promulgated by the Commission on Atomic Weights—Inorganic Chemistry Division of IUPAC in its 2005 report.[161] The uncertainties in the atomic weights are given in the tables on the inside front cover and last page of this book. Occasionally, a sample can display a significant difference from the accepted atomic weight because of artificial isotope fractionation, artificial nuclear reaction, or a rare geological occurrence in a small quantity. Tables showing the masses of the naturally-occurring isotopes can also be found in the "Isotopic Abundance Tables" section of this book.

For most elements, the uncertainty in the isotopic composition has an effect on the atomic weight that is at least two orders of magnitude greater than the uncertainties in the isotopic masses. Differences in the number of significant figures given on the Chart for the elemental and isotopic masses of mono-isotopic elements are the result of the different estimates of uncertainties given by the Commission on Atomic Weights and Audi and Wapstra, respectively.

D. Isotopic Abundances

The isotopic abundance values on the Chart are given in atom percent and were taken from Böhlke, *et al.*[162] Isotopic abundances are specified on the Chart for 288 nuclides. These include 266 stable and 22 radioactive isotopes. Of the radioactive isotopes, 20 are long-lived with half-lives greater than 5E+8 years (about one tenth of the age of the earth[163]) and are listed in Table V on page 26. The

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[159] X-ray energies are not included on the Chart. However, intensity-averaged X-ray energies are given on the Periodic Table on the inside back cover of this book.

[160] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. **A729** 337 (2003).

[161] M.E. Wieser, Pure Appl. Chem. **78** 2051 (2006).

[162] J.K. Böhlke, J.R. de Laeter, P. De Bievre, H. Hidaka, H.S. Peiser, K.J.R. Rosman, and P.D.P. Taylor, J. Phys. Chem. Ref. Data **34** 57 (2005).

[163] C.J. Allegre, G. Manhes, and C. Gopel, Geochim. Cosm. A., **59** 1445 (1995).

remaining two, ^{231}Pa ($t_{1/2}$ = 3.28E+4 years) and ^{234}U ($t_{1/2}$ = 2.46E+5 years), are continually being formed through the decay of ^{235}U and ^{238}U, respectively. Tables giving the isotopic abundances of the naturally-occurring isotopes are also given in the "Isotopic Abundance Tables" section of this book.

Unlike the mass of an individual nuclide, the atomic mass of an element having more than one stable isotope is not an intrinsic property of that element. It depends on the relative abundances of the different isotopes. The different isotopes are produced by different processes, at different places in the universe, and at different times. The earth is as homogeneous as it is with respect to isotopic abundance because it is so small compared to interstellar distances.

Some of the largest natural abundance variations on the earth are displayed by elements that have one or more isotopes that can be formed by decay of a natural radioisotope with a half-life in the range of ~1E+7 to 1E+11 years. Lead, which has isotopes formed by decay of both thorium and uranium, has already been mentioned. Helium and argon are two other prominent examples. The original atmosphere of the earth is believed to have had isotopic compositions similar to the sun, but most of this early atmosphere was apparently lost to space and replaced later by outgassing from the condensed earth. In the solar system as a whole, ^{36}Ar is the dominant argon isotope. The earth's atmosphere has almost the same ^{38}Ar/^{36}Ar ratio as the sun,[164] but a much greater ^{40}Ar/^{36}Ar ratio, because the argon remaining on the earth is dominated by ^{40}Ar from decay of ^{40}K. The helium isotopic composition on the Chart refers to helium in the earth's atmosphere. The atmospheric ^{4}He/^{3}He ratio is higher than the sun's due to loss of much of earth's primordial ^{3}He and replacement by ^{4}He produced by alpha decay of heavy elements. Helium in old uranium-rich crustal rock has an even higher ^{4}He/^{3}He ratio than the atmosphere, while rocks recently derived from mantle sources have lower ^{4}He/^{3}He ratios than the atmosphere. Among the mantle-derived rocks, those with the lower ^{4}He/^{3}He ratios are believed to come from sources deeper in the mantle.[165, 166] Strontium, neodymium, and hafnium also display variations in isotopic abundance, caused by decay of rubidium, samarium, and lutetium, respectively. Xenon isotope abundance is affected by spontaneous fission of actinoid elements and decay of primordial ^{129}I. Anomalous Mg isotope abundances, resulting from decay of ^{26}Al, have been found in some of the oldest meteorites (those that solidified earliest during the formation of the solar system).[167, 168, 169]

Natural fractionation processes can also cause variations in isotopic abundances, especially for the lighter elements. Deuterium-to-hydrogen ratios for terrestrial samples vary by up to 70 percent,[170] while freshwater, ice, and snow are depleted in deuterium relative to seawater. Oxygen (once used as a standard of atomic weight) is fractionated, but less so, by the same mechanisms that fractionate hydrogen. Compared to natural water, atmospheric O_2 has a higher ^{18}O/^{16}O ratio.[171]

In contrast to hydrogen from other sources, the isotopic composition of deep offshore ocean water is uniform. A composite of distilled ocean water samples called Vienna Standard Mean Ocean Water (VSMOW) was defined[172] by the International Atomic Energy Agency and is used as the international standard against which isotopic abundances of ^{1}H and ^{2}H (as well as ^{16}O, ^{17}O, and ^{18}O) are compared. The abundances[173,174] of ^{1}H and ^{2}H in VSMOW reference water are 99.984426(5) and 0.015574(5) atom percent, respectively. There have been changes in the isotopic abundances of the hydrogen isotopes recommended by IUPAC due to the differences in the samples studied. Prior to 1995, the recommended isotopic abundances of ^{1}H and ^{2}H were 99.985(1)% and 0.015(1)% and the basis for this determination was fresh water in temperate climates. In more recent studies the basis for the recommendation for the representative isotopic composition was broadened to include other terrestrial sources of hydrogen including water, silicates, hydroxides, organic hydrogen, methane and hydrogen gas. The recommended abundances from this study are 99.9885(70)% for ^{1}H and 0.0115(70)% for ^{2}H. These values are the current recommendations of IUPAC and are the values specified on the seventeenth edition of *Chart of the Nuclides*. For applications where the deuterium isotopic abundance is important, knowledge of the variation of the abundance in different samples is essential.

Human technology can also cause variation in isotopic abundances, intentionally or unintentionally. Purification by distillation can cause greater variations in isotopic abundance for elements such as calcium than are found naturally.

Off-the-shelf chemical reagents with a 3.75 percent ^{6}Li composition, instead of the 7.59 percent given on the Chart have been noted without any warning of the depletion in ^{6}Li content. Natural variations in the abundance of ^{10}B have been measured from 19.1 percent to 20.3 percent. The atomic weights and the thermal neutron absorption cross sections for those materials will then differ significantly from the values listed on the Chart. When atomic weights or neutron absorption cross section values are critical to an application, it is highly recommended that samples be checked for actual isotopic abundance before use.

The precision with which variations in isotopic abundance can be measured has improved greatly over the years, even as the necessary sample size has decreased. A large and growing community of scientists uses these variations to study subjects ranging from earth's former climates[175,176] to ancient trade routes.[177] The community has developed standard analysis procedures and standard reference materials for calibration. The books by E. Durrance[178] and by G. Faure[170] provide good introductions to the entire field.

E. Half-lives

The half-life is the period of time in which half of the nuclei initially present in a given radioactive sample disintegrate. On the Chart, half-lives for radioactive nuclides are given below the nuclide symbol and mass number. The units used for half-lives are:

ps	picoseconds (1.0E−12 s)
ns	nanoseconds (1.0E−9 s)
μs	microseconds (1.0E−6 s)
ms	milliseconds (1.0E−3 s)
s	seconds
m	minutes
h	hours
d	days
a	years[179]

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[164] A Meshik, *et al.*, Science **318** 433 (2007).

[165] C.J. Allegre, T. Staudacher, P. Sarda, and M. Kurz, Nature **303** 762 (1983).

[166] P.J. Tackley, Science **288** 2002 (2000).

[167] C.M.O'D. Alexander, A.P. Boss, and R.W. Carlson, Science **293** 64 (2001).

[168] A. Galy, E.D. Young, R.D. Ash, and K. O'Nions, Science **290** 1751 (2000).

[169] K.D. McKeegan, M. Chaussidon, and F. Robert, Science **289** 1334 (2000).

[170] G. Faure, *Principles of Isotope Geology, 2nd Edition*, (John Wiley and Sons, 1986), p. 430.

[171] *ibid.*, p. 436.

[172] R. Gonfiantini, Nature **271** 534 (1978).

[173] R. Hagemann, G. Nief, and E. Roth, Tellus **22** 712 (1970).

[174] K.J.R. Rosman and P.D.P. Taylor, Pure & Appl. Chem. **70** 217 (1998).

[175] C.F.T. Andrus, D.E. Crowe, D.H. Sandweiss, E.J. Reitz, and C.S. Romanek, Science **295** 1508 (2002).

[176] E.J. Hendy, *et al.*, Science **295** 1511 (2002).

[177] G. Giuliani, *et al.*, Science **287** 631 (2000).

[178] E.M. Durrance, *Radioactivity in Geology*, Ellis (Harwood Ltd., Chichester UK, 1986).

[179] The letter "a" is the international unit symbol for year (from the Latin *annus*).

A question mark following the half-life indicates uncertainty in the value of the half-life.

In converting units of time for half-lives, Audi, *et al.*,[180] have recommended the following conversion factors be used:

1 minute = 60 seconds
1 hour = 3600 seconds
1 day = 8.64E+4 seconds
1 year (mean solar year 1900) = 3.155 692 597 47E+7 seconds
or 365.242 198 78 days

A number of so-called particle unstable nuclides with extremely short half-lives are included on the Chart. All of these nuclides are located in the low mass region below A = 17, e.g., ^{5}He, ^{5}Li, ^{6}Be, ^{8}Be, ^{9}B, ^{11}N, ^{12}O, ^{15}F, and ^{16}F. The rationale for including these nuclides is that they can be formed in nuclear reactions involving nearby stable nuclides and resonances corresponding to the formation of these compound nuclei have been observed in the reactions. The half-lives of these nuclides cannot be measured directly, as they are too short to be determined with currently available techniques. Rather, the half-lives are inferred from the measured level widths of the resonances observed in the reactions using the Heisenberg uncertainty principle:

$$\Delta E \Delta t = \hbar.$$

Half-lives for beta decay, electron capture, or conversion electron emission depend on the local electron density as well as on the properties of the nucleus. Over the full range of astrophysical conditions, the variations in half-lives can be enormous, but under ordinary terrestrial conditions, the variations are so small that extraordinary care is needed to measure them experimentally. Low electron density slows electron capture and accelerates β^- decay or conversion electron emission. Fully ionized ^{7}Be nuclei, as cosmic rays, travel for many years without undergoing electron capture because there are no nearby electrons. Fully ionized ^{163}Dy nuclei have been observed in the laboratory to emit β^- particles with a half-life of 48 days resulting in the production of ^{163}Ho.[181] Under normal terrestrial conditions, the opposite process occurs—electron capture by ^{163}Ho to produce ^{163}Dy. At the opposite extreme, in dense stars the electron density is high enough to drive electron capture reactions that would not occur on earth. This process of forcing electrons into nuclei, converting protons into neutrons, culminates in the formation of a neutron star.

Under terrestrial conditions, variations in half-life depending on chemical environment are generally less than one percent, and can easily be swamped by experimental artifacts. Nevertheless, careful work has shown that real variations do exist. In contrast to isotopic abundance variations, the techniques for measurements of half-life variations have improved little over the years. For more information, the reader is referred to the review article by H. Daniel.[182]

The disintegration constants of individual nuclear states are not affected by temperature, but different nuclear states have different decay properties, and nuclides can change states through interaction with photons.[183] Only photons of high energy are able to induce nuclear transformations. On earth, there are too few ambient high-energy photons to have any effect on nuclear decay. At more extreme temperatures, though, more high-energy photons become available. In stars, the decay of ^{26}Al depends greatly on temperature because of a low-lying excited state that has a β^+ decay half-life more than twelve orders of magnitude shorter than that of the ground state.

F. Background Color of the Upper Half of the Chart Square

For nuclides with half-lives of one day or longer, the background color in the upper half of the Chart square indicates the relative magnitude of the half-life of the nuclide. The following ranges of half-lives are used:

1 day to 10 days	orange
> 10 days to 100 days	yellow
> 100 days to 10 years	green
> 10 years to 5E+8 years	blue

The color gray represents stable or naturally-occurring radioactive nuclides—the 288 nuclides for which isotopic abundances have been assigned by IUPAC (see Reference 162). For the 266 stable nuclides and for the 20 long-lived ($t_{1/2}$ > 5E+8 years) radioactive nuclides, the background color in the upper half of the square is gray. For ^{231}Pa and ^{234}U, with half-lives less than 5E+8 years, a gray band is used at the top of the squares (since they are continually being formed by the decay of ^{235}U and ^{238}U, respectively), while the color in the remainder of the upper half corresponds to the half-life of the nuclide.

G. Isomeric (Metastable) States

Certain squares on the Chart are divided, e.g., the square for ^{26}Al. Such divisions occur when a nuclide has one or more isomeric states: when nuclides have the same mass numbers and atomic numbers but possess different radioactive properties in different long-lived energy states. An isomeric state is included on the Chart if the half-life is one second or longer. This arbitrary cutoff point of one second was chosen for convenience in presenting the data. Shorter half-lives are included when they are fed in the decay of a parent nuclide with half-life longer than one second or are part of a naturally-occurring radioactive decay series. When referring to isomeric states, the lower energy state is generally referred to as the ground state and the higher energy state as the isomeric state. Frequently, the ground state is a stable nuclide. If one metastable state exists, it is shown on the left of the Chart square and the ground state is to the right. If two exist, the higher energy state is shown on the upper left of the square, the lower below it, and the ground state to the right of both. When a metastable and ground state (or two metastable states) cannot be unequivocally assigned to a given energy level, the designation "↔" is placed between the two states involved.

For ^{177}Lu (see the square on the Chart of the Nuclides) the ground state is the 6.65 d state on the right side of the square and is designated ^{177g}Lu, while the 160.7 d state on the left side of the square is the metastable state and is designated ^{177m}Lu. In cases where two metastable states exist, the superscripts "m_1" and "m_2" are used.

When the spins of both the ground state and an isomeric state are given for a particular nuclide, it is interesting to observe that these spins usually differ by two or more units of $\hbar$. A large angular momentum (spin) change is required for a gamma-ray transition between the states. Combining this spin change with the small energy difference (a few hundred keV) between the states leads to a relatively long lifetime of the metastable state.

H. Neutron Cross Sections and Resonance Integrals

Two quantities are given on the Chart to represent the probability of certain neutron-induced nuclear reactions for the stable nuclides and some long-lived radioactive nuclides. These quantities are the thermal neutron cross section and the resonance integral. Both of these quantities are discussed below.

Several types of reactions of neutrons with nuclei are possible. The neutron cross section is a measure of the probability of the interaction of a neutron with a nuclide and is a function of the incident neutron energy. The lowercase Greek letter sigma (σ) with

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[180] G. Audi, *et al.*, Nucl. Phys. **A624** 1 (1997).

[181] M. Jung, *et al.*, Phys. Rev. Lett. **69** 2164 (1992); O. Klepper, Nucl. Phys. **A626** 199 (1997).

[182] H. Daniel, At. Energy Rev. **17(2)** 287 (1979).

[183] R.A. Ward and W.A. Fowler, Astrophys. J. **238** 266 (1980).

various subscripts is used to denote cross sections for different types of reactions. The cross section can be most easily visualized as a cross-sectional target area presented to the neutron by the nucleus. Cross sections are usually measured in units of barns per atom. A barn is 1E−24 square centimeters. The name of the unit of cross section, barn, was first suggested in 1942 by M.G. Holloway and C.P. Baker[184] since "a cross section of 1E−24 cm^2 for nuclear processes was really as big as a barn."

Types of reactions of neutrons with nuclei include elastic scattering, where the target nucleus is left unchanged, inelastic scattering, where the target is left in an excited state, and absorption reactions where the neutron is "absorbed" by the target nucleus. Generally, the most probable absorption reaction (the reaction with the largest cross section) is the neutron capture reaction in which the absorption of the neutron by the nucleus is accompanied by high-energy gamma-ray emission; the capture cross section is indicated by the symbol $\sigma_\gamma(E_n)$, where E_n is the incident neutron energy. In other reactions, a proton, a triton, or an alpha particle may be emitted, or a nucleus may fission upon neutron absorption and the cross sections for these reactions are indicated by $\sigma_p(E_n)$, $\sigma_t(E_n)$, $\sigma_\alpha(E_n)$, and $\sigma_f(E_n)$, respectively. The neutron absorption or disappearance cross section, $\sigma_a(E_n)$, is the sum of the cross sections for all absorption reactions:

$$\sigma_a(E_n) = \sigma_\gamma(E_n) + \sigma_p(E_n) + \sigma_t(E_n) + \sigma_\alpha(E_n) + \sigma_f(E_n) + \dots$$

When ^{233}U, ^{235}U, or ^{239}Pu undergo fission, in addition to the medium mass fission products that are emitted, additional neutrons are emitted. For ^{235}U fission, these neutrons have an average energy of about 2 MeV. In a thermal reactor, these neutrons are slowed down by collisions with the moderator atoms (and can then cause the fissioning of other uranium nuclei, resulting in a chain reaction). A spectrum of neutron energies, therefore, exists in a reactor. The neutron flux[185] is the "intensity" of neutrons as a function of neutron energy in the reactor and this spectrum is frequently divided into three regions:

1. The thermal region, in which neutrons are in thermal equilibrium with the moderator. ($E_n \leq 1$ eV)
2. The intermediate or slowing-down region in which the neutron flux varies inversely with neutron energy ($1/E$) due to energy loss by elastic scattering. (1 eV $< E_n \leq 1$ MeV)
3. The fast region in which the neutron flux is governed by the yield from the fission process. ($E_n > 1$ MeV)

When neutrons reach thermal equilibrium with the moderator, their energies are determined by the thermal energy distribution of the moderator atoms and the neutron energy spectrum becomes a Maxwellian distribution at the temperature of the moderating material. Setting the kinetic energy of the neutron motion equal to the thermal energy of the moderator, one can obtain the most probable speed of the neutrons in thermal equilibrium. For a moderator at room temperature (20°C), this neutron speed, v, is 2,200 meters per second and the corresponding energy is 0.0253 eV. Neutron cross sections specified for this energy are called thermal neutron cross sections.

A graph of the capture cross section of ^{235}U versus incident neutron energy is shown in Figure 12.[186] In the thermal region, the ^{235}U capture cross section varies as $E^{-1/2}$ or as $1/v$ where v is the neutron speed. Many other nuclides have absorption cross sections that vary as $1/v$ and are called $1/v$ absorbers. At higher energies (the intermediate region), there are many sharp peaks in the cross section. The peaks are called resonances and occur at incident neutron energies corresponding to the discrete energy levels in the compound nucleus, ^{236}U.

For a parallel beam of neutrons having a neutron flux of φ neutrons per square centimeter per second, the reaction rate per atom (reactions per second per atom) is given by the product of the cross

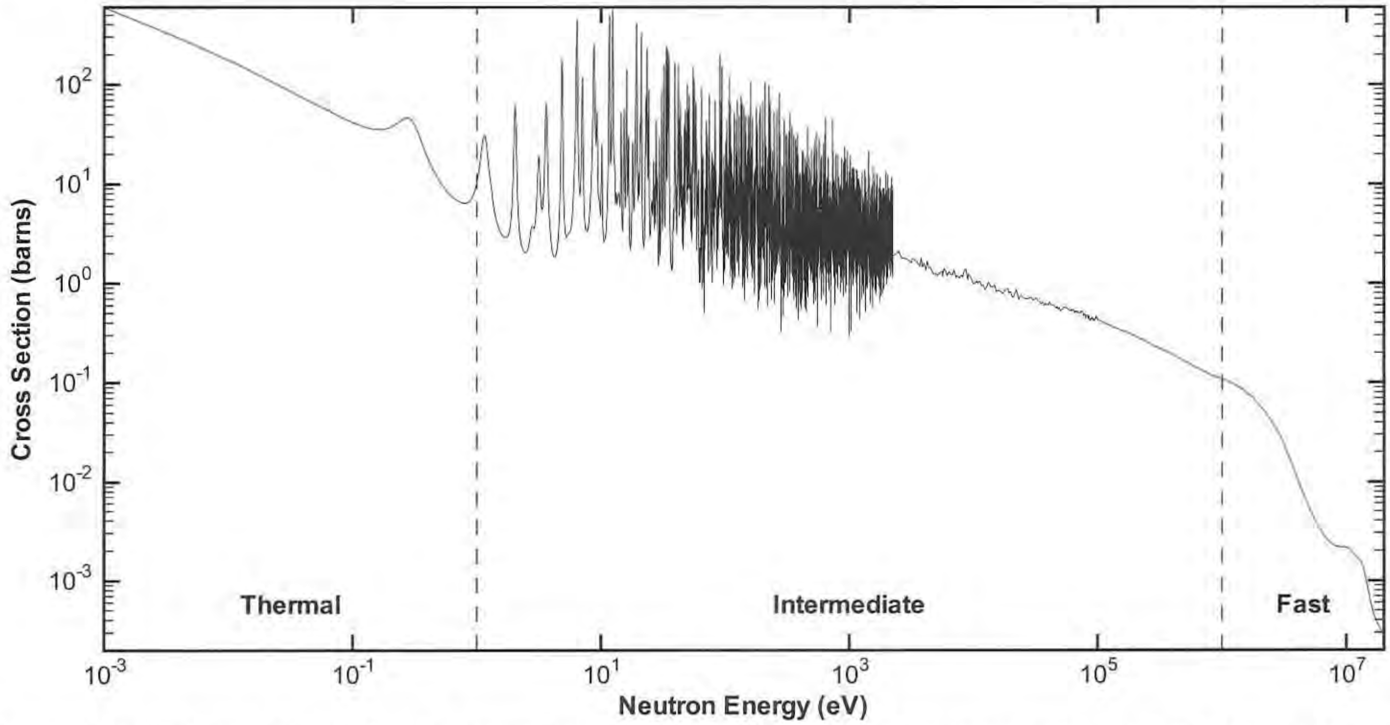

Figure 12. Capture Cross Section of ^{235}U. The thermal region corresponds to $E_n \leq 1$ eV, the intermediate region, 1 eV $< E_n \leq 1$ MeV, and the fast region $E_n > 1$ MeV.

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[184] M.G. Holloway and C.P. Baker, Physics Today, Vol. 25, p. 9, July 1972.

[185] Neutron flux is defined as the neutron density at a certain point in space (neutrons/cm^3) multiplied by the average neutron speed at the same point in space (cm/s); the flux therefore has units of neutrons/cm^2-s. For parallel beams, this quantity is often referred to as the number of neutrons traversing a unit area perpendicular to the beam in a unit period of time.

[186] From the Evaluated Neutron Data File, ENDF/B-VI, for ^{235}U. See V. McLane, Editor, "ENDF-102 Data Formats and Procedures for the Evaluated Nuclear Data File ENDF-6," BNL-NCS-44945, Brookhaven National Laboratory, April 2001.

section (in cm^2) and the flux, $\sigma\varphi$. When the neutron flux is not a monodirectional beam, the interaction rate per atom is still given by the product $\sigma\varphi$, where φ is the product of the neutron density (neutrons/cm^3) and the neutron speed (cm/sec).

A quantity called the resonance integral (RI) is used to represent the probability of neutron reactions in the energy range above thermal energies. In order to evaluate this integral over a typical neutron slowing down spectrum, where resonance absorption peaks occur, a $1/E$ function is used to represent the neutron spectrum. The range of integration is from a cutoff energy within the thermal range, E_c, typically about 0.5 eV, to the highest energy where appreciable contributions to the reaction rate occur:

$$\mathrm{RI} = \int_{E_c}^{E_{\max}} \sigma(E) \frac{dE}{E}.$$

In the present work, the absorbing nuclide is assumed to be present in such dilute quantities that there is no perturbation of the neutron slowing down spectrum. Thus, the resonance integral is called an infinitely dilute resonance integral.

Unlike the thermal cross section, the resonance integral is a reaction rate integral over a broad energy range. To derive an average cross section for the energy range, σ_{res}, the resonance integral is divided by the integral of dE/E over the same energy range:

$$\sigma_{\mathrm{res}} = \frac{\mathrm{RI}}{\int_{E_c}^{E_{\max}} \frac{dE}{E}}.$$

For historic reasons, and because the magnitudes of thermal cross section and resonance integral are similar, these two quantities are given for each nuclide to represent the reaction probabilities for the thermal and above thermal ranges even though the resonance integral is not itself a cross section. In the remainder of this discussion and in common practice, the resonance integral is treated as a cross section.

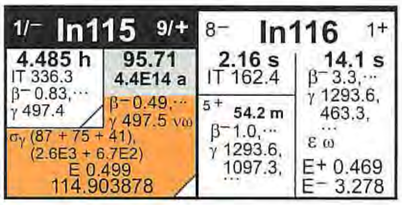
The measurement of the reaction rate in a reactor neutron spectrum produces contributions from intermediate energy neutrons with a $1/E$ distribution and from thermal neutrons with a Maxwellian distribution of energies. To distinguish between these two contributions, a cadmium cover is often used to filter out the thermal neutrons. Cadmium filters do not separate the thermal from the intermediate neutron spectrum sharply, but an "effective cadmium cutoff energy," E_{Cd}, can be defined for a $1/v$ absorber. Suitable cadmium filters have an E_{Cd} of approximately 0.5 eV. This energy is sufficiently high to exclude most of the low-energy deviations of the flux from a $1/E$ shape. The lower limit on the integral above defining the resonance integral is then taken as 0.5 eV.

On the Chart, the thermal (2,200 m/s value) cross section for a particular reaction is listed as **σ** with a subscript appropriate for that reaction. Question marks are used to indicate uncertainty in the value of the cross section or resonance integral.

For elemental materials, the absorption cross section is given on the leftmost square of each row. For a stable or long-lived nuclide, cross sections for specific significant reactions, e.g., capture, fission, etc., are given. In all cases, the thermal cross section symbol is given followed by the cross section value and the resonance integral value, separated by a comma. The designation **mb** or **μb** following the cross section value indicates that the units of the cross section and resonance integral are millibarns per atom or microbarns per atom, respectively. When no **mb** or **μb** appears on the Chart square, the units of the cross section are barns per atom. A given nuclide might undergo two or more types of reactions and its square would then contain two or more of these cross section values.

When neutron capture can lead to a metastable state as well as to the ground state, more than one value will appear beside the capture cross section symbol for that nuclide. The cross section value for metastable-state formation is listed on the left and that for direct-ground-state formation on the right followed by similar values for the resonance integral. For two metastable states, the higher of the two states is on the left. For example, ^{115}In (see Example 1, below) has an indicated cross section and resonance integral of (87 + 75 + 41), (2.6E3 + 6.7E2). This means that the thermal cross section for formation of the 2.16-second state of ^{116}In is 87 barns, the thermal cross section for the direct formation of the 54.2-minute ^{116}In is 75 barns, and the resonance integral for direct plus indirect formation (by decay of the 2.16-second state) is 2.6E+3 barns. The thermal cross section and resonance integral for formation of the 14.1-second ground state of ^{116}In are 41 barns and 6.7E+2 barns, respectively. When the ground state cross section is not known but one of the metastable cross sections is known, a question mark is used as a placeholder to designate this case (see ^{126}Te).

Example 1



As mentioned above, the cross section is a measure of the probability of the interaction of a neutron with a nuclide. Measurements of neutron cross sections therefore require a determination of the neutron fluence[187] on the sample of material under study. Neutron standards[188,189] are used to eliminate the need for a direct measurement of the fluence. The neutron standards are materials for which the neutron cross sections are accurately known and cross section measurements for other materials are made relative to these standards. For these standard materials, samples with good purity can be acquired and will yield strong and easily distinguishable signals in commonly used neutron detectors. A list of the materials recommended for use as standards and the neutron energy ranges over which they are to be used is given in Table IV.

Table IV. The Neutron Cross Section Standards

Reaction	Energy Range
^{1}H(n,n)	1 keV to 200 MeV
^{3}He(n,p)	thermal to 50 keV
^{6}Li(n,t)	thermal to 1 MeV
^{10}B(n,α)	thermal to 1 MeV
^{10}B(n,α$_1$γ)	thermal to 1 MeV
^{12}C(n,n)	thermal to 1.8 MeV
^{197}Au(n,γ)	thermal, 0.2 to 2.5 MeV
^{235}U(n,f)	thermal, 0.15 to 200 MeV
^{238}U(n,f)	2 to 200 MeV

Thermal cross sections and resonance integrals for the seventeenth edition of the Chart of the Nuclides were obtained from the Nuclear Science References (NSR) database and the Experimental Nuclear Reaction database (EXFOR/CSISRS) at the National Nuclear Data Center[190] (NNDC). Comparisons with other

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[187] The neutron fluence (frequently denoted by the uppercase Greek letter phi, Φ) is the total neutron flux to which the sample is exposed, accumulated over the entire exposure time.

[188] *International Evaluation of Neutron Cross Section Standards*, International Atomic Energy Agency, ISBN 92-0-100807-4, Vienna, 2007.

[189] A.D. Carlson and K. Shibata, *International Evaluation Co-operation, Volume 1, Nuclear Data Standards*, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, NEA/WPEC-7, ISBN 92-64-02313-5.

[190] On the internet at http://www.nndc.bnl.gov.

compilations[191,192] and with the Evaluated Neutron Data Files, ENDF/B-VII, were also carried out.

I. Background Color of the Lower Half of the Chart Square

The background color in the lower half of the Chart square is determined by the greater of the thermal neutron cross section or resonance integral. Four colors—blue, green, yellow, and orange—are used to indicate ranges of values from 10 barns to greater than 1,000 barns. The following ranges of neutron absorption properties are used:

10 to 100 barns . . . . blue
> 100 to 500 barns . . . . green
> 500 to 1,000 barns . . . . yellow
> 1,000 barns . . . . orange

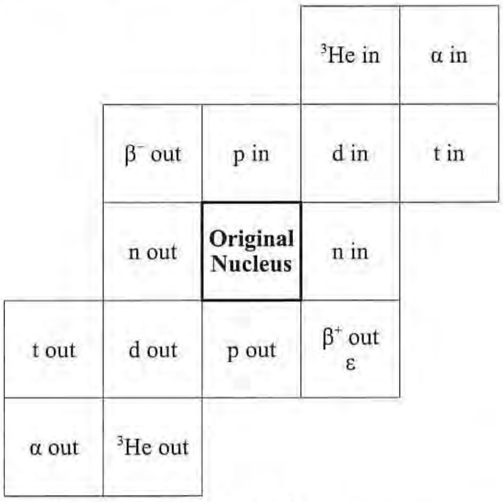
J. Major Modes of Decay and Decay Energies

The modes of decay indicated on the Chart include:

α	alpha particle (^{4}He nucleus)
β^-	beta minus (negative electron)
β^+	beta plus (positron)
γ	gamma ray
n	neutron
p	proton
d	deuteron (^{2}H nucleus)
t	triton (^{3}H nucleus)
ε	electron capture
IT	isomeric transition
e^-	conversion electron
SF	spontaneous fission
$\beta^-\beta^-$	double beta decay
⊗	cluster decay
D	delayed radiation

Question marks are used to indicate uncertainty in the mode of decay, e.g. ^{48}Ni.

As these processes occur, the nuclides change in accordance with the scheme shown in Figure 13. To understand the use of this scheme more fully, consider the decay of ^{238}U. As noted on the Chart, ^{238}U decays by the emission of an alpha particle. Thus, the nuclide loses two protons and two neutrons, and the daughter nucleus is located two spaces to the left (N − 2) and two spaces below (Z − 2) the original nucleus. This square represents the isotope ^{234}Th, which is also radioactive and decays by β^- emission. In this decay the mass number, A, does not change; however, the loss of one negative charge means that the atomic number Z increases by one. In effect, one neutron in the nucleus has changed to one proton. Thus, the nucleus has lost a neutron and gained a proton, and the resulting nucleus is located one space to the left (N − 1) and one space above (Z + 1) the original nucleus. This process leads to ^{234}Pa, which has isomeric states. Each of these states undergoes β^- emission, so another move diagonally upward to the left leads to ^{234}U. The effects of other modes of decay—β^+, ε, n, p, etc.—on the atomic number and neutron number can be seen in Figure 13.



n = neutron
p = proton
d = deuteron
t = triton
α = alpha particle
β^- = beta minus (negative electron)
β^+ = beta plus (positron)
ε = electron capture

Figure 13. Relative Locations of the Products of Various Nuclear Processes on the Chart of the Nuclides.

In order to better understand the display of decay data on the Chart, consider the decay of ^{38}Cl. A simplified decay scheme for the ground state of ^{38}Cl is shown in Figure 14. On the Chart square for ^{38}Cl (see Example 2, below), the β^- energies would be listed on the first line in order of their abundances, i.e., "β^- 4.91, 1.11, …." The following line would give the gamma rays in order of their abundances, i.e., "γ 2167.7, 1642.4, …." (Note: 3.8101 MeV − 2.1677 MeV = 1.6424 MeV = 1,642.4 keV). On the Chart, particle energies are given in MeV, while gamma-ray energies are given in keV.

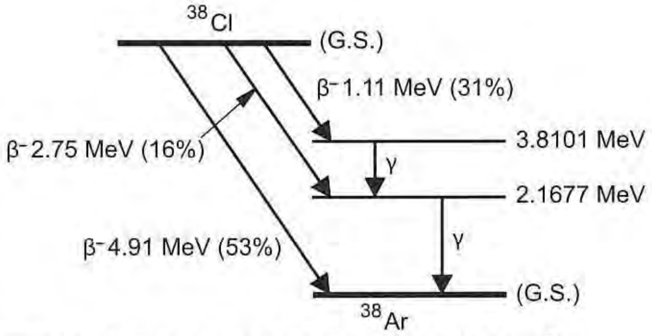
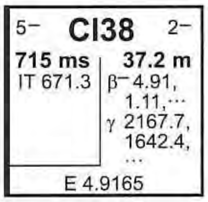


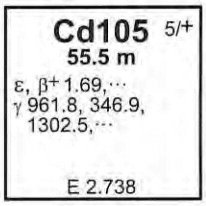
Figure 14. Decay scheme for the ground state (G.S.) of ^{38}Cl.

Example 2



When more than one mode of decay is possible, the modes are listed on the Chart in order of their **abundances or intensities**. Different modes of beta decay (ε, β^+, or β^-) appear on separate lines if the intensity of one of the modes of decay is less than 10 percent absolute intensity. Conversely, they appear on the same line if the intensities of both are greater than 10 percent absolute intensity, with the most abundant listed first. See the ^{105}Cd square (Example 3) below. Here, electron capture (ε) is more abundant

Example 3



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[191] N.E. Holden, "Neutron Scattering and Absorption Properties (Revised 2003)," in *CRC Handbook of Chemistry and Physics, 89th Edition*, (CRC Press, Inc., Boca Raton, FL, 2008).

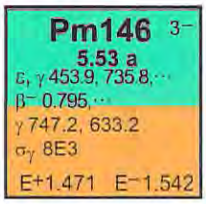
[192] S.F. Mughabghab, *Atlas of Neutron Resonances, Resonance Parameters and Thermal Cross Sections Z=1–100*, (Elsevier, Boston, 2006).

than positron (β^+) emission in the decay to ^{105}Ag. The gamma-ray energies on the second line are listed in order of their abundances.

In **electron capture**, an atomic electron is captured by the nucleus. The vacancy left behind is filled by an electron from a higher orbit. If a K-electron is captured, an L-electron may fill the empty state left behind. The energy equal to the difference in binding energies for the K- and L-electrons then becomes available and may be emitted as a K X-ray or may be given to another electron. X-ray energies are not included on the Chart, but the energies of the K and L X-rays are given on the periodic table included in this book. The user should consult standard compilations, e.g., Ref. 139, for these quantities.

When branching decay occurs by both β^- and β^+ and/or ε, and each decay is accompanied by gamma-ray emission, the format shown in the ^{146}Pm square is used (see Example 4, below). In that square, the 453.9 and 735.8 keV gamma rays accompany the ε decay, while the 747.2 and 633.2 keV gamma rays accompany the β^- decay.

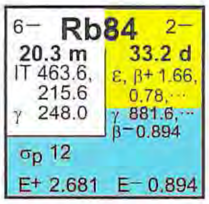
Example 4



The designations "ω" (weak), "υω" (very weak), and "υυω" (very very weak) are used to indicate particle and gamma-ray energies or decay modes with less than one percent, less than 10^{-3} percent, and less than 10^{-6} percent absolute intensity, respectively, e.g. ^{145}Pm. Of course, if one of a series of particle or gamma-ray energies has one of the above designations, then all succeeding energies have this designation also (since these energies are arranged in order of decreasing intensity). The designations "ω," "υω," and "υυω" are often placed in parentheses for clarity of expression.

A metastable (or isomeric) state of a nuclide will frequently decay to the ground state by **Isomeric Transition (IT)** gamma-ray emission, followed by one or more gamma rays in cascade. It is possible to have a more complicated decay scheme with more than one IT gamma ray, each with its cascading gamma rays as well as a simple decay scheme with only one IT gamma ray to the ground state of the daughter nucleus. In order to indicate which gamma rays are leaving the metastable level, the IT gamma rays are listed separately from the cascading gamma rays. For example, ^{84}Rb has a metastable state 463.6 keV above the ground state (see Example 5, below). This metastable state can decay directly to the ground state by emitting a single 463.6 keV IT gamma ray. The metastable state can also emit a 215.6 keV IT gamma ray, decaying to a state of intermediate energy; this intermediate state decays (with a half-life of less than a nanosecond) to the ground state by emitting a 248.0 keV (cascade) gamma. In the ^{84}Rb square, the IT gamma energies, 463.6 keV and 215.6 keV, are listed after "IT," while the cascade gamma-ray energy, 248.0 keV, is listed on a separate line.

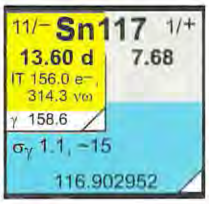
Example 5



Internal conversion, a process resulting from the interaction between the nucleus and its extra-nuclear electrons, competes with gamma-ray emission. Here the excitation energy of the nucleus is transferred to an orbital electron, usually K-shell, and the electron is emitted from the atom instead of a gamma ray. Neither Z nor N of the nucleus change in this process. The conversion electrons have kinetic energies equal to the difference between the energy of the nuclear transition involved and the binding energies of the electrons in the atom. Since internal conversion is an alternative to gamma-ray emission, the intensity of a given gamma ray may be reduced considerably, with the difference in intensity from that expected accounted for by the conversion electron intensity. Internal conversion is favored by high Z, low transition energy, and large angular momentum (spin) change. The total internal conversion coefficient, α_T, is the ratio of the total number of internal conversion electrons to the number of gamma rays emitted for a specific transition. It is the policy for the Chart to indicate conversion electrons (symbol $\mathbf{e}^-$) only if α_T is greater than or equal to 10. This arbitrary cutoff for inclusion of conversion electrons on the Chart is a compromise between significant effect on the gamma-ray intensity and the desire to increase the legibility of the Chart. Occasionally, the symbol $\mathbf{e}^-$ is included in parentheses to indicate that it is specific to a given, listed gamma ray.

Internal conversion coefficients vary over a wide range. For example, the 156.0 keV transition of ^{117m}Sn results from the decay of the $11/2^-$ state to an intermediate $3/2^+$ state (see Example 6, below). The total internal conversion coefficient for this transition is 46, so it is indicated with an $\mathbf{e}^-$ on the Chart. The cascading 158.6 keV gamma results from the decay of the $3/2^+$ state to the $1/2^+$ ground state. For the 158.6 keV transition, α_T is only 0.16, so it is not followed by $\mathbf{e}^-$ on the Chart. At the opposite extreme, the 28.6 keV transition of ^{117m}Ag from the $7/2^+$ state to the $1/2^-$ ground state has an internal conversion coefficient of 12,000. (When the $\mathbf{e}^-$ symbol is used, ω or other symbols indicating low photon abundance are sometimes omitted.)

Example 6



Spontaneous fission (SF) is a decay mode[193] of some heavy nuclei where the nucleus breaks up into two intermediate-mass fragments and several neutrons. It has been observed only for nuclei with A > 230. See, for example, the squares corresponding to ^{234}U, ^{238}Pu, or ^{242}Cm on the Chart. This mode of decay is discussed further on page 33.

Double beta decay ($\beta^-\beta^-$) is a very rare radioactive event, studied theoretically in 1935.[194] Geochemical evidence for double beta decay of ^{130}Te was reported[195] in 1950, but no direct laboratory observation was reported until the decay of ^{82}Se was detected[196] in 1987. In this process, two beta particles and two antineutrinos are generated, resulting in the original nucleus gaining two protons and losing two neutrons. Several nuclides, including ^{82}Se, ^{116}Cd, and ^{130}Te, have been observed to undergo this type of decay with half-lives greater than 10^{19} years. Decay by emission of two betas and no neutrinos may also be possible according to some theories that require neutrinos to have non-zero mass. Experiments are in progress to try to detect zero-neutrino double beta decay, but no positive evidence has been found.[197]

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[193] Spontaneous fission of uranium was first observed by G.N. Flerov and K.A. Petrzhak, J. Phys. U.S.S.R. **3** 275 (1940). The emission of neutrons with spontaneous fission was first reported by G. Scharff-Goldhaber and G.S. Klaiber, Phys. Rev. **70** 229 (1946).

[194] M. Goeppert-Meyer, Phys. Rev. **48** 512 (1935).

[195] M.G. Ingram and J.H. Reynolds, Phys. Rev. **78** 822 (1950).

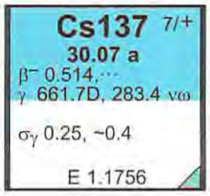
[196] S.R. Elliott, A.A. Hahn, and M.K. Moe, Phys. Rev. **36** 2129 (1987).

[197] V.I. Tretyak and Y.G. Zdesenko, At. Data Nucl. Data Tables **80** 84 (2002).

Cluster decay has been observed in several heavy nuclides. In this type of decay, the emission of ^{12}C, ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg, or ^{32}Si clusters has been observed. Specific nuclei that undergo cluster decay, the emitted cluster, and further information are listed in Table VII, page 34. Isotopes that decay by cluster radioactivity are denoted on the Chart by the symbol ⊗ located in the lower right hand corner of the square. All cluster decay observed is "υυω." More information on this mode of decay is given on page 33.

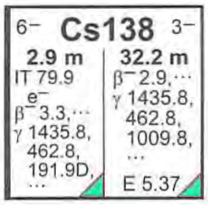
Delayed gamma radiation is denoted by the symbol **D**. Very often, a nuclide decays initially to an excited state of the daughter nuclide. The most common mode of decay for daughter excited levels is gamma-ray emission. When the daughter level has too short a half-life to have its own place on the Chart (or has a half-life much shorter than that of the parent nuclide), the gamma energy is listed with the parent nuclide. However, if the daughter level has a half-life greater than approximately one microsecond, the symbol **D** is placed after the gamma energy. An example is provided by 30.07-year ^{137}Cs (see Example 7, below). This long-lived parent decays by β^- emission to a short-lived daughter, 2.552-minute ^{137m}Ba. The 661.7 keV gamma ray, which is emitted by the ^{137m}Ba, is included on the ^{137}Cs square with a "**D**" to indicate delayed radiation proceeding through an isomeric level of the daughter nucleus.

Example 7



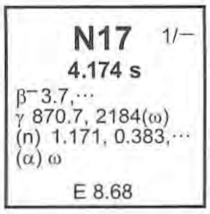
As another example of delayed radiation, the three gamma rays listed below the β^- symbol for the 2.9 minute state of ^{138}Cs (see Example 8, below) are all emitted from excited states of ^{138}Ba. The 191.9 keV gamma ray is marked with a **D** because it is emitted by a state with a 0.8 microsecond half-life, while the other two gammas are emitted by states with half-lives much shorter than a microsecond.

Example 8



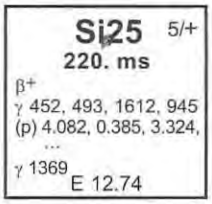
Delayed particle emission can also occur since excited states of daughter nuclides can decay by modes other than gamma-ray emission. A mode of decay shown in parentheses indicates that the decay results from emission of the indicated particle from an excited level of the daughter nucleus, following positive or negative beta-decay to that level. For example, ^{17}N, with a half-life of 4.174 seconds, decays by β^- emission into several exceedingly short-lived states of ^{17}O, which in turn emit neutrons. This is indicated on the Chart (see Example 9, below) by the symbol **(n)** followed by the energies of the most abundant neutrons, if they have been measured. Thus, ^{17}N emits "delayed neutrons" with a half-life of 4.174 seconds.

Example 9



Another example of delayed particle emission is ^{25}Si, with a half-life of 220 milliseconds, which decays by β^+ emission to short-lived states in the daughter nucleus ^{25}Al (see Example 10, below). These excited states, in turn, emit protons. The "delayed protons" are indicated in the Chart by the symbol **(p)**.

Example 10



Cases are also known where "delayed alphas" are emitted, indicated by the symbol **(α)**—see Example 9. Delayed emission of two protons is possible after the first beta-decay, and this process is indicated by the symbol **(2p)**. The emission of two particles following beta decay also occurs with delayed neutron-emission, **(2n)**, and delayed alpha-emission, **(2α)**. The energy requirement for the occurrence of delayed particle emission is that the energies of the levels in the daughter nucleus reached by the beta emission exceed the separation energy of the proton(s), neutron(s), or alpha(s) from this nucleus. Beta decay of some of the heaviest nuclides leads to excited daughter levels that decay by spontaneous fission. This is indicated on the Chart by the symbol **(SF)**. Among the lightest nuclides, delayed or direct particle emission may be followed by a rapid cascade of additional particle emissions, and several different particle-decay channels may occur in parallel. Space limitations make it impractical to convey the full complexity of some of these decay schemes on the Chart. Interested readers are encouraged to consult Nuclear Data Sheets[198] and primary sources for more detailed information.

Numeric decay information given on the Chart is obtained from a comprehensive literature search of published results as well as from other tabulations of this type of information.

K. Disintegration Energies

If the nuclide decays primarily (> 10 percent) by β^+, ε, or β^- decay, the disintegration energy, denoted by "E," is given in MeV. Where both β^+ and β^- decay occur, the respective decay energies are denoted by E+ and E−. The disintegration energy refers to the total energy difference between the ground state of a parent radionuclide and the ground state of its daughter. (See "Beta Decay and Electron Capture," page 30.) The energy given is the maximum possible energy for β^-, but for β^+ decay, 1.022 MeV ($2m_ec^2$) must be subtracted to get the maximum possible β^+-particle energy. In beta decay, the total energy is shared between the beta particle and the neutrino or antineutrino.

L. Naturally-Occurring Radioactive Isotopes

Many naturally-occurring nuclides are known by experiment to be radioactive, and many more are expected from theory to undergo radioactive decay, but with such extremely long half-lives that experimental evidence for the decay hasn't been found yet. As experiments with greater sensitivity and lower background are performed, the number of known naturally-occurring radioactive nuclides continues to grow. In addition, increasingly sensitive analyses of natural samples are reporting traces of nuclides known to be radioactive but not previously thought to exist in nature.

On the Chart, radioactive nuclides that meet certain criteria for half-life and natural abundance are highlighted either by a black band at the top of the square or, for nuclides forming the naturally-occurring radioactive decay chains, a smaller black rectangular area near the top of the square in which the symbol corresponding

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[198] J.K. Tuli, Ed., http://www.nndc.bnl.gov/nds.

to the historic name of the nuclide is given. These nuclides belong to one of three classes:

1. Nuclides produced by cosmogenic processes in the atmosphere. This class of naturally-occurring radioactive nuclides is produced by reactions of cosmic-ray particles with stable atoms present in the atmosphere. The three most abundant ones are ^{3}H, ^{7}Be, and ^{14}C. Both ^{3}H and ^{14}C decay by β^- emission and have half-lives of 12.32 and 5,715 years, respectively. Both have been used to determine the ages of objects that contain them. ^{7}Be decays by electron capture and has a half-life of 53.3 days. Filters through which air has passed are radioactive due to both ^{7}Be and radon chain products, which deposit on dust and airborne particles. All three of these nuclides are present in the atmosphere at concentrations greater than 0.01 picocuries per kilogram of air. Other cosmogenic nuclides are present at lower concentrations and do not have black bands. Further information on cosmogenic nuclides and other naturally-occurring radioactive isotopes is available in the book by Eisenbud and Gesell.[199]

2. Unstable nuclides having lifetimes sufficiently long to have survived from the time the elements on earth were formed. Materials belonging to this class, along with their half-lives (in years) and abundances, are listed in Table V. These isotopes decay by β^+, ε, β^-, or α decay and, with the exception of ^{232}Th, ^{235}U, and ^{238}U, form stable products. The three nuclides, ^{232}Th, ^{235}U, and ^{238}U, are the parents of naturally-occurring radioactive decay series and are discussed below. As noted in the Table, in addition to the very long half-lives, many materials in this group have very low abundances, resulting in low activities and making them difficult to detect. As experimental techniques improve, other isotopes may be added to this class of naturally-occurring radioactive materials.

A few nuclides, for example, ^{82}Se, ^{116}Cd, and ^{130}Te, have been found to decay by $\beta^-\beta^-$ emission with half-lives greater than 1E+18 years, and a few other nuclides have recently been reported to have comparably-long alpha-decay half-lives.[200] Because of the extremely low activities, these nuclides were not included in Table V and do not have black bands in the Chart square.

Table V. Long-Lived Naturally-Occurring Radioactive Isotopes

Isotope	Decay	Half-life (years)	Isotopic Abundance (%)	Decay Product
^{40}K	β^-, β^+	1.25E+9	0.0117	^{40}Ca, ^{40}Ar
^{50}V	ε, β^-	1.4E+17	0.250	^{50}Ti, ^{50}Cr
^{87}Rb	β^-	4.9E+10	27.83	^{87}Sr
^{113}Cd	β^-	8.04E+15	12.22	^{113}In
^{115}In	β^-	4.4E+14	95.71	^{115}Sn
^{123}Te	ε	> 9E+16	0.89	^{123}Sb
^{138}La	ε, β^-	1.05E+11	0.090	^{138}Ba, ^{138}Ce
^{144}Nd	α	2.38E+15	23.8	^{140}Ce
^{147}Sm	α	1.17E+11	14.99	^{143}Nd
^{148}Sm	α	7E+15	11.24	^{144}Nd
^{152}Gd	α	1.1E+14	0.20	^{148}Sm
^{176}Lu	β^-	~3.76E+10	2.59	^{176}Hf
^{174}Hf	α	2.0E+15	0.16	^{170}Yb
^{180m}Ta	ε, β^-	> 7.1E+15	0.012	^{180}Hf, ^{180}W
^{187}Re	β^-	4.12E+10	62.60	^{187}Os
^{186}Os	α	2E+15	1.59	^{182}W
^{190}Pt	α	6.5E+11	0.014	^{186}Os
^{232}Th	α	1.40E+10	100.	^{208}Pb
^{235}U	α	7.04E+8	0.7204	^{207}Pb
^{238}U	α	4.468E+9	99.2742	^{206}Pb

3. Naturally-occurring radioactive decay chains. The last three nuclides listed in Table V all decay to shorter-lived radioactive daughters forming long chains or radioactive series. Because the parents are found in nature, their daughters achieve significant equilibrium concentrations where the parent activity is found. The three series are named the thorium, uranium, and actinium series, after elements at or near the head of the series. Each of these series ends at a stable isotope of lead—^{206}Pb, ^{208}Pb, or ^{207}Pb. These series are shown in Figure 15. Excluding the stable end products and the parent nuclides, these three series contain a total of 42 radioactive nuclides.

The thorium series has ^{232}Th ($t_{1/2}$ = 1.40E+10 years) as the parent and after a series of alpha and β^- emissions, reaches ^{208}Pb, a stable end product. In many of the steps in the series, gamma rays and conversion electrons are also emitted. The uranium series has ^{238}U ($t_{1/2}$ = 4.468E+9 years) as the parent and ^{206}Pb as the end product. The actinium series has ^{235}U ($t_{1/2}$ = 7.04E+8 years) as the parent and ^{207}Pb as the end product. Collateral series, i.e., series running parallel to one of the naturally-occurring series, have also been investigated. For example, the nuclide ^{227}Pa decays by successive alpha emissions to ^{207}Pb; this series is comparable to the actinium series.

The historical symbols, e.g., RaA for ^{218}Po, are given on the Chart for members of these chains. The names corresponding to these symbols were assigned in the early 1900s while the series were being investigated. The symbols usually indicate the chain to which a given isotope belongs: RaA, RaB, …, RaG all belong to the uranium series; AcA, AcB, …, AcD belong to the actinium series; ThA, ThB, …, ThD belong to the thorium series. The relative position of an isotope in the chain can usually be determined from the historic name, i.e., "A" decays to "B," which decays to "C," etc. In addition, similarly named isotopes of the three series are isotopes of the same element: RaA, AcA, and ThA are all isotopes of Po; RaB, AcB, and ThB are all isotopes of Pb. As noted above, the members of these series decay by α or β^- emission. Since decay by alpha emission decreases the atomic mass, A, of a nuclide by four and beta emission has no effect on the value of A, the mass numbers of members of a given series differ by multiples of four. Accordingly, the A value of any member of the thorium, uranium, or actinium series can be characterized by the expression $4n$, $4n + 2$, or $4n + 3$, respectively, where n is an integer from ~50 to 59.

The radioactive series of nuclides whose mass numbers are represented by $4n + 1$ no longer exists in nature. This series, the neptunium series, beginning with ^{241}Pu and ending with ^{209}Bi, has been studied. The longest-lived member of this $4n + 1$ series is ^{237}Np, with a half-life of 2.14E+6 years. Since the age of the earth is about 5E+9 years, most of the ^{237}Np present when the earth was younger has already decayed and this series is no longer found in nature.

It should be noted that the end products of the naturally-occurring decay series—^{206}Pb, ^{207}Pb, and ^{208}Pb—are all "magic" nuclides (see "The Nuclear Shell Model," page 29) with Z = 82. ^{208}Pb is a "doubly magic" nuclide with N = 126. The end product of the neptunium series, ^{209}Bi, contains a "magic" number of neutrons with N = 126.

The earth's crust contains about 3 ppm of ^{238}U (parent of the uranium series), 11 ppm of ^{232}Th (parent of the thorium series) and 0.02 ppm ^{235}U (parent of the actinium series). In each of the series, an isotope of radon (a gas) is produced: ^{222}Rn ($t_{1/2}$ = 3.8235 d) in the uranium series, ^{220}Rn ($t_{1/2}$ = 55.6 s) in the thorium series and ^{219}Rn ($t_{1/2}$ = 3.96 s) in the actinium series. Radon atoms can diffuse through the earth's crust and find their way to the surface, becoming part of the atmosphere. Because of the short half-life, most of the ^{219}Rn decays before reaching the surface. Although outdoor concentrations of ^{222}Rn and ^{220}Rn are typically low, these gases can

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[199] M. Eisenbud and T.F. Gesell, *Environmental Radioactivity: From Natural, Industrial and Military Sources, 4th Edition*, (Academic Press, 1997).

[200] P. de Marcillac, N. Coron, G. Dambier, J. Lebla; J.P. Moalic, Nature **422** 876 (2003).; F.A. Danevich, *et al.*, Phys. Rev. **C67** 014310 (2003); C. Cozzini, *et al.*, Phys. Rev. **C70** 064606 (2004).

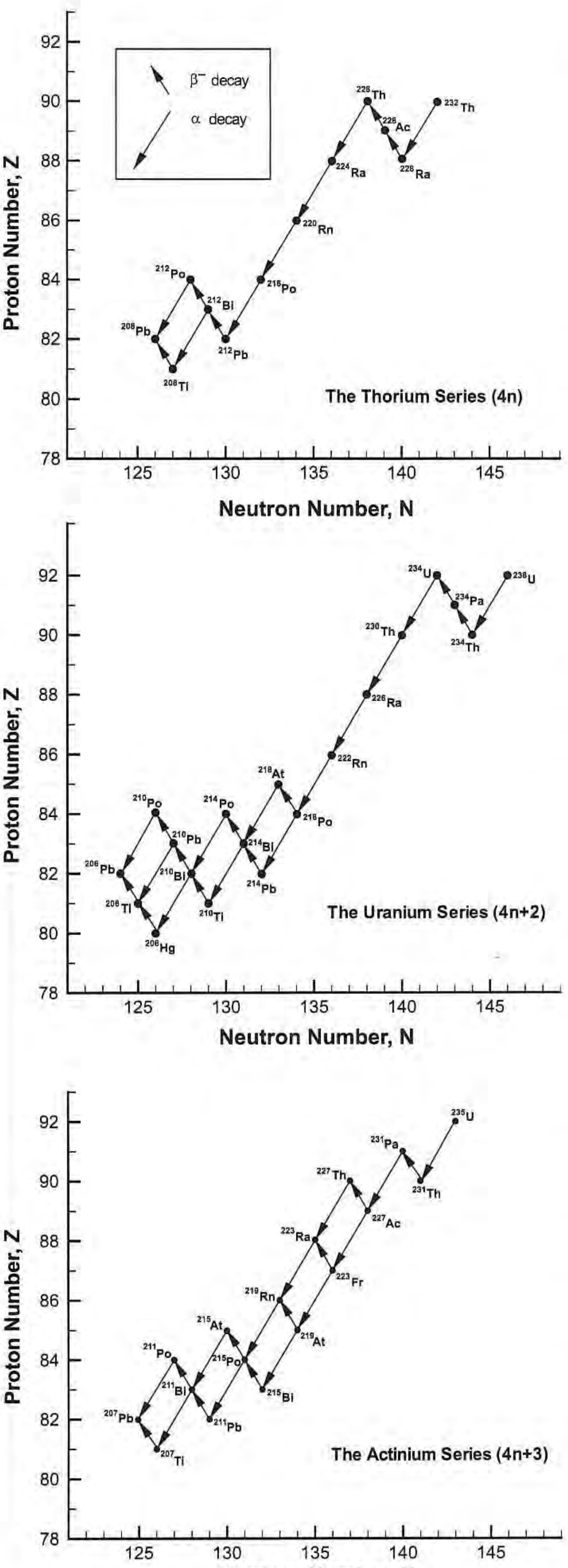

Figure 15. The Three Naturally-Occurring Radioactive Decay Chains.

accumulate in confined areas of buildings and homes and present a potential health risk.[201]

M. Fission Product Designations and Fission Yields

Binary fission of ^{233}U, ^{235}U, or ^{239}Pu produces many different fission products. Fission products range from vanadium (Z = 23) to hafnium (Z = 72) and from mass number A = 66 to A = 172 in the thermal neutron fission of ^{235}U. Ternary fission, or breakup into three products, occurs less frequently than binary fission. This process is a source of light particles such as ^{3}H, ^{3}He, ^{4}He, ^{7}Be, etc. These long-lived or stable light nuclides can build up in the nuclear fuel of an operating reactor.

Since the neutron-to-proton ratio is about 1.6 for ^{235}U and about 1.3 for the stable nuclides in the fission product region, the primary products of fission are on the neutron-rich side of stability. Each such product decays by successive β^- decays to a stable isobar. No neutron-deficient nuclides have been found among the products of thermal neutron fission; however, a few so-called shielded nuclides occur among the fission products. A shielded nuclide has a stable isobar one unit lower in Z so that it is not formed as a daughter product in a beta-decay chain. Examples are ^{86}Rb and ^{136}Cs. The fission yield of such a nuclide is presumably due entirely to its direct formation as a primary product (independent yield). However, its presence in fission products could also be due to neutron capture by the stable fission product to its left on the Chart.

The independent yield of a particular fission product is the direct or instantaneous yield of that nuclide without any contribution from decay of preceding members of the isobaric chain. The measured total cumulative yield of a particular fission product represents the sum of its independent yield and of the independent yields of all its precursors.

The cumulative chain yields[202] from the thermal neutron fission of ^{235}U, ^{239}Pu, and ^{233}U are plotted against mass number, A, in Figure 16. Fission into two equal fragments is by no means the most probable mode in thermal neutron fission. As can be seen in the figure, asymmetric modes are much more favored, with the maximum yields occurring at A ≈ 95 and A ≈ 140. The shape of the fission yield curve changes as a function of incident neutron energy,

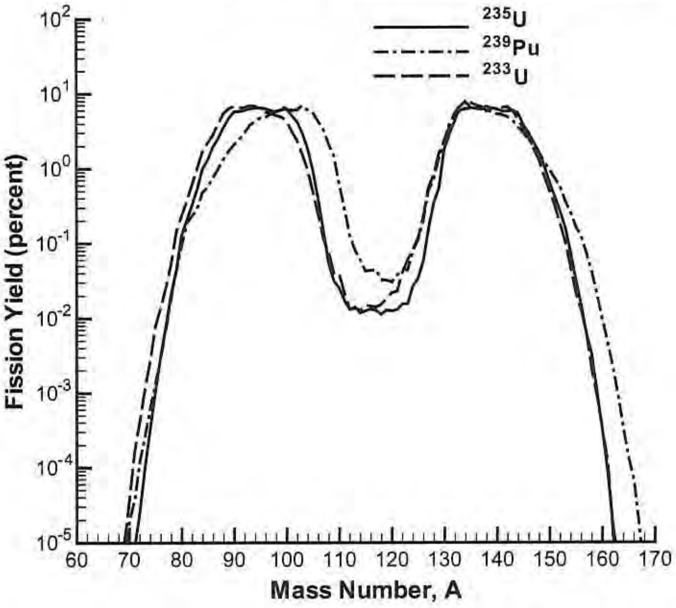

Figure 16. Comparison of the Thermal Fission Yields for ^{235}U, ^{239}Pu, and ^{233}U.

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[201] Committee on Health Risks of Exposure to Radon (BEIR VI), *Health Effects of Exposure to Radon: BEIR VI,* (National Research Council, National Academies Press, 1999).

[202] T.R. England and B.F. Rider, "Evaluation and Compilation of Fission Product Yields." LA-UR-94-3106, Los Alamos National Laboratory, Oct. 1994.

with the asymmetry becoming less pronounced at higher neutron energies, i.e., an increase in the height of the curve between the two peaks.

Figures 17 and 18 show graphs of the values of (N,Z) for the nuclides from Z = 20 to Z = 75, where the third dimension is the independent (thermal) fission yield in percent (on a linear scale) for ^{235}U and ^{239}Pu, respectively. The color scale used is:

> 3.0%	orange
> 1.0% to 3.0%	yellow
> 0.1% to 1.0%	green
> 0.01% to 0.1%	blue
2.5E−6% to 0.01%	grey

The resulting surface mirrors the asymmetric peaks shown in Figure 16. The comparison of Figure 17 to Figure 18 shows the shift of the fission peak yield from A = 93 for ^{235}U to A = 103 for ^{239}Pu and the shared fission yield peak at A = 134, but the general population of fission products (dark grey squares) is relatively the same.

The known isobaric fission chains are indicated on the Chart by lines drawn diagonally off the corner of the first or last nuclide square for each mass number, A. For a given A, near the end of the diagonal line extending downward from the isobar with lowest Z is the total cumulative yield for ^{235}U thermal neutron fission; at the end of the diagonal line extending upward from the isobar with the largest Z are total cumulative yields for ^{233}U thermal neutron fission (above) and ^{239}Pu thermal neutron fission (below in parentheses). The total cumulative yield of a nuclide is the percentage of the total fissions that leads directly or indirectly to that nuclide. Since two fission products are emitted for every binary fission, the total yields of all the isobaric chains add up to 200 percent. The fission yields given on the Chart of the Nuclides are total cumulative chain yields (in percent) of the last isobaric chain member of ^{235}U, ^{233}U, and ^{239}Pu thermal neutron fission.

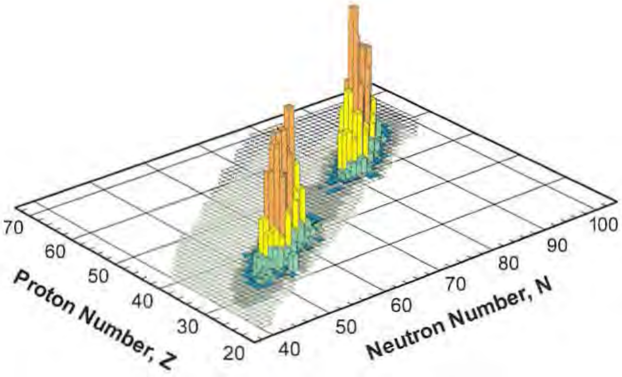

Figure 17. Independent Thermal Fission Yields for ^{235}U of Nuclides with Proton Number Z and Neutron Number N.

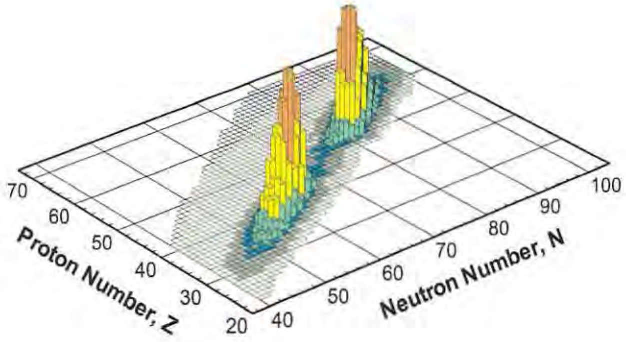

Figure 18. Independent Thermal Fission Yields for ^{239}Pu of Nuclides with Proton Number Z and Neutron Number N.

Fission products from the thermal neutron fission of ^{235}U are indicated on the Chart by small colored triangles or, for shielded yields greater than 2.5E−6 percent, squares in the lower right corner of the Chart square. The colors of the triangles and squares are used to indicate magnitudes of the independent yields. The color scale used is:

> 3.0%	orange
> 1.0% to 3.0%	yellow
> 0.1% to 1.0%	green
> 0.01% to 0.1%	blue
2.5E−6% to 0.01%	black

In addition, open triangles are used for nuclides having both independent yields less than 2.5E−6 percent and cumulative yields greater than 2.5E−6 percent.

An enormous amount of chemical and mass spectrometry work was required to arrive at our present state of knowledge about fission products. It was necessary to develop chemical separation procedures, analyze radioactive decay and growth patterns, determine beta- and gamma-ray energies, establish mass assignments of many previously unknown nuclides, and measure the fission yields. This work continues at many universities and national laboratories throughout the United States and the world.

Trends in Stability on the Chart

Stable Nuclides

As shown on the Chart, 266 stable nuclides (gray colored squares) exist. Figure 19 is a plot of the neutron number, N, versus the proton number, Z, for these nuclides. Also shown on the graph is the Z = N line. The deviation of the (N,Z) values of the stable nuclei from the Z = N line indicates the number of neutrons in these nuclei is always greater than or equal to the number of protons for $Z > 2$. (^{1}H and ^{3}He are the only stable nuclides with $N < Z$.) The light nuclides cluster around the Z = N line, but heavier stable nuclides have many "excess" neutrons. For these nuclides, as Z increases, the long-range Coulomb repulsion between protons is balanced by the presence of additional neutrons providing additional short-range attractive nuclear forces.

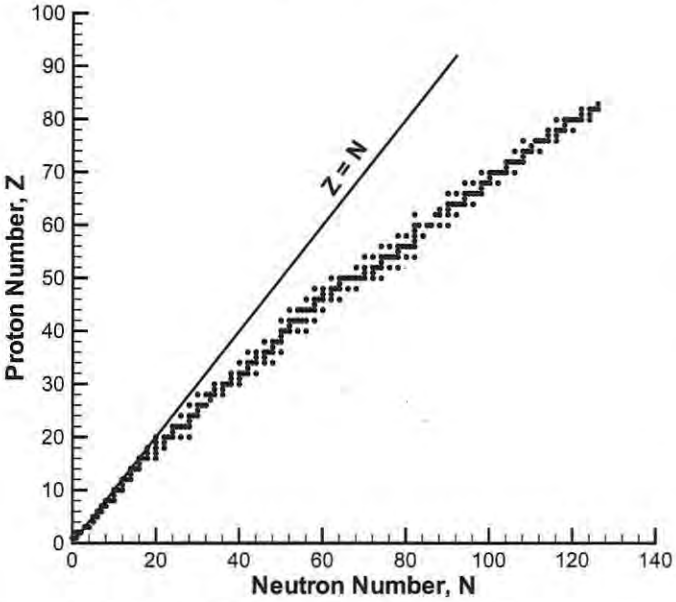

Figure 19. Values of (N,Z) for the 266 Stable Nuclides.

Classifying the stable nuclides by the evenness or oddness of Z and N gives four possible categories. The first category contains an even number of protons and an even number of neutrons (so called even-even nuclei). The other categories are even-odd, odd-even, and odd-odd. Table VI shows the number of stable nuclides that fall in each category.

As seen in Table VI, there are more stable nuclides with even Z and even N than in any other category. More stable nuclides with even Z exist than with odd Z; more stable nuclides exist with even N than with odd N. For the odd A nuclides, there are approximately as many nuclides with an even number of protons (even Z) as with an even number of neutrons (even N). This is evidence that the nuclear force between two nucleons is independent of whether the nucleons are protons or neutrons. Odd-odd stable nuclides are scarce, being found only among the lightest nuclides.

Table VI. Distribution of Stable Nuclides

A	Z	N	Number of Stable Nuclides
Even	Even	Even	159
Odd	Even	Odd	53
Odd	Odd	Even	50
Even	Odd	Odd	4
			266

The Nuclear Shell Model

The periodicity of many chemical properties of elements led to the development of the shell theory of the electronic structure of atoms. Similarly, studies[203] of properties of nuclides—the number of stable isotopes of each element, the relative natural abundances of isotopes, variations of the magnitude of the thermal neutron capture cross section for different nuclides—led to the development of a nuclear shell model for the neutrons and protons within a nucleus.[204] As pointed out earlier, isotopes (and isotones) with Z (or N) equal to the "magic numbers," 2, 8, 20, 28, 50, and 82, and N = 126, are indicated on the Chart by heavy lines. These values correspond to filled proton or neutron shells and represent the most stable configurations. There are more stable isotopes (or isotones) for nuclides having these values of N or Z than for other values. For example tin, Z = 50, has ten stable isotopes. Several nuclides, e.g., ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca, and ^{208}Pb, have both N and Z values that are magic numbers and are referred to as "doubly magic."

The scarcity of odd-odd stable nuclides is due to a "pairing energy" between particles in the same shell. Nucleons residing in the same shell increase the binding energy of these particles, making them more stable than particles in different shells. An odd-odd nuclide contains at least one unpaired proton and one unpaired neutron, which usually reside in different shells and hence contribute weakly to the binding. However, for the lightest nuclei, ^{2}H, ^{6}Li, ^{10}B, and ^{14}N, the unpaired neutron and proton are in the same shell.

Binding Energy

The difference between the actual nuclear mass of a nuclide and the mass of all the individual nucleons is called the total binding energy. It represents the work necessary to dissociate the nucleus into separate nucleons or, conversely, the energy that would be released if the separated nucleons were reassembled into a nucleus. For convenience, the masses of atoms, rather than the masses of the nuclei are used in all calculations. The binding energy, $B(A,Z)$, of an atom having Z protons and (A−Z) neutrons in the nucleus is given by

$$B(A,Z) = ZM_H + (A-Z)M_n - M(A,Z),$$

where M_H is the mass of the hydrogen atom (including the electron), M_n is the neutron mass, and $M(A,Z)$ is the mass of the neutral atom with atomic mass A and Z protons.[205] Since $B(A,Z)$ is positive, a stable atom has a smaller mass than the combined masses of the constituent particles. The binding energy per nucleon, $B(A,Z)/A$, for the stable nuclides, is plotted as a function of A in Figure 20. As seen in the figure, the binding energy per nucleon rises sharply, reaching a maximum value of about 8.8 MeV near A = 50 and then slowly decreases to a value of ~7.6 MeV near A = 230. Below A = 20, the three small spikes in the curve correspond to ^{4}He, ^{12}C, and ^{16}O. The binding energies per nucleon of these three nuclides are considerably larger than neighboring nuclides—for ^{4}He, it is approximately 7.1 MeV.

The fact that the curve in Figure 20 peaks at $A \approx 50$ indicates that the binding energy could be increased by either breaking heavy nuclides apart (fission) or by fusing light nuclides together (fusion). Both processes would result in the release of energy.

In a nuclear reaction, the difference in the rest masses of the initial particles and final products determines whether the reaction is endothermic or exothermic. For the reaction

$$X(x,y)Y,$$

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[203] O. Haxel, J.H.D. Jensen, and H.E. Suess, Phys. Rev. **75** 1766 (1949); M.G. Mayer, Phys. Rev. **75** 1969 (1949).

[204] See Mm. G.-Mayer and J.H.D. Jensen, *Elementary Theory of Nuclear Shell Structure*, (John Wiley and Sons, New York, 1955) and references within.

[205] The equation neglects the binding energy of the electron in the hydrogen atom and the binding energy of all electrons in the atom specified by A and Z. These energies are small compared to other terms in the equation.

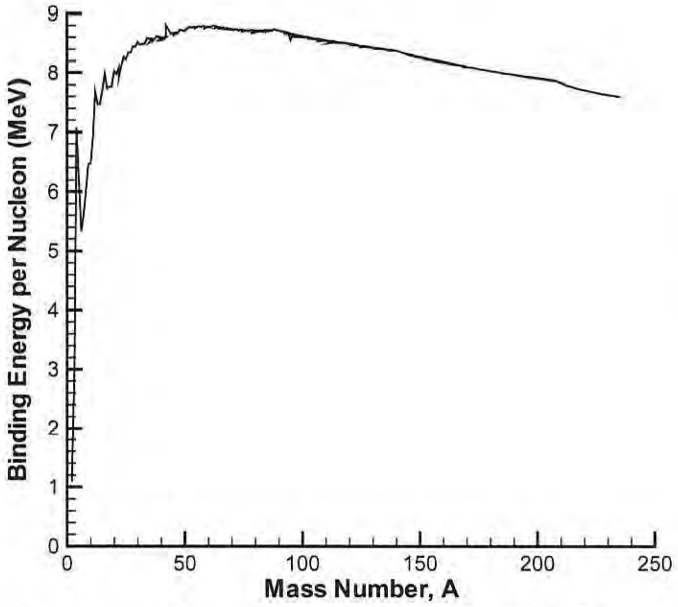

Figure 20. Binding Energy per Nucleon as a Function of Mass Number for the Stable Nuclides.

the Q-value of the reaction is defined as

$$Q = (M_X + M_x) - (M_Y + M_y).$$

If Q is positive for the reaction, the reaction is exothermic and energy is released during the reaction. If Q is negative, the reaction is endothermic and energy is required for the reaction to take place.

For ^{235}U, the fission reaction initiated by neutrons can be written as:

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}\mathrm{U}^* \rightarrow \mathrm{X} + \mathrm{Y} + \bar{\upsilon}\mathrm{n}.$$

where X and Y are two intermediate mass nuclides and $\bar{\upsilon}$ is the average number of neutrons released. The distribution of masses for thermal neutron fission of ^{235}U was shown in Figure 16. For nuclides near uranium, the binding energy per nucleon is about 7.6 MeV, while it is about 8.5 MeV near the fission products ($A \approx 70$ to $A \approx 160$). This is about 0.9 MeV/nucleon greater in the fission products. The total energy released in the fission reaction is, then, in excess of 200 MeV. The fission fragments are neutron rich (see below) and decay predominately by β^- emission. The average number of neutrons, $\bar{\upsilon}$, emitted in the thermal neutron fission of ^{235}U is approximately 2.43; the emission of these neutrons makes a chain reaction possible. Most are "prompt" neutrons, emitted at the time of fission, but a small fraction are emitted as "delayed" neutrons from specific fission products. The latter are very important in the control of nuclear reactors.

For small A, the binding energy per nucleon rises rapidly with mass number as shown in Figure 20. In fusion reactions, light nuclides are combined to form heavier nuclides. The products are more tightly bound and energy is released in the reaction. Some important examples of fusion reactions are:

$$^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{H} + \mathrm{p} \qquad (Q = 4.03\ \mathrm{MeV}),$$
$$^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{n} \qquad (Q = 3.27\ \mathrm{MeV}),$$
$$^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + \mathrm{n} \qquad (Q = 17.6\ \mathrm{MeV}),$$
$$^2\mathrm{H} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \mathrm{p} \qquad (Q = 18.4\ \mathrm{MeV}).$$

While the energy released in these fusion reactions is much less than that released in a fission reaction, the energy yield per unit mass of material is greater in fusion than in fission.

Unstable (Radioactive) Nuclides

Figure 21 shows a graph of the values of (N,Z) for all nuclides given on the Chart. The black squares indicate stable nuclides. The color of the other squares indicates the value of a "mass excess" defined as $M(A,Z)$—$M(A,Z')$, where $M(A,Z')$ is the mass of the lightest isobar of mass number A. For a given A, the stable nuclides are the most tightly bound; other isobars are less tightly bound, have larger masses, and are unstable. For a given value of A, those nuclides with squares lying above the stable nuclides have too many protons for stability (proton-rich), while those with squares lying below the stable nuclides have too many neutrons for stability (neutron-rich).

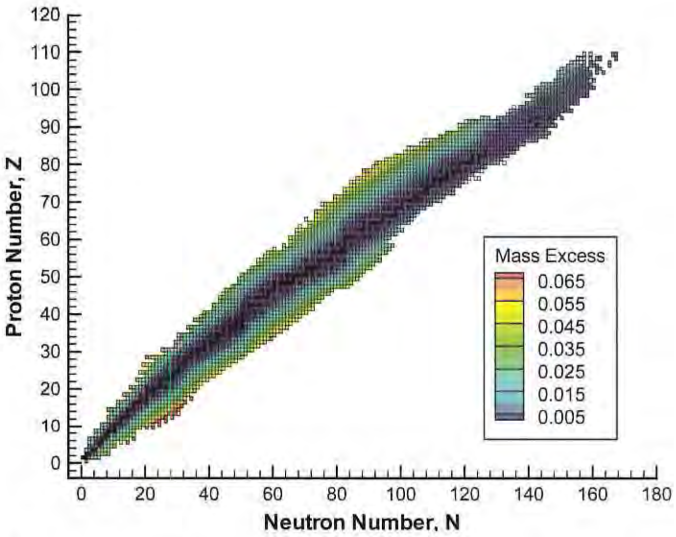

Figure 21. Plot of the "Mass Excess" for the Known Nuclides. Black squares represent stable nuclides.

If the mass excess were plotted as a third dimension to the graph in Figure 21, the resulting surface would resemble a valley with the stable nuclides along the bottom of the valley, as shown in Figure 22, for $40 \le A \le 159$. Rising on the "high-Z" side of the valley are the proton-rich nuclides while on the other are the neutron-rich nuclides. These unstable nuclides undergo radioactive decay bringing the final product closer to a stable configuration, moving towards the bottom of the valley. The modes of radioactive decay to achieve this differ, depending on the mass region of the Chart. The different decay modes are discussed below.

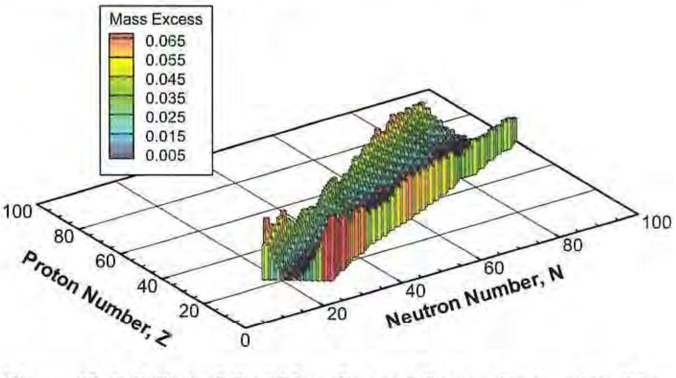

Figure 22. 3-D Plot of the "Mass Excess" for the Known Nuclides with $40 \le A \le 159$.

A. Beta Decay and Electron Capture

Below $Z \approx 83$, radioactive nuclides move towards stability by increasing or decreasing the nuclear charge through beta decay (β^+, β^-) or electron capture (ε). In these processes, either a positive or negative electron is emitted from the nucleus or an orbital electron is captured by the nucleus. Nuclides having an excess of neutrons (those below the stable nuclides shown in Figure 21) tend to undergo β^- decay. For β^- decay, a neutron within the nucleus decays as:

$$\mathrm{n} \rightarrow \mathrm{p} + \beta^- + \bar{\nu},$$

where $\bar{\nu}$ is an antineutrino. In this process, the atomic number of the initial nuclide increases by one, while A is unchanged:

$${}^{A}_{Z}X \rightarrow {}^{\ A}_{Z+1}Y + \beta^- + \bar{\nu}.$$

See Figure 13 for the effect of β^- decay on the Chart. In terms of atomic masses, the condition for β^- decay to be possible is:

$$M(A,Z) \geq M(A,Z+1).$$

The quantity $[M(A,Z) - M(A,Z+1)]c^2$ is the energy released in β^- decay (beta disintegration energy) and is given on the Chart for the neutron-rich nuclides. This energy difference is plotted in Figure 23. Nuclides for which this quantity is positive (and could undergo β^- decay) are shown as colored squares in Figure 23. Fission products are neutron-rich nuclides and tend to undergo successive β^- decays forming the decay chains described earlier.

Nuclides having an excess of protons (those above the stable nuclides in Figure 21) tend to undergo β^+ decay or electron capture. For β^+ decay, a proton in the nucleus decays as

$$p \rightarrow n + \beta^+ + \nu,$$

where ν is a neutrino. In this process, the atomic number of the initial nuclide is decreased by one:

$${}^{A}_{Z}X \rightarrow {}^{\ A}_{Z-1}Y + \beta^+ + \nu.$$

See Figure 13 for the effect of β^+ decay on the Chart. In terms of atomic masses, the condition for β^+ decay is

$$M(A,Z) \geq M(A,Z-1) + 2m_e,$$

where m_e is the mass of an electron.[206] The energy difference $[M(A,Z) - M(A,Z-1) - 2m_e]c^2$ is plotted in Figure 24. Nuclides for which this quantity is positive (and could undergo β^+ decay) are shown as colored squares in Figure 24.

In electron capture, ε, an atomic electron is captured by a proton in the nucleus:

$$p + e^- \rightarrow n + \nu,$$

resulting in the atomic number of the original nuclide decreasing by one. In terms of atomic masses, for electron capture to be possible,

$$M(A,Z) \geq M(A,Z-1).$$

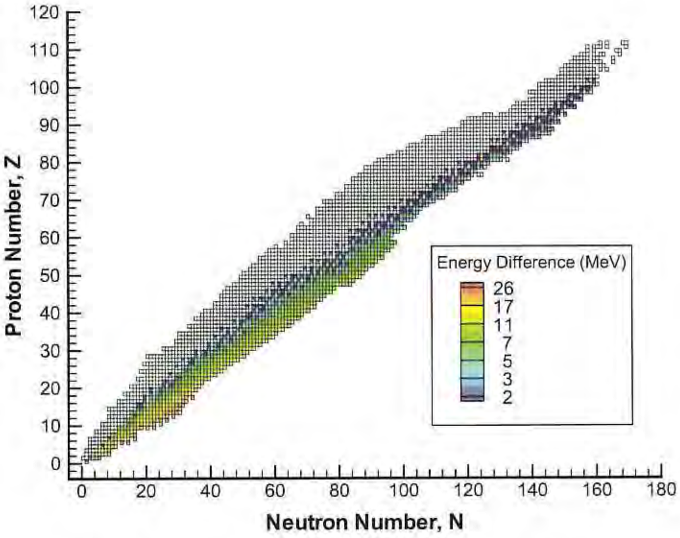

Figure 23. Colored Squares Indicate Nuclides for which the Energy Difference, $[M(A,Z) - M(A,Z+1)]c^2$, is Positive. For these nuclides, β^- decay is possible.

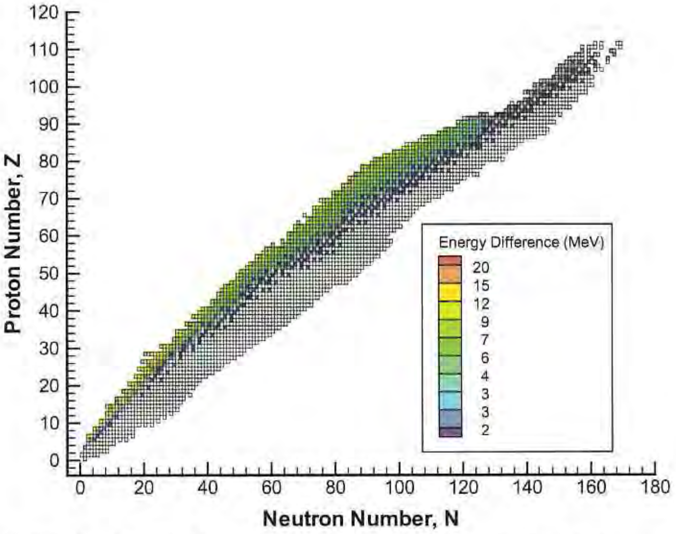

Figure 24. Colored Squares Indicate Nuclides for which the Energy Difference, $[M(A,Z) - M(A,Z-1) - 2m_e]c^2$, is Positive. For these nuclides, β^+ decay is possible.

The quantity $[M(A,Z) - M(A,Z-1)]c^2$ is the beta disintegration energy given on the Chart for proton-rich nuclides. Note that β^+ decay is possible only if the initial and final masses differ by at least $2m_e$ (1.022 MeV), while electron capture, ε, is possible if the initial mass is just greater than the final mass. If β^+ decay is possible, electron capture is also. Some nuclei that cannot undergo β^+ decay can, however, undergo decay by electron capture.

Figure 25 presents a plot of the masses of isobars with A = 61 as a function of Z. For this value of A, only one stable nuclide exists—^{61}Ni with Z = 28. Nuclides with larger Z values (proton-rich) decay by β^+ emission while nuclides with smaller values of Z (neutron-rich) decay by β^- emission. Both types of decay modes move towards stable ^{61}Ni. Generally, for a given odd value of A (Z-odd, N-even or Z-even, N-odd), a plot of the masses of the isobars versus the atomic number gives a parabola-like curve with the most stable isobar at the bottom of the curve. Typically, for a specific odd A only one stable isobar exists.

For even values of A, two or three stable isobars are typically found in nature. Even A nuclides have either Z and N odd, or Z and N even. Masses of the isobars with A = 40 are plotted in Figure 26. The upper curve connects the masses of the odd-odd nuclides,

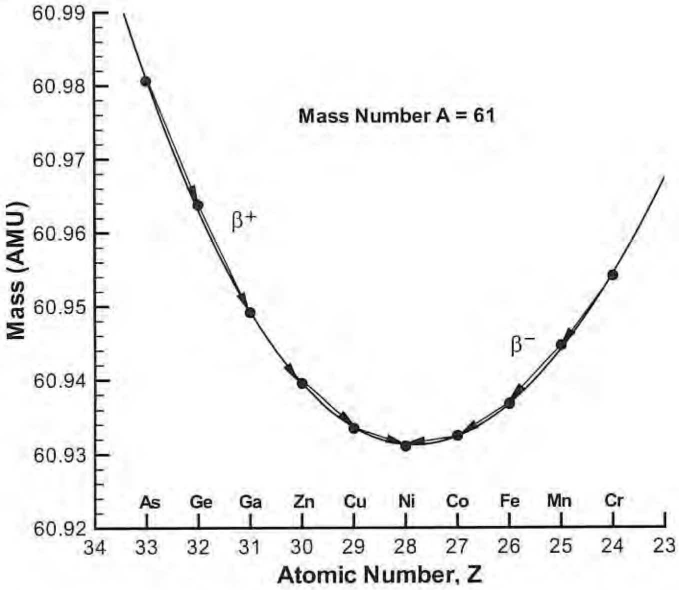

Figure 25. Masses of Isobars with A = 61. One stable isobar, ^{61}Ni, exists.

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[206] The $2m_e$ reflects the fact that the mass of the nucleus has decreased by m_e through the creation of a proton and the atomic number of the product nucleus has decreased by one unit, or an additional decrease of m_e in the mass of the atom as a whole.

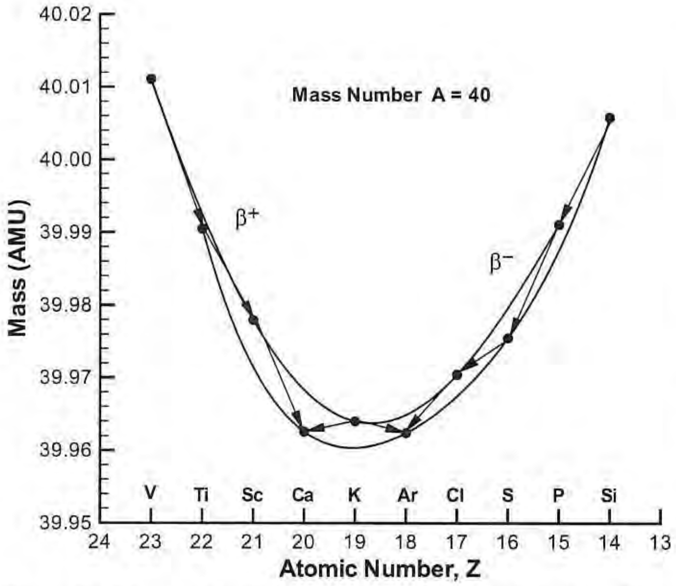

Figure 26. Masses of Isobars with A = 40. Two stable isobars, ^{40}Ca and ^{40}Ar, exist.

while the lower curve connects the masses of the even-even nuclides. Two stable nuclides, ^{40}Ca and ^{40}Ar, exist for this value of A; both are even-even. The odd-odd nuclide, ^{40}K, lies between them. It decays either by β^+ emission to ^{40}Ar or by β^- emission to ^{40}Ca.

The Chart lists 33 nuclides that undergo both β^+ and β^- decay, e.g., ^{36}Cl, ^{40}K, ^{70}Ga, and ^{74}As. These are all odd-odd nuclides and are located between beta-stable, even-even isobars for a given (even) value of A.

The modes of decay for isobars with A = 124 are shown in Figure 27. Neither β^+ decay of ^{124}Xe nor β^- decay of ^{124}Sn is energetically possible. ^{124}Sb decays by β^- emission and ^{124}I decays by ε and β^+, both to ^{124}Te. Three stable even-even isobars, then, exist for this value of A—^{124}Xe, ^{124}Te, and ^{124}Sn.

In the discussion of fission yields above, shielded nuclides were mentioned. Examples of these nuclides are ^{82}Br, ^{86}Rb, ^{100}Tc, ^{124}Sb, and ^{134}Cs; all are odd-odd nuclides. These nuclides all have a stable isobar one unit lower in Z so that they cannot be formed as a daughter product in a beta decay chain. The fission yields of these nuclides are due to their direct formation as primary fission products.

Beta decay processes are classified according to the differences in spin and parity between the initial and final states. Within a given class, the half-life is roughly proportional to the reciprocal of the fifth power of the decay energy. The fastest decays are those for which there is no change in spin or parity. Figure 28 shows the relationship between decay energies and half-lives for the 0^+ states of a series of N = Z odd-odd nuclides which decay predominantly to the 0^+ ground states of even-even daughters. The solid line is $t_{1/2} = 7500/E^5$ ($t_{1/2}$ in seconds, E in MeV). A great majority of all beta decay half-lives fall near or above this curve.

B. Alpha Decay

For nuclides with large A, alpha decay is a possible mode of decay. For alpha decay,

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He,$$

(see Figure 13) and for the decay to occur, the masses must satisfy the following:

$$M(A,Z) > M(A-4,Z-2) + M(4,2).$$

The energy difference, $[M(A,Z) - M(A-4,Z-2) - M(4,2)]c^2$, is plotted in Figure 29. Nuclides for which this quantity is positive could undergo alpha decay. As mentioned above, the binding energy per nucleon for the alpha particle is about 7.1 MeV and the total binding energy is about 28.3 MeV. For some nuclides with $A \approx 140$, the binding energy per nucleon is of the order of 7 MeV and decay by alpha emission is possible. Alpha decay becomes a dominant decay mode for proton-rich nuclides with $A \geq 160$ and for neutron-rich nuclides with $A \geq 211$.

Alpha decay half-lives depend strongly on the atomic number of the daughter nucleus, on the available energy, and on other factors such as whether Z and A are even or odd. For a given atomic number, the dependence of half-life on the energy of the emitted alpha particle is extremely steep. As shown in Figure 30, increasing the alpha energy from ~4 MeV to ~9 MeV for even-A uranium isotopes is associated with a decrease of about twenty orders of magnitude in half-life, compared to only about two orders of magnitude for beta decay over a similar energy range. For a given alpha energy, the half-life increases roughly exponentially with the daughter atomic number. Figure 31 illustrates this effect for a series of even-A, even-Z alpha emitters with similar alpha energies.

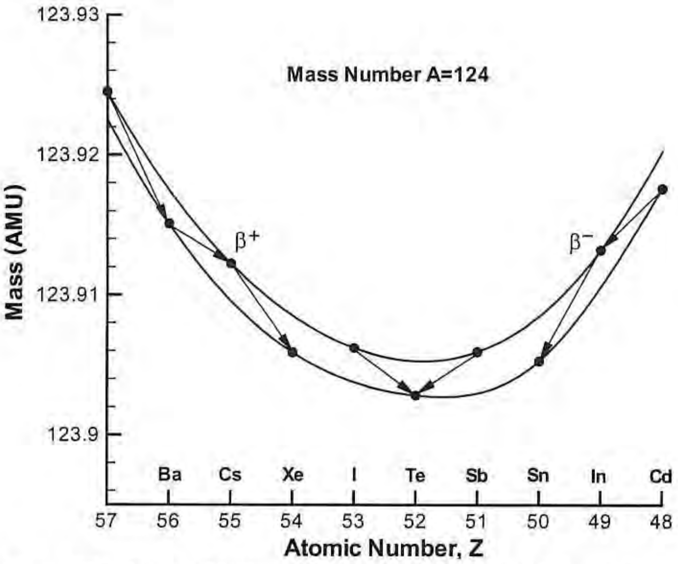

Figure 27. Masses of Isobars with A = 124. Three stable isobars, ^{124}Xe, ^{124}Te, and ^{124}Sn, exist.

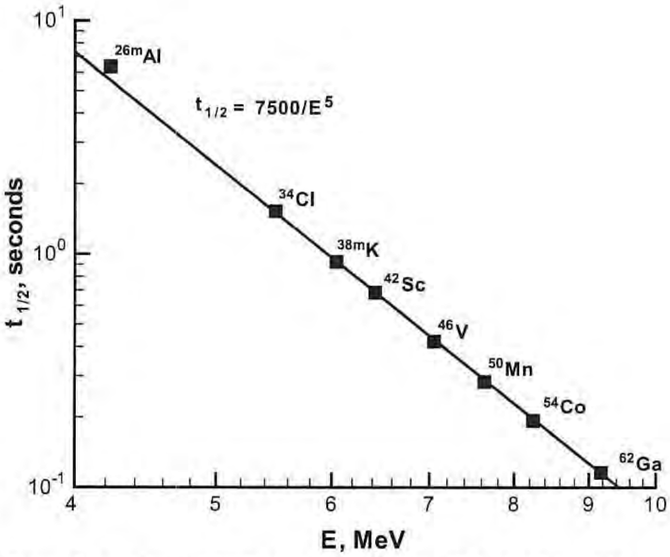

Figure 28. β^+ Decay Half-Lives of 0^+ States of Z = N Odd-Odd Nuclides versus Decay Energy.

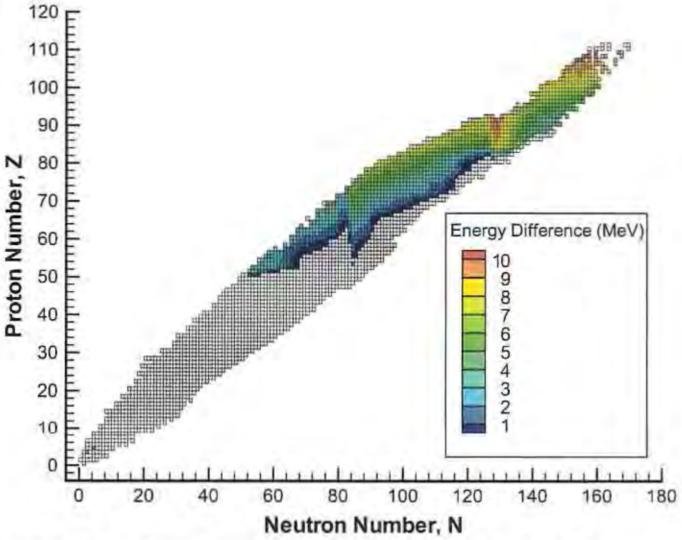

Figure 29. Colored Squares Indicate Nuclides for which the Energy Difference, $[M(A,Z) - M(A-4,Z-2) - M(4,2)]c^2$ is Positive.

C. Spontaneous Fission

For heavy nuclei, spontaneous fission (SF),

$$^{A}_{Z}X \rightarrow {}^{A'}_{Z'}Y + {}^{A-A'}_{Z-Z'}W,$$

becomes possible if

$$M(A,Z) > M(A',Z') + M(A-A',Z-Z').$$

Because the maximum in the binding energy per nucleon occurs near A = 60 (see Figure 20), all nuclides with A greater than approximately 100 are unstable with respect to spontaneous fission. However, measurable rates of spontaneous fission are found only for the heaviest nuclides (A > 230) because of the high Coulomb barriers for the emission of the fission fragments. For very heavy nuclei, then, spontaneous fission becomes a major mode of decay.

D. Cluster Decay

In addition to α-particle decay, certain heavy mass nuclei have been observed to decay by emitting ^{12}C, ^{14}C, ^{20}O, ^{24}Ne, ^{28}Mg, or ^{32}Si at extremely low rates. This form of decay has been designated "cluster radioactivity" and was first observed[207] in the emission of ^{14}C from ^{223}Ra. Since 1984, cluster radioactivity has been observed[208] in 22 nuclides. Cluster radioactivity begins with the formation of a cluster of nucleons within the nucleus, with the cluster tunneling through the potential barrier to decay.[209] Table VII shows the branching ratios for cluster decay relative to α-decay are on the order of 10^{-10} and lower, and detecting this type of decay requires sensitive equipment. The table lists the nuclides observed to decay through cluster radioactivity, the emitted isotopes, and the Q-value for the decay.

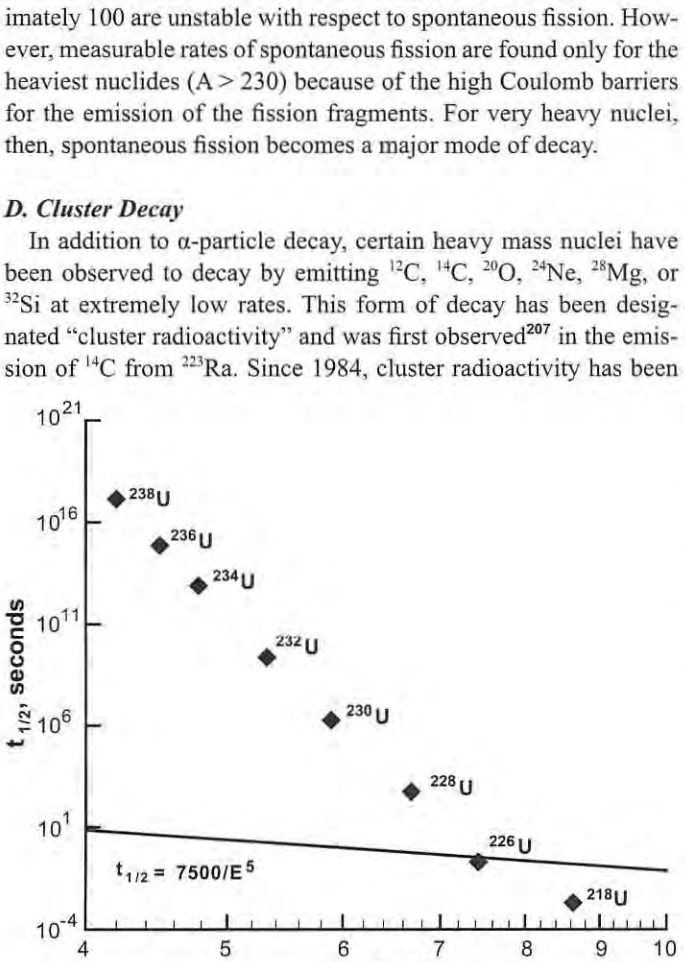

Figure 30. Alpha Decay Half-Lives of Even-A Uranium Isotopes versus Alpha Energy. The solid line corresponds to $t_{1/2} = 7500/E^5$.

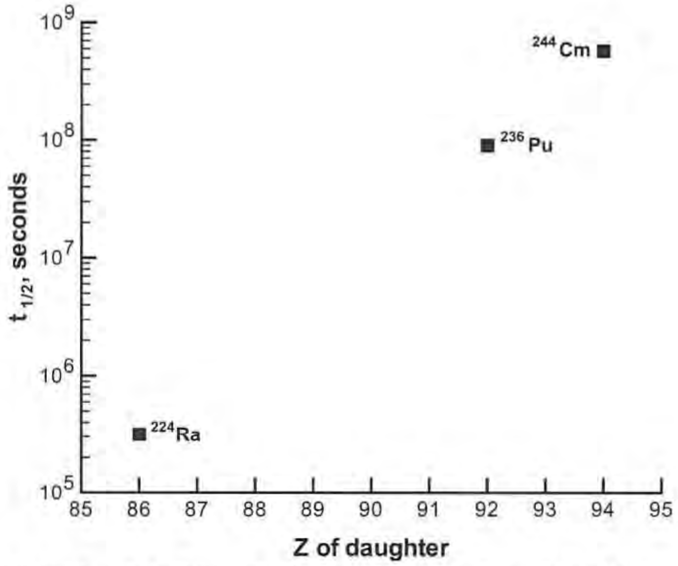

Figure 31. Alpha Decay Half-Lives of Even-A, Even-Z Nuclides with 5.68 MeV < E_α < 5.81 MeV versus Z of the Daughter.

Drip Lines

For a given value of the mass number, A, there are limits on the possible values of the proton number, Z, and the neutron number, N, for which bound nuclei can exist. The value of Z or N for which the last nucleon is no longer bound (the binding energy is negative) defines the "drip line." Near the proton drip line, the Coulomb force limits the addition of protons; near the neutron drip line, the gain in binding energy with the addition of neutrons is not large enough to actually bind the neutrons. The predictions of various nuclear models as to the exact locations of the drip lines vary greatly. Experimental knowledge of the drip line locations becomes increasingly uncertain with increasing mass. Nuclear reaction experiments, using high-energy beams of heavy ions, give a distribution of products whose yields vary smoothly for particle-stable nuclides but drop abruptly to zero at the drip line. For A up to ~30, yields of nuclides just inside the drip lines have often been high enough to provide a clear contrast with the zero yields beyond the drip lines. Between A ≈ 30 and A ≈ 50, the yields in recent experiments[210] for nuclides near the predicted drip lines have been barely above the detection limit (five or fewer ions). The number of nuclides that are predicted to be bound but that have not been observed at all grows rapidly above A ≈ 50. Future increases in beam intensities and detection sensitivities should establish the drip line locations up to higher masses.

For some nuclei near the proton or neutron drip lines, the weakly-bound constituent protons or neutrons are in spatially extended diffuse orbitals or "halos"[211] around the core. Neutron

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[207] H.J. Rose and G.A. Jones, Nature **307** 245 (1984).

[208] W. Greiner and R.K. Gupta, *Heavy Elements and Related Phenomena, Vol. II*, (World Scientific Publishing Company, Singapore, 1999).

[209] The process of this formation is still unknown. Two leading theories hold that the formation of the cluster is similar to the formation of a ^4He particle in the nucleus (prior to α-decay) or that the nucleons come together via the liquid drop mechanism (similar to the theory of fission). See Reference 208 for a more detailed discussion.

[210] B. Blank, J. Phys. G **25** 629 (1999).

[211] S.A. Austin and George F. Bertsch, Sci. Am., pp. 90–95, June, 1995.

Table VII. Cluster Decay Nuclides (See Reference 208)

Nuclide	Cluster	Q (MeV)	Branching Ratio (relative to α decay)	Ref.
^{221}Fr	^{14}C	31.28	(8.14 ± 1.14)E−13	212
^{221}Ra	^{14}C	32.39	(1.15 ± 0.91)E−12	212
^{222}Ra	^{14}C	33.05	(3.7 ± 0.6)E−10	213
^{223}Ra	^{14}C	31.85	(8.5 ± 2.5)E−10	207
^{224}Ra	^{14}C	30.54	(6.1 ± 1.0)E−10	213
^{225}Ac	^{14}C	30.48	(6.0 ± 1.3)E−12	214
^{226}Ra	^{14}C	28.21	(2.9 ± 1.0)E−11	215
^{228}Th	^{20}O	44.72	(1.13 ± 0.22)E−13	216
^{231}Pa	^{23}F	51.84	$(9.97^{+22.9}_{-8.26})$E−15	217
^{230}Th	^{24}Ne	57.78	(5.6 ± 1.0)E−13	218
^{232}Th	^{24,26}Ne	55.62, 55.97	< 2.82E−12	219
^{231}Pa	^{24}Ne	60.42	(1.34 ± 0.17)E−11	217
^{232}U	^{24}Ne	62.31	(2.0 ± 0.5)E−12	220
^{233}U	^{24,25}Ne	60.50, 60.75	(7.5 ± 2.5)E−13	221
^{234}U	^{24,26}Ne	58.84, 59.47	(9.06 ± 6.60)E−14	222
^{235}U	^{24,25}Ne	57.36, 57.83	(8.06 ± 4.32)E−12	223
^{236}U	^{24,26}Ne	55.96, 56.75	< 9.2E−12	223
^{232}U	^{28}Mg	74.32	< 1.18E−13	224
^{233}U	^{28}Mg	74.24	< 1.30E−15	225
^{234}U	^{28}Mg	74.13	(1.5 ± 0.5)E−13	222
^{235}U	^{28,29}Mg	72.20, 72.61	< 1.8E−12	223
^{236}U	^{28,30}Mg	71.69, 72.51	2.0E−13	226
^{237}Np	^{30}Mg	75.02	< 1.8E−14	218
^{236}Pu	^{28}Mg	79.67	2.0E−14	227
^{238}Pu	^{28,30}Mg	75.93, 77.03	(5.62 ± 3.97)E−17	228
^{238}Pu	^{32}Si	91.21	(1.38 ± 0.50)E−16	228
^{240}Pu	^{34}Si	90.95	< 6E−15	229
^{241}Am	^{34}Si	93.84	< 2.6E−13	230
^{242}Cm	^{34}Si	96.51	1.0E−16	231

halos have been found in ^{11}Li, ^{11}Be, ^{14}Be, ^{14}B, ^{19}C, and ^{22}C. There is also evidence for a proton halo in ^{8}B. The ^{11}Li nucleus appears to be a ^{9}Li core with two weakly bound neutrons forming the halo. The radius of the ^{11}Li halo is more than twice that of the core and the ^{11}Li nucleus is almost as large as the ^{208}Pb nucleus (which contains 197 more nucleons).

An Island of Stability for Superheavy Elements

The detection, by I. Curie and F. Joliot, of a short-lived radioactive isotope, ^{30}P, produced by the bombardment of aluminum with alpha particles showed that new isotopes could be "artificially" produced. In 1934, Fermi produced a new isotope of lead by bombarding a thallium target with slow neutrons. The capture of the neutron by the thallium nucleus, followed by β^- decay, produced the new nuclide that was one atomic number higher than the original target.

Nuclides with Z > 92 do not exist in nature. Beginning in about 1940, studies were undertaken to produce these materials using selected nuclear reactions. These studies (along with primary references) are summarized in Table VIII. As described earlier, McMillan and Abelson at the Lawrence Berkeley National Laboratory (LBNL), first produced ^{239}Np (Z = 93) from the β^- decay of ^{239}U, which had been formed by thermal neutron capture of ^{238}U. Plutonium was the next transuranium element to be discovered. At the LBNL, a ^{238}U target was bombarded by deuterons to produce ^{238}Np, which subsequently underwent β^- decay to form ^{238}Pu (Z = 94):

$$^{238}_{92}\mathrm{U} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{238}_{93}\mathrm{Np} + 2\,{}^{1}_{0}\mathrm{n},$$

and

$$^{238}_{93}\mathrm{Np} \rightarrow {}^{238}_{94}\mathrm{Pu} + \beta^- + \overline{\nu}.$$

Studies of the debris from the "Mike" thermonuclear explosion carried out in the Pacific in 1952 led to the discovery of two new elements. In a collaborative study carried out by scientists from Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), and the University of California at Berkeley, the isotopes ^{253}Es (Z = 99) and ^{255}Fm (Z = 100) were found in the debris. Beginning with ^{238}U, these nuclides were formed in the explosion through a combination of many neutron capture reactions, made possible because of the extremely high neutron flux, and β^- decay of some of the resulting products.

Some isotopes in the Z = 93 to 99 region can be produced in weighable quantities. To synthesize the new elements up to Z = 101, a "stepping-stone" procedure was used. Reactions of neutrons, deuterons, or alpha particles incident on newly synthesized high-Z materials produced new nuclides with still higher Z values. By the mid-1950s, elements up to Z = 101 had been produced (see Seaborg and Loveland[127] for details).

Producing weighable quantities of target isotopes with Z > 100 is not possible due to the short alpha decay and fission half-lives of these heavier elements, so light particle-induced reactions cannot be used to produce new, higher Z materials. To produce elements with Z > 101, heavy ion accelerators were required. Between 1958 and 1974, at Berkeley and the Joint Institute for Nuclear Research (JINR) at Dubna, Russia, nuclides with 102 ≤ Z ≤ 106 were produced with beams of carbon, boron, nitrogen, or oxygen ions bombarding californium and curium targets. Until about 1970, it was thought that a limit to the periodic table would be reached at about element 108. Beyond this, it was reasoned the half-lives of the heavier materials, particularly for decay by spontaneous fission, would probably be so short as to prevent them from being observed.

As mentioned earlier, shell model calculations successfully explained the relative stability of those nuclides having "magic" proton or neutron numbers 2, 8, 20, 50, and 82 and, for neutrons, 126. The calculations also predicted that the next magic number for protons would be 126 and for neutrons, 184. A number of nuclear structure calculations carried out in the late 1960s and early 1970s, however, suggested both Z = 114 and 126 as possible closed subshells, with later work[232] supporting a closed shell at Z = 114. Nuclei with 114 protons and 184 neutrons were predicted to have filled both neutron and proton shells (doubly magic) and would be particularly stable. Some early calculations indicated that these superheavy nuclides having "shell stabilization," could have half-lives of the order of the age[233] of the universe. In this mass region, then, nuclides with relatively long half-lives should exist forming an "island of stability" rising out of the "sea of instability." More recent calculations, while still supporting the existence of the island of stability, predict somewhat shorter half-lives.

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Table VIII. Synthesis of Isotopes with Z > 92

Z	Element Name	First Isotope Synthesized					Longest Lived Isotope Known	
		Isotope	Half-Life	Date	Laboratory	Reaction	Isotope	Half-Life
93	neptunium (Np)	$^{239}\mathrm{Np}$	2.356 d	1940	LBNL[125]	$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} + \gamma$ $^{239}\mathrm{U} \rightarrow {}^{239}\mathrm{Np} + \beta^-$	$^{237}\mathrm{Np}$	2.14E+6 a
94	plutonium (Pu)	$^{238}\mathrm{Pu}$	87.7 a	1941	LBNL[126]	$^{238}\mathrm{U} + {}^{2}\mathrm{H} \rightarrow {}^{238}\mathrm{Np} + 2n$ $^{238}\mathrm{Np} \rightarrow {}^{238}\mathrm{Pu} + \beta^-$	$^{244}\mathrm{Pu}$	8.11E+7 a
95	americium (Am)	$^{241}\mathrm{Am}$	432.7 a	1945	Metallurgical Laboratories, Univ. of Chicago[234]	$^{239}\mathrm{Pu} + n \rightarrow {}^{240}\mathrm{Pu} + \gamma$ $^{240}\mathrm{Pu} + n \rightarrow {}^{241}\mathrm{Pu} + \gamma$ $^{241}\mathrm{Pu} \rightarrow {}^{241}\mathrm{Am} + \beta^-$	$^{243}\mathrm{Am}$	7.37E+3 a
96	curium (Cm)	$^{242}\mathrm{Cm}$	162.8 d	1944	Metallurgical Laboratories, Univ. of Chicago[234]	$^{239}\mathrm{Pu} + {}^{4}\mathrm{He} \rightarrow {}^{242}\mathrm{Cm} + n$	$^{247}\mathrm{Cm}$	1.56E+7 a
97	berkelium (Bk)	$^{243}\mathrm{Bk}$	4.5 h	1949	LBNL[235]	$^{241}\mathrm{Am} + {}^{4}\mathrm{He} \rightarrow {}^{243}\mathrm{Bk} + 2n$	$^{247}\mathrm{Bk}$	1.4E+3 a
98	californium (Cf)	$^{245}\mathrm{Cf}$	46 m	1950	LBNL[236]	$^{242}\mathrm{Cm} + {}^{4}\mathrm{He} \rightarrow {}^{245}\mathrm{Cf} + n$	$^{251}\mathrm{Cf}$	9.0E+2 a
99	einsteinium (Es)	$^{253}\mathrm{Es}$	20.47 d	1952	LBNL, ANL, LANL[237]	"Mike" thermonuclear explosion	$^{252}\mathrm{Es}$	1.29 a
100	fermium (Fm)	$^{255}\mathrm{Fm}$	20.1 h	1952	LBNL, ANL, LANL[237]	"Mike" thermonuclear explosion	$^{257}\mathrm{Fm}$	100.5 d
101	mendelevium (Md)	$^{256}\mathrm{Md}$	1.29 h	1955	LBNL[238]	$^{253}\mathrm{Es} + {}^{4}\mathrm{He} \rightarrow {}^{256}\mathrm{Md} + n$	$^{258}\mathrm{Md}$	51.5 d
102	nobelium (No)	$^{252}\mathrm{No}$	2.45 s	1958	JINR[239]	$^{244}\mathrm{Cm} + {}^{12}\mathrm{C} \rightarrow {}^{252}\mathrm{No} + 4n$	$^{259}\mathrm{No}$	58 m
103	lawrencium (Lr)	$^{258}\mathrm{Lr}$	4.1 s	1961	LBNL,[240] JINR	$^{250}\mathrm{Cf} + {}^{11}\mathrm{B} \rightarrow {}^{258}\mathrm{Lr} + 3n$	$^{262}\mathrm{Lr}$	3.6 h
104	rutherfordium (Rf)	$^{257}\mathrm{Rf}$	4.7 s	1969	LBNL,[241] JINR	$^{249}\mathrm{Cf} + {}^{12}\mathrm{C} \rightarrow {}^{257}\mathrm{Rf} + 4n$	$^{267}\mathrm{Rf}$	2 h
105	dubnium (Db)	$^{260}\mathrm{Db}$	1.5 s	1970	LBNL,[242] JINR	$^{249}\mathrm{Cf} + {}^{15}\mathrm{N} \rightarrow {}^{260}\mathrm{Db} + 4n$	$^{268}\mathrm{Db}$	30 h
106	seaborgium (Sg)	$^{263}\mathrm{Sg}$	1.0 s	1974	LBNL[243]	$^{249}\mathrm{Cf} + {}^{18}\mathrm{O} \rightarrow {}^{263}\mathrm{Sg} + 4n$	$^{271}\mathrm{Sg}$	3 m
107	bohrium (Bh)	$^{262}\mathrm{Bh}$	0.10 s	1981	GSI[244]	$^{209}\mathrm{Bi} + {}^{54}\mathrm{Cr} \rightarrow {}^{262}\mathrm{Bh} + n$	$^{270}\mathrm{Bh}$	~51 s
108	hassium (Hs)	$^{265}\mathrm{Hs}$	1.7 ms	1984	GSI[245]	$^{208}\mathrm{Pb} + {}^{58}\mathrm{Fe} \rightarrow {}^{265}\mathrm{Hs} + n$	$^{269}\mathrm{Hs}$	13 s
109	meitnerium (Mt)	$^{266}\mathrm{Mt}$	~2.6 ms	1982	GSI[246]	$^{209}\mathrm{Bi} + {}^{58}\mathrm{Fe} \rightarrow {}^{266}\mathrm{Mt} + n$	$^{276}\mathrm{Mt}$	~0.72 s
110	darmstadtium (Ds)	$^{269}\mathrm{Ds}$	~0.27 ms	1995	GSI,[247] JINR	$^{208}\mathrm{Pb} + {}^{62}\mathrm{Ni} \rightarrow {}^{269}\mathrm{Ds} + n$	$^{281}\mathrm{Ds}$	~9.6 s
111	roentgenium (Rg)	$^{272}\mathrm{Rg}$	2 ms	1995	GSI,[248] JINR	$^{209}\mathrm{Bi} + {}^{64}\mathrm{Ni} \rightarrow {}^{272}\mathrm{Rg} + n$	$^{280}\mathrm{Rg}$	~3.6 s
112	copernicium (Cn)	$^{277}\mathrm{Cn}$	~0.69 ms	1996	GSI,[249] JINR	$^{208}\mathrm{Pb} + {}^{70}\mathrm{Zn} \rightarrow {}^{277}\mathrm{Cn} + n$	$^{285}\mathrm{Cn}$	~34 s
113	—	$^{283,\,284}113$	0.1 s, ~0.48 s	2003	JINR[250]	$^{287,\,288}115$ alpha decay	$^{284}113$	~0.48 s
114	—	$^{289}114$	~2.7 s	1999	JINR,[251] LLNL	$^{244}\mathrm{Pu} + {}^{48}\mathrm{Ca} \rightarrow {}^{289}114 + 3n$	$^{289}114$	~2.7 s
115	—	$^{287,\,288}115$	~32 ms, ~87 ms	2003	JINR[250]	$^{243}\mathrm{Am} + {}^{48}\mathrm{Ca} \rightarrow {}^{287,\,288}115 + 3n,4n$	$^{288}115$	~87 ms
116	—	$^{293}116$	~53 ms	2000	JINR[252]	$^{248}\mathrm{Cm} + {}^{48}\mathrm{Ca} \rightarrow {}^{292}116 + 4n$	$^{293}116$	~53 ms
117								
118	—	$^{294}118$	~1 ms	2002	JINR,[253] LLNL	$^{249}\mathrm{Cf} + {}^{48}\mathrm{Ca} \rightarrow {}^{294}118 + 3n$	$^{294}118$	~1 ms

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The reactions that had been used to produce the elements above $Z = 92$ and below $Z = 107$ used heavy targets, $92 \leq Z \leq 98$, and "light" incident particles (see Table VIII). The use of these types of reactions to produce elements with $Z \geq 107$ was not successful. For the "fusion" of the target and projectile to occur, enough energy must be available to overcome the Coulomb repulsion between the two ions. The resulting new compound system will be highly excited, however, and will likely undergo fission to reach a more stable configuration.

To synthesize the heavier elements, scientists at the Institute of Heavy Ion Research (Gesellschaft fur Schwerionenforschung, GSI) in Darmstadt, Germany and the JINR at Dubna, Russia used heavier incident particles to bombard somewhat lighter targets, ^{208}Pb and ^{209}Bi. These two nuclides are stabilized by the closed neutron shell $N = 126$, and the lead nucleus is further stabilized by the closed proton shell $Z = 82$. This results in lower excitation energy in the compound system decreasing the tendency to undergo fission. If the excitation energy is low enough, most of the excess energy is lost more often by the emission of neutrons from the nucleus—not by fission.

The use of lead and bismuth targets was eventually successful up to element 113, but the extra stability of the magic targets was not enough to compensate for the increased beam energy required to overcome the Coulomb repulsion of still higher-Z incident particles. Another consideration in forming new elements is that the ratio of neutrons to protons required for maximum stability continues to increase as Z increases, and eventually goes beyond the n/p ratios that can be achieved by fusing any two stable or long half-life radioactive nuclei. For this reason, all of the nuclides that have been made so far beyond about $Z = 101$ are proton-rich. To maximize the stability of the product nuclides, it is necessary to use both target nuclides and incident particles that are as neutron-rich as possible. The use of ^{48}Ca as an incident particle and heavy isotopes of Pu, Cm, and Cf as targets accomplishes that goal as well as is currently possible. Like ^{208}Pb, ^{48}Ca is a double-magic nucleus, which minimizes the excitation energy of the compound nucleus. Elements 114–116 and 118 have all been made using ^{48}Ca as the incident particle. By the time element 113 was made directly[254] by the ^{70}Zn + ^{209}Bi reaction, it had already been observed[250] as the alpha decay product of element 115.

New isotopes of elements 104–113 have also been identified as products of ^{48}Ca reactions, either as direct products or by the alpha decay of heavier elements. These newer isotopes[255] are closer to the optimum n/p ratio than the ones prepared earlier, and generally have much longer half-lives.

Both the production and detection of the high Z elements are extremely difficult. The low cross sections for the reactions involved have led to the development of ion sources and accelerators capable of delivering high currents of heavy ions.[256] Efficient means of isolating and detecting the products of these reactions are also necessary.[257] The identification of a new nuclide is carried out by correlating its decay with the decays of daughter products whose emissions, energies, and half-lives are known from previous measurements. Bohrium ($Z = 107$) was first produced at GSI using the reaction[244]:

$$^{209}\text{Bi} + {}^{54}\text{Cr} \rightarrow {}^{263}\text{Bh}^* \rightarrow {}^{262}\text{Bh} + \text{n}.$$

Five decay chains of ^{262}Bh were observed, one of which is shown in Figure 32. Specific decays in each of the decay chains were correlated with known decays in ^{254}Lr, ^{250}Fm, or ^{250}Md. The original parent was, then, assigned with a high probability to be ^{262}Bh.

As of 2009, ^{277}Cn represented both the highest Z and highest N for which two or more different laboratories had reported producing the same nuclide. Although element 113 has been reported by two different groups, they produced different isotopes. All of the nuclides with more than 165 neutrons have been produced only at Dubna by the JINR-LLNL (Lawrence Livermore National Laboratory) group.

The methods being used to produce and identify the heaviest nuclei provide a higher level of certainty for the atomic number of the products than for their mass. Some initial mass assignments have been changed after more data have been obtained. For example, the alpha-decay chain originally reported to begin with ^{292}116 is now believed[258] to begin with ^{293}116, and the one originally reported to begin with ^{289}114 is now believed to begin with ^{290}114.

The quest for longer-lived superheavy nuclides has provided strong support for the expectation that half-lives for the heaviest-known elements will continue to increase as more neutron-rich isotopes are produced. However, it is also clear that producing those nuclides with more neutrons will not be easy.

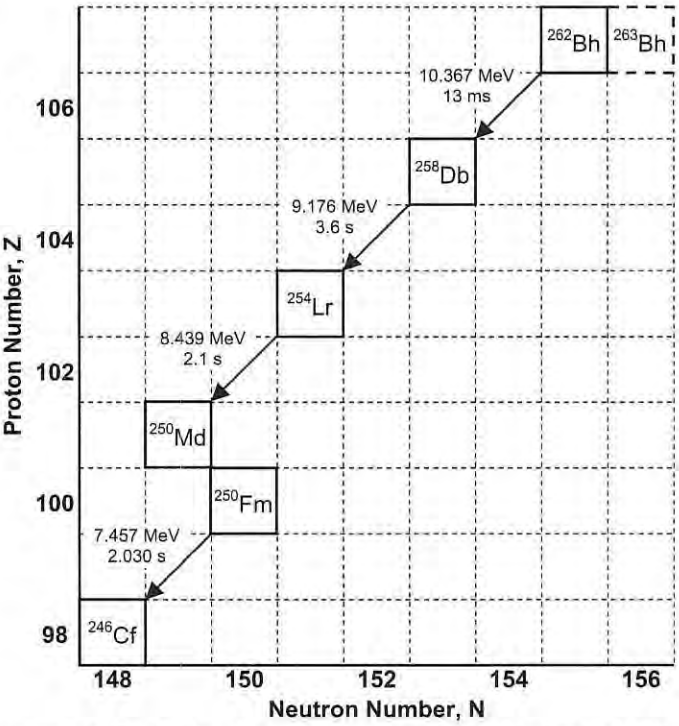

Figure 32. One of the Decay Chains Observed in the Synthesis of ^{262}Bh. Alpha decay energies and observed half-lives are shown for each decay. (From Reference 244.)

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[255] Y. Oganessian, *et al.*, Pure Appl. Chem. **78** 889 (2006).

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Related Topics

Origin of the Naturally-Occurring Nuclides

A "Big Bang" model of the history of the universe[259] has become widely, but not universally, accepted.[260] According to the Big Bang model, the universe started out unimaginably small, dense, and hot, about 14 billion years ago, and has been expanding and cooling[233] (on the average) ever since. George Gamow and others initially proposed that all the elements could have been created during the Big Bang.[261,262] Neutrons and protons would begin to condense into nuclei when the temperature of the expanding universe dropped below about 10^9 Kelvin. However, it was soon realized that the building up of heavy nuclei during the Big Bang could not have continued very far, because collisions between nuclei became less frequent as the universe cooled, and the thermal energy of the nuclei became too low to overcome the electrostatic repulsion of their positive charges. The absence of stable nuclides with mass five or eight hindered the buildup of the heavier nuclides.

As an alternative source of heavy elements, Burbidge, Burbidge, Fowler, and Hoyle[263] (B^2FH), proposed in 1957 a set of mechanisms by which most of the elements were formed in stars and a few by cosmic-ray processes. Subsequent observations, laboratory experiments, and calculational modeling have supported many of their hypotheses and filled in some of the details.[264] One difficulty in comparing theory with observation is that stars have enormous differences in composition, density, and temperature between their inner and outer regions, but the light we see comes only from the outer surface. Stellar spectra correspond to effective temperatures from ~2E+3 to ~4E+5 K, while fusion reactions begin at ~2E+7 K and core temperatures may eventually approach 1E+10 K. Although the temperature differences between core and surface are large, the distances are also large, so thermal gradients are rarely large enough to drive convective mixing of matter from inner regions to the surface. Another difficulty is that several of the reaction sequences go through unstable nuclides that are difficult to study in the laboratory. In addition, reactions that are too slow to measure with precision in the laboratory can be important in stars, where high density compensates for low cross sections.

One weakness in the "B^2FH" model became apparent when more data on the current cosmic abundances of light nuclides became available. The abundance of deuterium, in particular, is too high to be explained by stellar or cosmic-ray processes. Deuterium is consumed more easily than it is produced, and, if cosmic rays were the source of deuterium, they would have produced much more than the observed amount of ^{7}Li.

Most astrophysicists now attribute the formation of the lightest nuclides to the Big Bang and the heavier ones to subsequent stellar and cosmic-ray processes. Modern predictions of the relative abundance of the nuclides formed in the Big Bang are highly dependent on the density of the universe as it cooled through the temperature range where fusion reactions were possible. The composition of the early universe can be inferred from analysis of stellar spectra, cosmic rays, and meteorites, with corrections to account for changes believed to have occurred over time. The resulting estimates of primordial abundance for the five light nuclides ^{1}H, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li are all consistent with about the same value of the density of the early universe. This consistency is considered strong evidence in favor of the Big Bang model. This density is low compared to the densities in stars, where fusion of lighter nuclides into heavier ones is occurring today.

The energy necessary to overcome the Coulomb barrier between higher-Z nuclei comes from the release of gravitational potential energy as the star contracts. More massive stars are able to achieve higher temperatures and greater densities and do so on a shorter time scale than less massive stars. Only a small subset of stars, the most massive ones, is believed to have produced most of the nuclides heavier than ^{7}Li. Much of the heavier matter produced will never escape to be dispersed through the rest of the universe.

Fusion of hydrogen into helium is the first source of nuclear energy in the life cycle of a star. The subsequent steps depend strongly on the mass of the star. The sun and stars of comparable or lower mass remain in the hydrogen-burning stage for billions of years. Stars of the sun's mass have contributed little to the production of heavier elements since the Big Bang. Stars that are more massive than the sun consume their hydrogen more rapidly. Further gravitational contraction then heats them to the temperatures required to fuse helium into heavier nuclides. If the star is massive enough, it evolves through stages of carbon burning, neon burning, oxygen burning, and silicon burning. Later stages take less time than earlier stages and release less energy per unit mass of fuel, providing less resistance to the gravitational contraction.

The details of the earlier stages depend greatly on the relative rates of individual nuclear reactions, but in the later stages when temperature and density become sufficiently high, a quasi-equilibrium state can be reached, where rates are less important than binding energies. Nuclei near the peak of the binding energy curve dominate the composition in the quasi-equilibrium state. Evidence for quasi-equilibrium comes from the high abundance of ^{56}Fe and nearby nuclides, and from the observation of supernova remnants. The prodigious light output of the remnants is powered by radioactive decay of proton-rich nuclides near the binding energy peak, such as ^{56}Ni, ^{56}Co, ^{57}Ni, and ^{44}Ti. This conclusion is supported both by the rate of decay and by the observation of characteristic gamma-ray lines. (Heat and light are produced when some of the nuclear radiation is absorbed by the matter that was ejected in the explosion.)

Hydrogen burning begins with the cycle:

$$\begin{gathered} p + p \rightarrow {}^2H + \beta^+, \\ {}^2H + p \rightarrow {}^3He + \gamma, \\ {}^3He + {}^3He \rightarrow {}^4He + 2p. \end{gathered}$$

The first reaction is slow compared to the next two, so the intermediate products, ^{2}H and ^{3}He, remain in low concentrations. At higher temperatures, ^{7}Be is formed by the reaction of ^{3}He with ^{4}He. Proton reactions on ^{7}Be and the decay product, ^{7}Li, provide additional channels for the formation of ^{4}He.

Helium burning begins with the near-simultaneous fusion of three ^{4}He nuclei to form ^{12}C. The third ^{4}He can add to the unstable ^{8}Be intermediate before it decays only because the reaction can pass through an excited state of ^{12}C in the necessary energy range. (This state was postulated to exist in order to explain the astronomical observations before it was discovered in laboratory experiments.)[265] Helium can fuse with ^{12}C to form ^{16}O, but early predictions that ^{20}Ne would be produced by fusion of helium with

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[260] F. Hoyle, G. Burbidge, and J.V. Narlikar, *A Different Approach to Cosmology: From a Static Universe Through the Big Bang Towards Reality*, (Cambridge University Press, New York, 2000).

[261] G. Gamow, Phys. Rev. **70** 572 (1946).

[262] R.A. Alpher, H. Bethe, and G. Gamow, Phys. Rev. **73** 803 (1948); R.A. Alpher and R.C. Herman, Phys. Rev. **75** 1089 (1949).

[263] E.M. Burbidge, G.R. Burbidge, W.A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29** 547 (1957).

[264] G. Wallerstein, *et al.*, Rev. Mod. Phys. **69** 995 (1997); A. Burrows, Nature **403** 727 (2000); D. Arnett, *Supernovae and Nucleosynthesis: An Introduction to the History of Matter from the Big Bang to the Present*, (Princeton University Press, 1996); C.J. Copi, D.N. Schramm, and M.S. Turner, Science **267** 192 (1995); D.N. Schramm and M.S. Turner, Rev. Mod. Phys. **70** 303 (1998); S. Snedden and J.J. Corran, Science **229** 70 (2003).

[265] F. Hoyle, D.N.F. Dunbar, W.A. Wenzel, and W. Whaling, Phys. Rev. **92** 1095 (1953).

^{16}O have not been supported by later studies. ^{20}Ne lacks states of the necessary spin and parity in the appropriate energy range for this reaction to be important in stars. Instead, neon is formed by fusion of pairs of carbon nuclei and by successive proton capture reactions on the lighter elements.

When hydrogen and carbon are both present, hydrogen burning can be catalyzed by carbon in the CN cycle:

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N},$$
$$^{13}\mathrm{N} \rightarrow \beta^{+} + {}^{13}\mathrm{C},$$
$$^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N},$$
$$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O},$$
$$^{15}\mathrm{O} \rightarrow \beta^{+} + {}^{15}\mathrm{N},$$
$$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}.$$

This cycle can be written in a more convenient form as:

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+})^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^{+})^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}.$$

A small fraction of the ^{15}N is converted to ^{16}O by a (p,γ) reaction, but is returned to the CN cycle by the NO cycle:

$$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(\beta^{+})^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}.$$

The CN and NO cycles require higher temperatures than the $p + p$ reaction but at sufficiently high temperature, they proceed at a much greater rate. At still higher temperatures, the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction competes with the beta decay of ^{13}N, initiating a "hot CNO cycle" that leaves as a signature a $^{15}\mathrm{N}/^{14}\mathrm{N}$ ratio 25,000 times higher than the slower beta-limited cycle. The hot CNO cycle is believed to be the main source of energy in nova explosions.

As hydrogen is depleted and temperature increases, pairs of carbon nuclei begin to fuse into isotopes of neon and magnesium, with emission of alpha particles, protons, and neutrons. As the temperature increases further, the gamma-ray flux becomes sufficient to photodissociate neon:

$$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}.$$

The released alpha particles then fuse with other neon nuclei:

$$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}.$$

As the temperature increases still further, pairs of ^{16}O nuclei begin to fuse, forming isotopes of silicon, phosphorus, and sulfur, with the emission of alphas and lighter particles. At still higher temperatures (3–3.5E+9 K), more photodissociation reactions become possible. Alphas, protons, and neutrons released by photodissociation then fuse with silicon and other nuclei, forming products up to the binding energy peak.

Four more chain processes are required to explain the abundances of the nuclides beyond the peak of the binding energy curve. One of these is the "s-process" in which a slow succession of alternating neutron captures and β^{-} decays creates nuclides lying along the valley of stability. The main sources of neutrons for the s-process are the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reactions. Stable nuclides with magic neutron numbers and low neutron cross sections act as bottlenecks in the s-process and are produced in the highest yield. The s-process cannot produce elements beyond bismuth ($Z = 83$) because they decay by α-emission back to lighter elements before they can absorb the next neutron.

Under conditions of much higher neutron density, successive neutron captures take place faster than the products can decay. The rapid neutron capture, or "r-process," creates nuclides near the neutron drip line all the way up to the actinoids. While the r-process is occurring, it also preferentially produces nuclei with magic neutron numbers, but with fewer protons than those preferentially produced by the s-process. Subsequent β^{-} decay converts these drip line nuclei to stable nuclei with neutron numbers less than the magic neutron numbers, and mass numbers less than the nuclei produced in maximum yield in the s-process.

Some of the nuclides on the proton-rich side of the valley of stability, such as ^{74}Se and ^{92}Mo, cannot be produced by neutron capture. These nuclides are believed to be produced by proton capture and (γ,n) reactions, which may be slow (p-process) or fast (rp-process) relative to beta decay.

The conditions necessary for the r-process are believed to exist during the explosion of a type II supernova, when the core of a massive star collapses to a neutron star or a black hole. The rp-process is likely to occur in a more hydrogen-rich environment, such as occurs in a nova explosion following transfer of hydrogen from a nearby star onto a star that has already evolved beyond hydrogen burning.

Some of the lightest nuclides, ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B, are bypassed by the stellar nucleosynthesis chains and would be quickly consumed in stars by reactions with protons, neutrons, and alpha particles. Their abundances are explained in part by fragmentation of carbon and oxygen nuclei in interstellar cosmic-ray collisions.

A more thorough treatment of nucleosynthesis and stellar evolution can be found in Reference 264 and in the Additional Reading Material section on page 43.

The Solar Neutrino Problem and Neutrino Properties

Nuclear physics and astrophysics overlap in other areas besides synthesis of the elements. One of these areas is the "solar neutrino problem." In contrast to photons, neutrinos can escape from the very center of the sun to reach the earth. Starting in the 1960s large-scale experiments sought to measure the fluxes of solar neutrinos in various energy ranges. These experiments consistently found fewer neutrino interactions in their detectors than predicted. An explanation for the neutrino deficit has recently been found, but related questions remain unanswered.[266] Neutrinos come in three kinds or "flavors": electron, muon, or tau. The deficit of solar neutrinos is attributed to some of the neutrinos which leave the sun as electron neutrinos (or electron antineutrinos) changing into other "flavors" of neutrinos while in flight toward the earth. Mu and tau neutrinos do not interact with the detectors in the manner expected for electron neutrinos, causing a smaller-than-predicted signal for electron neutrinos. Neutrinos changing "flavors" is not consistent with the standard model of particle physics, but it is possible in other models in which neutrinos can have non-zero mass. The possibility of finite neutrino mass has placed increased importance on other experiments to determine the properties of neutrinos.

Experiments on flavor oscillation do not directly tell how much mass the neutrinos have. Double beta decay experiments are in principle better suited for that purpose. While the standard model predicts that double beta decay can occur only with the emission of two neutrinos, non-standard models in which neutrinos have finite mass and are Majorana particles (which means that they are identical with their antiparticles) predict that double beta decay could occur without any neutrinos being emitted. Several[267] large-scale experiments attempting to detect zero-neutrino double beta decay and measure the half-life have been performed or are still in progress. Some of the members of the team that performed the most sensitive experiment to date have claimed that the experiment did yield a positive result for ^{76}Ge. This claim has not been conclusively confirmed or refuted by any other experiment.

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[266] M.C. Gonzalez-Garcia and Y. Nir, Rev. Mod. Phys. **75** 345 (2003).

[267] H.V. Klapdor-Kleingrothaus, Phys. Scr. **T127** 40 (2006); F.T. Avignone III, S.R. Elliott and J. Engel., Rev. Mod. Phys. **80** 481 (2008).

Counting Atoms, Not Decays

There are many applications for a technique that would count atoms of long-lived radioactive nuclides, rather than waiting for their decay, or measuring their decay rate. For example, the ^{14}C dating method depends upon the measurement of the beta-counting rate of carbon[268] of biological origin. One gram of contemporary carbon has a beta-disintegration rate of about 13.5 decays per minute. However, this low decay rate is in the presence of ~6.5E+10 atoms of ^{14}C in a one-gram sample. Clearly, if ^{14}C atoms could be counted efficiently by some technique, it would be possible to determine the ^{14}C content of very small quantities of carbon. This has now been accomplished for milligram carbon samples even though the ratio of radioactive ^{14}C to stable ^{12}C was ~1E−12. The technique is ultra sensitive mass spectrometry using accelerators.

An accelerator, such as a cyclotron, can act as an extremely sensitive mass spectrometer. Only particles in the ion source with the proper charge-to-mass ratio (given by the cyclotron resonance equation) will be accelerated. Most radioactive atoms to be detected cannot be distinguished from stable contaminants of the same charge-to-mass ratio present in much higher amounts. Use of an accelerator to boost the particles to high energies makes the separation possible by measuring their different energy loss or ionization rates in a detector. For example, ^{14}C of +4 charge can be distinguished from ^{14}N of the same charge. In effect, the accelerator acts as a high-energy mass spectrometer characterized by both high mass resolution and extremely low background count rates. The sample count rate has to be low enough to avoid saturation and radiation damage effects in the detector and the sample has to be small enough to process through the cyclotron in a reasonable time. For application to the radiocarbon dating of archaeological samples, the cyclotron is tuned to accelerate the carbon isotope of interest, and the sample is introduced into the ion source, preferably as a gas. The accelerated ions with the proper signature in the energy loss detector are then counted. In this way, the sensitivity is so enhanced over counting decays that much smaller (milligram) samples can be used to obtain results that are more precise. The upper range of "ages" that can be dated is now potentially 40,000 to 100,000 years, rather than ~10,000 years.

The technique is not limited to radiocarbon dating. Any long-lived nuclide can potentially be detected in this way, including ^{3}H (tritium), ^{10}Be, ^{26}Al, ^{53}Mn, ^{36}Cl, ^{39}Ar, ^{81}Kr, ^{129}I, and even ^{205}Pb. This new technique has implications, then, for archaeology, geology, nuclear waste disposal, pollution monitoring, and measurement of nuclear properties such as half-lives. The longer the half-life of the radionuclide, the more valuable the new technique, i.e. it takes longer to count decays than atoms for long-lived nuclides. As examples, tritium has been used to tell how long it would take seepage to refill underground reservoirs, by measuring the age of the water. ^{36}Cl could be used to detect leakage into groundwater near nuclear power plants and waste disposal sites. ^{10}Be has been used in studies of both sea-floor spreading and manganese nodule formation. Its potential utilization with the ultra sensitive mass spectrometer technique should be practical for ages of 5 to 35 million years, or more, depending upon the size of the rock samples analyzed. Finally, a more precise value of the half-life of ^{32}Si has been measured by two independent groups using this new technique. Readers interested in this technique are referred to review articles by A.E. Litherland.[269]

Radioisotopic Power Data

Radioisotopes have been used to power earth orbit satellites as well as experiments left after lunar landings. The kinetic energy of the decay products is transformed into heat energy that is converted to electric power by several techniques. Thermocouples are one conversion device, while thermionic converters are another.

The fuel for a radioisotopic power generator must be safe, reliable, and low in both weight and cost. These requirements result in a rejection of radioisotopes with half-lives less than 100 days, because they would have to be replaced too often. Half-lives greater than 100 years would be rejected because the activity would be too low to obtain an initial power density greater than 0.1 watts/gram. Some of the candidates that would qualify as fuel sources for radioisotopic power generation and their calculated initial power densities in watts/gram are given in Table IX.

Table IX. Radioisotopic Power Data in Watts per Gram

Nuclide	Half-Life	W/g (Ref. 270)
^{3}H	12.32 a	0.325
^{60}Co	5.271 a	17.45
^{85}Kr	10.76 a	0.590
^{90}Sr	28.8 a	0.916
^{106}Ru	1.017 a	31.8
^{137}Cs	30.07 a	0.427
^{144}Ce	284.6 d	25.5
^{147}Pm	2.6234 a	0.340
^{170}Tm	128.6 d	11.86
^{210}Po	138.38 d	141.3
^{238}Pu	87.7 a	0.558
^{241}Am	432.7 a	0.113
^{242}Cm	162.8 d	120.0
^{244}Cm	18.1 a	2.78

Radioactive Decay as a Source of Geothermal Energy

The planet earth releases a significant amount of thermal energy from its interior. Geophysicists estimate that the total amount of power dissipated from the earth is between 30 and 45 terawatts (1 TW = 10^{12} W).[271, 272] This thermal activity is produced within both the earth's mantle (which is primarily molten rock) and the core (which is primarily solid iron and nickel). The energy produced within the mantle is dissipated through plate tectonics, which is the process that moves the tectonic plates that make up the earth's crust over the mantle and is responsible for earthquakes, plate boundary volcanoes, and many of the topographical features we see today. The energy produced within the earth's core is dissipated through mantle plumes, which are hot spots in the mantle that are responsible for many of the planet's volcano chains.

The source of much of the thermal energy released by the earth, both from the mantle and the core, has long been suspected to be radioactive decay. Since the long-lived radioactive isotopes ^{232}Th and ^{238}U are found in relatively large amounts within the earth's crust, one could postulate that similar concentrations of these two elements may be found in the mantle of the planet. If this assumption is correct, a significant amount of thermal energy may result from the decays of the thorium and uranium series.

Indirect studies have estimated that the heat contribution of the decay of the thorium and uranium series in the mantle of the earth is about 16 TW.[273] Both of these series include radioactive decay by β^- emission. As discussed earlier, when a nucleus emits a β^- particle, an antineutrino is emitted as well. Since antineutrinos have very small interaction cross sections, they can travel long distances

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[268] The half-life of ^{14}C is 5,715 years.

[269] A.E. Litherland, Ann. Rev. Nucl. Sci. **30** 437 (1980); Science **196** 489 (1977); **198** 507 (1977); Phys. Rev. Lett. **45(B)** 589 (1980).

[270] Includes daughter radiations.

[271] H.N. Pollack, S.J. Hurter, and J.R. Johnson, Rev. Geophys. **31** 267 (1993).

[272] A.M. Hofmeister and R.E. Criss, Tectonophysics **395** 159 (2005).

[273] W.F. McDonough and S.-s. Sun, Chem. Geol. **120** 223 (1995).

through large amounts of material before interacting. Thus, antineutrinos resulting from β^- decay within the earth's mantle could potentially be detected at the earth's surface.

In 2005, scientists at the Kamioka liquid scintillator antineutrino detector (KamLAND), located in Kamioka, Japan, were able to experimentally measure terrestrial antineutrinos. By comparing the energy spectra of these detected antineutrinos to the expected energy spectra of antineutrinos from the thorium and uranium series, the scientists were able to verify that the detected antineutrinos resulted from β^- decay in the series and to estimate the total production rate of antineutrinos within the mantle. Their results showed that the average cumulative decay heat production from the thorium and uranium series is about 24 TW, accounting for half or more of the total estimated thermal energy production rate. This experiment was the first to measure the contribution of the series to the earth's heat production rate directly.[274]

The decay of the thorium and uranium series accounts for a significant amount of energy loss from the mantle, but this cannot be the mechanism for energy production in the core because the amounts of these two elements are too small. One possible source may be ^{40}K decay within the core. The earth's core is essentially a large sphere of crystallized iron and nickel under large amounts of gravitational pressure (25–60 gigaPascals) and at a high temperature (3,000–4,000 K).[275,276] For ^{40}K to be a significant source of decay heat, it must first be possible for potassium to be soluble in iron and/or nickel crystals at such a high pressure and temperature. Until recently, experimental measurements of this solubility had been contradictory. In 2003, scientists from the University of Minnesota, the Carnegie Institution of Washington, and the Institute for Mineralogy and Petrography performed experiments on the solubility of potassium in several different materials. The scientists measured the potassium concentration in a sample of iron sulfide (FeS) relative to that in a sample of potassium-silicate glass at several temperatures in the range of 1,200–1,800°C (1,473–2,073 K). This ratio is known as the partition coefficient for potassium. Using these results, the scientists extrapolated to core temperatures and estimated that the partition coefficient at those temperatures is in the range of 0.2–0.5. Using this range, they estimate that the potassium content of the core is in the range of 60–130 ppm, which would result in a heat production rate of 0.4–0.8 TW.[277]

Based on studies such as those cited above, one could conclude that approximately 50 to 80 percent of the total heat output of the earth is due to natural radioactive decay, both β^- and α decay of the thorium and uranium series in the mantle and β^- decay of ^{40}K in the core. In any case, a significant amount of the energy released from the eruptions of volcanoes and from earthquakes, as well as artificial uses of geothermal energy, like geothermal electricity production, is a direct result of the decay of naturally-occurring radioactive materials.

Pre-Fermi (Natural) Nuclear Reactor

In 1956, P.K. Kuroda[278] speculated that an assemblage of uranium and water could easily become a self-supporting chain reacting system in the early history of the earth. These speculations were borne out by the French discovery in Oklo in the Gabon Republic in Africa of samples of natural uranium, which have been found to be depleted in ^{235}U. (There is measurably less ^{235}U in these samples than in "ordinary" natural uranium.) Samples that were slightly enriched in ^{235}U were also found. The abundances of various nuclides found in the samples did not agree with the natural abundance of these nuclides. The distribution of isotopes of particular elements, after correction for neutron capture and natural background, agreed with the fission yield distribution from ^{235}U.

From the Chart, it can be noted that neodymium has many stable isotopes at the end of short fission product chains that have large fission yields. The analysis[279] of neodymium provided much of the information about the Oklo samples.

From radioactive dating methods, the samples are determined to be about 1.7 billion years old. The ^{235}U abundance in this natural reactor would have been 3 percent or more (prior to the ^{235}U decay over the past 1.7 billion years to its present 0.72 percent abundance). The geological evidence implies that large quantities of water were present to provide moderation of the fission neutrons. After fissioning, the samples would have been depleted in ^{235}U. Samples enriched in ^{235}U would have resulted from neutron capture of ^{238}U, followed by β^- decay to ^{239}Pu, and subsequent alpha decay into ^{235}U. This conversion reaction would also have fed the reactor. Studies of the Oklo natural reactor[279] indicated that about two-thirds of the total fission events were caused by the ^{235}U initially present in the ore and nearly one-third from ^{235}U converted from ^{238}U by neutron capture and subsequent decay.

By studying the amounts of the various nuclides in the ore, a wealth of information has been obtained. This information includes values of neutron flux, time-integrated neutron flux, conversion ratio, and fraction of epithermal neutrons. Finally, a determination has been made of the number of fissions that had occurred within the reactor and the percentage that had been caused by each of the fissioning nuclides ^{235}U, ^{238}U, and ^{239}Pu. It has been estimated that a total released energy of 15,000 megawatt-years was generated by the Oklo reactor. This is approximately the same energy as generated by one large modern reactor[280] in four years.

Recently, strong evidence[281] was found that at least part of the Oklo mine operated in a cyclic fashion. Using mass spectrometry on a mineral sample obtained from the Oklo site, Meshik, *et al.*,[282] observed the highest concentrations of xenon ever observed in any natural mineral. The xenon appeared in cavities containing aluminum phosphate. The explanation was that during the operation of the reactor, the fission products (precursors of the xenon) migrated into the aluminum phosphate as that material was crystallizing. When the precursors decayed into xenon, the crystal structure of the aluminum phosphate prevented the escape of the xenon. Without cooling, however, the aluminum phosphate would not crystallize; this requires the reactor to shut down periodically. Using the known rates of the processes producing the xenon and the measured concentration of isotopes, it was calculated that the reactor turned on for about half an hour then shut down for about two and one half hours before starting up again.

Water was the cause of the cyclic operation. In reactors, water acts as a moderator, thermalizing the neutrons in a reactor. These thermal neutrons are needed to sustain a chain reaction. Enough water was present in the Oklo uranium deposits to start a chain reaction. In the thirty-minute active phase, the reactor became so hot that the water boiled away and the fission reaction stopped. As the reactor cooled below the boiling point of water, more water could flow in, restarting the cycle.

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[274] T. Araki, *et al.*, Nature **436** 499 (2005).

[275] J. Li and C.B. Agee, Geochim. Cosmochim. Acta, **65** 1821 (2001).

[276] V.J. Hillgren, C.K. Gessmann, and J. Li, *Origin of the Earth and Moon*, (Univ. Arizona Press, 2000).

[277] V. Rama Murthy, W. van Westrenen and Y. Fei, Nature **423** 163 (2003).

[278] P.K. Kuroda, J. Chem. Phys. **25** 781 (1956).

[279] M. Maurette, Ann. Rev. Nucl. Sci. **26** 319 (1976); R. Hagemann and E. Roth, Radiochim. Acta **25** 241 (1978); J.C. Ruffenach, R. Hagemann, and E. Roth, Z. Naturfor. **A35** 171 (1980).

[280] A.P. Meshik, Scientific American, Nov. 2005, pp. 83-91.

[281] P. Weiss, Science News, March 2005, p. 170.

[282] A.P. Meshik, C.M. Hohenberg, and O.V. Pravdivtseva, Phys. Rev. Lett. **93** 182302 (2004).

Recent studies[283] have shown that the values of some of the fundamental physics constants, e.g., the fine-structure constant, may have changed over very long periods. The fine-structure constant or Sommerfeld fine-structure constant, α, is the fundamental constant characterizing the strength of the electromagnetic interaction:

$$\alpha = \frac{e^2}{\hbar c 4\pi\varepsilon_0} = \frac{1}{137.035999679(94)}.$$

In 2004, based on measurements of the ratio of the abundance of ^{149}Sm to that of ^{147}Sm in the Oklo reactor, Lamoreaux and Torgerson[284] claimed that α has decreased by 0.0000045% over the last two billion years. In normal samarium, the ^{149}Sm/^{147}Sm ratio is approximately 0.92; in the Oklo ores the ratio is about 0.02. The low value of this ratio was explained by the depletion of ^{149}Sm by thermal neutrons during the time the reactor was active. This, in turn, was explained by a change in the ^{149}Sm capture cross section—a shift in the energy of the 97.3 meV resonance—which could be explained by a decrease in α.

At least one other feature of the Oklo natural reactor has stimulated interest. This feature has been the remarkable stability of the Oklo ore deposit. The ^{235}U and ^{238}U fuels have been confined within the grains of ore. Since almost half of the residual ^{235}U in the reactor zones is the daughter product of ^{239}Pu, this means that the plutonium has been "locked-up" for a time comparable to its 2.410E+4-year half-life. In addition, at least one-half of thirty or so fission product elements have remained immobilized in the ore. These findings have produced much interest from scientists working on the complex problem of waste storage and disposal of radioactive fuel and wastes.

It is interesting to note that the Oklo naturally-occurring enriched converter reactor operated nearly two billion years before Fermi initiated the first artificial neutron chain reaction in 1942 with natural uranium fuel. Clearly, in this instance, scientists were the unknowing imitator of nature.

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[283] See J.D. Barrow and J.K. Web, "Inconsistent Constants," Scientific American, June 2005, page 56.

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Guide for Using the
Chart of the Nuclides

Chart Square Information

The information given in a Chart square depends on whether the square represents an element, a stable (or long-lived) nuclide, or an unstable (radioactive) nuclide. The left-most, darkly-outlined square in a row on the Chart, represents the element corresponding to the isotopes in that row. Squares with grey shading in the upper half represent stable or long-lived radioactive nuclides. Squares with no grey shading correspond to radioactive nuclides. Squares split into two or three sections show the metastable states of a nuclide. The sample squares to the right show the types of information given for each of these categories of squares.

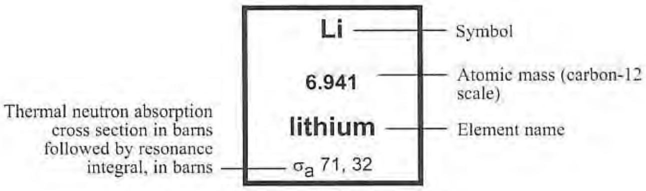
Relative Locations of the Products of Various Nuclear Processes

			^{3}He in	α in
	β⁻ out	p in	d in	t in
	n out	**Original Nucleus**	n in	
t out	d out	p out	β⁺ out ε	
α out	^{3}He out			

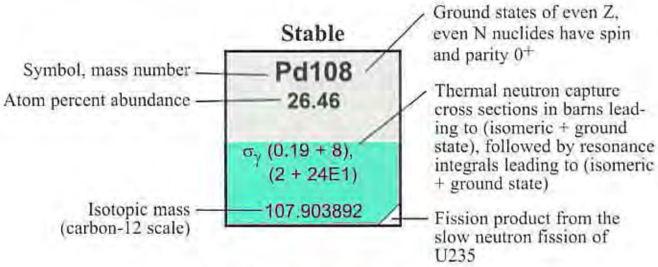
Displacement Caused by Nuclear Bombardment Reactions

	(α, 3n)	(α, 2n) (^{3}He, n)	(α, n)	
	(p, n)	(p, γ) (d, n) (^{3}He, np)	(α, np) (t, n) (^{3}He, p)	
	(p, pn) (γ, n) (n, 2n)	**Target Nucleus** (n, n)	(d, p) (n, γ) (t, np)	(t, p)
(p, α)	(n, t) (γ, np) (n, nd)	(n, d) (γ, p) (n, np)	(n, p) (t, ^{3}He)	
	(n, α) (n, n ^{3}He)	(n, ^{3}He) (n, pd)		

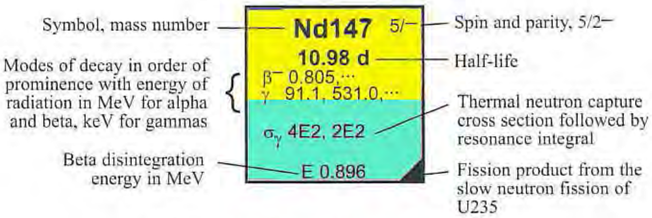
Chemical Element



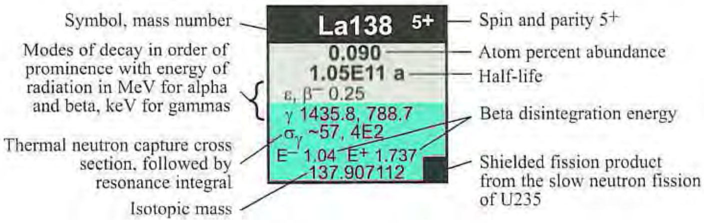
Stable



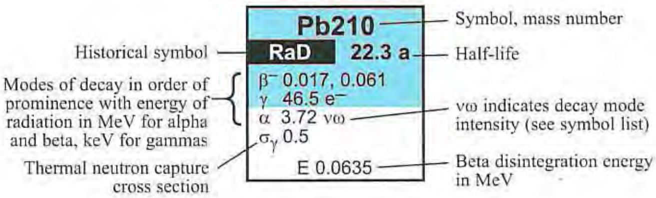
Artificially Radioactive



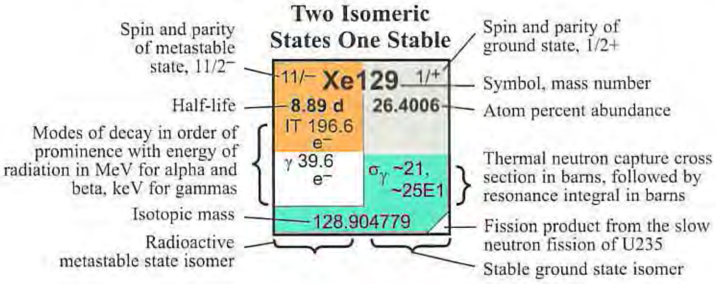
Naturally Occurring or Otherwise Available but Radioactive



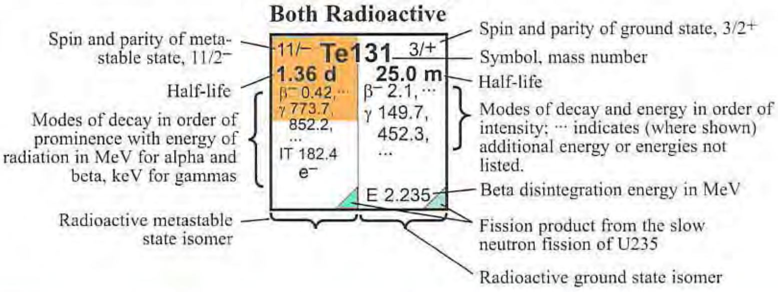
Member of Naturally Radioactive Decay Chain



Two Isomeric States One Stable



Two Isomeric States Both Radioactive



SYMBOLS

Radiation and Decay

α	alpha particle
β^-	beta minus
$\beta+$	beta plus (positron)
γ	gamma ray
n	neutron
p	proton
d	deuteron
t	triton
ε	electron capture
IT	isomeric transition
e^-	conversion electron
$\beta^-\beta^-$	double beta
☘	cluster
D	delayed radiation
SF	spontaneous fission
E, E^-, $E+$	disintegration energy

Time

s	seconds
m	minutes
h	hours
d	days
a	years

Unit Prefixes

p	pico	(1.0E–12)
n	nano	(1.0E–9)
μ	micro	(1.0E–6)
m	milli	(1.0E–3)

Other Symbols

σ	neutron cross section
b	barn
ω	absolute abundance less than 1% (weak)
$v\omega$	absolute abundance less than 1.0E–3% (very weak)
$vv\omega$	absolute abundance less than 1.0E–6% (very, very weak)
E	indicates exponential format, e.g., 1.06E11 a is 1.06 x 10^{11} years
↔	indicates assignment to metastable (m) and ground (g) states inconclusive
↕	indicates assignment of m_2 and m_1 states inconclusive
χ	unspecified number of particles of a given type emitted, e.g., χp

COLOR LEGEND

Neutron Absorption Properties*

🟦	10 barns to 100 barns
🟩	> 100 barns to 500 barns
🟨	> 500 barns to 1000 barns
🟧	> 1000 barns

Colors Used for Half-Lives**

🟧	1 day to 10 days
🟨	> 10 days to 100 days
🟩	> 100 days to 10 years
🟦	> 10 years to 5E8 years
⬜	> 5E8 years or stable

^{235}U Fission Yields***

◢	independent yield > 3.0%
◢	independent yield > 1.0% to 3.0%
◢	independent yield > 0.1% to 1.0%
◢	independent yield > 0.01% to 0.1%
◢	independent yield > 2.5E–6% to 0.01%
◿	independent yield < 2.5E–6% cumulative yield > 2.5E–6%
■	shielded nuclide with independent yield designated by color, as above.

* appear in lower half of the chart square
** appear in upper half of the chart square
*** appear in lower right corner of the chart square

Nuclides and Isotopes

Chart of the Nuclides

Knolls Atomic Power Laboratory

operated by Bechtel Marine Propulsion Corporation
under the direction of

Naval Reactors, U.S. Department of Energy

Seventeenth Edition – Revised to 2009

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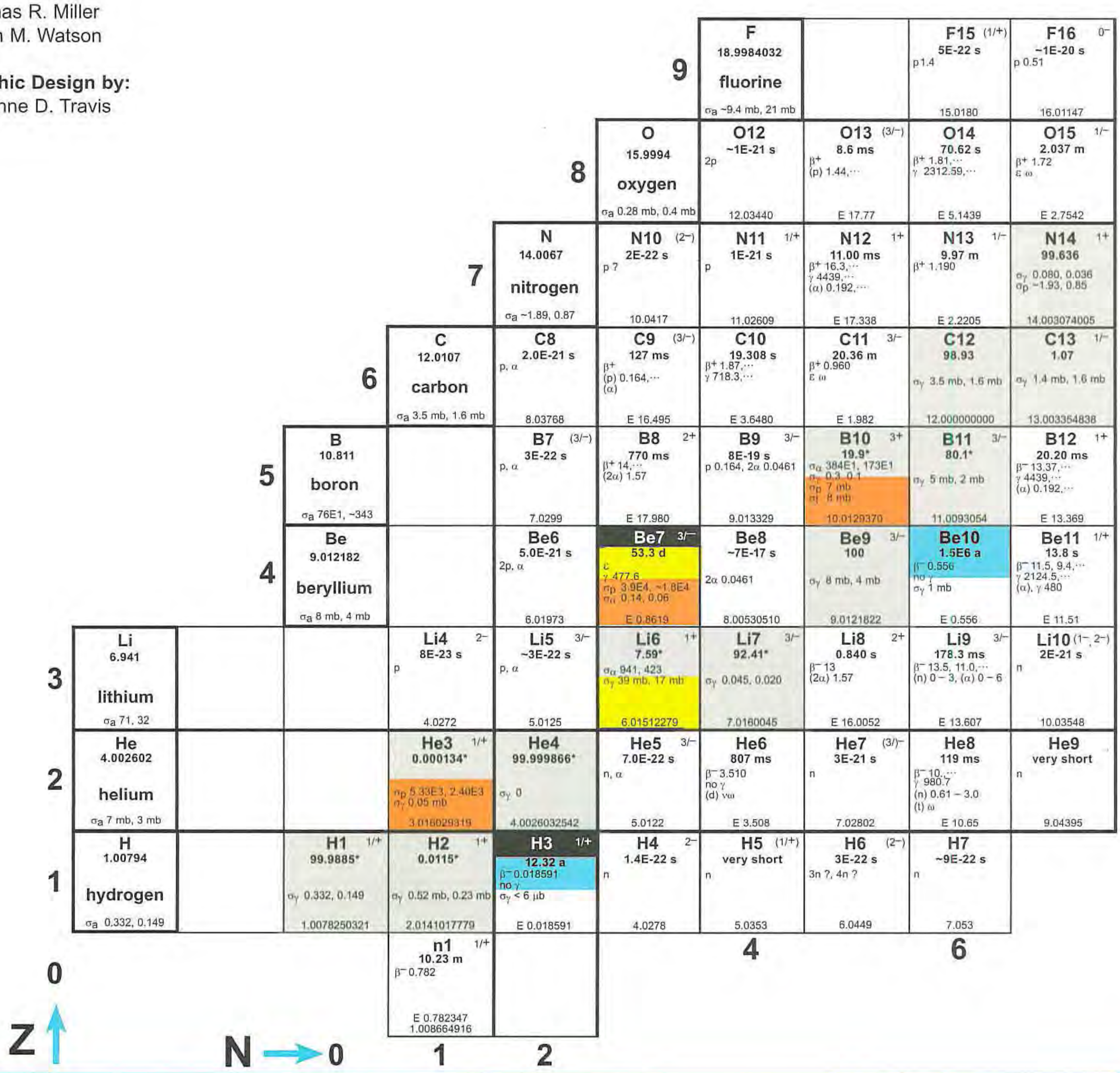
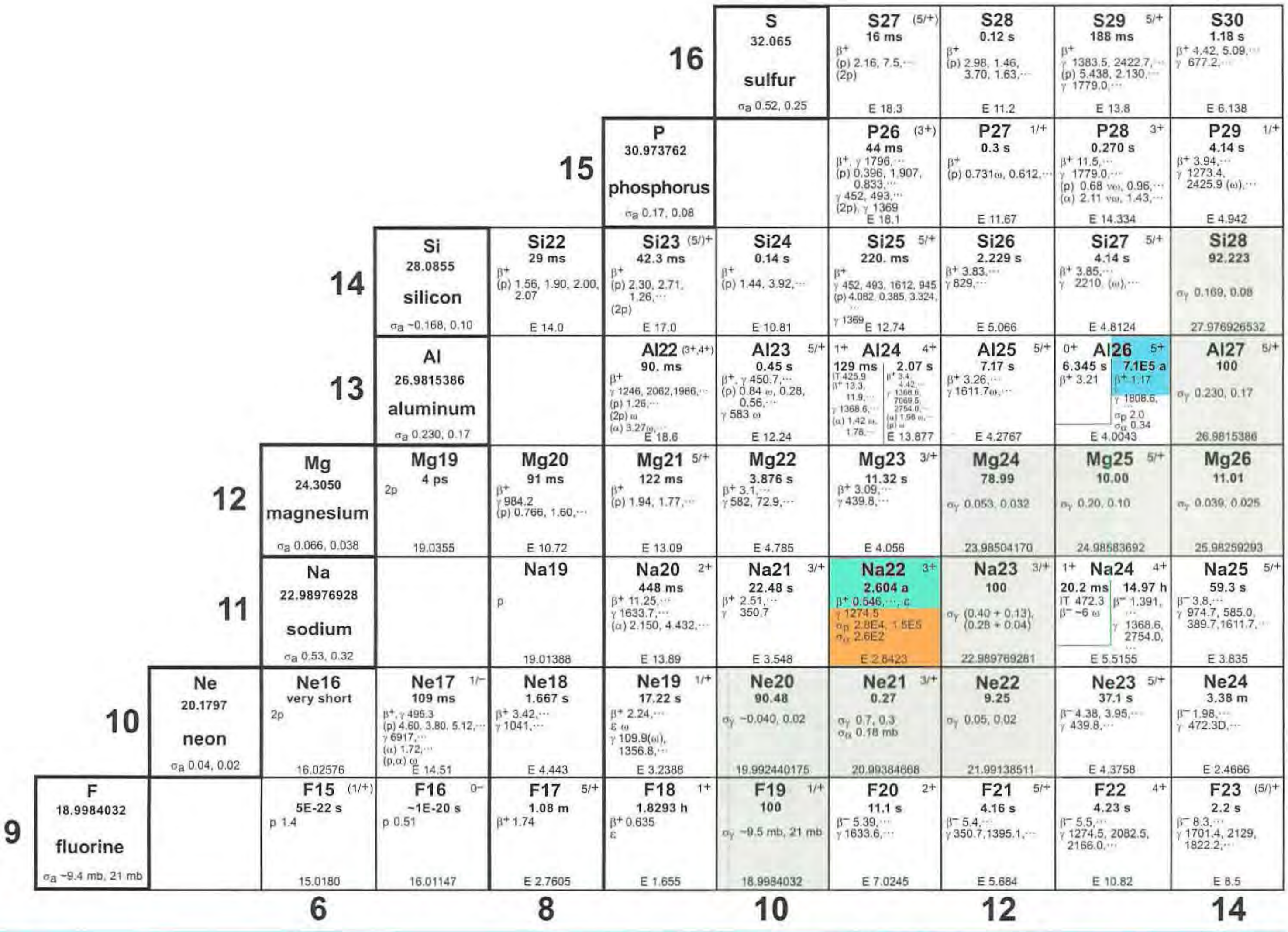


Z		N → 0	1	2		4		6	
9						F 18.9984032 fluorine σ_a ~9.4 mb, 21 mb		F15 (1/+) 5E-22 s p 1.4 15.0180	F16 0− ~1E-20 s p 0.51 16.01147
8					O 15.9994 oxygen σ_a 0.28 mb, 0.4 mb	O12 ~1E-21 s 2p 12.03440	O13 (3/−) 8.6 ms β^+ (p) 1.44,··· E 17.77	O14 70.62 s β^+ 1.81,··· γ 2312.59,··· E 5.1439	O15 1/− 2.037 m β^+ 1.72 ε ω E 2.7542
7				N 14.0067 nitrogen σ_a ~1.89, 0.87	N10 (2−) 2E-22 s p ? 10.0417	N11 1/+ 1E-21 s p 11.02609	N12 1+ 11.00 ms β^+ 16.3,··· γ 4439,··· (α) 0.192,··· E 17.338	N13 1/− 9.97 m β^+ 1.190 E 2.2205	N14 1+ 99.636 σ_γ 0.080, 0.036 σ_p ~1.93, 0.85 14.003074005
6			C 12.0107 carbon σ_a 3.5 mb, 1.6 mb	C8 2.0E-21 s p, α 8.03768	C9 (3/−) 127 ms β^+ (p) 0.164,··· (α) E 16.495	C10 19.308 s β^+ 1.87,··· γ 718.3,··· E 3.6480	C11 3/− 20.36 m β^+ 0.960 ε ω E 1.982	C12 98.93 σ_γ 3.5 mb, 1.6 mb 12.000000000	C13 1/− 1.07 σ_γ 1.4 mb, 1.6 mb 13.003354838
5		B 10.811 boron σ_a 76E1, ~343		B7 (3/−) 3E-22 s p, α 7.0299	B8 2+ 770 ms β^+ 14,··· (2α) 1.57 E 17.980	B9 3/− 8E-19 s p 0.164, 2α 0.0461 9.013329	B10 3+ 19.9* σ_α 384E1, 173E1 σ_γ 0.3, 0.1 σ_p 7 mb σ_t 8 mb 10.0129370	B11 3/− 80.1* σ_γ 5 mb, 2 mb 11.0093054	B12 1+ 20.20 ms β^- 13.37,··· γ 4439,··· (α) 0.192,··· E 13.369
4		Be 9.012182 beryllium σ_a 8 mb, 4 mb		Be6 5.0E-21 s 2p, α 6.01973	Be7 3/− 53.3 d ε γ 477.6 σ_p 3.9E4, ~1.8E4 σ_α 0.14, 0.06 E 0.8619	Be8 ~7E-17 s 2α 0.0461 8.00530510	Be9 3/− 100 σ_γ 8 mb, 4 mb 9.0121822	Be10 1.5E6 a β^- 0.556 no γ σ_γ 1 mb E 0.556	Be11 1/+ 13.8 s β^- 11.5, 9.4,··· γ 2124.5,··· (α), γ 480 E 11.51
3	Li 6.941 lithium σ_a 71, 32		Li4 2− 8E-23 s p 4.0272	Li5 3/− ~3E-22 s p, α 5.0125	Li6 1+ 7.59* σ_α 941, 423 σ_γ 39 mb, 17 mb 6.01512279	Li7 3/− 92.41* σ_γ 0.045, 0.020 7.0160045	Li8 2+ 0.840 s β^- 13 (2α) 1.57 E 16.0052	Li9 3/− 178.3 ms β^- 13.5, 11.0,··· (n) 0 − 3, (α) 0 − 6 E 13.607	Li10 (1−, 2−) 2E-21 s n 10.03548
2	He 4.002602 helium σ_a 7 mb, 3 mb		He3 1/+ 0.000134* σ_p 5.33E3, 2.40E3 σ_γ 0.05 mb 3.016029319	He4 99.999866* σ_γ 0 4.0026032542	He5 3/− 7.0E-22 s n, α 5.0122	He6 807 ms β^- 3.510 no γ (d) νω E 3.508	He7 (3/)− 3E-21 s n 7.02802	He8 119 ms β^- 10,··· γ 980.7 (n) 0.61 − 3.0 (t) ω E 10.65	He9 very short n 9.04395
1	H 1.00794 hydrogen σ_a 0.332, 0.149	H1 1/+ 99.9885* σ_γ 0.332, 0.149 1.0078250321	H2 1+ 0.0115* σ_γ 0.52 mb, 0.23 mb 2.0141017779	H3 1/+ 12.32 a β^- 0.018591 no γ σ_γ < 6 μb E 0.018591	H4 2− 1.4E-22 s n 4.0278	H5 (1/+) very short n 5.0353	H6 (2−) 3E-22 s 3n ?, 4n ? 6.0449	H7 ~9E-22 s n 7.053	
0			n1 1/+ 10.23 m β^- 0.782 E 0.782347 1.008664916						

	18		20		22
9	**F27** **5.0 ms** β^- (n) γ 2018 E 17.9		**F29** **2.5 ms** β^- (n) E 22		**F31** E 25

8		10		12		14		16		18
F17 5/+ **1.08 m** β^+ 1.74 E 2.7605	**F18** 1+ **1.8293 h** β^+ 0.635 ε E 1.655	**F19** 1/+ **100** σ_γ ~9.5 mb, 21 mb 18.9984032	**F20** 2+ **11.1 s** β^- 5.39,··· γ 1633.6,··· E 7.0245	**F21** 5/+ **4.16 s** β^- 5.4,··· γ 350.7, 1395.1,··· E 5.684	**F22** 4+ **4.23 s** β^- 5.5,··· γ 1274.5, 2082.5, 2166.0,··· E 10.82	**F23** (5/)+ **2.2 s** β^- 8.3,··· γ 1701.4, 2129, 1822.2,··· E 8.5	**F24** (3+) **0.39 s** β^- γ 1981.6 E 13.5	**F25** (5/+) **0.07 s** β^- γ 1703,··· (n) γ 1982,··· E 13.4	**F26** 1+ **10 ms** β^- γ 2018.2, 1673.0 (n) E 17.8	**F27** **5.0 ms** β^- (n) γ 2018 E 17.9
O16 **99.757** σ_γ 0.19 mb, 0.4 mb 15.9949146196	**O17** 5/+ **0.038** σ_α 0.24, 0.11 σ_γ 0.54 mb, 0.39 mb 16.9991317	**O18** **0.205** σ_γ 0.16 mb, 0.81 mb 17.999161	**O19** 5/+ **26.9 s** β^- 3.3, 4.60,··· γ 197.1, 1356.8,··· E 4.822	**O20** **13.5 s** β^- 2.75,··· γ 1056.8,··· E 3.815	**O21** (5/+) **3.4 s** β^- 4.6, 6.4,··· γ 1730.3, 3517.4, 280.1, 1787.2,··· E 8.11	**O22** **2.2 s** β^- γ 71.6, 637.4, 1862.6,··· E 6.5	**O23** 1/+ **0.10 s** β^- (n) E 11.3	**O24** **65 ms** β^- γ 1832, 522, 1310 (n) E 11.5		
N15 1/− **0.364** σ_γ 0.02 mb, 0.11 mb 15.000108898	**N16** 2− **7.13 s** β^- 4.27, 10.44,··· γ 6129, 7115,··· (α) 1.85 ω,··· E 10.421	**N17** 1/− **4.174 s** β^- 3.7,··· γ 870.7, 2184(ω) (n) 1.171, 0.383,··· (α) ω E 8.68	**N18** 1− **623 ms** β^- 9.4 γ 1981.9, 1651.5,··· (n) 0.58,··· (α) 0.81, ~2.3,1.4,··· E 13.90	**N19** 1/− **0.33 s** β^- γ 96.4, 1983, 3851,··· (n) 1.054, 0.452,··· γ 1983,··· E 12.53	**N20** 2− **135 ms** β^- γ 1674, 2397, 1898,··· (n) 2.071, 1.098, 1.254,··· γ 96.4, 1376 E 18.0	**N21** 1/− **83 ms** β^- γ 1222 (n) γ 1674, 2397, 2780, 3175 E 17.2	**N22** **24 ms** β^- (n) E 22.8	**N23** **14 ms** β^- (n) (2n) E 23.8		
C14 **5715 a** β^- 0.157 no γ σ_γ < 1 μb E 0.156476	**C15** 1/+ **2.450 s** β^- 4.51, 9.82,··· γ 5297.8,··· E 9.772	**C16** **0.75 s** β^- γ 120.4D ω (n) 0.81, 1.71,··· E 8.010	**C17** 3/+ **0.19 s** β^- γ 1375, 1849, 1906 (n) E 13.17	**C18** **92 ms** β^- γ 2614.2,··· (n) E 11.81	**C19** (1/+) **46 ms** β^- (n) 1.01, 1.50, 0.46 γ 115, 472 (2n) E 16.6	**C20** **18 ms** β^- (n) E 15.8		**C22** **~6 ms** β^- (n) E 21		
B13 3/− **17.4 ms** β^- 13.4,··· γ 3683.9,··· (n) 3.61ω, 2.40,··· E 13.437	**B14** 2− **13 ms** β^- 14,··· γ 6092.4,··· (n) E 20.64	**B15** 3/− **9.9 ms** β^- (n) 1.77, 3.20,··· (2n) ω E 19.10		**B17** (3/−) **5.06 ms** β^- (n) 2.91, 1.80,··· (2n), (3n) (4n) ω E 22.7		**B19** **2.9 ms** β^- (n) (2n) E 26.9				
Be12 **21.49 ms** β^- (n) ω E 11.71	**Be13** (1/+) **very short** n ? 13.0357	**Be14** **4.6 ms** β^- (n) 0.287 γ 3536 ω (t) ω E 16.3								
Li11 3/− **8.8 ms** β^-, γ 320.0 (n) 1.97, 3.11,··· γ 3368,··· (2n), (3n), (α) (t) ω, (d) E 20.62										
He10 **2E-21 s** 2n 10.0524										

* Significant differences in these abundance values have been observed in some samples. See page 18 for discussion.



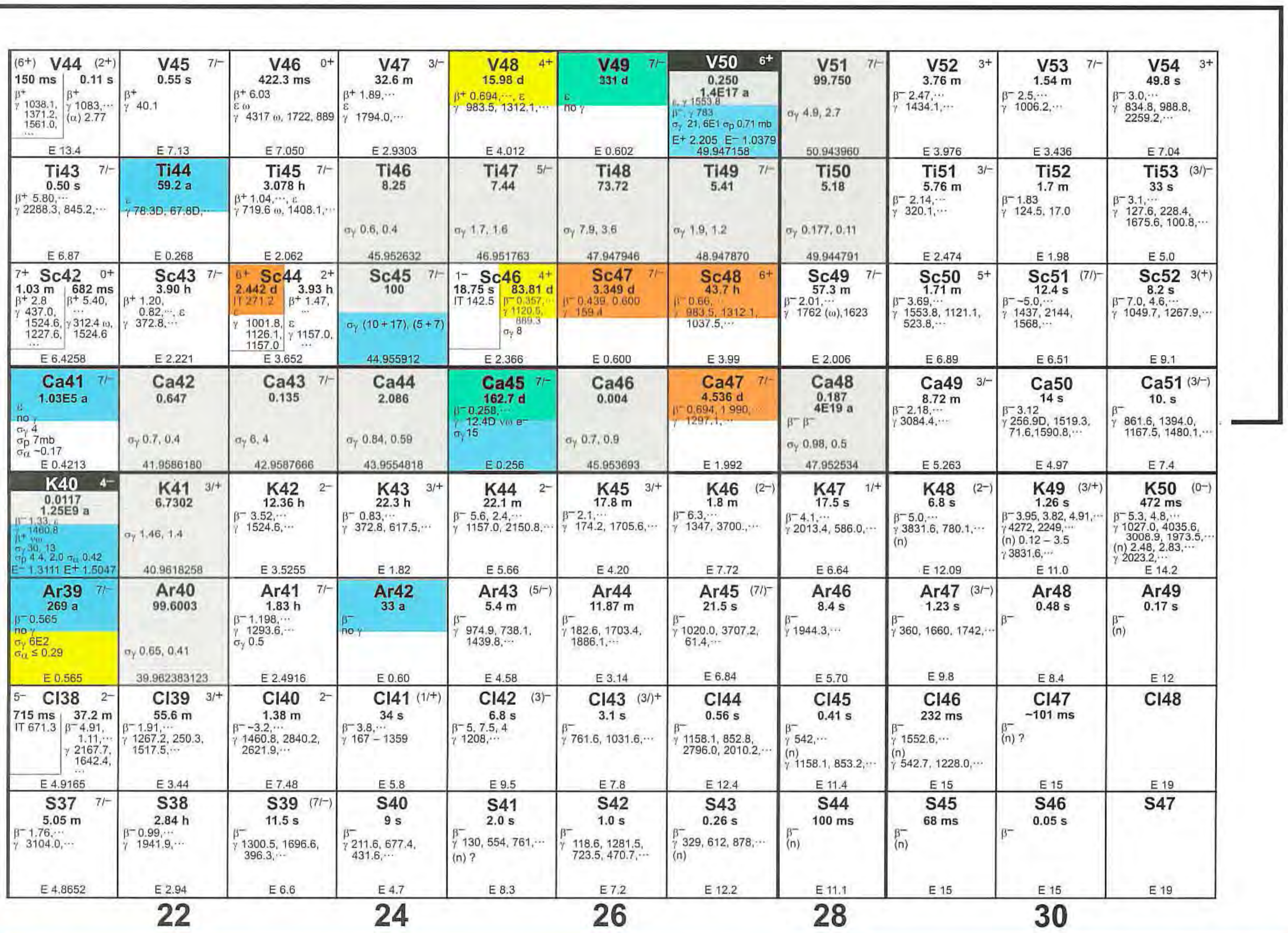
16							**S** 32.065 sulfur σ_a 0.52, 0.25	**S27** (5/+) 16 ms β^+ (p) 2.16, 7.5,··· (2p) E 18.3	**S28** 0.12 s β^+ (p) 2.98, 1.46, 3.70, 1.63,··· E 11.2	**S29** 5/+ 188 ms β^+ γ 1383.5, 2422.7,··· (p) 5.438, 2.130,··· γ 1779.0,··· E 13.8	**S30** 1.18 s β^+ 4.42, 5.09,··· γ 677.2,··· E 6.138
15						**P** 30.973762 phosphorus σ_a 0.17, 0.08		**P26** (3+) 44 ms β^+, γ 1796,··· (p) 0.396, 1.907, 0.833,··· γ 452, 493,··· (2p), γ 1369 E 18.1	**P27** 1/+ 0.3 s β^+ (p) 0.731ω, 0.612,··· E 11.67	**P28** 3+ 0.270 s β^+ 11.5,··· γ 1779.0,··· (p) 0.68 vω, 0.96,··· (α) 2.11 vω, 1.43,··· E 14.334	**P29** 1/+ 4.14 s β^+ 3.94,··· γ 1273.4, 2425.9 (ω),··· E 4.942
14				**Si** 28.0855 silicon σ_a ~0.168, 0.10	**Si22** 29 ms β^+ (p) 1.56, 1.90, 2.00, 2.07 E 14.0	**Si23** (5/)+ 42.3 ms β^+ (p) 2.30, 2.71, 1.26,··· (2p) E 17.0	**Si24** 0.14 s β^+ (p) 1.44, 3.92,··· E 10.81	**Si25** 5/+ 220. ms β^+ γ 452, 493, 1612, 945 (p) 4.082, 0.385, 3.324, ··· γ 1369 E 12.74	**Si26** 2.229 s β^+ 3.83,··· γ 829,··· E 5.066	**Si27** 5/+ 4.14 s β^+ 3.85,··· γ 2210. (ω),··· E 4.8124	**Si28** 92.223 σ_γ 0.169, 0.08 27.976926532
13				**Al** 26.9815386 aluminum σ_a 0.230, 0.17		**Al22** (3+,4+) 90. ms β^+ γ 1246, 2062,1986,··· (p) 1.26,··· (2p) ω (α) 3.27ω,··· E 18.6	**Al23** 5/+ 0.45 s β^+, γ 450.7,··· (p) 0.84 ω, 0.28, 0.56,··· γ 583 ω E 12.24	1+ **Al24** 4+ 129 ms IT 425.9 β^+ 13.3, 11.9,··· γ 1368.6,··· (α) 1.42 ω, 1.78,··· 2.07 s β^+ 3.4, 4.42,··· γ 1368.6, 7069.5, 2754.0,··· (α) 1.98 ω,··· (p) ω E 13.877	**Al25** 5/+ 7.17 s β^+ 3.26,··· γ 1611.7ω,··· E 4.2767	0+ **Al26** 5+ 6.345 s β^+ 3.21 7.1E5 a β^+ 1.17 γ 1808.6, ··· σ_p 2.0 σ_α 0.34 E 4.0043	**Al27** 5/+ 100 σ_γ 0.230, 0.17 26.9815386
12			**Mg** 24.3050 magnesium σ_a 0.066, 0.038	**Mg19** 4 ps 2p 19.0355	**Mg20** 91 ms β^+ γ 984.2 (p) 0.766, 1.60,··· E 10.72	**Mg21** 5/+ 122 ms β^+ (p) 1.94, 1.77,··· E 13.09	**Mg22** 3.876 s β^+ 3.1,··· γ 582, 72.9,··· E 4.785	**Mg23** 3/+ 11.32 s β^+ 3.09,··· γ 439.8,··· E 4.056	**Mg24** 78.99 σ_γ 0.053, 0.032 23.98504170	**Mg25** 5/+ 10.00 σ_γ 0.20, 0.10 24.98583692	**Mg26** 11.01 σ_γ 0.039, 0.025 25.98259293
11			**Na** 22.98976928 sodium σ_a 0.53, 0.32		**Na19** p 19.01388	**Na20** 2+ 448 ms β^+ 11.25,··· γ 1633.7,··· (α) 2.150, 4.432,··· E 13.89	**Na21** 3/+ 22.48 s β^+ 2.51,··· γ 350.7 E 3.548	**Na22** 3+ 2.604 a β^+ 0.546,···; ε γ 1274.5 σ_p 2.8E4, 1.5E5 σ_α 2.6E2 E 2.8423	**Na23** 3/+ 100 σ_γ (0.40 + 0.13), (0.28 + 0.04) 22.989769281	1+ **Na24** 4+ 20.2 ms IT 472.3 β^- ~6 ω 14.97 h β^- 1.391, ··· γ 1368.6, 2754.0, ··· E 5.5155	**Na25** 5/+ 59.3 s β^- 3.8,··· γ 974.7, 585.0, 389.7,1611.7,··· E 3.835
10		**Ne** 20.1797 neon σ_a 0.04, 0.02	**Ne16** very short 2p 16.02576	**Ne17** 1/− 109 ms β^+, γ 495.3 (p) 4.60, 3.80, 5.12,··· γ 6917,··· (α) 1.72,··· (p,α) ω E 14.51	**Ne18** 1.667 s β^+ 3.42,··· γ 1041,··· E 4.443	**Ne19** 1/+ 17.22 s β^+ 2.24,··· ε ω γ 109.9(ω), 1356.8,··· E 3.2388	**Ne20** 90.48 σ_γ ~0.040, 0.02 19.992440175	**Ne21** 3/+ 0.27 σ_γ 0.7, 0.3 σ_α 0.18 mb 20.99384668	**Ne22** 9.25 σ_γ 0.05, 0.02 21.99138511	**Ne23** 5/+ 37.1 s β^- 4.38, 3.95,··· γ 439.8,··· E 4.3758	**Ne24** 3.38 m β^- 1.98,··· γ 472.3D,··· E 2.4666
9	**F** 18.9984032 fluorine σ_a ~9.4 mb, 21 mb		**F15** (1/+) 5E-22 s p 1.4 15.0180	**F16** 0− ~1E-20 s p 0.51 16.01147	**F17** 5/+ 1.08 m β^+ 1.74 E 2.7605	**F18** 1+ 1.8293 h β^+ 0.635 ε E 1.655	**F19** 1/+ 100 σ_γ ~9.5 mb, 21 mb 18.9984032	**F20** 2+ 11.1 s β^- 5.39,··· γ 1633.6,··· E 7.0245	**F21** 5/+ 4.16 s β^- 5.4,··· γ 350.7,1395.1,··· E 5.684	**F22** 4+ 4.23 s β^- 5.5,··· γ 1274.5, 2082.5, 2166.0,··· E 10.82	**F23** (5/)+ 2.2 s β^- 8.3,··· γ 1701.4, 2129, 1822.2,··· E 8.5
			6		8		10		12		14

16	**S40** 9 s β^- γ 211.6, 677.4, 431.6,··· E 4.7	**S41** 2.0 s β^- γ 130, 554, 761,··· (n) ? E 8.3	**S42** 1.0 s β^- γ 118.6, 1281.5, 723.5, 470.7,··· (n) E 7.2	**S43** 0.26 s β^- γ 329, 612, 878,··· (n) E 12.2	**S44** 100 ms β^- (n) E 11.1	**S45** 68 ms β^- (n) E 15	**S46** 0.05 s β^- E 15	**S47** E 19	**S48** E 18
15	**P39** 0.28 s β^- γ 340, 398, 1126, 1525 (n) E 10.3	**P40** (2−, 3−) 0.15 s β^- γ 903.7,··· (n) γ 398.6,··· E 14.8	**P41** 0.11 s β^- (n) E 13.7	**P42** 48 ms β^- (n) E 18.6	**P43** 36 ms β^- (n) E 18	**P44** 18 ms β^- E 21	**P45** E 21	**P46** E 25	
14	**Si38** E 10.7	**Si39** 48 ms β^- (n) ? E 14.8	**Si40** 33 ms β^- (n) E 14	**Si41** 20. ms β^- E 19	**Si42** 12 ms β^- (n) ? E 17	**Si43** E 21	**Si44** E 21		
13	**Al37** 11 ms β^- E 16.5	**Al38** 8 ms β^- E 20.	**Al39** 8 ms β^- (n) ? E 19	**Al40** E 24	**Al41** E 22	**Al42** E 25	**Al43**		
12	**Mg36** 4 ms β^- E 16	**Mg37** E 19	**Mg38** E 19		**Mg40** E 21				
11	**Na35** 1.5 ms β^- (n) E 23		**Na37** E 26						
10	**Ne34** E 20.								
	24		**26**		**28**		**30**		**32**

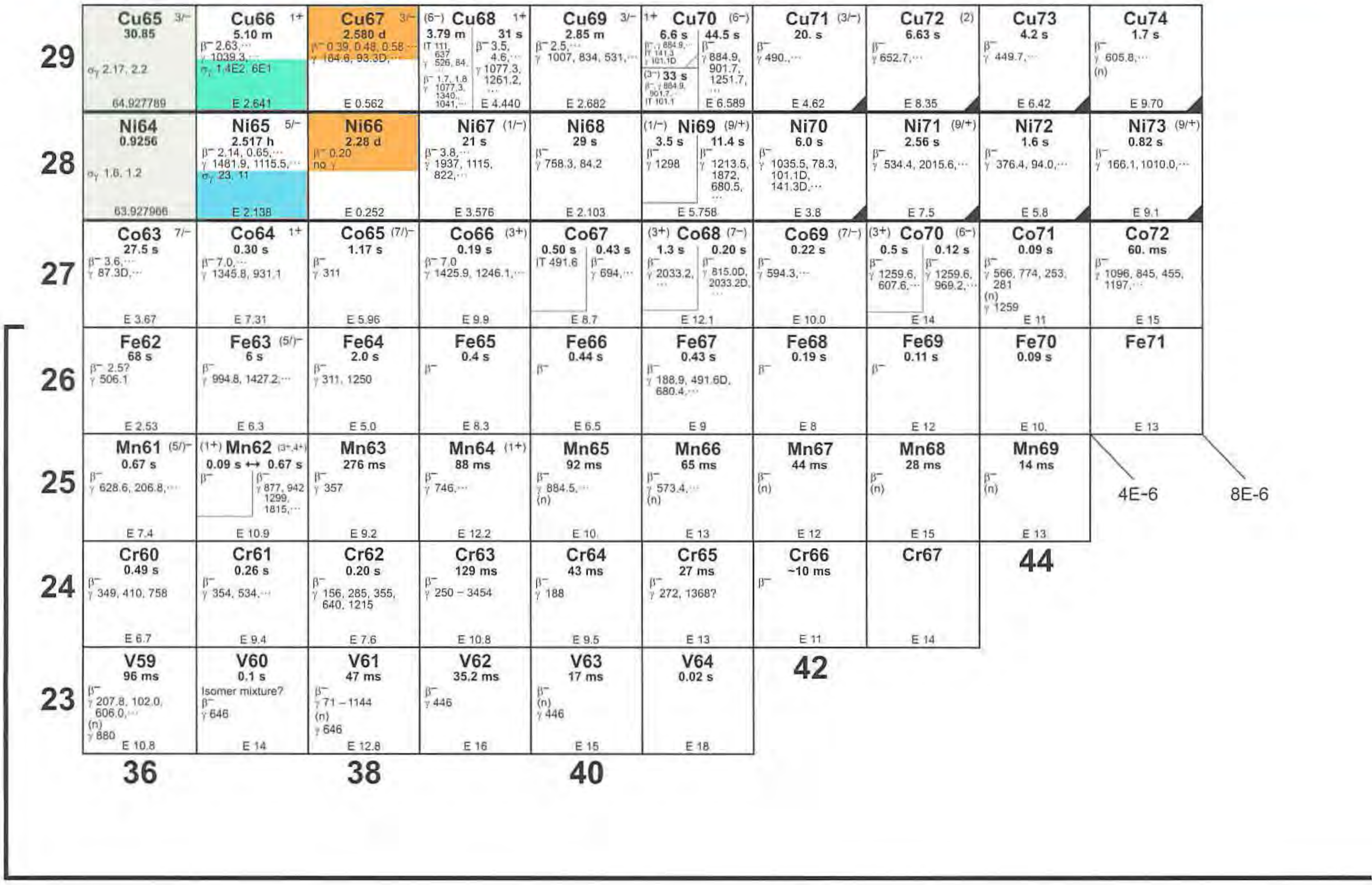
S31 1/+ 2.56 s β^+ 4.39,··· γ 1266.2,··· E 5.396	**S32** 94.99 σ_γ 0.53, 0.26 $\sigma_\alpha \le 0.5$ mb 31.9720710	**S33** 3/+ 0.75 σ_γ 0.45, 0.23 σ_α 0.14 σ_p 2 mb 32.9714588	**S34** 4.25 σ_γ 0.25, 0.13 33.9678669	**S35** 3/+ 87.2 d β^- 0.1674 no γ E 0.1672	**S36** 0.01 σ_γ 0.24, 0.17 35.9670808	**S37** 7/− 5.05 m β^- 1.76,··· γ 3104.0,··· E 4.8652	**S38** 2.84 h β^- 0.99,··· γ 1941.9,··· E 2.94	**S39** (7/−) 11.5 s β^- γ 1300.5, 1696.6, 396.3,··· E 6.6	**S40** 9 s β^- γ 211.6, 677.4, 431.6,··· E 4.7
P30 1+ 2.50 m β^+ 3.24,··· ε γ 2235.2 (ω),··· E 4.2324	**P31** 1/+ 100 σ_γ 0.17, 0.08 30.9737616	**P32** 1+ 14.28 d β^- 1.709 no γ E 1.7105	**P33** 1/+ 25.3 d β^- 0.249 no γ E 0.249	**P34** 1+ 12.4 s β^- 5.1, 3.2,··· γ 2127.7,··· E 5.37	**P35** (1/+) 47 s β^- 2.3 γ 1572.3 E 3.989	**P36** 5.7 s β^- γ 3290.5, 902.4, 1638.2, 2540.,··· E 10.41	**P37** 2.3 s β^- γ 646.2, 1582.9,··· E 7.90	**P38** 0.6 s β^- γ 1292.3, 2224,··· (n) E 12.1	**P39** 0.28 s β^- γ 340, 398, 1126, 1525 (n) E 10.3
Si29 1/+ 4.685 σ_γ 0.120, 0.08 28.97649470	**Si30** 3.092 σ_γ 0.107, 0.7 29.97377017	**Si31** 3/+ 2.62 h β^- 1.48,··· γ 1266.2 ω σ_γ 0.07 E 1.4919	**Si32** 1.6E2 a β^- 0.221 no γ E 0.2243	**Si33** (3/+) 6.1 s β^- 3.92,··· γ 1847.6,··· E 5.84	**Si34** 2.8 s β^- 3.09,··· γ 1178.5, 429.1, 1607.6,··· E 4.60	**Si35** 7/− 0.8 s β^- γ 4101, 2386, 3860., 241.4,··· E 10.50	**Si36** 0.5 s β^- γ 174.7, 250.3, 878,··· (n) E 7.8	**Si37** ~0.09 s β^- (n) E 12.4	**Si38** E 10.7
Al28 3+ 2.25 m β^- 2.86,··· γ 1779.0 E 4.6424	**Al29** 5/+ 6.5 m β^- 2.5,··· γ 1273.4,··· E 3.680	**Al30** 3+ 3.68 s β^- 5.0,··· γ 2235.2, 1263.0, 3498.0,··· E 8.56	**Al31** 5/+ 0.64 s β^- 5.6, 6.2,··· γ 2316.7, 1694.8,··· E 8.00	**Al32** 1+ 32 ms β^- γ 1941.4, 3042,··· (n) ω E 13.0	**Al33** 5/+ 41.7 ms β^- γ 4341, 1010.2,··· (n) γ 1940.5 E 12.0	**Al34** 4− 56 ms β^- γ 929.0, 3326, 124.2,··· (n) E 17.0	**Al35** 38 ms β^- γ 64.0, 910.1,··· (n) 3.00, 0.98 γ 3327 E 14.2	**Al36** 0.09 s β^- E 18.3	**Al37** 11 ms β^- E 16.5
Mg27 1/+ 9.45 m β^- 1.75, 1.59,··· γ 843.8, 1014.4,··· σ_γ 0.07 E 2.6100	**Mg28** 21.0 h β^- 0.459,··· γ 30.6, 1342.3,··· E 1.832	**Mg29** 3/+ 1.3 s β^- 5.4,··· γ 2224.0, 1398.0, 960.4,··· E 7.60	**Mg30** 0.32 s β^- γ 243.9, 443.9,··· (n) γ 1398 E 6.96	**Mg31** 1/+ 0.24 s β^- γ 1612.8, 947, 1626, 666,··· (n) E 11.74	**Mg32** 0.09 s β^- γ 2765, 735, 2467,··· (n) 0.37 – 4.51 E 10.1	**Mg33** 89 ms β^- γ 1618, 4730,··· (n) γ 2765, 735 E 13.4	**Mg34** 0.02 s β^- (n) E 11.7	**Mg35** 0.07 s β^- (n) E 16.3	**Mg36** 4 ms β^- E 16
Na26 3+ 1.0711 s β^- 7.4,··· γ 1808.6,··· E 9.35	**Na27** 5/+ 0.290 s β^- 8.0,··· γ 984.7, 1698.0,··· (n) ω γ 1809 E 9.069	**Na28** 1+ 30.5 ms β^- 12,··· γ 1474, 2389 (n) ω E 14.03	**Na29** 3/+ 44 ms β^- 12,··· γ 54.6, 2560.2, 1638.0, ··· (n) 4.13, 1.70, 2.25,··· γ 1474,··· E 13.28	**Na30** 2+ 50. ms β^- γ 1483, 1979,··· (n), γ 1041 (2n) (α) vω E 17.27	**Na31** 3/(+) 17.2 ms β^- ~8.6, ~6.8,··· γ 51, 2243,··· (n), γ 1482,··· (2n) ω E 15.9	**Na32** (3−) 13.2 ms β^- 15,··· γ 886, 2152,··· (n), γ 170.8, 239.9,··· (2n), γ 1483 E 20.0	**Na33** 8.3 ms β^- γ 546.2, 704.9, 484.1,··· (n) 0.8, 1.0,··· γ 885.3, 2551,··· (2n), γ 50.1, 171.2,··· E 20.	**Na34** 1+ 5 ms β^- (2n), γ 886 (n) E 24	**Na35** 1.5 ms β^- (n) E 23
Ne25 1/+ 0.61 s β^- 7.2, 6.3,··· γ 89.5, 979.8,··· E 7.25	**Ne26** 197 ms β^- γ 82.5, 1278, 232.5, 151,··· (n) ω E 7.29	**Ne27** 31 ms β^- γ 3019, 2736, 2225,··· (n) E 12.6	**Ne28** 19.9 ms β^- γ 2062.9, 864.5 (n), γ 63 (2n) E 12.2	**Ne29** 15.6 ms β^- γ 72, 1516, 1249, 1588,··· (n), γ 55,··· (2n), γ 63 E 15.4	**Ne30** 6.3 ms β^- γ 150.6, 365,··· (n), γ 244, 444 (2n) E 15	**Ne31** 3 ms β^- E 18	**Ne32** 4 ms β^- E 18		**Ne34** E 20.
F24 (3+) 0.39 s β^- γ 1981.6 E 13.5	**F25** (5/+) 0.07 s β^- γ 1703,··· (n) γ 1982,··· E 13.4	**F26** 1+ 10 ms β^- γ 2018.2, 1673.0 (n) E 17.8	**F27** 5.0 ms β^- (n) γ 2018 E 17.9		**F29** 2.5 ms β^- (n) E 22		**F31** E 25		
	16		**18**		**20**		**22**		**24**

23	**V54** 3+ **49.8 s** β^- 3.0,··· γ 834.8, 988.8, 2259.2,··· E 7.04	**V55** **6.5 s** β^- 5.4,··· γ 517.7, 880.6,··· E 6.0	**V56** (1+) **217 ms** β^- γ 1006.1, 668.4, 824, 1317.9 E 9.2	**V57** **0.35 s** β^- γ 267.8, 629.4, 941.7,··· E 8.3	**V58** **0.19 s** β^- γ 879.7, 1056.4, 2217,··· E 11.6	**V59** **96 ms** β^- γ 207.8, 102.0, 606.0,··· (n) γ 880 E 10.8	**V60** **0.1 s** Isomer mixture? β^- γ 646 E 14	**V61** **47 ms** β^- γ 71 – 1144 (n) γ 646 E 12.8	**V62** **35.2 ms** β^- γ 446 E 16	**V63** **17 ms** β^- (n) γ 446 E 15	**V64** **0.02 s** E 18
22	**Ti53** (3/)− **33 s** β^- 3.1,··· γ 127.6, 228.4, 1675.6, 100.8,··· E 5.0	**Ti54** **1.5 s** β^- E 4.3	**Ti55** **0.6 s** β^- γ 672.5, 323.4, 1330.1, 828.1,··· E 7.5	**Ti56** **0.20 s** β^- E 7.1	**Ti57** **0.10 s** β^- γ 174.8, 1579.4, 113.1, 1861.5,··· E 11	**Ti58** **0.05 s** β^- γ 114 E 9	**Ti59** **31 ms** β^- E 12	**Ti60** **22 ms** β^- E 11	**Ti61** E 14	**40**	
21	**Sc52** 3(+) **8.2 s** β^- 7.0, 4.6,··· γ 1049.7, 1267.9,··· E 9.1	**Sc53** β^- E 9.2	**Sc54** (3)+ **0.29 s** β^- γ 1495, 1001.2, 1021 E 11.4	**Sc55** **0.09 s** β^- γ 593 E 12	**Sc56** **~0.05 s** Isomer mixture? β^- γ 1128.5, 1160.5, 690.1,··· E 14	**Sc57** **13 ms** β^- E 13	**Sc58** **12 ms** β^- E 16	**38**			
20	**Ca51** (3/−) **10. s** β^- γ 861.6, 1394.0, 1167.5, 1480.1,··· E 7.4	**Ca52** **4.6 s** β^- 4.1,··· γ 675, 961, 1636,··· E 8	**Ca53** **0.2 s** β^- (n) E 10.	**Ca54** **0.09 s** β^- γ 247 E 10.	**Ca55** **25 ms** β^- E 11	**Ca56** **11 ms** β^- E 12					
19	**K50** (0−) **472 ms** β^- 5.3, 4.8,··· γ 1027.0, 4035.6, 3008.9, 1973.5,··· (n) 2.48, 2.83,··· γ 2023.2,··· E 14.2	**K51** **365 ms** β^- γ 3462 (n) 2.21, 0.86, 0.91,··· γ 1027, 1973 E 14	**K52** (2−) **105 ms** β^- γ 2563,··· (n) 1.02, 2.2, 0.81,··· γ 2377, 1718, 2934,··· (2n), γ 1027 ω E 16	**K53** (3/+) **30. ms** β^- γ 2200 (n) γ 2563, 3150 E 16	**K54** **10 ms** β^- (n) E 18	**36**					
18	**Ar49** **0.17 s** β^- (n) E 12	**Ar50** **0.8 s** β^- (n) E 11	**Ar51** E 14								
17	**Cl48** E 19	**Cl49** E 18		**Cl51** E 21							
16	**S47** E 19	**S48** E 18		**34**							
		32									

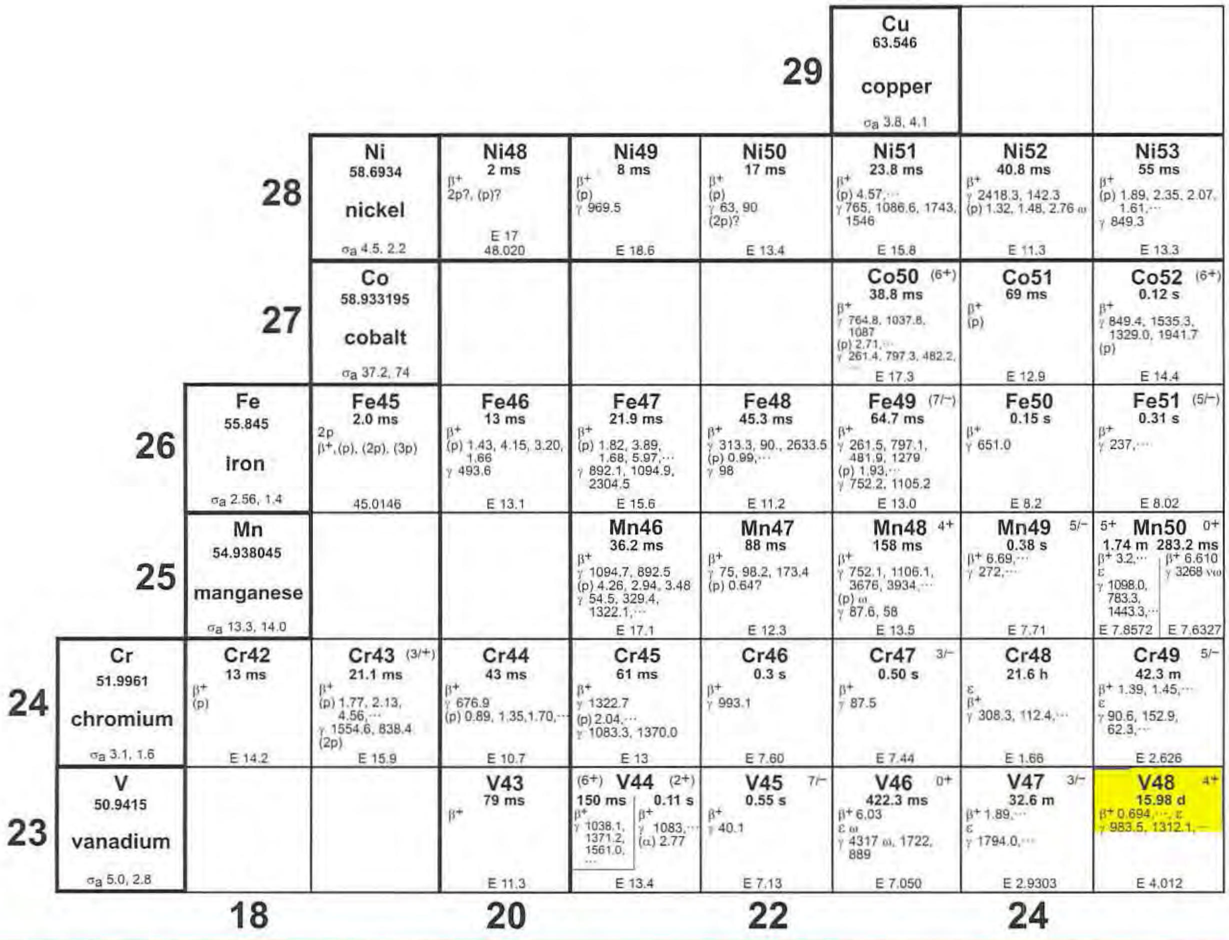
							23	**V** 50.9415 **vanadium** σ_a 5.0, 2.8			**V43** **79 ms** β^+ E 11.3
						22	**Ti** 47.867 **titanium** σ_a 6.1, 2.9	**Ti39** **29 ms** β^+ (p) γ 2212 (2p)? E 15.7	**Ti40** **52.5 ms** β^+ (p) 2.16, 3.73, 1.70,··· γ 2467.3 (2p) E 11.7	**Ti41** 3/+ **83 ms** β^+ (p) 4.734, 3.08,··· γ 3732 E 12.9	**Ti42** **0.20 s** β^+ 6,··· γ 611.2,··· E 7.00
						21	**Sc** 44.955912 **scandium** σ_a 27.2, 12		**Sc39** **very short** p 38.98479	**Sc40** 4− **182 ms** β^+ 5.7,··· γ 3734, 754,··· (p) 1.09 (ω), 1.00,··· (α) 3.32 ω, 3.75,··· E 14.323	**Sc41** 7/− **596 ms** β^+ 5.5,··· γ 2575 (ω), 2959 E 6.4954
				20	**Ca** 40.078 **calcium** σ_a 0.43, 0.23	**Ca35** **25.7 ms** β^+ (p) 1.43,··· γ 2090.9,··· (2p) E 15.8	**Ca36** **101 ms** β^+ γ 1618, 1112 (p) 2.53, 1.65,··· E 10.99	**Ca37** 3/+ **181 ms** β^+ γ 3239.3, 2750.4, 1370.9 (p) 3.103,··· E 11.64	**Ca38** **0.44 s** β^+ γ 1568,··· E 6.741	**Ca39** 3/+ **861 ms** β^+ 5.49,··· γ 2522 ω E 6.533	**Ca40** **96.941** σ_γ 0.41, 0.22 σ_α ≤ 0.13 mb 39.9625910
				19	**K** 39.0983 **potassium** σ_a 2.1, 1.0		**K35** 3/+ **0.19 s** β^+ γ 2982.7, 2589.9, 1750.6,··· (p) 1.42 (ω), 1.70, 1.56,··· E 11.88	**K36** 2+ **342 ms** β^+ 9.9, 5.3,··· γ 1970.9, 2433.7, 2208,··· (p) 0.97 ω, 0.69, 1.33,··· (α) 2.02 (ω), 2.72,··· E 12.81	**K37** 3/+ **1.23 s** β^+ 5.13,··· γ 2796,··· E 6.1475	0+ **K38** 3+ **924.3 ms** β^+ 5.021 IT 130.1 ω **7.63 m** β^+ 2.68,··· γ 2167.7, ··· E 5.9139	**K39** 3/+ **93.2581** σ_γ 2.1, 1.0 σ_α 4.3 mb 38.9637067
		18	**Ar** 39.948 **argon** σ_a 0.66, 0.42	**Ar31** 5/(+) **14 ms** β^+ 5.2,··· (p) 2.09, 1.45,··· γ 2210, 1196 (2p) E 18.4	**Ar32** **98 ms** β^+ γ 461.1, 707.4,··· (p) 3.348, 2.419, 2.118,··· E 11.13	**Ar33** 1/+ **174 ms** β^+ γ 810.5,··· (p) 3.168,··· E 11.619	**Ar34** **843.8 ms** β^+ 5.037,··· γ 666.5, 3129, 461.0, 2580, E 6.0626	**Ar35** 3/+ **1.775 s** β^+ 4.943,··· γ 1219.2, 1763.0 (ω), 2693.6,··· E 5.966	**Ar36** **0.3365** σ_γ 5.2 σ_α 5.5 mb σ_p < 1.6 mb 35.96754511	**Ar37** 3/+ **35.0 d** ε no γ σ_α 1.1E3 σ_p 37 E 0.8139	**Ar38** **0.0632** σ_γ 0.8 37.9627324
		17	**Cl** 35.453 **chlorine** σ_a 33.5, 12		**Cl31** 3/+ **0.17 s** β^+ γ 2234, 1249, 3536, 4045 (p) 0.98, 1.52 ω,··· E 12.0	**Cl32** 1+ **297 ms** β^+ 9.47, 4.7,··· γ 2231, 4770,,··· (α) 2.20 (ω), 1.67,··· (p) 0.99 (ω), 0.76, 1.32,··· E 12.69	**Cl33** 3/+ **2.511 s** β^+ 4.5,··· γ 840.9 (ω), 1966.2, 2866.3,··· E 5.5826	3+ **Cl34** 0+ **32.2 m** β^+ 2.5, 1.3,··· γ 2127.7, 1176.0, 3303.6,··· IT 146.4 **1.527 s** β^+ 4.47 E 5.4920	**Cl35** 3/+ **75.76** σ_γ 43.6, 15 σ_p 0.48, 0.59 σ_α 0.08 mb 34.96885268	**Cl36** 2+ **3.01E5 a** β^- 0.709 β^+ 0.12(ω) σ_γ < 10 σ_α ~0.6 mb σ_p 47 mb E^- 0.7097 E^+1.1422	**Cl37** 3/+ **24.24** σ_γ (0.05 + 0.38), 0.32 36.96590259
16	**S** 32.065 **sulfur** σ_a 0.52, 0.25	**S27** (5/+) **16 ms** β^+ (p) 2.16, 7.5,··· (2p) E 18.3	**S28** **0.12 s** β^+ (p) 2.98, 1.46, 3.70, 1.63,··· E 11.2	**S29** 5/+ **188 ms** β^+ γ 1383.5, 2422.7,··· (p) 5.438, 2.130,··· γ 1779.0,··· E 13.8	**S30** **1.18 s** β^+ 4.42, 5.09,··· γ 677.2,··· E 6.138	**S31** 1/+ **2.56 s** β^+ 4.39,··· γ 1266.2,··· E 5.396	**S32** **94.99** σ_γ 0.53, 0.26 σ_α ≤ 0.5 mb 31.9720710	**S33** 3/+ **0.75** σ_γ 0.45, 0.23 σ_α 0.14 σ_p 2 mb 32.9714588	**S34** **4.25** σ_γ 0.25, 0.13 33.9678669	**S35** 3/+ **87.2 d** β^- 0.1674 no γ E 0.1672	**S36** **0.01** σ_γ 0.24, 0.17 35.9670808
			12		**14**		**16**		**18**		**20**



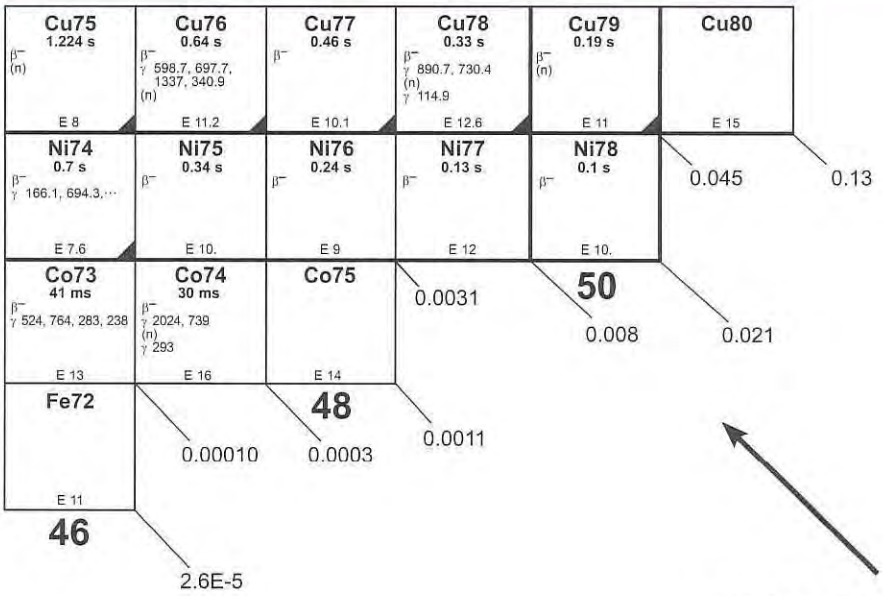
(6^+) **V44** (2^+) **150 ms** β^+ γ 1038.1, 1371.2, 1561.0, ··· **0.11 s** β^+ γ 1083,··· (α) 2.77 E 13.4	**V45** 7/− **0.55 s** β^+ γ 40.1 E 7.13	**V46** 0^+ **422.3 ms** β^+ 6.03 ε ω γ 4317 ω, 1722, 889 E 7.050	**V47** 3/− **32.6 m** β^+ 1.89,··· ε γ 1794.0,··· E 2.9303	**V48** 4^+ **15.98 d** β^+ 0.694,···, ε γ 983.5, 1312.1,··· E 4.012	**V49** 7/− **331 d** ε no γ E 0.602	**V50** 6^+ **0.250** **1.4E17 a** ε, γ 1553.8 β^-, γ 783 σ_γ 21, 6E1 σ_p 0.71 mb E^+ 2.205 E^- 1.0379 49.947158	**V51** 7/− **99.750** σ_γ 4.9, 2.7 50.943960	**V52** 3^+ **3.76 m** β^- 2.47,··· γ 1434.1,··· E 3.976	**V53** 7/− **1.54 m** β^- 2.5,··· γ 1006.2,··· E 3.436	**V54** 3^+ **49.8 s** β^- 3.0,··· γ 834.8, 988.8, 2259.2,··· E 7.04
Ti43 7/− **0.50 s** β^+ 5.80,··· γ 2288.3, 845.2,··· E 6.87	**Ti44** **59.2 a** ε γ 78.3D, 67.8D,··· E 0.268	**Ti45** 7/− **3.078 h** β^+ 1.04,···, ε γ 719.6 ω, 1408.1,··· E 2.062	**Ti46** **8.25** σ_γ 0.6, 0.4 45.952632	**Ti47** 5/− **7.44** σ_γ 1.7, 1.6 46.951763	**Ti48** **73.72** σ_γ 7.9, 3.6 47.947946	**Ti49** 7/− **5.41** σ_γ 1.9, 1.2 48.947870	**Ti50** **5.18** σ_γ 0.177, 0.11 49.944791	**Ti51** 3/− **5.76 m** β^- 2.14,··· γ 320.1,··· E 2.474	**Ti52** **1.7 m** β^- 1.83 γ 124.5, 17.0 E 1.98	**Ti53** (3/)− **33 s** β^- 3.1,··· γ 127.6, 228.4, 1675.6, 100.8,··· E 5.0
7^+ **Sc42** 0^+ **1.03 m** β^+ 2.8 γ 437.0, 1524.6, 1227.6, ··· **682 ms** β^+ 5.40, ··· γ 312.4 ω, 1524.6 E 6.4258	**Sc43** 7/− **3.90 h** β^+ 1.20, 0.82,···, ε γ 372.8,··· E 2.221	6^+ **Sc44** 2^+ **2.442 d** IT 271.2 ε γ 1001.8, 1126.1, 1157.0 **3.93 h** β^+ 1.47, ··· ε γ 1157.0, ··· E 3.652	**Sc45** 7/− **100** σ_γ (10 + 17), (5 + 7) 44.955912	1^- **Sc46** 4^+ **18.75 s** IT 142.5 **83.81 d** β^- 0.357,··· γ 1120.5, 889.3 σ_γ 8 E 2.366	**Sc47** 7/− **3.349 d** β^- 0.439, 0.600 γ 159.4 E 0.600	**Sc48** 6^+ **43.7 h** β^- 0.66,··· γ 983.5, 1312.1, 1037.5,··· E 3.99	**Sc49** 7/− **57.3 m** β^- 2.01,··· γ 1762 (ω),1623 E 2.006	**Sc50** 5^+ **1.71 m** β^- 3.69,··· γ 1553.8, 1121.1, 523.8,··· E 6.89	**Sc51** (7/)− **12.4 s** β^- ~5.0,··· γ 1437, 2144, 1568,··· E 6.51	**Sc52** $3(+)$ **8.2 s** β^- 7.0, 4.6,··· γ 1049.7, 1267.9,··· E 9.1
Ca41 7/− **1.03E5 a** ε no γ σ_γ 4 σ_p 7mb σ_α ~0.17 E 0.4213	**Ca42** **0.647** σ_γ 0.7, 0.4 41.9586180	**Ca43** 7/− **0.135** σ_γ 6, 4 42.9587666	**Ca44** **2.086** σ_γ 0.84, 0.59 43.9554818	**Ca45** 7/− **162.7 d** β^- 0.258,··· γ 12.4D νω e^- σ_γ 15 E 0.256	**Ca46** **0.004** σ_γ 0.7, 0.9 45.953693	**Ca47** 7/− **4.536 d** β^- 0.694, 1.990,··· γ 1297.1,··· E 1.992	**Ca48** **0.187** **4E19 a** $\beta^-\beta^-$ σ_γ 0.98, 0.5 47.952534	**Ca49** 3/− **8.72 m** β^- 2.18,··· γ 3084.4,··· E 5.263	**Ca50** **14 s** β^- 3.12 γ 256.9D, 1519.3, 71.6,1590.8,··· E 4.97	**Ca51** (3/−) **10. s** β^- γ 861.6, 1394.0, 1167.5, 1480.1,··· E 7.4
K40 4^- **0.0117** **1.25E9 a** β^- 1.33, ε γ 1460.8 β^+ νω σ_γ 30, 13 σ_p 4.4, 2.0 σ_α 0.42 E^- 1.3111 E^+ 1.5047	**K41** 3/+ **6.7302** σ_γ 1.46, 1.4 40.9618258	**K42** 2^- **12.36 h** β^- 3.52,··· γ 1524.6,··· E 3.5255	**K43** 3/+ **22.3 h** β^- 0.83,··· γ 372.8, 617.5,··· E 1.82	**K44** 2^- **22.1 m** β^- 5.6, 2.4,··· γ 1157.0, 2150.8,··· E 5.66	**K45** 3/+ **17.8 m** β^- 2.1,··· γ 174.2, 1705.6,··· E 4.20	**K46** (2^-) **1.8 m** β^- 6.3,··· γ 1347, 3700.,··· E 7.72	**K47** 1/+ **17.5 s** β^- 4.1,··· γ 2013.4, 586.0,··· E 6.64	**K48** (2^-) **6.8 s** β^- 5.0,··· γ 3831.6, 780.1,··· (n) E 12.09	**K49** (3/+) **1.26 s** β^- 3.95, 3.82, 4.91,··· γ 4272, 2249,··· (n) 0.12 – 3.5 γ 3831.6,··· E 11.0	**K50** (0^-) **472 ms** β^- 5.3, 4.8,··· γ 1027.0, 4035.6, 3008.9, 1973.5,··· (n) 2.48, 2.83,··· γ 2023.2,··· E 14.2
Ar39 7/− **269 a** β^- 0.565 no γ σ_γ 6E2 σ_α ≤ 0.29 E 0.565	**Ar40** **99.6003** σ_γ 0.65, 0.41 39.962383123	**Ar41** 7/− **1.83 h** β^- 1.198,··· γ 1293.6,··· σ_γ 0.5 E 2.4916	**Ar42** **33 a** β^- no γ E 0.60	**Ar43** (5/−) **5.4 m** β^- γ 974.9, 738.1, 1439.8,··· E 4.58	**Ar44** **11.87 m** β^- γ 182.6, 1703.4, 1886.1,··· E 3.14	**Ar45** (7/)− **21.5 s** β^- γ 1020.0, 3707.2, 61.4,··· E 6.84	**Ar46** **8.4 s** β^- γ 1944.3,··· E 5.70	**Ar47** (3/−) **1.23 s** β^- γ 360, 1660, 1742,··· E 9.8	**Ar48** **0.48 s** β^- E 8.4	**Ar49** **0.17 s** β^- (n) E 12
5^- **Cl38** 2^- **715 ms** IT 671.3 **37.2 m** β^- 4.91, 1.11,··· γ 2167.7, 1642.4, ··· E 4.9165	**Cl39** 3/+ **55.6 m** β^- 1.91,··· γ 1267.2, 250.3, 1517.5,··· E 3.44	**Cl40** 2^- **1.38 m** β^- ~3.2,··· γ 1460.8, 2840.2, 2621.9,··· E 7.48	**Cl41** (1/+) **34 s** β^- 3.8,··· γ 167 – 1359 E 5.8	**Cl42** $(3)^-$ **6.8 s** β^- 5, 7.5, 4 γ 1208,··· E 9.5	**Cl43** (3/)+ **3.1 s** β^- γ 761.6, 1031.6,··· E 7.8	**Cl44** **0.56 s** β^- γ 1158.1, 852.8, 2796.0, 2010.2,··· E 12.4	**Cl45** **0.41 s** β^- γ 542,··· (n) γ 1158.1, 853.2,··· E 11.4	**Cl46** **232 ms** β^- γ 1552.6,··· (n) γ 542.7, 1228.0,··· E 15	**Cl47** **~101 ms** β^- (n) ? E 15	**Cl48** E 19
S37 7/− **5.05 m** β^- 1.76,··· γ 3104.0,··· E 4.8652	**S38** **2.84 h** β^- 0.99,··· γ 1941.9,··· E 2.94	**S39** (7/−) **11.5 s** β^- γ 1300.5, 1696.6, 396.3,··· E 6.6	**S40** **9 s** β^- γ 211.6, 677.4, 431.6,··· E 4.7	**S41** **2.0 s** β^- γ 130, 554, 761,··· (n) ? E 8.3	**S42** **1.0 s** β^- γ 118.6, 1281.5, 723.5, 470.7,··· E 7.2	**S43** **0.26 s** β^- γ 329, 612, 878,··· (n) E 12.2	**S44** **100 ms** β^- (n) E 11.1	**S45** **68 ms** β^- (n) E 15	**S46** **0.05 s** β^- E 15	**S47** E 19
	22		**24**		**26**		**28**		**30**	



29	**Cu65** 3/− 30.85 σ_γ 2.17, 2.2 64.927789	**Cu66** 1+ 5.10 m β^- 2.63,··· γ 1039.3,··· σ_γ 1.4E2, 6E1 E 2.641	**Cu67** 3/− 2.580 d β^- 0.39, 0.48, 0.58··· γ 184.6, 93.3D,··· E 0.562	(6−) **Cu68** 1+ 3.79 m: IT 111, 637 γ 526, 84, ··· β^- 1.7, 1.8 γ 1077.3, 1340., 1041,··· 31 s: β^- 3.5, 4.6,··· γ 1077.3, 1261.2, ··· E 4.440	**Cu69** 3/− 2.85 m β^- 2.5,··· γ 1007, 834, 531,··· E 2.682	1+ **Cu70** (6−) 6.6 s: β^-, γ 884.9,··· IT 141.3 γ 101.1D (3−) 33 s: β^-, γ 884.9, 901.7,··· IT 101.1 44.5 s: β^- γ 884.9, 901.7, 1251.7, ··· E 6.589	**Cu71** (3/−) 20. s β^- γ 490.,··· E 4.62	**Cu72** (2) 6.63 s β^- γ 652.7,··· E 8.35	**Cu73** 4.2 s β^- γ 449.7,··· E 6.42	**Cu74** 1.7 s β^- γ 605.8,··· (n) E 9.70	
28	**Ni64** 0.9256 σ_γ 1.6, 1.2 63.927966	**Ni65** 5/− 2.517 h β^- 2.14, 0.65,··· γ 1481.9, 1115.5,··· σ_γ 23, 11 E 2.138	**Ni66** 2.28 d β^- 0.20 no γ E 0.252	**Ni67** (1/−) 21 s β^- 3.8,··· γ 1937, 1115, 822,··· E 3.576	**Ni68** 29 s β^- γ 758.3, 84.2 E 2.103	(1/−) **Ni69** (9/+) 3.5 s: β^- γ 1298 11.4 s: β^- γ 1213.5, 1872, 680.5, ··· E 5.758	**Ni70** 6.0 s β^- γ 1035.5, 78.3, 101.1D, 141.3D,··· E 3.8	**Ni71** (9/+) 2.56 s β^- γ 534.4, 2015.6,··· E 7.5	**Ni72** 1.6 s β^- γ 376.4, 94.0,··· E 5.8	**Ni73** (9/+) 0.82 s β^- γ 166.1, 1010.0,··· E 9.1	
27	**Co63** 7/− 27.5 s β^- 3.6,··· γ 87.3D,··· E 3.67	**Co64** 1+ 0.30 s β^- 7.0,··· γ 1345.8, 931.1 E 7.31	**Co65** (7/)− 1.17 s β^- γ 311 E 5.96	**Co66** (3+) 0.19 s β^- 7.0 γ 1425.9, 1246.1,··· E 9.9	**Co67** 0.50 s: IT 491.6 0.43 s: β^- γ 694,··· E 8.7	(3+) **Co68** (7−) 1.3 s: β^- γ 2033.2, ··· 0.20 s: β^- γ 815.0D, 2033.2D, ··· E 12.1	**Co69** (7/−) 0.22 s β^- γ 594.3,··· E 10.0	(3+) **Co70** (6−) 0.5 s: β^- γ 1259.6, 607.6,··· 0.12 s: β^- γ 1259.6, 969.2,··· E 14	**Co71** 0.09 s β^- γ 566, 774, 253, 281 (n) γ 1259 E 11	**Co72** 60. ms β^- γ 1096, 845, 455, 1197,··· E 15	
26	**Fe62** 68 s β^- 2.5? γ 506.1 E 2.53	**Fe63** (5/)− 6 s β^- γ 994.8, 1427.2,··· E 6.3	**Fe64** 2.0 s β^- γ 311, 1250 E 5.0	**Fe65** 0.4 s β^- E 8.3	**Fe66** 0.44 s β^- E 6.5	**Fe67** 0.43 s β^- γ 188.9, 491.6D, 680.4,··· E 9	**Fe68** 0.19 s β^- E 8	**Fe69** 0.11 s β^- E 12	**Fe70** 0.09 s E 10.	**Fe71** E 13	
25	**Mn61** (5/)− 0.67 s β^- γ 628.6, 206.8,··· E 7.4	(1+) **Mn62** (3+,4+) 0.09 s ↔ 0.67 s β^- β^- γ 877, 942 1299, 1815,··· E 10.9	**Mn63** 276 ms β^- γ 357 E 9.2	**Mn64** (1+) 88 ms β^- γ 746,··· E 12.2	**Mn65** 92 ms β^- γ 884.5,··· (n) E 10.	**Mn66** 65 ms β^- γ 573.4,··· (n) E 13	**Mn67** 44 ms β^- (n) E 12	**Mn68** 28 ms β^- (n) E 15	**Mn69** 14 ms β^- (n) E 13	4E-6	8E-6
24	**Cr60** 0.49 s β^- γ 349, 410, 758 E 6.7	**Cr61** 0.26 s β^- γ 354, 534,··· E 9.4	**Cr62** 0.20 s β^- γ 156, 285, 355, 640, 1215 E 7.6	**Cr63** 129 ms β^- γ 250 – 3454 E 10.8	**Cr64** 43 ms β^- γ 188 E 9.5	**Cr65** 27 ms β^- γ 272, 1368? E 13	**Cr66** ~10 ms β^- E 11	**Cr67** E 14	**44**		
23	**V59** 96 ms β^- γ 207.8, 102.0, 606.0,··· (n) γ 880 E 10.8	**V60** 0.1 s Isomer mixture? β^- γ 646 E 14	**V61** 47 ms β^- γ 71 – 1144 (n) γ 646 E 12.8	**V62** 35.2 ms β^- γ 446 E 16	**V63** 17 ms β^- (n) γ 446 E 15	**V64** 0.02 s E 18	**42**				
	36		**38**		**40**						



29							**Cu** 63.546 copper σ_a 3.8, 4.1		
28			**Ni** 58.6934 nickel σ_a 4.5, 2.2	**Ni48** 2 ms β^+ 2p?, (p)? E 17 48.020	**Ni49** 8 ms β^+ (p) γ 969.5 E 18.6	**Ni50** 17 ms β^+ (p) γ 63, 90 (2p)? E 13.4	**Ni51** 23.8 ms β^+ (p) 4.57,··· γ 765, 1086.6, 1743, 1546 E 15.8	**Ni52** 40.8 ms β^+ γ 2418.3, 142.3 (p) 1.32, 1.48, 2.76 ω E 11.3	**Ni53** 55 ms β^+ (p) 1.89, 2.35, 2.07, 1.61,··· γ 849.3 E 13.3
27			**Co** 58.933195 cobalt σ_a 37.2, 74				**Co50** (6+) 38.8 ms β^+ γ 764.8, 1037.8, 1087 (p) 2.71,··· γ 261.4, 797.3, 482.2, ··· E 17.3	**Co51** 69 ms β^+ (p) E 12.9	**Co52** (6+) 0.12 s β^+ γ 849.4, 1535.3, 1329.0, 1941.7 (p) E 14.4
26		**Fe** 55.845 iron σ_a 2.56, 1.4	**Fe45** 2.0 ms 2p β^+,(p), (2p), (3p) 45.0146	**Fe46** 13 ms β^+ (p) 1.43, 4.15, 3.20, 1.66 γ 493.6 E 13.1	**Fe47** 21.9 ms β^+ (p) 1.82, 3.89, 1.68, 5.97,··· γ 892.1, 1094.9, 2304.5 E 15.6	**Fe48** 45.3 ms β^+ γ 313.3, 90., 2633.5 (p) 0.99,··· γ 98 E 11.2	**Fe49** (7/−) 64.7 ms β^+ γ 261.5, 797.1, 481.9, 1279 (p) 1.93,··· γ 752.2, 1105.2 E 13.0	**Fe50** 0.15 s β^+ γ 651.0 E 8.2	**Fe51** (5/−) 0.31 s β^+ γ 237,··· E 8.02
25		**Mn** 54.938045 manganese σ_a 13.3, 14.0			**Mn46** 36.2 ms β^+ γ 1094.7, 892.5 (p) 4.26, 2.94, 3.48 γ 54.5, 329.4, 1322.1,··· E 17.1	**Mn47** 88 ms β^+ γ 75, 98.2, 173.4 (p) 0.64? E 12.3	**Mn48** 4+ 158 ms β^+ γ 752.1, 1106.1, 3676, 3934,··· (p) ω γ 87.6, 58 E 13.5	**Mn49** 5/− 0.38 s β^+ 6.69,··· γ 272,··· E 7.71	5+ **Mn50** 0+ 1.74 m: β^+ 3.2,··· ε γ 1098.0, 783.3, 1443.3,··· E 7.8572 283.2 ms: β^+ 6.610 γ 3268 vω E 7.6327
24	**Cr** 51.9961 chromium σ_a 3.1, 1.6	**Cr42** 13 ms β^+ (p) E 14.2	**Cr43** (3/+) 21.1 ms β^+ (p) 1.77, 2.13, 4.56,··· γ 1554.6, 838.4 (2p) E 15.9	**Cr44** 43 ms β^+ γ 676.9 (p) 0.89, 1.35,1.70,··· E 10.7	**Cr45** 61 ms β^+ γ 1322.7 (p) 2.04,··· γ 1083.3, 1370.0 E 13	**Cr46** 0.3 s β^+ γ 993.1 E 7.60	**Cr47** 3/− 0.50 s β^+ γ 87.5 E 7.44	**Cr48** 21.6 h ε β^+ γ 308.3, 112.4,··· E 1.66	**Cr49** 5/− 42.3 m β^+ 1.39, 1.45,··· ε γ 90.6, 152.9, 62.3,··· E 2.626
23	**V** 50.9415 vanadium σ_a 5.0, 2.8			**V43** 79 ms β^+ E 11.3	(6+) **V44** (2+) 150 ms: β^+ γ 1038.1, 1371.2, 1561.0, ··· 0.11 s: β^+ γ 1083,··· (α) 2.77 E 13.4	**V45** 7/− 0.55 s β^+ γ 40.1 E 7.13	**V46** 0+ 422.3 ms β^+ 6.03 ε ω γ 4317 ω, 1722, 889 E 7.050	**V47** 3/− 32.6 m β^+ 1.89,··· ε γ 1794.0,··· E 2.9303	**V48** 4+ 15.98 d β^+ 0.694,···, ε γ 983.5, 1312.1,··· E 4.012
		18		**20**		**22**		**24**	



Cu75 1.224 s β^- (n) E 8	**Cu76** 0.64 s β^- γ 598.7, 697.7, 1337, 340.9 (n) E 11.2	**Cu77** 0.46 s β^- E 10.1	**Cu78** 0.33 s β^- γ 890.7, 730.4 (n) γ 114.9 E 12.6	**Cu79** 0.19 s β^- (n) E 11	**Cu80** E 15	
Ni74 0.7 s β^- γ 166.1, 694.3,··· E 7.6	**Ni75** 0.34 s β^- E 10.	**Ni76** 0.24 s β^- E 9	**Ni77** 0.13 s β^- E 12	**Ni78** 0.1 s β^- E 10.	0.045	0.13
Co73 41 ms β^- γ 524, 764, 283, 238 E 13	**Co74** 30 ms β^- γ 2024, 739 (n) γ 293 E 16	**Co75** E 14	0.0031	**50** 0.008	0.021	
Fe72 E 11	0.00010	**48** 0.0003	0.0011			
46	2.6E-5					

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Cu55 ~27 ms β^+ (p) E 13.7	**Cu56** (4)+ 93 ms β^+ γ 2700.6, 1224.5, 2506.7,··· (p) ω E 15.3	**Cu57** 3/− 196 ms β^+ 7.7,··· γ 1113,··· E 8.77	**Cu58** 1+ 3.21 s β^+ 7.44,··· ε ω γ 1454.5, 1448.3,··· E 8.566	**Cu59** 3/− 1.36 m β^+ 3.8,··· γ 1301.5, 878.0,··· E 4.798	**Cu60** 2+ 23.7 m β^+ 3.00,··· ε γ 1332.5, 1791.5, 826.3,··· E 6.128	**Cu61** 3/− 3.35 h β^+ 1.21,···, ε γ 283.0, 656.0,··· E 2.237	**Cu62** 1+ 9.74 m β^+ 2.93,··· ε γ 1173.0 ω, 875.7,··· E 3.948	**Cu63** 3/− 69.15 σ_γ 4.5, 5.0 62.929597	**Cu64** 1+ 12.701 h ε, β^- 0.578 β^+ 0.651 γ 1345.8 ω σ_γ 270 E^- 0.579 E^+ 1.6750	**Cu65** 3/− 30.85 σ_γ 2.17, 2.2 64.927789
Ni54 0.10 s β^+ γ 937.1 ε ω E 8.8	**Ni55** 7/− 202 ms β^+ 7.66 E 8.69	**Ni56** 5.9 d ε γ 158.4, 811.8,··· E 2.14	**Ni57** 3/− 35.6 h ε, β^+ 0.85,··· γ 1377.6,··· E 3.262	**Ni58** 68.0769 σ_γ 4.6, 2.2 σ_α < 0.03 mb 57.935343	**Ni59** 3/− 7.6E4 a ε β^+ ω σ_γ 78, 1.2E2 σ_α 14, 20 σ_p 2, 3 E 1.0728	**Ni60** 26.2231 σ_γ 2.9, 1.5 59.930786	**Ni61** 3/− 1.1399 σ_γ ~2.5, ~1.8 σ_α ≤ 0.03 mb 60.931056	**Ni62** 3.6345 σ_γ 14.5, 6.6 61.928345	**Ni63** 1/− 101 a β^- 0.0669 no γ σ_γ 24 E 0.06698	**Ni64** 0.9256 σ_γ 1.6, 1.2 63.927966
(19/−) **Co53** (7/−) 0.25 s β^+ p 1.55 ε ω 0.24 s β^+ γ 1328.2 ε ω E 8.30	(7)+ **Co54** 0+ 1.46 m β^+ 4.5 γ 1407, 1130, 411 ε ω E 8.440 193.2 ms β^+ 7.220 ε ω γ 1153.1ω E 8.2429	**Co55** 7/− 17.53 h β^+ 1.50, 1.03,··· γ 931.2, 477.2, 1408.4,··· ε E 3.4518	**Co56** 4+ 77.3 d ε, β^+ 1.459,··· γ 846.8, 1238.3,··· E 4.566	**Co57** 7/− 271.8 d ε γ 122.1, 136.5, 14.4,··· σ_γ 52, 20 E 0.836	5+ **Co58** 2+ 9.1 h IT 24.9 e^- σ_γ 1.4E5, 3E5 70.88 d ε, β^+ 0.474, ··· γ 810.8,··· σ_γ 1.9E3, 7E3 E 2.308	**Co59** 7/− 100 σ_γ (21 + 16), (39 + 35) 58.933195	2+ **Co60** 5+ 10.47 m IT 58.6 e^- β^- 1.6 ω,··· γ 1332.5 ω,··· σ_γ 6E1, 2.3E2 5.271 a β^- 0.318, ··· γ 1332.5, 1173.2, ··· σ_γ 2.0, 4 E 2.8231	**Co61** 7/− 1.650 h β^- 1.22,··· γ 67.4,··· E 1.322	5+ **Co62** 2+ 13.9 m β^- 2.9,··· γ 1173.0, 1163.6, ··· E 5.34 1.50 m β^- 4.1, 2.9,··· γ 1173.0, ··· E 5.31	**Co63** 7/− 27.5 s β^- 3.6,··· γ 87.3D,··· E 3.67
(12+) **Fe52** 46 s β^+ 4.4 ε γ 929.5,··· IT 597.1 ω, 465 γ 849.5,··· 8.28 h β^+ 0.80, ε γ 168.7, ··· E 2.37	(19/−) **Fe53** 7/− 2.6 m IT 701.2,··· γ 1328.1, 1011.5, ··· E 6.783 8.51 m β^+ 2.8, 2.4,··· ε γ 377.9,··· E 3.743	**Fe54** 5.845 σ_γ 2.3, 1.4 σ_α 0.01 mb, 1.1 mb 53.939611	**Fe55** 3/− 2.75 a ε γ 126.0 vvω σ_γ 13 σ_α ~9 mb E 0.2312	**Fe56** 91.754 σ_γ 2.6, 1.4 55.934937	**Fe57** 1/− 2.119 σ_γ 2.5, 1.6 56.935394	**Fe58** 0.282 σ_γ 1.3, 1.2 57.933276	**Fe59** 3/− 44.50 d β^- 0.466, 0.274,··· γ 1099.2, 1291.6,··· σ_γ ~13 E 1.565	**Fe60** 1.5E6 a β^- 0.14? γ 58.6D e^- E 0.237	**Fe61** 6.0 m β^- 2.8, 2.6,··· γ 1205.1, 1027.5, 297.9,··· E 3.98	**Fe62** 68 s β^- 2.5? γ 506.1 E 2.53
Mn51 5/− 46.2 m β^+ 2.18,··· ε γ 749.1 (ω), 1148.0, 1164.4,··· E 3.2075	2+ **Mn52** 6+ 21.1 m β^+ 2.63,··· ε γ 1434.1,··· IT 377.7 E 5.089 5.591 d ε, β^+ 0.575 γ 1434.1, 935.5, 744.2,··· E 4.711	**Mn53** 7/− 3.7E6 a ε no γ σ_γ 7E1, 3E1 E 0.5968	**Mn54** 3+ 312.1 d ε γ 834.8 β^- vω ? β^+ vvω σ_γ < 10 E^+ 1.377 E^- 0.697	**Mn55** 5/− 100 σ_γ 13.3, 14.0 54.938045	**Mn56** 3+ 2.578 h β^- 2.84, 1.04,··· γ 846.8, 1810.8, 2113.1,··· E 3.6956	**Mn57** 5/− 1.45 m β^- 2.55,··· γ 122.1, 14.4, 692.0,··· E 2.693	(4)+ **Mn58** 1+ 65 s β^- 3.8,··· γ 810.8, 1323.1, 459.2, ··· IT 71.78 3.0 s β^- 6.1,··· γ 1446.5, 2433.1, ··· E 6.25	**Mn59** 5/− 4.6 s β^- 4.4, 4.7,··· γ 726.1, 472.6, 570.5,··· E 5.18	4+ **Mn60** 1+ 1.77 s β^- 5.7,··· γ 824,··· IT 272 0.28 s β^- γ 823.4, 1150.2, 1532.4 E 8.2	**Mn61** (5/)− 0.67 s β^- γ 628.6, 206.8,··· E 7.4
Cr50 4.345 σ_γ ~15.5, ~8.0 49.946044	**Cr51** 7/− 27.702 d ε γ 320.1 σ_a < 10 E 0.7526	**Cr52** 83.789 σ_γ 0.8, 0.5 51.940507	**Cr53** 3/− 9.501 σ_γ 18, 9 52.940649	**Cr54** 2.365 σ_γ 0.36, 0.2 53.938880	**Cr55** 3/− 3.497 m β^- 2.49,··· γ 1528.1 ω,··· E 2.6031	**Cr56** 5.9 m β^- 1.5 γ 83.9, 26.6 E 1.628	**Cr57** 3/− 21 s β^- γ 83.4, 850., 1752, 1535,··· E 4.963	**Cr58** 7.0 s β^- γ 683, 126,··· E 4.1	**Cr59** (1/)− 1.0 s β^- γ 1239,··· E 7.6	**Cr60** 0.49 s β^- γ 349, 410, 758 E 6.7
V49 7/− 331 d ε no γ E 0.602	**V50** 6+ 0.250 1.4E17 a ε, γ 1553.8 β^-, γ 783 σ_γ 21, 6E1 σ_p 0.71 mb E^+ 2.205 E^- 1.0379 49.947158	**V51** 7/− 99.750 σ_γ 4.9, 2.7 50.943960	**V52** 3+ 3.76 m β^- 2.47,··· γ 1434.1,··· E 3.976	**V53** 7/− 1.54 m β^- 2.5,··· γ 1006.2,··· E 3.436	**V54** 3+ 49.8 s β^- 3.0,··· γ 834.8, 988.8, 2259.2,··· E 7.04	**V55** 6.5 s β^- 5.4,··· γ 517.7, 880.6,··· E 6.0	**V56** (1+) 217 ms β^- γ 1006.1, 668.4, 824, 1317.9 E 9.2	**V57** 0.35 s β^- γ 267.8, 629.4, 941.7,··· E 8.3	**V58** 0.19 s β^- γ 879.7, 1056.4, 2217,··· E 11.6	**V59** 96 ms β^- γ 207.8, 102.0, 606.0,··· (n) γ 880 E 10.8
26		**28**		**30**		**32**		**34**		**36**

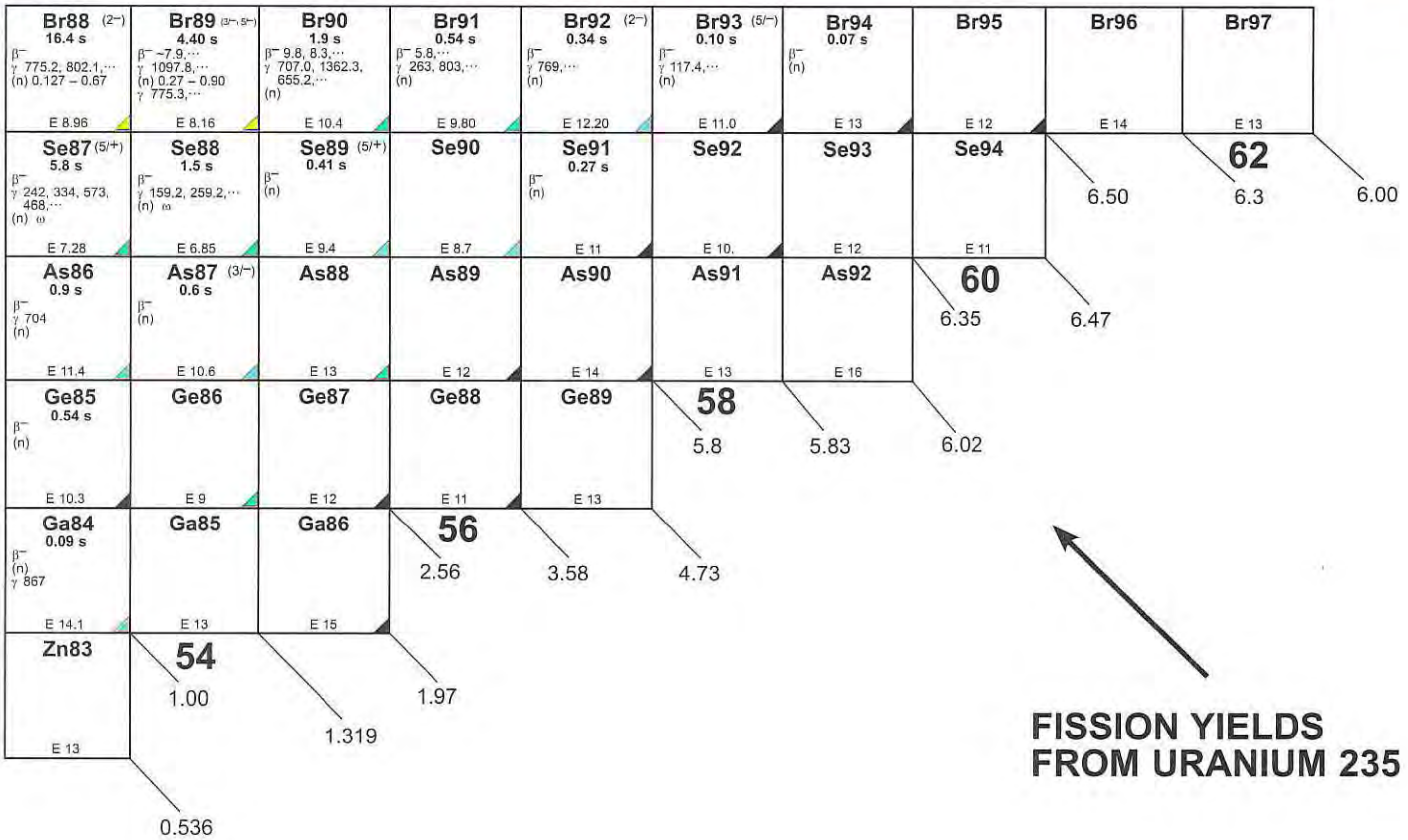
35	9/+ **Br79** 3/− 4.86 s IT 207.2 50.69 σ_γ (2.5 + 8.3), (3E1 + ~95) 78.918337	5− **Br80** 1+ 4.42 h IT 48.8 e^- γ 37.1 17.66 m β^- 2.00,⋯ γ 616.6,⋯ ε, β^+ 0.85 γ 665.9,⋯ E^- 2.003 E^+ 1.8705	**Br81** 3/− 49.31 σ_γ (2.4 + 0.25), ~51 80.916291	2− **Br82** 5− 6.1 m IT 45.9 e^- β^- γ 776.5 ω,⋯ 1.471 d β^- 0.444,⋯ γ 776.5, 554.3, 619.1, ⋯ E 3.093	**Br83** 3/− 2.40 h β^- 0.93,⋯ γ 9.4D (e^-), 32.2D (e^-), 529.6,⋯ E 0.973	(6−) **Br84** 2− 6.0 m β^- 2.2,⋯ γ 1463.7, 424, 881.7, ⋯ E 5.0 31.8 m β^- 4.65, 3.8, 2.7,⋯ γ 881.7, 1897.7, ⋯ E 4.63	**Br85** 3/− 2.87 m β^- 2.57,⋯ γ 304.9D, 802.4, 924.6,⋯ E 2.87	**Br86** (2−) 55.5 s β^- 3.3, 7.4,⋯ γ 1564.5, 2750.8,⋯ E 7.63	**Br87** (5/−) 55.9 s β^- 2.6, 6.7,⋯ γ 1419.8, 1476.2,⋯ (n) 0.018 (ω), 0.052, 0.248,⋯ E 6.85
34	**Se78** 23.77 σ_γ (0.4 + ?), (3.6 + ?) 77.917309	1/− **Se79** 7/+ 3.92 m IT 95.7 e^- β^- ω 3.5E5 a β^- 0.16 no γ E 0.151	**Se80** 49.61 σ_γ (0.057 + 0.19), (0.54 + 0.87) 79.916521	7/+ **Se81** 1/− 57.3 m IT 103.0 β^- ω γ 260.ω, 276,⋯ 18.5 m β^- 1.58, ⋯ γ 276.0, 290.1,⋯ E 1.585	**Se82** 8.73 9E19 a $\beta^-\beta^-$ σ_γ (0.039 + 0.0052) 81.916699	1/− **Se83** 9/+ 1.17 m β^- 2.88, 1.8, 3.92,⋯ γ 1030.6, 356.7, 988.0, 673.9,⋯ E 3.90 22.3 m β^- 1.0, 1.8,⋯ γ 356.7, 510.0, 225.2,⋯ E 3.67	**Se84** 3.2 m β^- 1.41,⋯ γ 408.2,⋯ E 1.85	**Se85** (5/+) 32 s β^- 5.9,⋯ γ 345.1,⋯ E 6.18	**Se86** 15 s β^- 2.6, 2.5,⋯ γ 2441.1, 2660.0,⋯ E 5.10
33	**As77** 3/− 38.8 h β^- 0.68,⋯ γ 239.0,⋯ E 0.683	**As78** (2−) 1.512 h β^- 4.3, 3.7, 1.7, 3.0,⋯ γ 613.7, 694.9, 1308.7,⋯ E 4.21	**As79** 3/− 9.0 m β^- 2.3,⋯ γ 95.7D e^-,⋯ E 2.28	**As80** 1+ 16 s β^- 5.4, 4.7,⋯ γ 665.9,⋯ E 5.60	**As81** 3/− 33 s β^- 3.8,⋯ γ 467.7, 491.0,⋯ E 3.86	(5−) **As82** (2−) 13.7 s β^- 3.6,⋯ γ 654.4, 343.5, 1895.4, ⋯ 19 s β^- 7.2,⋯ γ 654.4, ⋯ E 7.3	**As83** (5/−) 13.4 s β^- 3.4,⋯ γ 734.6, 1113.1, 2076.7,⋯ E 5.5	**As84** (3−) 4.0 s β^- 5.7,⋯ γ 1455.0, 667.0,⋯ (n) ω E 9.9	**As85** (3/−) 2.03 s β^- γ 1112,⋯ (n) 0.495, 0.516,⋯ E 9.1
32	**Ge76** 7.83 1.3E21 a $\beta^-\beta^-$ σ_γ (0.09 + 0.06), (1.3 + 0.6) 75.921403	1/− **Ge77** 7/+ 53 s β^- 2.9,⋯ γ 215.5, ⋯ IT 159.7 11.22 h β^- 2.20, 1.38,⋯ γ 264.4, 211.0, 215.5,⋯ E 2.703	**Ge78** 1.45 h β^- 0.70,⋯ γ 277,⋯ E 0.96	(7/+) **Ge79** (1/−) 39 s β^- 4.1,⋯ γ 230.5, 542,⋯ IT 186.0 19.0 s β^- 2.6,⋯ γ 109.6, 1505.8, ⋯ E 4.1	**Ge80** 29.5 s β^- 2.37,⋯ γ 265.3,⋯ E 2.64	(1/+) **Ge81** (9/+) ~7.6 s β^- 3.75,⋯ γ 336.0, ⋯ E 6.9 ~7.6 s β^- 3.61, ⋯ γ 336.0, 792.9, ⋯ E 6.2	**Ge82** 4.6 s β^- 3.6,⋯ γ 1091.9,⋯ E 4.7	**Ge83** (5/+) 1.9 s β^- γ 306.5,⋯ E 9.0	**Ge84** 0.96 s β^- γ 242.4, 100.9 (n) E 7.8
31	**Ga75** (3/)− 2.10 m β^- 3.2,⋯ γ 252.9, 574.7,⋯ E 3.392	**Ga76** 29 s β^- ~6.0,⋯ γ 562.9, 545.5, 1108.4,⋯ E 6.916	**Ga77** (3/−) 13.0 s β^- 5.2,⋯ γ 470., 459,⋯ E 5.222	**Ga78** (3+) 5.09 s β^- 7.5,⋯ γ 619.5, 1186.6, 567.2, 1025.3,⋯ E 8.156	**Ga79** (3/−) 2.85 s β^- 6.6, 4.7, 4.8,⋯ γ 464.7, 516.4, 1187.2,⋯ (n) ω E 6.98	**Ga80** (3) 1.70 s β^- 10.,⋯ γ 659.1, 1083.4, 1109.3,⋯ (n) ω E 10.4	**Ga81** (5/−) 1.22 s β^- 5.1,⋯ γ 216.5, 828.3, 711.2,⋯ (n) 0.33,⋯ γ 659.1 E 8.3	**Ga82** 599 ms β^- γ 1348.1, 2215.0,⋯ (n) γ 711.0,⋯ E 12.5	**Ga83** 0.31 s β^- γ 867, 1238.2 (n) γ 1348 E 11.5
30	**Zn74** 1.60 m β^- 2.1,⋯ γ 57.1, 49.4, 144, 192.5,⋯ E 2.34	**Zn75** (7/+) 10.2 s β^- γ 228.7, 432.3, 155.9,⋯ E 6.0	**Zn76** 5.7 s β^- 3.7,⋯ γ 199, 76,⋯ E 4.2	(1/−) **Zn77** (7/+) 1.0 s IT 772.4 β^- 2.1 s β^- 4.8,⋯ γ 189.5, 473.9, ⋯ E 7.3	**Zn78** 1.5 s β^- 5.1,⋯ γ 224.8, 181.7, 860.3,⋯ E 6.4	**Zn79** (9/+) 1.0 s β^- γ 702.1, 866,⋯ (n) E 9.1	**Zn80** 0.54 s β^- γ 712.5, 715.4,⋯ (n) E 7.3	**Zn81** 0.32 s β^- γ 351.1, 451.7, 1621.6 (n) E 11.9	**Zn82** E 11
29	**Cu73** 4.2 s β^- γ 449.7,⋯ E 6.42	**Cu74** 1.7 s β^- γ 605.8,⋯ (n) E 9.70	**Cu75** 1.224 s β^- (n) E 8	**Cu76** 0.64 s β^- γ 598.7, 697.7, 1337, 340.9 (n) E 11.2	**Cu77** 0.46 s β^- E 10.1	**Cu78** 0.33 s β^- γ 890.7, 730.4 (n) γ 114.9 E 12.6	**Cu79** 0.19 s β^- (n) E 11	**Cu80** E 15	**52**
	44		**46**		**48**		**50**		

0.20

0.32

0.13

35									**Br** 79.904 bromine σ_a 6.8, ~89		
34							**Se** 78.96 selenium σ_a 11.7, 14	**Se64**	**Se65** β^+ (p) E 14	**Se66** 0.3 s β^+ E 10.	**Se67** (5/−) 0.13 s β^+ γ 352 (p) ω E 10.2
33							**As** 74.92160 arsenic σ_a 4.2, 61		**As64** ~18 ms β^+ E 14.8	**As65** 0.13 s β^+ E 9.4	**As66** (0+) 95.8 ms β^+ E 10.
32					**Ge** 72.64 germanium σ_a 2.2, 6	**Ge60** β^+ (p) E 12.2	**Ge61** (3/−) 44 ms β^+ (p) 3.1 E 13.4	**Ge62** 0.13 s β^+ E 9.8	**Ge63** 0.14 s β^+ E 9.6	**Ge64** 1.06 m β^+ 3.0,⋯ ε γ 427.0, 667.1, 128.2,⋯ E 4.48	**Ge65** (3/−) 31 s β^+ ε γ 649.7, 62.0, 809.1,⋯ (p) 1.28 (ω), 1.16,⋯ E 6.2
31					**Ga** 69.723 gallium σ_a 2.9, 21		**Ga60** 0.07 s β^+ γ 1003.7, 3348,⋯ (p) 1.5 – 5.5 E 14.2	**Ga61** 3/− 168 ms β^+ 8.23,⋯ γ 88, 123, 418,⋯ E 9.26	**Ga62** 0+ 116.12 ms β^+ 8.3 ε ω γ 953.7 ω,⋯ E 9.17	**Ga63** (3/−) 32 s β^+ 4.5,⋯ ε ω γ 636.9, 626.9,⋯ E 5.666	**Ga64** 0+ 2.63 m β^+ 2.8, 6.14,⋯ ε γ 991.5, 807.9, 3365.9,⋯ E 7.169
30	**Zn** 65.409 zinc σ_a 1.1, 2.8	**Zn54** 3 ms 2p 53.9930	**Zn55** 20. ms β^+ (p) 4.60 54.9840	**Zn56** 30. ms β^+ (p) 2.88, 2.08, 1.15 E 12.9	**Zn57** (7/−) 45 ms β^+ (p) 1.87, 2.50, 3.04, 4.53 γ 2701 E 14.5	**Zn58** 0.08 s β^+ γ 203, 848 E 9.4	**Zn59** 3/− 183 ms β^+ 8.1,⋯ ε γ 491.4, 914.2 (p) 1.78 ω, 2.09, 1.82, 1.38,⋯ E 9.10	**Zn60** 2.40 m β^+ 2.5, 3.1,⋯ ε γ 670., 61,⋯ E 4.16	**Zn61** 3/− 1.485 m β^+ 4.4,⋯ ε γ 474.9, 1660.3,⋯ E 5.64	**Zn62** 9.22 h ε β^+ 0.66,⋯ γ 596.7, 40.8, 548.4, 507.6,⋯ E 1.63	**Zn63** 3/− 38.5 m β^+ 2.32,⋯ ε γ 669.7, 962.1,⋯ E 3.367
29	**Cu** 63.546 copper σ_a 3.8, 4.1			**Cu55** ~27 ms β^+ (p) E 13.7	**Cu56** (4)+ 93 ms β^+ γ 2700.6, 1224.5, 2506.7,⋯ (p) ω E 15.3	**Cu57** 3/− 196 ms β^+ 7.7,⋯ γ 1113,⋯ E 8.77	**Cu58** 1+ 3.21 s β^+ 7.44,⋯ ε ω γ 1454.5, 1448.3,⋯ E 8.566	**Cu59** 3/− 1.36 m β^+ 3.8,⋯ γ 1301.5, 878.0,⋯ E 4.798	**Cu60** 2+ 23.7 m β^+ 3.00,⋯ ε γ 1332.5, 1791.5, 826.3,⋯ E 6.128	**Cu61** 3/− 3.35 h β^+ 1.21,⋯, ε γ 283.0, 656.0,⋯ E 2.237	**Cu62** 1+ 9.74 m β^+ 2.93,⋯ ε γ 1173.0 ω, 875.7,⋯ E 3.948
		24		**26**		**28**		**30**		**32**	



Br88 (2−) 16.4 s β^- γ 775.2, 802.1,⋯ (n) 0.127 – 0.67 E 8.96	**Br89** (3/−, 5/−) 4.40 s β^- ~7.9,⋯ γ 1097.8,⋯ (n) 0.27 – 0.90 γ 775.3,⋯ E 8.16	**Br90** 1.9 s β^- 9.8, 8.3,⋯ γ 707.0, 1362.3, 655.2,⋯ (n) E 10.4	**Br91** 0.54 s β^- 5.8,⋯ γ 263, 803,⋯ (n) E 9.80	**Br92** (2−) 0.34 s β^- γ 769,⋯ (n) E 12.20	**Br93** (5/−) 0.10 s β^- γ 117.4,⋯ (n) E 11.0	**Br94** 0.07 s β^- (n) E 13	**Br95** E 12	**Br96** E 14	**Br97** E 13
Se87 (5/+) 5.8 s β^- γ 242, 334, 573, 468,⋯ (n) ω E 7.28	**Se88** 1.5 s β^- γ 159.2, 259.2,⋯ (n) ω E 6.85	**Se89** (5/+) 0.41 s β^- (n) E 9.4	**Se90** E 8.7	**Se91** 0.27 s β^- (n) E 11	**Se92** E 10.	**Se93** E 12	**Se94** E 11		
As86 0.9 s β^- γ 704 (n) E 11.4	**As87** (3/−) 0.6 s β^- (n) E 10.6	**As88** E 13	**As89** E 12	**As90** E 14	**As91** E 13	**As92** E 16			
Ge85 0.54 s β^- (n) E 10.3	**Ge86** E 9	**Ge87** E 12	**Ge88** E 11	**Ge89** E 13					
Ga84 0.09 s β^- (n) γ 867 E 14.1	**Ga85** E 13	**Ga86** E 15							
Zn83 E 13									

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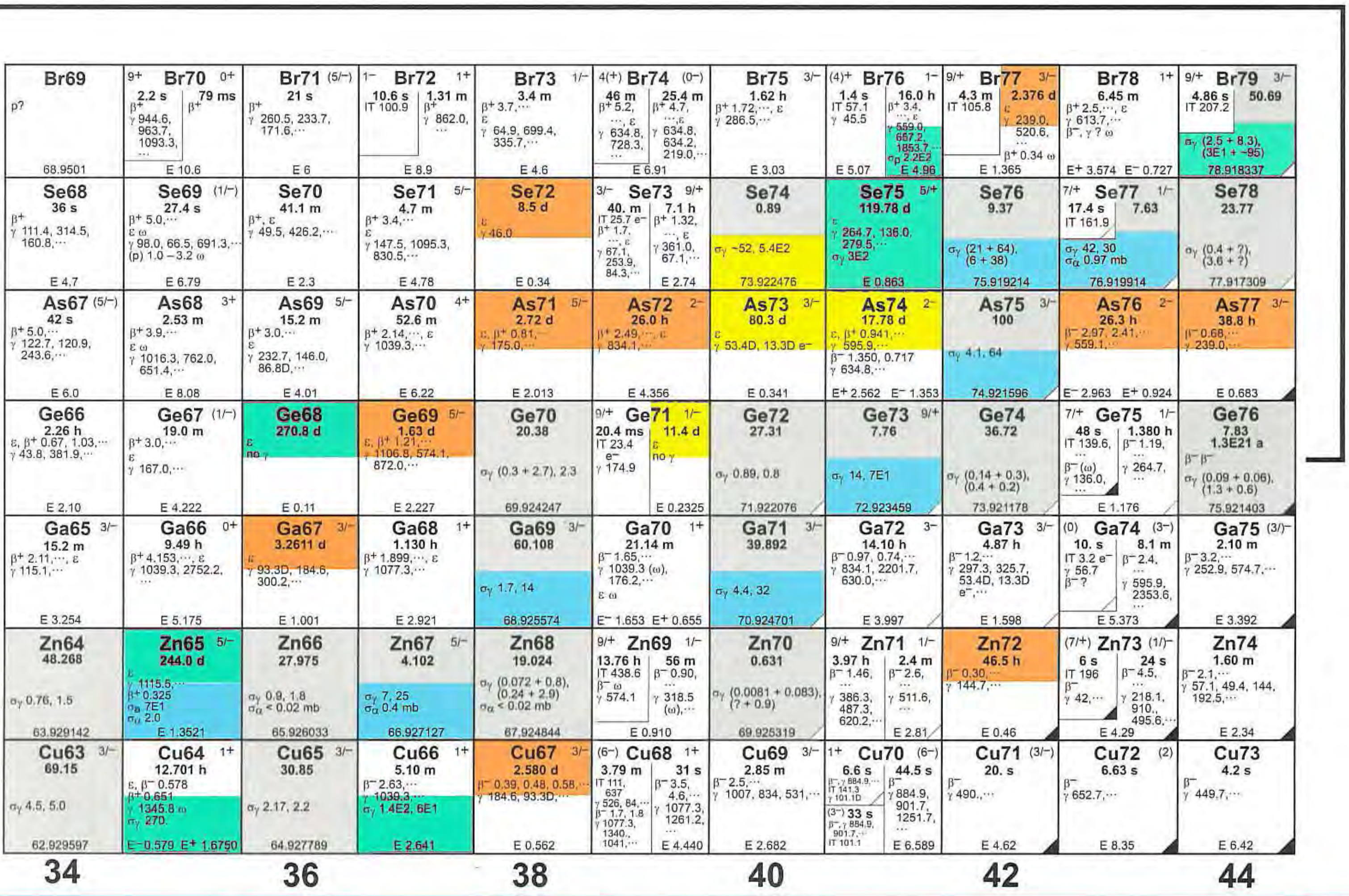
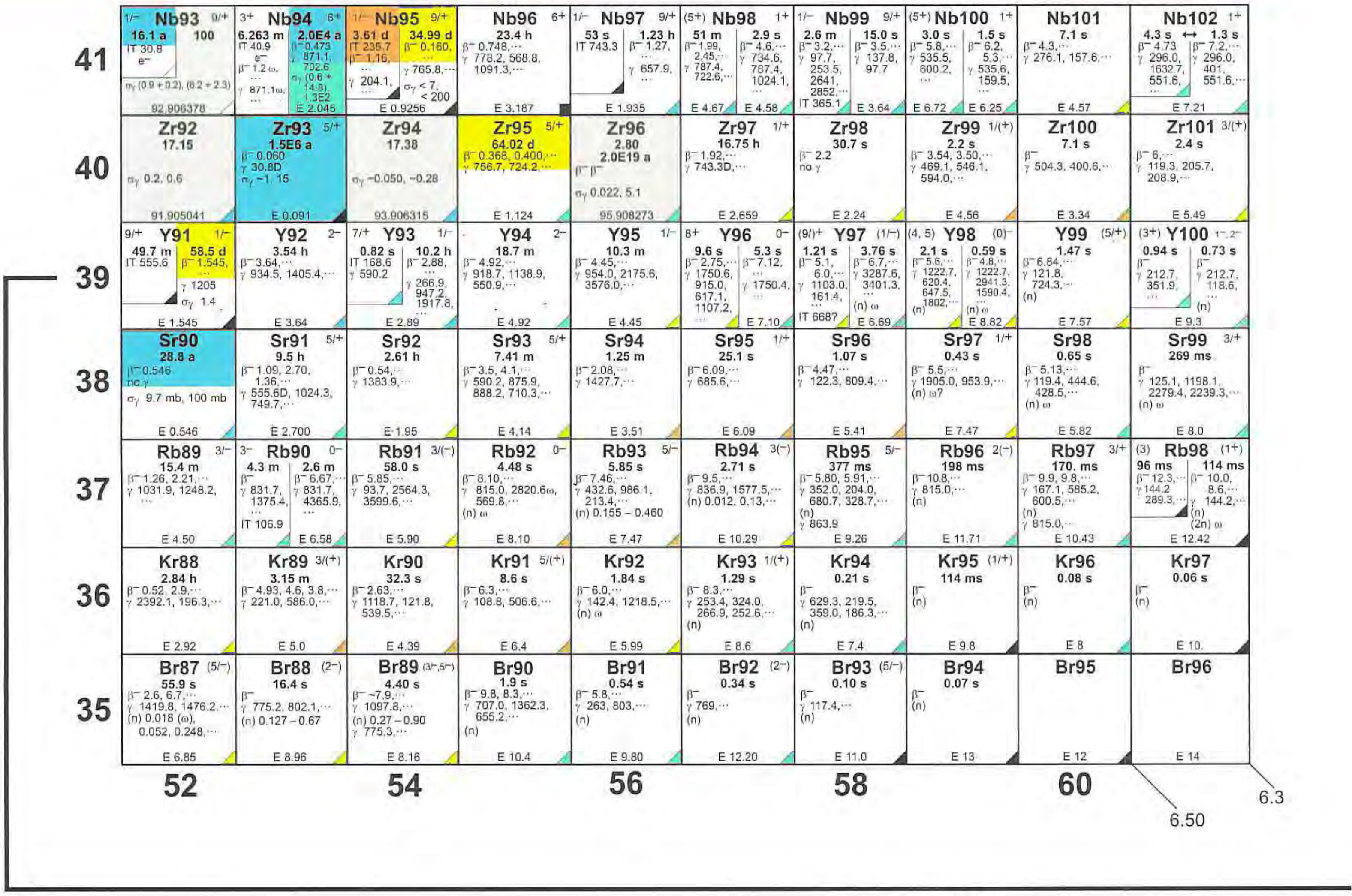
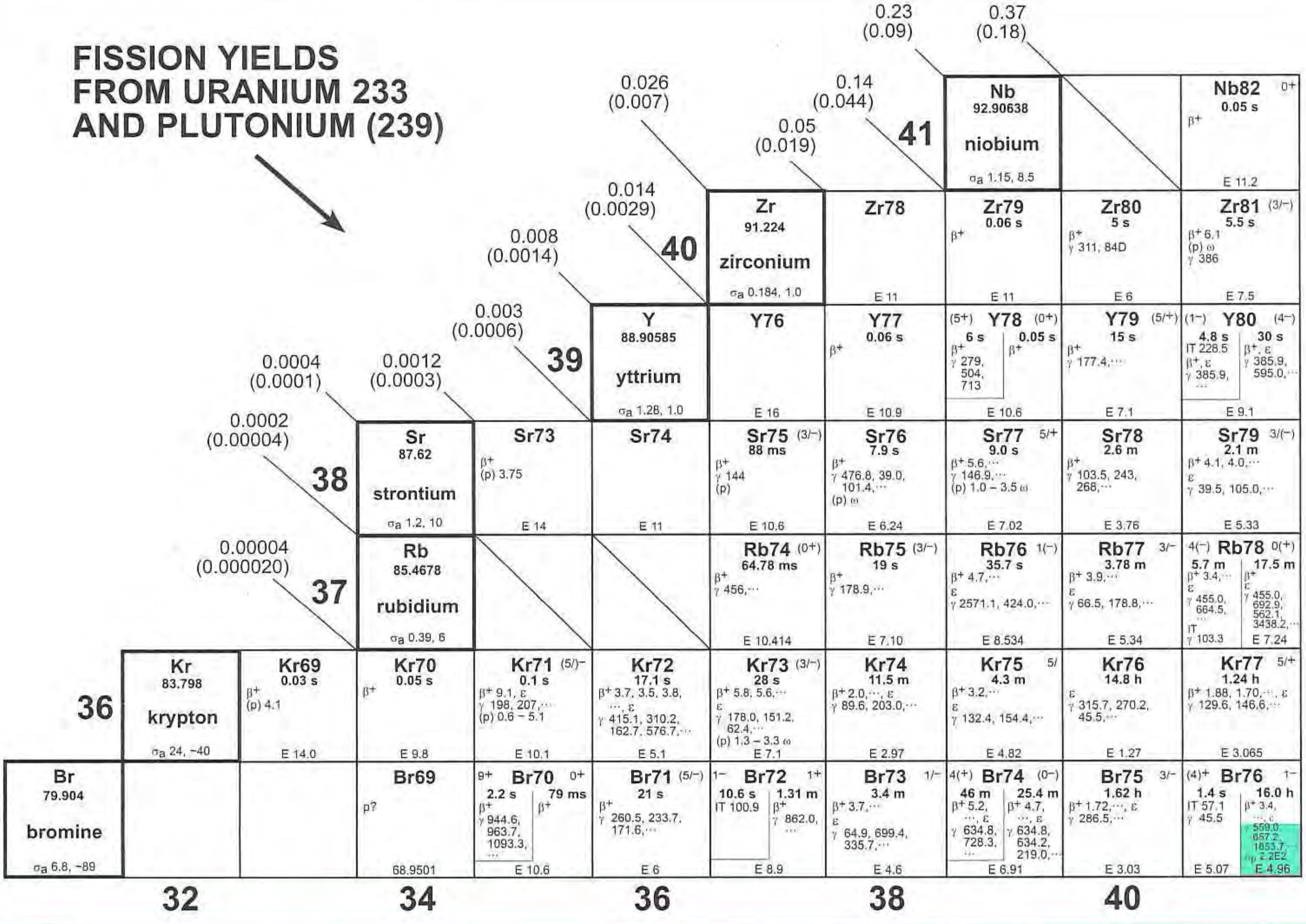


Br69 p? 68.9501	9+ **Br70** 0+ 2.2 s | 79 ms β^+ | β^+ γ 944.6, 963.7, 1093.3, ⋯ E 10.6	**Br71** (5/−) 21 s β^+ γ 260.5, 233.7, 171.6,⋯ E 6	1− **Br72** 1+ 10.6 s | 1.31 m IT 100.9 | β^+ γ 862.0, ⋯ E 8.9	**Br73** 1/− 3.4 m β^+ 3.7,⋯ ε γ 64.9, 699.4, 335.7,⋯ E 4.6	4(+) **Br74** (0−) 46 m | 25.4 m β^+ 5.2, ⋯, ε γ 634.8, 728.3, ⋯ | β^+ 4.7, ⋯, ε γ 634.8, 634.2, 219.0,⋯ E 6.91	**Br75** 3/− 1.62 h β^+ 1.72,⋯, ε γ 286.5,⋯ E 3.03	(4)+ **Br76** 1− 1.4 s | 16.0 h IT 57.1 γ 45.5 | β^+ 3.4, ⋯, ε γ 559.0, 657.2, 1853.7,⋯ σ_p 2.2E2 E 5.07 | E 4.96	9/+ **Br77** 3/− 4.3 m | 2.376 d IT 105.8 | ε γ 239.0, 520.6, ⋯ β^+ 0.34 ω E 1.365	**Br78** 1+ 6.45 m β^+ 2.5,⋯, ε γ 613.7,⋯ β^-, γ ? ω E+ 3.574 E− 0.727	9/+ **Br79** 3/− 4.86 s | 50.69 IT 207.2 σ_γ (2.5 + 8.3), (3E1 + ~95) 78.918337
Se68 36 s β^+ γ 111.4, 314.5, 160.8,⋯ E 4.7	**Se69** (1/−) 27.4 s β^+ 5.0,⋯ ε ω γ 98.0, 66.5, 691.3,⋯ (p) 1.0 – 3.2 ω E 6.79	**Se70** 41.1 m β^+, ε γ 49.5, 426.2,⋯ E 2.3	**Se71** 5/− 4.7 m β^+ 3.4,⋯ ε γ 147.5, 1095.3, 830.5,⋯ E 4.78	**Se72** 8.5 d ε γ 46.0 E 0.34	3/− **Se73** 9/+ 40. m | 7.1 h IT 25.7 e− β^+ 1.7, ⋯, ε γ 67.1, 253.9, 84.3,⋯ | β^+ 1.32, ⋯, ε γ 361.0, 67.1,⋯ E 2.74	**Se74** 0.89 σ_γ ~52, 5.4E2 73.922476	**Se75** 5/+ 119.78 d ε γ 264.7, 136.0, 279.5,⋯ σ_γ 3E2 E 0.863	**Se76** 9.37 σ_γ (21 + 64), (6 + 38) 75.919214	7/+ **Se77** 1/− 17.4 s | 7.63 IT 161.9 σ_γ 42, 30 σ_α 0.97 mb 76.919914	**Se78** 23.77 σ_γ (0.4 + ?), (3.6 + ?) 77.917309
As67 (5/−) 42 s β^+ 5.0,⋯ γ 122.7, 120.9, 243.6,⋯ E 6.0	**As68** 3+ 2.53 m β^+ 3.9,⋯ ε ω γ 1016.3, 762.0, 651.4,⋯ E 8.08	**As69** 5/− 15.2 m β^+ 3.0,⋯ ε γ 232.7, 146.0, 86.8D,⋯ E 4.01	**As70** 4+ 52.6 m β^+ 2.14,⋯, ε γ 1039.3,⋯ E 6.22	**As71** 5/− 2.72 d ε, β^+ 0.81,⋯ γ 175.0,⋯ E 2.013	**As72** 2− 26.0 h β^+ 2.49,⋯, ε γ 834.1,⋯ E 4.356	**As73** 3/− 80.3 d ε γ 53.4D, 13.3D e− E 0.341	**As74** 2− 17.78 d ε, β^+ 0.941,⋯ γ 595.9,⋯ β^- 1.350, 0.717 γ 634.8,⋯ E+ 2.562 E− 1.353	**As75** 3/− 100 σ_γ 4.1, 64 74.921596	**As76** 2− 26.3 h β^- 2.97, 2.41,⋯ γ 559.1,⋯ E− 2.963 E+ 0.924	**As77** 3/− 38.8 h β^- 0.68,⋯ γ 239.0,⋯ E 0.683
Ge66 2.26 h ε, β^+ 0.67, 1.03,⋯ γ 43.8, 381.9,⋯ E 2.10	**Ge67** (1/−) 19.0 m β^+ 3.0,⋯ ε γ 167.0,⋯ E 4.222	**Ge68** 270.8 d ε no γ E 0.11	**Ge69** 5/− 1.63 d ε, β^+ 1.21,⋯ γ 1106.8, 574.1, 872.0,⋯ E 2.227	**Ge70** 20.38 σ_γ (0.3 + 2.7), 2.3 69.924247	9/+ **Ge71** 1/− 20.4 ms | 11.4 d IT 23.4 e− γ 174.9 | ε no γ E 0.2325	**Ge72** 27.31 σ_γ 0.89, 0.8 71.922076	**Ge73** 9/+ 7.76 σ_γ 14, 7E1 72.923459	**Ge74** 36.72 σ_γ (0.14 + 0.3), (0.4 + 0.2) 73.921178	7/+ **Ge75** 1/− 48 s | 1.380 h IT 139.6, ⋯ β^- (ω) γ 136.0, ⋯ | β^- 1.19, ⋯ γ 264.7, ⋯ E 1.176	**Ge76** 7.83 1.3E21 a $\beta^-\beta^-$ σ_γ (0.09 + 0.06), (1.3 + 0.6) 75.921403
Ga65 3/− 15.2 m β^+ 2.11,⋯, ε γ 115.1,⋯ E 3.254	**Ga66** 0+ 9.49 h β^+ 4.153,⋯, ε γ 1039.3, 2752.2, ⋯ E 5.175	**Ga67** 3/− 3.2611 d ε γ 93.3D, 184.6, 300.2,⋯ E 1.001	**Ga68** 1+ 1.130 h β^+ 1.899,⋯, ε γ 1077.3,⋯ E 2.921	**Ga69** 3/− 60.108 σ_γ 1.7, 14 68.925574	**Ga70** 1+ 21.14 m β^- 1.65,⋯ γ 1039.3 (ω), 176.2,⋯ ε ω E− 1.653 E+ 0.655	**Ga71** 3/− 39.892 σ_γ 4.4, 32 70.924701	**Ga72** 3− 14.10 h β^- 0.97, 0.74,⋯ γ 834.1, 2201.7, 630.0,⋯ E 3.997	**Ga73** 3/− 4.87 h β^- 1.2,⋯ γ 297.3, 325.7, 53.4D, 13.3D e−,⋯ E 1.598	(0) **Ga74** (3−) 10. s | 8.1 m IT 3.2 e− γ 56.7 β^- ? | β^- 2.4, ⋯ γ 595.9, 2353.6, ⋯ E 5.373	**Ga75** (3/)− 2.10 m β^- 3.2,⋯ γ 252.9, 574.7,⋯ E 3.392
Zn64 48.268 σ_γ 0.76, 1.5 63.929142	**Zn65** 5/− 244.0 d ε γ 1115.5,⋯ β^+ 0.325 σ_γ 7E1 σ_α 2.0 E 1.3521	**Zn66** 27.975 σ_γ 0.9, 1.8 σ_α < 0.02 mb 65.926033	**Zn67** 5/− 4.102 σ_γ 7, 25 σ_α 0.4 mb 66.927127	**Zn68** 19.024 σ_γ (0.072 + 0.8), (0.24 + 2.9) σ_α < 0.02 mb 67.924844	9/+ **Zn69** 1/− 13.76 h | 56 m IT 438.6 β^- ω γ 574.1 | β^- 0.90, ⋯ γ 318.5 (ω),⋯ E 0.910	**Zn70** 0.631 σ_γ (0.0081 + 0.083), (? + 0.9) 69.925319	9/+ **Zn71** 1/− 3.97 h | 2.4 m β^- 1.46, ⋯ γ 386.3, 487.3, 620.2,⋯ | β^- 2.6, ⋯ γ 511.6, ⋯ E 2.81	**Zn72** 46.5 h β^- 0.30,⋯ γ 144.7,⋯ E 0.46	(7/+) **Zn73** (1/)− 6 s | 24 s IT 196 β^- γ 42,⋯ | β^- 4.5, ⋯ γ 218.1, 910., 495.6,⋯ E 4.29	**Zn74** 1.60 m β^- 2.1,⋯ γ 57.1, 49.4, 144, 192.5,⋯ E 2.34
Cu63 3/− 69.15 σ_γ 4.5, 5.0 62.929597	**Cu64** 1+ 12.701 h ε, β^- 0.578 β^+ 0.651 γ 1345.8 ω σ_γ 270. E− 0.579 E+ 1.6750	**Cu65** 3/− 30.85 σ_γ 2.17, 2.2 64.927789	**Cu66** 1+ 5.10 m β^- 2.63,⋯ γ 1039.3,⋯ σ_γ 1.4E2, 6E1 E 2.641	**Cu67** 3/− 2.580 d β^- 0.39, 0.48, 0.58,⋯ γ 184.6, 93.3D,⋯ E 0.562	(6−) **Cu68** 1+ 3.79 m | 31 s IT 111, 637 γ 526, 84,⋯ β^- 1.7, 1.8 γ 1077.3, 1340., 1041,⋯ | β^- 3.5, 4.6,⋯ γ 1077.3, 1261.2, ⋯ E 4.440	**Cu69** 3/− 2.85 m β^- 2.5,⋯ γ 1007, 834, 531,⋯ E 2.682	1+ **Cu70** (6−) 6.6 s | 44.5 s β^-, γ 884.9,⋯ IT 141.3 γ 101.1D (3−) 33 s β^-, γ 884.9, 901.7,⋯ IT 101.1 | β^- γ 884.9, 901.7, 1251.7, ⋯ E 6.589	**Cu71** (3/−) 20. s β^- γ 490.,⋯ E 4.62	**Cu72** (2) 6.63 s β^- γ 652.7,⋯ E 8.35	**Cu73** 4.2 s β^- γ 449.7,⋯ E 6.42
34		36		38		40		42		44



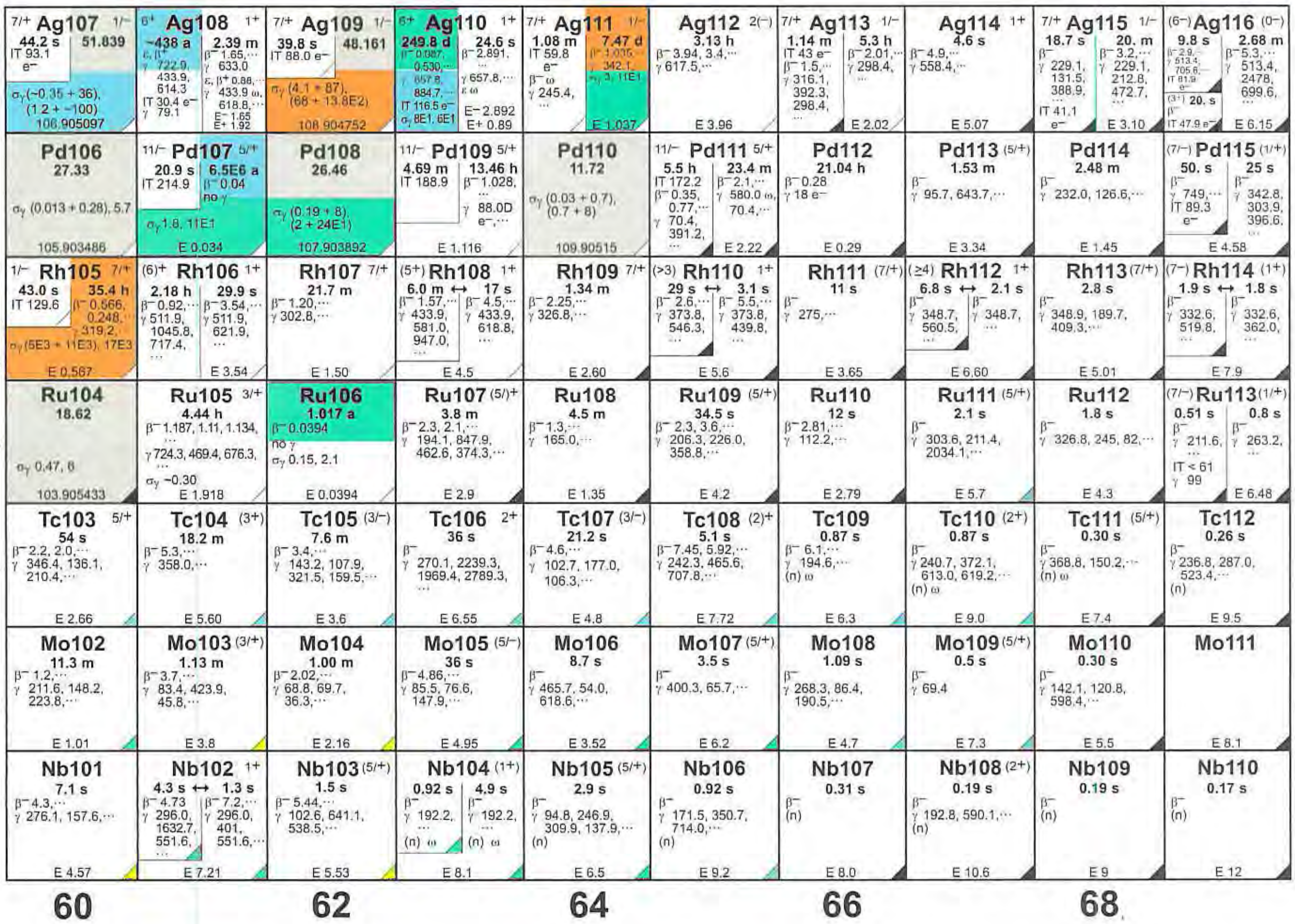
FISSION YIELDS FROM URANIUM 233 AND PLUTONIUM (239)



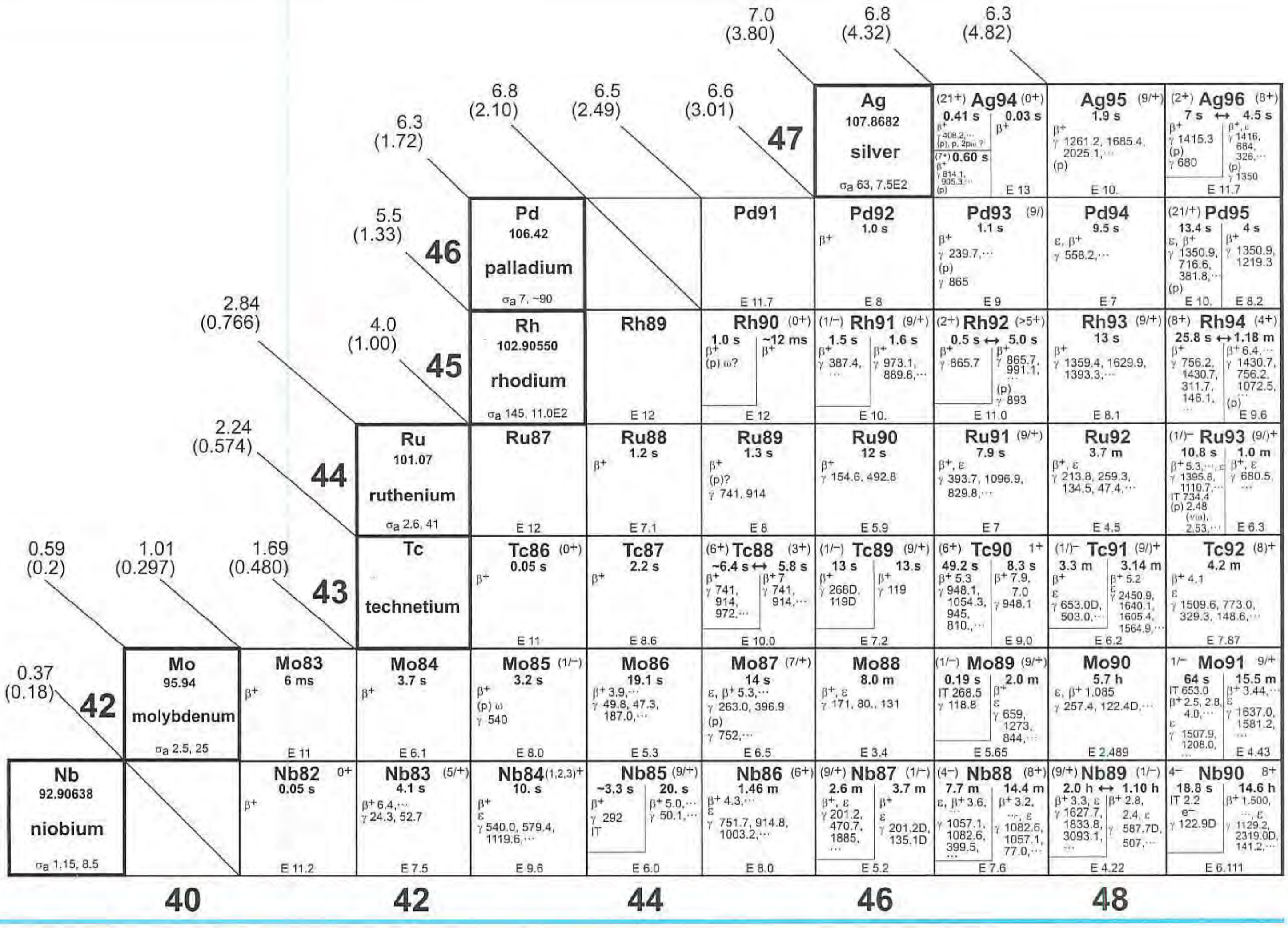
Nb103 (5/+) 1.5 s β^- 5.44,··· γ 102.6, 641.1, 538.5,··· E 5.53	Nb104 (1+) 0.92 s β^- γ 192.2, ··· (n) ω 4.9 s β^- γ 192.2, ··· (n) ω E 8.1	Nb105 (5/+) 2.9 s β^- γ 94.8, 246.9, 309.9, 137.9,··· (n) E 6.5	Nb106 0.92 s β^- γ 171.5, 350.7, 714.0,··· (n) E 9.2	Nb107 0.31 s β^- (n) E 8.0	Nb108 (2+) 0.19 s β^- γ 192.8, 590.1,··· (n) E 10.6	Nb109 0.19 s β^- (n) E 9	Nb110 0.17 s β^- (n) E 12	Nb111 E 10.	Nb112 E 13	Nb113 E 12	
Zr102 2.9 s β^- γ 599.6, 535.3, 64.5,··· E 4.61	Zr103 (5/−) 1.3 s β^- 6.8,··· γ 247.6, 163.9, 126.3,··· E 6.9	Zr104 1.2 s β^- γ 100.9, 263.7, 250.6,··· E 5.9	Zr105 0.6 s β^- E 8.5	Zr106 E 7	Zr107 E 9.7	Zr108 E 8	Zr109 E 11	Zr110 E 10.	0.0174	72 0.013	0.014
Y101 (5/+) 0.43 s β^- γ 98.3, 133.8,··· (n) E 8.5	Y102 (2, 3) 0.36 s ↔ 0.30 s β^- γ 151.7, 326.6, ··· (n) β^- γ 151.7, 1211.1, ··· (n) E 9.9	Y103 (5/+) 0.22 s β^- γ 258.9, 98.2, 109.1 (n) E 9.4	Y104 0.2 s β^- (n) E 11	Y105 E 11	Y106 E 13	Y107 E 12	0.054	70 0.031	0.025		
Sr100 201 ms β^- γ 963.9, 898.5, 65.6,··· (n) ω E 7.1	Sr101 (5/−) 116 ms β^- γ 128.3, 1124.8,··· (n) E 9.5	Sr102 68 ms β^- γ 243.8, 150.1,··· (n) E 8.8	Sr103 E 11	Sr104 E 11	Sr105 E 13	68 0.402	0.146				
Rb99 (5/+) 54 ms β^- γ 90.8, 125.2,··· (n) γ 144.6, 289.4,··· E 11.3	Rb100 (3+) 53 ms β^- γ 129, 288,··· (n) E 13.5	Rb101 (3/+) 0.03 s β^- 11.6 γ 272.1, 251.6, 111.6, 1092,··· (n) E 11.8	Rb102 0.04 s β^- (n) γ 126.2 E 15	66 3.03	1.88	0.96					
Kr98 0.05 s β^- (n) E 9	Kr99 0.04 s β^- (n) E 11	Kr100 E 10.	5.2	4.30							
Br97 E 13	5.79	64 6.1	6.29								
62 6.00											

FISSION YIELDS FROM URANIUM 235

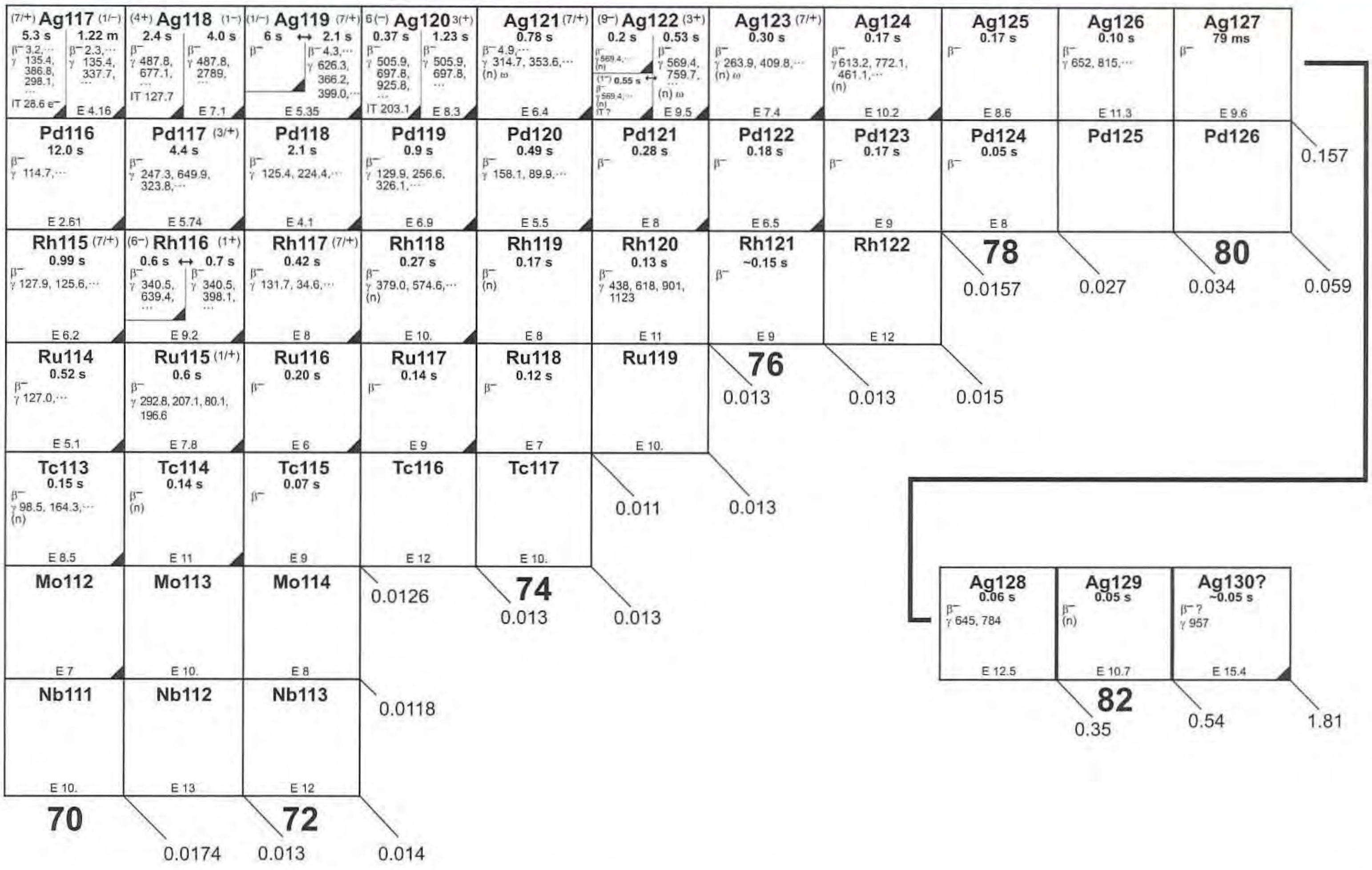
Nb83 (5/+) 4.1 s β^+ 6.4,··· γ 24.3, 52.7 E 7.5	Nb84 (1,2,3)+ 10. s β^+ ε γ 540.0, 579.4, 1119.6,··· E 9.6	Nb85 (9/+) ~3.3 s β^+ γ 292 IT 20. s β^+ 5.0,··· γ 50.1,··· E 6.0	Nb86 (6+) 1.46 m β^+ 4.3,··· ε γ 751.7, 914.8, 1003.2,··· E 8.0	(9/+) Nb87 (1/−) 2.6 m β^+, ε γ 201.2, 470.7, 1885, ··· 3.7 m β^+ ε γ 201.2D, 135.1D E 5.2	(4−) Nb88 (8+) 7.7 m ε, β^+ 3.6, ··· γ 1057.1, 1082.6, 399.5, ··· 14.4 m β^+ 3.2, ···, ε γ 1082.6, 1057.1, 77.0,··· E 7.6	(9/+) Nb89 (1/−) 2.0 h ↔ 1.10 h β^+ 3.3, ε γ 1627.7, 1833.8, 3093.1, ··· β^+ 2.8, 2.4, ε γ 587.7D, 507,··· E 4.22	4− Nb90 8+ 18.8 s IT 2.2 e^- γ 122.9D 14.6 h β^+ 1.500, ···, ε γ 1129.2, 2319.0D, 141.2,··· E 6.111	1/− Nb91 9/+ 62 d IT 104.5 e^- ε γ 1205 β^+ ω 7E2 a ε β^+ ω E 1.258	(2)+ Nb92 (7)+ 10.13 d ε β^+ ω γ 934.5, ··· 3.5E7 a ε γ 561.1, 934.5 E 2.006	1/− Nb93 9/+ 16.1 a IT 30.8 e^- 100 σ_γ (0.9 + 0.2), (6.2 + 2.3) 92.906378
Zr82 32 s β^+ γ 129 – 525 E 4.0	Zr83 (1/−) 44 s β^+ 4.8,···, ε γ 55.6, 105.0, 474.4,··· (p) E 5.9	Zr84 26 m ε, β^+ γ 112.5, 44.9,··· E 2.7	(1/−) Zr85 7/+ 10.9 s IT 292.2 β^+, ε γ 416.5 7.9 m β^+ 3.1, 3.3,··· ε γ 454.3, 416.3,··· E 4.7	Zr86 16.5 h ε γ 242.8, 29.1,··· E 1.48	1/− Zr87 (9/)+ 14.0 s IT 135.1 γ 201.2 1.71 h β^+ 2.26, ···, ε γ 380.8D, 1227, 1211,··· E 3.67	Zr88 83.4 d ε γ 392.9D E 0.68	1/− Zr89 9/+ 4.16 m IT 587.8 ε, β^+ 0.86, 2.4,··· γ 1507.3 3.27 d ε, β^+ 0.90 γ 909.1D, ··· E 2.833	5− Zr90 809 ms IT 2319.0, 132.6 γ 2186.2, ··· 51.45 σ_γ 0.077, 0.2 89.904704	Zr91 5/+ 11.22 σ_γ 1.2, 5.4 90.905646	Zr92 17.15 σ_γ 0.2, 0.6 91.905041
Y81 (5/+) 1.21 m β^+ 4.5,···, ε γ 124.2, 79.2, 408.3,··· E 5.5	Y82 1+ 8.6 s β^+ 6.2, 6.7,··· ε γ 573.4,··· E 7.8	(3/−) Y83 (9/+) 2.85 m β^+ 2.9, ···, ε γ 259.1D, 421.8,··· IT 62.1 e^- E 4.53 7.1 m β^+ 3.3, ···, ε γ 35.5, 882.1, 489.9,··· E 4.47	(5−) Y84 1+ 40. m ↔ 4.6 s β^+ 1.6, 4.7,··· ε γ 793.0, 974.1, 1039.8,··· β^+ ε γ 793.0, ··· E 6.5	9/+ Y85 (1/)− 4.9 h β^+ 2.24, ···, ε γ 231.7D, ··· 2.6 h β^+ 1.6, ···, ε γ 231.7D, 504.4,··· E 3.26	(8+) Y86 4− 48 m IT 10.2 e^- γ 208.1 β^+ ω, ε γ 627.2, 1076.7, 1153.2, 98.6 14.74 h ε, β^+ 1.2,··· γ 1076.7, 627.8, 1153.1, ··· E 5.24	9/+ Y87 1/− 13.37 h IT 380.8 β^+ 1.15, ε 3.35 d ε β^+ 0.8ω,··· γ 484.5, 388.5D E 1.862	Y88 4− 106.63 d ε β^+ 0.76 ω γ 1836.1, 898.0,··· E 3.623	9/+ Y89 1/− 15.7 s IT 909.1 100 σ_γ (1.0 mb + 1.28), (0.006 + 1.0) 88.905848	7+ Y90 2− 3.19 h IT 479.5, 681.8 ω γ 202.5 β^- ω γ 2319.0D 2.669 d β^- 2.281, ··· γ 2186.2 νω σ_γ < 7 E 2.280	9/+ Y91 1/− 49.7 m IT 555.6 58.5 d β^- 1.545, ··· γ 1205 σ_γ 1.4 E 1.545
Sr80 1.77 h ε β^+ γ 589, 175, 553,··· E 1.86	Sr81 1/− 22.3 m β^+ 2.68, 2.4,···, ε γ 153.5, 147.8, 443.3, 188.3,··· E 3.93	Sr82 25.36 d ε no γ E 0.18	1/− Sr83 7/+ 5.0 s IT 259.1 1.350 d ε, β^+ 1.23,··· γ 762.7, 381.5, ··· E 2.28	Sr84 0.56 σ_γ (0.6 + 0.2), 10 83.913425	1/− Sr85 9/+ 1.127 h IT 238.8, 6.9 e^- γ 231.8 ε γ 151.2 64.84 d ε γ 514.0D, ··· E 1.065	Sr86 9.86 σ_γ (0.82 + ?), (4 + ?) 85.909260	1/− Sr87 9/+ 2.805 h IT 388.5 ε ω 7.00 σ_γ 17, 117 86.908877	Sr88 82.58 σ_γ 5.8 mb, 0.06 87.905612	Sr89 5/+ 50.61 d β^- 1.488,··· γ 909.1D ω σ_γ 0.42 E 1.493	Sr90 28.8 a β^- 0.546 no γ σ_γ 9.7 mb, 100 mb E 0.546
Rb79 5/+ 23.2 m β^+ 2.0,···, ε γ 688.2, 182.8, 143.4,··· E 3.64	Rb80 1+ 33 s β^+ 4.1,··· ε γ 616.6,··· E 5.72	9/+ Rb81 3/− 30.5 m IT 86.3 e^- β^+ 1.4, ε γ 49.6 ω 4.57 h ε, β^+ 1.05 γ 190.3D, 446.2, ··· E 2.24	5− Rb82 1+ 6.47 h ε, β^+ 0.80,··· γ 776.5, 554.3, 619.1, ··· 1.260 m β^+ 3.4,··· ε γ 776.5,··· E 4.401	Rb83 5/− 86.2 d ε γ 520.4, 529.6, 552.6,··· E 0.91	6− Rb84 2− 20.3 m IT 463.6, 215.6 γ 248.0 33.2 d ε, β^+ 1.66, 0.78,··· γ 881.6, ··· β^- 0.894 σ_p 12 E^+ 2.681 E^- 0.894	Rb85 5/− 72.17 σ_γ (0.06 + 0.44), 8 84.91178974	6− Rb86 2− 1.018 m IT 556.1 18.65 d β^- 1.775, ··· γ 1076.7 ε ω σ_γ < 20 E^- 1.777 E^+ 0.5186	Rb87 3/− 27.83 4.9E10 a β^- 0.282 no γ σ_γ 0.10, 2.4 E 0.283 86.90918053	Rb88 2− 17.7 m β^- 5.31,··· γ 1836.1, 898.1,··· σ_γ 1.0 E 5.313	Rb89 3/− 15.4 m β^- 1.26, 2.21,··· γ 1031.9, 1248.2,··· E 4.50
Kr78 0.355 σ_γ (0.17 + 6), ~20 77.920365	7/+ Kr79 1/− 53 s IT 129.9 1.455 d ε β^+ 0.60,··· γ 261.3, 397.5, 606.1,··· E 1.626	Kr80 2.286 σ_γ (4.6 + 8), ~60 79.916379	1/− Kr81 7/+ 13.1 s IT 190.4 ε ω 2.3E5 a ε γ 276.0 ω E 0.2808	Kr82 11.593 σ_γ (14 + ~7), 13E1 81.913484	1/− Kr83 9/+ 1.86 h IT 32.2 e^- γ 9.4 e^- 11.500 σ_γ 1.8E2, 1.9E2 82.914136	Kr84 56.987 σ_γ (0.09 + 0.02), 3 83.911507	1/− Kr85 9/+ 4.48 h β^- 0.840 γ 151.2, ··· IT 304.9 10.76 a β^- 0.687, ··· γ 514.0D ω σ_γ 1.7, 2 E 0.687	Kr86 17.279 σ_γ 3 mb 85.9106107	Kr87 5/+ 1.27 h β^- 3.5, 3.9,··· γ 402.6, 2554.8,··· E 3.8884	Kr88 2.84 h β^- 0.52, 2.9,··· γ 2392.1, 196.3,··· E 2.92
9/+ Br77 3/− 4.3 m IT 105.8 2.376 d ε γ 239.0, 520.6, ··· β^+ 0.34 ω E 1.365	Br78 1+ 6.45 m β^+ 2.5,···, ε γ 613.7,··· β^-, γ ? ω E^+ 3.574 E^- 0.727	9/+ Br79 3/− 4.86 s IT 207.2 50.69 σ_γ (2.5 + 8.3), (3E1 + ~95) 78.918337	5− Br80 1+ 4.42 h IT 48.8 e^- γ 37.1 17.66 m β^- 2.00,··· γ 616.6,··· ε, β^+ 0.85 γ 665.9,··· E^- 2.003 E^+ 1.8705	Br81 3/− 49.31 σ_γ (2.4 + 0.25), ~51 80.916291	2− Br82 5− 6.1 m IT 45.9 e^- β^- γ 776.5 ω,··· 1.471 d β^- 0.444,··· γ 776.5, 554.3, 619.1,··· E 3.093	Br83 3/− 2.40 h β^- 0.93,··· γ 9.4D (e^-), 32.2D (e^-), 529.6,··· E 0.973	(6−) Br84 2− 6.0 m β^- 2.2,··· γ 1463.7, 424, 881.7, ··· E 5.0 31.8 m β^- 4.65, 3.8, 2.7,··· γ 881.7, 1897.7,··· E 4.63	Br85 3/− 2.87 m β^- 2.57,··· γ 304.9D, 802.4, 924.6,··· E 2.87	Br86 (2−) 55.5 s β^- 3.3, 7.4,··· γ 1564.5, 2750.8,··· E 7.63	Br87 (5/−) 55.9 s β^- 2.6, 6.7,··· γ 1419.8, 1476.2,··· (n) 0.018 (ω), 0.052, 0.248,··· E 6.85
42		44		46		48		50		52



47	7/+ Ag107 1/− 44.2 s IT 93.1 e^- 51.839 σ_γ(~0.35 + 36), (1.2 + ~100) 106.905097	6+ Ag108 1+ ~438 a ε, β^+ γ 722.9, 433.9, 614.3 IT 30.4 e^- γ 79.1 2.39 m β^- 1.65,⋯ γ 633.0 ε, β^+ 0.88,⋯ γ 433.9 ω, 618.8,⋯ E^- 1.65 E^+ 1.92	7/+ Ag109 1/− 39.8 s IT 88.0 e^- 48.161 σ_γ (4.1 + 87), (68 + 13.8E2) 108.904752	6+ Ag110 1+ 249.8 d β^- 0.087, 0.530,⋯ γ 657.8, 884.7,⋯ IT 116.5 e^- σ_γ 8E1, 6E1 24.6 s β^- 2.891, ⋯ γ 657.8,⋯ ε ω E^- 2.892 E^+ 0.89	7/+ Ag111 1/− 1.08 m IT 59.8 e^- β^- ω γ 245.4, ⋯ 7.47 d β^- 1.035,⋯ γ 342.1, σ_γ 3, 11E1 E 1.037	Ag112 2(−) 3.13 h β^- 3.94, 3.4,⋯ γ 617.5,⋯ E 3.96	7/+ Ag113 1/− 1.14 m IT 43 e^- β^- 1.5,⋯ γ 316.1, 392.3, 298.4, ⋯ 5.3 h β^- 2.01,⋯ γ 298.4, ⋯ E 2.02	Ag114 1+ 4.6 s β^- 4.9,⋯ γ 558.4,⋯ E 5.07	7/+ Ag115 1/− 18.7 s β^- γ 229.1, 131.5, 388.9, ⋯ IT 41.1 e^- 20. m β^- 3.2,⋯ γ 229.1, 212.8, 472.7, ⋯ E 3.10	(6−) Ag116 (0−) 9.8 s β^- 2.9,⋯ γ 513.4, 705.6,⋯ IT 81.9 e^- (3+) 20. s β^- IT 47.9 e^- 2.68 m β^- 5.3,⋯ γ 513.4, 2478, 699.6, ⋯ E 6.15
46	Pd106 27.33 σ_γ (0.013 + 0.28), 5.7 105.903486	11/− Pd107 5/+ 20.9 s IT 214.9 6.5E6 a β^- 0.04 no γ σ_γ 1.8, 11E1 E 0.034	Pd108 26.46 σ_γ (0.19 + 8), (2 + 24E1) 107.903892	11/− Pd109 5/+ 4.69 m IT 188.9 13.46 h β^- 1.028, ⋯ γ 88.0D e^-,⋯ E 1.116	Pd110 11.72 σ_γ (0.03 + 0.7), (0.7 + 8) 109.90515	11/− Pd111 5/+ 5.5 h IT 172.2 β^- 0.35, 0.77,⋯ γ 70.4, 391.2, ⋯ 23.4 m β^- 2.1,⋯ γ 580.0 ω, 70.4,⋯ E 2.22	Pd112 21.04 h β^- 0.28 γ 18 e^- E 0.29	Pd113 (5/+) 1.53 m β^- γ 95.7, 643.7,⋯ E 3.34	Pd114 2.48 m β^- γ 232.0, 126.6,⋯ E 1.45	(7/−) Pd115 (1/+) 50. s β^- γ 749,⋯ IT 89.3 e^- 25 s β^- γ 342.8, 303.9, 396.6, ⋯ E 4.58
45	1/− Rh105 7/+ 43.0 s IT 129.6 35.4 h β^- 0.566, 0.248,⋯ γ 319.2,⋯ σ_γ (5E3 + 11E3), 17E3 E 0.567	(6)+ Rh106 1+ 2.18 h β^- 0.92,⋯ γ 511.9, 1045.8, 717.4, ⋯ 29.9 s β^- 3.54,⋯ γ 511.9, 621.9, ⋯ E 3.54	Rh107 7/+ 21.7 m β^- 1.20,⋯ γ 302.8,⋯ E 1.50	(5+) Rh108 1+ 6.0 m ↔ 17 s β^- 1.57,⋯ γ 433.9, 581.0, 947.0, ⋯ β^- 4.5,⋯ γ 433.9, 618.8, ⋯ E 4.5	Rh109 7/+ 1.34 m β^- 2.25,⋯ γ 326.8,⋯ E 2.60	(>3) Rh110 1+ 29 s ↔ 3.1 s β^- 2.6,⋯ γ 373.8, 546.3, ⋯ β^- 5.5,⋯ γ 373.8, 439.8, ⋯ E 5.6	Rh111 (7/+) 11 s β^- γ 275,⋯ E 3.65	(≥4) Rh112 1+ 6.8 s ↔ 2.1 s β^- γ 348.7, 560.5, ⋯ β^- γ 348.7, ⋯ E 6.60	Rh113 (7/+) 2.8 s β^- γ 348.9, 189.7, 409.3,⋯ E 5.01	(7−) Rh114 (1+) 1.9 s ↔ 1.8 s β^- γ 332.6, 519.8, ⋯ β^- γ 332.6, 362.0, ⋯ E 7.9
44	Ru104 18.62 σ_γ 0.47, 6 103.905433	Ru105 3/+ 4.44 h β^- 1.187, 1.11, 1.134, ⋯ γ 724.3, 469.4, 676.3, ⋯ σ_γ ~0.30 E 1.918	Ru106 1.017 a β^- 0.0394 no γ σ_γ 0.15, 2.1 E 0.0394	Ru107 (5/)+ 3.8 m β^- 2.3, 2.1,⋯ γ 194.1, 847.9, 462.6, 374.3,⋯ E 2.9	Ru108 4.5 m β^- 1.3,⋯ γ 165.0,⋯ E 1.35	Ru109 (5/+) 34.5 s β^- 2.3, 3.6,⋯ γ 206.3, 226.0, 358.8,⋯ E 4.2	Ru110 12 s β^- 2.81,⋯ γ 112.2,⋯ E 2.79	Ru111 (5/+) 2.1 s β^- γ 303.6, 211.4, 2034.1,⋯ E 5.7	Ru112 1.8 s β^- γ 326.8, 245, 82,⋯ E 4.3	(7/−) Ru113 (1/+) 0.51 s β^- γ 211.6, ⋯ IT < 61 γ 99 0.8 s β^- γ 263.2, ⋯ E 6.48
43	Tc103 5/+ 54 s β^- 2.2, 2.0,⋯ γ 346.4, 136.1, 210.4,⋯ E 2.66	Tc104 (3+) 18.2 m β^- 5.3,⋯ γ 358.0,⋯ E 5.60	Tc105 (3/−) 7.6 m β^- 3.4,⋯ γ 143.2, 107.9, 321.5, 159.5,⋯ E 3.6	Tc106 2+ 36 s β^- γ 270.1, 2239.3, 1969.4, 2789.3, ⋯ E 6.55	Tc107 (3/−) 21.2 s β^- 4.6,⋯ γ 102.7, 177.0, 106.3,⋯ E 4.8	Tc108 (2)+ 5.1 s β^- 7.45, 5.92,⋯ γ 242.3, 465.6, 707.8,⋯ E 7.72	Tc109 0.87 s β^- 6.1,⋯ γ 194.6,⋯ (n) ω E 6.3	Tc110 (2+) 0.87 s β^- γ 240.7, 372.1, 613.0, 619.2,⋯ (n) ω E 9.0	Tc111 (5/+) 0.30 s β^- γ 368.8, 150.2,⋯ (n) ω E 7.4	Tc112 0.26 s β^- γ 236.8, 287.0, 523.4,⋯ (n) E 9.5
42	Mo102 11.3 m β^- 1.2,⋯ γ 211.6, 148.2, 223.8,⋯ E 1.01	Mo103 (3/+) 1.13 m β^- 3.7,⋯ γ 83.4, 423.9, 45.8,⋯ E 3.8	Mo104 1.00 m β^- 2.02,⋯ γ 68.8, 69.7, 36.3,⋯ E 2.16	Mo105 (5/−) 36 s β^- 4.86,⋯ γ 85.5, 76.6, 147.9,⋯ E 4.95	Mo106 8.7 s β^- γ 465.7, 54.0, 618.6,⋯ E 3.52	Mo107 (5/+) 3.5 s β^- γ 400.3, 65.7,⋯ E 6.2	Mo108 1.09 s β^- γ 268.3, 86.4, 190.5,⋯ E 4.7	Mo109 (5/+) 0.5 s β^- γ 69.4 E 7.3	Mo110 0.30 s β^- γ 142.1, 120.8, 598.4,⋯ E 5.5	Mo111 E 8.1
41	Nb101 7.1 s β^- 4.3,⋯ γ 276.1, 157.6,⋯ E 4.57	Nb102 1+ 4.3 s ↔ 1.3 s β^- 4.73 γ 296.0, 1632.7, 551.6, ⋯ β^- 7.2,⋯ γ 296.0, 401, 551.6,⋯ E 7.21	Nb103 (5/+) 1.5 s β^- 5.44,⋯ γ 102.6, 641.1, 538.5,⋯ E 5.53	Nb104 (1+) 0.92 s β^- γ 192.2, ⋯ (n) ω 4.9 s β^- γ 192.2, ⋯ (n) ω E 8.1	Nb105 (5/+) 2.9 s β^- γ 94.8, 246.9, 309.9, 137.9,⋯ (n) E 6.5	Nb106 0.92 s β^- γ 171.5, 350.7, 714.0,⋯ (n) E 9.2	Nb107 0.31 s β^- (n) E 8.0	Nb108 (2+) 0.19 s β^- γ 192.8, 590.1,⋯ (n) E 10.6	Nb109 0.19 s β^- (n) E 9	Nb110 0.17 s β^- (n) E 12
	60		62		64		66		68	

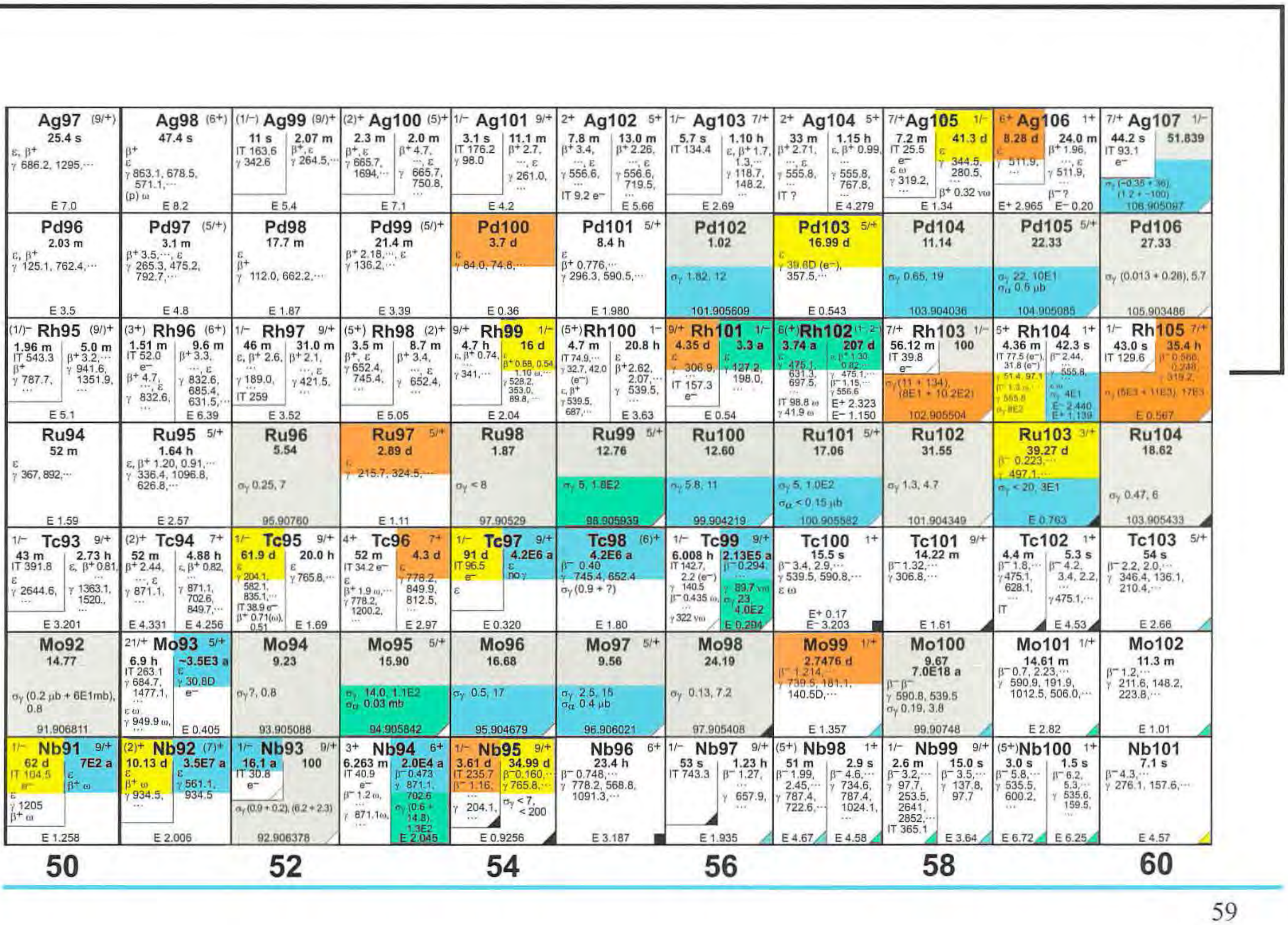


47								Ag 107.8682 silver σ_a 63, 7.5E2	(21+) Ag94 (0+) 0.41 s β^+ γ 408.2,⋯ (p), p, 2p ω ? (7+) 0.60 s β^+ γ 814.1, 905.3,⋯ (p) 0.03 s β^+ E 13	Ag95 (9/+) 1.9 s β^+ γ 1261.2, 1685.4, 2025.1,⋯ (p) E 10.	(2+) Ag96 (8+) 7 s ↔ 4.5 s β^+ γ 1415.3 (p) γ 680 β^+, ε γ 1416, 684, 326,⋯ (p) γ 1350 E 11.7
46					Pd 106.42 palladium σ_a 7, ~90		Pd91 E 11.7	Pd92 1.0 s β^+ E 8	Pd93 (9/) 1.1 s β^+ γ 239.7,⋯ (p) γ 865 E 9	Pd94 9.5 s ε, β^+ γ 558.2,⋯ E 7	(21/+) Pd95 13.4 s ε, β^+ γ 1350.9, 716.6, 381.8,⋯ (p) E 10. 4 s β^+ γ 1350.9, 1219.3 E 8.2
45					Rh 102.90550 rhodium σ_a 145, 11.0E2	Rh89 E 12	Rh90 (0+) 1.0 s β^+ (p) ω? ~12 ms β^+ E 12	(1/−) Rh91 (9/+) 1.5 s β^+ γ 387.4, ⋯ 1.6 s β^+ γ 973.1, 889.8,⋯ E 10.	(2+) Rh92 (>5+) 0.5 s ↔ 5.0 s β^+ γ 865.7 β^+ γ 865.7, 991.1, ⋯ (p) γ 893 E 11.0	Rh93 (9/+) 13 s β^+ γ 1359.4, 1629.9, 1393.3,⋯ E 8.1	(8+) Rh94 (4+) 25.8 s ↔ 1.18 m β^+ γ 756.2, 1430.7, 311.7, 146.1, ⋯ β^+ 6.4,⋯ γ 1430.7, 756.2, 1072.5, ⋯ (p) E 9.6
44				Ru 101.07 ruthenium σ_a 2.6, 41	Ru87 E 12	Ru88 1.2 s β^+ E 7.1	Ru89 1.3 s β^+ (p)? γ 741, 914 E 8	Ru90 12 s β^+ γ 154.6, 492.8 E 5.9	Ru91 (9/+) 7.9 s β^+, ε γ 393.7, 1096.9, 829.8,⋯ E 7	Ru92 3.7 m β^+, ε γ 213.8, 259.3, 134.5, 47.4,⋯ E 4.5	(1/)− Ru93 (9/)+ 10.8 s β^+ 5.3,⋯, ε γ 1395.8, 1110.7,⋯ IT 734.4 (p) 2.48 (γω), 2.53,⋯ 1.0 m β^+, ε γ 680.5, ⋯ E 6.3
43				Tc technetium	Tc86 (0+) 0.05 s β^+ E 11	Tc87 2.2 s β^+ E 8.6	(6+) Tc88 (3+) ~6.4 s ↔ 5.8 s β^+ γ 741, 914, 972,⋯ β^+ 7 γ 741, 914,⋯ E 10.0	(1/−) Tc89 (9/+) 13 s β^+ γ 268D, 119D 13 s β^+ γ 119 E 7.2	(6+) Tc90 1+ 49.2 s β^+ 5.3 γ 948.1, 1054.3, 945, 810.,⋯ 8.3 s β^+ 7.9, 7.0 γ 948.1 E 9.0	(1/)− Tc91 (9/)+ 3.3 m β^+ ε γ 653.0D, 503.0,⋯ 3.14 m β^+ 5.2 ε γ 2450.9, 1640.1, 1605.4, 1564.9,⋯ E 6.2	Tc92 (8)+ 4.2 m β^+ 4.1 ε γ 1509.6, 773.0, 329.3, 148.6,⋯ E 7.87
42		Mo 95.94 molybdenum σ_a 2.5, 25	Mo83 6 ms β^+ E 11	Mo84 3.7 s β^+ E 6.1	Mo85 (1/−) 3.2 s β^+ (p) ω γ 540 E 8.0	Mo86 19.1 s β^+ 3.9,⋯ γ 49.8, 47.3, 187.0,⋯ E 5.3	Mo87 (7/+) 14 s ε, β^+ 5.3,⋯ γ 263.0, 396.9 (p) γ 752,⋯ E 6.5	Mo88 8.0 m β^+, ε γ 171, 80., 131 E 3.4	(1/−) Mo89 (9/+) 0.19 s IT 268.5 γ 118.8 2.0 m β^+ ε γ 659, 1273, 844,⋯ E 5.65	Mo90 5.7 h ε, β^+ 1.085 γ 257.4, 122.4D,⋯ E 2.489	1/− Mo91 9/+ 64 s IT 653.0 β^+ 2.5, 2.8, 4.0,⋯ ε γ 1507.9, 1208.0, ⋯ 15.5 m β^+ 3.44,⋯ ε γ 1637.0, 1581.2, ⋯ E 4.43
41	Nb 92.90638 niobium σ_a 1.15, 8.5		Nb82 0+ 0.05 s β^+ E 11.2	Nb83 (5/+) 4.1 s β^+ 6.4,⋯ γ 24.3, 52.7 E 7.5	Nb84 (1,2,3)+ 10. s β^+ ε γ 540.0, 579.4, 1119.6,⋯ E 9.6	Nb85 (9/+) ~3.3 s β^+ γ 292 IT 20. s β^+ 5.0,⋯ γ 50.1,⋯ E 6.0	Nb86 (6+) 1.46 m β^+ 4.3,⋯ ε γ 751.7, 914.8, 1003.2,⋯ E 8.0	(9/+) Nb87 (1/−) 2.6 m β^+, ε γ 201.2, 470.7, 1885, ⋯ 3.7 m β^+ ε γ 201.2D, 135.1D E 5.2	(4−) Nb88 (8+) 7.7 m ε, β^+ 3.6, ⋯ γ 1057.1, 1082.6, 399.5, ⋯ 14.4 m β^+ 3.2, ⋯, ε γ 1082.6, 1057.1, 77.0,⋯ E 7.6	(9/+) Nb89 (1/−) 2.0 h ↔ 1.10 h β^+ 3.3, ε γ 1627.7, 1833.8, 3093.1, ⋯ β^+ 2.8, 2.4, ε γ 587.7D, 507,⋯ E 4.22	4− Nb90 8+ 18.8 s IT 2.2 e^- γ 122.9D 14.6 h β^+ 1.500, ⋯, ε γ 1129.2, 2319.0D, 141.2,⋯ E 6.111
		40		42		44		46		48	

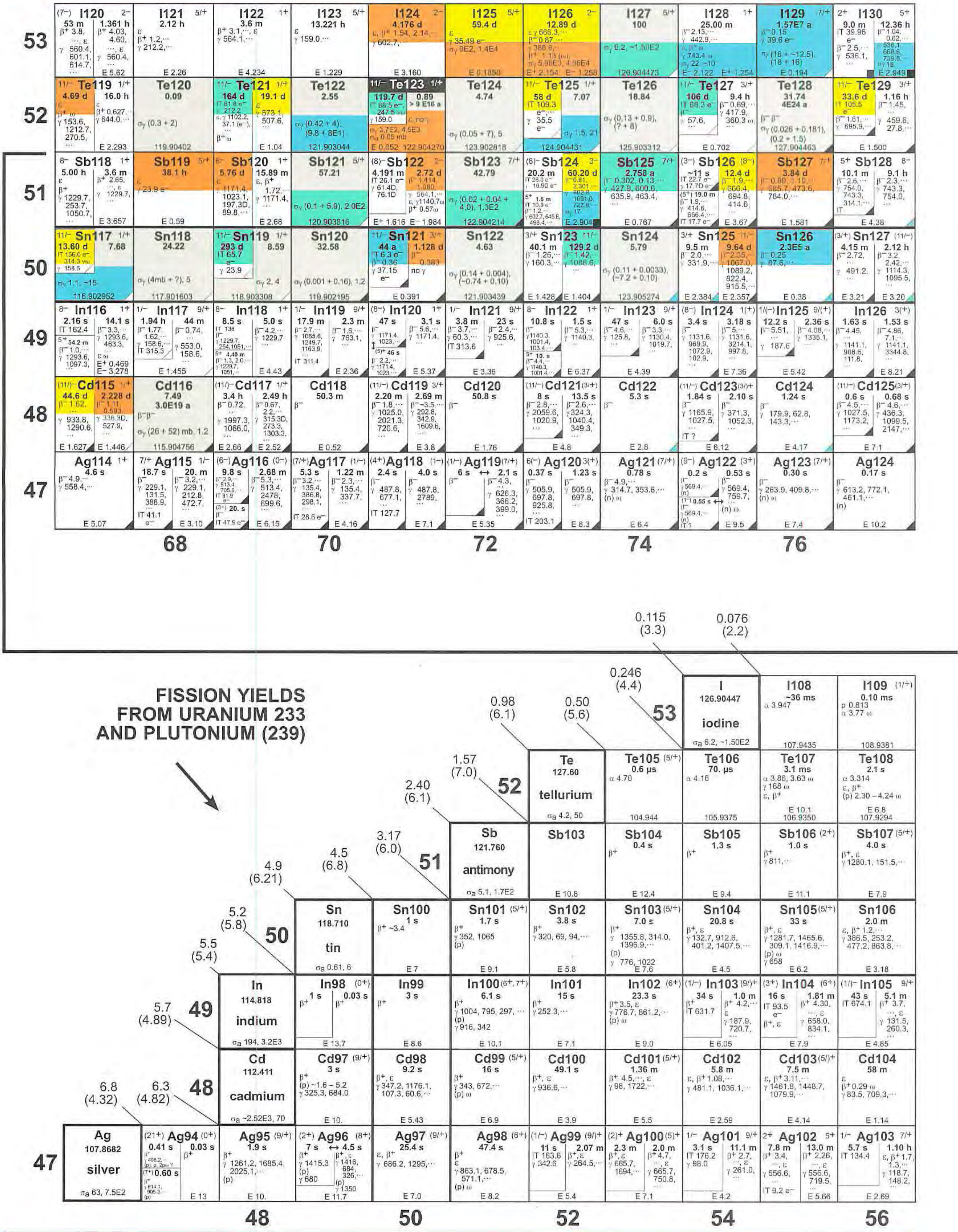


(7/+) **Ag117** (1/−) 5.3 s β^- 3.2, ⋯ γ 135.4, 386.8, 298.1, ⋯ IT 28.6 e^- 1.22 m β^- 2.3, ⋯ γ 135.4, 337.7, ⋯ E 4.16	(4+) **Ag118** (1−) 2.4 s β^- γ 487.8, 677.1, ⋯ IT 127.7 4.0 s β^- γ 487.8, 2789, ⋯ E 7.1	(1/−) **Ag119** (7/+) 6 s ↔ 2.1 s β^- β^- 4.3, ⋯ γ 626.3, 366.2, 399.0, ⋯ E 5.35	6(−) **Ag120** 3(+) 0.37 s β^- γ 505.9, 697.8, 925.8, ⋯ IT 203.1 1.23 s β^- γ 505.9, 697.8, ⋯ E 8.3	**Ag121** (7/+) 0.78 s β^- 4.9, ⋯ γ 314.7, 353.6, ⋯ (n) ω E 6.4	(9−) **Ag122** (3+) 0.2 s β^- γ 569.4, ⋯ (n) (1−) 0.55 s ↔ β^- γ 569.4, ⋯ (n) IT ? 0.53 s β^- γ 569.4, 759.7, ⋯ (n) ω E 9.5	**Ag123** (7/+) 0.30 s β^- γ 263.9, 409.8, ⋯ (n) ω E 7.4	**Ag124** 0.17 s β^- γ 613.2, 772.1, 461.1, ⋯ (n) E 10.2	**Ag125** 0.17 s β^- E 8.6	**Ag126** 0.10 s β^- γ 652.4, 815, ⋯ E 11.3	**Ag127** 79 ms β^- E 9.6	
Pd116 12.0 s β^- γ 114.7, ⋯ E 2.61	**Pd117** (3/+) 4.4 s β^- γ 247.3, 649.9, 323.8, ⋯ E 5.74	**Pd118** 2.1 s β^- γ 125.4, 224.4, ⋯ E 4.1	**Pd119** 0.9 s β^- γ 129.9, 256.6, 326.1, ⋯ E 6.9	**Pd120** 0.49 s β^- γ 158.1, 89.9, ⋯ E 5.5	**Pd121** 0.28 s β^- E 8	**Pd122** 0.18 s β^- E 6.5	**Pd123** 0.17 s β^- E 9	**Pd124** 0.05 s β^- E 8	**Pd125**	**Pd126**	0.157
Rh115 (7/+) 0.99 s β^- γ 127.9, 125.6, ⋯ E 6.2	(6−) **Rh116** (1+) 0.6 s ↔ 0.7 s β^- γ 340.5, 639.4, ⋯ β^- γ 340.5, 398.1, ⋯ E 9.2	**Rh117** (7/+) 0.42 s β^- γ 131.7, 34.6, ⋯ E 8	**Rh118** 0.27 s β^- γ 379.0, 574.6, ⋯ (n) E 10.	**Rh119** 0.17 s β^- (n) E 8	**Rh120** 0.13 s β^- γ 438, 618, 901, 1123 E 11	**Rh121** ~0.15 s β^- E 9	**Rh122** E 12	78 0.0157	0.027	80 0.034	0.059
Ru114 0.52 s β^- γ 127.0, ⋯ E 5.1	**Ru115** (1/+) 0.6 s β^- γ 292.8, 207.1, 80.1, 196.6 E 7.8	**Ru116** 0.20 s β^- E 6	**Ru117** 0.14 s β^- E 9	**Ru118** 0.12 s β^- E 7	**Ru119** E 10.	76 0.013	0.013	0.015			
Tc113 0.15 s β^- γ 98.5, 164.3, ⋯ (n) E 8.5	**Tc114** 0.14 s β^- (n) E 11	**Tc115** 0.07 s β^- E 9	**Tc116** E 12	**Tc117** E 10.	0.011	0.013					
Mo112 E 7	**Mo113** E 10.	**Mo114** E 8	0.0126	74 0.013	0.013						
Nb111 E 10.	**Nb112** E 13	**Nb113** E 12	0.0118								
70	0.0174	72 0.013	0.014								

Ag128 0.06 s β^- γ 645, 784 E 12.5	**Ag129** 0.05 s β^- (n) E 10.7	**Ag130?** ~0.05 s β^- ? γ 957 E 15.4	
	82 0.35	0.54	1.81



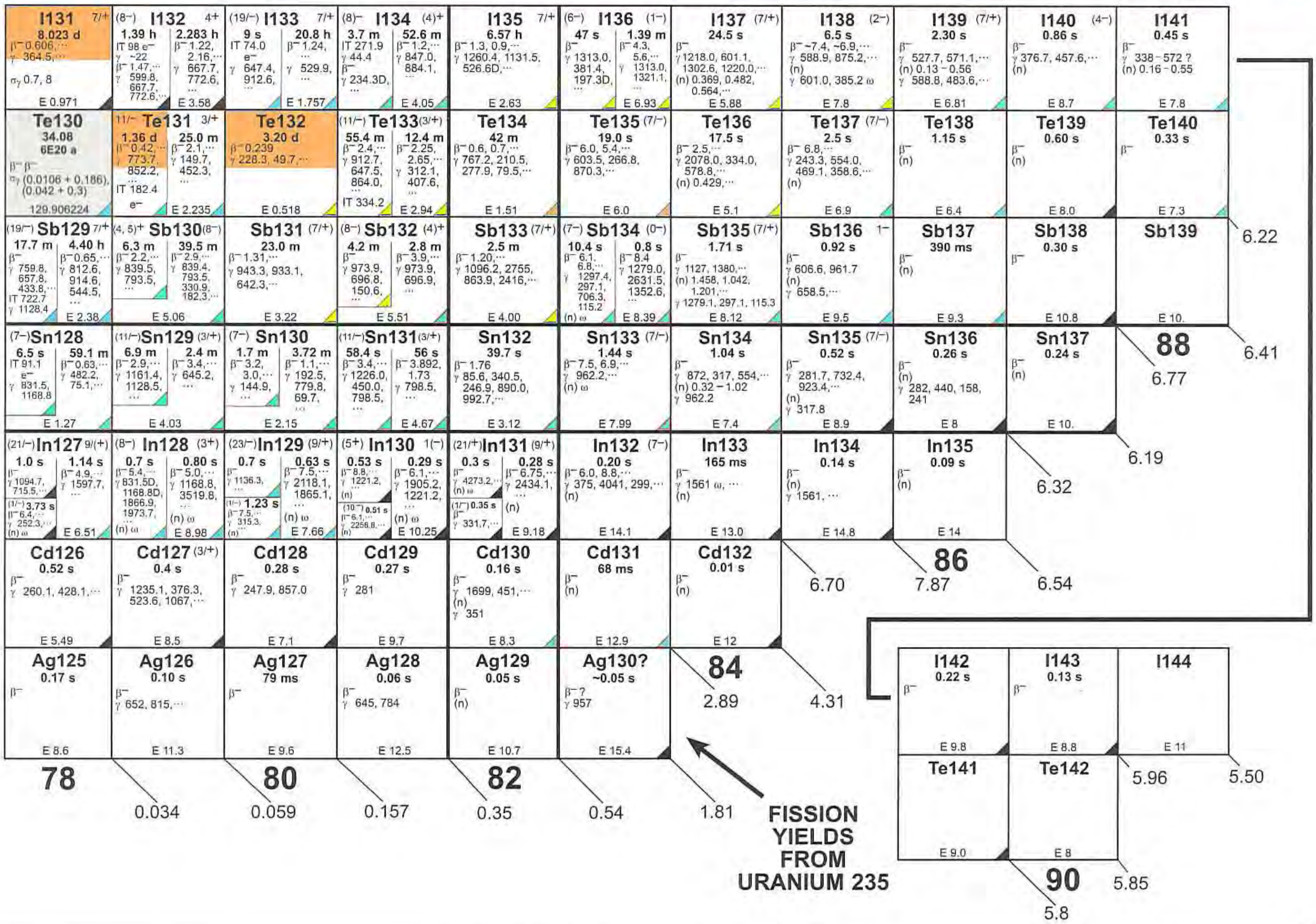
Ag97 (9/+) 25.4 s ε, β^+ γ 686.2, 1295, ⋯ E 7.0	**Ag98** (6+) 47.4 s β^+ ε γ 863.1, 678.5, 571.1, ⋯ (p) ω E 8.2	(1/−) **Ag99** (9/)+ 11 s IT 163.6 γ 342.6 2.07 m β^+, ε γ 264.5, ⋯ E 5.4	(2)+ **Ag100** (5)+ 2.3 m β^+, ε γ 665.7, 1694, ⋯ 2.0 m β^+ 4.7, ⋯, ε γ 665.7, 750.8, ⋯ E 7.1	1/− **Ag101** 9/+ 3.1 s IT 176.2 γ 98.0 11.1 m β^+ 2.7, ⋯, ε γ 261.0, ⋯ E 4.2	2+ **Ag102** 5+ 7.8 m β^+ 3.4, ⋯, ε γ 556.6, ⋯ IT 9.2 e^- 13.0 m β^+ 2.26, ⋯, ε γ 556.6, 719.5, ⋯ E 5.66	1/− **Ag103** 7/+ 5.7 s IT 134.4 1.10 h ε, β^+ 1.7, 1.3, ⋯ γ 118.7, 148.2, ⋯ E 2.69	2+ **Ag104** 5+ 33 m β^+ 2.71, ⋯, ε γ 555.8, ⋯ IT ? 1.15 h ε, β^+ 0.99, ⋯ γ 555.8, 767.8, ⋯ E 4.279	7/+ **Ag105** 1/− 7.2 m IT 25.5 e^- ε ω γ 319.2, ⋯ 41.3 d ε γ 344.5, 280.5, ⋯ β^+ 0.32 vω E 1.34	6+ **Ag106** 1+ 8.28 d ε γ 511.9, ⋯ 24.0 m β^+ 1.96, ⋯, ε γ 511.9, ⋯ β^- ? E^+ 2.965 E^- 0.20	7/+ **Ag107** 1/− 44.2 s IT 93.1 e^- 51.839 σ_γ (~0.35 + 36) (1.2 + ~100) 106.905097
Pd96 2.03 m ε, β^+ γ 125.1, 762.4, ⋯ E 3.5	**Pd97** (5/+) 3.1 m β^+ 3.5, ⋯, ε γ 265.3, 475.2, 792.7, ⋯ E 4.8	**Pd98** 17.7 m ε β^+ γ 112.0, 662.2, ⋯ E 1.87	**Pd99** (5/)+ 21.4 m β^+ 2.18, ⋯, ε γ 136.2, ⋯ E 3.39	**Pd100** 3.7 d ε γ 84.0, 74.8, ⋯ E 0.36	**Pd101** 5/+ 8.4 h ε β^+ 0.776, ⋯ γ 296.3, 590.5, ⋯ E 1.980	**Pd102** 1.02 σ_γ 1.82, 12 101.905609	**Pd103** 5/+ 16.99 d ε γ 39.8D (e^-), 357.5, ⋯ E 0.543	**Pd104** 11.14 σ_γ 0.65, 19 103.904036	**Pd105** 5/+ 22.33 σ_γ 22, 10E1 σ_α 0.5 μb 104.905085	**Pd106** 27.33 σ_γ (0.013 + 0.28), 5.7 105.903486
(1/)− **Rh95** (9/)+ 1.96 m IT 543.3 β^+ γ 787.7, ⋯ 5.0 m β^+ 3.2, ⋯ γ 941.6, 1351.9, ⋯ E 5.1	(3+) **Rh96** (6+) 1.51 m IT 52.0 e^- β^+ 4.7, ⋯, ε γ 832.6, ⋯ 9.6 m β^+ 3.3, ⋯, ε γ 832.6, 685.4, 631.5, ⋯ E 6.39	1/− **Rh97** 9/+ 46 m ε, β^+ 2.6, ⋯ γ 189.0, ⋯ IT 259 31.0 m β^+ 2.1, ⋯, ε γ 421.5, ⋯ E 3.52	(5+) **Rh98** (2)+ 3.5 m β^+, ε γ 652.4, 745.4, ⋯ 8.7 m β^+ 3.4, ⋯, ε γ 652.4, ⋯ E 5.05	9/+ **Rh99** 1/− 4.7 h ε, β^+ 0.74, ⋯ γ 341, ⋯ 16 d ε β^+ 0.68, 0.54, 1.10 ω, ⋯ γ 528.2, 353.0, 89.8, ⋯ E 2.04	(5+) **Rh100** 1− 4.7 m IT 74.9, ⋯ γ 32.7, 42.0 (e^-) ε, β^+ γ 539.5, 687, ⋯ 20.8 h ε β^+ 2.62, 2.07, ⋯ γ 539.5, ⋯ E 3.63	9/+ **Rh101** 1/− 4.35 d ε γ 306.9, ⋯ IT 157.3 e^- 3.3 a ε γ 127.2, 198.0, ⋯ E 0.54	6(+) **Rh102** (1−, 2−) 3.74 a ε γ 475.1, 631.3, 697.5, ⋯ IT 98.8 ω γ 41.9 ω 207 d ε, β^+ 1.30, 0.82, ⋯ γ 475.1, ⋯ β^- 1.15, ⋯ γ 556.6 E^+ 2.323 E^- 1.150	7/+ **Rh103** 1/− 56.12 m IT 39.8 e^- 100 σ_γ (11 + 134), (8E1 + 10.2E2) 102.905504	5+ **Rh104** 1+ 4.36 m IT 77.5 (e^-), 31.8 (e^-) γ 51.4, 97.1 β^- 1.3 ω, ⋯ γ 555.8 σ_γ 8E2 42.3 s β^- 2.44, ⋯ γ 555.8, ⋯ ε ω σ_γ 4E1 E^- 2.440 E^+ 1.139	1/− **Rh105** 7/+ 43.0 s IT 129.6 35.4 h β^- 0.566, 0.248, γ 319.2, σ_γ (5E3 + 11E3), 17E3 E 0.567
Ru94 52 m ε γ 367, 892, ⋯ E 1.59	**Ru95** 5/+ 1.64 h ε, β^+ 1.20, 0.91, ⋯ γ 336.4, 1096.8, 626.8, ⋯ E 2.57	**Ru96** 5.54 σ_γ 0.25, 7 95.90760	**Ru97** 5/+ 2.89 d ε γ 215.7, 324.5, ⋯ E 1.11	**Ru98** 1.87 σ_γ < 8 97.90529	**Ru99** 5/+ 12.76 σ_γ 5, 1.8E2 98.905939	**Ru100** 12.60 σ_γ 5.8, 11 99.904219	**Ru101** 5/+ 17.06 σ_γ 5, 1.0E2 σ_α < 0.15 μb 100.905582	**Ru102** 31.55 σ_γ 1.3, 4.7 101.904349	**Ru103** 3/+ 39.27 d β^- 0.223, ⋯ γ 497.1, ⋯ σ_γ < 20, 3E1 E 0.763	**Ru104** 18.62 σ_γ 0.47, 6 103.905433
1/− **Tc93** 9/+ 43 m IT 391.8 ε γ 2644.6, ⋯ 2.73 h ε, β^+ 0.81, ⋯ γ 1363.1, 1520., ⋯ E 3.201	(2)+ **Tc94** 7+ 52 m β^+ 2.44, ⋯, ε γ 871.1, ⋯ E 4.331 4.88 h ε, β^+ 0.82, ⋯ γ 871.1, 702.6, 849.7, ⋯ E 4.256	1/− **Tc95** 9/+ 61.9 d ε γ 204.1, 582.1, 835.1, ⋯ IT 38.9 e^- β^+ 0.71(ω), 0.51 20.0 h ε γ 765.8, ⋯ E 1.69	4+ **Tc96** 7+ 52 m IT 34.2 e^- ε β^+ 1.9 ω, ⋯ γ 778.2, 1200.2, ⋯ 4.3 d ε γ 778.2, 849.9, 812.5, ⋯ E 2.97	1/− **Tc97** 9/+ 91 d IT 96.5 e^- ε 4.2E6 a ε no γ E 0.320	**Tc98** (6)+ 4.2E6 a β^- 0.40 γ 745.4, 652.4 σ_γ (0.9 + ?) E 1.80	1/− **Tc99** 9/+ 6.008 h IT 142.7, 2.2 (e^-) γ 140.5 β^- 0.435 ω, ⋯ γ 322 vω 2.13E5 a β^- 0.294, ⋯ γ 89.7 vω σ_γ 23, 4.0E2 E 0.294	**Tc100** 1+ 15.5 s β^- 3.4, 2.9, ⋯ γ 539.5, 590.8, ⋯ ε ω E^+ 0.17 E^- 3.203	**Tc101** 9/+ 14.22 m β^- 1.32, ⋯ γ 306.8, ⋯ E 1.61	**Tc102** 1+ 4.4 m β^- 1.8, ⋯ γ 475.1, 628.1, ⋯ IT 5.3 s β^- 4.2, 3.4, 2.2, ⋯ γ 475.1, ⋯ E 4.53	**Tc103** 5/+ 54 s β^- 2.2, 2.0, ⋯ γ 346.4, 136.1, 210.4, ⋯ E 2.66
Mo92 14.77 σ_γ (0.2 μb + 6E1mb), 0.8 91.906811	21/+ **Mo93** 5/+ 6.9 h IT 263.1 γ 684.7, 1477.1, ⋯ ε ω γ 949.9 ω, ⋯ ~3.5E3 a ε γ 30.8D e^- E 0.405	**Mo94** 9.23 σ_γ 7, 0.8 93.905088	**Mo95** 5/+ 15.90 σ_γ 14.0, 1.1E2 σ_α 0.03 mb 94.905842	**Mo96** 16.68 σ_γ 0.5, 17 95.904679	**Mo97** 5/+ 9.56 σ_γ 2.5, 15 σ_α 0.4 μb 96.906021	**Mo98** 24.19 σ_γ 0.13, 7.2 97.905408	**Mo99** 1/+ 2.7476 d β^- 1.214, ⋯ γ 739.5, 181.1, 140.5D, ⋯ E 1.357	**Mo100** 9.67 7.0E18 a $\beta^-\beta^-$ γ 590.8, 539.5 σ_γ 0.19, 3.8 99.90748	**Mo101** 1/+ 14.61 m β^- 0.7, 2.23, ⋯ γ 590.9, 191.9, 1012.5, 506.0, ⋯ E 2.82	**Mo102** 11.3 m β^- 1.2, ⋯ γ 211.6, 148.2, 223.8, ⋯ E 1.01
1/− **Nb91** 9/+ 62 d IT 104.5 e^- ε γ 1205 β^+ ω 7E2 a ε β^+ ω E 1.258	(2)+ **Nb92** (7)+ 10.13 d ε β^+ ω γ 934.5, ⋯ 3.5E7 a ε γ 561.1, 934.5 E 2.006	1/− **Nb93** 9/+ 16.1 a IT 30.8 e^- 100 σ_γ (0.9 + 0.2), (6.2 + 2.3) 92.906378	3+ **Nb94** 6+ 6.263 m IT 40.9 e^- β^- 1.2 ω, ⋯ γ 871.1ω, ⋯ 2.0E4 a β^- 0.473 γ 871.1, 702.6 σ_γ (0.6 + 14.8), 1.3E2 E 2.045	1/− **Nb95** 9/+ 3.61 d IT 235.7 β^- 1.16, ⋯ γ 204.1, ⋯ 34.99 d β^- 0.160, ⋯ γ 765.8, ⋯ σ_γ < 7, < 200 E 0.9256	**Nb96** 6+ 23.4 h β^- 0.748, ⋯ γ 778.2, 568.8, 1091.3, ⋯ E 3.187	1/− **Nb97** 9/+ 53 s IT 743.3 1.23 h β^- 1.27, ⋯ γ 657.9, ⋯ E 1.935	(5+) **Nb98** 1+ 51 m β^- 1.99, 2.45, ⋯ γ 787.4, 722.6, ⋯ E 4.67 2.9 s β^- 4.6, ⋯ γ 734.6, 787.4, 1024.1, ⋯ E 4.58	1/− **Nb99** 9/+ 2.6 m β^- 3.2, ⋯ γ 97.7, 253.5, 2641, 2852, ⋯ IT 365.1 15.0 s β^- 3.5, ⋯ γ 137.8, 97.7 E 3.64	(5+) **Nb100** 1+ 3.0 s β^- 5.8, ⋯ γ 535.5, 600.2, ⋯ E 6.72 1.5 s β^- 6.2, 5.3, ⋯ γ 535.6, 159.5, ⋯ E 6.25	**Nb101** 7.1 s β^- 4.3, ⋯ γ 276.1, 157.6, ⋯ E 4.57
50		52		54		56		58		60



53	(7−) **I120** 2− **53 m** β^+ 3.8, ···, ε γ 560.4, 601.1, 614.7, ··· **1.361 h** β^+ 4.03, 4.60, ···, ε γ 560.4, ··· E 5.62	**I121** 5/+ **2.12 h** ε β^+ 1.2,··· γ 212.2,··· E 2.26	**I122** 1+ **3.6 m** β^+ 3.1,···, ε γ 564.1,··· E 4.234	**I123** 5/+ **13.221 h** ε γ 159.0,··· E 1.229	**I124** 2− **4.176 d** ε, β^+ 1.54, 2.14,··· γ 602.7,··· E 3.160	**I125** 5/+ **59.4 d** ε γ 35.49 e^- σ_γ 9E2, 1.4E4 E 0.1856	**I126** 2− **12.89 d** ε γ 666.3,··· β^- 0.87,··· γ 388.6,··· β^+ 1.13 (ω) σ_γ 5.96E3, 4.06E4 E^+ 2.154 E^- 1.258	**I127** 5/+ **100** σ_γ 6.2, ~1.50E2 126.904473	**I128** 1+ **25.00 m** β^- 2.13,··· γ 442.9,··· ε, β^+ ω γ 743.4 ω σ_γ 22, ~10 E^- 2.122 E^+ 1.254	**I129** 7/+ **1.57E7 a** β^- 0.15 γ 39.6 e^- σ_γ (18 + ~12.5), (18 + 16) E 0.194	2+ **I130** 5+ **9.0 m** IT 39.96 e^- β^- 2.5,··· γ 536.1, ··· **12.36 h** β^- 1.04, 0.62,··· γ 536.1, 668.6, 739.5,··· σ_γ 18 E 2.949
52	11/− **Te119** 1/+ **4.69 d** ε β^+ ω γ 153.6, 1212.7, 270.5, ··· **16.0 h** ε β^+ 0.627,··· γ 644.0,··· E 2.293	**Te120** **0.09** σ_γ (0.3 + 2) 119.90402	11/− **Te121** 1/+ **164 d** IT 81.8 e^- γ 212.2 ε, γ 1102.2, 37.1 (e^-), ··· β^+ ω **19.1 d** ε γ 573.1, 507.6, ··· E 1.04	**Te122** **2.55** σ_γ (0.42 + 4), (9.8 + 8E1) 121.903044	11/− **Te123** 1/+ **119.7 d** IT 88.5 e^-, 247.5 γω γ 159.0 **0.89** **>9 E16 a** ε, no γ σ_γ 3.7E2, 4.5E3 σ_α 0.05 mb E 0.052 122.904270	**Te124** **4.74** σ_γ (0.05 + 7), 5 123.902818	11/− **Te125** 1/+ **58 d** IT 109.3 e^-,··· γ 35.5 e^- **7.07** σ_γ 1.5, 21 124.904431	**Te126** **18.84** σ_γ (0.13 + 0.9), (? + 8) 125.903312	11/− **Te127** 3/+ **106 d** IT 88.3 e^- β^- γ 57.6, ··· **9.4 h** β^- 0.69,··· γ 417.9, 360.3 ω, ··· E 0.702	**Te128** **31.74** **4E24 a** $\beta^-\beta^-$ σ_γ (0.026 + 0.181), (0.2 + 1.5) 127.904463	11/− **Te129** 3/+ **33.6 d** IT 105.5 e^- β^- 1.61,··· γ 695.9,··· **1.16 h** β^- 1.45, ··· γ 459.6, 27.8,··· E 1.500
51	8− **Sb118** 1+ **5.00 h** ε β^+ γ 1229.7, 253.7, 1050.7, ··· **3.6 m** β^+ 2.65, ···, ε γ 1229.7, ··· E 3.657	**Sb119** 5/+ **38.1 h** ε γ 23.9 e^- E 0.59	8− **Sb120** 1+ **5.76 d** ε γ 1171.4, 1023.1, 197.3D, 89.8,··· **15.89 m** ε, β^+ 1.72,··· γ 1171.4, ··· E 2.68	**Sb121** 5/+ **57.21** σ_γ (0.1 + 5.9), 2.0E2 120.903816	(8)− **Sb122** 2− **4.191 m** IT 26.1 e^- γ 61.4D, 76.1D **2.72 d** β^- 1.414, 1.980,··· γ 564.1,··· ε, γ1140.7ω β^+ 0.57ω E^+ 1.616 E^- 1.984	**Sb123** 7/+ **42.79** σ_γ (0.02 + 0.04 + 4.0), 1.3E2 122.904214	(8)− **Sb124** 3− **20.2 m** IT 26.0 e^- γ 10.9D e^- 5+ **1.6 m** IT 10.9 e^- β^- 1.2,··· γ 602.7, 645.8, 498.4,··· **60.20 d** β^- 0.61, 2.301,··· γ 602.8, 1691.0, 722.8,··· σ_γ 17 E 2.904	**Sb125** 7/+ **2.758 a** β^- 0.302, 0.13,··· γ 427.9, 600.6, 635.9, 463.4, ··· E 0.767	(3−) **Sb126** (8−) **~11 s** IT 22.7 e^- γ 17.7D e^- (5+) **19.0 m** β^- 1.9,··· γ 414.6, 666.4,··· IT 17.7 e^- **12.4 d** β^- 1.9,··· γ 666.4, 694.8, 414.6, ··· E 3.67	**Sb127** 7/+ **3.84 d** β^- 0.89, 1.10,··· γ 685.7, 473.6, 784.0,··· E 1.581	5+ **Sb128** 8− **10.1 m** β^- 2.6,··· γ 754.0, 743.3, 314.1,··· IT **9.1 h** β^- 2.3,··· γ 743.3, 754.0, ··· E 4.38
50	11/− **Sn117** 1/+ **13.60 d** IT 156.0 e^-, 314.3 γω γ 158.6 **7.68** σ_γ 1.1, ~15 116.902952	**Sn118** **24.22** σ_γ (4mb + ?), 5 117.901603	11/− **Sn119** 1/+ **293 d** IT 65.7 e^- γ 23.9 **8.59** σ_γ 2, 4 118.903308	**Sn120** **32.58** σ_γ (0.001 + 0.16), 1.2 119.902195	11/− **Sn121** 3/+ **44 a** IT 6.3 e^- β^- 0.36 γ 37.15 e^- **1.128 d** β^- 0.383 no γ E 0.391	**Sn122** **4.63** σ_γ (0.14 + 0.004), (~0.74 + 0.10) 121.903439	3/+ **Sn123** 11/− **40.1 m** β^- 1.26,··· γ 160.3,··· E 1.428 **129.2 d** β^- 1.42,··· γ 1088.6, ··· E 1.404	**Sn124** **5.79** σ_γ (0.11 + 0.0033), (~7.2 + 0.10) 123.905274	3/+ **Sn125** 11/− **9.5 m** β^- 2.0,··· γ 331.9,··· E 2.384 **9.64 d** β^- 2.35,··· γ 1067.0, 1089.2, 822.4, 915.5,··· E 2.357	**Sn126** **2.3E5 a** β^- 0.25 γ 87.6,··· E 0.38	(3/+) **Sn127** (11/−) **4.15 m** β^- 2.72, ··· γ 491.2, ··· E 3.21 **2.12 h** β^- 3.2, 2.42,··· γ 1114.3, 1095.5, ··· E 3.20
49	8− **In116** 1+ **2.16 s** IT 162.4 5+ **54.2 m** β^- 1.0,··· γ 1293.6, 1097.3, ··· **14.1 s** β^- 3.3,··· γ 1293.6, 463.3, ··· ε ω E^+ 0.469 E^- 3.278	1/− **In117** 9/+ **1.94 h** β^- 1.77, 1.62,··· γ 158.6,··· IT 315.3 **44 m** β^- 0.74, ··· γ 553.0, 158.6, ··· E 1.455	8− **In118** 1+ **8.5 s** IT 138 β^- γ 1229.7, 254,1051,··· 5+ **4.40 m** β^- 1.3, 2.0,··· γ 1229.7, 1051,··· **5.0 s** β^- 4.2,··· γ 1229.7 ··· E 4.43	1/− **In119** 9/+ **17.9 m** β^- 2.7,··· γ 1065.6, 1249.7, 1163.9, ··· IT 311.4 **2.3 m** β^- 1.6,··· γ 763.1, ··· E 2.36	(8−) **In120** 1+ **47 s** β^- γ 1171.4, 1023,··· ↕ (5)+ **46 s** β^- 2.2,··· γ 1171.4, 1023,··· **3.1 s** β^- 5.6,··· γ 1171.4, ··· E 5.37	1/− **In121** 9/+ **3.8 m** β^- 3.7,··· γ 60.3,··· IT 313.6 **23 s** β^- 2.4,··· γ 925.6, ··· E 3.36	8− **In122** 1+ **10.8 s** β^- γ1140.3, 1001.4, 103.4,··· 5+ **10. s** β^- 4.4,··· γ 1140.3, 1001.4,··· **1.5 s** β^- 5.3,··· γ 1140.3, ··· E 6.37	1/− **In123** 9/+ **47 s** β^- 4.6,··· γ 125.8, ··· **6.0 s** β^- 3.3,··· γ 1130.4, 1019.7, ··· E 4.39	(8−) **In124** 1(+) **3.4 s** β^- γ 1131.6, 969.9, 1072.9, 102.9, ··· **3.18 s** β^- 5,··· γ 1131.6, 3214.1, 997.8, ··· E 7.36	1/(−) **In125** 9/(+) **12.2 s** β^- 5.51, ··· γ 187.6 **2.36 s** β^- 4.08,··· γ 1335.1, ··· E 5.42	**In126** 3(+) **1.63 s** β^- 4.45, ··· γ 1141.1, 908.6, 111.8, ··· **1.53 s** β^- 4.86, 7.1,··· γ 1141.1, 3344.8, ··· E 8.21
48	(11/)− **Cd115** 1/+ **44.6 d** β^- 1.62, ··· γ 933.8, 1290.6, ··· E 1.627 **2.228 d** β^- 1.11, 0.593,··· γ 336.3D, 527.9, ··· E 1.446	**Cd116** **7.49** **3.0E19 a** $\beta^-\beta^-$ σ_γ (26 + 52) mb, 1.2 115.904756	(11/)− **Cd117** 1/+ **3.4 h** β^- 0.72, ··· γ 1997.3, 1066.0, ··· E 2.66 **2.49 h** β^- 0.67, 2.2,··· γ 315.3D, 273.3, 1303.3, ··· E 2.52	**Cd118** **50.3 m** β^- E 0.52	(11/−) **Cd119** 3/+ **2.20 m** β^- 1.8,··· γ 1025.0, 2021.3, 720.6, ··· **2.69 m** β^- ~3.5,··· γ 292.8, 342.9, 1609.6, ··· E 3.8	**Cd120** **50.8 s** β^- E 1.76	(11/−) **Cd121** (3/+) **8 s** β^- 2.8,··· γ 2059.6, 1020.9, ··· **13.5 s** β^- 2.6,··· γ324.3, 1040.4, 349.3, ··· E 4.8	**Cd122** **5.3 s** β^- E 2.8	(11/−) **Cd123** (3/)+ **1.84 s** β^- γ 1165.9, 1027.5, ··· IT ? **2.10 s** β^- γ 371.3, 1052.3, ··· E 6.12	**Cd124** **1.24 s** β^- γ 179.9, 62.8, 143.3,··· E 4.17	(11/−) **Cd125** (3/+) **0.6 s** β^- 4.5,··· γ 1027.5, 1173.2, ··· **0.68 s** β^- 4.6,··· γ 436.3, 1099.5, 2147,··· E 7.1
47	**Ag114** 1+ **4.6 s** β^- 4.9,··· γ 558.4,··· E 5.07	7/+ **Ag115** 1/− **18.7 s** β^- γ 229.1, 131.5, 388.9, ··· IT 41.1 e^- **20. m** β^- 3.2,··· γ 229.1, 212.8, 472.7, ··· E 3.10	(6−) **Ag116** (0−) **9.8 s** β^- 2.9,··· γ 513.4, 705.6,··· IT 81.9 e^- (3+) **20. s** β^- IT 47.9 e^- **2.68 m** β^- 5.3,··· γ 513.4, 2478, 699.6, ··· E 6.15	(7/+) **Ag117** (1/−) **5.3 s** β^- 3.2,··· γ 135.4, 386.8, 298.1, ··· IT 28.6 e^- **1.22 m** β^- 2.3,··· γ 135.4, 337.7, ··· E 4.16	(4+) **Ag118** (1−) **2.4 s** β^- γ 487.8, 677.1, ··· IT 127.7 **4.0 s** β^- γ 487.8, 2789, ··· E 7.1	(1/−) **Ag119** (7/+) **6 s** ↔ **2.1 s** β^- β^- 4.3, ··· γ 626.3, 366.2, 399.0, ··· E 5.35	6(−) **Ag120** 3(+) **0.37 s** β^- γ 505.9, 697.8, 925.8, ··· IT 203.1 **1.23 s** β^- γ 505.9, 697.8, ··· E 8.3	**Ag121** (7/+) **0.78 s** β^- 4.9,··· γ 314.7, 353.6,··· (n) ω E 6.4	(9−) **Ag122** (3+) **0.2 s** β^- γ 569.4,··· (n) (1−) **0.55 s** ↔ β^- γ 569.4,··· (n) IT ? **0.53 s** β^- γ 569.4, 759.7, ··· (n) ω E 9.5	**Ag123** (7/+) **0.30 s** β^- γ 263.9, 409.8,··· (n) ω E 7.4	**Ag124** **0.17 s** β^- γ 613.2, 772.1, 461.1,··· (n) E 10.2
		68		70		72		74		76	

FISSION YIELDS FROM URANIUM 233 AND PLUTONIUM (239)

53									**I** 126.90447 **iodine** σ_a 6.2, ~1.50E2	**I108** **~36 ms** α 3.947 107.9435	**I109** (1/+) **0.10 ms** p 0.813 α 3.77 ω 108.9381
52							**Te** 127.60 **tellurium** σ_a 4.2, 50	**Te105** (5/+) **0.6 μs** α 4.70 104.944	**Te106** **70. μs** α 4.16 105.9375	**Te107** **3.1 ms** α 3.86, 3.63 ω γ 168 ω ε, β^+ E 10.1 106.9350	**Te108** **2.1 s** α 3.314 ε, β^+ (p) 2.30 – 4.24 ω E 6.8 107.9294
51						**Sb** 121.760 **antimony** σ_a 5.1, 1.7E2	**Sb103** E 10.8	**Sb104** **0.4 s** β^+ E 12.4	**Sb105** **1.3 s** β^+ E 9.4	**Sb106** (2+) **1.0 s** β^+ γ 811,··· E 11.1	**Sb107** (5/+) **4.0 s** β^+, ε γ 1280.1, 151.5,··· E 7.9
50				**Sn** 118.710 **tin** σ_a 0.61, 6	**Sn100** **1 s** β^+ ~3.4 E 7	**Sn101** (5/+) **1.7 s** β^+ γ 352, 1065 (p) E 9.1	**Sn102** **3.8 s** β^+ γ 320, 69, 94,··· E 5.8	**Sn103** (5/+) **7.0 s** β^+ γ 1355.8, 314.0, 1396.9,··· (p) γ 776, 1022 E 7.6	**Sn104** **20.8 s** β^+, ε γ 132.7, 912.6, 401.2, 1407.5,··· E 4.5	**Sn105** (5/+) **33 s** β^+, ε γ 1281.7, 1465.6, 309.1, 1416.9,··· (p) ω γ 658 E 6.2	**Sn106** **2.0 m** ε, β^+ 1.2,··· γ 386.5, 253.2, 477.2, 863.8,··· E 3.18
49			**In** 114.818 **indium** σ_a 194, 3.2E3	**In98** (0+) **1 s** β^+ **0.03 s** β^+ E 13.7	**In99** **3 s** β^+ E 8.6	**In100** (6+, 7+) **6.1 s** β^+ γ 1004, 795, 297, ··· (p) γ 916, 342 E 10.1	**In101** **15 s** β^+ γ 252.3,··· E 7.1	**In102** (6+) **23.3 s** β^+ 3.5, ε γ 776.7, 861.2,··· (p) ω E 9.0	(1/−) **In103** (9/)+ **34 s** β^+ IT 631.7 **1.0 m** β^+ 4.2,··· ε γ 187.9, 720.7, ··· E 6.05	(3+) **In104** (6+) **16 s** IT 93.5 e^- β^+, ε **1.81 m** β^+ 4.30, ···, ε γ 658.0, 834.1, ··· E 7.9	(1/)− **In105** 9/+ **43 s** IT 674.1 **5.1 m** β^+ 3.7, ···, ε γ 131.5, 260.3, ··· E 4.85
48			**Cd** 112.411 **cadmium** σ_a ~2.52E3, 70	**Cd97** (9/+) **3 s** β^+ (p) ~1.6 – 5.2 γ 325.3, 684.0 E 10.	**Cd98** **9.2 s** β^+, ε γ 347.2, 1176.1, 107.3, 60.6,··· E 5.43	**Cd99** (5/+) **16 s** β^+ γ 343, 672,··· (p) ω E 6.9	**Cd100** **49.1 s** β^+, ε γ 936.6,··· E 3.9	**Cd101** (5/+) **1.36 m** β^+ 4.5,···, ε γ 98, 1722,··· E 5.5	**Cd102** **5.8 m** ε, β^+ 1.08,··· γ 481.1, 1036.1,··· E 2.59	**Cd103** (5/)+ **7.5 m** ε, β^+ 3.11,··· γ 1461.8, 1448.7, 1079.9,··· E 4.14	**Cd104** **58 m** ε β^+ 0.29 ω γ 83.5, 709.3,··· E 1.14
47	**Ag** 107.8682 **silver** σ_a 63, 7.5E2	(21+) **Ag94** (0+) **0.41 s** β^+ γ 408.2,··· (p), p, 2p ω ? (7+) **0.60 s** β^+ γ 814.1, 905.3,··· (p) **0.03 s** β^+ E 13	**Ag95** (9/+) **1.9 s** β^+ γ 1261.2, 1685.4, 2025.1,··· (p) E 10.	(2+) **Ag96** (8+) **7 s** ↔ **4.5 s** β^+ γ 1415.3 (p) γ 680 β^+, ε γ 1416, 684, 326,··· (p) γ 1350 E 11.7	**Ag97** (9/+) **25.4 s** ε, β^+ γ 686.2, 1295,··· E 7.0	**Ag98** (6+) **47.4 s** β^+ ε γ 863.1, 678.5, 571.1,··· (p) ω E 8.2	(1/−) **Ag99** (9/)+ **11 s** IT 163.6 γ 342.6 **2.07 m** β^+, ε γ 264.5,··· E 5.4	(2)+ **Ag100** (5)+ **2.3 m** β^+, ε γ 665.7, 1694,··· **2.0 m** β^+ 4.7, ···, ε γ 665.7, 750.8, ··· E 7.1	1/− **Ag101** 9/+ **3.1 s** IT 176.2 γ 98.0 **11.1 m** β^+ 2.7, ···, ε γ 261.0, ··· E 4.2	2+ **Ag102** 5+ **7.8 m** β^+ 3.4, ···, ε γ 556.6, ··· IT 9.2 e^- **13.0 m** β^+ 2.26, ···, ε γ 556.6, 719.5, ··· E 5.66	1/− **Ag103** 7/+ **5.7 s** IT 134.4 **1.10 h** ε, β^+ 1.7, 1.3,··· γ 118.7, 148.2, ··· E 2.69
			48		50		52		54		56


I131 7/+ 8.023 d
I132 4+ 1.39 h 2.283 h
I133 7/+ 9 s 20.8 h
I134 (4)+ 3.7 m 52.6 m
I135 7/+ 6.57 h
I136 (1−) 47 s 1.39 m
I137 (7/+) 24.5 s
I138 (2−) 6.5 s
I139 (7/+) 2.30 s
I140 (4−) 0.86 s
I141 0.45 s
Te130 34.08 6E20 a
Te131 3/+ 1.36 d 25.0 m
Te132 3.20 d
Te133 (3/+) 55.4 m 12.4 m
Te134 42 m
Te135 (7/−) 19.0 s
Te136 17.5 s
Te137 (7/−) 2.5 s
Te138 1.15 s
Te139 0.60 s
Te140 0.33 s
Sb129 7/+ 17.7 m 4.40 h
Sb130 (8−) 6.3 m 39.5 m
Sb131 (7/+) 23.0 m
Sb132 (4)+ 4.2 m 2.8 m
Sb133 (7/+) 2.5 m
Sb134 (0−) 10.4 s 0.8 s
Sb135 (7/+) 1.71 s
Sb136 1− 0.92 s
Sb137 390 ms
Sb138 0.30 s
Sb139
Sn128 6.5 s 59.1 m
Sn129 (3/+) 6.9 m 2.4 m
Sn130 1.7 m 3.72 m
Sn131 (3/+) 58.4 s 56 s
Sn132 39.7 s
Sn133 (7/−) 1.44 s
Sn134 1.04 s
Sn135 (7/−) 0.52 s
Sn136 0.26 s
Sn137 0.24 s
In127 9/(+) 1.0 s 1.14 s
In128 (3+) 0.7 s 0.80 s
In129 (9/+) 0.7 s 0.63 s
In130 1(−) 0.53 s 0.29 s
In131 (9/+) 0.3 s 0.28 s
In132 (7−) 0.20 s
In133 165 ms
In134 0.14 s
In135 0.09 s
Cd126 0.52 s
Cd127 (3/+) 0.4 s
Cd128 0.28 s
Cd129 0.27 s
Cd130 0.16 s
Cd131 68 ms
Cd132 0.01 s
Ag125 0.17 s
Ag126 0.10 s
Ag127 79 ms
Ag128 0.06 s
Ag129 0.05 s
Ag130? ~0.05 s
I142 0.22 s
I143 0.13 s
I144
Te141
Te142
78
80
82
84
86
88
90
0.034
0.059
0.157
0.35
0.54
1.81
2.89
4.31
6.70
7.87
6.54
6.32
6.19
6.77
6.41
6.22
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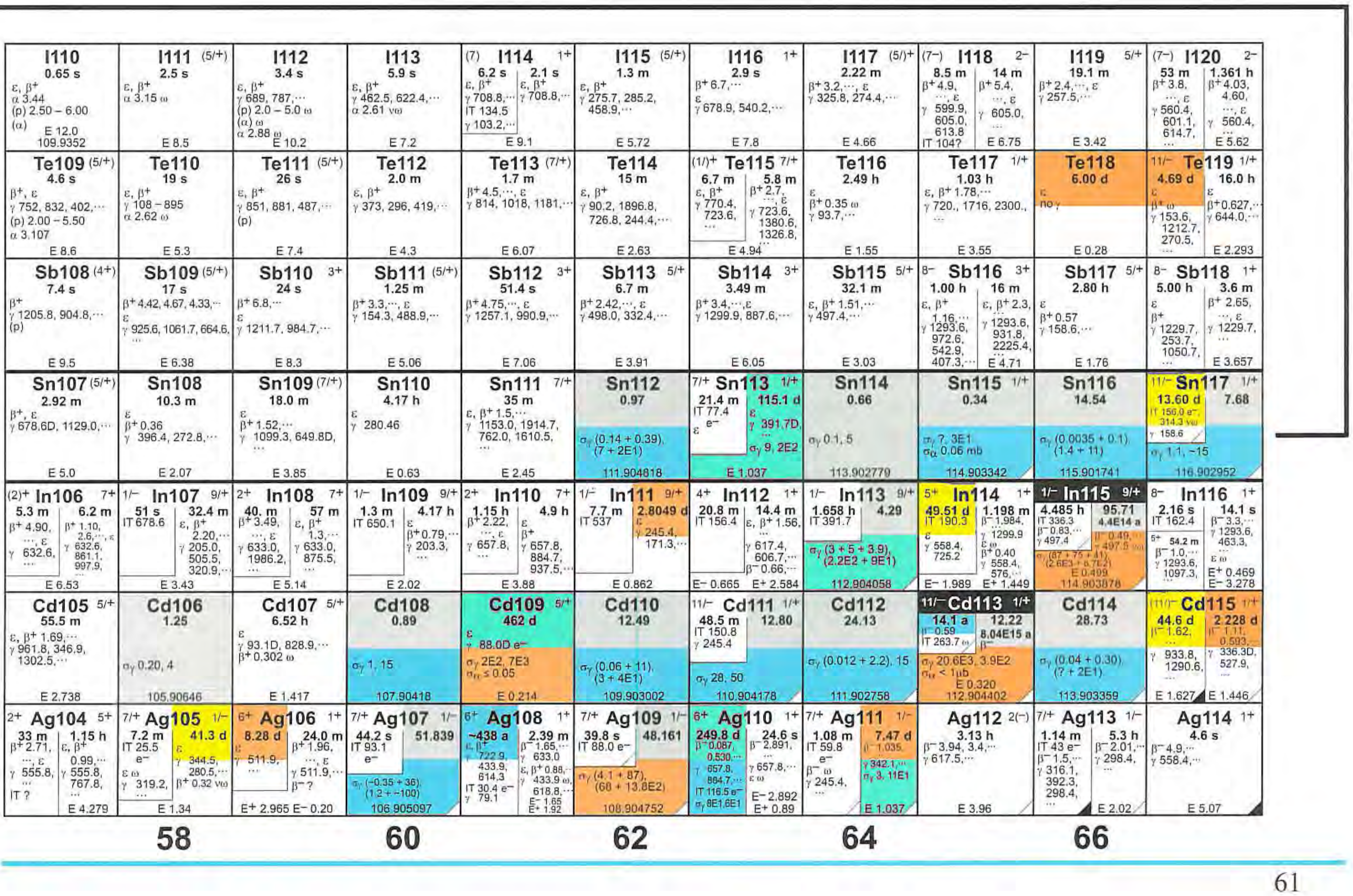
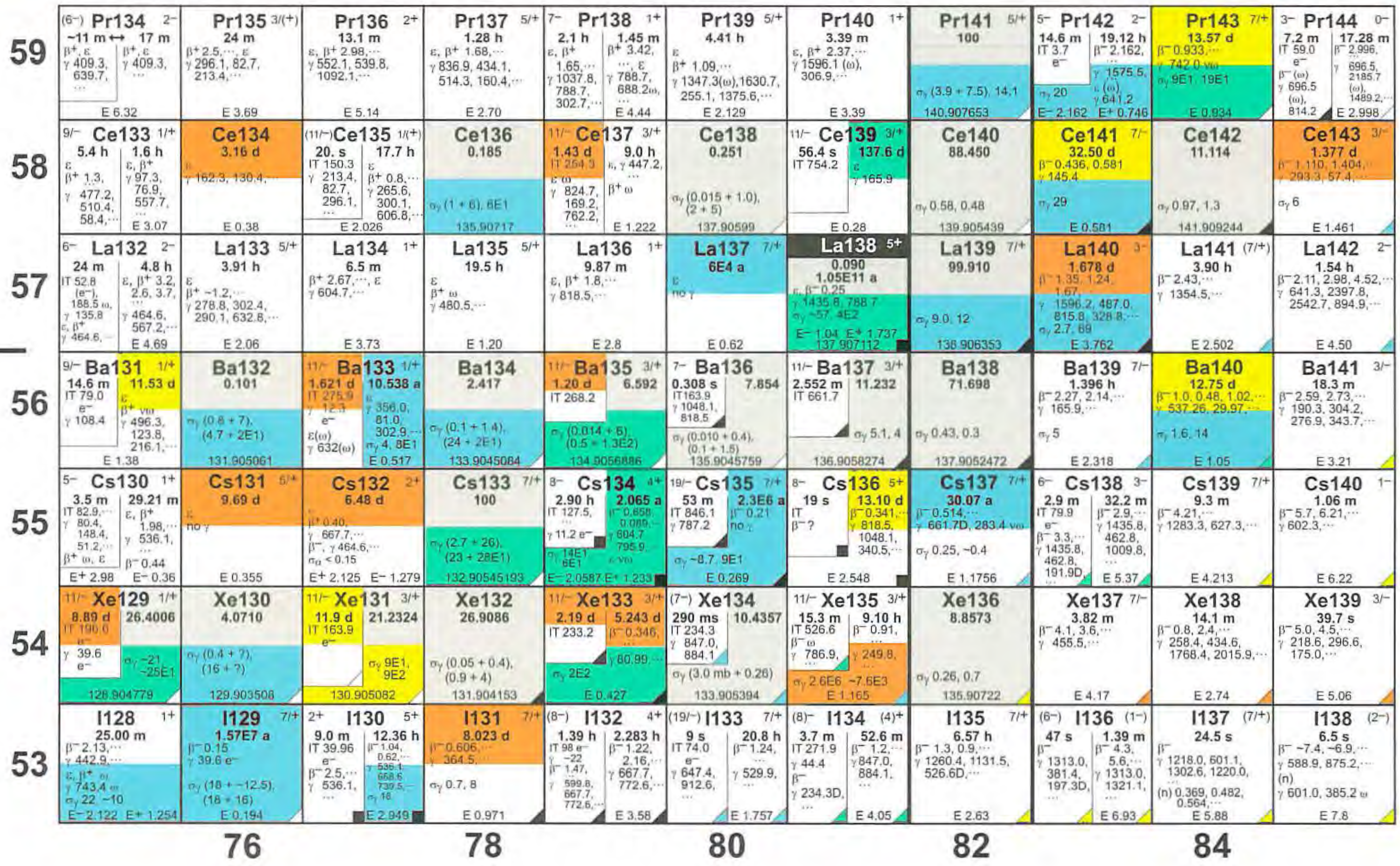
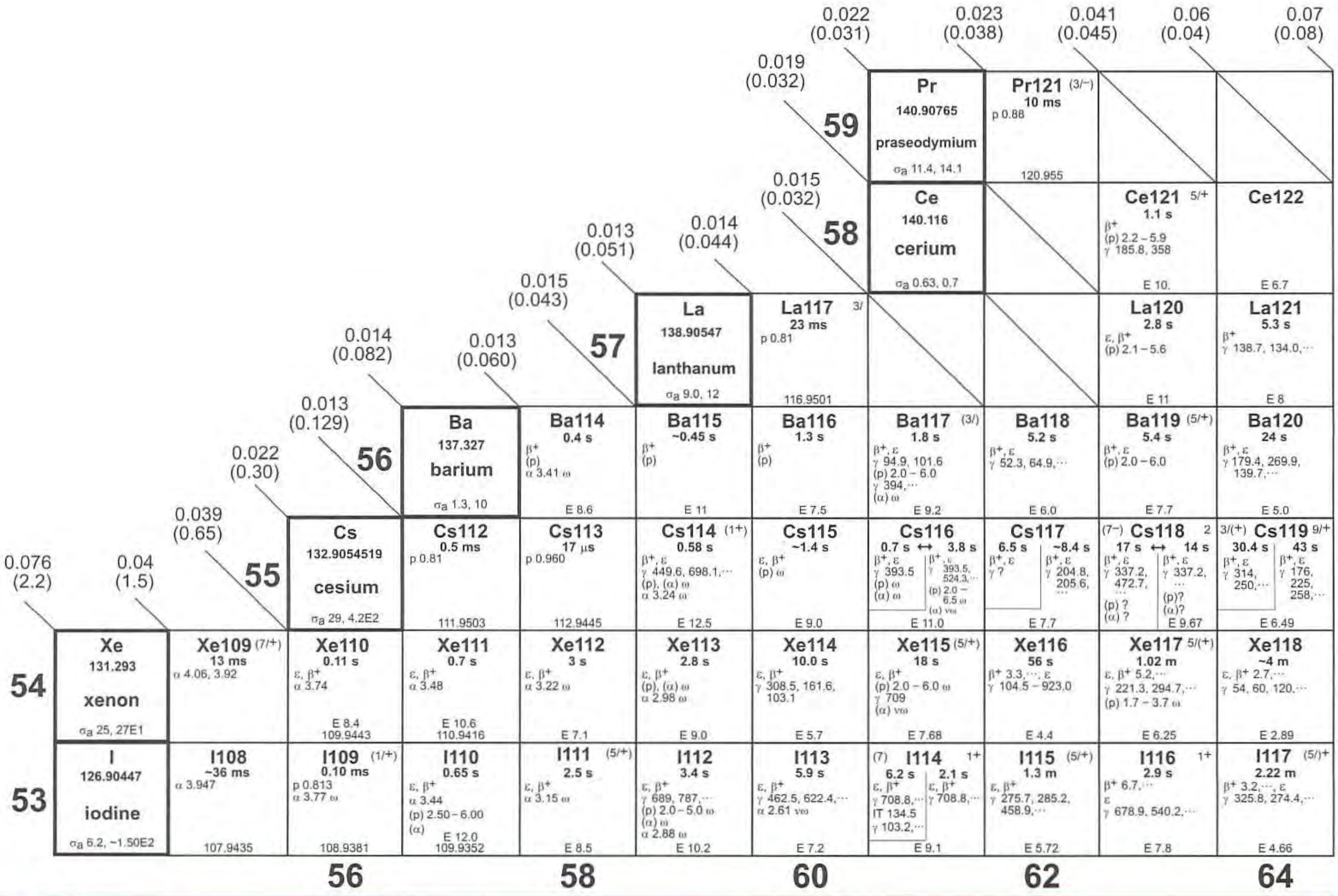
5.85
5.8
FISSION YIELDS FROM URANIUM 235

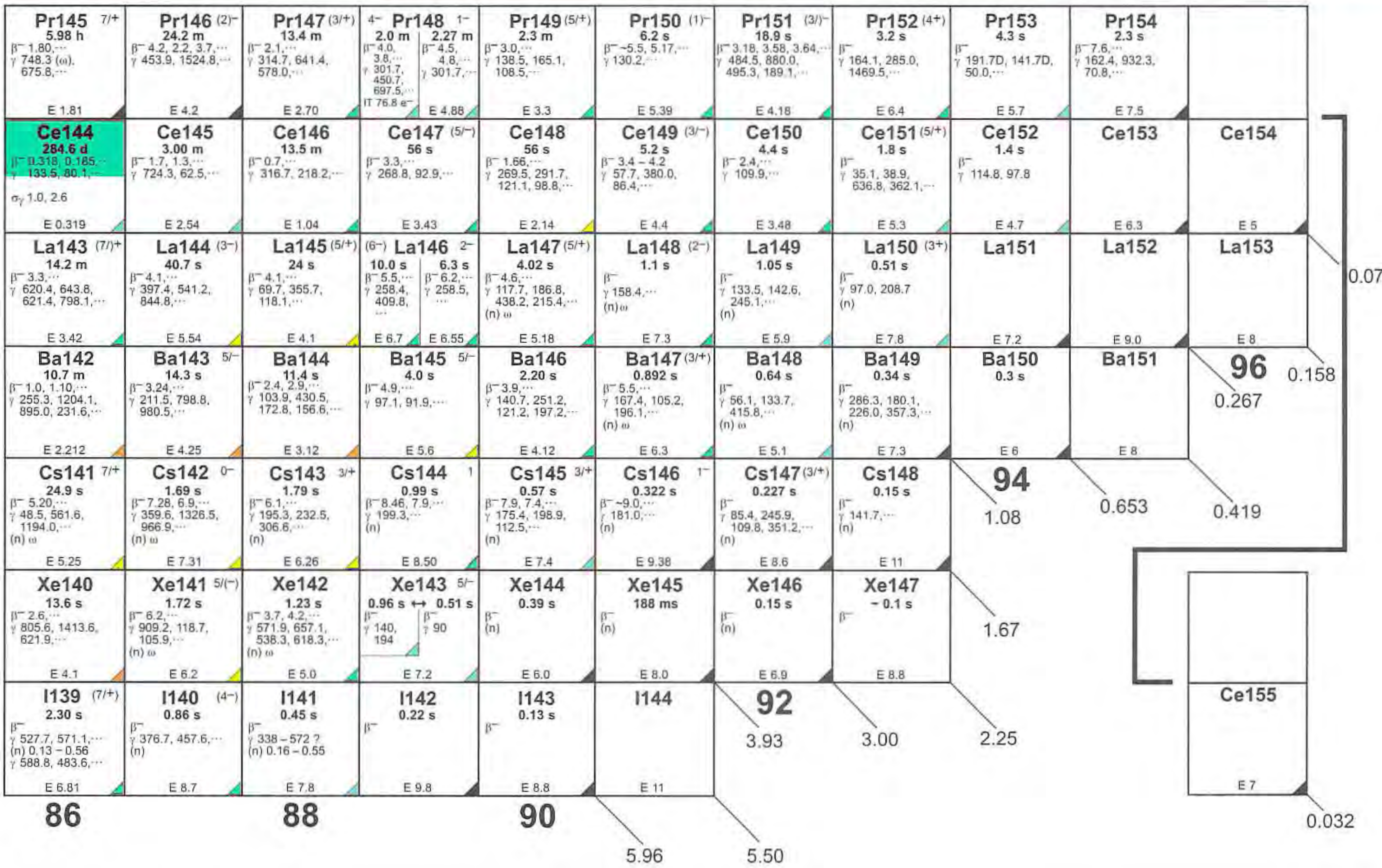

I110 0.65 s
I111 (5/+) 2.5 s
I112 3.4 s
I113 5.9 s
I114 1+ 6.2 s 2.1 s
I115 (5/+) 1.3 m
I116 1+ 2.9 s
I117 (5/)+ 2.22 m
I118 2− 8.5 m 14 m
I119 5/+ 19.1 m
I120 2− 53 m 1.361 h
Te109 (5/+) 4.6 s
Te110 19 s
Te111 (5/+) 26 s
Te112 2.0 m
Te113 (7/+) 1.7 m
Te114 15 m
Te115 7/+ 6.7 m 5.8 m
Te116 2.49 h
Te117 1/+ 1.03 h
Te118 6.00 d
Te119 1/+ 4.69 d 16.0 h
Sb108 (4+) 7.4 s
Sb109 (5/+) 17 s
Sb110 3+ 24 s
Sb111 (5/+) 1.25 m
Sb112 3+ 51.4 s
Sb113 5/+ 6.7 m
Sb114 3+ 3.49 m
Sb115 5/+ 32.1 m
Sb116 3+ 1.00 h 16 m
Sb117 5/+ 2.80 h
Sb118 1+ 5.00 h 3.6 m
Sn107 (5/+) 2.92 m
Sn108 10.3 m
Sn109 (7/+) 18.0 m
Sn110 4.17 h
Sn111 7/+ 35 m
Sn112 0.97
Sn113 1/+ 21.4 m 115.1 d
Sn114 0.66
Sn115 1/+ 0.34
Sn116 14.54
Sn117 1/+ 13.60 d 7.68
In106 7+ 5.3 m 6.2 m
In107 9/+ 51 s 32.4 m
In108 7+ 40. m 57 m
In109 9/+ 1.3 m 4.17 h
In110 7+ 1.15 h 4.9 h
In111 9/+ 7.7 m 2.8049 d
In112 1+ 20.8 m 14.4 m
In113 9/+ 1.658 h 4.29
In114 1+ 49.51 d 1.198 m
In115 9/+ 4.485 h 95.71
In116 1+ 2.16 s 14.1 s
Cd105 5/+ 55.5 m
Cd106 1.25
Cd107 5/+ 6.52 h
Cd108 0.89
Cd109 5/+ 462 d
Cd110 12.49
Cd111 1/+ 48.5 m 12.80
Cd112 24.13
Cd113 1/+ 14.1 a 12.22
Cd114 28.73
Cd115 1/+ 44.6 d 2.228 d
Ag104 5+ 33 m 1.15 h
Ag105 1/− 7.2 m 41.3 d
Ag106 1+ 8.28 d 24.0 m
Ag107 1/− 44.2 s 51.839
Ag108 1+ ~438 a 2.39 m
Ag109 1/− 39.8 s 48.161
Ag110 1+ 249.8 d 24.6 s
Ag111 1/− 1.08 m 7.47 d
Ag112 2(−) 3.13 h
Ag113 1/− 1.14 m 5.3 h
Ag114 1+ 4.6 s
58
60
62
64
66



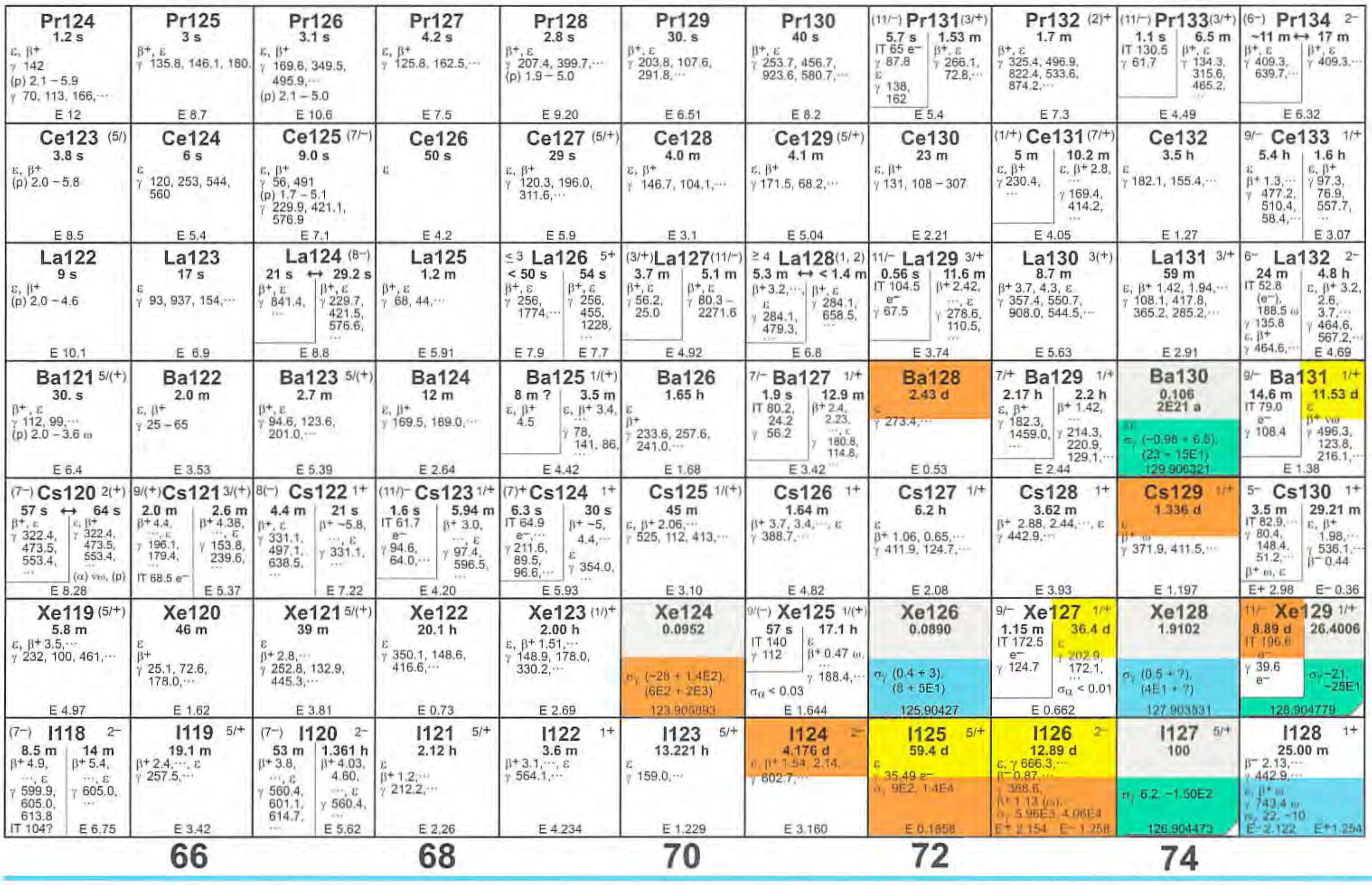
59	(6−) **Pr134** 2− ~11 m ↔ 17 m β^+, ε γ 409.3, 639.7, ⋯ β^+, ε γ 409.3, ⋯ E 6.32	**Pr135** 3/(+) 24 m β^+ 2.5, ⋯, ε γ 296.1, 82.7, 213.4, ⋯ E 3.69	**Pr136** 2+ 13.1 m ε, β^+ 2.98, ⋯ γ 552.1, 539.8, 1092.1, ⋯ E 5.14	**Pr137** 5/+ 1.28 h ε, β^+ 1.68, ⋯ γ 836.9, 434.1, 514.3, 160.4, ⋯ E 2.70	7− **Pr138** 1+ 2.1 h ε, β^+ 1.65, ⋯ γ 1037.8, 788.7, 302.7, ⋯ 1.45 m β^+ 3.42, ⋯, ε γ 788.7, 688.2ω, ⋯ E 4.44	**Pr139** 5/+ 4.41 h ε β^+ 1.09, ⋯ γ 1347.3(ω), 1630.7, 255.1, 1375.6, ⋯ E 2.129	**Pr140** 1+ 3.39 m ε, β^+ 2.37, ⋯ γ 1596.1 (ω), 306.9, ⋯ E 3.39	**Pr141** 5/+ 100 σ_γ (3.9 + 7.5), 14.1 140.907653	5− **Pr142** 2− 14.6 m IT 3.7 e^- σ_γ 20 19.12 h β^- 2.162, ⋯ γ 1575.5, ε (ω) γ 641.2 E^- 2.162 E^+ 0.746	**Pr143** 7/+ 13.57 d β^- 0.933, ⋯ γ 742.0 vω σ_γ 9E1, 19E1 E 0.934	3− **Pr144** 0− 7.2 m IT 59.0 e^- β^- (ω) γ 696.5 (ω), 814.2 17.28 m β^- 2.996, ⋯ γ 696.5, 2185.7 (ω), 1489.2, ⋯ E 2.998
58	9/− **Ce133** 1/+ 5.4 h ε β^+ 1.3, ⋯ γ 477.2, 510.4, 58.4, ⋯ 1.6 h ε, β^+ γ 97.3, 76.9, 557.7, ⋯ E 3.07	**Ce134** 3.16 d ε γ 162.3, 130.4, ⋯ E 0.38	(11/−) **Ce135** 1/(+) 20. s IT 150.3 γ 213.4, 82.7, 296.1, ⋯ 17.7 h ε β^+ 0.8, ⋯ γ 265.6, 300.1, 606.8, ⋯ E 2.026	**Ce136** 0.185 σ_γ (1 + 6), 6E1 135.90717	11/− **Ce137** 3/+ 1.43 d IT 254.3 ε ω γ 824.7, 169.2, 762.2, ⋯ 9.0 h ε, γ 447.2, ⋯ β^+ ω E 1.222	**Ce138** 0.251 σ_γ (0.015 + 1.0), (2 + 5) 137.90599	11/− **Ce139** 3/+ 56.4 s IT 754.2 137.6 d ε γ 165.9 E 0.28	**Ce140** 88.450 σ_γ 0.58, 0.48 139.905439	**Ce141** 7/− 32.50 d β^- 0.436, 0.581 γ 145.4 σ_γ 29 E 0.581	**Ce142** 11.114 σ_γ 0.97, 1.3 141.909244	**Ce143** 3/− 1.377 d β^- 1.110, 1.404, ⋯ γ 293.3, 57.4, ⋯ σ_γ 6 E 1.461
57	6− **La132** 2− 24 m IT 52.8 (e^-), 188.5 ω, γ 135.8 ε, β^+ γ 464.6, ⋯ 4.8 h ε, β^+ 3.2, 2.6, 3.7, ⋯ γ 464.6, 567.2, ⋯ E 4.69	**La133** 5/+ 3.91 h ε β^+ ~1.2, ⋯ γ 278.8, 302.4, 290.1, 632.8, ⋯ E 2.06	**La134** 1+ 6.5 m β^+ 2.67, ⋯, ε γ 604.7, ⋯ E 3.73	**La135** 5/+ 19.5 h ε β^+ ω γ 480.5, ⋯ E 1.20	**La136** 1+ 9.87 m ε, β^+ 1.8, ⋯ γ 818.5, ⋯ E 2.8	**La137** 7/+ 6E4 a ε no γ E 0.62	**La138** 5+ 0.090 1.05E11 a ε, β^- 0.25 γ 1435.8, 788.7 σ_γ ~57, 4E2 E^- 1.04 E^+ 1.737 137.907112	**La139** 7/+ 99.910 σ_γ 9.0, 12 138.906353	**La140** 3− 1.678 d β^- 1.35, 1.24, 1.67, ⋯ γ 1596.2, 487.0, 815.8, 328.8, ⋯ σ_γ 2.7, 69 E 3.762	**La141** (7/+) 3.90 h β^- 2.43, ⋯ γ 1354.5, ⋯ E 2.502	**La142** 2− 1.54 h β^- 2.11, 2.98, 4.52, ⋯ γ 641.3, 2397.8, 2542.7, 894.9, ⋯ E 4.50
56	9/− **Ba131** 1/+ 14.6 m IT 79.0 e^- γ 108.4 11.53 d ε β^+ vω γ 496.3, 123.8, 216.1, ⋯ E 1.38	**Ba132** 0.101 σ_γ (0.8 + 7), (4.7 + 2E1) 131.905061	11/− **Ba133** 1/+ 1.621 d IT 275.9 γ 12.3 e^- ε(ω) γ 632(ω) 10.538 a ε γ 356.0, 81.0, 302.9, ⋯ σ_γ 4, 8E1 E 0.517	**Ba134** 2.417 σ_γ (0.1 + 1.4), (24 + 2E1) 133.9045084	11/− **Ba135** 3/+ 1.20 d IT 268.2 6.592 σ_γ (0.014 + 6), (0.5 + 1.3E2) 134.9056886	7− **Ba136** 0.308 s IT 163.9 γ 1048.1, 818.5 7.854 σ_γ (0.010 + 0.4), (0.1 + 1.5) 135.9045759	11/− **Ba137** 3/+ 2.552 m IT 661.7 11.232 σ_γ 5.1, 4 136.9058274	**Ba138** 71.698 σ_γ 0.43, 0.3 137.9052472	**Ba139** 7/− 1.396 h β^- 2.27, 2.14, ⋯ γ 165.9, ⋯ σ_γ 5 E 2.318	**Ba140** 12.75 d β^- 1.0, 0.48, 1.02, ⋯ γ 537.26, 29.97, ⋯ σ_γ 1.6, 14 E 1.05	**Ba141** 3/− 18.3 m β^- 2.59, 2.73, ⋯ γ 190.3, 304.2, 276.9, 343.7, ⋯ E 3.21
55	5− **Cs130** 1+ 3.5 m IT 82.9, ⋯ γ 80.4, 148.4, 51.2, ⋯ β^+ ω, ε 29.21 m ε, β^+ 1.98, ⋯ γ 536.1, ⋯ β^- 0.44 E^+ 2.98 E^- 0.36	**Cs131** 5/+ 9.69 d ε no γ E 0.355	**Cs132** 2+ 6.48 d ε β^+ 0.40, γ 667.7, ⋯ β^-, γ 464.6, ⋯ σ_α < 0.15 E^+ 2.125 E^- 1.279	**Cs133** 7/+ 100 σ_γ (2.7 + 26), (23 + 28E1) 132.90545193	8− **Cs134** 4+ 2.90 h IT 127.5, ⋯ γ 11.2 e^- σ_γ 14E1 6E1 2.065 a β^- 0.658, 0.089, ⋯ γ 604.7 795.9, ε vω E^- 2.0587 E^+ 1.233	19/− **Cs135** 7/+ 53 m IT 846.1 γ 787.2 2.3E6 a β^- 0.21 no γ σ_γ ~8.7, 9E1 E 0.269	8− **Cs136** 5+ 19 s IT β^- ? 13.10 d β^- 0.341, ⋯ γ 818.5, 1048.1, 340.5, ⋯ E 2.548	**Cs137** 7/+ 30.07 a β^- 0.514, ⋯ γ 661.7D, 283.4 vω σ_γ 0.25, ~0.4 E 1.1756	6− **Cs138** 3− 2.9 m IT 79.9 e^- β^- 3.3, ⋯ γ 1435.8, 462.8, 191.9D, ⋯ 32.2 m β^- 2.9, ⋯ γ 1435.8, 462.8, 1009.8, ⋯ E 5.37	**Cs139** 7/+ 9.3 m β^- 4.21, ⋯ γ 1283.3, 627.3, ⋯ E 4.213	**Cs140** 1− 1.06 m β^- 5.7, 6.21, ⋯ γ 602.3, ⋯ E 6.22
54	11/− **Xe129** 1/+ 8.89 d IT 196.6 e^- γ 39.6 e^- 26.4006 σ_γ ~21, ~25E1 128.904779	**Xe130** 4.0710 σ_γ (0.4 + ?), (16 + ?) 129.903508	11/− **Xe131** 3/+ 11.9 d IT 163.9 e^- 21.2324 σ_γ 9E1, 9E2 130.905082	**Xe132** 26.9086 σ_γ (0.05 + 0.4), (0.9 + 4) 131.904153	11/− **Xe133** 3/+ 2.19 d IT 233.2 5.243 d β^- 0.346, ⋯ γ 80.99, ⋯ σ_γ 2E2 E 0.427	(7−) **Xe134** 290 ms IT 234.3 γ 847.0, 884.1 10.4357 σ_γ (3.0 mb + 0.26) 133.905394	11/− **Xe135** 3/+ 15.3 m IT 526.6 β^- ω γ 786.9, ⋯ 9.10 h β^- 0.91, ⋯ γ 249.8, ⋯ σ_γ 2.6E6 ~7.6E3 E 1.165	**Xe136** 8.8573 σ_γ 0.26, 0.7 135.90722	**Xe137** 7/− 3.82 m β^- 4.1, 3.6, ⋯ γ 455.5, ⋯ E 4.17	**Xe138** 14.1 m β^- 0.8, 2.4, ⋯ γ 258.4, 434.6, 1768.4, 2015.9, ⋯ E 2.74	**Xe139** 3/− 39.7 s β^- 5.0, 4.5, ⋯ γ 218.6, 296.6, 175.0, ⋯ E 5.06
53	**I128** 1+ 25.00 m β^- 2.13, ⋯ γ 442.9, ⋯ ε, β^+ ω γ 743.4 ω σ_γ 22, ~10 E^- 2.122 E^+ 1.254	**I129** 7/+ 1.57E7 a β^- 0.15 γ 39.6 e^- σ_γ (18 + ~12.5), (18 + 16) E 0.194	2+ **I130** 5+ 9.0 m IT 39.96 e^- β^- 2.5, ⋯ γ 536.1, ⋯ 12.36 h β^- 1.04, 0.62, ⋯ γ 536.1, 668.6, 739.5, ⋯ σ_γ 18 E 2.949	**I131** 7/+ 8.023 d β^- 0.606, ⋯ γ 364.5, ⋯ σ_γ 0.7, 8 E 0.971	(8−) **I132** 4+ 1.39 h IT 98 e^- γ ~22 β^- 1.47, ⋯ γ 599.8, 667.7, 772.6, ⋯ 2.283 h β^- 1.22, 2.16, ⋯ γ 667.7, 772.6, ⋯ E 3.58	(19/−) **I133** 7/+ 9 s IT 74.0 e^- γ 647.4, 912.6, ⋯ 20.8 h β^- 1.24, ⋯ γ 529.9, ⋯ E 1.757	(8)− **I134** (4)+ 3.7 m IT 271.9 γ 44.4 β^- γ 234.3D, ⋯ 52.6 m β^- 1.2, ⋯ γ 847.0, 884.1, ⋯ E 4.05	**I135** 7/+ 6.57 h β^- 1.3, 0.9, ⋯ γ 1260.4, 1131.5, 526.6D, ⋯ E 2.63	(6−) **I136** (1−) 47 s β^- γ 1313.0, 381.4, 197.3D, ⋯ 1.39 m β^- 4.3, 5.6, ⋯ γ 1313.0, 1321.1, ⋯ E 6.93	**I137** (7/+) 24.5 s β^- γ 1218.0, 601.1, 1302.6, 1220.0, ⋯ (n) 0.369, 0.482, 0.564, ⋯ E 5.88	**I138** (2−) 6.5 s β^- ~7.4, ~6.9, ⋯ γ 588.9, 875.2, ⋯ (n) γ 601.0, 385.2 ω E 7.8
		76		**78**		**80**		**82**		**84**	



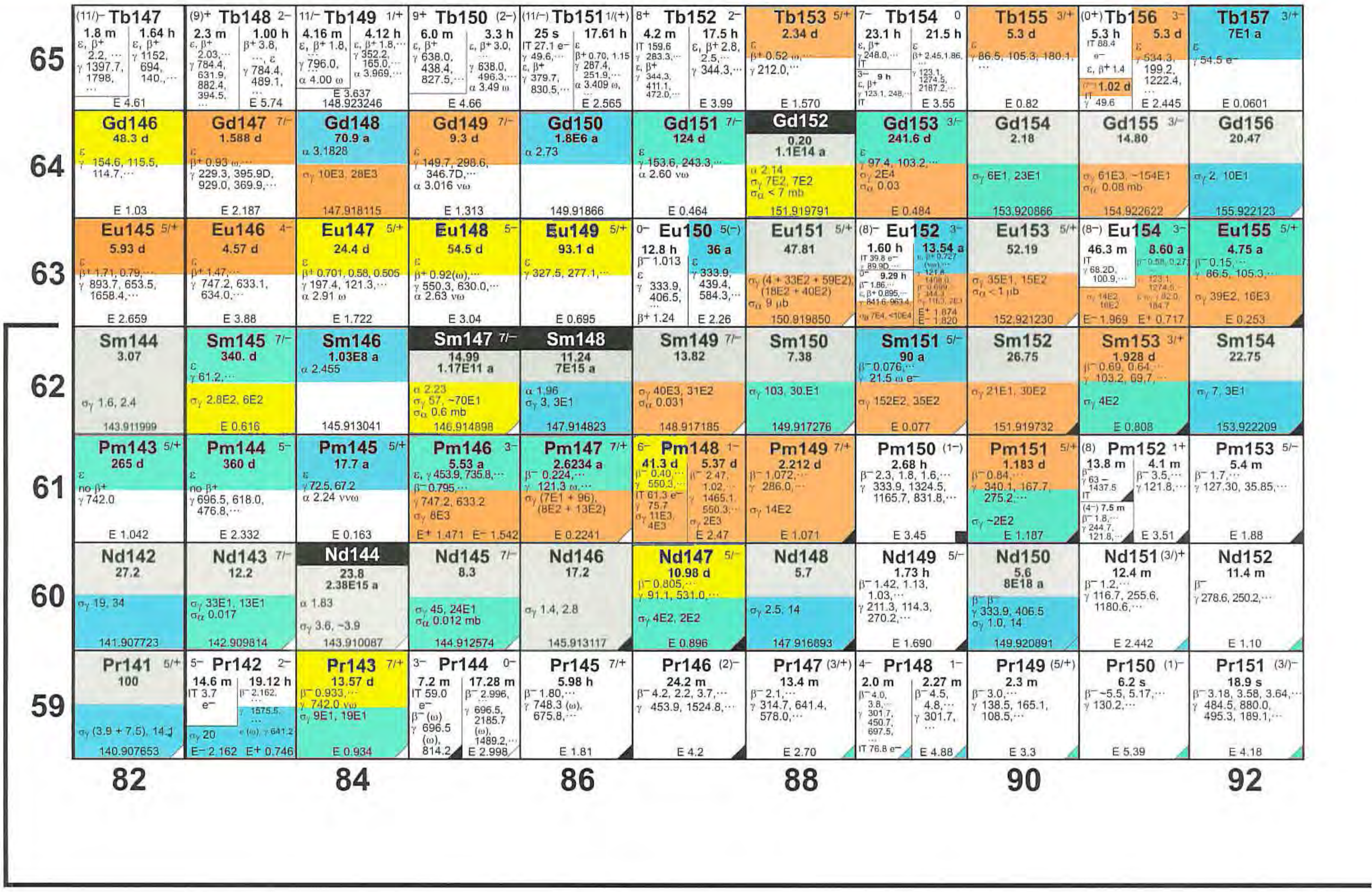
59								**Pr** 140.90765 praseodymium σ_a 11.4, 14.1	**Pr121** (3/−) 10 ms p 0.88 120.955		
58								**Ce** 140.116 cerium σ_a 0.63, 0.7		**Ce121** 5/+ 1.1 s β^+ (p) 2.2 – 5.9 γ 185.8, 358 E 10.	**Ce122** E 6.7
57						**La** 138.90547 lanthanum σ_a 9.0, 12	**La117** 3/ 23 ms p 0.81 116.9501			**La120** 2.8 s ε, β^+ (p) 2.1 – 5.6 E 11	**La121** 5.3 s β^+ γ 138.7, 134.0, ⋯ E 8
56				**Ba** 137.327 barium σ_a 1.3, 10	**Ba114** 0.4 s β^+ (p) α 3.41 ω E 8.6	**Ba115** ~0.45 s β^+ (p) E 11	**Ba116** 1.3 s β^+ (p) E 7.5	**Ba117** (3/) 1.8 s β^+, ε γ 94.9, 101.6 (p) 2.0 – 6.0 γ 394, ⋯ (α) ω E 9.2	**Ba118** 5.2 s β^+, ε γ 52.3, 64.9, ⋯ E 6.0	**Ba119** (5/+) 5.4 s β^+, ε (p) 2.0 – 6.0 E 7.7	**Ba120** 24 s β^+, ε γ 179.4, 269.9, 139.7, ⋯ E 5.0
55			**Cs** 132.9054519 cesium σ_a 29, 4.2E2	**Cs112** 0.5 ms p 0.81 111.9503	**Cs113** 17 µs p 0.960 112.9445	**Cs114** (1+) 0.58 s β^+, ε γ 449.6, 698.1, ⋯ (p), (α) ω α 3.24 ω E 12.5	**Cs115** ~1.4 s ε, β^+ (p) ω E 9.0	**Cs116** 0.7 s ↔ 3.8 s β^+, ε γ 393.5 (p) ω (α) ω β^+, ε γ 393.5, 524.3, ⋯ (p) 2.0 – 6.5 ω (α) vω E 11.0	**Cs117** 6.5 s β^+, ε γ ? ~8.4 s β^+, ε γ 204.8, 205.6, ⋯ E 7.7	(7−) **Cs118** 2 17 s ↔ 14 s β^+, ε γ 337.2, 472.7, ⋯ (p) ? (α) ? β^+, ε γ 337.2, ⋯ (p)? (α)? E 9.67	3/(+) **Cs119** 9/+ 30.4 s β^+, ε γ 314, 250, ⋯ 43 s β^+, ε γ 176, 225, 258, ⋯ E 6.49
54	**Xe** 131.293 xenon σ_a 25, 27E1	**Xe109** (7/+) 13 ms α 4.06, 3.92	**Xe110** 0.11 s ε, β^+ α 3.74 E 8.4 109.9443	**Xe111** 0.7 s ε, β^+ α 3.48 E 10.6 110.9416	**Xe112** 3 s ε, β^+ α 3.22 ω E 7.1	**Xe113** 2.8 s ε, β^+ (p), (α) ω α 2.98 ω E 9.0	**Xe114** 10.0 s ε, β^+ γ 308.5, 161.6, 103.1 E 5.7	**Xe115** (5/+) 18 s ε, β^+ (p) 2.0 – 6.0 ω γ 709 (α) vω E 7.68	**Xe116** 56 s β^+ 3.3, ⋯; ε γ 104.5 – 923.0 E 4.4	**Xe117** 5/(+) 1.02 m ε, β^+ 5.2, ⋯ γ 221.3, 294.7, ⋯ (p) 1.7 – 3.7 ω E 6.25	**Xe118** ~4 m ε, β^+ 2.7, ⋯ γ 54, 60, 120, ⋯ E 2.89
53	**I** 126.90447 iodine σ_a 6.2, ~1.50E2	**I108** ~36 ms α 3.947 107.9435	**I109** (1/+) 0.10 ms p 0.813 α 3.77 ω 108.9381	**I110** 0.65 s ε, β^+ α 3.44 (p) 2.50 – 6.00 (α) E 12.0 109.9352	**I111** (5/+) 2.5 s ε, β^+ α 3.15 ω E 8.5	**I112** 3.4 s ε, β^+ γ 689, 787, ⋯ (p) 2.0 – 5.0 ω (α) ω α 2.88 ω E 10.2	**I113** 5.9 s ε, β^+ γ 462.5, 622.4, ⋯ α 2.61 vω E 7.2	(7) **I114** 1+ 6.2 s ε, β^+ γ 708.8, ⋯ IT 134.5 γ 103.2, ⋯ 2.1 s ε, β^+ γ 708.8, ⋯ E 9.1	**I115** (5/+) 1.3 m ε, β^+ γ 275.7, 285.2, 458.9, ⋯ E 5.72	**I116** 1+ 2.9 s β^+ 6.7, ⋯ ε γ 678.9, 540.2, ⋯ E 7.8	**I117** (5/)+ 2.22 m β^+ 3.2, ⋯, ε γ 325.8, 274.4, ⋯ E 4.66
			56		**58**		**60**		**62**		**64**



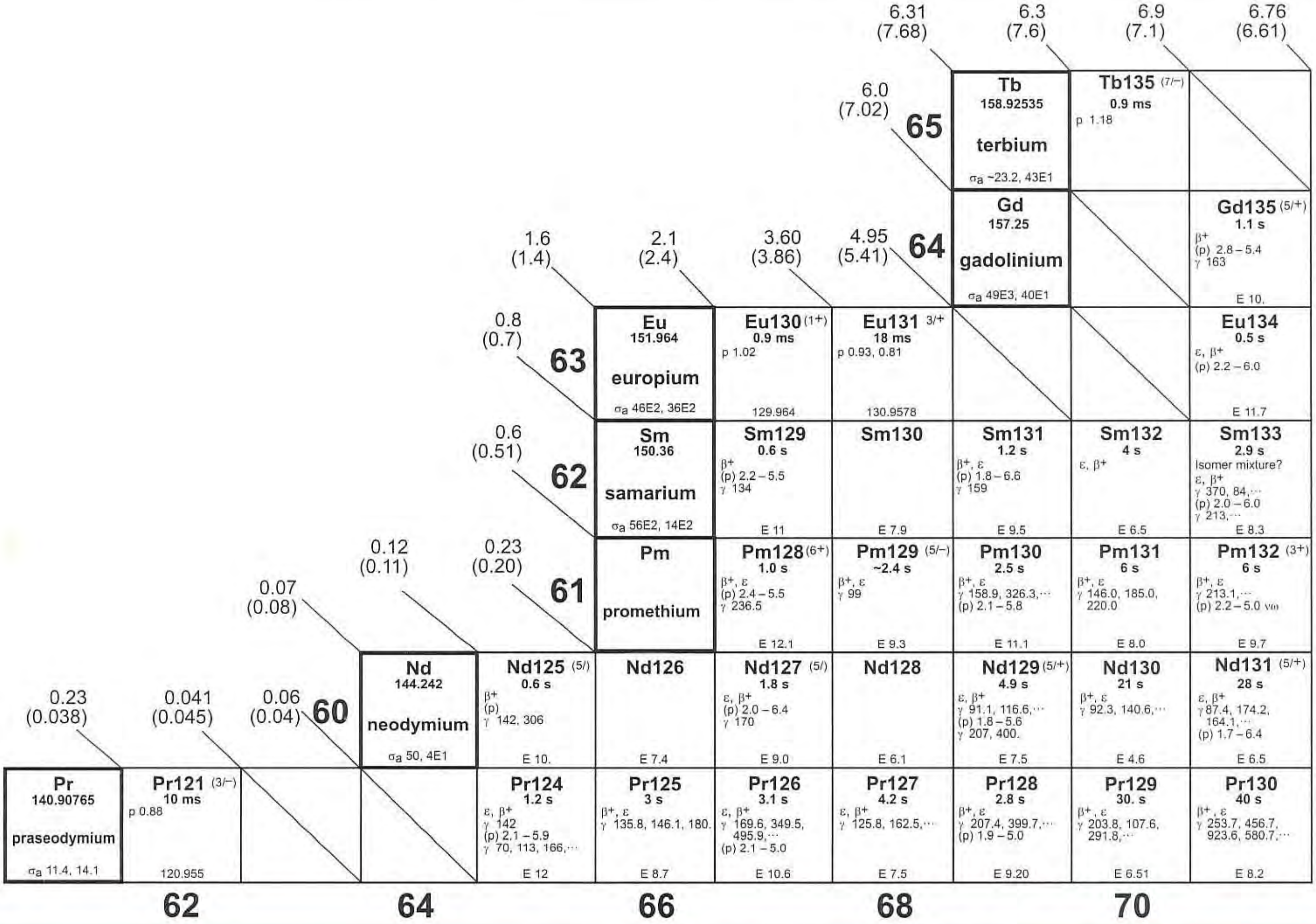
Pr145 7/+ 5.98 h β^- 1.80,⋯ γ 748.3 (ω), 675.8,⋯ E 1.81	**Pr146** (2)− 24.2 m β^- 4.2, 2.2, 3.7,⋯ γ 453.9, 1524.8,⋯ E 4.2	**Pr147** (3/+) 13.4 m β^- 2.1,⋯ γ 314.7, 641.4, 578.0,⋯ E 2.70	4− **Pr148** 1− 2.0 m β^- 4.0, 3.8,⋯ γ 301.7, 450.7, 697.5,⋯ IT 76.8 e^- 2.27 m β^- 4.5, 4.8,⋯ γ 301.7,⋯ E 4.88	**Pr149** (5/+) 2.3 m β^- 3.0,⋯ γ 138.5, 165.1, 108.5,⋯ E 3.3	**Pr150** (1)− 6.2 s β^- ~5.5, 5.17,⋯ γ 130.2,⋯ E 5.39	**Pr151** (3/)− 18.9 s β^- 3.18, 3.58, 3.64,⋯ γ 484.5, 880.0, 495.3, 189.1,⋯ E 4.18	**Pr152** (4+) 3.2 s β^- γ 164.1, 285.0, 1469.5,⋯ E 6.4	**Pr153** 4.3 s β^- γ 191.7D, 141.7D, 50.0,⋯ E 5.7	**Pr154** 2.3 s β^- 7.6,⋯ γ 162.4, 932.3, 70.8,⋯ E 7.5		
Ce144 284.6 d β^- 0.318, 0.185,⋯ γ 133.5, 80.1,⋯ σ_γ 1.0, 2.6 E 0.319	**Ce145** 3.00 m β^- 1.7, 1.3,⋯ γ 724.3, 62.5,⋯ E 2.54	**Ce146** 13.5 m β^- 0.7,⋯ γ 316.7, 218.2,⋯ E 1.04	**Ce147** (5/−) 56 s β^- 3.3,⋯ γ 268.8, 92.9,⋯ E 3.43	**Ce148** 56 s β^- 1.66,⋯ γ 269.5, 291.7, 121.1, 98.8,⋯ E 2.14	**Ce149** (3/−) 5.2 s β^- 3.4 – 4.2 γ 57.7, 380.0, 86.4,⋯ E 4.4	**Ce150** 4.4 s β^- 2.4,⋯ γ 109.9,⋯ E 3.48	**Ce151** (5/+) 1.8 s β^- γ 35.1, 38.9, 636.8, 362.1,⋯ E 5.3	**Ce152** 1.4 s β^- γ 114.8, 97.8 E 4.7	**Ce153** E 6.3	**Ce154** E 5	
La143 (7/)+ 14.2 m β^- 3.3,⋯ γ 620.4, 643.8, 621.4, 798.1,⋯ E 3.42	**La144** (3−) 40.7 s β^- 4.1,⋯ γ 397.4, 541.2, 844.8,⋯ E 5.54	**La145** (5/+) 24 s β^- 4.1,⋯ γ 69.7, 355.7, 118.1,⋯ E 4.1	(6−) **La146** 2− 10.0 s β^- 5.5,⋯ γ 258.4, 409.8, ⋯ E 6.7 6.3 s β^- 6.2,⋯ γ 258.5, ⋯ E 6.55	**La147** (5/+) 4.02 s β^- 4.6,⋯ γ 117.7, 186.8, 438.2, 215.4,⋯ (n) ω E 5.18	**La148** (2−) 1.1 s β^- γ 158.4,⋯ (n) ω E 7.3	**La149** 1.05 s β^- γ 133.5, 142.6, 245.1,⋯ (n) E 5.9	**La150** (3+) 0.51 s β^- γ 97.0, 208.7 (n) E 7.8	**La151** E 7.2	**La152** E 9.0	**La153** E 8	0.074
Ba142 10.7 m β^- 1.0, 1.10,⋯ γ 255.3, 1204.1, 895.0, 231.6,⋯ E 2.212	**Ba143** 5/− 14.3 s β^- 3.24,⋯ γ 211.5, 798.8, 980.5,⋯ E 4.25	**Ba144** 11.4 s β^- 2.4, 2.9,⋯ γ 103.9, 430.5, 172.8, 156.6,⋯ E 3.12	**Ba145** 5/− 4.0 s β^- 4.9,⋯ γ 97.1, 91.9,⋯ E 5.6	**Ba146** 2.20 s β^- 3.9,⋯ γ 140.7, 251.2, 121.2, 197.2,⋯ E 4.12	**Ba147** (3/+) 0.892 s β^- 5.5,⋯ γ 167.4, 105.2, 196.1,⋯ (n) ω E 6.3	**Ba148** 0.64 s β^- γ 56.1, 133.7, 415.8,⋯ (n) ω E 5.1	**Ba149** 0.34 s β^- γ 286.3, 180.1, 226.0, 357.3,⋯ (n) E 7.3	**Ba150** 0.3 s E 6	**Ba151** E 8	**96** 0.267	0.158
Cs141 7/+ 24.9 s β^- 5.20,⋯ γ 48.5, 561.6, 1194.0,⋯ (n) ω E 5.25	**Cs142** 0− 1.69 s β^- 7.28, 6.9,⋯ γ 359.6, 1326.5, 966.9,⋯ (n) ω E 7.31	**Cs143** 3/+ 1.79 s β^- 6.1,⋯ γ 195.3, 232.5, 306.6,⋯ (n) E 6.26	**Cs144** 1 0.99 s β^- 8.46, 7.9,⋯ γ 199.3,⋯ (n) E 8.50	**Cs145** 3/+ 0.57 s β^- 7.9, 7.4,⋯ γ 175.4, 198.9, 112.5,⋯ (n) E 7.4	**Cs146** 1− 0.322 s β^- ~9.0,⋯ γ 181.0,⋯ (n) E 9.38	**Cs147** (3/+) 0.227 s β^- γ 85.4, 245.9, 109.8, 351.2,⋯ (n) E 8.6	**Cs148** 0.15 s β^- γ 141.7,⋯ (n) E 11	**94** 1.08	0.653	0.419	
Xe140 13.6 s β^- 2.6,⋯ γ 805.6, 1413.6, 621.9,⋯ E 4.1	**Xe141** 5/(−) 1.72 s β^- 6.2,⋯ γ 909.2, 118.7, 105.9,⋯ (n) ω E 6.2	**Xe142** 1.23 s β^- 3.7, 4.2,⋯ γ 571.9, 657.1, 538.3, 618.3,⋯ (n) ω E 5.0	**Xe143** 5/− 0.96 s ↔ 0.51 s β^- γ 140, 194 β^- γ 90 E 7.2	**Xe144** 0.39 s β^- (n) E 6.0	**Xe145** 188 ms β^- (n) E 8.0	**Xe146** 0.15 s β^- (n) E 6.9	**Xe147** ~ 0.1 s β^- E 8.8	1.67			
I139 (7/+) 2.30 s β^- γ 527.7, 571.1,⋯ (n) 0.13 – 0.56 γ 588.8, 483.6,⋯ E 6.81	**I140** (4−) 0.86 s β^- γ 376.7, 457.6,⋯ (n) E 8.7	**I141** 0.45 s β^- γ 338 – 572 ? (n) 0.16 – 0.55 E 7.8	**I142** 0.22 s β^- E 9.8	**I143** 0.13 s β^- E 8.8	**I144** E 11	**92** 3.93	3.00	2.25		**Ce155** E 7	
86		**88**		**90**	5.96	5.50					0.032



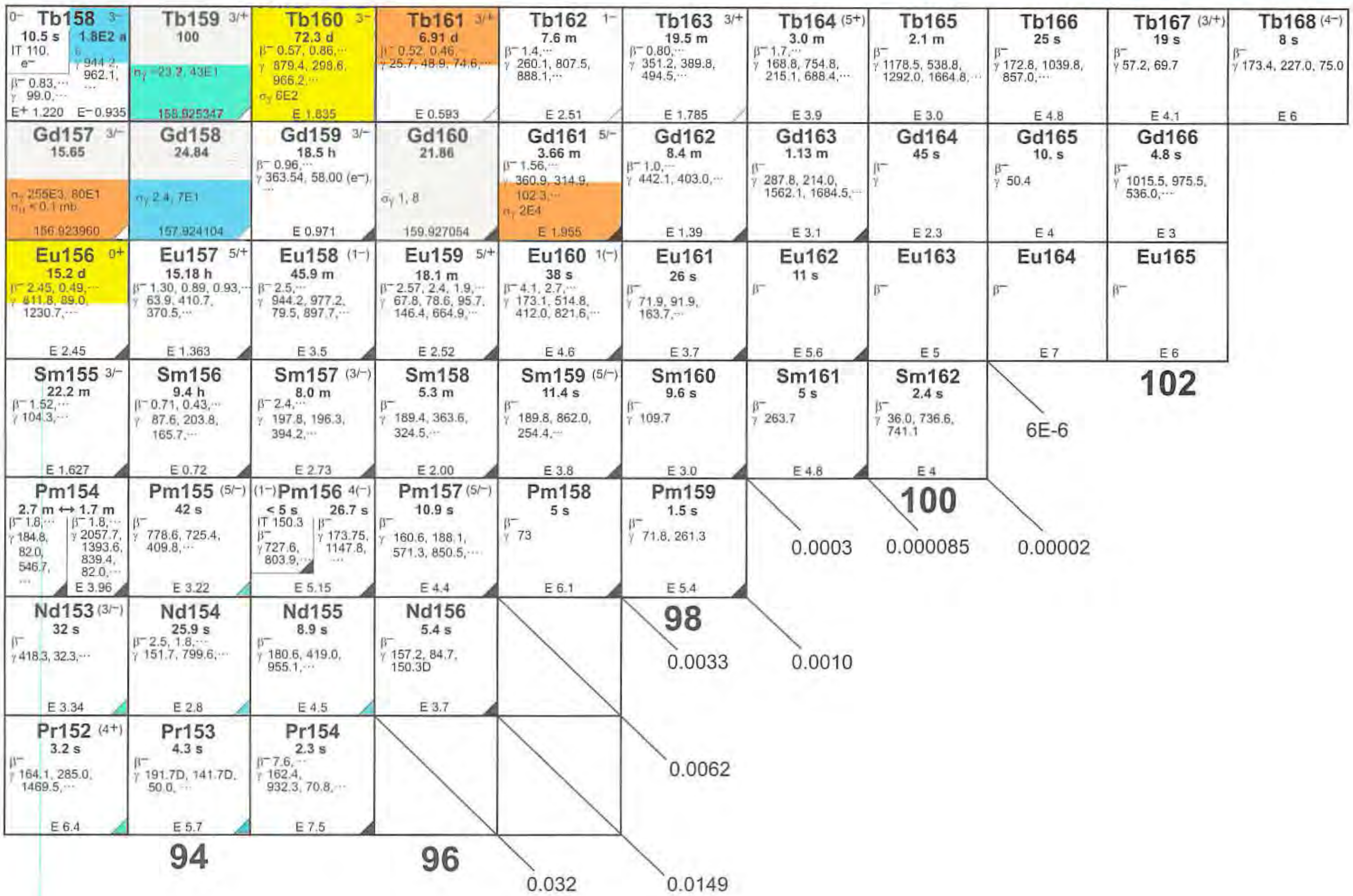
Pr124 1.2 s ε, β^+ γ 142 (p) 2.1 – 5.9 γ 70, 113, 166,⋯ E 12	**Pr125** 3 s β^+, ε γ 135.8, 146.1, 180. E 8.7	**Pr126** 3.1 s ε, β^+ γ 169.6, 349.5, 495.9,⋯ (p) 2.1 – 5.0 E 10.6	**Pr127** 4.2 s ε, β^+ γ 125.8, 162.5,⋯ E 7.5	**Pr128** 2.8 s β^+, ε γ 207.4, 399.7,⋯ (p) 1.9 – 5.0 E 9.20	**Pr129** 30. s β^+, ε γ 203.8, 107.6, 291.8,⋯ E 6.51	**Pr130** 40 s β^+, ε γ 253.7, 456.7, 923.6, 580.7,⋯ E 8.2	(11/−) **Pr131** (3/+) 5.7 s IT 65 e^- γ 87.8 ε γ 138, 162 1.53 m β^+, ε γ 266.1, 72.8,⋯ E 5.4	**Pr132** (2)+ 1.7 m β^+, ε γ 325.4, 496.9, 822.4, 533.6, 874.2,⋯ E 7.3	(11/−) **Pr133** (3/+) 1.1 s IT 130.5 γ 61.7 6.5 m β^+, ε γ 134.3, 315.6, 465.2, ⋯ E 4.49	(6−) **Pr134** 2− ~11 m ↔ 17 m β^+, ε γ 409.3, 639.7,⋯ β^+, ε γ 409.3,⋯ E 6.32
Ce123 (5/) 3.8 s ε, β^+ (p) 2.0 – 5.8 E 8.5	**Ce124** 6 s ε γ 120, 253, 544, 560 E 5.4	**Ce125** (7/−) 9.0 s ε, β^+ γ 56, 491 (p) 1.7 – 5.1 γ 229.9, 421.1, 576.9 E 7.1	**Ce126** 50 s ε E 4.2	**Ce127** (5/+) 29 s ε, β^+ γ 120.3, 196.0, 311.6,⋯ E 5.9	**Ce128** 4.0 m ε, β^+ γ 146.7, 104.1,⋯ E 3.1	**Ce129** (5/+) 4.1 m ε, β^+ γ 171.5, 68.2,⋯ E 5.04	**Ce130** 23 m ε, β^+ γ 131, 108 – 307 E 2.21	(1/+) **Ce131** (7/+) 5 m ε, β^+ γ 230.4, ⋯ 10.2 m ε, β^+ 2.8, ⋯ γ 169.4, 414.2, ⋯ E 4.05	**Ce132** 3.5 h ε γ 182.1, 155.4,⋯ E 1.27	9/− **Ce133** 1/+ 5.4 h ε β^+ 1.3,⋯ γ 477.2, 510.4, 58.4,⋯ 1.6 h ε, β^+ γ 97.3, 76.9, 557.7, ⋯ E 3.07
La122 9 s ε, β^+ (p) 2.0 – 4.6 E 10.1	**La123** 17 s ε γ 93, 937, 154,⋯ E 6.9	**La124** (8−) 21 s ↔ 29.2 s β^+, ε γ 841.4, ⋯ β^+, ε γ 229.7, 421.5, 576.6, ⋯ E 8.8	**La125** 1.2 m β^+, ε γ 68, 44,⋯ E 5.91	≤ 3 **La126** 5+ < 50 s β^+, ε γ 256, 1774,⋯ E 7.9 54 s β^+, ε γ 256, 455, 1228, ⋯ E 7.7	(3/+) **La127** (11/−) 3.7 m β^+, ε γ 56.2, 25.0 5.1 m β^+, ε γ 80.3 – 2271.6 E 4.92	≥ 4 **La128** (1, 2) 5.3 m ↔ < 1.4 m β^+ 3.2,⋯, ε γ 284.1, 479.3, ⋯ β^+, ε γ 284.1, 658.5, ⋯ E 6.8	11/− **La129** 3/+ 0.56 s IT 104.5 e^- γ 67.5 11.6 m β^+ 2.42, ⋯, ε γ 278.6, 110.5, ⋯ E 3.74	**La130** 3(+) 8.7 m β^+ 3.7, 4.3, ε γ 357.4, 550.7, 908.0, 544.5,⋯ E 5.63	**La131** 3/+ 59 m ε, β^+ 1.42, 1.94,⋯ γ 108.1, 417.8, 365.2, 285.2,⋯ E 2.91	6− **La132** 2− 24 m IT 52.8 (e^-), 188.5 ω γ 135.8 ε, β^+ γ 464.6,⋯ 4.8 h ε, β^+ 3.2, 2.6, 3.7,⋯ γ 464.6, 567.2,⋯ E 4.69
Ba121 5/(+) 30. s β^+, ε γ 112, 99,⋯ (p) 2.0 – 3.6 ω E 6.4	**Ba122** 2.0 m ε, β^+ γ 25 – 65 E 3.53	**Ba123** 5/(+) 2.7 m β^+, ε γ 94.6, 123.6, 201.0,⋯ E 5.39	**Ba124** 12 m ε, β^+ γ 169.5, 189.0,⋯ E 2.64	**Ba125** 1/(+) 8 m ? ε, β^+ 4.5 3.5 m ε, β^+ 3.4, ⋯ γ 78, 141, 86, ⋯ E 4.42	**Ba126** 1.65 h ε β^+ γ 233.6, 257.6, 241.0,⋯ E 1.68	7/− **Ba127** 1/+ 1.9 s IT 80.2, 24.2 γ 56.2 12.9 m β^+ 2.4, 2.23, ⋯, ε γ 180.8, 114.8, ⋯ E 3.42	**Ba128** 2.43 d ε γ 273.4,⋯ E 0.53	7/+ **Ba129** 1/+ 2.17 h ε, β^+ γ 182.3, 1459.0, ⋯ 2.2 h β^+ 1.42, ⋯ γ 214.3, 220.9, 129.1,⋯ E 2.44	**Ba130** 0.106 2E21 a 2ε σ_γ (~0.98 + 6.5), (23 + 15E1) 129.906321	9/− **Ba131** 1/+ 14.6 m IT 79.0 e^- γ 108.4 11.53 d ε β^+ νω γ 496.3, 123.8, 216.1,⋯ E 1.38
(7−) **Cs120** 2(+) 57 s ↔ 64 s β^+, ε γ 322.4, 473.5, 553.4, ⋯ ε, β^+ γ 322.4, 473.5, 553.4, ⋯ (α) νω, (p) E 8.28	9/(+) **Cs121** 3/(+) 2.0 m β^+ 4.4, ⋯, ε γ 196.1, 179.4, ⋯ IT 68.5 e^- 2.6 m β^+ 4.38, ⋯, ε γ 153.8, 239.6, ⋯ E 5.37	8(−) **Cs122** 1+ 4.4 m β^+, ε γ 331.1, 497.1, 638.5, ⋯ 21 s β^+ ~5.8, ⋯, ε γ 331.1, ⋯ E 7.22	(11/)− **Cs123** 1/+ 1.6 s IT 61.7 e^- γ 94.6, 64.0,⋯ 5.94 m β^+ 3.0, ⋯, ε γ 97.4, 596.5, ⋯ E 4.20	(7)+ **Cs124** 1+ 6.3 s IT 64.9 e^-,⋯ γ 211.6, 89.5, 96.6,⋯ 30 s β^+ ~5, 4.4,⋯ ε γ 354.0, ⋯ E 5.93	**Cs125** 1/(+) 45 m ε, β^+ 2.06,⋯ γ 525, 112, 413,⋯ E 3.10	**Cs126** 1+ 1.64 m β^+ 3.7, 3.4,⋯, ε γ 388.7,⋯ E 4.82	**Cs127** 1/+ 6.2 h ε β^+ 1.06, 0.65,⋯ γ 411.9, 124.7,⋯ E 2.08	**Cs128** 1+ 3.62 m β^+ 2.88, 2.44,⋯, ε γ 442.9,⋯ E 3.93	**Cs129** 1/+ 1.336 d ε β^+ ω γ 371.9, 411.5,⋯ E 1.197	5− **Cs130** 1+ 3.5 m IT 82.9,⋯ γ 80.4, 148.4, 51.2,⋯ β^+ ω, ε E+ 2.98 29.21 m ε, β^+ 1.98,⋯ γ 536.1,⋯ β^- 0.44 E− 0.36
Xe119 (5/+) 5.8 m ε, β^+ 3.5,⋯ γ 232, 100, 461,⋯ E 4.97	**Xe120** 46 m ε β^+ γ 25.1, 72.6, 178.0,⋯ E 1.62	**Xe121** 5/(+) 39 m ε β^+ 2.8,⋯ γ 252.8, 132.9, 445.3,⋯ E 3.81	**Xe122** 20.1 h ε γ 350.1, 148.6, 416.6,⋯ E 0.73	**Xe123** (1/)+ 2.00 h ε, β^+ 1.51,⋯ γ 148.9, 178.0, 330.2,⋯ E 2.69	**Xe124** 0.0952 σ_γ (~28 + 1.4E2), (6E2 + 2E3) 123.905893	9/(−) **Xe125** 1/(+) 57 s IT 140 γ 112 17.1 h ε β^+ 0.47 ω, ⋯ γ 188.4,⋯ σ_α < 0.03 E 1.644	**Xe126** 0.0890 σ_γ (0.4 + 3), (8 + 5E1) 125.90427	9/− **Xe127** 1/+ 1.15 m IT 172.5 e^- γ 124.7 36.4 d ε γ 202.9, 172.1, ⋯ σ_α < 0.01 E 0.662	**Xe128** 1.9102 σ_γ (0.5 + ?), (4E1 + ?) 127.903531	11/− **Xe129** 1/+ 8.89 d IT 196.6 e^- γ 39.6 e^- 26.4006 σ_γ ~21, ~25E1 128.904779
(7−) **I118** 2− 8.5 m β^+ 4.9, ⋯, ε γ 599.9, 605.0, 613.8 IT 104? 14 m β^+ 5.4, ⋯, ε γ 605.0, ⋯ E 6.75	**I119** 5/+ 19.1 m β^+ 2.4,⋯, ε γ 257.5,⋯ E 3.42	(7−) **I120** 2− 53 m β^+ 3.8, ⋯, ε γ 560.4, 601.1, 614.7, ⋯ 1.361 h β^+ 4.03, 4.60, ⋯, ε γ 560.4, ⋯ E 5.62	**I121** 5/+ 2.12 h ε β^+ 1.2,⋯ γ 212.2,⋯ E 2.26	**I122** 1+ 3.6 m β^+ 3.1,⋯, ε γ 564.1,⋯ E 4.234	**I123** 5/+ 13.221 h ε γ 159.0,⋯ E 1.229	**I124** 2− 4.176 d ε, β^+ 1.54, 2.14, ⋯ γ 602.7,⋯ E 3.160	**I125** 5/+ 59.4 d ε γ 35.49 e^- σ_γ 9E2, 1.4E4 E 0.1858	**I126** 2− 12.89 d ε, γ 666.3,⋯ β^- 0.87,⋯ γ 388.6, ⋯ β^+ 1.13 (ω),⋯ σ_γ 5.96E3, 4.06E4 E+ 2.154 E− 1.258	**I127** 5/+ 100 σ_γ 6.2, ~1.50E2 126.904473	**I128** 1+ 25.00 m β^- 2.13,⋯ γ 442.9,⋯ ε, β^+ ω γ 743.4 ω σ_γ 22, ~10 E− 2.122 E+ 1.254
	66		**68**		**70**		**72**		**74**	



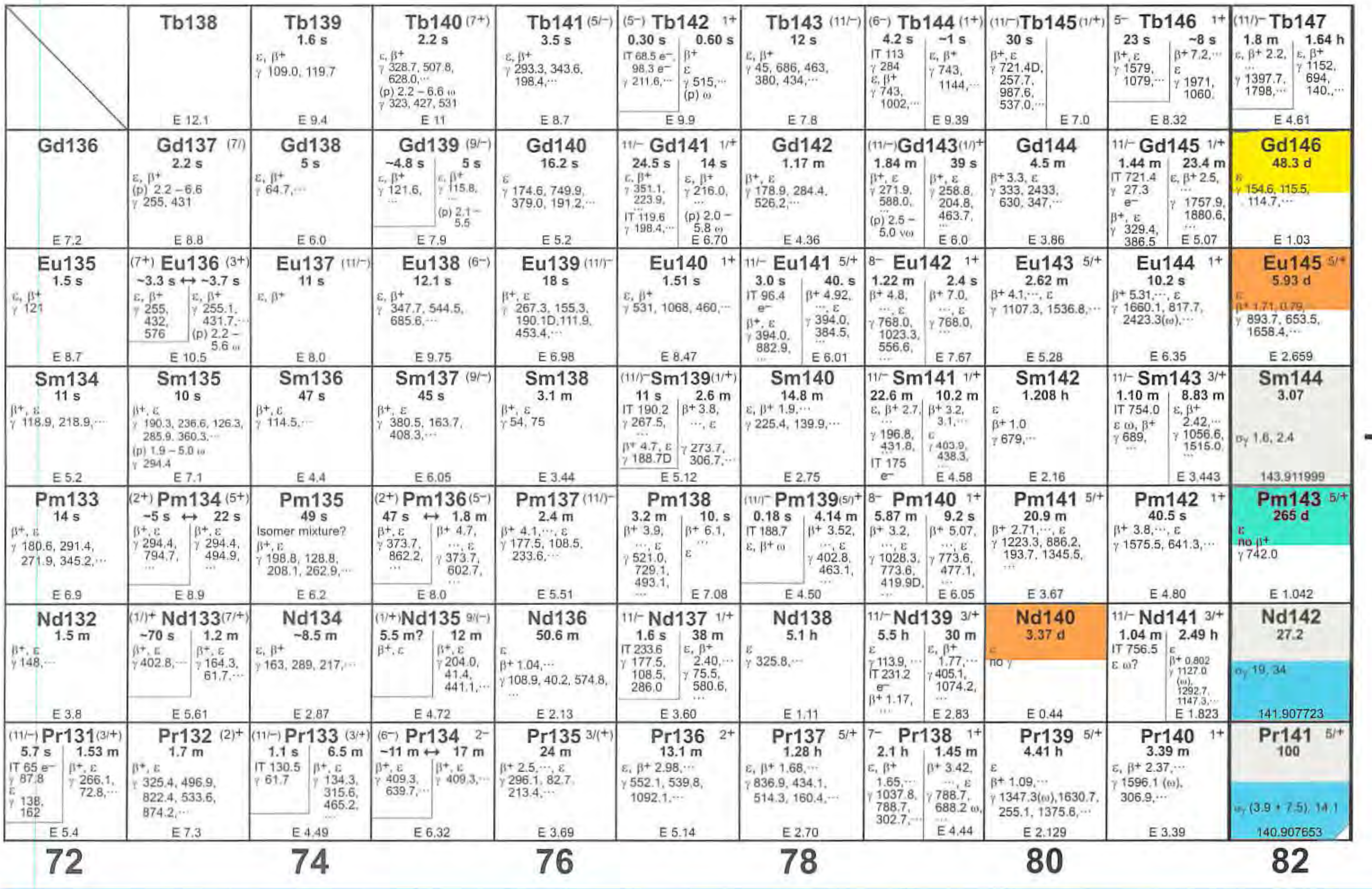
Z	82		84		86		88		90		92
65	(11/)− **Tb147** 1.8 m ε, β^+ 2.2, ··· γ 1397.7, 1798, ··· 1.64 h ε, β^+ γ 1152, 694, 140.,··· E 4.61	(9)+ **Tb148** 2− 2.3 m ε, β^+ 2.03,··· γ 784.4, 631.9, 882.4, 394.5, ··· 1.00 h β^+ 3.8, ···, ε γ 784.4, 489.1, ··· E 5.74	11/− **Tb149** 1/+ 4.16 m ε, β^+ 1.8, ··· γ 796.0, ··· α 4.00 ω 4.12 h ε, β^+ 1.8,··· γ 352.2, 165.0,··· α 3.969,··· E 3.637 148.923246	9+ **Tb150** (2−) 6.0 m ε, β^+ γ 638.0, 438.4, 827.5,··· 3.3 h ε, β^+ 3.0, ··· γ 638.0, 496.3,··· α 3.49 ω E 4.66	(11/−) **Tb151** 1/(+) 25 s IT 27.1 e^- γ 49.6,··· ε, β^+ γ 379.7, 830.5,··· 17.61 h ε β^+ 0.70, 1.15 γ 287.4, 251.9,··· α 3.409 ω, ··· E 2.565	8+ **Tb152** 2− 4.2 m IT 159.6 γ 283.3,··· ε, β^+ γ 344.3, 411.1, 472.0,··· 17.5 h ε, β^+ 2.8, 2.5,··· γ 344.3,··· E 3.99	**Tb153** 5/+ 2.34 d ε β^+ 0.52 ω,··· γ 212.0,··· E 1.570	7− **Tb154** 0 23.1 h ε, β^+ γ 248.0,··· IT 3− 9 h ε, β^+ γ 123.1, 248,··· IT 21.5 h ε β^+ 2.45,1.86, ··· γ 123.1, 1274.5, 2187.2,··· E 3.55	**Tb155** 3/+ 5.3 d ε γ 86.5, 105.3, 180.1, ··· E 0.82	(0+) **Tb156** 3− 5.3 h IT 88.4 e^- ε, β^+ 1.4 (7−) 1.02 d IT γ 49.6 5.3 d ε γ 534.3, 199.2, 1222.4, ··· E 2.445	**Tb157** 3/+ 7E1 a ε γ 54.5 e^- E 0.0601
64	**Gd146** 48.3 d ε γ 154.6, 115.5, 114.7,··· E 1.03	**Gd147** 7/− 1.588 d ε β^+ 0.93 ω,··· γ 229.3, 395.9D, 929.0, 369.9,··· E 2.187	**Gd148** 70.9 a α 3.1828 σ_γ 10E3, 28E3 147.918115	**Gd149** 7/− 9.3 d ε γ 149.7, 298.6, 346.7D,··· α 3.016 vω E 1.313	**Gd150** 1.8E6 a α 2.73 149.91866	**Gd151** 7/− 124 d ε γ 153.6, 243.3,··· α 2.60 vω E 0.464	**Gd152** 0.20 1.1E14 a α 2.14 σ_γ 7E2, 7E2 σ_α < 7 mb 151.919791	**Gd153** 3/− 241.6 d ε γ 97.4, 103.2,··· σ_γ 2E4 σ_α 0.03 E 0.484	**Gd154** 2.18 σ_γ 6E1, 23E1 153.920866	**Gd155** 3/− 14.80 σ_γ 61E3, ~154E1 σ_α 0.08 mb 154.922622	**Gd156** 20.47 σ_γ 2, 10E1 155.922123
63	**Eu145** 5/+ 5.93 d ε β^+ 1.71, 0.79,··· γ 893.7, 653.5, 1658.4,··· E 2.659	**Eu146** 4− 4.57 d ε β^+ 1.47,··· γ 747.2, 633.1, 634.0,··· E 3.88	**Eu147** 5/+ 24.4 d ε β^+ 0.701, 0.58, 0.505 γ 197.4, 121.3,··· α 2.91 ω E 1.722	**Eu148** 5− 54.5 d ε β^+ 0.92(ω),··· γ 550.3, 630.0,··· α 2.63 vω E 3.04	**Eu149** 5/+ 93.1 d ε γ 327.5, 277.1,··· E 0.695	0− **Eu150** 5(−) 12.8 h β^- 1.013 ε γ 333.9, 406.5, ··· β^+ 1.24 36 a ε γ 333.9, 439.4, 584.3,··· E 2.26	**Eu151** 5/+ 47.81 σ_γ (4 + 33E2 + 59E2), (18E2 + 40E2) σ_α 9 μb 150.919850	(8)− **Eu152** 3− 1.60 h IT 39.8 e^- γ 89.9D,··· 0− 9.29 h β^- 1.86,··· ε, β^+ 0.895,··· γ 841.6, 963.4, σ_γ 7E4, <10E4 13.54 a ε, β^+ 0.727 (vω),··· γ 121.8, 1408.0 β^- 0.699 γ 344.3 σ_γ 11E3, 2E3 E^+ 1.874 E^- 1.820	**Eu153** 5/+ 52.19 σ_γ 35E1, 15E2 σ_α < 1 μb 152.921230	(8−) **Eu154** 3− 46.3 m IT γ 68.2D, 100.9,··· σ_γ 14E2, 16E2 8.60 a β^- 0.58, 0.27, ··· γ 123.1, 1274.5,··· ε (ω), γ 82.0, 184.7 E^- 1.969 E^+ 0.717	**Eu155** 5/+ 4.75 a β^- 0.15,··· γ 86.5, 105.3,··· σ_γ 39E2, 16E3 E 0.253
62	**Sm144** 3.07 σ_γ 1.6, 2.4 143.911999	**Sm145** 7/− 340. d ε γ 61.2,··· σ_γ 2.8E2, 6E2 E 0.616	**Sm146** 1.03E8 a α 2.455 145.913041	**Sm147** 7/− 14.99 1.17E11 a α 2.23 σ_γ 57, ~70E1 σ_α 0.6 mb 146.914898	**Sm148** 11.24 7E15 a α 1.96 σ_γ 3, 3E1 147.914823	**Sm149** 7/− 13.82 σ_γ 40E3, 31E2 σ_α 0.031 148.917185	**Sm150** 7.38 σ_γ 103, 30.E1 149.917276	**Sm151** 5/− 90 a β^- 0.076,··· γ 21.5 ω e^- σ_γ 152E2, 35E2 E 0.077	**Sm152** 26.75 σ_γ 21E1, 30E2 151.919732	**Sm153** 3/+ 1.928 d β^- 0.69, 0.64,··· γ 103.2, 69.7,··· σ_γ 4E2 E 0.808	**Sm154** 22.75 σ_γ 7, 3E1 153.922209
61	**Pm143** 5/+ 265 d ε no β^+ γ 742.0 E 1.042	**Pm144** 5− 360 d ε no β^+ γ 696.5, 618.0, 476.8,··· E 2.332	**Pm145** 5/+ 17.7 a ε γ 72.5, 67.2 α 2.24 vvω E 0.163	**Pm146** 3− 5.53 a ε, γ 453.9, 735.8,··· β^- 0.795,··· γ 747.2, 633.2 σ_γ 8E3 E^+ 1.471 E^- 1.542	**Pm147** 7/+ 2.6234 a β^- 0.224,··· γ 121.3 ω,··· σ_γ (7E1 + 96), (8E2 + 13E2) E 0.2241	6− **Pm148** 1− 41.3 d β^- 0.40,··· γ 550.3,··· IT 61.3 e^- γ 75.7 σ_γ 11E3, 4E3 5.37 d β^- 2.47, 1.02,··· γ 1465.1, 550.3,··· σ_γ 2E3 E 2.47	**Pm149** 7/+ 2.212 d β^- 1.072,··· γ 286.0,··· σ_γ 14E2 E 1.071	**Pm150** (1−) 2.68 h β^- 2.3, 1.8, 1.6,··· γ 333.9, 1324.5, 1165.7, 831.8,··· E 3.45	**Pm151** 5/+ 1.183 d β^- 0.84,··· γ 340.1, 167.7, 275.2,··· σ_γ ~2E2 E 1.187	(8) **Pm152** 1+ 13.8 m β^- γ 63 – 1437.5 IT (4−) 7.5 m β^- 1.8,··· γ 244.7, 121.8,··· 4.1 m β^- 3.5,··· γ 121.8,··· E 3.51	**Pm153** 5/− 5.4 m β^- 1.7,··· γ 127.30, 35.85,··· E 1.88
60	**Nd142** 27.2 σ_γ 19, 34 141.907723	**Nd143** 7/− 12.2 σ_γ 33E1, 13E1 σ_α 0.017 142.909814	**Nd144** 23.8 2.38E15 a α 1.83 σ_γ 3.6, ~3.9 143.910087	**Nd145** 7/− 8.3 σ_γ 45, 24E1 σ_α 0.012 mb 144.912574	**Nd146** 17.2 σ_γ 1.4, 2.8 145.913117	**Nd147** 5/− 10.98 d β^- 0.805,··· γ 91.1, 531.0,··· σ_γ 4E2, 2E2 E 0.896	**Nd148** 5.7 σ_γ 2.5, 14 147.916893	**Nd149** 5/− 1.73 h β^- 1.42, 1.13, 1.03,··· γ 211.3, 114.3, 270.2,··· E 1.690	**Nd150** 5.6 8E18 a $\beta^-\beta^-$ γ 333.9, 406.5 σ_γ 1.0, 14 149.920891	**Nd151** (3/)+ 12.4 m β^- 1.2,··· γ 116.7, 255.6, 1180.6,··· E 2.442	**Nd152** 11.4 m β^- γ 278.6, 250.2,··· E 1.10
59	**Pr141** 5/+ 100 σ_γ (3.9 + 7.5), 14.1 140.907653	5− **Pr142** 2− 14.6 m IT 3.7 e^- σ_γ 20 19.12 h β^- 2.162, ··· γ 1575.5, ··· ε (ω), γ 641.2 E^- 2.162 E^+ 0.746	**Pr143** 7/+ 13.57 d β^- 0.933,··· γ 742.0 vω σ_γ 9E1, 19E1 E 0.934	3− **Pr144** 0− 7.2 m IT 59.0 e^- β^- (ω) γ 696.5 (ω), 814.2 17.28 m β^- 2.996, ··· γ 696.5, 2185.7 (ω), 1489.2,··· E 2.998	**Pr145** 7/+ 5.98 h β^- 1.80,··· γ 748.3 (ω), 675.8,··· E 1.81	**Pr146** (2)− 24.2 m β^- 4.2, 2.2, 3.7,··· γ 453.9, 1524.8,··· E 4.2	**Pr147** (3/+) 13.4 m β^- 2.1,··· γ 314.7, 641.4, 578.0,··· E 2.70	4− **Pr148** 1− 2.0 m β^- 4.0, 3.8,··· γ 301.7, 450.7, 697.5, ··· IT 76.8 e^- 2.27 m β^- 4.5, 4.8,··· γ 301.7, ··· E 4.88	**Pr149** (5/+) 2.3 m β^- 3.0,··· γ 138.5, 165.1, 108.5,··· E 3.3	**Pr150** (1)− 6.2 s β^- ~5.5, 5.17,··· γ 130.2,··· E 5.39	**Pr151** (3/)− 18.9 s β^- 3.18, 3.58, 3.64,··· γ 484.5, 880.0, 495.3, 189.1,··· E 4.18



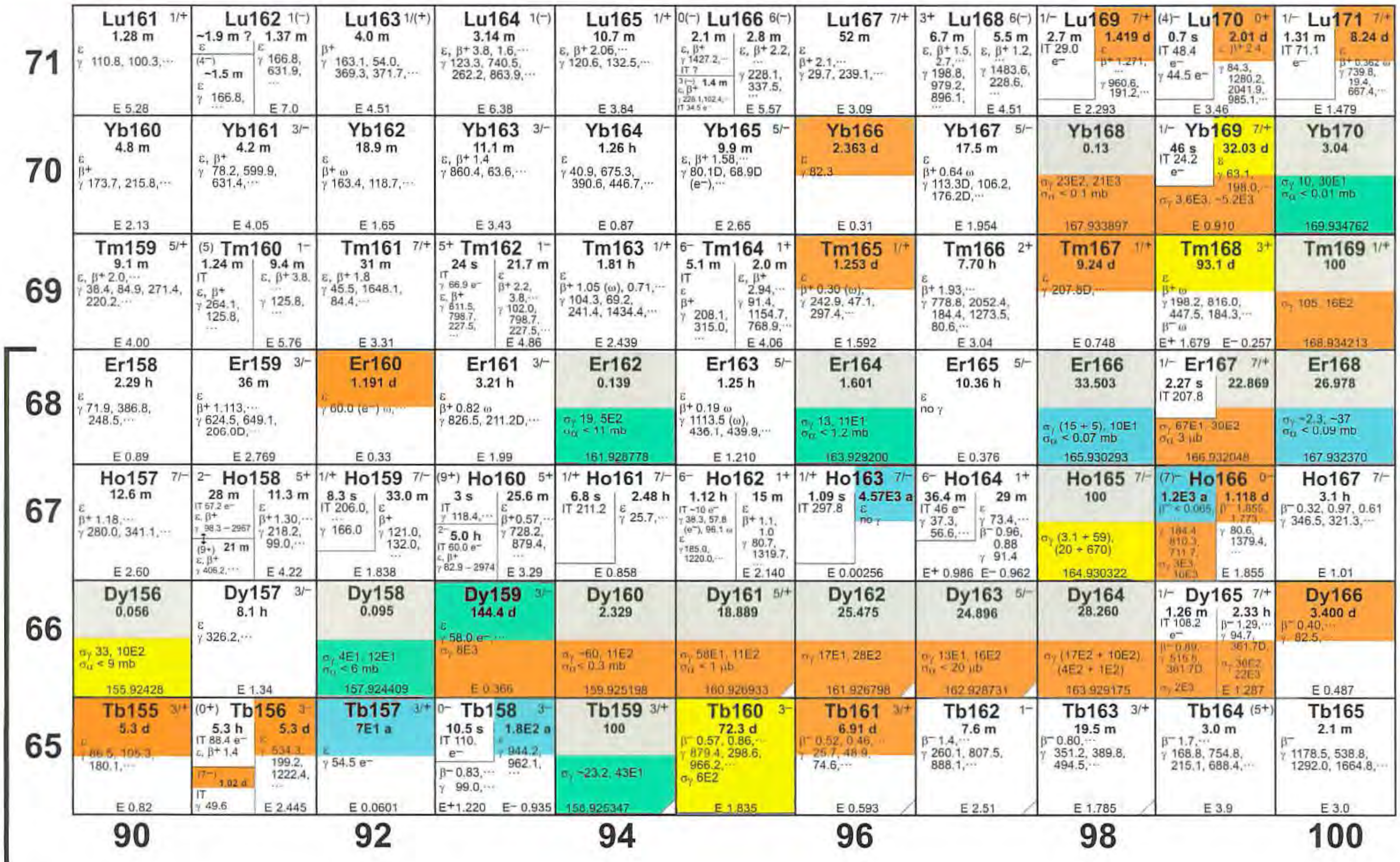
Z		62		64		66		68		70	
65									**Tb** 158.92535 terbium σ_a ~23.2, 43E1	**Tb135** (7/−) 0.9 ms p 1.18	
64									**Gd** 157.25 gadolinium σ_a 49E3, 40E1		**Gd135** (5/+) 1.1 s β^+ (p) 2.8 – 5.4 γ 163 E 10.
63						**Eu** 151.964 europium σ_a 46E2, 36E2	**Eu130** (1+) 0.9 ms p 1.02 129.964	**Eu131** 3/+ 18 ms p 0.93, 0.81 130.9578			**Eu134** 0.5 s ε, β^+ (p) 2.2 – 6.0 E 11.7
62						**Sm** 150.36 samarium σ_a 56E2, 14E2	**Sm129** 0.6 s β^+ (p) 2.2 – 5.5 γ 134 E 11	**Sm130** E 7.9	**Sm131** 1.2 s β^+, ε (p) 1.8 – 6.6 γ 159 E 9.5	**Sm132** 4 s ε, β^+ E 6.5	**Sm133** 2.9 s Isomer mixture? ε, β^+ γ 370, 84,··· (p) 2.0 – 6.0 γ 213,··· E 8.3
61						**Pm** promethium	**Pm128** (6+) 1.0 s β^+, ε (p) 2.4 – 5.5 γ 236.5 E 12.1	**Pm129** (5/−) ~2.4 s β^+, ε γ 99 E 9.3	**Pm130** 2.5 s β^+, ε γ 158.9, 326.3,··· (p) 2.1 – 5.8 E 11.1	**Pm131** 6 s β^+, ε γ 146.0, 185.0, 220.0 E 8.0	**Pm132** (3+) 6 s β^+, ε γ 213.1,··· (p) 2.2 – 5.0 vω E 9.7
60				**Nd** 144.242 neodymium σ_a 50, 4E1	**Nd125** (5/) 0.6 s β^+ (p) γ 142, 306 E 10.	**Nd126** E 7.4	**Nd127** (5/) 1.8 s ε, β^+ (p) 2.0 – 6.4 γ 170 E 9.0	**Nd128** E 6.1	**Nd129** (5/+) 4.9 s ε, β^+ γ 91.1, 116.6,··· (p) 1.8 – 5.6 γ 207, 400. E 7.5	**Nd130** 21 s β^+, ε γ 92.3, 140.6,··· E 4.6	**Nd131** (5/+) 28 s ε, β^+ γ 87.4, 174.2, 164.1,··· (p) 1.7 – 6.4 E 6.5
59	**Pr** 140.90765 praseodymium σ_a 11.4, 14.1	**Pr121** (3/−) 10 ms p 0.88 120.955			**Pr124** 1.2 s ε, β^+ γ 142 (p) 2.1 – 5.9 γ 70, 113, 166,··· E 12	**Pr125** 3 s β^+, ε γ 135.8, 146.1, 180. E 8.7	**Pr126** 3.1 s ε, β^+ γ 169.6, 349.5, 495.9,··· (p) 2.1 – 5.0 E 10.6	**Pr127** 4.2 s ε, β^+ γ 125.8, 162.5,··· E 7.5	**Pr128** 2.8 s β^+, ε γ 207.4, 399.7,··· (p) 1.9 – 5.0 E 9.20	**Pr129** 30. s β^+, ε γ 203.8, 107.6, 291.8,··· E 6.51	**Pr130** 40 s β^+, ε γ 253.7, 456.7, 923.6, 580.7,··· E 8.2



0− Tb158 3− 10.5 s 1.8E2 a IT 110, e− ε γ 944.2, 962.1, … β− 0.83, … γ 99.0, … E+ 1.220 E− 0.935	Tb159 3/+ 100 σγ 23.2, 43E1 158.925347	Tb160 3− 72.3 d β− 0.57, 0.86, … γ 879.4, 298.6, 966.2, … σγ 6E2 E 1.835	Tb161 3/+ 6.91 d β− 0.52, 0.46, … γ 25.7, 48.9, 74.6, … E 0.593	Tb162 1− 7.6 m β− 1.4, … γ 260.1, 807.5, 888.1, … E 2.51	Tb163 3/+ 19.5 m β− 0.80, … γ 351.2, 389.8, 494.5, … E 1.785	Tb164 (5+) 3.0 m β− 1.7, … γ 168.8, 754.8, 215.1, 688.4, … E 3.9	Tb165 2.1 m β− γ 1178.5, 538.8, 1292.0, 1664.8, … E 3.0	Tb166 25 s β− γ 172.8, 1039.8, 857.0, … E 4.8	Tb167 (3/+) 19 s β− γ 57.2, 69.7 E 4.1	Tb168 (4−) 8 s β− γ 173.4, 227.0, 75.0 E 6
Gd157 3/− 15.65 σγ 255E3, 80E1 σα <0.1 mb 156.923960	Gd158 24.84 σγ 2.4, 7E1 157.924104	Gd159 3/− 18.5 h β− 0.96, … γ 363.54, 58.00 (e−), … E 0.971	Gd160 21.86 σγ 1, 8 159.927054	Gd161 5/− 3.66 m β− 1.56, … γ 360.9, 314.9, 102.3, … σγ 2E4 E 1.955	Gd162 8.4 m β− 1.0, … γ 442.1, 403.0, … E 1.39	Gd163 1.13 m β− γ 287.8, 214.0, 1562.1, 1684.5, … E 3.1	Gd164 45 s β− γ E 2.3	Gd165 10. s β− γ 50.4 E 4	Gd166 4.8 s β− γ 1015.5, 975.5, 536.0, … E 3	
Eu156 0+ 15.2 d β− 2.45, 0.49, … γ 811.8, 89.0, 1230.7, … E 2.45	Eu157 5/+ 15.18 h β− 1.30, 0.89, 0.93, … γ 63.9, 410.7, 370.5, … E 1.363	Eu158 (1−) 45.9 m β− 2.5, … γ 944.2, 977.2, 79.5, 897.7, … E 3.5	Eu159 5/+ 18.1 m β− 2.57, 2.4, 1.9, … γ 67.8, 78.6, 95.7, 146.4, 664.9, … E 2.52	Eu160 1(−) 38 s β− 4.1, 2.7, … γ 173.1, 514.8, 412.0, 821.6, … E 4.6	Eu161 26 s β− γ 71.9, 91.9, 163.7, … E 3.7	Eu162 11 s β− E 5.6	Eu163 β− E 5	Eu164 β− E 7	Eu165 β− E 6	
Sm155 3/− 22.2 m β− 1.52, … γ 104.3, … E 1.627	Sm156 9.4 h β− 0.71, 0.43, … γ 87.6, 203.8, 165.7, … E 0.72	Sm157 (3/−) 8.0 m β− 2.4, … γ 197.8, 196.3, 394.2, … E 2.73	Sm158 5.3 m β− γ 189.4, 363.6, 324.5, … E 2.00	Sm159 (5/−) 11.4 s β− γ 189.8, 862.0, 254.4, … E 3.8	Sm160 9.6 s β− γ 109.7 E 3.0	Sm161 5 s β− γ 263.7 E 4.8	Sm162 2.4 s β− γ 36.0, 736.6, 741.1 E 4	6E-6	102	
Pm154 2.7 m ↔ 1.7 m β− 1.8, … γ 184.8, 82.0, 546.7, … β− 1.8, … γ 2057.7, 1393.6, 839.4, 82.0, … E 3.96	Pm155 (5/−) 42 s β− γ 778.6, 725.4, 409.8, … E 3.22	(1−) Pm156 4(−) < 5 s 26.7 s IT 150.3 β− γ 727.6, 803.9, … β− γ 173.75, 1147.8, … E 5.15	Pm157 (5/−) 10.9 s β− γ 160.6, 188.1, 571.3, 850.5, … E 4.4	Pm158 5 s β− γ 73 E 6.1	Pm159 1.5 s β− γ 71.8, 261.3 E 5.4	0.0003	100 0.000085	0.00002		
Nd153 (3/−) 32 s β− γ 418.3, 32.3, … E 3.34	Nd154 25.9 s β− 2.5, 1.8, … γ 151.7, 799.6, … E 2.8	Nd155 8.9 s β− γ 180.6, 419.0, 955.1, … E 4.5	Nd156 5.4 s β− γ 157.2, 84.7, 150.3D E 3.7		98 0.0033	0.0010				
Pr152 (4+) 3.2 s β− γ 164.1, 285.0, 1469.5, … E 6.4	Pr153 4.3 s β− γ 191.7D, 141.7D, 50.0, … E 5.7	Pr154 2.3 s β− 7.6, … γ 162.4, 932.3, 70.8, … E 7.5			0.0062					
	94		96	0.032	0.0149					

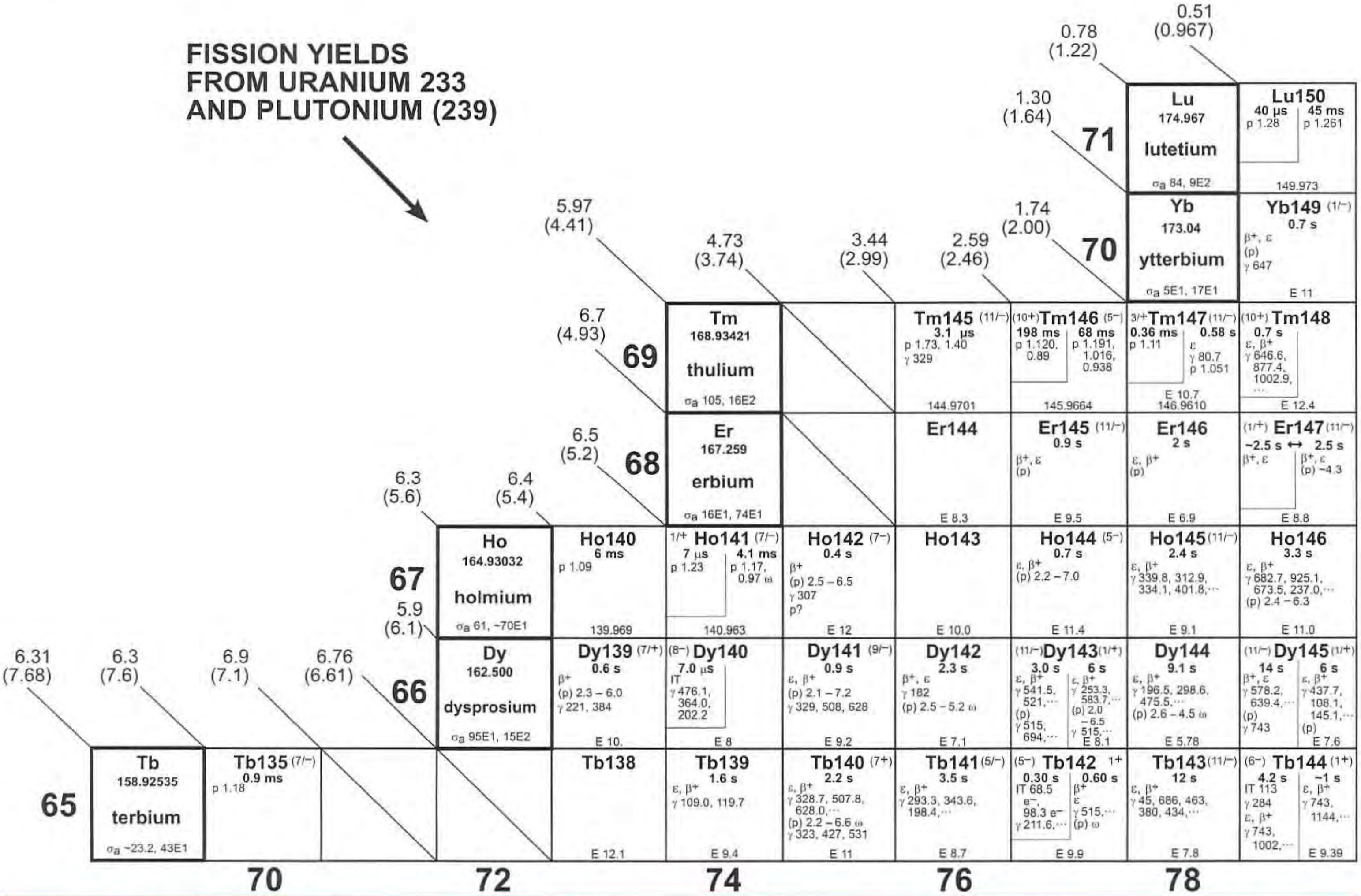


	Tb138 E 12.1	Tb139 1.6 s ε, β+ γ 109.0, 119.7 E 9.4	Tb140 (7+) 2.2 s ε, β+ γ 328.7, 507.8, 628.0, … (p) 2.2 − 6.6 ω γ 323, 427, 531 E 11	Tb141 (5/−) 3.5 s ε, β+ γ 293.3, 343.6, 198.4, … E 8.7	(5−) Tb142 1+ 0.30 s 0.60 s IT 68.5 e−, 98.3 e− γ 211.6, … β+ ε γ 515, … (p) ω E 9.9	Tb143 (11/−) 12 s ε, β+ γ 45, 686, 463, 380, 434, … E 7.8	(6−) Tb144 (1+) 4.2 s ~1 s IT 113 γ 284 ε, β+ γ 743, 1002, … ε, β+ γ 743, 1144, … E 9.39	(11/−) Tb145 (1/+) 30 s β+, ε γ 721.4D, 257.7, 987.6, 537.0, … E 7.0	5− Tb146 1+ 23 s ~8 s β+, ε γ 1579, 1079, … β+ 7.2, … ε γ 1971, 1060. E 8.32	(11/)− Tb147 1.8 m 1.64 h ε, β+ 2.2, … γ 1397.7, 1798, … ε, β+ γ 1152, 694, 140., … E 4.61
Gd136 E 7.2	Gd137 (7/) 2.2 s ε, β+ (p) 2.2 − 6.6 γ 255, 431 E 8.8	Gd138 5 s ε, β+ γ 64.7, … E 6.0	Gd139 (9/−) ~4.8 s 5 s ε, β+ γ 121.6, … ε, β+ γ 115.8, … (p) 2.1 − 5.5 E 7.9	Gd140 16.2 s ε γ 174.6, 749.9, 379.0, 191.2, … E 5.2	11/− Gd141 1/+ 24.5 s 14 s ε, β+ γ 351.1, 223.9, … IT 119.6 γ 198.4, … ε, β+ γ 216.0, … (p) 2.0 − 5.8 ω E 6.70	Gd142 1.17 m β+, ε γ 178.9, 284.4, 526.2, … E 4.36	(11/−) Gd143 (1/)+ 1.84 m 39 s β+, ε γ 271.9, 588.0, … (p) 2.5 − 5.0 νω β+, ε γ 258.8, 204.8, 463.7, … E 6.0	Gd144 4.5 m β+ 3.3, ε γ 333, 2433, 630, 347, … E 3.86	11/− Gd145 1/+ 1.44 m 23.4 m IT 721.4 γ 27.3 e− β+, ε γ 329.4, 386.5 ε, β+ 2.5, … γ 1757.9, 1880.6, … E 5.07	Gd146 48.3 d ε γ 154.6, 115.5, 114.7, … E 1.03
Eu135 1.5 s ε, β+ γ 121 E 8.7	(7+) Eu136 (3+) ~3.3 s ↔ ~3.7 s ε, β+ γ 255, 432, 576 ε, β+ γ 255.1, 431.7, … (p) 2.2 − 5.6 ω E 10.5	Eu137 (11/−) 11 s ε, β+ E 8.0	Eu138 (6−) 12.1 s ε, β+ γ 347.7, 544.5, 685.6, … E 9.75	Eu139 (11/)− 18 s β+, ε γ 267.3, 155.3, 190.1D, 111.9, 453.4, … E 6.98	Eu140 1+ 1.51 s ε, β+ γ 531, 1068, 460, … E 8.47	11/− Eu141 5/+ 3.0 s 40. s IT 96.4 e− β+, ε γ 394.0, 882.9, … β+ 4.92, …, ε γ 394.0, 384.5, … E 6.01	8− Eu142 1+ 1.22 m 2.4 s β+ 4.8, …, ε γ 768.0, 1023.3, 556.6, … β+ 7.0, …, ε γ 768.0, … E 7.67	Eu143 5/+ 2.62 m β+ 4.1, …, ε γ 1107.3, 1536.8, … E 5.28	Eu144 1+ 10.2 s β+ 5.31, …, ε γ 1660.1, 817.7, 2423.3(ω), … E 6.35	Eu145 5/+ 5.93 d ε β+ 1.71, 0.79, … γ 893.7, 653.5, 1658.4, … E 2.659
Sm134 11 s β+, ε γ 118.9, 218.9, … E 5.2	Sm135 10 s β+, ε γ 190.3, 236.6, 126.3, 285.9, 360.3, … (p) 1.9 − 5.0 ω γ 294.4 E 7.1	Sm136 47 s β+, ε γ 114.5, … E 4.4	Sm137 (9/−) 45 s β+, ε γ 380.5, 163.7, 408.3, … E 6.05	Sm138 3.1 m β+, ε γ 54, 75 E 3.44	(11/)− Sm139 (1/+) 11 s 2.6 m IT 190.2 γ 267.5, … β+ 4.7, ε γ 188.7D β+ 3.8, …, ε γ 273.7, 306.7, … E 5.12	Sm140 14.8 m ε, β+ 1.9, … γ 225.4, 139.9, … E 2.75	11/− Sm141 1/+ 22.6 m 10.2 m ε, β+ 2.7, … γ 196.8, 431.8, … IT 175 e− β+ 3.2, 3.1, … ε γ 403.9, 438.3, … E 4.58	Sm142 1.208 h ε β+ 1.0 γ 679, … E 2.16	11/− Sm143 3/+ 1.10 m 8.83 m IT 754.0 ε ω, β+ γ 689, … ε, β+ 2.42, … γ 1056.6, 1515.0, … E 3.443	Sm144 3.07 σγ 1.6, 2.4 143.911999
Pm133 14 s β+, ε γ 180.6, 291.4, 271.9, 345.2, … E 6.9	(2+) Pm134 (5+) ~5 s ↔ 22 s β+, ε γ 294.4, 794.7, … β+, ε γ 294.4, 494.9, … E 8.9	Pm135 49 s Isomer mixture? β+, ε γ 198.8, 128.8, 208.1, 262.9, … E 6.2	(2+) Pm136 (5−) 47 s ↔ 1.8 m β+, ε γ 373.7, 862.2, … β+ 4.7, …, ε γ 373.7, 602.7, … E 8.0	Pm137 (11/)− 2.4 m β+ 4.1, …, ε γ 177.5, 108.5, 233.6, … E 5.51	Pm138 3.2 m 10. s β+ 3.9, …, ε γ 521.0, 729.1, 493.1, … β+ 6.1, … ε E 7.08	(11/)− Pm139 (5/)+ 0.18 s 4.14 m IT 188.7 ε, β+ ω β+ 3.52, …, ε γ 402.8, 463.1, … E 4.50	8− Pm140 1+ 5.87 m 9.2 s β+ 3.2, …, ε γ 1028.3, 773.6, 419.9D, … β+ 5.07, …, ε γ 773.6, 477.1, … E 6.05	Pm141 5/+ 20.9 m β+ 2.71, …, ε γ 1223.3, 886.2, 193.7, 1345.5, … E 3.67	Pm142 1+ 40.5 s β+ 3.8, …, ε γ 1575.5, 641.3, … E 4.80	Pm143 5/+ 265 d ε no β+ γ 742.0 E 1.042
Nd132 1.5 m β+, ε γ 148, … E 3.8	(1/)+ Nd133 (7/+) ~70 s 1.2 m β+, ε γ 402.8, … β+, ε γ 164.3, 61.7, … E 5.61	Nd134 ~8.5 m ε, β+ γ 163, 289, 217, … E 2.87	(1/+) Nd135 9/(−) 5.5 m? 12 m β+, ε β+, ε γ 204.0, 41.4, 441.1, … E 4.72	Nd136 50.6 m ε β+ 1.04, … γ 108.9, 40.2, 574.8, … E 2.13	11/− Nd137 1/+ 1.6 s 38 m IT 233.6 γ 177.5, 108.5, 286.0 ε, β+ 2.40, … γ 75.5, 580.6, … E 3.60	Nd138 5.1 h ε γ 325.8, … E 1.11	11/− Nd139 3/+ 5.5 h 30 m ε γ 113.9, … IT 231.2 e− β+ 1.17, … ε, β+ 1.77, … γ 405.1, 1074.2, … E 2.83	Nd140 3.37 d ε no γ E 0.44	11/− Nd141 3/+ 1.04 m 2.49 h IT 756.5 ε ω? ε β+ 0.802 γ 1127.0 (ω), 1292.7, 1147.3, … E 1.823	Nd142 27.2 σγ 19, 34 141.907723
(11/−) Pr131 (3/+) 5.7 s 1.53 m IT 65 e− γ 87.8 ε γ 138, 162 β+, ε γ 266.1, 72.8, … E 5.4	Pr132 (2)+ 1.7 m β+, ε γ 325.4, 496.9, 822.4, 533.6, 874.2, … E 7.3	(11/−) Pr133 (3/+) 1.1 s 6.5 m IT 130.5 γ 61.7 β+, ε γ 134.3, 315.6, 465.2, … E 4.49	(6−) Pr134 2− ~11 m ↔ 17 m β+, ε γ 409.3, 639.7, … β+, ε γ 409.3, … E 6.32	Pr135 3/(+) 24 m β+ 2.5, …, ε γ 296.1, 82.7, 213.4, … E 3.69	Pr136 2+ 13.1 m ε, β+ 2.98, … γ 552.1, 539.8, 1092.1, … E 5.14	Pr137 5/+ 1.28 h ε, β+ 1.68, … γ 836.9, 434.1, 514.3, 160.4, … E 2.70	7− Pr138 1+ 2.1 h 1.45 m ε, β+ 1.65, … γ 1037.8, 788.7, 302.7, … β+ 3.42, …, ε γ 788.7, 688.2 ω, … E 4.44	Pr139 5/+ 4.41 h ε β+ 1.09, … γ 1347.3(ω), 1630.7, 255.1, 1375.6, … E 2.129	Pr140 1+ 3.39 m ε, β+ 2.37, … γ 1596.1 (ω), 306.9, … E 3.39	Pr141 5/+ 100 σγ (3.9 + 7.5), 14.1 140.907653
72		74		76		78		80		82

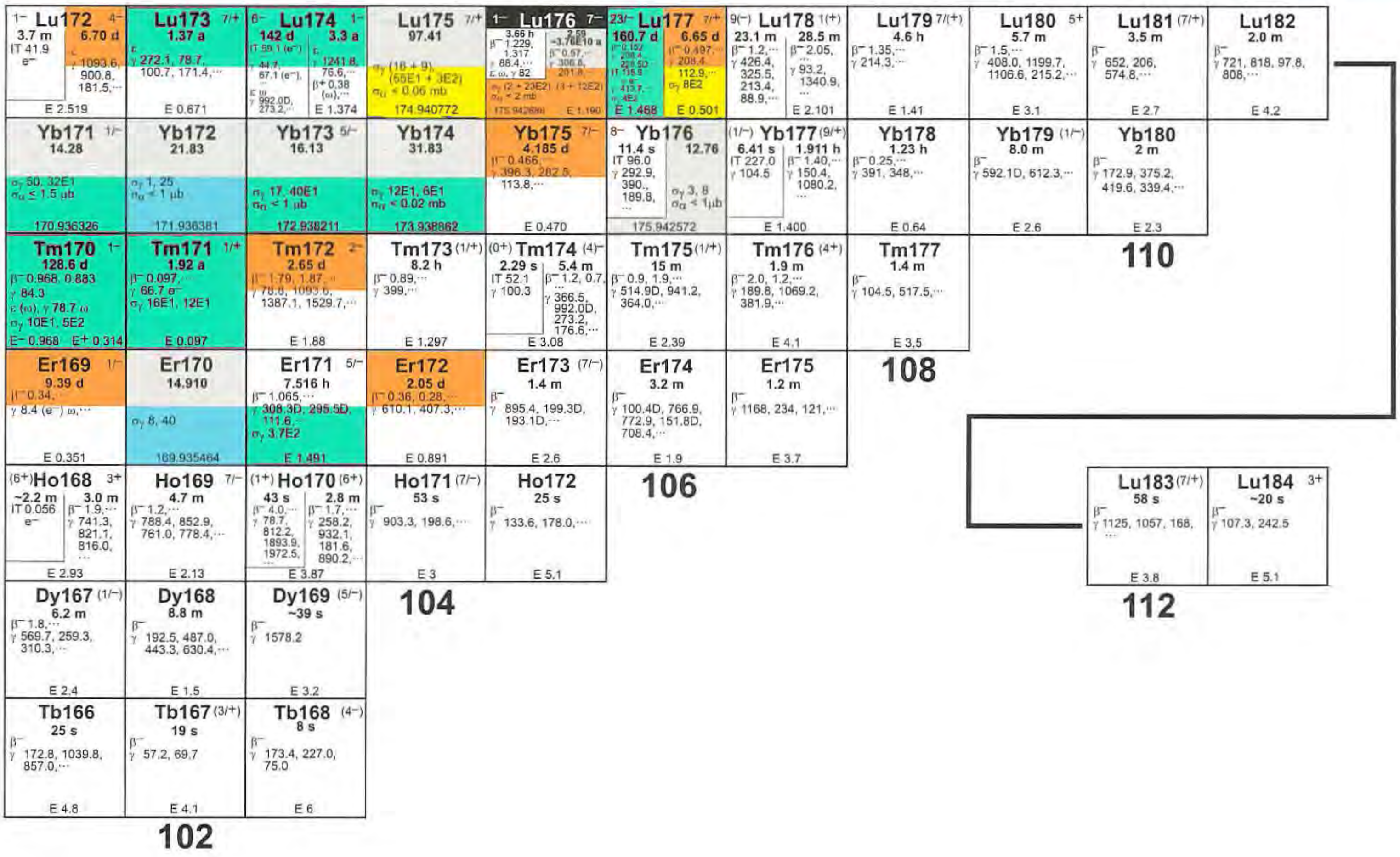


	90		92		94		96		98		100
71	**Lu161** 1/+ 1.28 m ε γ 110.8, 100.3,··· E 5.28	**Lu162** 1(−) ~1.9 m ? 1.37 m ε (4−) ~1.5 m ε γ 166.8, ··· ε γ 166.8, 631.9, ··· E 7.0	**Lu163** 1/(+) 4.0 m β+ γ 163.1, 54.0, 369.3, 371.7,··· E 4.51	**Lu164** 1(−) 3.14 m ε, β+ 3.8, 1.6,··· γ 123.3, 740.5, 262.2, 863.9,··· E 6.38	**Lu165** 1/+ 10.7 m ε, β+ 2.06,··· γ 120.6, 132.5,··· E 3.84	0(−) **Lu166** 6(−) 2.1 m 2.8 m ε, β+ γ 1427.2,··· IT ? 3(−) 1.4 m ε, β+ γ 228.1, 102.4,··· IT 34.5 e− ε, β+ 2.2, ··· γ 228.1, 337.5, ··· E 5.57	**Lu167** 7/+ 52 m ε β+ 2.1,··· γ 29.7, 239.1,··· E 3.09	3+ **Lu168** 6(−) 6.7 m 5.5 m ε, β+ 1.5, 2.7,··· γ 198.8, 979.2, 896.1, ··· ε, β+ 1.2, ··· γ 1483.6, 228.6, ··· E 4.51	1/− **Lu169** 7/+ 2.7 m 1.419 d IT 29.0 e− ε β+ 1.271, ··· γ 960.6, 191.2,··· E 2.293	(4)− **Lu170** 0+ 0.7 s 2.01 d IT 48.4 e− γ 44.5 e− ε, β+ 2.4, γ 84.3, 1280.2, 2041.9, 985.1,··· E 3.46	1/− **Lu171** 7/+ 1.31 m 8.24 d IT 71.1 e− ε β+ 0.362 ω γ 739.8, 19.4, 667.4,··· E 1.479
70	**Yb160** 4.8 m ε β+ γ 173.7, 215.8,··· E 2.13	**Yb161** 3/− 4.2 m ε, β+ γ 78.2, 599.9, 631.4,··· E 4.05	**Yb162** 18.9 m ε β+ ω γ 163.4, 118.7,··· E 1.65	**Yb163** 3/− 11.1 m ε, β+ 1.4 γ 860.4, 63.6,··· E 3.43	**Yb164** 1.26 h ε γ 40.9, 675.3, 390.6, 446.7,··· E 0.87	**Yb165** 5/− 9.9 m ε, β+ 1.58,··· γ 80.1D, 68.9D (e−),··· E 2.65	**Yb166** 2.363 d ε γ 82.3 E 0.31	**Yb167** 5/− 17.5 m ε β+ 0.64 ω γ 113.3D, 106.2, 176.2D,··· E 1.954	**Yb168** 0.13 σγ 23E2, 21E3 σα < 0.1 mb 167.933897	1/− **Yb169** 7/+ 46 s 32.03 d IT 24.2 e− ε γ 63.1, 198.0,··· σγ 3.6E3, ~5.2E3 E 0.910	**Yb170** 3.04 σγ 10, 30E1 σα < 0.01 mb 169.934762
69	**Tm159** 5/+ 9.1 m ε, β+ 2.0,··· γ 38.4, 84.9, 271.4, 220.2,··· E 4.00	(5) **Tm160** 1− 1.24 m 9.4 m IT ε, β+ γ 264.1, 125.8, ··· ε, β+ 3.8, ··· γ 125.8, ··· E 5.76	**Tm161** 7/+ 31 m ε, β+ 1.8 γ 45.5, 1648.1, 84.4,··· E 3.31	5+ **Tm162** 1− 24 s 21.7 m IT γ 66.9 e− ε, β+ γ 811.5, 798.7, 227.5, ··· ε β+ 2.2, 3.8,··· γ 102.0, 798.7, 227.5,··· E 4.86	**Tm163** 1/+ 1.81 h ε β+ 1.05 (ω), 0.71,··· γ 104.3, 69.2, 241.4, 1434.4,··· E 2.439	6− **Tm164** 1+ 5.1 m 2.0 m IT ε β+ γ 208.1, 315.0, ··· ε, β+ 2.94,··· γ 91.4, 1154.7, 768.9,··· E 4.06	**Tm165** 1/+ 1.253 d ε β+ 0.30 (ω), γ 242.9, 47.1, 297.4,··· E 1.592	**Tm166** 2+ 7.70 h ε β+ 1.93,··· γ 778.8, 2052.4, 184.4, 1273.5, 80.6,··· E 3.04	**Tm167** 1/+ 9.24 d ε γ 207.8D,··· E 0.748	**Tm168** 3+ 93.1 d ε β+ ω γ 198.2, 816.0, 447.5, 184.3,··· β− ω E+ 1.679 E− 0.257	**Tm169** 1/+ 100 σγ 105, 16E2 168.934213
68	**Er158** 2.29 h ε γ 71.9, 386.8, 248.5,··· E 0.89	**Er159** 3/− 36 m ε β+ 1.113,··· γ 624.5, 649.1, 206.0D,··· E 2.769	**Er160** 1.191 d ε γ 60.0 (e−) ω,··· E 0.33	**Er161** 3/− 3.21 h ε β+ 0.82 ω γ 826.5, 211.2D,··· E 1.99	**Er162** 0.139 σγ 19, 5E2 σα < 11 mb 161.928778	**Er163** 5/− 1.25 h ε β+ 0.19 ω γ 1113.5 (ω), 436.1, 439.9,··· E 1.210	**Er164** 1.601 σγ 13, 11E1 σα < 1.2 mb 163.929200	**Er165** 5/− 10.36 h ε no γ E 0.376	**Er166** 33.503 σγ (15 + 5), 10E1 σα < 0.07 mb 165.930293	1/− **Er167** 7/+ 2.27 s 22.869 IT 207.8 σγ 67E1, 30E2 σα 3 μb 166.932048	**Er168** 26.978 σγ ~2.3, ~37 σα < 0.09 mb 167.932370
67	**Ho157** 7/− 12.6 m ε β+ 1.18,··· γ 280.0, 341.1,··· E 2.60	2− **Ho158** 5+ 28 m 11.3 m IT 67.2 e− ε, β+ γ 98.3 − 2967 (9+) 21 m ε, β+ γ 406.2,··· ε β+ 1.30,··· γ 218.2, 99.0,··· E 4.22	1/+ **Ho159** 7/− 8.3 s 33.0 m IT 206.0, ··· γ 166.0 ε β+ γ 121.0, 132.0, ··· E 1.838	(9+) **Ho160** 5+ 3 s 25.6 m IT γ 118.4,··· 2− 5.0 h IT 60.0 e− ε, β+ γ 82.9 − 2974 ε β+ 0.57,··· γ 728.2, 879.4, ··· E 3.29	1/+ **Ho161** 7/− 6.8 s 2.48 h IT 211.2 ε γ 25.7,··· E 0.858	6− **Ho162** 1+ 1.12 h 15 m IT ~10 e− γ 38.3, 57.8 (e−), 96.1 ω ε γ 185.0, 1220.0,··· ε β+ 1.1, 1.0 γ 80.7, 1319.7, ··· E 2.140	1/+ **Ho163** 7/− 1.09 s 4.57E3 a IT 297.8 ε no γ E 0.00256	6− **Ho164** 1+ 36.4 m 29 m IT 46 e− γ 37.3, 56.6,··· ε γ 73.4,··· β− 0.96, 0.88 γ 91.4 E+ 0.986 E− 0.962	**Ho165** 7/− 100 σγ (3.1 + 59), (20 + 670) 164.930322	(7)− **Ho166** 0− 1.2E3 a 1.118 d β− < 0.065, γ 184.4, 810.3, 711.7, σγ 3E3, 10E3 β− 1.855, 1.773, γ 80.6, 1379.4, ··· E 1.855	**Ho167** 7/− 3.1 h β− 0.32, 0.97, 0.61 γ 346.5, 321.3,··· E 1.01
66	**Dy156** 0.056 σγ 33, 10E2 σα < 9 mb 155.92428	**Dy157** 3/− 8.1 h ε γ 326.2,··· E 1.34	**Dy158** 0.095 σγ 4E1, 12E1 σα < 6 mb 157.924409	**Dy159** 3/− 144.4 d ε γ 58.0 e−,··· σγ 8E3 E 0.366	**Dy160** 2.329 σγ ~60, 11E2 σα < 0.3 mb 159.925198	**Dy161** 5/+ 18.889 σγ 58E1, 11E2 σα < 1 μb 160.926933	**Dy162** 25.475 σγ 17E1, 28E2 161.926798	**Dy163** 5/− 24.896 σγ 13E1, 16E2 σα < 20 μb 162.928731	**Dy164** 28.260 σγ (17E2 + 10E2), (4E2 + 1E2) 163.929175	1/− **Dy165** 7/+ 1.26 m 2.33 h IT 108.2 e− β− 0.89,··· γ 515.5, 361.7D, σγ 2E3 β− 1.29,··· γ 94.7, 361.7D, σγ 30E2, 22E3 E 1.287	**Dy166** 3.400 d β− 0.40,··· γ 82.5,··· E 0.487
65	**Tb155** 3/+ 5.3 d ε γ 86.5, 105.3, 180.1,··· E 0.82	(0+) **Tb156** 3− 5.3 h 5.3 d IT 88.4 e− ε, β+ 1.4 (7−) 1.02 d IT γ 49.6 ε γ 534.3, 199.2, 1222.4, ··· E 2.445	**Tb157** 3/+ 7E1 a ε γ 54.5 e− E 0.0601	0− **Tb158** 3− 10.5 s 1.8E2 a IT 110, e− ε γ 944.2, 962.1, ··· β− 0.83,··· γ 99.0,··· E+1.220 E− 0.935	**Tb159** 3/+ 100 σγ ~23.2, 43E1 158.925347	**Tb160** 3− 72.3 d β− 0.57, 0.86,··· γ 879.4, 298.6, 966.2,··· σγ 6E2 E 1.835	**Tb161** 3/+ 6.91 d β− 0.52, 0.46,··· γ 25.7, 48.9, 74.6,··· E 0.593	**Tb162** 1− 7.6 m β− 1.4,··· γ 260.1, 807.5, 888.1,··· E 2.51	**Tb163** 3/+ 19.5 m β− 0.80,··· γ 351.2, 389.8, 494.5,··· E 1.785	**Tb164** (5+) 3.0 m β− 1.7,··· γ 168.8, 754.8, 215.1, 688.4,··· E 3.9	**Tb165** 2.1 m β− γ 1178.5, 538.8, 1292.0, 1664.8,··· E 3.0

FISSION YIELDS FROM URANIUM 233 AND PLUTONIUM (239)



		70		72		74		76		78	
71										**Lu** 174.967 lutetium σa 84, 9E2	**Lu150** 40 μs 45 ms p 1.28 p 1.261 149.973
70										**Yb** 173.04 ytterbium σa 5E1, 17E1	**Yb149** (1/−) 0.7 s β+, ε (p) γ 647 E 11
69						**Tm** 168.93421 thulium σa 105, 16E2		**Tm145** (11/−) 3.1 μs p 1.73, 1.40 γ 329 144.9701	(10+) **Tm146** (5−) 198 ms 68 ms p 1.120, 0.89 p 1.191, 1.016, 0.938 145.9664	3/+ **Tm147** (11/−) 0.36 ms 0.58 s p 1.11 ε γ 80.7 p 1.051 E 10.7 146.9610	(10+) **Tm148** 0.7 s ε, β+ γ 646.6, 877.4, 1002.9, ··· E 12.4
68						**Er** 167.259 erbium σa 16E1, 74E1		**Er144** E 8.3	**Er145** (11/−) 0.9 s β+, ε (p) E 9.5	**Er146** 2 s ε, β+ (p) E 6.9	(1/+) **Er147** (11/−) ~2.5 s ↔ 2.5 s β+, ε β+, ε (p) ~4.3 E 8.8
67				**Ho** 164.93032 holmium σa 61, ~70E1	**Ho140** 6 ms p 1.09 139.969	1/+ **Ho141** (7/−) 7 μs 4.1 ms p 1.23 p 1.17, 0.97 ω 140.963	**Ho142** (7−) 0.4 s β+ (p) 2.5 − 6.5 γ 307 p? E 12	**Ho143** E 10.0	**Ho144** (5−) 0.7 s ε, β+ (p) 2.2 − 7.0 E 11.4	**Ho145** (11/−) 2.4 s ε, β+ γ 339.8, 312.9, 334.1, 401.8,··· E 9.1	**Ho146** 3.3 s ε, β+ γ 682.7, 925.1, 673.5, 237.0,··· (p) 2.4 − 6.3 E 11.0
66				**Dy** 162.500 dysprosium σa 95E1, 15E2	**Dy139** (7/+) 0.6 s β+ (p) 2.3 − 6.0 γ 221, 384 E 10.	(8−) **Dy140** 7.0 μs IT γ 476.1, 364.0, 202.2 E 8	**Dy141** (9/−) 0.9 s ε, β+ (p) 2.1 − 7.2 γ 329, 508, 628 E 9.2	**Dy142** 2.3 s β+, ε γ 182 (p) 2.5 − 5.2 ω E 7.1	(11/−) **Dy143** (1/+) 3.0 s 6 s ε, β+ γ 541.5, 521,··· (p) γ 515, 694,··· ε, β+ γ 253.3, 583.7,··· (p) 2.0 − 6.5 γ 515,··· E 8.1	**Dy144** 9.1 s ε, β+ γ 196.5, 298.6, 475.5,··· (p) 2.6 − 4.5 ω E 5.78	(11/−) **Dy145** (1/+) 14 s 6 s β+, ε γ 578.2, 639.4,··· (p) γ 743 ε, β+ γ 437.7, 108.1, 145.1,··· (p) E 7.6
65	**Tb** 158.92535 terbium σa ~23.2, 43E1	**Tb135** (7/−) 0.9 ms p 1.18			**Tb138** E 12.1	**Tb139** 1.6 s ε, β+ γ 109.0, 119.7 E 9.4	**Tb140** (7+) 2.2 s ε, β+ γ 328.7, 507.8, 628.0,··· (p) 2.2 − 6.6 ω γ 323, 427, 531 E 11	**Tb141** (5/−) 3.5 s ε, β+ γ 293.3, 343.6, 198.4,··· E 8.7	(5−) **Tb142** 1+ 0.30 s 0.60 s IT 68.5 e−, 98.3 e− γ 211.6,··· β+ ε γ 515,··· (p) ω E 9.9	**Tb143** (11/−) 12 s ε, β+ γ 45, 686, 463, 380, 434,··· E 7.8	(6−) **Tb144** (1+) 4.2 s ~1 s IT 113 γ 284 ε, β+ γ 743, 1002,··· ε, β+ γ 743, 1144,··· E 9.39



1− **Lu172** 4− 3.7 m IT 41.9 e^- 6.70 d ε γ 1093.6, 900.8, 181.5,… E 2.519	**Lu173** 7/+ 1.37 a ε γ 272.1, 78.7, 100.7, 171.4,… E 0.671	6− **Lu174** 1− 142 d IT 59.1 (e^-) γ 44.7, 67.1 (e^-), … ε ω γ 992.0D, 273.2,… 3.3 a ε γ 1241.8, 76.6,… β^+ 0.38 (ω),… E 1.374	**Lu175** 7/+ 97.41 σ_γ (16 + 9), (55E1 + 3E2) σ_α < 0.06 mb 174.940772	1− **Lu176** 7− 3.66 h β^- 1.229, 1.317 γ 88.4,… ε ω, γ 82 2.59 ~3.76E10 a β^- 0.57,… γ 306.8, 201.8,… σ_γ (2 + 23E2) (3 + 12E2) σ_α < 2 mb 175.942686 E 1.190	23/− **Lu177** 7/+ 160.7 d β^- 0.152 γ 208.4, 228.5D IT 115.9 γ e^- γ 413.7,… σ_γ 4E2 E 1.468 6.65 d β^- 0.497,… γ 208.4, 112.9,… σ_γ 8E2 E 0.501	9(−) **Lu178** 1(+) 23.1 m β^- 1.2,… γ 426.4, 325.5, 213.4, 88.9,… 28.5 m β^- 2.05, … γ 93.2, 1340.9, … E 2.101	**Lu179** 7/(+) 4.6 h β^- 1.35,… γ 214.3,… E 1.41	**Lu180** 5+ 5.7 m β^- 1.5,… γ 408.0, 1199.7, 1106.6, 215.2,… E 3.1	**Lu181** (7/+) 3.5 m β^- γ 652, 206, 574.8,… E 2.7	**Lu182** 2.0 m β^- γ 721, 818, 97.8, 808,… E 4.2
Yb171 1/− 14.28 σ_γ 50, 32E1 σ_α ≤ 1.5 μb 170.936326	**Yb172** 21.83 σ_γ 1, 25 σ_α < 1 μb 171.936381	**Yb173** 5/− 16.13 σ_γ 17, 40E1 σ_α < 1 μb 172.938211	**Yb174** 31.83 σ_γ 12E1, 6E1 σ_α < 0.02 mb 173.938862	**Yb175** 7/− 4.185 d β^- 0.466,… γ 396.3, 282.5, 113.8,… E 0.470	8− **Yb176** 11.4 s IT 96.0 γ 292.9, 390., 189.8, … 12.76 σ_γ 3, 8 σ_α < 1μb 175.942572	(1/−) **Yb177** (9/+) 6.41 s IT 227.0 γ 104.5 1.911 h β^- 1.40,… γ 150.4, 1080.2, … E 1.400	**Yb178** 1.23 h β^- 0.25,… γ 391, 348,… E 0.64	**Yb179** (1/−) 8.0 m β^- γ 592.1D, 612.3,… E 2.6	**Yb180** 2 m β^- γ 172.9, 375.2, 419.6, 339.4,… E 2.3	
Tm170 1− 128.6 d β^- 0.968, 0.883 γ 84.3 ε (ω), γ 78.7 ω σ_γ 10E1, 5E2 E^- 0.968 E^+ 0.314	**Tm171** 1/+ 1.92 a β^- 0.097,… γ 66.7 e^- σ_γ 16E1, 12E1 E 0.097	**Tm172** 2− 2.65 d β^- 1.79, 1.87,… γ 78.8, 1093.6, 1387.1, 1529.7,… E 1.88	**Tm173** (1/+) 8.2 h β^- 0.89,… γ 399,… E 1.297	(0+) **Tm174** (4)− 2.29 s IT 52.1 γ 100.3 5.4 m β^- 1.2, 0.7, … γ 366.5, 992.0D, 273.2, 176.6,… E 3.08	**Tm175** (1/+) 15 m β^- 0.9, 1.9,… γ 514.9D, 941.2, 364.0,… E 2.39	**Tm176** (4+) 1.9 m β^- 2.0, 1.2,… γ 189.8, 1069.2, 381.9,… E 4.1	**Tm177** 1.4 m β^- γ 104.5, 517.5,… E 3.5		110	
Er169 1/− 9.39 d β^- 0.34,… γ 8.4 (e^-) ω,… E 0.351	**Er170** 14.910 σ_γ 8, 40 169.935464	**Er171** 5/− 7.516 h β^- 1.065,… γ 308.3D, 295.5D, 111.6,… σ_γ 3.7E2 E 1.491	**Er172** 2.05 d β^- 0.36, 0.28,… γ 610.1, 407.3,… E 0.891	**Er173** (7/−) 1.4 m β^- γ 895.4, 199.3D, 193.1D,… E 2.6	**Er174** 3.2 m β^- γ 100.4D, 766.9, 772.9, 151.8D, 708.4,… E 1.9	**Er175** 1.2 m β^- γ 1168, 234, 121,… E 3.7	108			
(6+) **Ho168** 3+ ~2.2 m IT 0.056 e^- 3.0 m β^- 1.9,… γ 741.3, 821.1, 816.0, … E 2.93	**Ho169** 7/− 4.7 m β^- 1.2,… γ 788.4, 852.9, 761.0, 778.4,… E 2.13	(1+) **Ho170** (6+) 43 s β^- 4.0,… γ 78.7, 812.2, 1893.9, 1972.5, … 2.8 m β^- 1.7,… γ 258.2, 932.1, 181.6, 890.2,… E 3.87	**Ho171** (7/−) 53 s β^- γ 903.3, 198.6,… E 3	**Ho172** 25 s β^- γ 133.6, 178.0,… E 5.1	106					
Dy167 (1/−) 6.2 m β^- 1.8,… γ 569.7, 259.3, 310.3,… E 2.4	**Dy168** 8.8 m β^- γ 192.5, 487.0, 443.3, 630.4,… E 1.5	**Dy169** (5/−) ~39 s β^- γ 1578.2 E 3.2	104							
Tb166 25 s β^- γ 172.8, 1039.8, 857.0,… E 4.8	**Tb167** (3/+) 19 s β^- γ 57.2, 69.7 E 4.1	**Tb168** (4−) 8 s β^- γ 173.4, 227.0, 75.0 E 6								
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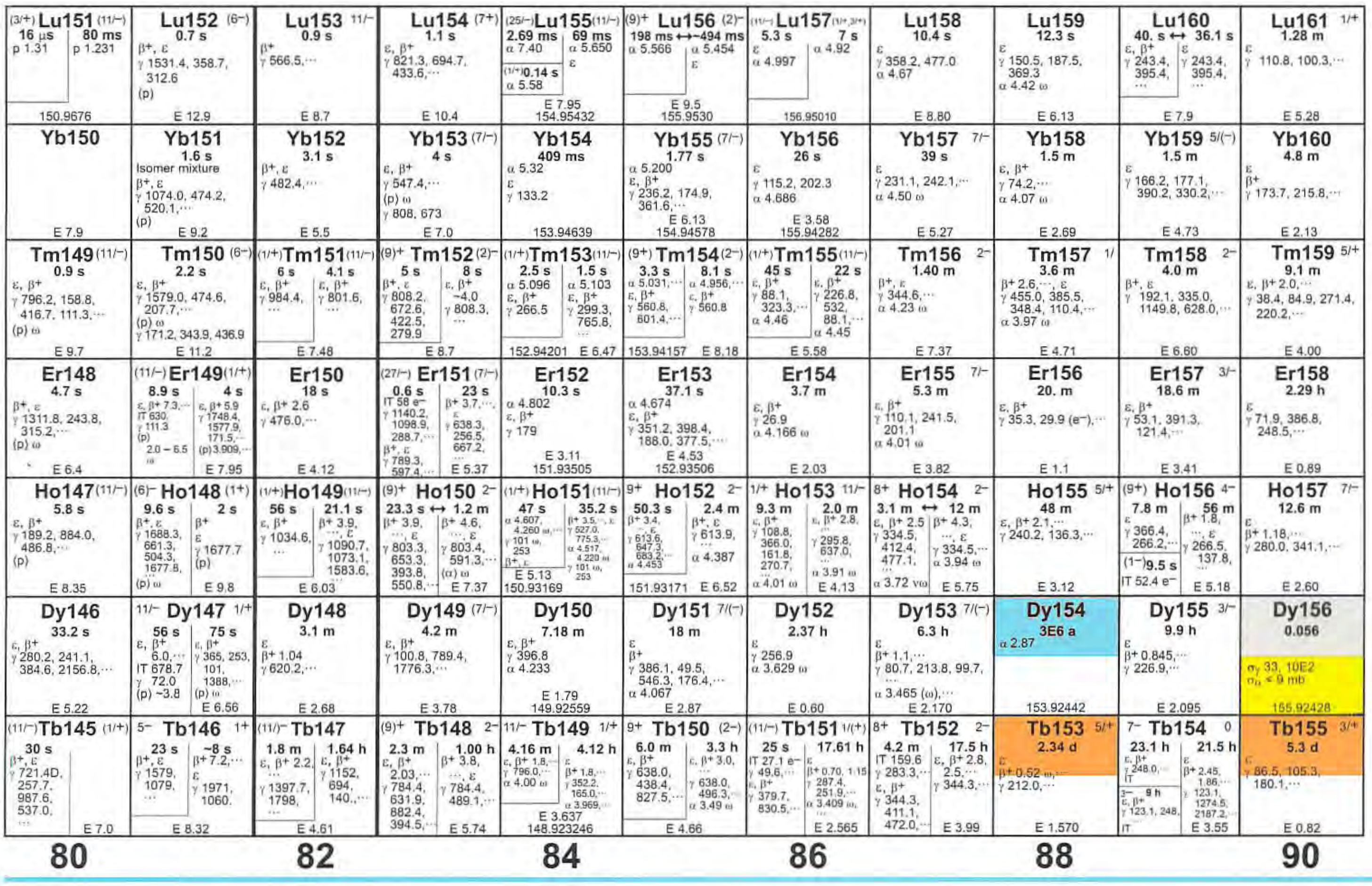
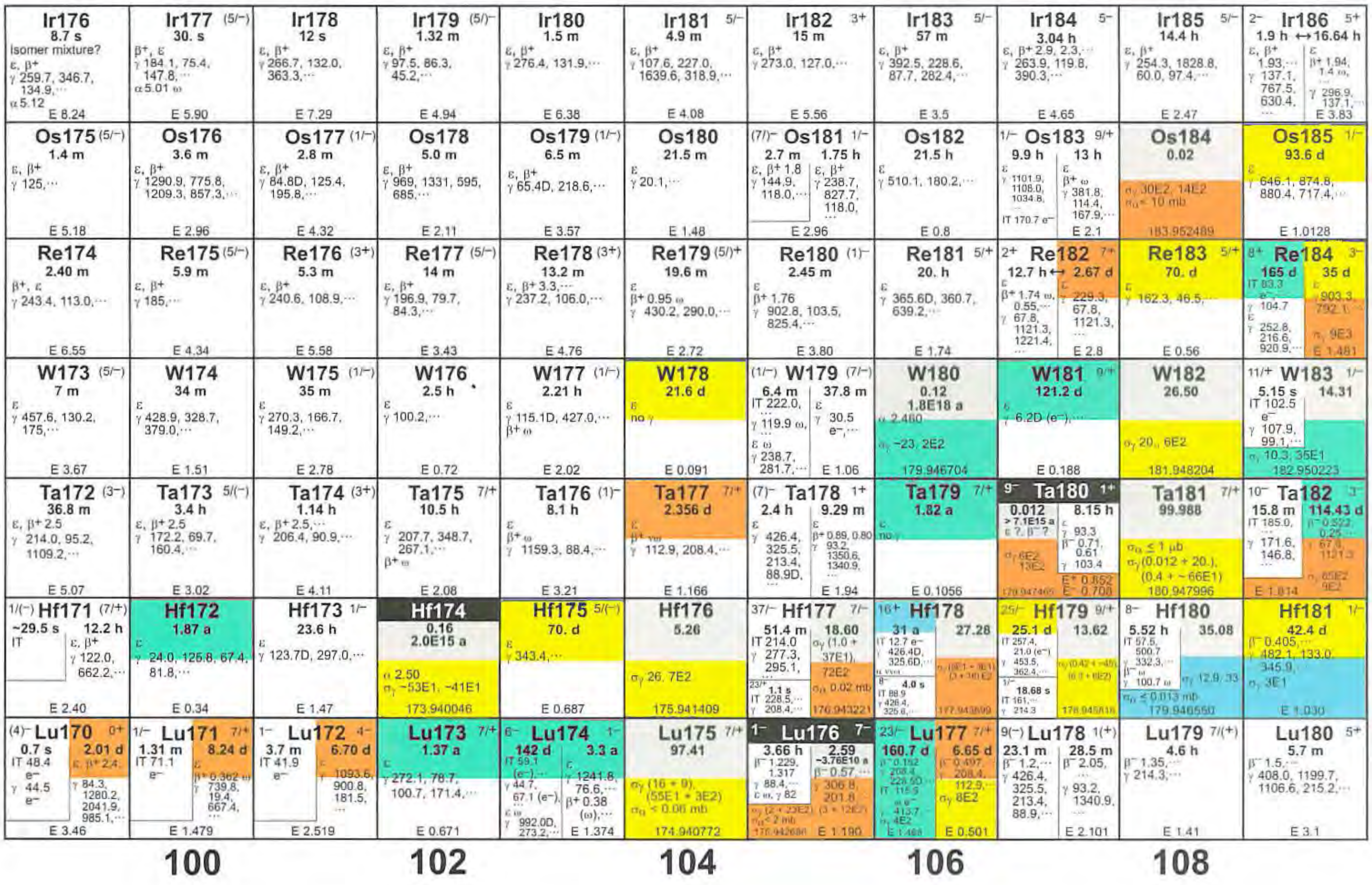
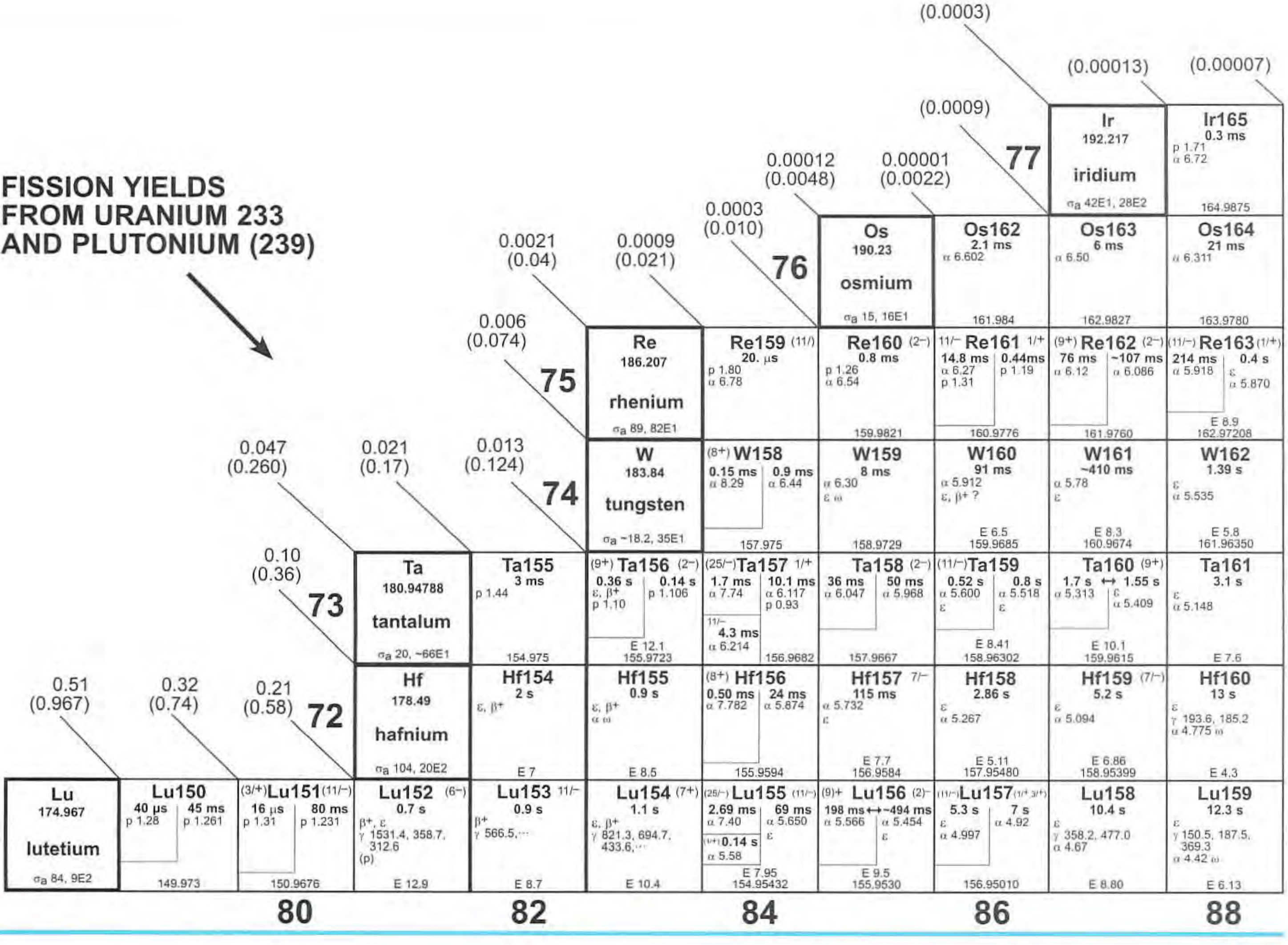
Lu183 (7/+) 58 s β^- γ 1125, 1057, 168, … E 3.8	**Lu184** 3+ ~20 s β^- γ 107.3, 242.5 E 5.1
112	

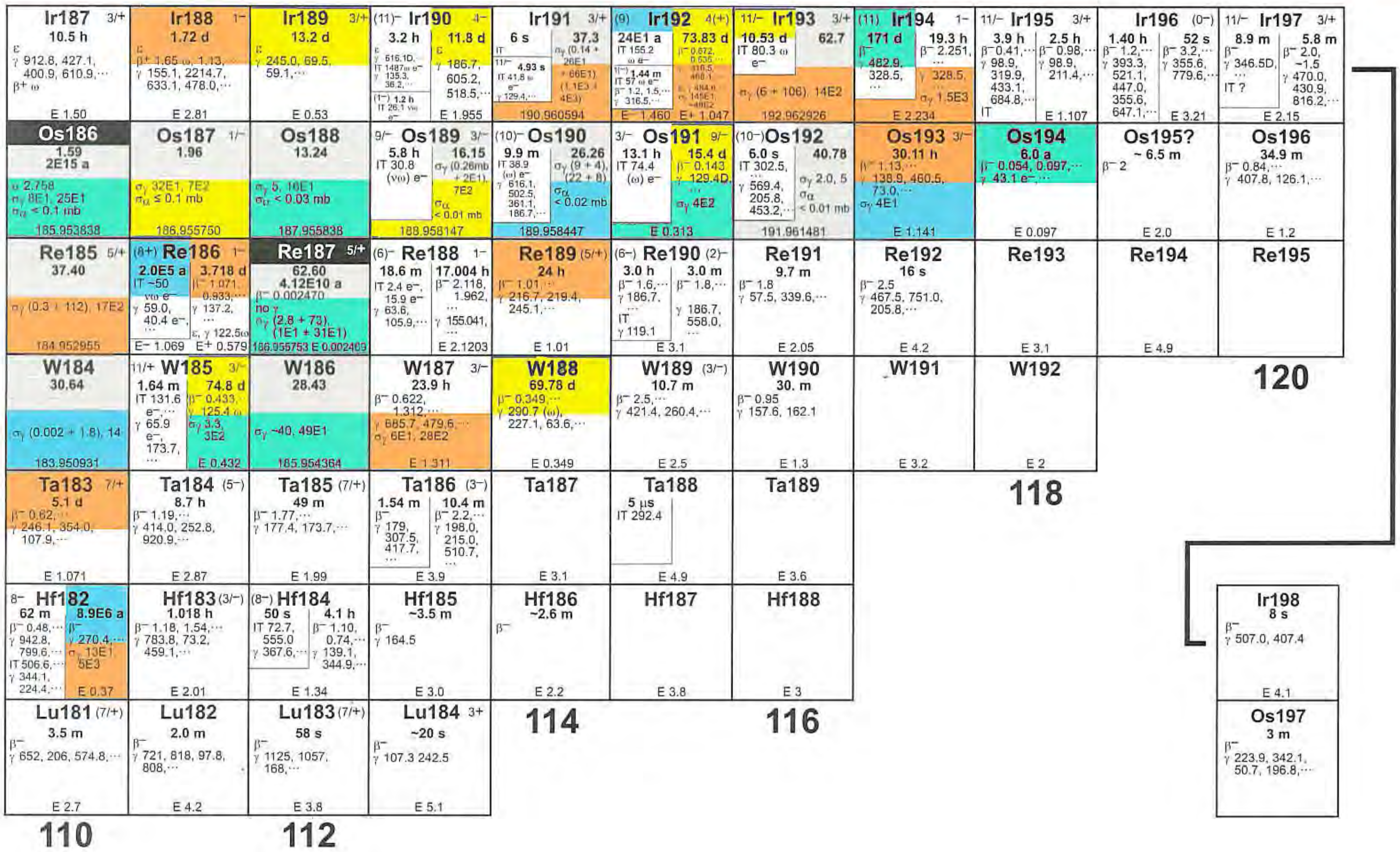


(3/+) **Lu151** (11/−) 16 μs p 1.31 80 ms p 1.231 150.9676	**Lu152** (6−) 0.7 s β^+, ε γ 1531.4, 358.7, 312.6 (p) E 12.9	**Lu153** 11/− 0.9 s β^+ γ 566.5,… E 8.7	**Lu154** (7+) 1.1 s ε, β^+ γ 821.3, 694.7, 433.6,… E 10.4	(25/−) **Lu155** (11/−) 2.69 ms α 7.40 (1/+) 0.14 s α 5.58 69 ms α 5.650 ε E 7.95 154.95432	(9)+ **Lu156** (2)− 198 ms ↔ ~494 ms α 5.566 α 5.454 ε E 9.5 155.9530	(11/−) **Lu157** (1/+,3/+) 5.3 s ε α 4.997 7 s α 4.92 156.95010	**Lu158** 10.4 s ε γ 358.2, 477.0 α 4.67 E 8.80	**Lu159** 12.3 s ε γ 150.5, 187.5, 369.3 α 4.42 ω E 6.13	**Lu160** 40. s ↔ 36.1 s ε, β^+ γ 243.4, 395.4, … ε γ 243.4, 395.4, … E 7.9	**Lu161** 1/+ 1.28 m ε γ 110.8, 100.3,… E 5.28
Yb150 E 7.9	**Yb151** 1.6 s Isomer mixture β^+, ε γ 1074.0, 474.2, 520.1,… (p) E 9.2	**Yb152** 3.1 s β^+, ε γ 482.4,… E 5.5	**Yb153** (7/−) 4 s ε, β^+ γ 547.4,… (p) ω γ 808, 673 E 7.0	**Yb154** 409 ms α 5.32 ε γ 133.2 153.94639	**Yb155** (7/−) 1.77 s α 5.200 ε, β^+ γ 236.2, 174.9, 361.6,… E 6.13 154.94578	**Yb156** 26 s ε γ 115.2, 202.3 α 4.686 E 3.58 155.94282	**Yb157** 7/− 39 s ε γ 231.1, 242.1,… α 4.50 ω E 5.27	**Yb158** 1.5 m ε, β^+ γ 74.2,… α 4.07 ω E 2.69	**Yb159** 5/(−) 1.5 m ε γ 166.2, 177.1, 390.2, 330.2,… E 4.73	**Yb160** 4.8 m ε β^+ γ 173.7, 215.8,… E 2.13
Tm149 (11/−) 0.9 s ε, β^+ γ 796.2, 158.8, 416.7, 111.3,… (p) ω E 9.7	**Tm150** (6−) 2.2 s ε, β^+ γ 1579.0, 474.6, 207.7,… (p) ω γ 171.2, 343.9, 436.9 E 11.2	(1/+) **Tm151** (11/−) 6 s ε, β^+ γ 984.4, … 4.1 s ε, β^+ γ 801.6, … E 7.48	(9)+ **Tm152** (2)− 5 s β^+, ε γ 808.2, 672.6, 422.5, 279.9 8 s ε, β^+ ~4.0 γ 808.3, … E 8.7	(1/+) **Tm153** (11/−) 2.5 s α 5.096 ε, β^+ γ 266.5 1.5 s α 5.103 ε, β^+ γ 299.3, 765.8, … 152.94201 E 6.47	(9+) **Tm154** (2−) 3.3 s α 5.031,… ε, β^+ γ 560.8, 601.4,… 8.1 s α 4.956,… ε, β^+ γ 560.8 153.94157 E 8.18	(1/+) **Tm155** (11/−) 45 s ε, β^+ γ 88.1, 323.3,… α 4.46 22 s ε, β^+ γ 226.8, 532, 88.1,… α 4.45 E 5.58	**Tm156** 2− 1.40 m β^+, ε γ 344.6,… α 4.23 ω E 7.37	**Tm157** 1/ 3.6 m β^+ 2.6,…, ε γ 455.0, 385.5, 348.4, 110.4,… α 3.97 ω E 4.71	**Tm158** 2− 4.0 m β^+, ε γ 192.1, 335.0, 1149.8, 628.0,… E 6.60	**Tm159** 5/+ 9.1 m ε, β^+ 2.0,… γ 38.4, 84.9, 271.4, 220.2,… E 4.00
Er148 4.7 s β^+, ε γ 1311.8, 243.8, 315.2,… (p) ω E 6.4	(11/−) **Er149** (1/+) 8.9 s ε, β^+ 7.3,… IT 630, γ 111.3 (p) 2.0 − 6.5 ω 4 s ε, β^+ 5.9 γ 1748.4, 1577.9, 171.5,… (p) 3.909,… E 7.95	**Er150** 18 s ε, β^+ 2.6 γ 476.0,… E 4.12	(27/−) **Er151** (7/−) 0.6 s IT 58 e^- γ 1140.2, 1098.9, 288.7,… β^+, ε γ 789.3, 597.4,… 23 s β^+ 3.7,…, ε γ 638.3, 256.5, 667.2, … E 5.37	**Er152** 10.3 s α 4.802 ε, β^+ γ 179 E 3.11 151.93505	**Er153** 37.1 s α 4.674 ε, β^+ γ 351.2, 398.4, 188.0, 377.5,… E 4.53 152.93506	**Er154** 3.7 m ε, β^+ γ 26.9 α 4.166 ω E 2.03	**Er155** 7/− 5.3 m ε, β^+ γ 110.1, 241.5, 201.1 α 4.01 ω E 3.82	**Er156** 20. m ε, β^+ γ 35.3, 29.9 (e^-),… E 1.1	**Er157** 3/− 18.6 m ε, β^+ γ 53.1, 391.3, 121.4,… E 3.41	**Er158** 2.29 h ε γ 71.9, 386.8, 248.5,… E 0.89
Ho147 (11/−) 5.8 s ε, β^+ γ 189.2, 884.0, 486.8,… (p) E 8.35	(6)− **Ho148** (1+) 9.6 s β^+, ε γ 1688.3, 661.3, 504.3, 1677.8, … (p) ω 2 s β^+ ε γ 1677.7 (p) E 9.8	(1/+) **Ho149** (11/−) 56 s ε, β^+ γ 1034.6, … 21.1 s β^+ 3.9, …, ε γ 1090.7, 1073.1, 1583.6, … E 6.03	(9)+ **Ho150** 2− 23.3 s ↔ 1.2 m β^+ 3.9, …, ε γ 803.3, 653.3, 393.8, 550.8,… β^+ 4.6, …, ε γ 803.4, 591.3,… (α) ω E 7.37	(1/+) **Ho151** (11/−) 47 s α 4.607, 4.260 ω,… γ 101 ω, 253 β^+, ε 35.2 s β^+ 3.5,…, ε γ 527.0, 775.3,… α 4.517, 4.220 ω γ 101 ω, 253 E 5.13 150.93169	9+ **Ho152** 2− 50.3 s β^+ 3.4, …, ε γ 613.6, 647.3, 683.2,… α 4.453 2.4 m β^+, ε γ 613.9, … α 4.387 151.93171 E 6.52	1/+ **Ho153** 11/− 9.3 m ε, β^+ γ 108.8, 366.0, 161.8, 270.7, … α 4.01 ω 2.0 m ε, β^+ 2.8, … γ 295.8, 637.0, … α 3.91 ω E 4.13	8+ **Ho154** 2− 3.1 m ↔ 12 m ε, β^+ 2.5 γ 334.5, 412.4, 477.1, … α 3.72 νω β^+ 4.3, …, ε γ 334.5,… α 3.94 ω E 5.75	**Ho155** 5/+ 48 m ε, β^+ 2.1,… γ 240.2, 136.3,… E 3.12	(9+) **Ho156** 4− 7.8 m ε γ 366.4, 266.2,… (1−) 9.5 s IT 52.4 e^- 56 m β^+ 1.8, …, ε γ 266.5, 137.8, … E 5.18	**Ho157** 7/− 12.6 m ε β^+ 1.18,… γ 280.0, 341.1,… E 2.60
Dy146 33.2 s ε, β^+ γ 280.2, 241.1, 384.6, 2156.8,… E 5.22	11/− **Dy147** 1/+ 56 s ε, β^+ 6.0,… IT 678.7 γ 72.0 (p) ~3.8 75 s ε, β^+ γ 365, 253, 101, 1388,… (p) ω E 6.56	**Dy148** 3.1 m ε β^+ 1.04 γ 620.2,… E 2.68	**Dy149** (7/−) 4.2 m ε, β^+ γ 100.8, 789.4, 1776.3,… E 3.78	**Dy150** 7.18 m ε, β^+ γ 396.8 α 4.233 E 1.79 149.92559	**Dy151** 7/(−) 18 m ε β^+ γ 386.1, 49.5, 546.3, 176.4,… α 4.067 E 2.87	**Dy152** 2.37 h ε γ 256.9 α 3.629 ω E 0.60	**Dy153** 7/(−) 6.3 h ε β^+ 1.1,… γ 80.7, 213.8, 99.7, … α 3.465 (ω),… E 2.170	**Dy154** 3E6 a α 2.87 153.92442	**Dy155** 3/− 9.9 h ε β^+ 0.845,… γ 226.9,… E 2.095	**Dy156** 0.056 σ_γ 33, 10E2 σ_α < 9 mb 155.92428
(11/−) **Tb145** (1/+) 30 s β^+, ε γ 721.4D, 257.7, 987.6, 537.0, … E 7.0	5− **Tb146** 1+ 23 s β^+, ε γ 1579, 1079, … ~8 s β^+ 7.2,… ε γ 1971, 1060. E 8.32	(11/)− **Tb147** 1.8 m ε, β^+ 2.2, … γ 1397.7, 1798, … 1.64 h ε, β^+ γ 1152, 694, 140.,… E 4.61	(9)+ **Tb148** 2− 2.3 m ε, β^+ 2.03,… γ 784.4, 631.9, 882.4, 394.5,… 1.00 h β^+ 3.8, …, ε γ 784.4, 489.1,… E 5.74	11/− **Tb149** 1/+ 4.16 m ε, β^+ 1.8,… γ 796.0,… α 4.00 ω 4.12 h ε β^+ 1.8,… γ 352.2, 165.0,… α 3.969,… E 3.637 148.923246	9+ **Tb150** (2−) 6.0 m ε, β^+ γ 638.0, 438.4, 827.5,… 3.3 h ε, β^+ 3.0, … γ 638.0, 496.3,… α 3.49 ω E 4.66	(11/−) **Tb151** 1/(+) 25 s IT 27.1 e^- γ 49.6,… ε, β^+ γ 379.7, 830.5,… 17.61 h ε β^+ 0.70, 1.15 γ 287.4, 251.9,… α 3.409 ω, … E 2.565	8+ **Tb152** 2− 4.2 m IT 159.6 γ 283.3,… ε, β^+ γ 344.3, 411.1, 472.0,… 17.5 h ε, β^+ 2.8, 2.5,… γ 344.3,… E 3.99	**Tb153** 5/+ 2.34 d ε β^+ 0.52 ω,… γ 212.0,… E 1.570	7− **Tb154** 0 23.1 h ε, β^+ γ 248.0,… IT 3− 9 h ε, β^+ γ 123.1, 248, … IT 21.5 h ε β^+ 2.45, 1.86,… γ 123.1, 1274.5, 2187.2,… E 3.55	**Tb155** 3/+ 5.3 d ε γ 86.5, 105.3, 180.1,… E 0.82
80		82		84		86		88		90

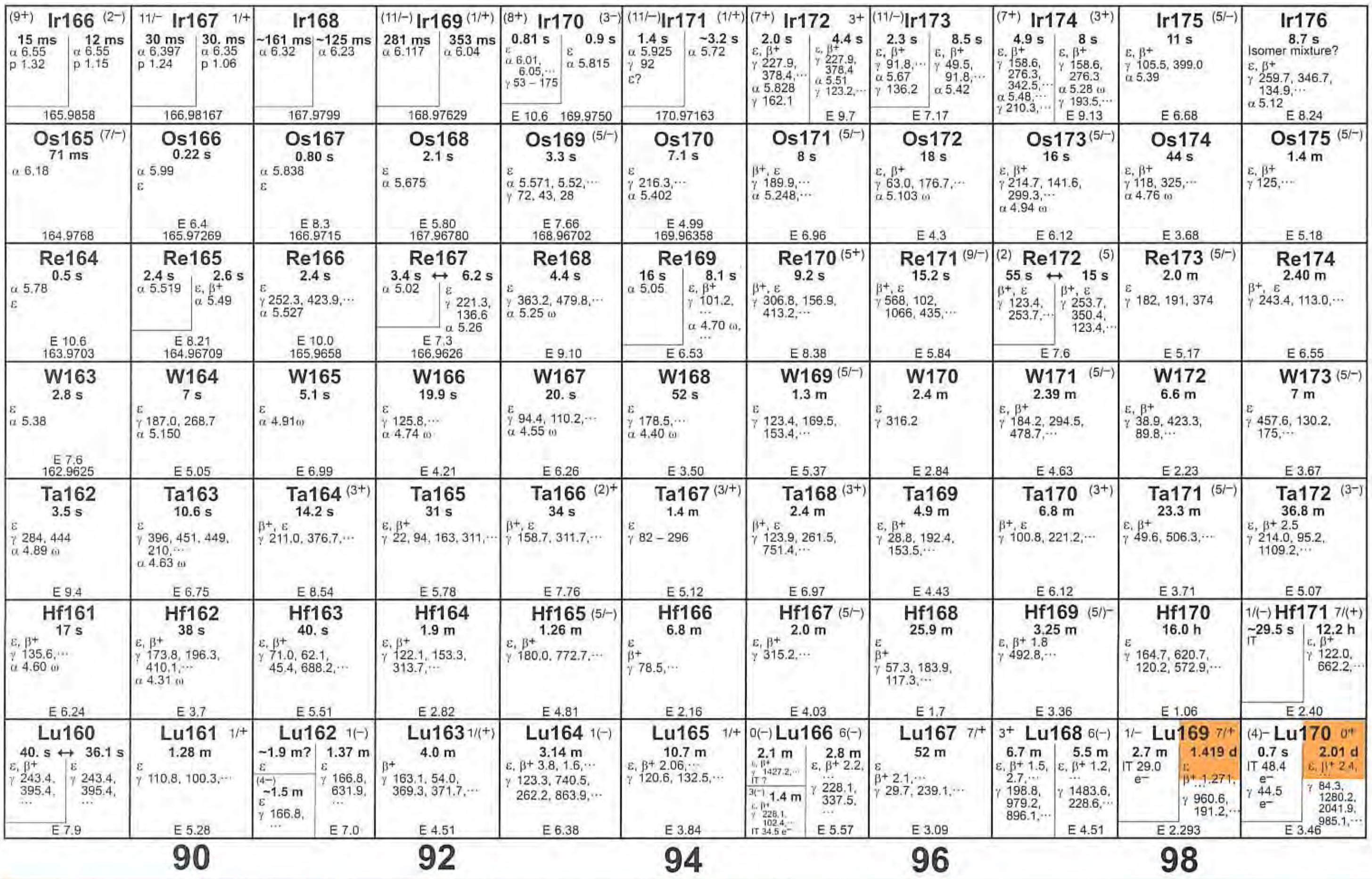


FISSION YIELDS FROM URANIUM 233 AND PLUTONIUM (239)

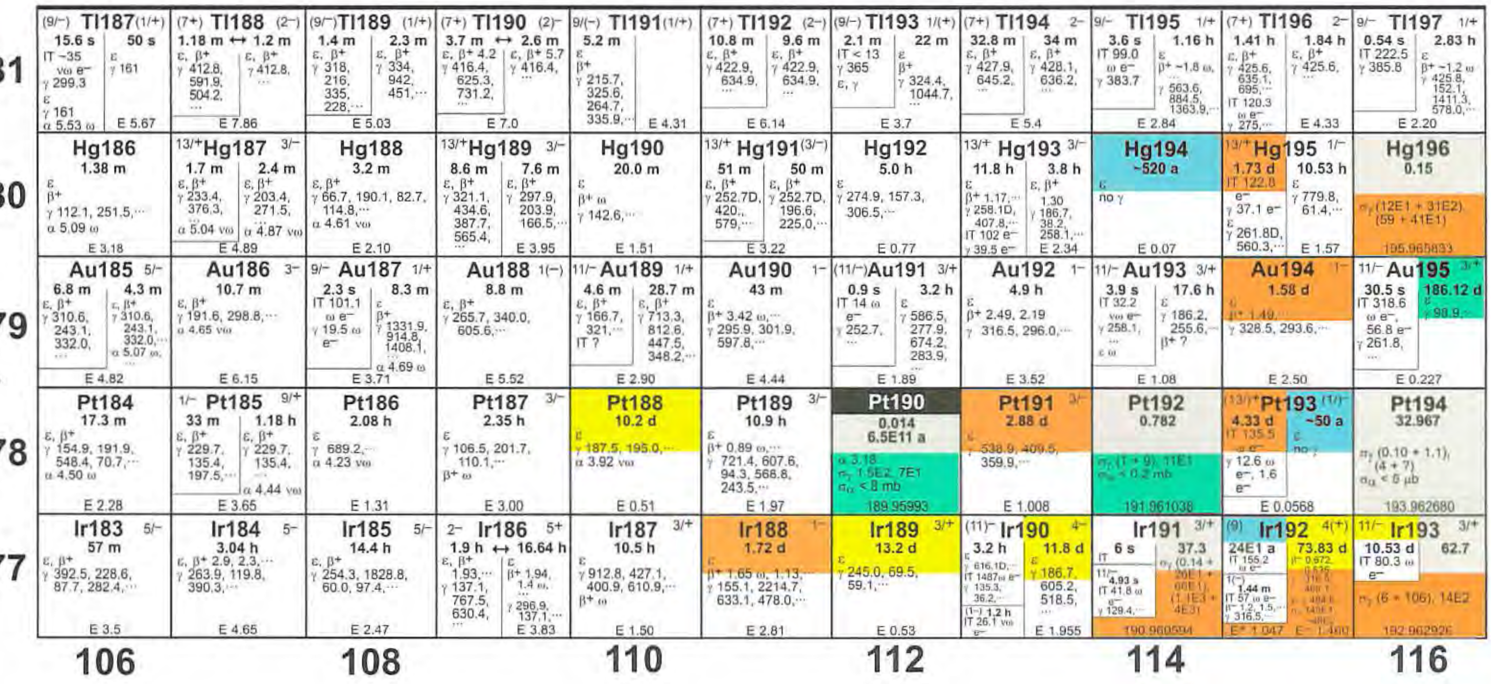




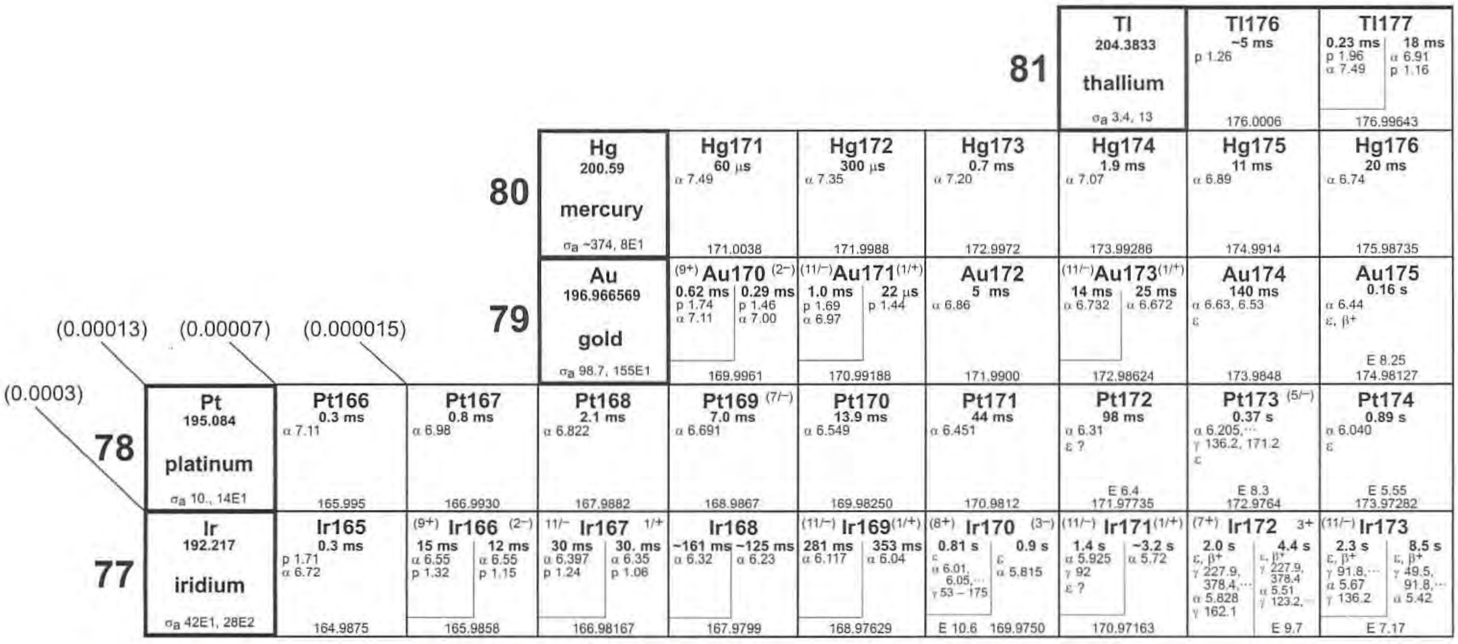
Ir187 3/+ 10.5 h ε γ 912.8, 427.1, 400.9, 610.9,··· β+ ω E 1.50	**Ir188** 1− 1.72 d ε β+ 1.65 ω, 1.13, γ 155.1, 2214.7, 633.1, 478.0,··· E 2.81	**Ir189** 3/+ 13.2 d ε γ 245.0, 69.5, 59.1,··· E 0.53	(11)− **Ir190** 4− 3.2 h: ε γ 616.1D,··· IT 1487ω e− γ 135.3, 36.2,··· (1−) 1.2 h: IT 26.1 νω e− 11.8 d: ε γ 186.7, 605.2, 518.5,··· E 1.955	**Ir191** 3/+ 6 s: IT 11/− 4.93 s: IT 41.8 ω e− γ 129.4,··· 37.3: σγ (0.14 + 26E1 + 66E1), (1.1E3 + 4E3) 190.960594	(9) **Ir192** 4(+) 24E1 a: IT 155.2 ω e− 1(−) 1.44 m: IT 57 ω e− β− 1.2, 1.5,··· γ 316.5,··· 73.83 d: β− 0.672, 0.535,··· γ 316.5, 468.1 ε, γ 484.6 σγ 145E1, ~48E2 E− 1.460 E+ 1.047	11/− **Ir193** 3/+ 10.53 d: IT 80.3 ω e− 62.7 σγ (6 + 106), 14E2 192.962926	(11) **Ir194** 1− 171 d: β− γ 482.9, 328.5,··· 19.3 h: β− 2.251,··· γ 328.5,··· σγ 1.5E3 E 2.234	11/− **Ir195** 3/+ 3.9 h: β− 0.41,··· γ 98.9, 319.9, 433.1, 684.8,··· IT 2.5 h: β− 0.98,··· γ 98.9, 211.4,··· E 1.107	**Ir196** (0−) 1.40 h: β− 1.2,··· γ 393.3, 521.1, 447.0, 355.6, 647.1,··· 52 s: β− 3.2,··· γ 355.6, 779.6,··· E 3.21	11/− **Ir197** 3/+ 8.9 m: β− γ 346.5D,··· IT ? 5.8 m: β− 2.0, ~1.5 γ 470.0, 430.9, 816.2,··· E 2.15
Os186 1.59 2E15 a α 2.758 σγ 8E1, 25E1 σα < 0.1 mb 185.953838	**Os187** 1/− 1.96 σγ 32E1, 7E2 σα ≤ 0.1 mb 186.955750	**Os188** 13.24 σγ 5, 16E1 σα < 0.03 mb 187.955838	9/− **Os189** 3/− 5.8 h: IT 30.8 (νω) e− 16.15: σγ (0.26mb + 2E1), 7E2 σα < 0.01 mb 188.958147	(10)− **Os190** 9.9 m: IT 38.9 (ω) e− γ 616.1, 502.5, 361.1, 186.7,··· 26.26: σγ (9 + 4), (22 + 8) σα < 0.02 mb 189.958447	3/− **Os191** 9/− 13.1 h: IT 74.4 (ω) e− 15.4 d: β− 0.143 γ 129.4D,··· σγ 4E2 E 0.313	(10−)**Os192** 6.0 s: IT 302.5,··· γ 569.4, 205.8, 453.2,··· 40.78: σγ 2.0, 5 σα < 0.01 mb 191.961481	**Os193** 3/− 30.11 h β− 1.13,··· γ 138.9, 460.5, 73.0,··· σγ 4E1 E 1.141	**Os194** 6.0 a β− 0.054, 0.097,··· γ 43.1 e−,··· E 0.097	**Os195?** ~ 6.5 m β− 2 E 2.0	**Os196** 34.9 m β− 0.84,··· γ 407.8, 126.1,··· E 1.2
Re185 5/+ 37.40 σγ (0.3 + 112), 17E2 184.952955	(8+) **Re186** 1− 2.0E5 a: IT ~50 νω e− γ 59.0, 40.4 e−,··· 3.718 d: β− 1.071, 0.933,··· γ 137.2,··· ε, γ 122.5ω E− 1.069 E+ 0.579	**Re187** 5/+ 62.60 4.12E10 a β− 0.002470 no γ σγ (2.8 + 73), (1E1 + 31E1) 186.955753 E 0.002469	(6)− **Re188** 1− 18.6 m: IT 2.4 e−, 15.9 e− γ 63.6, 105.9,··· 17.004 h: β− 2.118, 1.962,··· γ 155.041,··· E 2.1203	**Re189** (5/+) 24 h β− 1.01,··· γ 216.7, 219.4, 245.1,··· E 1.01	(6−) **Re190** (2)− 3.0 h: β− 1.6,··· γ 186.7,··· IT γ 119.1 3.0 m: β− 1.8,··· γ 186.7, 558.0,··· E 3.1	**Re191** 9.7 m β− 1.8 γ 57.5, 339.6,··· E 2.05	**Re192** 16 s β− 2.5 γ 467.5, 751.0, 205.8,··· E 4.2	**Re193** E 3.1	**Re194** E 4.9	**Re195**
W184 30.64 σγ (0.002 + 1.8), 14 183.950931	11/+ **W185** 3/− 1.64 m: IT 131.6 e−,··· γ 65.9 e−, 173.7,··· 74.8 d: β− 0.433,··· γ 125.4 ω σγ 3.3, 3E2 E 0.432	**W186** 28.43 σγ ~40, 49E1 185.954364	**W187** 3/− 23.9 h β− 0.622, 1.312,··· γ 685.7, 479.6,··· σγ 6E1, 28E2 E 1.311	**W188** 69.78 d β− 0.349,··· γ 290.7 (ω), 227.1, 63.6,··· E 0.349	**W189** (3/−) 10.7 m β− 2.5,··· γ 421.4, 260.4,··· E 2.5	**W190** 30. m β− 0.95 γ 157.6, 162.1 E 1.3	**W191** E 3.2	**W192** E 2		**120**
Ta183 7/+ 5.1 d β− 0.62,··· γ 246.1, 354.0, 107.9,··· E 1.071	**Ta184** (5−) 8.7 h β− 1.19,··· γ 414.0, 252.8, 920.9,··· E 2.87	**Ta185** (7/+) 49 m β− 1.77,··· γ 177.4, 173.7,··· E 1.99	**Ta186** (3−) 1.54 m: β− γ 179, 307.5, 417.7,··· 10.4 m: β− 2.2,··· γ 198.0, 215.0, 510.7,··· E 3.9	**Ta187** E 3.1	**Ta188** 5 μs: IT 292.4 E 4.9	**Ta189** E 3.6		**118**		
8− **Hf182** 62 m: β− 0.48,··· γ 942.8, 799.6,··· IT 506.6,··· γ 344.1, 224.4,··· 8.9E6 a: β− γ 270.4,··· σγ 13E1, 5E3 E 0.37	**Hf183** (3/−) 1.018 h β− 1.18, 1.54,··· γ 783.8, 73.2, 459.1,··· E 2.01	(8−) **Hf184** 50 s: IT 72.7, 555.0 γ 367.6,··· 4.1 h: β− 1.10, 0.74,··· γ 139.1, 344.9,··· E 1.34	**Hf185** ~3.5 m β− γ 164.5 E 3.0	**Hf186** ~2.6 m β− E 2.2	**Hf187** E 3.8	**Hf188** E 3				**Ir198** 8 s β− γ 507.0, 407.4 E 4.1
Lu181 (7/+) 3.5 m β− γ 652, 206, 574.8,··· E 2.7	**Lu182** 2.0 m β− γ 721, 818, 97.8, 808,··· E 4.2	**Lu183** (7/+) 58 s β− γ 1125, 1057, 168,··· E 3.8	**Lu184** 3+ ~20 s β− γ 107.3 242.5 E 5.1	**114**		**116**				**Os197** 3 m β− γ 223.9, 342.1, 50.7, 196.8,··· E 4.1
110		**112**								



(9+) **Ir166** (2−) 15 ms: α 6.55 p 1.32 12 ms: α 6.55 p 1.15 165.9858	11/− **Ir167** 1/+ 30 ms: α 6.397 p 1.24 30. ms: α 6.35 p 1.06 166.98167	**Ir168** ~161 ms: α 6.32 ~125 ms: α 6.23 167.9799	(11/−) **Ir169** (1/+) 281 ms: α 6.117 353 ms: α 6.04 168.97629	(8+) **Ir170** (3−) 0.81 s: ε α 6.01, 6.05,··· γ 53 – 175 0.9 s: ε α 5.815 E 10.6 169.9750	(11/−)**Ir171** (1/+) 1.4 s: α 5.925 γ 92 ε? ~3.2 s: α 5.72 170.97163	(7+) **Ir172** 3+ 2.0 s: ε, β+ γ 227.9, 378.4,··· α 5.828 γ 162.1 4.4 s: ε, β+ γ 227.9, 378.4 α 5.51 γ 123.2,··· E 9.7	(11/−)**Ir173** 2.3 s: ε, β+ γ 91.8,··· α 5.67 γ 136.2 8.5 s: ε, β+ γ 49.5, 91.8,··· α 5.42 E 7.17	(7+) **Ir174** (3+) 4.9 s: ε, β+ γ 158.6, 276.3, 342.5,··· α 5.48,··· γ 210.3,··· 8 s: ε, β+ γ 158.6, 276.3 α 5.28 ω γ 193.5,··· E 9.13	**Ir175** (5/−) 11 s ε, β+ γ 105.5, 399.0 α 5.39 E 6.68	**Ir176** 8.7 s Isomer mixture? ε, β+ γ 259.7, 346.7, 134.9,··· α 5.12 E 8.24
Os165 (7/−) 71 ms α 6.18 164.9768	**Os166** 0.22 s α 5.99 ε E 6.4 165.97269	**Os167** 0.80 s α 5.838 ε E 8.3 166.9715	**Os168** 2.1 s ε α 5.675 E 5.80 167.96780	**Os169** (5/−) 3.3 s ε α 5.571, 5.52,··· γ 72, 43, 28 E 7.66 168.96702	**Os170** 7.1 s ε γ 216.3,··· α 5.402 E 4.99 169.96358	**Os171** (5/−) 8 s β+, ε γ 189.9,··· α 5.248,··· E 6.96	**Os172** 18 s ε, β+ γ 63.0, 176.7,··· α 5.103 ω E 4.3	**Os173** (5/−) 16 s ε, β+ γ 214.7, 141.6, 299.3,··· α 4.94 ω E 6.12	**Os174** 44 s ε, β+ γ 118, 325,··· α 4.76 ω E 3.68	**Os175** (5/−) 1.4 m ε, β+ γ 125,··· E 5.18
Re164 0.5 s α 5.78 ε E 10.6 163.9703	**Re165** 2.4 s: α 5.519 2.6 s: ε, β+ α 5.49 E 8.21 164.96709	**Re166** 2.4 s ε γ 252.3, 423.9,··· α 5.527 E 10.0 165.9658	**Re167** 3.4 s ↔ 6.2 s 3.4 s: α 5.02 6.2 s: ε γ 221.3, 136.6 α 5.26 E 7.3 166.9626	**Re168** 4.4 s ε γ 363.2, 479.8,··· α 5.25 ω E 9.10	**Re169** 16 s: α 5.05 8.1 s: ε, β+ γ 101.2,··· α 4.70 ω,··· E 6.53	**Re170** (5+) 9.2 s β+, ε γ 306.8, 156.9, 413.2,··· E 8.38	**Re171** (9/−) 15.2 s β+, ε γ 568, 102, 1066, 435,··· E 5.84	(2) **Re172** (5) 55 s ↔ 15 s 55 s: β+, ε γ 123.4, 253.7,··· 15 s: β+, ε γ 253.7, 350.4, 123.4,··· E 7.6	**Re173** (5/−) 2.0 m ε γ 182, 191, 374 E 5.17	**Re174** 2.40 m β+, ε γ 243.4, 113.0,··· E 6.55
W163 2.8 s ε α 5.38 E 7.6 162.9625	**W164** 7 s ε γ 187.0, 268.7 α 5.150 E 5.05	**W165** 5.1 s ε α 4.91ω E 6.99	**W166** 19.9 s ε γ 125.8,··· α 4.74 ω E 4.21	**W167** 20. s ε γ 94.4, 110.2,··· α 4.55 ω E 6.26	**W168** 52 s ε γ 178.5,··· α 4.40 ω E 3.50	**W169** (5/−) 1.3 m ε γ 123.4, 169.5, 153.4,··· E 5.37	**W170** 2.4 m ε γ 316.2 E 2.84	**W171** (5/−) 2.39 m ε, β+ γ 184.2, 294.5, 478.7,··· E 4.63	**W172** 6.6 m ε, β+ γ 38.9, 423.3, 89.8,··· E 2.23	**W173** (5/−) 7 m ε γ 457.6, 130.2, 175,··· E 3.67
Ta162 3.5 s ε γ 284, 444 α 4.89 ω E 9.4	**Ta163** 10.6 s ε γ 396, 451, 449, 210,··· α 4.63 ω E 6.75	**Ta164** (3+) 14.2 s β+, ε γ 211.0, 376.7,··· E 8.54	**Ta165** 31 s ε, β+ γ 22, 94, 163, 311,··· E 5.78	**Ta166** (2)+ 34 s β+, ε γ 158.7, 311.7,··· E 7.76	**Ta167** (3/+) 1.4 m ε γ 82 – 296 E 5.12	**Ta168** (3+) 2.4 m β+, ε γ 123.9, 261.5, 751.4,··· E 6.97	**Ta169** 4.9 m ε, β+ γ 28.8, 192.4, 153.5,··· E 4.43	**Ta170** (3+) 6.8 m β+, ε γ 100.8, 221.2,··· E 6.12	**Ta171** (5/−) 23.3 m ε, β+ γ 49.6, 506.3,··· E 3.71	**Ta172** (3−) 36.8 m ε, β+ 2.5 γ 214.0, 95.2, 1109.2,··· E 5.07
Hf161 17 s ε, β+ γ 135.6,··· α 4.60 ω E 6.24	**Hf162** 38 s ε, β+ γ 173.8, 196.3, 410.1,··· α 4.31 ω E 3.7	**Hf163** 40. s ε, β+ γ 71.0, 62.1, 45.4, 688.2,··· E 5.51	**Hf164** 1.9 m ε, β+ γ 122.1, 153.3, 313.7,··· E 2.82	**Hf165** (5/−) 1.26 m ε, β+ γ 180.0, 772.7,··· E 4.81	**Hf166** 6.8 m ε β+ γ 78.5,··· E 2.16	**Hf167** (5/−) 2.0 m ε, β+ γ 315.2,··· E 4.03	**Hf168** 25.9 m ε β+ γ 57.3, 183.9, 117.3,··· E 1.7	**Hf169** (5/)− 3.25 m ε, β+ 1.8 γ 492.8,··· E 3.36	**Hf170** 16.0 h ε γ 164.7, 620.7, 120.2, 572.9,··· E 1.06	1/(−) **Hf171** 7/(+) ~29.5 s: IT 12.2 h: ε, β+ γ 122.0, 662.2,··· E 2.40
Lu160 40. s ↔ 36.1 s 40. s: ε, β+ γ 243.4, 395.4,··· 36.1 s: ε γ 243.4, 395.4,··· E 7.9	**Lu161** 1/+ 1.28 m ε γ 110.8, 100.3,··· E 5.28	**Lu162** 1(−) ~1.9 m?: ε (4−) ~1.5 m: ε γ 166.8,··· 1.37 m: ε γ 166.8, 631.9,··· E 7.0	**Lu163** 1/(+) 4.0 m β+ γ 163.1, 54.0, 369.3, 371.7,··· E 4.51	**Lu164** 1(−) 3.14 m ε, β+ 3.8, 1.6,··· γ 123.3, 740.5, 262.2, 863.9,··· E 6.38	**Lu165** 1/+ 10.7 m ε, β+ 2.06,··· γ 120.6, 132.5,··· E 3.84	0(−) **Lu166** 6(−) 2.1 m: ε, β+ γ 1427.2,··· IT ? 3(−) 1.4 m: ε, β+ γ 228.1, 102.4,··· IT 34.5 e− 2.8 m: ε, β+ 2.2,··· γ 228.1, 337.5,··· E 5.57	**Lu167** 7/+ 52 m ε β+ 2.1,··· γ 29.7, 239.1,··· E 3.09	3+ **Lu168** 6(−) 6.7 m: ε, β+ 1.5, 2.7,··· γ 198.8, 979.2, 896.1,··· 5.5 m: ε, β+ 1.2,··· γ 1483.6, 228.6,··· E 4.51	1/− **Lu169** 7/+ 2.7 m: IT 29.0 e− 1.419 d: ε β+ 1.271,··· γ 960.6, 191.2,··· E 2.293	(4)− **Lu170** 0+ 0.7 s: IT 48.4 e− γ 44.5 e− 2.01 d: ε, β+ 2.4,··· γ 84.3, 1280.2, 2041.9, 985.1,··· E 3.46
	90		**92**		**94**		**96**		**98**	



Z	106		108		110		112		114		116
81	(9/−) **Tl187** (1/+) 15.6 s IT ~35 vω e^- γ 299.3 ε γ 161 α 5.53 ω 50 s ε γ 161 E 5.67	(7+) **Tl188** (2−) 1.18 m ↔ 1.2 m ε, β^+ γ 412.8, 591.9, 504.2, … ε, β^+ γ 412.8, … E 7.86	(9/−) **Tl189** (1/+) 1.4 m ε, β^+ γ 318, 216, 335, 228,… 2.3 m ε, β^+ γ 334, 942, 451,… E 5.03	(7+) **Tl190** (2)− 3.7 m ↔ 2.6 m ε, β^+ 4.2 γ 416.4, 625.3, 731.2, … ε, β^+ 5.7 γ 416.4, … E 7.0	9/(−) **Tl191** (1/+) 5.2 m ε β^+ γ 215.7, 325.6, 264.7, 335.9,… E 4.31	(7+) **Tl192** (2−) 10.8 m ε, β^+ γ 422.9, 634.9, … 9.6 m ε, β^+ γ 422.9, 634.9, … E 6.14	(9/−) **Tl193** 1/(+) 2.1 m IT < 13 γ 365 ε, γ 22 m ε β^+ γ 324.4, 1044.7, … E 3.7	(7+) **Tl194** 2− 32.8 m ε, β^+ γ 427.9, 645.2, … 34 m ε, β^+ γ 428.1, 636.2, … E 5.4	9/− **Tl195** 1/+ 3.6 s IT 99.0 ω e^- γ 383.7 1.16 h ε β^+ ~1.8 ω, … γ 563.6, 884.5, 1363.9,… E 2.84	(7+) **Tl196** 2− 1.41 h ε, β^+ γ 425.6, 635.1, 695,… IT 120.3 ω e^- γ 275,… 1.84 h ε, β^+ γ 425.6, … E 4.33	9/− **Tl197** 1/+ 0.54 s IT 222.5 γ 385.8 2.83 h ε β^+ ~1.2 ω γ 425.8, 152.1, 1411.3, 578.0,… E 2.20
80	**Hg186** 1.38 m ε β^+ γ 112.1, 251.5,… α 5.09 ω E 3.18	13/+ **Hg187** 3/− 1.7 m ε, β^+ γ 233.4, 376.3, … α 5.04 vω 2.4 m ε, β^+ γ 203.4, 271.5, … α 4.87 vω E 4.89	**Hg188** 3.2 m ε, β^+ γ 66.7, 190.1, 82.7, 114.8,… α 4.61 vω E 2.10	13/+ **Hg189** 3/− 8.6 m ε, β^+ γ 321.1, 434.6, 387.7, 565.4, … 7.6 m ε, β^+ γ 297.9, 203.9, 166.5,… E 3.95	**Hg190** 20.0 m ε β^+ ω γ 142.6,… E 1.51	13/+ **Hg191** (3/−) 51 m ε, β^+ γ 252.7D, 420., 579,… 50 m ε, β^+ γ 252.7D, 196.6, 225.0,… E 3.22	**Hg192** 5.0 h ε γ 274.9, 157.3, 306.5,… E 0.77	13/+ **Hg193** 3/− 11.8 h ε β^+ 1.17,… γ 258.1D, 407.8,… IT 102 e^- γ 39.5 e^- 3.8 h ε, β^+ 1.30 γ 186.7, 38.2, 258.1,… E 2.34	**Hg194** ~520 a ε no γ E 0.07	13/+ **Hg195** 1/− 1.73 d IT 122.8 e^- γ 37.1 e^- ε γ 261.8D, 560.3,… 10.53 h ε γ 779.8, 61.4,… E 1.57	**Hg196** 0.15 σ_γ (12E1 + 31E2), (59 + 41E1) 195.965833
79	**Au185** 5/− 6.8 m ε, β^+ γ 310.6, 243.1, 332.0, … 4.3 m ε, β^+ γ 310.6, 243.1, 332.0,… α 5.07 ω, … E 4.82	**Au186** 3− 10.7 m ε, β^+ γ 191.6, 298.8,… α 4.65 vω E 6.15	9/− **Au187** 1/+ 2.3 s IT 101.1 ω e^- γ 19.5 ω e^- 8.3 m ε β^+ γ 1331.9, 914.8, 1408.1, … α 4.69 ω E 3.71	**Au188** 1(−) 8.8 m ε, β^+ γ 265.7, 340.0, 605.6,… E 5.52	11/− **Au189** 1/+ 4.6 m ε, β^+ γ 166.7, 321,… IT ? 28.7 m ε, β^+ γ 713.3, 812.6, 447.5, 348.2,… E 2.90	**Au190** 1− 43 m ε β^+ 3.42 ω,… γ 295.9, 301.9, 597.8,… E 4.44	(11/−) **Au191** 3/+ 0.9 s IT 14 ω e^- γ 252.7, … 3.2 h ε γ 586.5, 277.9, 674.2, 283.9, … E 1.89	**Au192** 1− 4.9 h ε β^+ 2.49, 2.19 γ 316.5, 296.0,… E 3.52	11/− **Au193** 3/+ 3.9 s IT 32.2 vω e^- γ 258.1, … ε ω 17.6 h ε γ 186.2, 255.6,… β^+ ? E 1.08	**Au194** 1− 1.58 d ε β^+ 1.49,… γ 328.5, 293.6,… E 2.50	11/− **Au195** 3/+ 30.5 s IT 318.6 ω e^-, 56.8 e^- γ 261.8, … 186.12 d ε γ 98.9,… E 0.227
78	**Pt184** 17.3 m ε, β^+ γ 154.9, 191.9, 548.4, 70.7,… α 4.50 ω E 2.28	1/− **Pt185** 9/+ 33 m ε, β^+ γ 229.7, 135.4, 197.5,… 1.18 h ε, β^+ γ 229.7, 135.4, … α 4.44 vω E 3.65	**Pt186** 2.08 h ε γ 689.2,… α 4.23 vω E 1.31	**Pt187** 3/− 2.35 h ε γ 106.5, 201.7, 110.1,… β^+ ω E 3.00	**Pt188** 10.2 d ε γ 187.5, 195.0,… α 3.92 vω E 0.51	**Pt189** 3/− 10.9 h ε β^+ 0.89 ω,… γ 721.4, 607.6, 94.3, 568.8, 243.5,… E 1.97	**Pt190** 0.014 6.5E11 a α 3.18 σ_γ 1.5E2, 7E1 σ_α < 8 mb 189.95993	**Pt191** 3/− 2.88 d ε γ 538.9, 409.5, 359.9,… E 1.008	**Pt192** 0.782 σ_γ (1 + 9), 11E1 σ_α < 0.2 mb 191.961038	(13/)+ **Pt193** (1/)− 4.33 d IT 135.5 ω e^- γ 12.6 ω e^-, 1.6 e^- ~50 a ε no γ E 0.0568	**Pt194** 32.967 σ_γ (0.10 + 1.1), (4 + 7) σ_α < 5 μb 193.962680
77	**Ir183** 5/− 57 m ε, β^+ γ 392.5, 228.6, 87.7, 282.4,… E 3.5	**Ir184** 5− 3.04 h ε, β^+ 2.9, 2.3,… γ 263.9, 119.8, 390.3,… E 4.65	**Ir185** 5/− 14.4 h ε, β^+ γ 254.3, 1828.8, 60.0, 97.4,… E 2.47	2− **Ir186** 5+ 1.9 h ↔ 16.64 h ε, β^+ 1.93,… γ 137.1, 767.5, 630.4, … ε β^+ 1.94, 1.4 ω, … γ 296.9, 137.1,… E 3.83	**Ir187** 3/+ 10.5 h ε γ 912.8, 427.1, 400.9, 610.9,… β^+ ω E 1.50	**Ir188** 1− 1.72 d ε β^+ 1.65 ω, 1.13,… γ 155.1, 2214.7, 633.1, 478.0,… E 2.81	**Ir189** 3/+ 13.2 d ε γ 245.0, 69.5, 59.1,… E 0.53	(11)− **Ir190** 4− 3.2 h ε γ 616.1D,… IT 1487 ω e^- γ 135.3, 36.2,… (1−) 1.2 h IT 26.1 vω e^- 11.8 d ε γ 186.7, 605.2, 518.5, … E 1.955	**Ir191** 3/+ 6 s IT 11/− 4.93 s IT 41.8 ω e^- γ 129.4,… 37.3 σ_γ (0.14 + 26E1 + 66E1), (1.1E3 + 4E3) 190.960594	(9) **Ir192** 4(+) 24E1 a IT 155.2 ω e^- 1(−) 1.44 m IT 57 ω e^- β^- 1.2, 1.5,… γ 316.5,… 73.83 d β^- 0.672, 0.536, [illegible] E^+ 1.047 E^- 1.460	11/− **Ir193** 3/+ 10.53 d IT 80.3 ω e^- 62.7 σ_γ (6 + 106), 14E2 192.962926



Z		88		90		92		94		96
81								**Tl** 204.3833 thallium σ_a 3.4, 13	**Tl176** ~5 ms p 1.26 176.0006	**Tl177** 0.23 ms p 1.96 α 7.49 18 ms α 6.91 p 1.16 176.99643
80				**Hg** 200.59 mercury σ_a ~374, 8E1	**Hg171** 60 μs α 7.49 171.0038	**Hg172** 300 μs α 7.35 171.9988	**Hg173** 0.7 ms α 7.20 172.9972	**Hg174** 1.9 ms α 7.07 173.99286	**Hg175** 11 ms α 6.89 174.9914	**Hg176** 20 ms α 6.74 175.98735
79				**Au** 196.966569 gold σ_a 98.7, 155E1	(9+) **Au170** (2−) 0.62 ms p 1.74 α 7.11 0.29 ms p 1.46 α 7.00 169.9961	(11/−) **Au171** (1/+) 1.0 ms p 1.69 α 6.97 22 μs p 1.44 170.99188	**Au172** 5 ms α 6.86 171.9900	(11/−) **Au173** (1/+) 14 ms α 6.732 25 ms α 6.672 172.98624	**Au174** 140 ms α 6.63, 6.53 ε 173.9848	**Au175** 0.16 s α 6.44 ε, β^+ E 8.25 174.98127
78	**Pt** 195.084 platinum σ_a 10., 14E1	**Pt166** 0.3 ms α 7.11 165.995	**Pt167** 0.8 ms α 6.98 166.9930	**Pt168** 2.1 ms α 6.822 167.9882	**Pt169** (7/−) 7.0 ms α 6.691 168.9867	**Pt170** 13.9 ms α 6.549 169.98250	**Pt171** 44 ms α 6.451 170.9812	**Pt172** 98 ms α 6.31 ε ? E 6.4 171.97735	**Pt173** (5/−) 0.37 s α 6.205,… γ 136.2, 171.2 ε E 8.3 172.9764	**Pt174** 0.89 s α 6.040 ε E 5.55 173.97282
77	**Ir** 192.217 iridium σ_a 42E1, 28E2	**Ir165** 0.3 ms p 1.71 α 6.72 164.9875	(9+) **Ir166** (2−) 15 ms α 6.55 p 1.32 12 ms α 6.55 p 1.15 165.9858	11/− **Ir167** 1/+ 30 ms α 6.397 p 1.24 30. ms α 6.35 p 1.06 166.98167	**Ir168** ~161 ms α 6.32 ~125 ms α 6.23 167.9799	(11/−) **Ir169** (1/+) 281 ms α 6.117 353 ms α 6.04 168.97629	(8+) **Ir170** (3−) 0.81 s ε α 6.01, 6.05,… γ 53 – 175 0.9 s ε α 5.815 E 10.6 169.9750	(11/−) **Ir171** (1/+) 1.4 s α 5.925 γ 92 ε ? ~3.2 s α 5.72 170.97163	(7+) **Ir172** 3+ 2.0 s ε, β^+ γ 227.9, 378.4,… α 5.828 γ 162.1 4.4 s ε, β^+ γ 227.9, 378.4 α 5.51 γ 123.2,… E 9.7	(11/−) **Ir173** 2.3 s ε, β^+ γ 91.8,… α 5.67 γ 136.2 8.5 s ε, β^+ γ 49.5, 91.8,… α 5.42 E 7.17

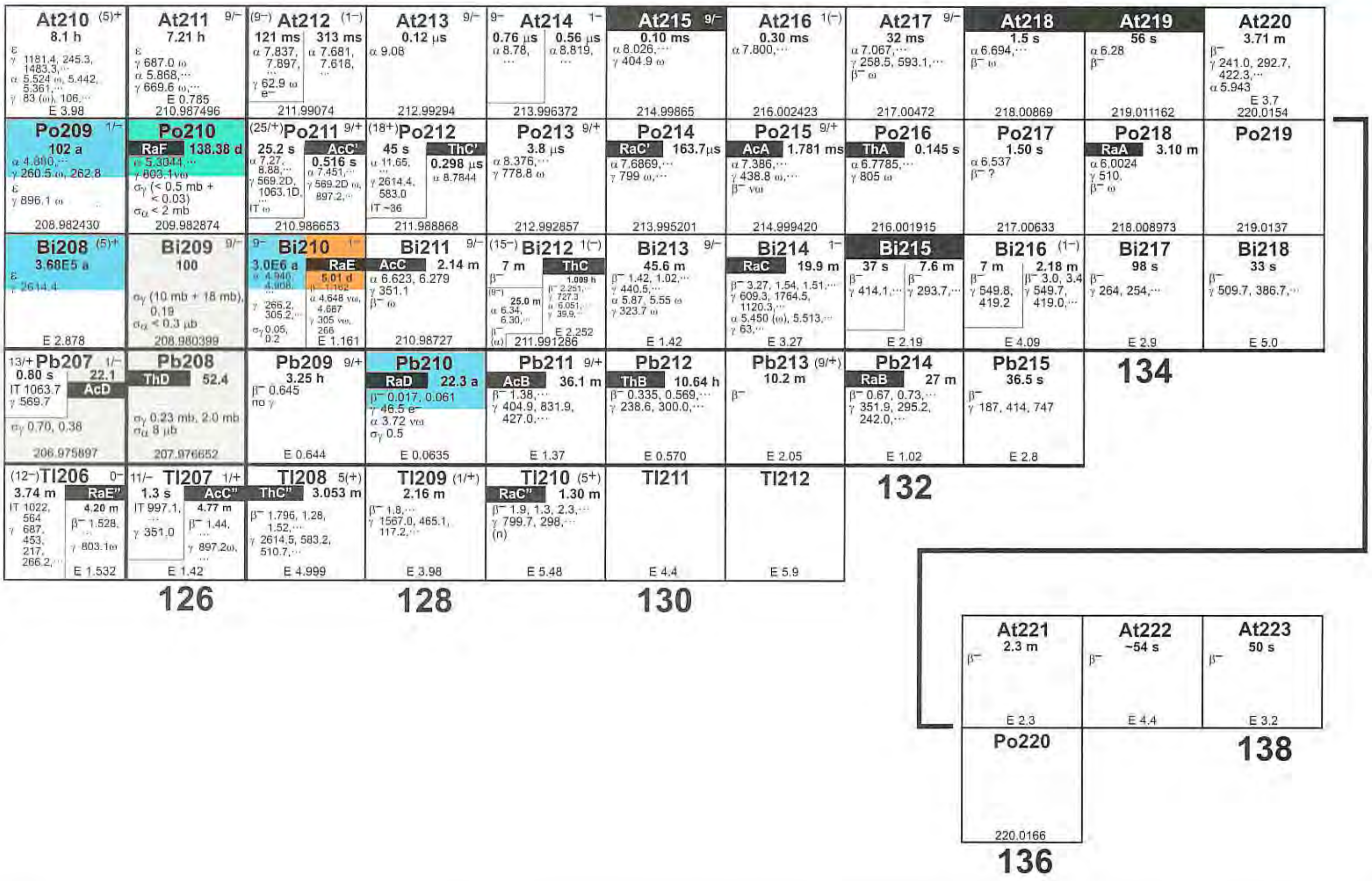
7+ **Tl198** 2− 1.87 h ε β+ γ 411.8, 636.7, 587.2,… IT 261 e− γ 282.6,… 5.3 h ε β+ 2.4 (ω), 2.1, 1.4,… γ 411.8,… E 3.5	**Tl199** 1/+ 7.4 h ε γ 455.5, 208.2, 247.3, 158.4,… E 1.49	**Tl200** 2− 1.087 d ε β+ 1.07 (ω), 1.44 γ 368.0, 1205.7,… E 2.46	**Tl201** 1/+ 3.043 d ε γ 167.4, 135.3,… E 0.48	**Tl202** 2− 12.23 d ε β+ νω γ 439.6,… E 1.36	**Tl203** 1/+ 29.52 σγ 11.4, 41 σα < 0.3 mb 202.972344	**Tl204** 2− 3.78 a β− 0.7634 no γ ε σγ 22, 9E1 E− 0.7638 E+ 0.344	**Tl205** 1/+ 70.48 σγ 0.10, 0.7 204.974428	(12−) **Tl206** 0− 3.74 m IT 1022, 564 γ 687, 453, 217, 266.2,… RaE" 4.20 m β− 1.528,… γ 803.1ω E 1.532	11/− **Tl207** 1/+ 1.3 s IT 997.1,… γ 351.0 AcC" 4.77 m β− 1.44,… γ 897.2 ω,… E 1.42	**Tl208** 5(+) ThC" 3.053 m β− 1.796, 1.28, 1.52,… γ 2614.5, 583.2, 510.7,… E 4.999
13/+ **Hg197** 1/− 23.8 h IT 165.0 ω e− γ 134.0 ε γ 279.1D,… 2.672 d ε γ 77.3,… E 0.600	**Hg198** 9.97 σγ (0.017 + 1.9), 7E1 197.9667690	13/+ **Hg199** 1/− 42.6 m IT 374.1,… γ 158.4,… 16.87 σγ 2.2E3, 4E2 198.9682799	**Hg200** 23.10 σγ < 60 199.9683260	**Hg201** 3/− 13.18 σγ 8, 3E1 200.970302	**Hg202** 29.86 σγ 4.9, 4.5 201.970643	**Hg203** 5/− 46.61 d β− 0.213 γ 279.2 E 0.492	**Hg204** 6.87 σγ 0.4, 0.8 203.9734939	**Hg205** 1/− 5.2 m β− 1.6,… γ 203.7,… E 1.533	**Hg206** 8.2 m β− 0.94,… γ 305.2,… E 1.31	**Hg207** (9/+) 3.0 m β− γ 351.0, 997.1, 1637.1,… E 4.8
12− **Au196** 2− 9.6 h IT 174.9 ω e− γ 147.8, 188.2,… 5+ 8.1 s IT 84.66 ω e− 6.167 d ε γ 355.6, 332.9,… β− 0.259 γ 425.6 β+ νω E+ 1.507 E− 0.687	11/− **Au197** 3/+ 7.8 s IT 130.2 e−,… γ 279.1,… 100 σγ (0 + 98.7), 155E1 196.966569	(12−) **Au198** 2− 2.27 d IT 115 ω e− γ 214.9, 97.2,… 2.6949 d β− 0.961,… γ 411.8021, σγ 26E3 E 1.372	**Au199** 3/+ 3.14 d β− 0.292, 0.25, 0.453 γ 158.4, 208.2,… σγ 3E1 E 0.452	12− **Au200** 1(−) 18.7 h β− 0.56 γ 368.0, 497.8, 579.3, 255.9,… IT γ 333,… 48.4 m β− 2.3, 0.7,… γ 368.0, 1225.5,… E 2.24	**Au201** 3/+ 26 m β− 1.3,… γ 542.6, 517.0, 613.2,… E 1.262	**Au202** (1−) 29 s β− 3.5,… γ 439.6,… E 2.9	**Au203** 3/+ ~60 s β− ~2.1,… γ 217.6,… E 2.126	**Au204** (2−) 40. s β− γ 436.5, 1511.1, 691.8, 723.0, 1392.1,… E 3.9	**Au205** 31 s β− γ 379.4, 467.4, 946.0,… E 3.5	
13/+ **Pt195** 1/− 4.010 d IT 129.5 ω e−,… γ 98.9, 129.8,… 33.832 σγ 29, 36E1 σα < 5 μb 194.964791	**Pt196** 25.242 σγ (0.04 + 0.6), 5 195.964952	13/+ **Pt197** 1/− 1.590 h IT 346.5 γ 53.1 e− β− 0.709 γ 279.1D,… 19.96 h β− 0.642, 0.719,… γ 77.3, 191.4,… E 0.719	**Pt198** 7.163 σγ (0.3 + 3.5), ~56 197.967893	(13/)+ **Pt199** 5/− 13.6 s IT 391.9 γ 32 e− σγ2E1 30.8 m β− 1.69,… γ 543.0, 493.7, 317.0,… E 1.703	**Pt200** 12.5 h β− γ 76.2, 135.9, 243.7, 60.0, 227.4,… E 0.7	**Pt201** 2.5 m β− 2.7,… γ 1760.,… E 2.66	**Pt202?** E 1.8		126	
(11) **Ir194** 1− 171 d β− γ 482.9, 328.5,… 19.3 h β− 2.251, γ 328.5, σγ 1.5E3 E 2.234	11/− **Ir195** 3/+ 3.9 h β− 0.41,… γ 98.9, 319.9, 433.1, 684.8,… IT 2.5 h β− 0.98,… γ 98.9, 211.4,… E 1.107	**Ir196** (0−) 1.40 h β− 1.2,… γ 393.3, 521.1, 447.0, 355.6, 647.1,… 52 s β− 3.2,… γ 355.6, 779.6,… E 3.21	11/− **Ir197** 3/+ 8.9 m β− γ 346.5D,… IT ? 5.8 m β− 2.0, ~1.5 γ 470.0, 430.9, 816.2,… E 2.15	**Ir198** 8 s β− γ 507.0, 407.4 E 4.1	122		124			
	118		120							

Tl209 (1/+) 2.16 m β− 1.8,… γ 1567.0, 465.1, 117.2,… E 3.98	**Tl210** (5+) RaC" 1.30 m β− 1.9, 1.3, 2.3,… γ 799.7, 298,… (n) E 5.48	**Tl211** E 4.4	**Tl212** E 5.9
Hg208 41 m β− γ 892.3, 266.9, 968.0,… E 3.7	**Hg209** ~35 s β− γ 324.0, 465.1,… E 5.3	**Hg210** E 4.1	
128		130	

Tl178 ~254 ms α 6.704, 6.785,… 177.9949	**Tl179** 1.6 ms α 7.20, 7.10 0.27 s α 6.57 178.99109	**Tl180** 0.7 s ε, β+ α 6.28, 6.36,… E 10.8 179.9899	**Tl181** 1.4 ms ↔ 3.2 s α 6.47 α 6.18 180.98626	**Tl182** (7+) 3 s ε, β+ γ 351.4, 261.4,… α 6.41 E 10.2	(9/−) **Tl183** (1/+) 53 ms α 6.34, 6.38,… 7 s β+, ε γ 208 E 7.21	**Tl184** 11 s β+, ε γ 366.5, 286.8,… α 6.162, 5.988,… E 9.5	(9/−) **Tl185** (1/+) 1.9 s IT 169 γ 284, 168.8 α 5.975,… 19.5 s ε, β+ E 6.4	**Tl186** (7+) 2.9 s IT 374.0 28 s ε, β+ γ 405.3, 402.6, 356.7,… α 5.64 ω E 8.3	(9/−) **Tl187** (1/+) 15.6 s IT ~35 νω e− γ 299.3 ε γ 161 α 5.53 ω 50 s ε γ 161 E 5.67
Hg177 127 ms α 6.58 ε E 8.8 176.9863	**Hg178** 269 ms α 6.43 ε E 6.0 177.98248	**Hg179** 7/− 1.0 s α 6.29 ε (p) ω E 8.03 178.98183	**Hg180** 2.6 s ε γ 301, 381,… α 6.120,… γ 179 ω, 263, 443 E 5.35 179.97827	**Hg181** 1/(−) 3.6 s β+, ε α 6.006,… (p) 3.5 – 5.5 ω (α) νω E 7.21 180.97782	**Hg182** 10.8 s ε, β+ γ 129.5, 217.6, 413.5,… α 5.867,… E 4.72 181.97469	**Hg183** 1/− 9 s ε, β+ γ 61, 160.,… α 5.905,… (p) 5.1 ω E 6.39 182.97445	**Hg184** 30.9 s ε, β+ γ 236.4, 156.4,… α 5.54,… E 3.97	13/+ **Hg185** 1/− 21 s IT 65.3 ω e− γ 26.1 ω e− ε γ 212.5,… α 5.37,… 51 s ε, β+ γ 222.8, 258.7,… α 5.653,… E 5.69	**Hg186** 1.38 m ε β+ γ 112.1, 251.5,… α 5.09 ω E 3.18
Au176 0.9 s α 6.23, 6.29 γ 168.4 ε γ 264, 300, 342,… 175.9801	**Au177** 1.22 s α 6.11, 6.15 E 7.82 176.97686	**Au178** 2.6 s ε γ 170.4, 257.3, 337.9,… α 5.92, 5.98,… E 9.7 177.9760	**Au179** 7.1 s ε, β+ α 5.848 E 7.31 178.97321	**Au180** 8.1 s ε γ 153.0, 524.3, 257.6,… α 5.68,… γ 37, 42, 118, 195 E 8.84	**Au181** (3/−) 14 s ε, β+ γ 198.6, 79.4 e−,… α 5.48, 5.63,… γ 148 ω,… E 6.50	**Au182** 2+ 21 s ε, β+ γ 154.9, 264.8,… α 5.352 ω E 7.87	**Au183** (5/)− 42 s ε γ 161.3, 214.1, 313.2, 179.6,… α 5.349 ω E 5.59	(2+) **Au184** (5+) 49 s ε, β+ γ 162.8, 272.8,… α 5.109 ω, 5.187,… 21 s ε ? E 7.01	**Au185** 5/− 6.8 m ε, β+ γ 310.6, 243.1, 332.0,… 4.3 m ε, β+ γ 310.6, 243.1, 332.0,… α 5.07 ω,… E 4.82
Pt175 (7/−) 2.5 s α 5.960,… γ 76.4, 134.4, 211.8 ε E 7.74 174.97242	**Pt176** 6.5 s ε α 5.75,… γ 227 ω E 4.93 175.96894	**Pt177** (5/−) 10.6 s ε γ 148.0, 85.4, 223.1,… α 5.52, 5.48 γ 91.8 ω E 6.68	**Pt178** 21 s ε γ 84.6, 90.4, 101.3,… α 5.446,… E 4.25	**Pt179** 1/− 21.2 s β+, ε γ 171.7, 193.1, 99.8,… α 5.20 ω E 5.81	**Pt180** 56 s ε γ 95.2, 80.6,… α 5.14 ω E 3.54	**Pt181** 1/− 52 s ε γ 111.9, 289.2, 230.1,… α 5.036 ω,… E 5.10	**Pt182** 2.7 m ε, β+ γ 74.8, 136.2, 81.5,… α 4.843 ω E 2.88	7/− **Pt183** 1/− 43 s ε, β+ γ 629.6, 316.4,… IT 35.0 e− 7 m ε, β+ α 4.72 ω E 4.42	**Pt184** 17.3 m ε, β+ γ 154.9, 191.9, 548.4, 70.7,… α 4.50 ω E 2.28
(7+) **Ir174** (3+) 4.9 s ε, β+ γ 158.6, 276.3, 342.5,… α 5.48,… γ 210.3,… 8 s ε, β+ γ 158.6, 276.3 α 5.28 ω γ 193.5,… E 9.13	**Ir175** (5/−) 11 s ε, β+ γ 105.5, 399.0 α 5.39 E 6.68	**Ir176** 8.7 s Isomer mixture? ε, β+ γ 259.7, 346.7, 134.9,… α 5.12 E 8.24	**Ir177** (5/−) 30. s β+, ε γ 184.1, 75.4, 147.8,… α 5.01 ω E 5.90	**Ir178** 12 s ε, β+ γ 266.7, 132.0, 363.3,… E 7.29	**Ir179** (5/)− 1.32 m ε, β+ γ 97.5, 86.3, 45.2,… E 4.94	**Ir180** 1.5 m ε, β+ γ 276.4, 131.9,… E 6.38	**Ir181** 5/− 4.9 m ε, β+ γ 107.6, 227.0, 1639.6, 318.9,… E 4.08	**Ir182** 3+ 15 m ε, β+ γ 273.0, 127.0,… E 5.56	**Ir183** 5/− 57 m ε, β+ γ 392.5, 228.6, 87.7, 282.4,… E 3.5
	98		100		102		104		106

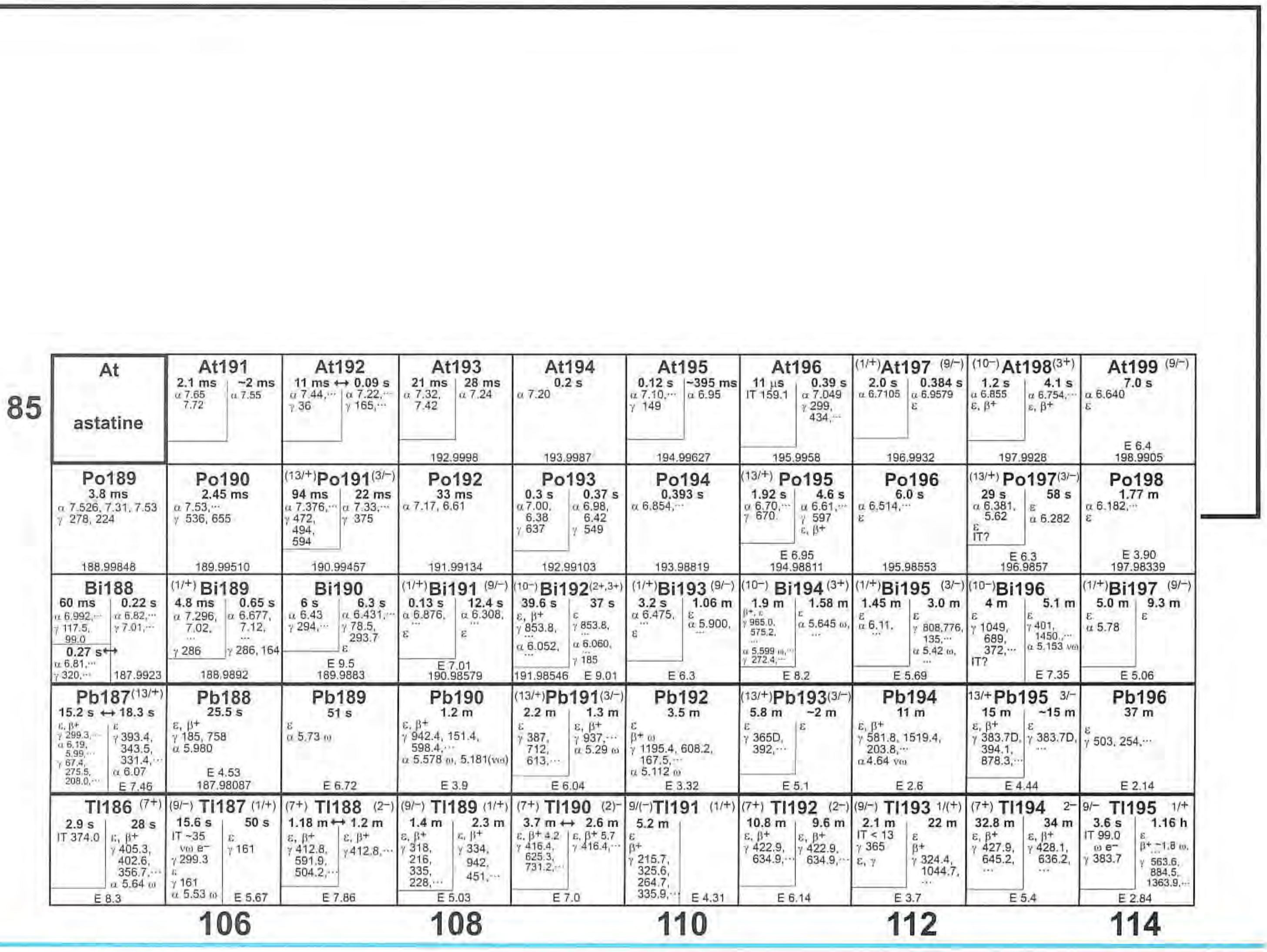
85	**At199** (9/−) **7.0 s** α 6.640 ε E 6.4 198.9905	(10−)**At200** (5+) **3.7 s** IT 230.9 α 6.530 (7+)**47 s** ε, β^+ α 6.413, … **43 s** α 6.463 ε γ 666.0, 611.1, … E 7.97 199.99035	**At201** (9/−) **1.41 m** α 6.343 ε, β^+ γ 592, 616, 622, 723,… E 5.74 200.98842	(10−)**At202** (5+) **0.46 s** IT 391.7 α 6.277ω (7+)**3.03 m** ε, β^+ α 6.134 **3.07 m** ε, β^+ γ 677.2, 571.6,… α 6.228,… E 7.33 201.98863	**At203** 9/− **7.4 m** ε, β^+ 2.4 γ 639.4, 641.5, 738.1,… α 6.088 E 5.14 202.98694	**At204** 7+ **9.1 m** ε, β^+ γ 684.3, 516.3, 426.2,… α 5.951 E 6.46	**At205** 9/− **26 m** ε β^+ γ 719.3, 669.4, 628.9,… α 5.902 E 4.54 204.98607	**At206** 5+ **29.4 m** ε, β^+ 3.1,… γ 700.7, 477.2, 395.6,… α 5.703 ω,… γ 65.0 ω E 5.76	**At207** 9/− **1.81 h** ε β^+ γ 814.4, 588.3, 300.7,… α 5.758 E 3.90	**At208** 6+ **1.63 h** ε β^+ γ 686.5, 660.0, 177.6,… α 5.641 ω,… E 4.98	**At209** 9/− **5.4 h** ε γ 545.0, 781.9, 790.2,… α 5.647,… E 3.49
84	**Po198** **1.77 m** α 6.182,… ε E 3.90 197.98339	13/+ **Po199**(3/−) **4.20 m** ε γ 1002, 1034, 362,… α 6.059 IT γ 72, 238 **5.2 m** ε γ 246, 846, 880,… α 5.952 E 5.58	**Po200** **11.5 m** ε, β^+ γ 671.0, 617.7, 434.4,… α 5.863 E 3.42 199.98180	13/+**Po201** 3/− **8.9 m** ε, β^+ γ 967.4, 964.3, … IT 418 γ ~7 vω α 5.786 **15.3 m** ε, β^+ γ 890.1, 240.1, 904.2,… α 5.683,… E 4.89	**Po202** **44.7 m** ε γ 688.8, 316.1, 165.8,… α 5.588 E 2.81	13/+**Po203** 5/− **45 s** IT 641.4 ε ? **35 m** ε, β^+ γ 908.6, 1090.9, 893.5,… α 5.384 ω, … E 4.23	**Po204** **3.53 h** ε γ 884.0, 270.1, 1016.3,… α 5.377 ω E 2.33	**Po205** 5/− **1.7 h** ε γ 872.4, 1001.2, 849.8, 836.8,… α 5.22 ω E 3.55	**Po206** **8.8 d** ε γ 1032.3, 511.3, 286.4, 807.4,… α 5.223 E 1.85	19/−**Po207** 5/− **2.8 s** IT 268.1 γ 814.5D, 300.5D **5.80 h** ε β^+ 0.89 (ω), 1.14 γ 992.3, 742.6, 911.8,… α 5.115 ω E 2.91	**Po208** **2.898 a** α 5.115,… ε ω γ 291.8 vω, 570.1, 601.5,… 207.981246
83	(1/+)**Bi197** (9/−) **5.0 m** ε α 5.78 **9.3 m** ε E 5.06	(10−) **Bi198**(2+,3+) **7.7 s** IT 248.5 (7+) **11.8 m** ε γ 1063.5, 562,… **10.3 m** ε, β^+ E 6.68	(1/+) **Bi199** 9/− **24.7 m** ε α 5.484 ω **27 m** ε, β^+ γ 425D, 842,… E 4.43	(10−)**Bi200** 7+ **0.4 s** IT 428 (2+)**31 m** ε, β^+ γ 1026.6, 462.3,… IT **36 m** ε, β^+ γ 1026.6, 462.3, 419.7, … E 5.87	1/+ **Bi201** 9/− **59 m** ε IT 846 α 5.24 ω **1.72 h** ε β^+ γ 629.1D, 936, 1014, 786,… E 3.84	**Bi202** 5+ **1.72 h** ε β^+ γ 960.7D, 422.2D, 657.5D, … E 5.20	**Bi203** 9/− **11.8 h** ε β^+ 1.35(ω), 0.74 γ 820.3, 825.2D, 897, 1847,… α ~4.85? vω E 3.25	**Bi204** 6+ **11.2 h** ε γ 899.2D, 374.8D, 984.0,… β^+ ω E 4.44	**Bi205** 9/− **15.31 d** ε β^+ 0.98 ω γ 1764.3, 703.5, 987.6D,… E 2.71	**Bi206** 6+ **6.243 d** ε β^+ 0.98 vω γ 803.1, 881.0, 516.2,… E 3.76	**Bi207** 9/− **32 a** ε β^+ ω γ 569.7, 1063.7D,… E 2.397
82	**Pb196** **37 m** ε γ 503, 254,… E 2.14	13/+ **Pb197** 3/− **43 m** ε β^+ γ 385.8D, 387.6, 222.6D,… IT 234 ω e^- γ 84.9 **8 m** ε β^+ γ 385.8D, 761.2, 375.4, … E 3.59	**Pb198** **2.4 h** ε γ 290.3, 365.4, 173.4,… E 1.4	13/+ **Pb199** 3/− **12.2 m** IT 424,… ε γ 367.0,… **1.5 h** ε β^+ γ 367.0, 353.4, 1135.1, … E 2.83	**Pb200** **21.5 h** ε γ 147.6,… E 0.80	13/+**Pb201** 5/− **1.02 m** IT 629 **9.33 h** ε β^+ 0.55,… γ 331.2, 361.3, 945.9, … E 1.92	9− **Pb202** **3.54 h** IT 787.0, … γ 960.7, 422.1, … ε γ 490.5, 459.7, … **5.3E4 a** ε no γ E 0.05	13/+**Pb203** 5/− **6.2 s** IT 825.2 γ 820.3 **2.164 d** ε γ 279.2, E 0.97	9− **Pb204** **1.12 h** IT 911.7, … γ 899.2, 374.8, … **1.4** σ_γ 0.70, 2.0 203.973044	**Pb205** 5/− **1.5E7 a** ε no γ σ_γ 4.5 E 0.0505	**Pb206** **24.1** RaG σ_γ 0.027, 0.10 205.974465
81	9/− **Tl195** 1/+ **3.6 s** IT 99.0 ω e^- γ 383.7 **1.16 h** ε β^+ ~1.8 ω, … γ 563.6, 884.5, 1363.9,… E 2.84	(7+) **Tl196** 2− **1.41 h** ε, β^+ γ 425.6, 635.1, 695,… IT 120.3 ω e^- γ 275,… **1.84 h** ε, β^+ γ 425.6, … E 4.33	9/− **Tl197** 1/+ **0.54 s** IT 222.5 γ 385.8 **2.83 h** ε β^+ ~1.2 ω γ 425.8, 152.1, 1411.3, 578.0,… E 2.20	7+ **Tl198** 2− **1.87 h** ε β^+ γ 411.8, 636.7, 587.2, … IT 261 e^- γ 282.6,… **5.3 h** ε β^+ 2.4 (ω), 2.1, 1.4, … γ 411.8,… E 3.5	**Tl199** 1/+ **7.4 h** ε γ 455.5, 208.2, 247.3, 158.4,… E 1.49	**Tl200** 2− **1.087 d** ε β^+ 1.07 (ω), 1.44 γ 368.0, 1205.7,… E 2.46	**Tl201** 1/+ **3.043 d** ε γ 167.4, 135.3,… E 0.48	**Tl202** 2− **12.23 d** ε β^+ vω γ 439.6,… E 1.36	**Tl203** 1/+ **29.52** σ_γ 11.4, 41 σ_α < 0.3 mb 202.972344	**Tl204** 2− **3.78 a** β^- 0.7634 no γ ε σ_γ 22, 9E1 E^- 0.7638 E^+ 0.344	**Tl205** 1/+ **70.48** σ_γ 0.10, 0.7 204.974428
	114		**116**		**118**		**120**		**122**		**124**

								84	**Po** polonium	**Po187** **1.4 ms** α 7.53 γ 286	**Po188** **0.27 ms** α 7.92, 7.35 187.99942
						83	**Bi** 208.98040 bismuth σ_a 0.034, 0.19	**Bi184** **~6.6 ms ↔ 13 ms** α 7.45, 7.22 γ 449 α 7.19 γ 124 184.0011	**Bi185** **57 µs** p 1.60 α 8.08 184.9976	**Bi186** **15 ms ↔ 9.8ms** α 7.16 α 7.26 γ 108.5 185.9966	(1/+)**Bi187** (9/−) **0.36 ms** α 7.72 **37 ms** α 6.999, … 186.99316
			82	**Pb** 207.2 lead σ_a 0.171, 0.14	**Pb180** **4 ms** α 7.25 179.99792	**Pb181**(13/+) **37 ms** α 7.05 γ 77 180.9966	**Pb182** **55 ms** α 6.91 181.99267	**Pb183** (1/−) **0.42 s** α 6.698, 6.86 γ 111, 61 **0.54 s** α 6.93, 6.72 γ 217 182.99187	**Pb184** **0.49 s** α 6.63 183.98814	**Pb185** 3/− **4.3 s** α 6.408 **6.3 s** α 6.288, 6.486 γ 205, 269 184.98761	**Pb186** **4.82 s** α 6.33 ε E 5.5 185.98424
81	**Tl** 204.3833 thallium σ_a 3.4, 13	**Tl176** **~5 ms** p 1.26 176.0006	**Tl177** **0.23 ms** p 1.96 α 7.49 **18 ms** α 6.91 p 1.16 176.99643	**Tl178** **~254 ms** α 6.704, 6.785,… 177.9949	**Tl179** **1.6 ms** α 7.20, 7.10 **0.27 s** α 6.57 178.99109	**Tl180** **0.7 s** ε, β^+ α 6.28, 6.36,… E 10.8 179.9899	**Tl181** **1.4 ms ↔ 3.2 s** α 6.47 α 6.18 180.98626	**Tl182** (7+) **3 s** ε, β^+ γ 351.4, 261.4,… α 6.41 E 10.2	(9/−) **Tl183** (1/+) **53 ms** α 6.34, 6.38,… **7 s** β^+, ε γ 208 E 7.21	**Tl184** **11 s** β^+, ε γ 366.5, 286.8,… α 6.162, 5.988,… E 9.5	(9/−) **Tl185** (1/+) **1.9 s** IT 169 γ 284, 168.8 α 5.975, … **19.5 s** ε, β^+ E 6.4
			96		**98**		**100**		**102**		**104**



At210 (5)+ 8.1 h ε γ 1181.4, 245.3, 1483.3,⋯ α 5.524 ω, 5.442, 5.361,⋯ γ 83 (ω), 106,⋯ E 3.98	At211 9/− 7.21 h ε γ 687.0 ω α 5.868,⋯ γ 669.6 ω,⋯ E 0.785 210.987496	(9−) At212 (1−) 121 ms α 7.837, 7.897, ⋯ γ 62.9 ω e− 313 ms α 7.681, 7.618, ⋯ 211.99074	At213 9/− 0.12 μs α 9.08 212.99294	9− At214 1− 0.76 μs α 8.78, ⋯ 0.56 μs α 8.819, ⋯ 213.996372	At215 9/− 0.10 ms α 8.026,⋯ γ 404.9 ω 214.99865	At216 1(−) 0.30 ms α 7.800,⋯ 216.002423	At217 9/− 32 ms α 7.067,⋯ γ 258.5, 593.1,⋯ β− ω 217.00472	At218 1.5 s α 6.694,⋯ β− ω 218.00869	At219 56 s α 6.28 β− 219.011162	At220 3.71 m β− γ 241.0, 292.7, 422.3,⋯ α 5.943 E 3.7 220.0154
Po209 1/− 102 a α 4.880,⋯ γ 260.5 ω, 262.8 ε γ 896.1 ω 208.982430	Po210 RaF 138.38 d α 5.3044,⋯ γ 803.1 vω σγ (< 0.5 mb + < 0.03) σα < 2 mb 209.982874	(25/+)Po211 9/+ 25.2 s α 7.27, 8.88,⋯ γ 569.2D, 1063.1D, ⋯ IT ω AcC' 0.516 s α 7.451,⋯ γ 569.2D ω, 897.2,⋯ 210.986653	(18+)Po212 45 s α 11.65, ⋯ γ 2614.4, 583.0 IT ~36 ThC' 0.298 μs α 8.7844 211.988868	Po213 9/+ 3.8 μs α 8.376,⋯ γ 778.8 ω 212.992857	Po214 RaC' 163.7μs α 7.6869,⋯ γ 799 ω,⋯ 213.995201	Po215 9/+ AcA 1.781 ms α 7.386,⋯ γ 438.8 ω,⋯ β− vω 214.999420	Po216 ThA 0.145 s α 6.7785,⋯ γ 805 ω 216.001915	Po217 1.50 s α 6.537 β− ? 217.00633	Po218 RaA 3.10 m α 6.0024 γ 510, β− ω 218.008973	Po219 219.0137
Bi208 (5)+ 3.68E5 a ε γ 2614.4 E 2.878	Bi209 9/− 100 σγ (10 mb + 18 mb), 0.19 σα < 0.3 μb 208.980399	9− Bi210 1− 3.0E6 a α 4.946, 4.908, ⋯ γ 266.2, 305.2,⋯ σγ 0.05, 0.2 RaE 5.01 d β− 1.162 α 4.648 vω, 4.687 γ 305 vω, 266 E 1.161	Bi211 9/− AcC 2.14 m α 6.623, 6.279 γ 351.1 β− ω 210.98727	(15−) Bi212 1(−) 7 m β− (9−) 25.0 m α 6.34, 6.30,⋯ β− (α) ThC 1.009 h β− 2.251,⋯ γ 727.3 α 6.051,⋯ γ 39.9,⋯ E 2.252 211.991286	Bi213 9/− 45.6 m β− 1.42, 1.02,⋯ γ 440.5,⋯ α 5.87, 5.55 ω γ 323.7 ω E 1.42	Bi214 1− RaC 19.9 m β− 3.27, 1.54, 1.51,⋯ γ 609.3, 1764.5, 1120.3,⋯ α 5.450 (ω), 5.513,⋯ γ 63,⋯ E 3.27	Bi215 37 s β− γ 414.1,⋯ 7.6 m β− γ 293.7,⋯ E 2.19	Bi216 (1−) 7 m β− γ 549.8, 419.2 2.18 m β− 3.0, 3.4 γ 549.7, 419.0,⋯ E 4.09	Bi217 98 s β− γ 264, 254,⋯ E 2.9	Bi218 33 s β− γ 509.7, 386.7,⋯ E 5.0
13/+ Pb207 1/− 0.80 s IT 1063.7 γ 569.7 22.1 AcD σγ 0.70, 0.38 206.975897	Pb208 ThD 52.4 σγ 0.23 mb, 2.0 mb σα 8 μb 207.976652	Pb209 9/+ 3.25 h β− 0.645 no γ E 0.644	Pb210 RaD 22.3 a β− 0.017, 0.061 γ 46.5 e− α 3.72 vω σγ 0.5 E 0.0635	Pb211 9/+ AcB 36.1 m β− 1.38,⋯ γ 404.9, 831.9, 427.0,⋯ E 1.37	Pb212 ThB 10.64 h β− 0.335, 0.569,⋯ γ 238.6, 300.0,⋯ E 0.570	Pb213 (9/+) 10.2 m β− E 2.05	Pb214 RaB 27 m β− 0.67, 0.73,⋯ γ 351.9, 295.2, 242.0,⋯ E 1.02	Pb215 36.5 s β− γ 187, 414, 747 E 2.8	**134**	
(12−)Tl206 0− 3.74 m IT 1022, 564 γ 687, 453, 217, 266.2,⋯ RaE" 4.20 m β− 1.528, ⋯ γ 803.1ω E 1.532	11/− Tl207 1/+ 1.3 s IT 997.1, ⋯ γ 351.0 AcC" 4.77 m β− 1.44, ⋯ γ 897.2ω, ⋯ E 1.42	Tl208 5(+) ThC" 3.053 m β− 1.796, 1.28, 1.52,⋯ γ 2614.5, 583.2, 510.7,⋯ E 4.999	Tl209 (1/+) 2.16 m β− 1.8,⋯ γ 1567.0, 465.1, 117.2,⋯ E 3.98	Tl210 (5+) RaC" 1.30 m β− 1.9, 1.3, 2.3,⋯ γ 799.7, 298,⋯ (n) E 5.48	Tl211 E 4.4	Tl212 E 5.9	**132**			
	126		**128**		**130**					

At221 2.3 m β− E 2.3	At222 ~54 s β− E 4.4	At223 50 s β− E 3.2
Po220 220.0166		**138**
136		



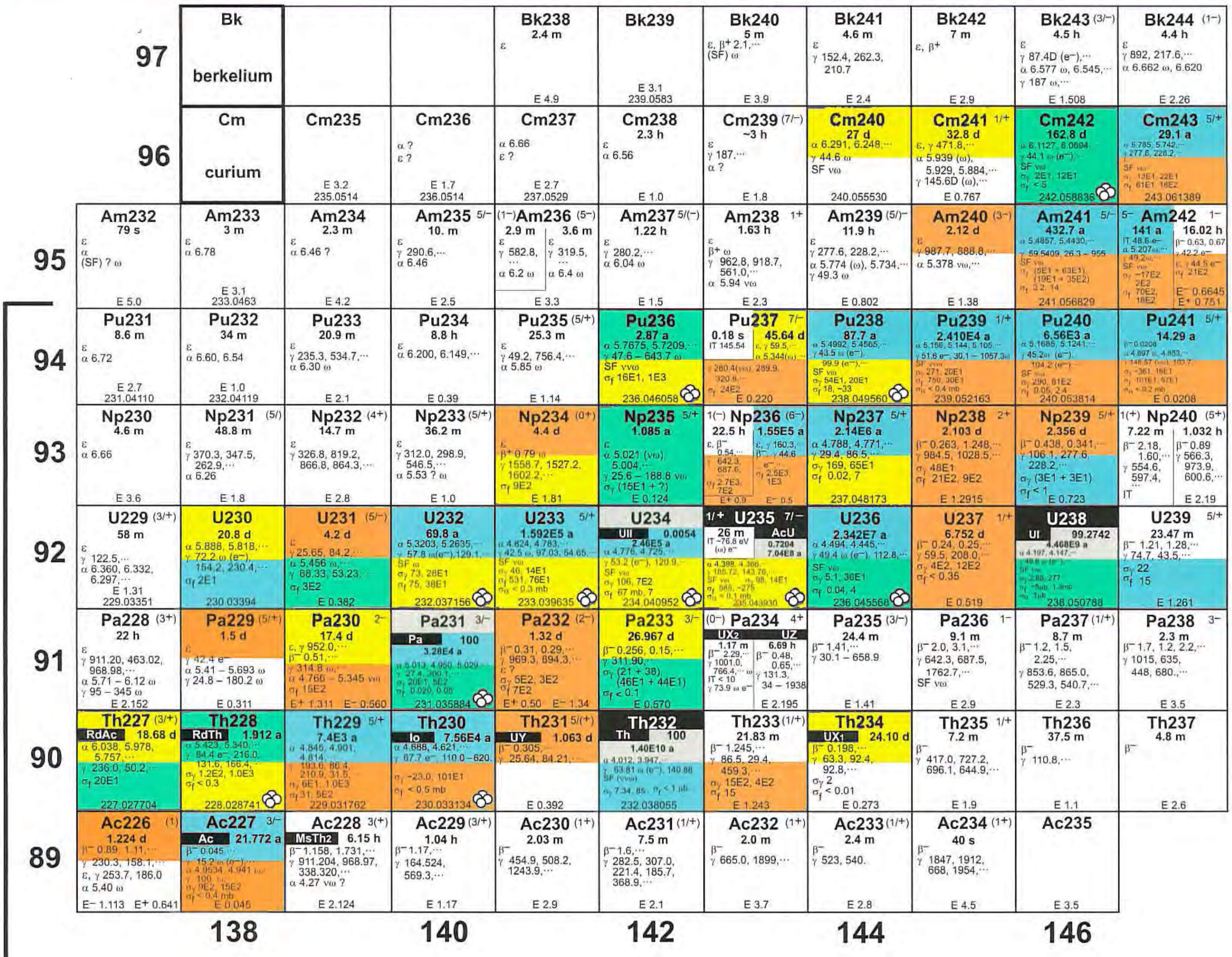
85	**At** **astatine**	At191 2.1 ms α 7.65 7.72 ~2 ms α 7.55	At192 11 ms ↔ 0.09 s α 7.44,⋯ γ 36 α 7.22,⋯ γ 165,⋯	At193 21 ms α 7.32, 7.42 28 ms α 7.24 192.9998	At194 0.2 s α 7.20 193.9987	At195 0.12 s α 7.10,⋯ γ 149 ~395 ms α 6.95 194.99627	At196 11 μs IT 159.1 0.39 s α 7.049 γ 299, 434,⋯ 195.9958	(1/+)At197 (9/−) 2.0 s α 6.7105 0.384 s α 6.9579 ε 196.9932	(10−) At198(3+) 1.2 s α 6.855 ε, β+ 4.1 s α 6.754,⋯ ε, β+ 197.9928	At199 (9/−) 7.0 s α 6.640 ε E 6.4 198.9905
	Po189 3.8 ms α 7.526, 7.31, 7.53 γ 278, 224 188.99848	Po190 2.45 ms α 7.53,⋯ γ 536, 655 189.99510	(13/+)Po191(3/−) 94 ms α 7.376,⋯ γ 472, 494, 594 22 ms α 7.33,⋯ γ 375 190.99457	Po192 33 ms α 7.17, 6.61 191.99134	Po193 0.3 s α 7.00, 6.38 γ 637 0.37 s α 6.98, 6.42 γ 549 192.99103	Po194 0.393 s α 6.854,⋯ 193.98819	(13/+) Po195 1.92 s α 6.70,⋯ γ 670 4.6 s α 6.61,⋯ γ 597 ε, β+ E 6.95 194.98811	Po196 6.0 s α 6.514,⋯ ε 195.98553	(13/+) Po197(3/−) 29 s α 6.381, 5.62 ε IT? 58 s ε α 6.282 E 6.3 196.9857	Po198 1.77 m α 6.182,⋯ ε E 3.90 197.98339
	Bi188 60 ms α 6.992,⋯ γ 117.5, 99.0 0.27 s↔ α 6.81,⋯ γ 320,⋯ 0.22 s α 6.82,⋯ γ 7.01,⋯ 187.9923	(1/+) Bi189 4.8 ms α 7.296, 7.02, ⋯ γ 286 0.65 s α 6.677, 7.12, ⋯ γ 286, 164 188.9892	Bi190 6 s α 6.43 γ 294,⋯ 6.3 s α 6.431,⋯ γ 78.5, 293.7 ε E 9.5 189.9883	(1/+)Bi191 (9/−) 0.13 s α 6.876, ⋯ ε 12.4 s α 6.308, ⋯ ε E 7.01 190.98579	(10−) Bi192(2+,3+) 39.6 s ε, β+ γ 853.8, ⋯ α 6.052, ⋯ 37 s ε γ 853.8, ⋯ α 6.060, ⋯ γ 185 191.98546 E 9.01	(1/+)Bi193 (9/−) 3.2 s α 6.475, ⋯ ε 1.06 m ε α 5.900, ⋯ E 6.3	(10−) Bi194 (3+) 1.9 m β+, ε γ 965.0, 575.2, ⋯ α 5.599 ω,⋯ γ 272.4,⋯ 1.58 m ε α 5.645 ω, ⋯ E 8.2	(1/+)Bi195 (3/−) 1.45 m ε α 6.11, ⋯ 3.0 m ε γ 808,776, 135,⋯ α 5.42 ω, ⋯ E 5.69	(10−)Bi196 4 m ε γ 1049, 689, 372,⋯ IT? 5.1 m ε γ 401, 1450,,⋯ α 5.153 vω E 7.35	(1/+)Bi197 (9/−) 5.0 m ε α 5.78 9.3 m ε E 5.06
	Pb187(13/+) 15.2 s ↔ 18.3 s ε, β+ γ 299.3,⋯ α 6.19, 5.99,⋯ γ 67.4, 275.5, 208.0,⋯ ε γ 393.4, 343.5, 331.4,⋯ α 6.07 E 7.46	Pb188 25.5 s ε, β+ γ 185, 758 α 5.980 E 4.53 187.98087	Pb189 51 s ε α 5.73 ω E 6.72	Pb190 1.2 m ε, β+ γ 942.4, 151.4, 598.4,⋯ α 5.578 ω, 5.181(vω) E 3.9	(13/+)Pb191(3/−) 2.2 m ε γ 387, 712, 613,⋯ 1.3 m ε, β+ γ 937,⋯ α 5.29 ω E 6.04	Pb192 3.5 m ε β+ ω γ 1195.4, 608.2, 167.5,⋯ α 5.112 ω E 3.32	(13/+)Pb193(3/−) 5.8 m ε γ 365D, 392,⋯ ~2 m ε E 5.1	Pb194 11 m ε, β+ γ 581.8, 1519.4, 203.8,⋯ α 4.64 vω E 2.6	13/+ Pb195 3/− 15 m ε, β+ γ 383.7D, 394.1, 878.3,⋯ ~15 m ε γ 383.7D, ⋯ E 4.44	Pb196 37 m ε γ 503, 254,⋯ E 2.14
	Tl186 (7+) 2.9 s IT 374.0 28 s ε, β+ γ 405.3, 402.6, 356.7,⋯ α 5.64 ω E 8.3	(9/−) Tl187 (1/+) 15.6 s IT ~35 vω e− γ 299.3 ε γ 161 α 5.53 ω 50 s ε γ 161 E 5.67	(7+) Tl188 (2−) 1.18 m ↔ 1.2 m ε, β+ γ 412.8, 591.9, 504.2,⋯ ε, β+ γ 412.8,⋯ E 7.86	(9/−) Tl189 (1/+) 1.4 m ε, β+ γ 318, 216, 335, 228,⋯ 2.3 m ε, β+ γ 334, 942, 451,⋯ E 5.03	(7+) Tl190 (2)− 3.7 m ↔ 2.6 m ε, β+ 4.2 γ 416.4, 625.3, 731.2,⋯ ε, β+ 5.7 γ 416.4,⋯ E 7.0	9/(−)Tl191 (1/+) 5.2 m ε β+ γ 215.7, 325.6, 264.7, 335.9,⋯ E 4.31	(7+) Tl192 (2−) 10.8 m ε, β+ γ 422.9, 634.9,⋯ 9.6 m ε, β+ γ 422.9, 634.9,⋯ E 6.14	(9/−) Tl193 1/(+) 2.1 m IT < 13 γ 365 ε, γ 22 m ε β+ γ 324.4, 1044.7, ⋯ E 3.7	(7+) Tl194 2− 32.8 m ε, β+ γ 427.9, 645.2, ⋯ 34 m ε, β+ γ 428.1, 636.2, ⋯ E 5.4	9/− Tl195 1/+ 3.6 s IT 99.0 ω e− γ 383.7 1.16 h ε β+ ~1.8 ω, ⋯ γ 563.6, 884.5, 1363.9,⋯ E 2.84
		106		**108**		**110**		**112**		**114**

Z	126		128		130		132		134		136
89	**Ac215** 9/− 0.17 s α 7.602,··· γ 395.8,··· ε ω 215.00645	(9−) **Ac216** (1−) 0.43 ms α 9.028, 9.106, ··· γ 537, 82.4 0.44 ms α 9.06, 8.99 γ 82.6 216.00872	(29/)+ **Ac217** 9/− 0.7 μs α 10.54, ··· γ 498, 1105 0.07 μs α 9.65 217.00935	**Ac218** 1.1 μs α 9.20 218.0116	**Ac219** (9/−) 11 μs α 8.66 219.0124	**Ac220** 26.4 ms α 7.85, 7.61, 7.68,··· γ 133.0, 342.7, 160.0,··· 220.01476	**Ac221** 52 ms α 7.64, 7.44,··· 221.0156	**Ac222** 1− 63 s α 6.81, 6.75, 6.89, 7.00,··· IT ? ε ? 5 s α 7.010, 6.97 222.01784	**Ac223** (5/−) 2.1 m α 6.646, 6.661,··· γ 191.3 ω, 73, 99, 84,··· ε 223.01914	**Ac224** 0− 2.7 h ε γ 215.8, 131.5,··· α 6.1383, 6.056,··· γ 25 – 376 ω E 1.408 224.021723	**Ac225** (3/) 10.0 d α 5.829, 5.793, 5.731,··· γ 99.8,··· 225.02323
88	**Ra214** 2.46 s α 7.136,··· γ 642.8 ε ω 214.00011	**Ra215** (9/+) 1.68 ms α 8.700,··· γ 539.6, 833.5 215.00272	**Ra216** 0.18 μs α 9.35 216.00353	**Ra217** (9/+) 1.6 μs α 8.99 217.00632	**Ra218** 25.2 μs α 8.39 218.00714	**Ra219** 7/+ 0.010 s α 7.678, 7.988,··· γ 315.82,··· 219.01009	**Ra220** 18 ms α 7.45,··· γ 465 220.01103	**Ra221** 29 s α 6.608, 6.758, 6.669,··· γ 90., 152,··· 221.013917	**Ra222** 36.2 s α 6.556,··· γ 324.2,··· 222.015375	**Ra223** 3/+ AcX 11.435 d α 5.7164, 5.607,··· γ 269.4, 154.2, 323.9,··· σ_γ 13E1, σ_f 0.7 223.018502	**Ra224** ThX 3.63 d α 5.6855, 5.449,··· γ 240.99,··· σ_γ 12 224.020212
87	**Fr213** 9/− 34.6 s α 6.775 γ 408.32,··· ε ω 212.99619	(9−) **Fr214** (1−) 3.4 ms α 8.476, 8.546, ··· γ 72.8 5.1 ms α 8.427 213.99897	**Fr215** 9/− 0.09 μs α 9.36,··· 215.00034	(3−) **Fr216** (1−) 0.07 μs α 8.93 γ 160.3, 45.0 0.70 μs α 9.004, 8.86, 8.81 γ 160.3, 45.0, 55.0 216.00320	**Fr217** 9/− 18 μs α 8.32 217.00463	(8−) **Fr218** (1−) 22 ms α 7.62, 7.68, 7.66,··· IT ? γ 145, 111,··· 1 ms α 7.867, ··· γ 187, 117, 304,··· 218.00758	**Fr219** 9/− 21 ms α 7.314,··· γ 169.9 – 517.0 ω 219.00925	**Fr220** 1+ 27.4 s α 6.677, 6.633, 6.573,··· γ 44.60, 105.88, 160.73,··· β^- ω 220.012327	**Fr221** 5/(−) 4.79 m α 6.341, 6.127,··· γ 218.2,··· 221.01425	**Fr222** 2− 14.3 m β^- 1.72, 1.92,··· γ 206.2, 111.1,··· E 2.03	**Fr223** 3/(−) AcK 21.8 m β^- 1.15,··· γ 50.1, 79.7, 234.8,··· α 5.291 (ω), 5.314,··· γ 150.9 (ω), 58.9, 145.3 E 1.149
86	**Rn212** 24 m α 6.263,··· 211.990704	**Rn213** (9/+) 20 ms α 8.09,··· γ 540.3 212.99388	**Rn214** 0.27 μs α 9.04 213.99536	**Rn215** 9/+ 2.3 μs α 8.67 214.99875	**Rn216** 45 μs α 8.05 216.00027	**Rn217** 9/+ 0.6 ms α 7.741,··· 217.003928	**Rn218** 35 ms α 7.133,··· γ 609.3 ω 218.005601	**Rn219** 5/+ An 3.96 s α 6.8193, 6.553, 6.425,··· γ 271.23, 401.81,··· 219.009480	**Rn220** Tn 55.6 s α 6.2882,··· γ 549.7 σ_γ < 0.2 220.011394	**Rn221** 25 m β^- 0.83,··· γ 186.4,··· α 6.037,··· γ 254, 265 E 1.19 221.01554	**Rn222** Rn 3.8235 d α 5.4895,··· γ 510. ω σ_γ 0.7 222.017578
85	**At211** 9/− 7.21 h ε γ 687.0 ω α 5.868,··· γ 669.6 ω,··· E 0.785 210.987496	(9−) **At212** (1−) 121 ms α 7.837, 7.897, ··· γ 62.9 ω e− 313 ms α 7.681, 7.618, ··· 211.99074	**At213** 9/− 0.12 μs α 9.08 212.99294	9− **At214** 1− 0.76 μs α 8.78, ··· 0.56 μs α 8.819, ··· 213.996372	**At215** 9/− 0.10 ms α 8.026,··· γ 404.9 ω 214.99865	**At216** 1(−) 0.30 ms α 7.800,··· 216.002423	**At217** 9/− 32 ms α 7.067,··· γ 258.5, 593.1,··· β^- ω 217.00472	**At218** 1.5 s α 6.694,··· β^- ω 218.00869	**At219** 56 s α 6.28 β^- 219.011162	**At220** 3.71 m β^- γ 241.0, 292.7, 422.3,··· α 5.943 E 3.7 220.0154	**At221** 2.3 m β^- E 2.3

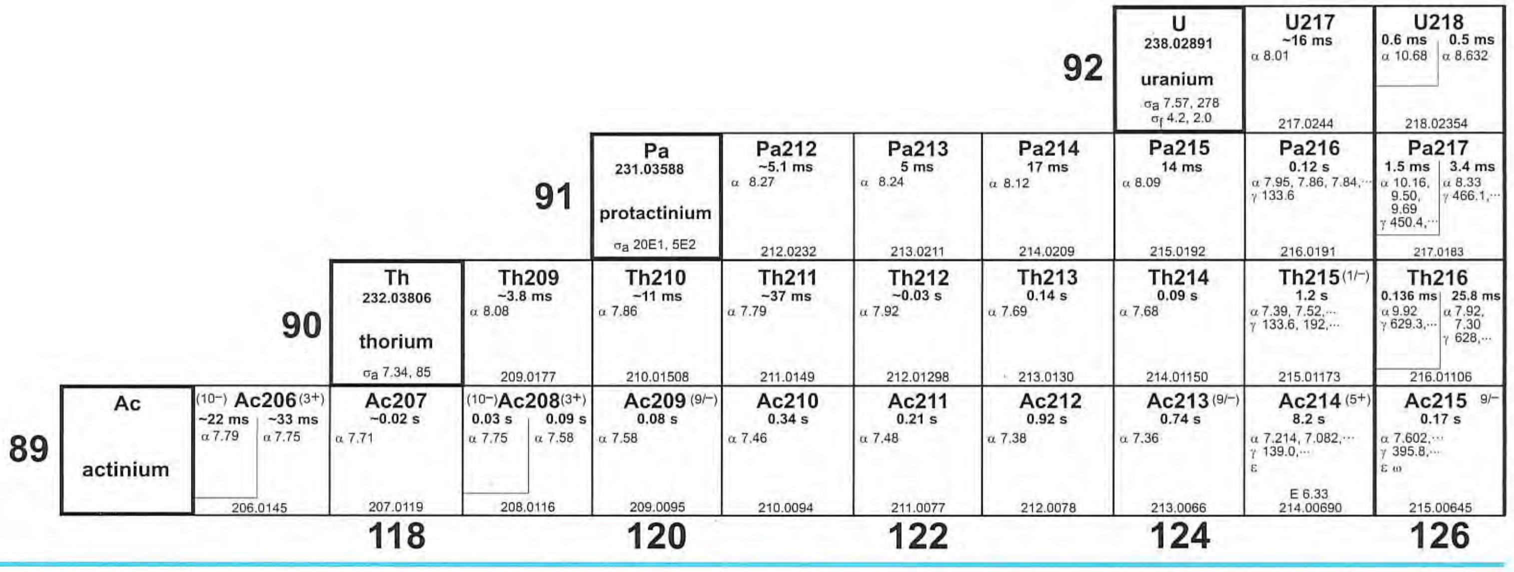
Z		106		108		110		112		114	
88								**Ra** radium	**Ra201** ~1.6 ms α 7.91	**Ra202** 2 ms α 7.9 202.0099	**Ra203** ~36 ms α 7.62 0.03 s α 7.58 203.0093
87							**Fr** francium	**Fr199** ~12 ms α 7.66 199.00726	**Fr200** 49 ms α 7.47 200.0066	**Fr201** (9/−) ~19 ms α 7.45 62 ms α 7.37 201.0039	**Fr202** 0.32 s α 7.24 202.0034
86		**Rn** radon	**Rn193** 1.2 ms α 7.69, 7.88 γ 194	**Rn194** 0.8 ms α 7.70	**Rn195** 5 ms α 7.56 6 ms α 7.54 195.0054	**Rn196** 4 ms α 7.46 196.00212	**Rn197** 24 ms α 7.36 0.05 s α 7.26 197.0016	**Rn198** 64 ms α 7.200, 6.89 197.99868	(13/+) **Rn199** (3/−) 0.32 s α 7.06 ε 0.60 s α 6.99 ε 198.9984	**Rn200** 1.03 s α 6.902, 6.36 (ω), 6.45 ε 199.99570	(13/+) **Rn201** (3/−) 3.8 s α 6.77 ε 7.0 s α 6.72 ε E 6.7 200.9956
85	**At** astatine	**At191** 2.1 ms α 7.65 7.72 ~2 ms α 7.55	**At192** 11 ms ↔ 0.09 s α 7.44,··· γ 36 α 7.22,··· γ 165,···	**At193** 21 ms α 7.32, 7.42 28 ms α 7.24 192.9998	**At194** 0.2 s α 7.20 193.9987	**At195** 0.12 s α 7.10,··· γ 149 ~395 ms α 6.95 194.99627	**At196** 11 μs IT 159.1 0.39 s α 7.049 γ 299, 434,··· 195.9958	(1/+) **At197** (9/−) 2.0 s α 6.7105 0.384 s α 6.9579 ε 196.9932	(10−) **At198** (3+) 1.2 s α 6.855 ε, β^+ 4.1 s α 6.754, ··· ε, β^+ 197.9928	**At199** (9/−) 7.0 s α 6.640 ε E 6.4 198.9905	(10−) **At200** (5+) 3.7 s IT 230.9 α 6.530 (7+) 47 s ε, β^+ α 6.413, ··· 43 s α 6.463 ε γ 666.0, 611.1, ··· E 7.97 199.99035

Ac226 (1) 1.224 d β^- 0.89, 1.11,⋯ γ 230.3, 158.1, ε, γ 253.7, 186.0 α 5.40 ω E^- 1.113 E^+ 0.641	**Ac227** 3/− Ac 21.772 a β^- 0.045,⋯ γ 15.2 ω (e^-), α 4.9534, 4.941 ω, γ 100, ω,⋯ σ_γ 9E2, 15E2 σ_f < 0.4 mb E 0.045	**Ac228** 3(+) MsTh2 6.15 h β^- 1.158, 1.731,⋯ γ 911.204, 968.97, 338.320,⋯ α 4.27 νω ? E 2.124	**Ac229** (3/+) 1.04 h β^- 1.17,⋯ γ 164.524, 569.3,⋯ E 1.17	**Ac230** (1+) 2.03 m β^- γ 454.9, 508.2, 1243.9,⋯ E 2.9	**Ac231** (1/+) 7.5 m β^- 1.6,⋯ γ 282.5, 307.0, 221.4, 185.7, 368.9,⋯ E 2.1	**Ac232** (1+) 2.0 m β^- γ 665.0, 1899,⋯ E 3.7	**Ac233** (1/+) 2.4 m β^- γ 523, 540. E 2.8	**Ac234** (1+) 40 s β^- γ 1847, 1912, 668, 1954,⋯ E 4.5	**Ac235** E 3.5
Ra225 1/+ 14.9 d β^- 0.32,⋯ γ 40.3 α 5.006 (νω), 4.976 E 0.356	**Ra226** Ra 1599 a α 4.7844, 4.602,⋯ γ 186.2,⋯ σ_γ 13, 28E1 σ_f < 7 μb 226.025410	**Ra227** 3/+ 42 m β^- 1.31, 1.03,⋯ γ 27.4, 300.1, 302.7, 283.7,⋯ E 1.328	**Ra228** MsTh1 5.76 a β^- 0.039, 0.015, 0.026 γ 13.52 ω,⋯ σ_γ ~36 σ_f < 2 E 0.046	**Ra229** 5/+ 4.0 m β^- 1.76 γ 14.5 (ω) – 171.5 E 1.81	**Ra230** 1.5 h β^- 0.5,⋯ γ 72.0, 63.1, 202.8, 469.8,⋯ E 0.7	**Ra231** 5/+ 1.74 m β^- γ 205.0, 409.9, 469.3, 456.2,⋯ E 2.5	**Ra232** 4 m β^- γ 470.9, 97.7,⋯ E 1.5	**Ra233** 30. s β^- E 3	**Ra234** ~30 s β^- E 2
Fr224 1(−) 3.0 m β^- 2.6, 1.8,⋯ γ 216.0, 131.6, 836.9,⋯ E 2.83	**Fr225** 3/ 3.9 m β^- ≥ 1.64 E 1.82	**Fr226** 1 49 s β^- 3.6,⋯ γ 253.7, 186.1,⋯ E 3.7	**Fr227** 1/+ 2.48 m β^- 1.8, 2.2,⋯ γ 90.04, 585.8, 64.3,⋯ E 2.5	**Fr228** 2− 39 s β^- γ 473.7, 410.4, 140.8,⋯ E 4.3	**Fr229** 50.2 s β^- γ 310.1 (e^-), 336.2, 142.7,⋯ E 3.25	**Fr230** (3) 19 s β^- γ 711.0, 129.1,⋯ E 5.1	**Fr231** 1/+ 17.6 s β^- γ 432.6, 454.1,⋯ E 4	**Fr232** 5 s β^- γ 15.3, 125 E 6	**146**
Rn223 7/ 23 m β^- γ 592, 635, 416.0, 654,⋯ E 1.9	**Rn224** 1.8 h β^- γ 260.6, 265.8,⋯ E 0.8	**Rn225** 4.5 m β^- γ 750.1, 696.2, 91.2,⋯ E 2.7	**Rn226** 7.4 m β^- E 1.4	**Rn227** 5/+ 21 s β^- γ 162.2, 739.16, 686.22,⋯ E 3.3	**Rn228** 65 s β^- γ 124.72, 62.62 E 2.1		**144**		
At222 ~54 s β^- E 4.4	**At223** 50 s β^- E 3.2		**140**		**142**				
	138								

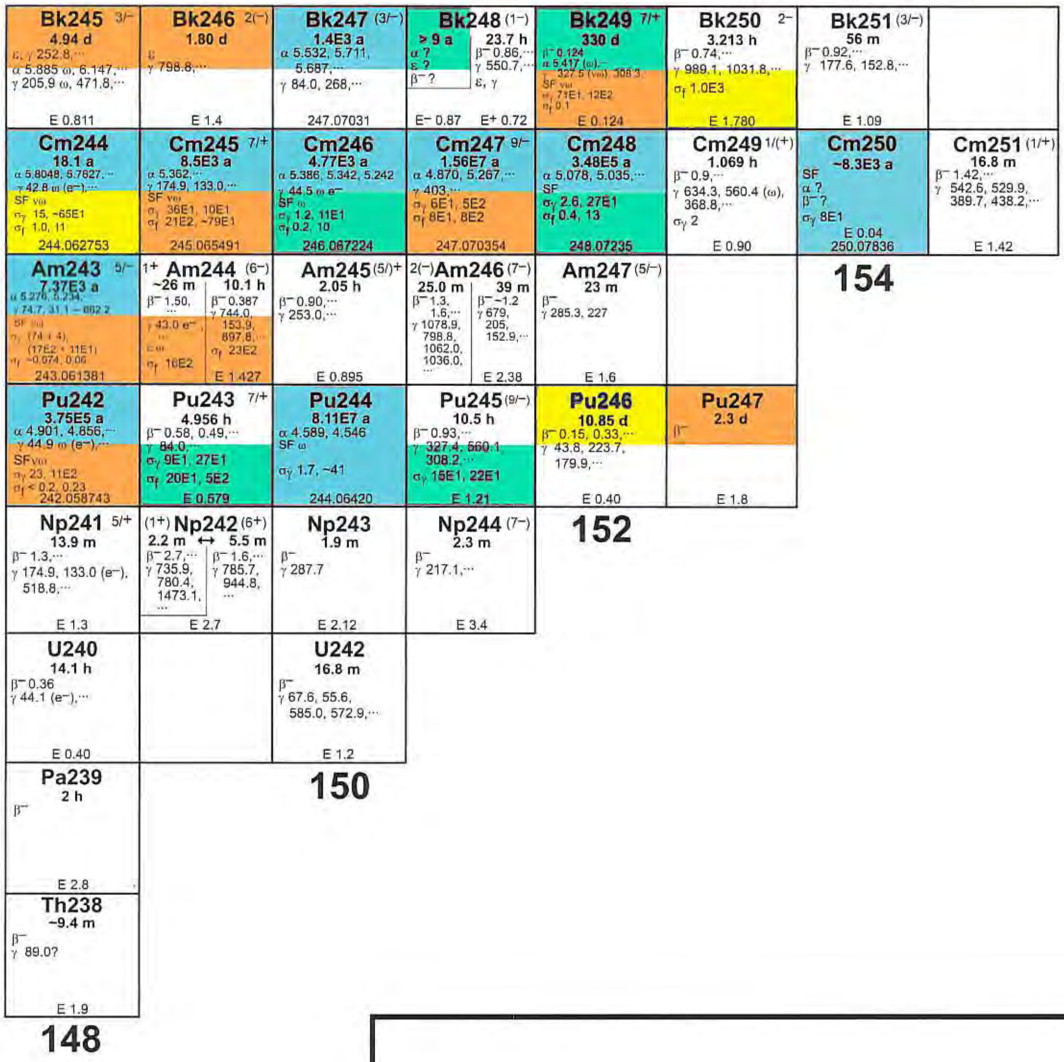
89	**Ac** **actinium**	(10−)**Ac206** (3+) ~22 ms α 7.79 ~33 ms α 7.75 206.0145	**Ac207** ~0.02 s α 7.71 207.0119	(10−)**Ac208**(3+) 0.03 s α 7.75 0.09 s α 7.58 208.0116	**Ac209** (9/−) 0.08 s α 7.58 209.0095	**Ac210** 0.34 s α 7.46 210.0094	**Ac211** 0.21 s α 7.48 211.0077	**Ac212** 0.92 s α 7.38 212.0078	**Ac213** (9/−) 0.74 s α 7.36 213.0066	**Ac214** (5+) 8.2 s α 7.214, 7.082,⋯ γ 139.0,⋯ ε E 6.33 214.00690	**Ac215** 9/− 0.17 s α 7.602,⋯ γ 395.8,⋯ ε ω 215.00645
	Ra204 0.06 s α 7.48 204.00650	**Ra205** ~195 ms α 7.37 0.2 s α 7.36 205.0063	**Ra206** 0.24 s α 7.271 ε ? 206.00383	**Ra207** 57 ms α 7.33 1.2 s α 7.133, ⋯ ε ? E 6.4 207.0038	**Ra208** 1.4 s α 7.133 ε ? 208.00184	**Ra209** 5/− 4.6 s α 7.005,⋯ γ 387, 634 E 5.6 209.0020	**Ra210** 3.7 s α 7.020,⋯ γ 574.9 ε ? 210.00049	**Ra211** 5/(−) 13 s α 6.912,⋯ γ 120.0,⋯ ε ? 211.00090	**Ra212** 13.0 s α 6.900,⋯ γ 635.1 ε ? 211.99979	**Ra213** 1/− 2.1 ms IT γ 546.3, 1062.5, ⋯ α 8.467, 8.356,⋯ γ 214 (ω), 110.1,⋯ 2.7 m α 6.624, 6.732,⋯ γ 110.1,⋯ ε E 3.91 213.00038	**Ra214** 2.46 s α 7.136,⋯ γ 642.8 ε ω 214.00011
	Fr203 (9/−) 0.54 s α 7.132 ε ? 203.00092	(10−)**Fr204** (3+) 0.8 s α 7.015 γ 230.9 (7+) 1.6 s α 6.969, ⋯ 1.9 s α 7.029, ⋯ γ 113 ε, β^+ 204.00065	**Fr205** (9/−) 3.87 s α 6.915 204.99859	(10−)**Fr206** (7+) 0.7 s IT 531 α 6.93 16.0 s α 6.791 ε γ 575, 559, 629,⋯ E 7.87 205.99867	**Fr207** 9/− 14.8 s α 6.767 ε γ ? 206.9969	**Fr208** 7+ 59.1 s α 6.636 ε, β^+ γ 635.8, 778.5, 325.2,⋯ E 6.98 207.99714	**Fr209** 9/− 50.0 s α 6.646 ε, β^+ γ 797.8, 547.1,⋯ E 5.16 208.99595	**Fr210** 6+ 3.2 m α 6.544,⋯ γ 126.3, 148,⋯ ε γ 644, 817,⋯ E 6.25 209.99641	**Fr211** 9/− 3.10 m α 6.534,⋯ γ 344.5 ε γ 539, 917, 280.,⋯ E 4.60 210.99554	**Fr212** 5+ 20. m ε, β^+ γ 1275, 227.7,⋯ α 6.261, 6.383, 6.406,⋯ γ 124.2, 84 ω, 72,⋯ E 5.12 211.99620	**Fr213** 9/− 34.6 s α 6.775,⋯ γ 408.32,⋯ ε ω 212.99619
	Rn202 9.7 s α 6.641 ε E 4.32 201.99326	(13/+)**Rn203** (5/)− 26.9 s α 6.550 ε 44 s α 6.498, ⋯ ε E 6.00 202.99339	**Rn204** 1.23 m α 6.419 ε E 3.89 203.99143	**Rn205** 5/− 2.8 m ε, β^+ γ 265, 620., 465, 730.,⋯ α 6.262,⋯ E 5.3 204.9917	**Rn206** 5.7 m α 6.258 ε, β^+ γ 497.3, 324.5,⋯ E 3.30 205.99021	**Rn207** 5/− 9.3 m ε, β^+ γ 344.5, 747.2, 402.7,⋯ α 6.133,⋯ E 4.61 206.99073	**Rn208** 24.3 m α 6.141,⋯ ε, β^+ γ 426.8, 251.0, 350.0, 287.2,⋯ E 2.84 207.98964	**Rn209** 5/− 29 m ε β^+ 2.16, 2.6 γ 408.4, 745.9, 337.5,⋯ α 6.039 E 3.95 208.99041	**Rn210** 2.4 h α 6.040,⋯ ε γ 458.2, 571.0 ω, 648.7,⋯ 209.98970	**Rn211** 1/− 14.6 h ε γ 674.1, 1363.0, 678.4,⋯ α 5.784, 5.851,⋯ γ 68.6 ω e^-,⋯ E 2.89 210.99060	**Rn212** 24 m α 6.263,⋯ 211.990704
	At201 (9/−) 1.41 m α 6.343 ε, β^+ γ 592, 616, 622, 723,⋯ E 5.74 200.98842	(10−)**At202** (5+) 0.46 s IT 391.7 α 6.277 ω (7+) 3.03 m ε, β^+ α 6.134 3.07 m ε, β^+ γ 677.2, 571.6, ⋯ α 6.228,⋯ E 7.33 201.98863	**At203** 9/− 7.4 m ε, β^+ 2.4 γ 639.4, 641.5, 738.1,⋯ α 6.088 E 5.14 202.98694	**At204** 7+ 9.1 m ε, β^+ γ 684.3, 516.3, 426.2,⋯ α 5.951 E 6.46	**At205** 9/− 26 m ε β^+ γ 719.3, 669.4, 628.9, ⋯ α 5.902 E 4.54 204.98607	**At206** 5+ 29.4 m ε, β^+ 3.1,⋯ γ 700.7, 477.2, 395.6,⋯ α 5.703 ω,⋯ γ 65.0 ω E 5.76	**At207** 9/− 1.81 h ε β^+ γ 814.4, 588.3, 300.7,⋯ α 5.758 E 3.90	**At208** 6+ 1.63 h ε β^+ γ 686.5, 660.0, 177.6,⋯ α 5.641 ω,⋯ E 4.98	**At209** 9/− 5.4 h ε γ 545.0, 781.9, 790.2,⋯ α 5.647,⋯ E 3.49	**At210** (5)+ 8.1 h ε γ 1181.4, 245.3, 1483.3,⋯ α 5.524 ω, 5.442, 5.361,⋯ γ 83 (ω), 106,⋯ E 3.98	**At211** 9/− 7.21 h ε γ 687.0 ω α 5.868,⋯ γ 669.6 ω,⋯ E 0.785 210.987496
	116		**118**		**120**		**122**		**124**		**126**



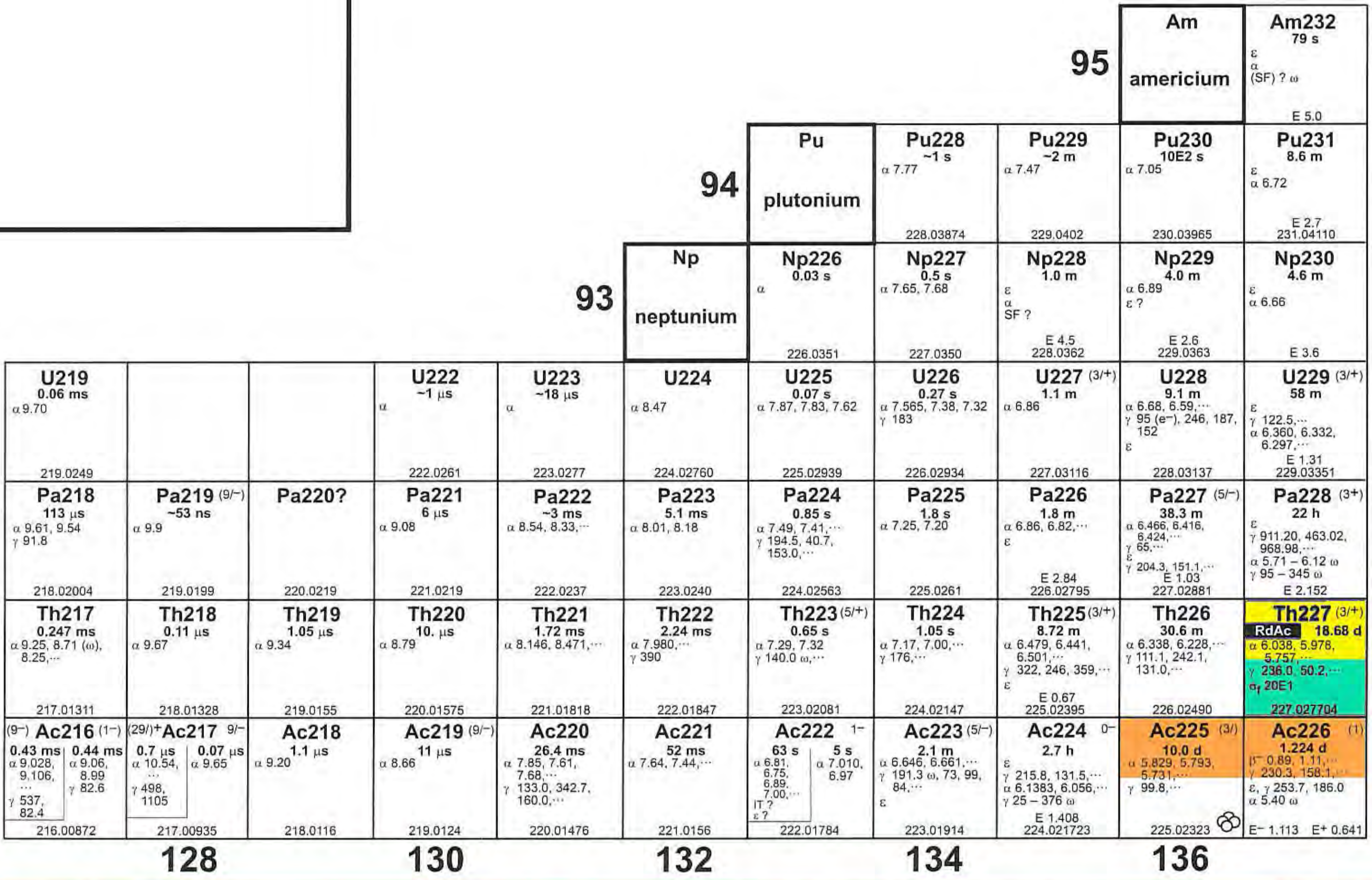
97		**Bk** berkelium			Bk238 2.4 m ε E 4.9	Bk239 E 3.1 239.0583	Bk240 5 m ε, β^+ 2.1,··· (SF) ω E 3.9	Bk241 4.6 m ε γ 152.4, 262.3, 210.7 E 2.4	Bk242 7 m ε, β^+ E 2.9	Bk243 (3/−) 4.5 h ε γ 87.4D (e^-),··· α 6.577 ω, 6.545,··· γ 187 ω,··· E 1.508	Bk244 (1−) 4.4 h ε γ 892, 217.6,··· α 6.662 ω, 6.620 E 2.26
96		**Cm** curium	Cm235 E 3.2 235.0514	Cm236 α ? ε ? E 1.7 236.0514	Cm237 α 6.66 ε ? E 2.7 237.0529	Cm238 2.3 h ε α 6.56 E 1.0	Cm239 (7/−) ~3 h ε γ 187,··· α ? E 1.8	Cm240 27 d α 6.291, 6.248,··· γ 44.6 ω SF vω 240.055530	Cm241 1/+ 32.8 d ε, γ 471.8,··· α 5.939 (ω), 5.929, 5.884,··· γ 145.6D (ω),··· E 0.767	Cm242 162.8 d α 6.1127, 6.0694 γ 44.1 ω (e^-),··· SF vω σ_γ 2E1, 12E1 σ_f < 5 242.058836	Cm243 5/+ 29.1 a α 5.785, 5.742,··· γ 277.6, 228.2,··· SF vω σ_γ 13E1, 22E1 σ_f 61E1, 16E2 243.061389
95	Am232 79 s ε α (SF) ? ω E 5.0	Am233 3 m ε α 6.78 E 3.1 233.0463	Am234 2.3 m ε α 6.46 ? E 4.2	Am235 5/− 10. m ε γ 290.6,··· α 6.46 E 2.5	(1−)Am236 (5−) 2.9 m ε γ 582.8, ··· α 6.2 ω 3.6 m ε γ 319.5, ··· α 6.4 ω E 3.3	Am237 5/(−) 1.22 h ε γ 280.2,··· α 6.04 ω E 1.5	Am238 1+ 1.63 h ε β^+ ω γ 962.8, 918.7, 561.0,··· α 5.94 vω E 2.3	Am239 (5/)− 11.9 h ε γ 277.6, 228.2,··· α 5.774 (ω), 5.734,··· γ 49.3 ω E 0.802	Am240 (3−) 2.12 d ε γ 987.7, 888.8,··· α 5.378 vω,··· E 1.38	Am241 5/− 432.7 a α 5.4857, 5.4430,··· γ 59.5409, 26.3 – 955 SF vω σ_γ (5E1 + 63E1) (19E1 + 35E2) σ_f 3.2, 14 241.056829	5− Am242 1− 141 a IT 48.6 e^- α 5.207ω,··· γ 49.2ω,··· SF vω σ_γ ~17E2 2E2 σ_f 70E2, 18E2 16.02 h β^- 0.63, 0.67 γ 42.2 e^- ε, γ 44.5 e^- σ_f 21E2 E^- 0.6645 E^+ 0.751
94	Pu231 8.6 m ε α 6.72 E 2.7 231.04110	Pu232 34 m ε α 6.60, 6.54 E 1.0 232.04119	Pu233 20.9 m ε γ 235.3, 534.7,··· α 6.30 ω E 2.1	Pu234 8.8 h ε α 6.200, 6.149,··· E 0.39	Pu235 (5/+) 25.3 m ε γ 49.2, 756.4,··· α 5.85 ω E 1.14	Pu236 2.87 a α 5.7675, 5.7209,··· γ 47.6 – 643.7 ω SF vvω σ_f 16E1, 1E3 236.046058	Pu237 7/− 0.18 s IT 145.54 45.64 d ε, γ 59.5,··· α 5.344(ω)··· γ 280.4(vω), 289.9, 320.8,··· σ_f 24E2 E 0.220	Pu238 87.7 a α 5.4992, 5.4565,··· γ 43.5 ω (e^-), 99.9 (e^-),··· SF vω σ_γ 54E1, 20E1 σ_f 18, ~33 238.049560	Pu239 1/+ 2.410E4 a α 5.156, 5.144, 5.105,··· γ 51.6 e^-, 30.1 – 1057.3ω SF vvω σ_γ 271, 20E1 σ_f 750, 30E1 σ_α < 0.4 mb 239.052163	Pu240 6.56E3 a α 5.1685, 5.1241,··· γ 45.2ω (e^-), 104.2 (e^-),··· SF vω σ_γ 290, 81E2 σ_f 0.05, 2.4 240.053814	Pu241 5/+ 14.29 a β^- 0.0208 α 4.897 ω, 4.853,··· γ 148.57 (vω), 103.7,··· σ_γ ~361, 16E1 σ_f 101E1, 57E1 σ_α < 0.2 mb E 0.0208
93	Np230 4.6 m ε α 6.66 E 3.6	Np231 (5/) 48.8 m ε γ 370.3, 347.5, 262.9,··· α 6.26 E 1.8	Np232 (4+) 14.7 m ε γ 326.8, 819.2, 866.8, 864.3,··· E 2.8	Np233 (5/+) 36.2 m ε γ 312.0, 298.9, 546.5,··· α 5.53 ? ω E 1.0	Np234 (0+) 4.4 d ε β^+ 0.79 ω γ 1558.7, 1527.2, 1602.2,··· σ_f 9E2 E 1.81	Np235 5/+ 1.085 a ε α 5.021 (vω), 5.004,··· γ 25.6 – 188.8 vω σ_γ (15E1 + ?) E 0.124	1(−) Np236 (6−) 22.5 h ε, β^- 0.54,··· γ 642.3, 687.6, ··· σ_f 2.7E3, 7E2 E^+ 0.9 1.55E5 a ε, γ 160.3,··· β^-, γ 44.6 e^-,··· σ_f 2.5E3, 1E3 E^- 0.5	Np237 5/+ 2.14E6 a α 4.788, 4.771,··· γ 29.4, 86.5,··· σ_γ 169, 65E1 σ_f 0.02, 7 237.048173	Np238 2+ 2.103 d β^- 0.263, 1.248,··· γ 984.5, 1028.5,··· σ_γ 48E1 σ_f 21E2, 9E2 E 1.2915	Np239 5/+ 2.356 d β^- 0.438, 0.341,··· γ 106.1, 277.6, 228.2,··· σ_γ (3E1 + 3E1) σ_f < 1 E 0.723	1(+) Np240 (5+) 7.22 m β^- 2.18, 1.60,··· γ 554.6, 597.4, ··· IT 1.032 h β^- 0.89 γ 566.3, 973.9, 600.6,··· E 2.19
92	U229 (3/+) 58 m ε γ 122.5,··· α 6.360, 6.332, 6.297,··· E 1.31 229.03351	U230 20.8 d α 5.888, 5.818,··· γ 72.2 ω (e^-), 154.2, 230.4,··· σ_f 2E1 230.03394	U231 (5/−) 4.2 d ε γ 25.65, 84.2,··· α 5.456 ω,··· γ 68.33, 53.23,··· σ_f 3E2 E 0.382	U232 69.8 a α 5.3203, 5.2635,··· γ 57.8 ω(e^-), 129.1,··· SF ω σ_γ 73, 28E1 σ_f 75, 38E1 232.037156	U233 5/+ 1.592E5 a α 4.824, 4.783,··· γ 42.5 ω, 97.03, 54.65,··· SF vω σ_γ 46, 14E1 σ_f 531, 76E1 σ_α < 0.3 mb 233.039635	U234 UII 0.0054 2.46E5 a α 4.776, 4.725,··· γ 53.2 (e^-), 120.9,··· SF vω σ_γ 106, 7E2 σ_f 67 mb, 7 234.040952	1/+ U235 7/− 26 m IT ~76.8 eV (ω) e^- AcU 0.7204 7.04E8 a α 4.398, 4.366,··· γ 185.72, 143.76,··· SF vω σ_γ 98, 14E1 σ_f 585, ~275 σ_α < 0.1 mb 235.043930	U236 2.342E7 a α 4.494, 4.445,··· γ 49.4 ω (e^-), 112.8,··· SF vω σ_γ 5.1, 36E1 σ_f 0.04, 4 236.045568	U237 1/+ 6.752 d β^- 0.24, 0.25,··· γ 59.5, 208.0,··· σ_γ 4E2, 12E2 σ_f < 0.35 E 0.519	U238 UI 99.2742 4.468E9 a α 4.197, 4.147,··· γ 49.6 ω (e^-),··· SF vω σ_γ 2.68, 277 σ_f ~5μb, 1.3mb σ_α 3μb 238.050788	U239 5/+ 23.47 m β^- 1.21, 1.28,··· γ 74.7, 43.5,··· σ_γ 22 σ_f 15 E 1.261
91	Pa228 (3+) 22 h ε γ 911.20, 463.02, 968.98,··· α 5.71 – 6.12 ω γ 95 – 345 ω E 2.152	Pa229 (5/+) 1.5 d ε γ 42.4 e^- α 5.41 – 5.693 ω γ 24.8 – 180.2 ω E 0.311	Pa230 2− 17.4 d ε, γ 952.0,··· β^- 0.51,··· γ 314.8 ω,··· α 4.766 – 5.345 vω σ_f 15E2 E^+ 1.311 E^- 0.560	Pa231 3/− Pa 100 3.28E4 a α 5.013, 4.950, 5.029,··· γ 27.4, 300.1,··· σ_γ 20E1, 5E2 σ_f 0.020, 0.05 231.035884	Pa232 (2−) 1.32 d β^- 0.31, 0.29,··· γ 969.3, 894.3,··· ε ? σ_γ 5E2, 3E2 σ_f 7E2 E^+ 0.50 E^- 1.34	Pa233 3/− 26.967 d β^- 0.256, 0.15,··· γ 311.90,··· σ_γ (21 + 38), (46E1 + 44E1) σ_f < 0.1 E 0.570	(0−) Pa234 4+ UX2 1.17 m β^- 2.29,··· γ 1001.0, 766.4,··· ω IT < 10 γ 73.9 ω e^- UZ 6.69 h β^- 0.48, 0.65,··· γ 131.3, 34 – 1938 E 2.195	Pa235 (3/−) 24.4 m β^- 1.41,··· γ 30.1 – 658.9 E 1.41	Pa236 1− 9.1 m β^- 2.0, 3.1,··· γ 642.3, 687.5, 1762.7,··· SF vω E 2.9	Pa237 (1/+) 8.7 m β^- 1.2, 1.5, 2.25,··· γ 853.6, 865.0, 529.3, 540.7,··· E 2.3	Pa238 3− 2.3 m β^- 1.7, 1.2, 2.2,··· γ 1015, 635, 448, 680.,··· E 3.5
90	Th227 (3/+) RdAc 18.68 d α 6.038, 5.978, 5.757,··· γ 236.0, 50.2,··· σ_f 20E1 227.027704	Th228 RdTh 1.912 a α 5.423, 5.340,··· γ 84.4 e^-, 216.0, 131.6, 166.4,··· σ_γ 1.2E2, 1.0E3 σ_f < 0.3 228.028741	Th229 5/+ 7.4E3 a α 4.845, 4.901, 4.814,··· γ 193.6, 86.4, 210.9, 31.5,··· σ_γ 6E1, 1.0E3 σ_f 31, 5E2 229.031762	Th230 Io 7.56E4 a α 4.688, 4.621,··· γ 67.7 e^-, 110.0 – 620. σ_γ ~23.0, 101E1 σ_f < 0.5 mb 230.033134	Th231 5/(+) UY 1.063 d β^- 0.305,··· γ 25.64, 84.21,··· E 0.392	Th232 Th 100 1.40E10 a α 4.012, 3.947,··· γ 63.81 ω (e^-), 140.88 SF (vvω) σ_γ 7.34, 85. σ_f < 1 μb 232.038055	Th233 (1/+) 21.83 m β^- 1.245,··· γ 86.5, 29.4, 459.3,··· σ_γ 15E2, 4E2 σ_f 15 E 1.243	Th234 UX1 24.10 d β^- 0.198,··· γ 63.3, 92.4, 92.8,··· σ_γ 2 σ_f < 0.01 E 0.273	Th235 1/+ 7.2 m β^- γ 417.0, 727.2, 696.1, 644.9,··· E 1.9	Th236 37.5 m β^- γ 110.8,··· E 1.1	Th237 4.8 m β^- E 2.6
89	Ac226 (1) 1.224 d β^- 0.89, 1.11,··· γ 230.3, 158.1,··· ε, γ 253.7, 186.0 α 5.40 ω E^- 1.113 E^+ 0.641	Ac227 3/− Ac 21.772 a β^- 0.045,··· γ 15.2 ω (e^-),··· α 4.9534, 4.941 ω/ γ 100 ω,··· σ_γ 9E2, 15E2 σ_f < 0.4 mb E 0.045	Ac228 3(+) MsTh2 6.15 h β^- 1.158, 1.731,··· γ 911.204, 968.97, 338.320,··· α 4.27 vω ? E 2.124	Ac229 (3/+) 1.04 h β^- 1.17,··· γ 164.524, 569.3,··· E 1.17	Ac230 (1+) 2.03 m β^- γ 454.9, 508.2, 1243.9,··· E 2.9	Ac231 (1/+) 7.5 m β^- 1.6,··· γ 282.5, 307.0, 221.4, 185.7, 368.9,··· E 2.1	Ac232 (1+) 2.0 m β^- γ 665.0, 1899,··· E 3.7	Ac233 (1/+) 2.4 m β^- γ 523, 540. E 2.8	Ac234 (1+) 40 s β^- γ 1847, 1912, 668, 1954,··· E 4.5	Ac235 E 3.5	
		138		**140**		**142**		**144**		**146**	



92									**U** 238.02891 uranium σ_a 7.57, 278 σ_f 4.2, 2.0	U217 ~16 ms α 8.01 217.0244	U218 0.6 ms α 10.68 0.5 ms α 8.632 218.02354
91					**Pa** 231.03588 protactinium σ_a 20E1, 5E2	Pa212 ~5.1 ms α 8.27 212.0232	Pa213 5 ms α 8.24 213.0211	Pa214 17 ms α 8.12 214.0209	Pa215 14 ms α 8.09 215.0192	Pa216 0.12 s α 7.95, 7.86, 7.84,··· γ 133.6 216.0191	Pa217 1.5 ms α 10.16, 9.50, 9.69 γ 450.4,··· 3.4 ms α 8.33 γ 466.1,··· 217.0183
90			**Th** 232.03806 thorium σ_a 7.34, 85	Th209 ~3.8 ms α 8.08 209.0177	Th210 ~11 ms α 7.86 210.01508	Th211 ~37 ms α 7.79 211.0149	Th212 ~0.03 s α 7.92 212.01298	Th213 0.14 s α 7.69 213.0130	Th214 0.09 s α 7.68 214.01150	Th215 (1/−) 1.2 s α 7.39, 7.52,··· γ 133.6, 192,··· 215.01173	Th216 0.136 ms α 9.92 γ 629.3,··· 25.8 ms α 7.92, 7.30 γ 628,··· 216.01106
89	**Ac** actinium	(10−) Ac206 (3+) ~22 ms α 7.79 ~33 ms α 7.75 206.0145	Ac207 ~0.02 s α 7.71 207.0119	(10−)Ac208(3+) 0.03 s α 7.75 0.09 s α 7.58 208.0116	Ac209 (9/−) 0.08 s α 7.58 209.0095	Ac210 0.34 s α 7.46 210.0094	Ac211 0.21 s α 7.48 211.0077	Ac212 0.92 s α 7.38 212.0078	Ac213 (9/−) 0.74 s α 7.36 213.0066	Ac214 (5+) 8.2 s α 7.214, 7.082,··· γ 139.0,··· ε E 6.33 214.00690	Ac215 9/− 0.17 s α 7.602,··· γ 395.8,··· ε ω 215.00645
			118		**120**		**122**		**124**		**126**



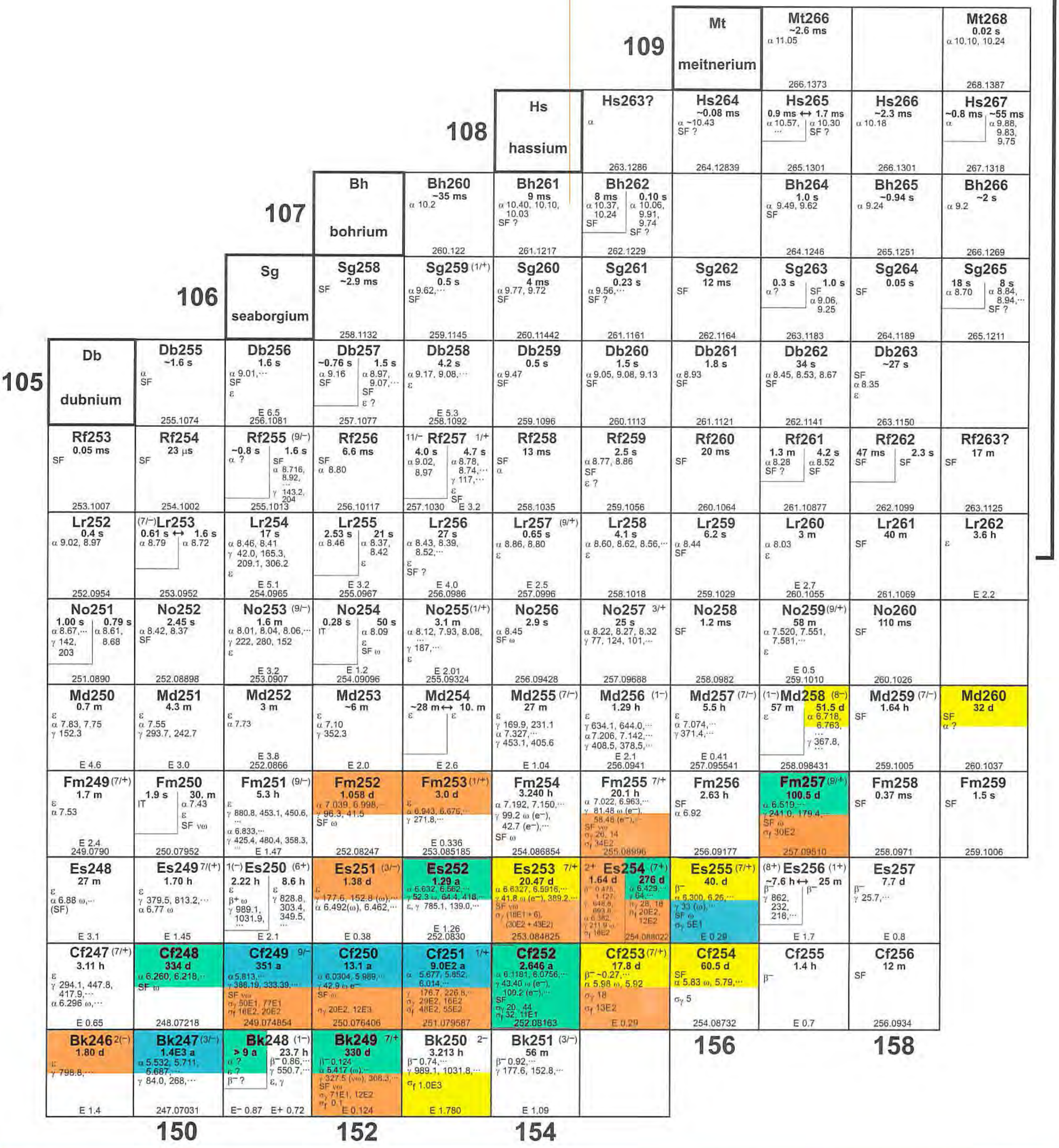
Bk245 3/– **4.94 d** ε, γ 252.8,··· α 5.885 ω, 6.147,··· γ 205.9 ω, 471.8,··· E 0.811	**Bk246** 2(–) **1.80 d** ε γ 798.8,··· E 1.4	**Bk247** (3/–) **1.4E3 a** α 5.532, 5.711, 5.687,··· γ 84.0, 268,··· 247.07031	**Bk248** (1–) **>9 a** α ? ε ? β^- ? **23.7 h** β^- 0.86,··· γ 550.7,··· ε, γ E^- 0.87 E^+ 0.72	**Bk249** 7/+ **330 d** β^- 0.124 α 5.417 (ω),··· γ 327.5 (vω), 308.3, SF vω σ_γ 71E1, 12E2 σ_f 0.1 E 0.124	**Bk250** 2– **3.213 h** β^- 0.74,··· γ 989.1, 1031.8,··· σ_f 1.0E3 E 1.780	**Bk251** (3/–) **56 m** β^- 0.92,··· γ 177.6, 152.8,··· E 1.09	
Cm244 **18.1 a** α 5.8048, 5.7627,··· γ 42.8 ω (e^-),··· SF vω σ_γ 15, ~65E1 σ_f 1.0, 11 244.062753	**Cm245** 7/+ **8.5E3 a** α 5.362,··· γ 174.9, 133.0,··· SF vω σ_γ 36E1, 10E1 σ_f 21E2, ~79E1 245.065491	**Cm246** **4.77E3 a** α 5.386, 5.342, 5.242 γ 44.5 ω e^- SF ω σ_γ 1.2, 11E1 σ_f 0.2, 10 246.067224	**Cm247** 9/– **1.56E7 a** α 4.870, 5.267,··· γ 403,··· σ_γ 6E1, 5E2 σ_f 8E1, 8E2 247.070354	**Cm248** **3.48E5 a** α 5.078, 5.035,··· SF σ_γ 2.6, 27E1 σ_f 0.4, 13 248.07235	**Cm249** 1/(+) **1.069 h** β^- 0.9,··· γ 634.3, 560.4 (ω), 368.8,··· σ_γ 2 E 0.90	**Cm250** **~8.3E3 a** SF α ? β^- ? σ_γ 8E1 E 0.04 250.07836	**Cm251** (1/+) **16.8 m** β^- 1.42,··· γ 542.6, 529.9, 389.7, 438.2,··· E 1.42
Am243 5/– **7.37E3 a** α 5.276, 5.234, γ 74.7, 31.1 – 862.2 SF vω σ_γ (74 + 4), (17E2 + 11E1) σ_f ~0.074, 0.06 243.061381	1+ **Am244** (6–) **~26 m** β^- 1.50, ··· γ 43.0 e^-, ··· ε ω σ_f 16E2 **10.1 h** β^- 0.387 γ 744.0, 153.9, 897.8,··· σ_f 23E2 E 1.427	**Am245** (5/)+ **2.05 h** β^- 0.90,··· γ 253.0,··· E 0.895	2(–) **Am246** (7–) **25.0 m** β^- 1.3, 1.6,··· γ 1078.9, 798.8, 1062.0, 1036.0, ··· **39 m** β^- ~1.2 γ 679, 205, 152.9,··· E 2.38	**Am247** (5/–) **23 m** β^- γ 285.3, 227 E 1.6		**154**	
Pu242 **3.75E5 a** α 4.901, 4.856,··· γ 44.9 ω (e^-),··· SF vω σ_γ 23, 11E2 σ_f < 0.2, 0.23 242.058743	**Pu243** 7/+ **4.956 h** β^- 0.58, 0.49,··· γ 84.0,··· σ_γ 9E1, 27E1 σ_f 20E1, 5E2 E 0.579	**Pu244** **8.11E7 a** α 4.589, 4.546 SF ω σ_γ 1.7, ~41 244.06420	**Pu245** (9/–) **10.5 h** β^- 0.93,··· γ 327.4, 560.1, 308.2,··· σ_γ 15E1, 22E1 E 1.21	**Pu246** **10.85 d** β^- 0.15, 0.33,··· γ 43.8, 223.7, 179.9,··· E 0.40	**Pu247** **2.3 d** β^- E 1.8		
Np241 5/+ **13.9 m** β^- 1.3,··· γ 174.9, 133.0 (e^-), 518.8,··· E 1.3	(1+) **Np242** (6+) **2.2 m** ↔ **5.5 m** β^- 2.7,··· γ 735.9, 780.4, 1473.1, ··· β^- 1.6,··· γ 785.7, 944.8, ··· E 2.7	**Np243** **1.9 m** β^- γ 287.7 E 2.12	**Np244** (7–) **2.3 m** β^- γ 217.1,··· E 3.4	**152**			
U240 **14.1 h** β^- 0.36 γ 44.1 (e^-),··· E 0.40		**U242** **16.8 m** β^- γ 67.6, 55.6, 585.0, 572.9,··· E 1.2					
Pa239 **2 h** β^- E 2.8		**150**					
Th238 **~9.4 m** β^- γ 89.0? E 1.9							
148							



								95	**Am** **americium**	**Am232** **79 s** ε α (SF) ? ω E 5.0
					94	**Pu** **plutonium**	**Pu228** **~1 s** α 7.77 228.03874	**Pu229** **~2 m** α 7.47 229.0402	**Pu230** **10E2 s** α 7.05 230.03965	**Pu231** **8.6 m** ε α 6.72 E 2.7 231.04110
				93	**Np** **neptunium**	**Np226** **0.03 s** α 226.0351	**Np227** **0.5 s** α 7.65, 7.68 227.0350	**Np228** **1.0 m** ε α SF ? E 4.5 228.0362	**Np229** **4.0 m** α 6.89 ε ? E 2.6 229.0363	**Np230** **4.6 m** ε α 6.66 E 3.6
U219 **0.06 ms** α 9.70 219.0249			**U222** **~1 µs** α 222.0261	**U223** **~18 µs** α 223.0277	**U224** α 8.47 224.02760	**U225** **0.07 s** α 7.87, 7.83, 7.62 225.02939	**U226** **0.27 s** α 7.565, 7.38, 7.32 γ 183 226.02934	**U227** (3/+) **1.1 m** α 6.86 227.03116	**U228** **9.1 m** α 6.68, 6.59,··· γ 95 (e^-), 246, 187, 152 ε 228.03137	**U229** (3/+) **58 m** ε γ 122.5,··· α 6.360, 6.332, 6.297,··· E 1.31 229.03351
Pa218 **113 µs** α 9.61, 9.54 γ 91.8 218.02004	**Pa219** (9/–) **~53 ns** α 9.9 219.0199	**Pa220?** 220.0219	**Pa221** **6 µs** α 9.08 221.0219	**Pa222** **~3 ms** α 8.54, 8.33,··· 222.0237	**Pa223** **5.1 ms** α 8.01, 8.18 223.0240	**Pa224** **0.85 s** α 7.49, 7.41,··· γ 194.5, 40.7, 153.0,··· 224.02563	**Pa225** **1.8 s** α 7.25, 7.20 225.0261	**Pa226** **1.8 m** α 6.86, 6.82,··· ε E 2.84 226.02795	**Pa227** (5/–) **38.3 m** α 6.466, 6.416, 6.424,··· γ 65,··· ε γ 204.3, 151.1,··· E 1.03 227.02881	**Pa228** (3+) **22 h** ε γ 911.20, 463.02, 968.98,··· α 5.71 – 6.12 ω γ 95 – 345 ω E 2.152
Th217 **0.247 ms** α 9.25, 8.71 (ω), 8.25,··· 217.01311	**Th218** **0.11 µs** α 9.67 218.01328	**Th219** **1.05 µs** α 9.34 219.0155	**Th220** **10. µs** α 8.79 220.01575	**Th221** **1.72 ms** α 8.146, 8.471,··· 221.01818	**Th222** **2.24 ms** α 7.980,··· γ 390 222.01847	**Th223** (5/+) **0.65 s** α 7.29, 7.32 γ 140.0 ω,··· 223.02081	**Th224** **1.05 s** α 7.17, 7.00,··· γ 176,··· 224.02147	**Th225** (3/+) **8.72 m** α 6.479, 6.441, 6.501,··· γ 322, 246, 359,··· ε E 0.67 225.02395	**Th226** **30.6 m** α 6.338, 6.228,··· γ 111.1, 242.1, 131.0,··· 226.02490	**Th227** (3/+) **RdAc** **18.68 d** α 6.038, 5.978, 5.757,··· γ 236.0, 50.2,··· σ_f 20E1 227.027704
(9–) **Ac216** (1–) **0.43 ms** α 9.028, 9.106, ··· γ 537, 82.4 **0.44 ms** α 9.06, 8.99 γ 82.6 216.00872	(29/)+ **Ac217** 9/– **0.7 µs** α 10.54, ··· γ 498, 1105 **0.07 µs** α 9.65 217.00935	**Ac218** **1.1 µs** α 9.20 218.0116	**Ac219** (9/–) **11 µs** α 8.66 219.0124	**Ac220** **26.4 ms** α 7.85, 7.61, 7.68,··· γ 133.0, 342.7, 160.0,··· 220.01476	**Ac221** **52 ms** α 7.64, 7.44,··· 221.0156	**Ac222** 1– **63 s** α 6.81, 6.75, 6.89, 7.00,··· IT ? ε ? **5 s** α 7.010, 6.97 222.01784	**Ac223** (5/–) **2.1 m** α 6.646, 6.661,··· γ 191.3 ω, 73, 99, 84,··· ε 223.01914	**Ac224** 0– **2.7 h** ε γ 215.8, 131.5,··· α 6.1383, 6.056,··· γ 25 – 376 ω E 1.408 224.021723	**Ac225** (3/) **10.0 d** α 5.829, 5.793, 5.731,··· γ 99.8,··· 225.02323	**Ac226** (1) **1.224 d** β^- 0.89, 1.11,··· γ 230.3, 158.1,··· ε, γ 253.7, 186.0 α 5.40 ω E^- 1.113 E^+ 0.641
	128		**130**		**132**		**134**		**136**	

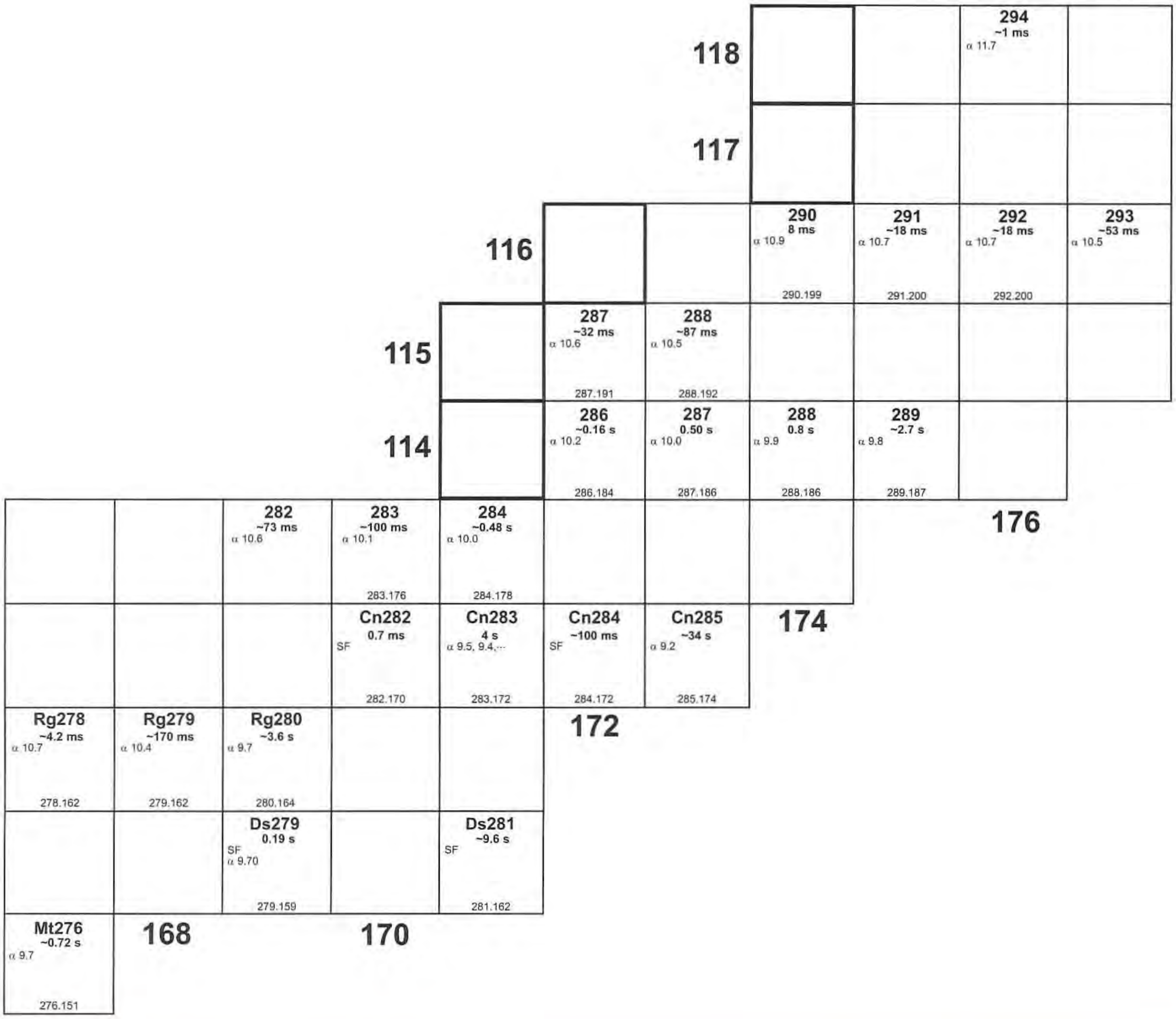
109	**Mt268** **0.02 s** α 10.10, 10.24 268.1387		**Mt270** **5 ms** α 10.0 270.141				**Mt274** **~440 ms** α 10. 274.147	**Mt275** **~9.7 ms** α 10.3 275.149	**Mt276** **~0.72 s** α 9.7 276.151		
108	**Hs267** **~0.8 ms** α **~55 ms** α 9.88, 9.83, 9.75 267.1318		**Hs269** **13 s** α 9.20,··· 269.1341	**Hs270** **~3.6 s** α 9.2 270.1347					**Hs275** **0.2 s** α 9.4 275.146		**Hs277?** 277.150
107	**Bh266** **~2 s** α 9.2 266.1269	**Bh267** **~17 s** α 8.83 267.1277			**Bh270** **~61 s** α 8.9 270.134		**Bh272** **~9.8 s** α 9.02 272.138	**166**		**168**	
106	**Sg265** **18 s** α 8.70 **8 s** α 8.84, 8.94,··· SF ? 265.1211	**Sg266** **~21 s** α 8.77, 8.52 SF 266.1221					**Sg271** **3 m** α 8.5 SF 271.133				
105				**Db267** **~73 m** SF 267.122	**Db268** **30 h** SF 268.125	**164**					
104	**Rf263?** **17 m** SF 263.1125				**Rf267** **2 h** SF 267.122						
103	**Lr262** **3.6 h** ε E 2.2			**162**							
102		**No262** **~5 ms** SF ? 262.1073									
101	**Md260** **32 d** SF α ? 260.1037										
100	**Fm259** **1.5 s** SF 259.1006	**Fm260** **~4 ms** SF 260.103									
		160									

										104	**Rf** rutherfordium
									103	**Lr** lawrencium	
								102	**No** nobelium	**No249** **~54 μs** SF α 249.0878	**No250** **0.25 ms** SF α 250.0875
					101	**Md** mendelevium	**Md245** (7/) **0.4 s** α 8.64,··· 245.0808	**Md246** **~4.4 s** α 8.72 **0.9 s** α 8.74, 8.53 γ 169, 232.5, 396.4 246.0819	**Md247** **0.3 s** α 8.78 SF **1.3 s** α 8.42, 8.66 γ 209.6, 158 SF? 247.0816	**Md248** **7 s** ε α 8.32, 8.36 E 5.2 248.0828	**Md249** **1.9 s** α **24 s** α 8.03 γ 253.2, 200, 223 ε E 3.7 249.0830
		100	**Fm** fermium	**Fm241** **0.7 ms** SF	**Fm242** **0.8 ms** SF νω α ? 242.0734	**Fm243** **0.23 s** α 8.55 SF 243.0744	**Fm244** **3.2 ms** SF 244.0741	**Fm245** **4 s** α 8.15 245.0754	**Fm246** **1.4 s** α 8.24 SF 246.07530	**Fm247** **4.9 s** α 8.17 **32 s** α 7.87, 7.93 γ 166, 141, 121 ε E 3.0 247.0768	**Fm248** **34 s** α 7.86, 7.83 SF ω 248.07719
		99	**Es** einsteinium		**Es241** **~8 s** α 8.11 241.0685	**Es242** **12 s** ε ? α 7.9 (SF) 242.0697	**Es243** **21 s** α 7.899, 7.939 ε ? E 3.8 243.0695	**Es244** **37 s** ε (SF) ω α 7.57 E 4.5	**Es245** **1.1 m** ε α 7.74 E 3.1 245.0713	**Es246** **7.4 m** ε α 7.35 (SF) E 3.8 246.0729	**Es247** **4.4 m** ε α 7.323 E 2.47
98	**Cf** californium	**Cf237** **2.1 s** SF 237.062	**Cf238** **21 ms** SF 238.0614	**Cf239** **~0.7 m** α 7.63 239.0624	**Cf240** **1.0 m** α 7.59 SF 240.0623	**Cf241** **4 m** ε α 7.33 E 3.3 241.0637	**Cf242** **3.5 m** α 7.385, 7.35 ε ? E 1.6 242.06370	**Cf243** (1/+) **11 m** ε α 7.06, 7.17 E 2.3 243.0654	**Cf244** **20. m** α 7.213, 7.176 244.066001	**Cf245** 1/+ **46 m** ε, β^+ γ 616.3,··· α 7.14,··· γ 56.1, 50.6 E 1.571 245.068049	**Cf246** **1.49 d** α 6.750, 6.708,··· γ 42.2 ω (e$^-$), 95 (e$^-$),··· SF νω 246.068805
97	**Bk** berkelium			**Bk238** **2.4 m** ε E 4.9	**Bk239** E 3.1 239.0583	**Bk240** **5 m** ε, β^+ 2.1,··· (SF) ω E 3.9	**Bk241** **4.6 m** ε γ 152.4, 262.3, 210.7 E 2.4	**Bk242** **7 m** ε, β^+ E 2.9	**Bk243**(3/−) **4.5 h** ε γ 87.4D (e$^-$),··· α 6.577 ω, 6.545,··· γ 187 ω,··· E 1.508	**Bk244** (1−) **4.4 h** ε γ 892, 217.6,··· α 6.662 ω, 6.620 E 2.26	**Bk245** 3/− **4.94 d** ε, γ 252.8,··· α 5.885 ω, 6.147,··· γ 205.9 ω, 471.8,··· E 0.811
			140		**142**		**144**		**146**		**148**



109								**Mt** meitnerium	**Mt266** ~2.6 ms α 11.05 266.1373		**Mt268** 0.02 s α 10.10, 10.24 268.1387
108						**Hs** hassium	**Hs263?** α 263.1286	**Hs264** ~0.08 ms α ~10.43 SF ? 264.12839	**Hs265** 0.9 ms ↔ 1.7 ms α 10.57, ··· α 10.30 SF ? 265.1301	**Hs266** ~2.3 ms α 10.18 266.1301	**Hs267** ~0.8 ms ~55 ms α α 9.88, 9.83, 9.75 267.1318
107				**Bh** bohrium	**Bh260** ~35 ms α 10.2 260.122	**Bh261** 9 ms α 10.40, 10.10, 10.03 SF ? 261.1217	**Bh262** 8 ms 0.10 s α 10.37, 10.24 SF α 10.06, 9.91, 9.74 SF ? 262.1229		**Bh264** 1.0 s α 9.49, 9.62 SF 264.1246	**Bh265** ~0.94 s α 9.24 265.1251	**Bh266** ~2 s α 9.2 266.1269
106			**Sg** seaborgium	**Sg258** ~2.9 ms SF 258.1132	**Sg259** (1/+) 0.5 s α 9.62,··· SF 259.1145	**Sg260** 4 ms α 9.77, 9.72 SF 260.11442	**Sg261** 0.23 s α 9.56,··· SF ? 261.1161	**Sg262** 12 ms SF 262.1164	**Sg263** 0.3 s 1.0 s α ? SF α 9.06, 9.25 263.1183	**Sg264** 0.05 s SF 264.1189	**Sg265** 18 s 8 s α 8.70 α 8.84, 8.94,··· SF ? 265.1211
105	**Db** dubnium	**Db255** ~1.6 s α SF 255.1074	**Db256** 1.6 s α 9.01,··· SF ε E 6.5 256.1081	**Db257** ~0.76 s 1.5 s α 9.16 SF α 8.97, 9.07,··· SF ε ? 257.1077	**Db258** 4.2 s α 9.17, 9.08,··· ε E 5.3 258.1092	**Db259** 0.5 s α 9.47 SF 259.1096	**Db260** 1.5 s α 9.05, 9.08, 9.13 SF 260.1113	**Db261** 1.8 s α 8.93 SF 261.1121	**Db262** 34 s α 8.45, 8.53, 8.67 SF 262.1141	**Db263** ~27 s SF α 8.35 ε 263.1150	
	Rf253 0.05 ms SF 253.1007	**Rf254** 23 μs SF 254.1002	**Rf255** (9/−) ~0.8 s 1.6 s α ? SF α 8.716, 8.92, ··· γ 143.2, 204 255.1013	**Rf256** 6.6 ms SF α 8.80 256.10117	11/− **Rf257** 1/+ 4.0 s 4.7 s α 9.02, 8.97 α 8.78, 8.74,··· γ 117,··· ε SF 257.1030 E 3.2	**Rf258** 13 ms SF α 258.1035	**Rf259** 2.5 s α 8.77, 8.86 SF ε ? 259.1056	**Rf260** 20 ms SF 260.1064	**Rf261** 1.3 m 4.2 s α 8.28 SF ? α 8.52 SF 261.10877	**Rf262** 47 ms 2.3 s SF SF 262.1099	**Rf263?** 17 m SF 263.1125
	Lr252 0.4 s α 9.02, 8.97 252.0954	(7/−)**Lr253** 0.61 s ↔ 1.6 s α 8.79 α 8.72 253.0952	**Lr254** 17 s α 8.46, 8.41 γ 42.0, 165.3, 209.1, 306.2 ε E 5.1 254.0965	**Lr255** 2.53 s 21 s α 8.46 α 8.37, 8.42 ε E 3.2 255.0967	**Lr256** 27 s α 8.43, 8.39, 8.52,··· ε SF ? E 4.0 256.0986	**Lr257** (9/+) 0.65 s α 8.86, 8.80 ε E 2.5 257.0996	**Lr258** 4.1 s α 8.60, 8.62, 8.56,··· ε 258.1018	**Lr259** 6.2 s α 8.44 SF 259.1029	**Lr260** 3 m α 8.03 ε E 2.7 260.1055	**Lr261** 40 m SF 261.1069	**Lr262** 3.6 h ε E 2.2
	No251 1.00 s 0.79 s α 8.67,··· γ 142, 203 α 8.61, 8.68 251.0890	**No252** 2.45 s α 8.42, 8.37 SF 252.08898	**No253** (9/−) 1.6 m α 8.01, 8.04, 8.06,··· γ 222, 280, 152 ε E 3.2 253.0907	**No254** 0.28 s 50 s IT α 8.09 ε SF ω E 1.2 254.09096	**No255** (1/+) 3.1 m α 8.12, 7.93, 8.08, ··· γ 187,··· ε E 2.01 255.09324	**No256** 2.9 s α 8.45 SF ω 256.09428	**No257** 3/+ 25 s α 8.22, 8.27, 8.32 γ 77, 124, 101,··· 257.09688	**No258** 1.2 ms SF 258.0982	**No259** (9/+) 58 m α 7.520, 7.551, 7.581,··· ε E 0.5 259.1010	**No260** 110 ms SF 260.1026	
	Md250 0.7 m ε α 7.83, 7.75 γ 152.3 E 4.6	**Md251** 4.3 m ε α 7.55 γ 293.7, 242.7 E 3.0	**Md252** 3 m ε α 7.73 E 3.8 252.0866	**Md253** ~6 m ε α 7.10 γ 352.3 E 2.0	**Md254** ~28 m ↔ 10. m ε ε E 2.6	**Md255** (7/−) 27 m ε γ 169.9, 231.1 α 7.327,··· γ 453.1, 405.6 E 1.04	**Md256** (1−) 1.29 h ε γ 634.1, 644.0,··· α 7.206, 7.142,··· γ 408.5, 378.5,··· E 2.1 256.0941	**Md257** (7/−) 5.5 h ε α 7.074,··· γ 371.4,··· E 0.41 257.095541	(1−)**Md258** (8−) 57 m 51.5 d ε α 6.718, 6.763, ··· γ 367.8, ··· 258.098431	**Md259** (7/−) 1.64 h SF 259.1005	**Md260** 32 d SF α ? 260.1037
	Fm249 (7/+) 1.7 m ε α 7.53 E 2.4 249.0790	**Fm250** 1.9 s 30. m IT α 7.43 ε SF νω 250.07952	**Fm251** (9/−) 5.3 h ε γ 880.8, 453.1, 450.6, ··· α 6.833,··· γ 425.4, 480.4, 358.3, ··· E 1.47	**Fm252** 1.058 d α 7.039, 6.998,··· γ 96.3, 41.5 SF ω 252.08247	**Fm253** (1/+) 3.0 d ε α 6.943, 6.676,··· γ 271.8,··· E 0.336 253.085185	**Fm254** 3.240 h α 7.192, 7.150,··· γ 99.2 ω (e^-), 42.7 (e^-),··· SF ω 254.086854	**Fm255** 7/+ 20.1 h α 7.022, 6.963,··· γ 81.48 ω (e^-), 58.48 (e^-),··· SF νω σ_γ 26, 14 σ_f 34E2 255.08996	**Fm256** 2.63 h SF α 6.92 256.09177	**Fm257** (9/+) 100.5 d α 6.519,··· γ 241.0, 179.4,··· SF ω σ_f 30E2 257.09510	**Fm258** 0.37 ms SF 258.0971	**Fm259** 1.5 s SF 259.1006
	Es248 27 m ε α 6.88 ω,··· (SF) E 3.1	**Es249** 7/(+) 1.70 h ε γ 379.5, 813.2,··· α 6.77 ω E 1.45	1(−) **Es250** (6+) 2.22 h 8.6 h ε β^+ ω γ 989.1, 1031.9, ··· ε γ 828.8, 303.4, 349.5, ··· E 2.1	**Es251** (3/−) 1.38 d ε γ 177.6, 152.8 (ω),··· α 6.492(ω), 6.462,··· E 0.38	**Es252** 1.29 a α 6.632, 6.562,··· γ 52.3 ω, 64.4, 418,··· ε, γ 785.1, 139.0,··· E 1.26 252.0830	**Es253** 7/+ 20.47 d α 6.6327, 6.5916,··· γ 41.8 ω (e^-), 389.2,··· SF νω σ_γ (18E1 + 6), (30E2 + 43E2) 253.084825	2+ **Es254** (7+) 1.64 d 276 d β^- 0.475, 1.127, γ 648.8, 693.8, α 6.382, γ 211.9 ω, σ_f 18E2 α 6.429,··· γ 64,··· σ_γ 28, 18 σ_f 20E2, 12E2 254.088022	**Es255** (7/+) 40. d β^- α 6.300, 6.26,··· γ 33 (ω),··· SF ω σ_γ 5E1 E 0.29	(8+) **Es256** (1+) ~7.6 h ↔ 25 m β^- γ 862, 232, 218,··· β^- E 1.7	**Es257** 7.7 d β^- γ 25.7,··· E 0.8	
	Cf247 (7/+) 3.11 h ε γ 294.1, 447.8, 417.9,··· α 6.296 ω,··· E 0.65	**Cf248** 334 d α 6.260, 6.218,··· SF ω 248.07218	**Cf249** 9/− 351 a α 5.813,··· γ 388.19, 333.39,··· SF νω σ_γ 50E1, 77E1 σ_f 16E2, 20E2 249.074854	**Cf250** 13.1 a α 6.0304, 5.989,··· γ 42.9 ω e^- SF ω σ_γ 20E2, 12E3 250.076406	**Cf251** 1/+ 9.0E2 a α 5.677, 5.852, 6.014,··· γ 176.7, 226.8,··· σ_γ 29E2, 16E2 σ_f 48E2, 55E2 251.079587	**Cf252** 2.646 a α 6.1181, 6.0756,··· γ 43.40 ω (e^-), 100.2 (e^-),··· SF σ_γ 20, 44 σ_f 32, 11E1 252.08163	**Cf253** (7/+) 17.8 d β^- ~0.27,··· α 5.98 ω, 5.92 σ_γ 18 σ_f 13E2 E 0.29	**Cf254** 60.5 d SF α 5.83 ω, 5.79,··· σ_γ 5 254.08732	**Cf255** 1.4 h β^- E 0.7	**Cf256** 12 m SF 256.0934	
	Bk246 2(−) 1.80 d ε γ 798.8,··· E 1.4	**Bk247** (3/−) 1.4E3 a α 5.532, 5.711, 5.687,··· γ 84.0, 268,··· 247.07031	**Bk248** (1−) >9 a 23.7 h α ? ε ? β^- ? β^- 0.86,··· γ 550.7,··· ε, γ E^- 0.87 E^+ 0.72	**Bk249** 7/+ 330 d β^- 0.124 α 5.417 (ω),··· γ 327.5 (νω), 308.3,··· SF νω σ_γ 71E1, 12E2 σ_f 0.1 E 0.124	**Bk250** 2− 3.213 h β^- 0.74,··· γ 989.1, 1031.8,··· σ_f 1.0E3 E 1.780	**Bk251** (3/−) 56 m β^- 0.92,··· γ 177.6, 152.8,··· E 1.09					
		150		152		154		156		158	

								113		**278** ~0.2 ms α 11.7	
								112	**Cn** copernicium	**Cn277** ~0.69 ms α 11.45, 11.31 277.1639	
				111	**Rg** roentgenium	**Rg272** 2 ms α 10.99 272.1536		**Rg274** ~6 ms α 11.2 274.156			
110	**Ds** darmstadtium	**Ds267** ~3 µs α 11.60 267.1443		**Ds269** ~0.27 ms α 11.13 269.1451	**Ds270** ~6 ms α 10.95, 11.15, 12.15 γ 218 0.08 ms α 11.03 270.1447	**Ds271** ~69 ms ↔ 1.6 ms α 10.71, 10.4 α 10.74, 10.68 271.1461		**Ds273** ~170 µs α 11.11 ~310 µs α 11.20 273.1489			
109	**Mt** meitnerium	**Mt266** ~2.6 ms α 11.05 266.1373		**Mt268** 0.02 s α 10.10, 10.24 268.1387		**Mt270** 5 ms α 10.0 270.141				**Mt274** ~440 ms α 10. 274.147	**Mt275** ~9.7 ms α 10.3 275.149
			158		160		162		164		166



		168		170		172		174		176	
118										294 ~1 ms α 11.7	
117											
116								290 8 ms α 10.9 290.199	291 ~18 ms α 10.7 291.200	292 ~18 ms α 10.7 292.200	293 ~53 ms α 10.5
115						287 ~32 ms α 10.6 287.191	288 ~87 ms α 10.5 288.192				
114						286 ~0.16 s α 10.2 286.184	287 0.50 s α 10.0 287.186	288 0.8 s α 9.9 288.186	289 ~2.7 s α 9.8 289.187		
			282 ~73 ms α 10.6	283 ~100 ms α 10.1 283.176	284 ~0.48 s α 10.0 284.178						
				Cn282 0.7 ms SF 282.170	Cn283 4 s α 9.5, 9.4,··· 283.172	Cn284 ~100 ms SF 284.172	Cn285 ~34 s α 9.2 285.174				
	Rg278 ~4.2 ms α 10.7 278.162	Rg279 ~170 ms α 10.4 279.162	Rg280 ~3.6 s α 9.7 280.164								
			Ds279 0.19 s SF α 9.70 279.159		Ds281 ~9.6 s SF 281.162						
	Mt276 ~0.72 s α 9.7 276.151										

Conversion Factors

The International System of Units, developed and maintained by the General Conference on Weights and Measures (abbreviated CGPM from the official French name) is intended as a basis for worldwide standardization of measurement units. The name International System of Units and the international abbreviation SI (from the French name Le System Internationale d'Unites) were adopted by the 11th CGPM in 1960. SI is based on a selected set of dimensionally independent SI Base Units. These are the meter, kilogram, second, ampere, kelvin, candela, and mole. In the SI system, there is one and only one SI unit for each physical quantity. This is either the appropriate SI Base Unit itself or the appropriate SI Derived Unit formed by multiplication and/or division of two or more SI Base Units. For example, newtons, pascals, and joules are the names of SI Derived Units for force, pressure (stress), and energy, respectively.

Prefixes and symbols are used to form names of decimal multiples of the SI units. These are listed below.

SI Prefixes

Prefix	Symbol	Multiplication Factor
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deka	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

In the following sections, SI units are emphasized. Each section (Angle, Length, Area, etc.) consists of two parts: one in which the conversion of other units to the appropriate SI units are given and one in which conversion factors are given for non-SI units. The conventions used are as follows: Conversion factors set in **boldface** are exact. When four or more digits are given, they are broken up into groups of three for ease of readability. Exponential nomenclature is used, i.e., 2.011 684 E+01 means $2.011\ 684\times10^{1}$.

The reader is cautioned that the SI system is evolving, and that there will be changes from time to time as this occurs. For example, the SI Base Unit for length, the meter, was redefined by CGPM in 1983 as the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second. For a more complete discussion of SI Units, the reader should consult references 285, 286, and 287.

Angle

The SI unit of plane angle is the radian (rad). The radian is the plane angle between two radii of a circle, which cut off on the circumference an arc equal in length to the radius.

The SI unit of solid angle is the steradian (sr). The steradian is the solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

Conversion to radians and steradians from other units

To convert from	to	Multiply by
degree (angle)	radian (rad)	1.745 329 E−02
grade (gon)	radian (rad)	1.570 796 E−02
minute (angle)	radian (rad)	2.908 882 E−04
second (angle)	radian (rad)	4.848 137 E−06
solid angle	steradians (sr)	1.256 637 E+01
square degree	steradians (sr)	3.046 174 E−04

Other Unit Conversions of Angle[288]

1 degree = **60** minutes
1 grade (gon) = **9.0 E−01** degrees
1 minute = **60** seconds
1 mil (angle) = **360/6400** degrees
= **5.625 E−02** degrees
1 radian = **360°/2π**
= 5.729 578 E+01 degrees
1 sec slope = 4.848 137 E+00 microinches/inch
= 0.001 inches/17.188 73 feet
1 solid angle = **4π** steradians
= 1.256 637 E+01 steradian
= **1** sphere
1 steradian = 7.957 747 E−02 solid angle

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[285] ASTM Committee E43 on SI Practice and IEEE Standards Coordinating Committee S4, "American National Standard for Use of the International System of Units (SI): The Modern Metric System," published by The Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY, 10017-2394 and the American Society for Testing and Materials (ASTM), 100 Bar Harbor Drive, West Conshohocken, PA 19428-2959, USA. (see http://www.astm.org).

[286] A. Thompson and B.N. Taylor, "Guide for the Use of the International System of Units (SI)," NIST Special Publication 811, 2008 Edition (version 3.0). Available: http://physics.nist.gov/SP811 (2009, March 19). National Institute of Standards and Technology, Gaithersburg, MD.

[287] T. Butcher, S. Cook, and L. Crown, "Specifications, Tolerances and Other Technical Requirements for Weighing and Measuring Devices," NIST Handbook 44, National Institute of Standards and Technology, Gaithersburg, Md, 2009.

[288] See R.A. Young and T. J. Glover, *Measure for Measure*, (Sequoia Publishing, Inc., Littleton CO, 2006), for additional conversion factors for all units.

Length

The SI unit for length is the meter, symbol m. The meter currently in use is the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.

Since 1893, the definition of the U.S. yard has been derived from the meter. In 1959, the definition of the yard was modified to bring the U.S. yard and the yard used in other countries into agreement. The U.S. yard was changed from 3600/3937 m to 0.9144 m exactly.

In 1959, it also was decided that any data in feet derived from and published as a result of geodetic surveys within the U.S. would remain with the old standard (1 foot = 1200/3937 m) until further decision. This foot is named the U.S. survey foot. Conversions to meters for U.S. survey units are given in a separate table, below.

1 foot (international) = **0.3048** m

1 foot (U.S. survey) = **1200/3937** m = 3.048 006 E−01 m

Conversion to meters from other units

To convert from	to	Multiply by
angstrom	meter (m)	**1.0 E−10**
astronomical unit, international	meter (m)	1.495 979 E+11
foot	meter (m)	**3.048 E−01**
inch	meter (m)	**2.54 E−02**
light year[289]	meter (m)	9.460 730 E+15
mil (0.001 in)	meter (m)	**2.54 E−05**
mile, international (5280 ft)	meter (m)	**1.609 344 E+03**
mile, international nautical[290]	meter (m)	**1.852 E+03**
parsec	meter (m)	3.085 678 E+16
yard	meter (m)	**9.144 E−01**

Conversion to meters from U.S. survey[291] units

To convert from	to	Multiply by
link	meter (m)	2.011 684 E−01
survey foot	meter (m)	3.048 006 E−01
rod (16 ½ survey feet)	meter (m)	5.029 210 E+00
chain (66 survey feet)	meter (m)	2.011 684 E+01
mile, statute (5280 survey feet)	meter (m)	1.609 347 E+03

Other Unit Conversions of Length

1 inch = **1.0** **E+03** mils
1 furlong = **660** survey feet
1 light year[289] = 5.878 625 E+12 miles (international)
= 3.066 014 E−01 parsecs
1 mile, international nautical = 6.076 116 E+03 feet
1 mile, U.S. statute = 1.760 003 E+03 yards
= 5.280 010 E+03 feet
= 6.336 012 E+04 inches
= 8.689 779 E−01 miles (nautical)

Area

The SI unit of area is the square meter (m^2). Conversions for U.S. Survey units are given in a separate table, below.

Conversion to square meters from other units

To convert from	to	Multiply by
barn	square meter (m^2)	**1.0 E−28**
circular mil[292]	square meter (m^2)	5.067 075 E−10
hectare	square meter (m^2)	**1.0 E+04**
square foot	square meter (m^2)	**9.290 304 E−02**
square inch	square meter (m^2)	**6.451 6 E−04**
square mile	square meter (m^2)	2.589 988 E+06
square yard	square meter (m^2)	8.361 274 E−01

Conversion to square meters from U.S. survey units

To convert from	to	Multiply by
square foot	square meter (m^2)	9.290 341 E−02
square rod	square meter (m^2)	2.529 295 E+01
square chain	square meter (m^2)	4.046 873 E+02
acre	square meter (m^2)	4.046 873 E+03
square mile	square meter (m^2)	2.589 998 E+06

Other Unit Conversions of Area

1 acre = **4.356** **E+04** square survey feet
1 circular mil = **1.0** **E−06** circular inches
= 7.853 982 E−01 square mils
1 square inch = 1.273 244 E+06 circular mils
= **6.451 6** **E+00** square centimeters
1 square yard = **9.0** **E+00** square feet

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[289] This conversion factor is based on 1 d = 86 400 s and 1 Julian year = 365.25 d. See "Time," page 85.

[290] The international nautical mile of 1.852E+03 meters was adopted in 1954 in the U.S.

[291] All conversion factors for units of land measure in this section are based on the U.S. survey foot and the following relationships:

1 rod (pole or perch) = 25 links
1 chain = 4 rods = 100 links
1 mile (U.S. statute) = 80 chains = 320 rods = 8,000 links
1 acre = 160 square rods
1 square mile (U.S. statute) = 640 acres
1 section of land = 1 mile square
1 township = 6 miles square = 36 sections = 36 square miles

[292] A circular mil is the area of a circle 1 mil (0.001 inch) in diameter.

Volume

The SI unit for volume is the cubic meter (m^3). Separate tables are given for U.S. units of dry volume and liquid volume, below.

Conversion to cubic meters from other units of volume

To convert from	to	Multiply by
cubic foot	cubic meter (m^3)	2.831 685 E−02
cubic inch[293]	cubic meter (m^3)	1.638 706 E−05
cubic yard	cubic meter (m^3)	7.645 549 E−01
liter[294]	cubic meter (m^3)	**1.0 E−03**
stere	cubic meter (m^3)	**1.0 E+00**

Conversion to cubic meters from other units of dry volume measure

To convert from	to	Multiply by
dry pint	cubic meter (m^3)	5.506 105 E−04
dry quart	cubic meter (m^3)	1.101 221 E−03
peck	cubic meter (m^3)	8.809 768 E−03
bushel	cubic meter (m^3)	3.523 907 E−02

Conversion to cubic meters from other units of liquid volume measure

To convert from	to	Multiply by
fluid ounce	cubic meter (m^3)	2.957 353 E−05
liquid pint	cubic meter (m^3)	4.731 765 E−04
liquid quart	cubic meter (m^3)	9.463 529 E−04
gallon	cubic meter (m^3)	3.785 412 E−03

Other Unit Conversions of Volume

1 cubic centimeter = 6.102 374 E−02 cubic inches
= 3.381 402 E−02 fluid ounces
1 cubic foot = **1.728 E+03** cubic inches
= 2.831 685 E+01 liters
= 7.480 519 E+00 gallons
= 8.035 640 E−01 bushels
1 gallon = 2.310 001 E+02 cubic inches
= 1.336 806 E−01 cubic feet
= 3.785 412 E+00 liters
1 liter = **1.0 E+03** cubic centimeters
= 3.381 402 E+01 fluid ounces
= 1.056 688 E+00 liquid quarts
= 2.641 721 E−01 liquid gallons
1 liquid pint = **0.5** liquid quart
= **2.887 5 E+01** cubic inches
1 liquid quart = **32** fluid ounces
= 9.463 529 E−01 liters

Mass

The SI unit of mass is the kilogram (kg). It is equal to the mass of the international prototype of the kilogram, which is a cylinder of platinum-iridium alloy kept near Paris, France. Three English systems of weights exist: the avoirdupois, the apothecary, and the troy system.

The avoirdupois system is the system of weights customarily used in the U.S. In Britain, the stone (14 lbs) was included as a unit and definitions of the hundredweight and ton were altered to be easily converted to stone. The resulting "long hundredweight" and "long ton" are 112 lb and 2240 lb, respectively. In 1958, the avoirdupois pound was defined to be 4.535 923 7 E−01 kg.

The apothecary system is used in compounding and dispensing drugs and the troy system is used for precious gems and metals.

The grain (gr) is a unit common to all three systems and, since 1958, has been internationally defined as 6.479 891 E−05 kg, exactly. While the ounce and pound are used in all three systems, the definitions of these units in the avoirdupois system differ from those in the apothecary and troy systems.

Conversion to kilograms from avoirdupois units

To convert from	to	Multiply by
grain	kilogram (kg)	**6.479 891 E−05**
dram (1/16 ounce or 27 11/32 grains)	kilogram (kg)	1.771 845 E−03
ounce (1/16 pound)	kilogram (kg)	2.834 952 E−02
pound[295]	kilogram (kg)	4.535 924 E−01
hundredweight, short (100 lbs)	kilogram (kg)	4.535 924 E+01
ton, short (2000 lbs)	kilogram (kg)	**9.071 847 E+02**
stone (14 lb)	kilogram (kg)	6.350 293 E+00
hundredweight, long (8 stone or 112 lbs)	kilogram (kg)	5.080 235 E+01
ton, long (2240 lbs)	kilogram (kg)	1.016 047 E+03
ton (metric)	kilogram (kg)	**1.0 E+03**
tonne	kilogram (kg)	**1.0 E+03**

Conversion to kilograms from apothecary units

To convert from	to	Multiply by
grain	kilogram (kg)	**6.479 891 E−05**
scruple (20 grains)	kilogram (kg)	1.295 978 E−03
dram (3 scruples)	kilogram (kg)	3.887 935 E−03
ounce (8 drams)	kilogram (kg)	3.110 348 E−02
pound (12 oz)	kilogram (kg)	3.732 417 E−01

Conversion to kilograms from troy units

To convert from	to	Multiply by
grain	kilogram (kg)	**6.479 891 E−05**
pennyweight (24 grains)	kilogram (kg)	1.555 174 E−03
ounce (20 pennyweights)	kilogram (kg)	3.110 348 E−02
pound (12 oz)	kilogram (kg)	3.732 417 E−01

Other Unit Conversions of Mass

1 gram = 3.527 396 E−02 ounce (avoirdupois)
= 1.543 236 E+01 grains

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[293] The exact conversion factor is **1.638 706 4 E-05**.

[294] In 1964, the General Conference on Weights and Measures reestablished the name liter as a special name for the cubic decimeter. Between 1901 and 1964, the liter was slightly larger (1.000 028 dm^3); in the use of high-accuracy volume data of that time interval, this fact must be kept in mind.

[295] The exact conversion factor is **4.535 923 7 E-01**.

Time

The unit of time, the System Internationale (SI) second, s, is defined as the duration of 9 192 531 770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of ^{133}Cs. This definition refers to a cesium atom at rest and at a temperature of 0 K. Several non-SI units of time accepted for use with the International System are:

minute	1 min = 60 s (SI)
hour	1 h = 60 min (SI) = 3,600 s (SI)
day	1 d = 24 h (SI) = 86,400 s (SI)

The year is a unit of time intended to equal the period of revolution of the earth around the sun. Several types of "years" have been defined—all having different reference points and slightly different lengths. The solar (or tropical) year is the length of time it takes the sun, as seen from the earth, to return to the same position on the ecliptic—the intersection of the plane of the earth's orbit around the sun and the celestial sphere. The length of the solar year, however, depends on the starting point on the ecliptic and a mean solar year is, therefore, defined as an average over all starting points on the ecliptic. The length of the mean tropical or solar year is 365.242 19 mean solar days.

The sidereal year is the time for the earth to complete one revolution of its orbit as measured relative to a "fixed" distant star. This is 366.256 40 sidereal days. A sidereal day is the time it takes the earth to complete a rotation around its axis. A solar day is the time it takes the sun to return to its highest point in the sky on two consecutive days. During a sidereal day, the earth moves a short distance (about 1 degree) along its orbit around the sun. After a sidereal day, the earth must then rotate a small amount before the sun reaches its highest point in the sky. The solar day is then longer (by about 4 minutes) than the sidereal day. With this difference, the stars rise in the sky ~4 minutes earlier each night allowing us to see different constellations at different times of the year.

Development of the modern calendar started with Julius Caesar in 48 B.C. The calendar adopted by the Romans at that time had twelve months with a total of 365 days, with an extra day added every fourth year (a leap year). Over a four-year period, then, the average length of the year was 365.25 days—longer than the mean tropical year by about 11 minutes per year. This difference caused the calendar to be increasingly out of step with the equinoxes and solstices as time went on. By ~A.D. 1500, the calendar was ahead by about 10 days. In 1582, Pope Gregory XIII established what is now called the Gregorian calendar. Among other changes, the rule for leap years was changed. In the Julian calendar, a year was a leap year if it was divisible by four. In the Gregorian calendar a year is a leap year a) if it is divisible by four but not by 100, or b) if it is divisible by 400. Thus the years 1700, 1800, 1900, and 2100 are not leap years, while 1600 and 2000 are. With this definition, the difference between the average Gregorian calendar year and the mean solar year is 0.00031 days. After ~ 3,000 years, the difference will approach one day.

It should be noted that although the Julian year is not a fundamental unit of time, astronomers and other scientists use it for convenience to measure lengthy durations. Its use is recommended by the International Astronomical Union[296] (IAU). The definition of the light-year as a unit of distance is based on the Julian year.

In referring to dates in the past, the terms B.C. and A.D. are typically used in many parts of the world. This system was created by the monk Dionysius Exiguus in or about the year A.D. 525. The abbreviation B.C. is the abbreviation for "before Christ" and marks the date believed to be the birth of Jesus Christ. A.D. is the abbreviation for *anno Domini* (Latin for "in the year of the Lord") and designates the years after the birth of Christ. In usage, "A.D." precedes the year number, A.D. 320, while "B.C." follows the year number, 429 B.C., and both are written with small capital letters. In the Gregorian calendar, there is no year zero—the sequence of years around that time would be 3 B.C., 2 B.C., 1 B.C., A.D. 1, A.D. 2, A.D. 3, etc.

To avoid the religious connotations of B.C. and A.D., the use of B.C.E. and C.E., essentially equivalent to B.C. and A.D., has been suggested. B.C.E. stands for "before the common era" and C.E. stands for "common era." Both B.C.E. and C.E. are used as suffixes and are not written in small capital letters.

The international time standard[297] is International Atomic Time (TAI from the French name Temps Atomique International). It is calculated by the Bureau International de Poids and Measures[298] (BIPM) in Sevres, France, by averaging the time kept by approximately 300 atomic clocks in over 30 countries worldwide.

Universal Time (UT) is calculated from astronomical observations and the unit of duration is the mean solar day. UT0 is a universal time measurement calculated by the International Earth Rotation and Reference Systems Service (IERS) based on observation of the diurnal motion of the stars, extragalactic radio sources, and also from ranging observations of the moon and of earth satellites. UT0 is then corrected for the polar motion of the earth to give UT1.

The international standard on which civil time is based is Coordinated Universal Time (UTC). In order to ensure that UTC does not differ from the earth's rotational time (UT1), by more than 0.9 seconds, leap seconds can be added to or subtracted from UTC. The decision to add or subtract a leap second is made by IERS. The leap seconds are always introduced after the last second of a month, usually June 30 or December 31.

Conversion to seconds from other units

To convert from	**to**	**Multiply by**	
minute	seconds (s)	**6.0**	**E+01**
hour	seconds (s)	**3.6**	**E+03**
day	seconds (s)	**8.64**	**E+04**
year (365 days)	seconds (s)	**3.153 6**	**E+07**
second (sidereal)	seconds (s)	9.972 696	E−01
minute (sidereal)	seconds (s)	5.983 617	E+01
hour (sidereal)	seconds (s)	3.590 170	E+03
day (sidereal)	seconds (s)	8.616 409	E+04
year (sidereal)	seconds (s)	3.155 815	E+07
year (tropical)	seconds (s)	3.155 693	E+07
shake	seconds (s)	**1.0**	**E−08**

Other Unit Conversions of Time

1 day (tropical) = **24** hours (tropical)
= 1.002 738 E+00 days (sidereal)
= 2.406 571 E+01 hours (sidereal)
1 day (sidereal) = **24** hours (sidereal)
= 9.972 696 E−01 days (tropical)
= 1.436 0682 E+03 minutes (tropical)
1 week (calendar) = **7** days (tropical)
= **168** hours (mean solar)
= 7.019 1654 E+00 days (sidereal)
= 1.684 5997 E+02 hours (sidereal)
1 year (calendar) = **365** days (tropical)
= **8,760** hours (tropical)
1 year (tropical) = 3.652 4219 E+02 days (tropical)
= 3.662 4219 E+02 days (sidereal)
1 year (sidereal) = 3.652 5636 E+02 days (tropical)
= 3.662 5640 E+02 days (sidereal)

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[296] See the IAU website at http://www.iau.org/Units.234.0.html.

[297] See "Timekeeping at the U.S. Naval Observatory" at http://tychoj.usno.navy.mil/systime.html.

[298] See the BIPM Website at http://www.bipm.org.

Density

The SI unit for mass per unit volume (density) is kilograms per cubic meter (kg/m^3).

Conversion to kilograms per cubic meter from other units

To convert from	to	Multiply by	
grams per cubic centimeter	kilogram per cubic meter	**1.0**	**E+03**
pounds per cubic foot	kilogram per cubic meter	1.601 846	E+01
pounds per cubic inch	kilogram per cubic meter	2.767 990	E+04

Other Unit Conversions of Density

1 gram per cubic centimeter = 6.242 796 E+01 pounds per cubic foot
= 3.612 729 E−02 pounds per cubic inch
1 pound per cubic foot = 5.787 037 E−04 pounds per cubic inch

Velocity

The SI unit of velocity is meter per second (m/s).

Conversion to meter per second from other units

To convert from	to	Multiply by	
foot per hour	meter per second (m/s)	8.466 667	E−05
foot per minute	meter per second (m/s)	**5.08**	**E−03**
foot per second	meter per second (m/s)	**3.048**	**E−01**
inch per second	meter per second (m/s)	**2.54**	**E−02**
kilometer per hour	meter per second (m/s)	2.777 778	E−01
knot (international)	meter per second (m/s)	5.144 444	E−01
mile per hour (international)	meter per second (m/s)	**4.470 4**	**E−01**
mile per minute (international)	meter per second (m/s)	**2.682 24**	**E+01**
mile per second (international)	meter per second (m/s)	**1.609 344**	**E+03**

Other Unit Conversions of Velocity

1 meter per second = 2.236 936 E+00 miles (international) per hour
1 mile (international) per hour = 1.466 667 E+00 feet per second
= 8.689 762 E−01 knots (international)
= 2.777 778 E−04 miles (international) per second
= **1.609 344 E+00** kilometer per hour (km/h)[299]
1 knot (international) = **1** mile (international nautical) per hour
= 1.687 810 E+00 feet per second

Angular Velocity

The SI unit of angular velocity is radian per second (rad/s).

Conversion to radian per second from other units

To convert from	to	Multiply by	
revolution per second	radian per second (rad/s)	6.283 185	E+00
revolution per minute (RPM)	radian per second (rad/s)	1.047 198	E−01
degree per second	radian per second (rad/s)	1.745 329	E−02

Other Unit Conversions of Angular Velocity

1 RPM = **6** degrees per second
= 1.666 667 E−02 revolutions per second

Acceleration

The SI unit of acceleration is the meter per second squared (m/s^2). The SI unit of angular acceleration is radians per second squared (rad/s^2).

Conversion to meters per second squared from other units

To convert from	to	Multiply by	
foot per second squared	meter per second squared (m/s^2)	**3.048**	**E−01**
free fall, standard (g)	meter per second squared (m/s^2)	**9.806 65**	**E+00**
gal[300]	meter per second squared (m/s^2)	**1.0**	**E−02**
inch per second squared	meter per second squared (m/s^2)	**2.54**	**E−02**

Other Unit Conversions of Acceleration

1 foot per second squared = **3.048 E+01** centimeter per second squared

Force

The SI Derived Unit of force is the newton (N), which is the force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one meter per second squared. The principal departure of SI from the gravimetric system of metric engineering units is the use of explicitly distinct units for mass and force. In SI, the name kilogram is restricted to the unit of mass and the kilogram-force (from which the suffix force was in practice often erroneously dropped) should not be used. In its place the SI unit of force, the newton, is used.

Conversion to newton from other units

To convert from	to	Multiply by	
dyne	newton (N)	**1.0**	**E−05**
kilogram-force	newton (N)	**9.806 65**	**E+00**
kilopond (kp)	newton (N)	**9.806 65**	**E+00**
kip (1000 lbf)	newton (N)	4.448 222	E+03
ounce-force	newton (N)	2.780 139	E−01
poundal	newton (N)	1.382 550	E−01
pound-force (lbf)[301]	newton (N)	4.448 222	E+00

Other Unit Conversions of Force

1 newton = **1.0 E+05** dyne
= 2.248 089 E−01 pound-force
1 dyne = 2.248 089 E−06 pound-force
= 7.233 014 E−05 poundal
= 1.019 716 E−03 gram-force
1 gram weight, now called gram-force = 7.093 164 E−02 poundal
= 9.806 650 E+02 dynes
= 2.204 622 E−03 pound-force
1 pound (avoirdupois) weight, now called pound-force = 3.217 404 E+01 poundal
= 4.535 924 E+02 gram-force
1 poundal = 3.108 096 E−02 pound-force
= 1.409 808 E+01 gram-force
= 1.382 550 E+04 dyne
1 lbf/lb (thrust/weight [mass] ratio) = **9.806 65 E+00** newton per kilogram (N/kg)

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[299] Although speedometers may read km/h, the SI unit is m/s.

[300] The unit gal, not to be confused with the gallon, refers to the local acceleration due to gravity, and is 1 centimeter per second squared.

[301] The exact conversion factor is **4.448 221 615 260 5 E+00**. Pound-force was formerly called pound (avoirdupois) weight. Gram-force was formerly called gram weight.

Work and Energy

The SI Derived Unit of energy is the joule (J), which is the work done when the point of application of a force of one newton is displaced a distance of one meter in the direction of the force. The units of the joule are kg $m^2 s^{-2}$.

The calorie has two major definitions. The gram calorie is defined as the amount of energy required to raise the temperature of one gram of water by 1°C at a pressure of 1 standard atmosphere. The kilogram calorie is the amount of energy required to raise the temperature of one kilogram of water by 1°C at a pressure of 1 standard atmosphere. Since the quantity of heat represented by the calorie differs at different temperatures, definitions of the calorie are made at certain specific temperatures i.e., the "15° calorie" was defined as the amount of heat that will raise the temperature of 1 gram of water from 14.5°C to 15.5°C. A mean calorie has also been defined as 1/100 of the heat necessary to raise the temperature of 1 gram of water from 0°C to 100°C.

Another definition of the calorie, the International Table (IT) calorie was defined at the *International Conference on the Properties of Steam* (London, July 1956) as 1/860 of the international watt-hour. This unit is used in engineering steam tables. A thermochemical calorie used as the unit for heat capacities, latent heats, and heats of reaction has also been defined.

The British thermal unit (Btu) is a unit of energy used in power, heating, steam generation, and air conditioning applications. The Btu is defined as the amount of heat necessary to raise the temperature of 1 pound of water from 60°F to 61°F at a pressure of 1 atmosphere. As with the calorie, several different definitions of the Btu exist, each based on different water temperatures.

Conversion to joules from other units

To convert from	to	Multiply by	
calorie (15°C)	joule (J)	4.185 80	E+00
calorie (20°C)	joule (J)	4.181 90	E+00
calorie (mean)	joule (J)	4.190 02	E+00
calorie (International Table)	joule (J)	**4.186 8**	**E+00**
calorie (thermochemical)	joule (J)	**4.184**	**E+00**
calorie (kilogram, mean)	joule (J)	4.190 02	E+03
calorie (kilogram, International Table)	joule (J)	**4.186 8**	**E+03**
calorie (kilogram, thermochemical)	joule (J)	**4.184**	**E+03**
Btu (39°F)	joule (J)	1.059 67	E+03
Btu (59°F)	joule (J)	1.054 80	E+03
Btu (60°F)	joule (J)	1.054 68	E+03
Btu (mean)	joule (J)	1.055 87	E+03
Btu (International Table)[302]	joule (J)	1.055 056	E+03
Btu (thermochemical)	joule (J)	1.054 350	E+03
electronvolt	joule (J)	1.602 176	E−19
erg	joule (J)	**1.0**	**E−07**
foot poundal	joule (J)	4.214 011	E−02
foot pound-force	joule (J)	1.355 818	E+00
kilowatt hour	joule (J)	**3.6**	**E+06**
therm (European Community)[303]	joule (J)	**1.055 06**	**E+08**
therm (U.S.)[303]	joule (J)	**1.054 804**	**E+08**
ton (nuclear equivalent of TNT)	joule (J)	**4.184**	**E+09**
watt hour	joule (J)	**3.6**	**E+03**
watt second	joule (J)	**1.0**	**E+00**

Other Unit Conversions of Energy

1 joule = **1** newton meter
= **1.0** **E+07** erg
= **1.0** **E+07** dyne centimeter
= **1** watt second
= **1** volt coulomb
= 7.375 621 E−01 foot pound-force
= 2.386 624 E−04 calorie (kilogram, mean)
= 9.470 863 E−04 Btu (mean)
= 2.373 036 E+01 foot poundal
= 2.777 778 E−07 kilowatt-hour
= 3.725 088 E−07 horsepower (electric) hour
1 joule (international) = 1.000 165 E+00 joule[304]

Power

The SI unit of power is the watt (W or kg $m^2 s^{-3}$). The watt is the power that gives rise to the production of energy at the rate of one joule per second (Js^{-1}).

Horsepower is the name of a unit of power, originally used to compare the power output of steam engines with the power output of draft horses. The original unit is the "mechanical" or "hydraulic" horsepower. Other definitions of horsepower were developed for other applications. These include boiler horsepower, used for boilers in industrial applications, electric horsepower, used for electrical machines, and others.

Conversion to watts from other units

To convert from	to	Multiply by	
Btu (mean) per second	watt (W)	1.055 87	E+03
Btu (International Table) per hour	watt (W)	2.930 711	E−01
Btu (International Table) per second	watt (W)	1.055 056	E+03
Btu (thermochemical) per hour	watt (W)	2.928 751	E−01
Btu (thermochemical) per minute	watt (W)	1.757 250	E+01
Btu (thermochemical) per second	watt (W)	1.054 350	E+03
calorie (thermochemical) per minute	watt (W)	6.973 333	E−02
calorie (thermochemical) per second	watt (W)	**4.184**	**E+00**
erg per second	watt (W)	**1.0**	**E−07**
foot pound-force per hour	watt (W)	3.766 161	E−04
foot pound-force per minute	watt (W)	2.259 697	E−02
foot pound-force per second	watt (W)	1.355 818	E+00
horsepower (550 ft lbf/s)	watt (W)	7.456 999	E+02
horsepower (boiler)	watt (W)	9.809 50	E+03
horsepower (electric)	watt (W)	**7.46**	**E+02**
horsepower (metric)	watt (W)	7.354 988	E+02
horsepower (water)	watt (W)	7.460 43	E+02
horsepower (U.K.)	watt (W)	7.456 999	E+02
kilocalorie (thermochemical) per minute	watt (W)	6.973 333	E+01
kilocalorie (thermochemical) per second	watt (W)	**4.184**	**E+03**
ton of refrigeration (=12,000 Btu/hour)	watt (W)	3.516 853	E+03

Other Unit Conversions of Power

1 Btu (International Table) per minute = 2.357 141 E−02 horsepower (electric)
= 1.758 426 E+01 watt
= 7.781 694 E+02 foot pound-force per minute
1 erg per second = 5.682 518 E−09 Btu (mean) per minute
= 1.431 97 E−09 kilogram calorie (mean) per minute
= 7.375 621 E−08 foot pound-force per second
1 horsepower (U.K.) = 7.062 43 E−01 Btu (mean) per second
= **550** foot pound-force per second
1 quad = **1.0** **E+15 Btu**

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[302] The Fifth International Conference on the Properties of Steam in 1956 defined the calorie (International Table) as 4.1868 J. Therefore, the exact conversion for Btu (International Table) is 1.055 055 852 62 E+03 J.

[303] The therm (European Community) is legally defined in the Council of the European Communities Directive 80 [8] EC of December 20, 1979. The therm (U.S.) is legally defined in the Federal Register, Vol. 33, No. 146, p. 10756, of July 27, 1968. Although the European therm, which is based on the International Table Btu, is frequently used by engineers in the U.S., the therm (U.S.) is the legal unit used by the U.S. gas industry.

[304] The SI Derived Unit, the joule, was formerly called the absolute joule, to distinguish it from the International Table joule.

Torque

The SI unit for torque (or bending moment) is newton meter (N·m).[305]

Conversion from newton meter from other units

To convert from	to	Multiply by	
dyne centimeter	newton meter (N m)	**1.0**	**E−07**
kilogram-force[306] meter	newton meter (N m)	**9.806 65**	**E+00**
ounce-force inch	newton meter (N m)	7.061 552	E−03
pound-force inch	newton meter (N m)	1.129 848	E−01
pound-force foot	newton meter (N m)	1.355 818	E+00

Other Unit Conversions of Torque

1 dyne centimeter = 1.019 716 E−08 kilogram-force meter
= 7.375 621 E−08 pound-force foot
= 8.850 748 E−07 pound-force inch
= 2.373 036 E−06 poundal foot
1 kilogram-force meter = **9.806 65** **E+07** dyne centimeter
1 pound-force foot = 1.355 818 E+07 dyne centimeter
1 poundal foot = 4.214 012 E+05 dyne centimeter
1 pound-force inch = 1.129 848 E+06 dyne centimeter

Temperature

The SI unit of temperature is the kelvin (K). The kelvin, a unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.[307]

Wide use is also made of the degree Celsius (°C), which is the SI unit for expressing Celsius temperature and temperature intervals. The temperature interval one degree Celsius (formerly called centigrade) equals one kelvin exactly. Celsius temperature (t) is related to thermodynamic temperature (T) by the equation $t = T - T_0$, where $T_0 = \mathbf{273.15}$ K by definition. To convert from degrees Fahrenheit to degrees Celsius:

$$t_{^\circ C} = (t_{^\circ F} - \mathbf{32})/\mathbf{1.8}.$$

Conversion to kelvin from other temperature units

To convert from	to	Use
degree Celsius	kelvin (K)	$T_K = t_{^\circ C} + \mathbf{273.15}$
degree Fahrenheit	kelvin (K)	$T_K = (t_{^\circ F} + \mathbf{459.67})/\mathbf{1.8}$
degree Rankine	kelvin (K)	$T_K = T_{^\circ R}/\mathbf{1.8}$

Temperature Differences

Δ1° Celsius (C) = Δ**1.8**° Fahrenheit (F)
= Δ**1.8**° Rankine (R)
= Δ**1** kelvin (K)

Other Unit Conversions of Temperature

0°C = **273.15** K
= **32**°F
= **491.67**°R
100°C = **373.15** K
= **212**°F
= **671.67**°R
0K = **−273.15**°C
= **−459.67**°F

Pressure

The SI unit of pressure or stress is the pascal, Pa (newton per square meter, or N m^{-2}).

Conversion to pascal from other units

To convert from	to	Multiply by	
atmosphere, standard	pascal (Pa)	**1.013 25**	**E+05**
atmosphere, technical (1 kilogram-force/cm^2)	pascal (Pa)	**9.806 65**	**E+04**
bar	pascal (Pa)	**1.0**	**E+05**
centimeter of mercury (0°C)	pascal (Pa)	1.333 224	E+03
centimeter of water (4°C)	pascal (Pa)	9.806 650	E+01
dyne per cm^2	pascal (Pa)	**1.0**	**E−01**
foot of water (39.2°F)	pascal (Pa)	2.988 98	E+03
gram-force per cm^2	pascal (Pa)	**9.806 65**	**E+01**
inch of mercury (32°F)	pascal (Pa)	3.386 38	E+03
inch of mercury (60°F)	pascal (Pa)	3.376 85	E+03
inch of water (39.2°F)	pascal (Pa)	2.490 82	E+02
inch of water (60°F)	pascal (Pa)	2.488 4	E+02
kilogram-force per cm^2	pascal (Pa)	**9.806 65**	**E+04**
kilogram-force per m^2	pascal (Pa)	**9.806 65**	**E+00**
kilogram-force per mm^2	pascal (Pa)	**9.806 65**	**E+06**
kip (1000 pound-force) per in^2 (ksi)	pascal (Pa)	6.894 757	E+06
millibar	pascal (Pa)	**1.0**	**E+02**
millimeter of mercury (0°C)	pascal (Pa)	1.333 22	E+02
poundal per ft^2	pascal (Pa)	1.488 164	E+00
pound-force per ft^2	pascal (Pa)	4.788 026	E+01
pound-force per in^2 (psi)	pascal (Pa)	6.894 757	E+03
torr (mm Hg, 0°C)	pascal (Pa)	1.333 22	E+02

Other Unit Conversions of Pressure or Stress

1 standard atmosphere = 1.013 250 E+00 bars
= 1.469 595 E+01 pound-force per in^2 (psi)
= 1.013 250 E+06 dynes per cm^2
= **7.60** **E+02** torr (mm Hg, 0°C)
= 2.992 13 E+01 inches Hg, 32°F
= 3.389 853 E+01 feet of water (39.2°F)
1 dyne per cm^2 = 1.450 377 E−05 pound-force per in^2 (psi)
1 bar = **1.0** **E+06** dynes per cm^2
= 9.869 233 E−01 standard atmosphere
1 pound-force per in^2 = 6.894 757 E+04 dynes per cm^2

Electromagnetic Units

For most units the difference between the cgs (centimeter-gram-second) system and SI are just powers of 10, but this is not the case for electromagnetic units. The cause of these differences is due to different definitions of the units of charge and current in the two systems (see Jackson[308]). Three systems are discussed below: SI and two cgs systems, the electrostatic (esu), and the electromagnetic (emu) systems.

The SI unit of electric current is the ampere (A), the coulomb (C) for quantity of charge, the volt (V) for electric potential difference, the farad (F) for electric capacitance, the ohm (W) for electric resistance, the siemens (S) for electric conductance, the henry (H) for electric inductance, volts/meter for the electric field, and tesla for the magnetic field. The corresponding electrostatic and electromagnetic units can be seen in the table below. In that table the abbreviation "esu" means cgs electrostatic units, and "emu" means cgs electromagnetic unit. A prefix "stat" to a unit implies that it is an esu unit; a prefix "ab" implies it is an emu unit.

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[305] The vector product of force and moment arm is widely designated by the unit newton meter. This unit for bending moment or torque results in confusion with the unit for energy, which is also newton meter. If torque is expressed as newton meter per radian, the relationship to energy is clarified, since the product of torque and angular rotation is energy: (Nm/rad) rad = Nm. If the vectors were shown, the distinction between energy and torque would be obvious since the orientation of force and length is different in the two cases.

[306] See discussion under FORCE section. Considerable confusion exists in the use of the term "weight" as a quantity to mean either "force" or "mass." In commercial and everyday use, the term weight nearly always means mass; thus when one speaks of a person's weight, the quantity referred to is mass. This non-technical use of the term weight will probably persist. In science and technology, the term "weight of a body" has usually meant the force that, if applied to the body, would give it an acceleration equal to the local acceleration of free fall ("local" usually means a location on the surface of the earth). When non-SI units are used, a distinction should be made between force and mass. For example, pound-force to denote force in gravimetric engineering units and pound for mass.

[307] The triple point of water is 273.16 K (0.01°C), which is 0.01 K above the freezing point of water at a pressure of 101.325 kPa.

[308] J.D. Jackson, *Classical Electrodynamics*, (John Wiley & Sons, New York, 1975), p. 811.

Conversion to SI electrical units from other units[309]

To convert from	to	Multiply by	
esu of current (statampere)	ampere (A)	3.335 641	E−10
emu of current (abampere)	ampere (A)	**1.0**	**E+01**
esu of charge (statcoulomb)	coulomb (C)	3.335 641	E−10
emu of charge (abcoulomb)	coulomb (C)	**1.0**	**E+01**
esu of electric potential (statvolt)	volt (V)	2.997 925	E+02
emu of electric potential (abvolt)	volt (V)	**1.0**	**E−08**
esu of capacitance (statfarad)	farad (F)	1.112 650	E−12
emu of capacitance (abfarad)	farad (F)	**1.0**	**E+09**
esu of resistance (statohm)	ohm (Ω)	8.987 552	E+11
emu of resistance (abohm)	ohm (Ω)	**1.0**	**E−09**
esu of conductance (statmho)	siemens (S)	1.112 650	E−12
emu of conductance (abmho)	siemens (S)	**1.0**	**E+09**
esu of inductance (stathenry)	henry (H)	8.987 552	E+11
emu of inductance (abhenry)	henry (H)	**1.0**	**E−09**
esu of electric field	volt/meter	2.997 925	E+04
emu of electric field	volt/meter	**1.0**	**E−06**
esu of magnetic field	tesla	2.997 925	E+06
emu of magnetic field (gauss)	tesla	**1.0**	**E−04**

Other Electrical Unit Conversions

ampere hour	coulomb (C)	**3.6**	**E+03**
faraday (based on C-12)	coulomb (C)	9.648 531	E+04
faraday (chemical)	coulomb (C)	9.649 57	E+04
faraday (physical)	coulomb (C)	9.652 19	E+04

Magnetic Units

The SI Derived Unit of magnetic flux is the weber (Wb): the magnetic flux that, linking a circuit of one turn, produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second. The SI Derived Unit for magnetic flux density is the tesla (T), which is the magnetic flux density given by a magnetic flux of one weber per square meter.

Conversion to SI magnetic units from other units

To convert from	to	Multiply by	
maxwell	weber (Wb)	**1.0**	**E−08**
unit pole	weber (Wb)	1.256 637	E−07
gamma	tesla (T)	**1.0**	**E−09**
gauss	tesla (T)	**1.0**	**E−04**

Radiation Units

Four different types of units will be discussed here: those for exposure, decay rate, absorbed dose, and equivalent dose. The roentgen is a non-SI unit of exposure used only for X-ray and gamma-ray radiation in air and is the quantity of ionizing radiation that will produce one coulomb of charged particles (electrons) in one kilogram of dry air at 0°C and STP. One roentgen is equivalent to 2.58E−4 C/kg.

The activity of a radioactive material is the rate of disintegration of that material. The SI unit of activity is the becquerel (Bq) and is the number of disintegrations per second. An earlier unit of activity was the curie (Ci), which was based on the decay rate of 1 gram of ^{226}Ra and is 3.7 E+10 disintegrations per second.

The term "dose" refers to the effect that radiation has on a material. It can refer either to the energy deposited in the material by the radiation (absorbed dose) or to the biological effect of the radiation in tissue (equivalent dose). As radiation passes through material, energy is deposited and the amount of energy deposited per unit mass in the material is called the dose, or absorbed dose. The SI unit of absorbed dose is the gray (Gy); 1 gray is equivalent to one joule of radiation energy deposited per kilogram of material. The gray[310] is used for all types of radiation. The rad (radiation absorbed dose) is an older unit and is defined as an absorbed dose of 0.01 joules of energy per kilogram of material.

Since different types of radiation—alpha particles, beta particles, gamma rays, X-rays—affect material (tissue) differently, the biologic effect of each type of radiation is different. The dose equivalent is a measure of the biologic damage to tissue and, for a specific type of radiation, is obtained by multiplying the absorbed dose of the radiation (in grays) times a quality factor (now called the radiation weighting factor, W_R), which depends on the type and energy of the radiation. The SI unit of dose equivalent is the sievert (Sv) and is equal to 1 joule of energy deposited per kilogram of tissue. Values of the radiation weighting factor for various types of radiation are given below.

Radiation Weighting Factors, W_R

Type of Radiation	W_R
X-rays and gamma rays	1
beta particles	1
protons	10
alpha particles	10–20
neutrons	5–20

It is estimated that the yearly average dose equivalent of radiation received by a person[311] in the United States is about 3.6 mSv. About 80 percent of the radiation comes from natural sources and 20 percent from manmade sources. The natural sources include radon gas in the air, internal radiation in the human body (^{40}K and ^{14}C), cosmic radiation, and naturally-occurring terrestrial radiation. The manmade sources include medical and dental X-rays, diagnostic medical procedures, jet plane travel, and consumer products (color television, video displays, etc.)

An earlier unit of dose equivalent was the rem (roentgen equivalent man) defined as the product of the exposure (in roentgens) and the radiation weighting factor. Although still in common use, NIST policy discourages continued use of the roentgen, curie, rad, and rem in favor of the corresponding SI units.[286]

Conversion to SI radiation units from other units

To convert from	to	Multiply by	
roentgen	coulomb per kilogram (C/kg)	**2.58**	**E−04**
curie	becquerel (Bq)	**3.7**	**E+10**
rad	gray (Gy)	**1.0**	**E−02**
rem	sievert (Sv)	**1.0**	**E−02**

Other SI Units

The SI Base Unit for amount of substance is the mole (mol), the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilograms of carbon-12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified group of particles.

The SI Derived Unit of frequency is the hertz (Hz), which is the frequency of a periodic phenomenon of which the period is one second.

The SI Derived Unit of luminous flux is the lumen (lm), which is the luminous flux emitted in a solid angle of one steradian by a point source having a uniform intensity of one candela.

The SI Derived Unit of illuminance is the lux (lx), which is the illuminance produced by a luminous flux of one lumen uniformly distributed over a surface of one square meter.

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[309] The conversion factors in the table can be written more simply as:
3.335 641 E−10 = 1E+01/c where c is the velocity of light, 2.997 924 58 E+10 cm/sec
2.997 925 E+02 = c/1E−08
8.987 552 E+11 = 1E−09c^2
1.112 650 E−12 = 1E+09/c^2.

[310] The gray is also used for the ionizing radiation quantities: specific energy imparted, kerma, and absorbed dose index, which have the SI unit joule per kilogram.

[311] At the American Nuclear Society website, http://www.ans.org/pi/resources/dosechart you can estimate your personal annual radiation dose.

Isotopic Abundance Tables

The tables presented in this section give the isotopic abundance in atom percent of the naturally-occurring isotopes. Table A, Abundances of the Naturally-Occurring Isotopes, gives the isotopic abundance and mass number for each naturally-occurring isotope of all elements. Table B, Isotopic Masses and Abundances of the Naturally-Occurring Isotopes, gives the isotopic mass and abundance for each naturally-occurring isotope. *Note that the abundances given in Table A have been rounded for better legibility.* Those in Table B have not. The isotopic masses and abundances are from References 160 and 161, respectively.

These tables are particularly useful in identifying isobaric species in commonly employed mass spectrometric[312] techniques, in particular, in eliminating mass interferences. In spectrometric measurements of a particular mass, isobaric and/or molecular interferences can exist at the same mass as the measured nuclide.

Isobaric interferences are caused by isotopes of different elements but having the same mass as the mass of interest. For example, as shown in Table A, three elements have isotopes having A = 50: titanium, vanadium, and chromium. A measurement at mass 50 for ^{50}Cr could be perturbed by interferences due to ^{50}Ti and/or ^{50}V.

Molecular interferences are caused by the combination of two or more "species," not necessarily chemically stable, of the same mass as that of interest. For example, a measurement at mass 155 for ^{155}Gd could have a molecular interference of ^{139}La^{16}O, also at mass 155.

Table A can also be used to determine the location of "clean" masses for a given element, i.e., where no isobaric interferences should exist. For example, for barium, the isotopes ^{135}Ba and ^{137}Ba are the only stable nuclides having A = 135 and A = 137.

The abundances listed in Table A are also useful for troubleshooting purposes. If, for example, ^{58}Ni is to be measured, there is the possibility of an ^{58}Fe contamination. In the mass 58 measurement, masses 56 and 57 should also be examined for the presence of ^{56}Fe and ^{57}Fe. Comparison of the measured ^{56}Fe/^{57}Fe signal ratio to the ^{56}Fe/^{57}Fe abundance ratio provides a check that the interfering species is indeed ^{58}Fe. The iron abundances can then be used to estimate the proportion of the mass 58 signal that is due to the ^{58}Fe contamination and can provide a corrected ^{58}Ni value.

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[312] I.T. Platzner with contributions by K. Habast, A.J. Walder, A. Goetz, *Modern Isotope Ratio Mass Spectrometry* (John Wiley & Sons, Ltd. 1997).

Table A. Abundances of the Naturally-Occurring Isotopes (atom percent)

A▶	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	◀A
H	99.99	0.01																			H
He			0.01	99.99																	He
Li						7.59	92.41														Li
Be									100.												Be
B										19.9	80.1										B
C												98.93	1.07								C
N														99.64	0.36						N
O																99.76	0.04	0.20			O
F																			100.		F
Ne																				90.48	Ne
A▶	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	◀A
(Ne)	0.27	9.25																			(Ne)
Na			100.																		Na
Mg				78.99	10.00	11.01															Mg
Al							100.														Al
Si								92.22	4.69	3.09											Si
P											100.										P
S												94.99	0.75	4.25		0.01					S
Cl															75.76		24.24				Cl
Ar																0.337		0.063		99.60	Ar
K																			93.26	0.01	K
Ca																				96.94	Ca
A▶	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	◀A
(K)	6.73																				(K)
(Ca)		0.65	0.13	2.09		0.01		0.18													(Ca)
Sc					100.																Sc
Ti						8.25	7.44	73.72	5.41	5.18											Ti
V										0.25	99.75										V
Cr										4.35		83.79	9.50	2.36							Cr
Mn															100.						Mn
Fe														5.85		91.75	2.12	0.28			Fe
Co																			100.		Co
Ni																		68.08		26.22	Ni
A▶	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	◀A
(Ni)	1.14	3.63		0.93																	(Ni)
Cu			69.15		30.85																Cu
Zn				48.27		27.98	4.10	19.02		0.63											Zn
Ga									60.11		39.89										Ga
Ge										20.38		27.31	7.76	36.72		7.83					Ge
As															100.						As
Se														0.89		9.37	7.63	23.77		49.61	Se
Br																			50.69		Br
Kr																		0.35		2.29	Kr

Table A. Abundances of the Naturally-Occurring Isotopes (atom percent) (continued)

A▶	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	◀A
(Se)		8.73																			(Se)
(Br)	49.31																				(Br)
(Kr)		11.59	11.50	56.99		17.28															(Kr)
Rb					72.17		27.83														Rb
Sr				0.56		9.86	7.00	82.58													Sr
Y									100.												Y
Zr										51.45	11.22	17.15		17.38		2.80					Zr
Nb													100.								Nb
Mo												14.77		9.23	15.90	16.68	9.56	24.19		9.67	Mo
Tc																					Tc
Ru																5.54		1.87	12.76	12.60	Ru
A▶	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	◀A
(Ru)	17.06	31.55		18.62																	(Ru)
Rh			100.																		Rh
Pd		1.02		11.14	22.33	27.33		26.46		11.72											Pd
Ag							51.84		48.16												Ag
Cd						1.25		0.89		12.49	12.80	24.13	12.22	28.73		7.49					Cd
In													4.29		95.71						In
Sn												0.97		0.66	0.34	14.54	7.68	24.22	8.59	32.58	Sn
Sb																					Sb
Te																				0.09	Te
A▶	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	◀A
(Sn)		4.63		5.79																	(Sn)
(Sb)	57.21		42.79																		(Sb)
(Te)		2.55	0.89	4.74	7.07	18.84		31.74		34.08											(Te)
I							100.														I
Xe				0.10		0.09		1.91	26.40	4.07	21.23	26.90		10.44		8.86					Xe
Cs													100.								Cs
Ba										0.11		0.10		2.42	6.59	7.85	11.23	71.70			Ba
La																		0.09	99.91		La
Ce																0.19		0.25		88.45	Ce
A▶	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	◀A
(Ce)		11.11																			(Ce)
Pr	100.																				Pr
Nd		27.2	12.2	23.8	8.3	17.2		5.7		5.6											Nd
Pm																					Pm
Sm				3.07			14.99	11.24	13.82	7.38		26.75		22.75							Sm
Eu											47.81		52.19								Eu
Gd												0.20		2.18	14.80	20.47	15.65	24.84		21.86	Gd
Tb																			100.		Tb
Dy																0.05		0.09		2.33	Dy
A▶	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	◀A
(Dy)	18.89	25.48	24.90	28.26																	(Dy)
Ho					100.																Ho
Er		0.14		1.60		33.50	22.87	26.98		14.91											Er
Tm									100.												Tm
Yb								0.13		3.04	14.28	21.83	16.13	31.83		12.76					Yb
Lu															97.41	2.59					Lu
Hf														0.16		5.26	18.60	27.28	13.62	35.08	Hf
Ta																				0.01	Ta
W																				0.12	W
A▶	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	◀A
(Ta)	99.99																				(Ta)
(W)		26.50	14.31	30.64		28.43															(W)
Re					37.40		62.60														Re
Os				0.02		1.59	1.96	13.24	16.15	26.26		40.78									Os
Ir											37.3		62.7								Ir
Pt										0.02		0.78		32.97	33.83	25.24		7.16			Pt
Au																	100.				Au
Hg																0.15		9.97	16.87	23.10	Hg
A▶	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	◀A
(Hg)	13.18	29.86		6.87																	(Hg)
Tl			29.52		70.48																Tl
Pb				1.4		24.1	22.1	52.4													Pb
Bi									100.												Bi
A▶	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	◀A
Th												100.									Th
Pa											100.										Pa
U														0.01	0.72			99.27			U

Table B. Isotopic Masses and Abundances (atom percent) of the Naturally-Occurring Isotopes

symbol	mass	abundance
H-1	1.007 825 032 07	99.9885
H-2	2.014 101 777 85	0.0115
He-3	3.016 029 319 14	0.000 134
He-4	4.002 603 254 15	99.999 866
Li-6	6.015 122 794	7.59
Li-7	7.016 004 548	92.41
Be-9	9.012 182 201	100.
B-10	10.012 936 992	19.9
B-11	11.009 305 406	80.1
C-12	12.000 0000	98.93
C-13	13.003 354 837 78	1.07
N-14	14.003 074 004 78	99.636
N-15	15.000 108 898 23	0.364
O-16	15.994 914 619 56	99.757
O-17	16.999 131 703	0.038
O-18	17.999 161 001	0.205
F-19	18.998 403 224	100.
Ne-20	19.992 440 175 42	90.48
Ne-21	20.993 846 684	0.27
Ne-22	21.991 385 113	9.25
Na-23	22.989 769 280 87	100.
Mg-24	23.985 041 699	78.99
Mg-25	24.985 836 917	10.00
Mg-26	25.982 592 929	11.01
Al-27	26.981 538 627	100.
Si-28	27.976 926 532 46	92.223
Si-29	28.976 494 700	4.685
Si-30	29.973 770 171	3.092
P-31	30.973 761 629	100.
S-32	31.972 070 999	94.99
S-33	32.971 458 759	0.75
S-34	33.967 866 902	4.25
S-36	35.967 080 760	0.01
Cl-35	34.968 852 682	75.76
Cl-37	36.965 902 591	24.24
Ar-36	35.967 545 105	0.3365
Ar-38	37.962 732 394	0.0632
Ar-40	39.962 383 122 51	99.6003
K-39	38.963 706 679	93.2581
K-40	39.963 998 475	0.0117
K-41	40.961 825 762	6.7302
Ca-40	39.962 590 983	96.941
Ca-42	41.958 618 014	0.647
Ca-43	42.958 766 628	0.135
Ca-44	43.955 481 754	2.086
Ca-46	45.953 692 587	0.004
Ca-48	47.952 534 177	0.187
Sc-45	44.955 911 909	100.
Ti-46	45.952 631 555	8.25
Ti-47	46.951 763 088	7.44
Ti-48	47.947 946 281	73.72
Ti-49	48.947 869 982	5.41
Ti-50	49.944 791 194	5.18
V-50	49.947 158 485	0.250
V-51	50.943 959 507	99.750
Cr-50	49.946 044 205	4.345
Cr-52	51.940 507 472	83.789
Cr-53	52.940 649 386	9.501
Cr-54	53.938 880 395	2.365
Mn-55	54.938 045 141	100.
Fe-54	53.939 610 501	5.845
Fe-56	55.934 937 475	91.754
Fe-57	56.935 393 969	2.119
Fe-58	57.933 275 558	0.282
Co-59	58.933 195 048	100.
Ni-58	57.935 342 907	68.0769
Ni-60	59.930 786 372	26.2231
Ni-61	60.931 056 033	1.1399
Ni-62	61.928 345 115	3.6345
Ni-64	63.927 965 959	0.9256
Cu-63	62.929 597 474	69.15
Cu-65	64.927 789 485	30.85
Zn-64	63.929 142 222	48.268
Zn-66	65.926 033 419	27.975
Zn-67	66.927 127 345	4.102
Zn-68	67.924 844 154	19.024
Zn-70	69.925 319 274	0.631
Ga-69	68.925 573 587	60.108
Ga-71	70.924 701 349	39.892
Ge-70	69.924 247 381	20.38
Ge-72	71.922 075 815	27.31
Ge-73	72.923 458 945	7.76
Ge-74	73.921 177 767	36.72
Ge-76	75.921 402 557	7.83
As-75	74.921 596 478	100.
Se-74	73.922 476 436	0.89
Se-76	75.919 213 597	9.37
Se-77	76.919 914 038	7.63
Se-78	77.917 309 090	23.77
Se-80	79.916 521 271	49.61
Se-82	81.916 699 401	8.73
Br-79	78.918 337 087	50.69
Br-81	80.916 290 563	49.31
Kr-78	77.920 364 783	0.355
Kr-80	79.916 378 965	2.286
Kr-82	81.913 483 600	11.593
Kr-83	82.914 136 099	11.500
Kr-84	83.911 506 687	56.987
Kr-86	85.910 610 729	17.279
Rb-85	84.911 789 737	72.17
Rb-87	86.909 180 526	27.83
Sr-84	83.913 425 275	0.56
Sr-86	85.909 260 204	9.86
Sr-87	86.908 877 124	7.00
Sr-88	87.905 612 124	82.58
Y-89	88.905 848 295	100.
Zr-90	89.904 704 416	51.45
Zr-91	90.905 645 767	11.22
Zr-92	91.905 040 847	17.15
Zr-94	93.906 315 192	17.38
Zr-96	95.908 273 386	2.80
Nb-93	92.906 378 058	100.
Mo-92	91.906 810 991	14.77
Mo-94	93.905 088 269	9.23
Mo-95	94.905 842 129	15.90
Mo-96	95.904 679 477	16.68
Mo-97	96.906 021 465	9.56
Mo-98	97.905 408 169	24.19
Mo-100	99.907 477 336	9.67
Ru-96	95.907 597 835	5.54
Ru-98	97.905 287 132	1.87
Ru-99	98.905 939 302	12.76
Ru-100	99.904 219 476	12.60
Ru-101	100.905 582 087	17.06
Ru-102	101.904 349 312	31.55
Ru-104	103.905 432 701	18.62
Rh-103	102.905 504 292	100.
Pd-102	101.905 608 544	1.02
Pd-104	103.904 035 834	11.14
Pd-105	104.905 084 920	22.33
Pd-106	105.903 485 715	27.33
Pd-108	107.903 891 701	26.46
Pd-110	109.905 153 254	11.72
Ag-107	106.905 096 820	51.839
Ag-109	108.904 752 292	48.161
Cd-106	105.906 459 410	1.25
Cd-108	107.904 183 683	0.89
Cd-110	109.903 002 070	12.49
Cd-111	110.904 178 107	12.80
Cd-112	111.902 757 809	24.13
Cd-113	112.904 401 662	12.22
Cd-114	113.903 358 540	28.73
Cd-116	115.904 755 809	7.49
In-113	112.904 057 761	4.29
In-115	114.903 878 484	95.71
Sn-112	111.904 818 207	0.97
Sn-114	113.902 778 869	0.66
Sn-115	114.903 342 397	0.34
Sn-116	115.901 740 530	14.54
Sn-117	116.902 951 656	7.68
Sn-118	117.901 603 167	24.22
Sn-119	118.903 307 630	8.59
Sn-120	119.902 194 676	32.58
Sn-122	121.903 439 046	4.63
Sn-124	123.905 273 946	5.79
Sb-121	120.903 815 686	57.21
Sb-123	122.904 213 970	42.79
Te-120	119.904 020 222	0.09
Te-122	121.903 043 898	2.55
Te-123	122.904 270 029	0.89
Te-124	123.902 817 896	4.74
Te-125	124.904 430 731	7.07
Te-126	125.903 311 696	18.84
Te-128	127.904 463 056	31.74
Te-130	129.906 224 399	34.08
I-127	126.904 472 681	100.
Xe-124	123.905 893 003	0.0952
Xe-126	125.904 273 634	0.0890
Xe-128	127.903 531 275	1.9102
Xe-129	128.904 779 435	26.4006
Xe-130	129.903 508 007	4.0710
Xe-131	130.905 082 362	21.2324
Xe-132	131.904 153 457	26.9086
Xe-134	133.905 394 464	10.4357
Xe-136	135.907 218 794	8.8573
Cs-133	132.905 451 932	100.
Ba-130	129.906 320 811	0.106
Ba-132	131.905 061 288	0.101
Ba-134	133.904 508 383	2.417
Ba-135	134.905 688 591	6.592
Ba-136	135.904 575 945	7.854
Ba-137	136.905 827 384	11.232
Ba-138	137.905 247 237	71.698
La-138	137.907 111 930	0.090
La-139	138.906 353 267	99.910
Ce-136	135.907 172 422	0.185
Ce-138	137.905 991 321	0.251
Ce-140	139.905 438 706	88.450
Ce-142	141.909 244 205	11.114
Pr-141	140.907 652 769	100.
Nd-142	141.907 723 297	27.2
Nd-143	142.909 814 290	12.2
Nd-144	143.910 087 274	23.8
Nd-145	144.912 573 636	8.3
Nd-146	145.913 116 939	17.2
Nd-148	147.916 893 288	5.7
Nd-150	149.920 890 888	5.6
Sm-144	143.911 999 478	3.07
Sm-147	146.914 897 923	14.99
Sm-148	147.914 822 674	11.24
Sm-149	148.917 184 735	13.82
Sm-150	149.917 275 539	7.38
Sm-152	151.919 732 425	26.75
Sm-154	153.922 209 273	22.75
Eu-151	150.919 850 161	47.81
Eu-153	152.921 230 339	52.19
Gd-152	151.919 790 996	0.20
Gd-154	153.920 865 598	2.18
Gd-155	154.922 622 022	14.80
Gd-156	155.922 122 743	20.47
Gd-157	156.923 960 135	15.65
Gd-158	157.924 103 912	24.84
Gd-160	159.927 054 146	21.86
Tb-159	158.925 346 757	100.
Dy-156	155.924 283 110	0.056
Dy-158	157.924 409 487	0.095
Dy-160	159.925 197 517	2.329
Dy-161	160.926 933 364	18.889
Dy-162	161.926 798 447	25.475
Dy-163	162.928 731 159	24.896
Dy-164	163.929 174 751	28.260
Ho-165	164.930 322 070	100.
Er-162	161.928 778 264	0.139
Er-164	163.929 200 229	1.601
Er-166	165.930 293 061	33.503
Er-167	166.932 048 159	22.869
Er-168	167.932 370 224	26.978
Er-170	169.935 464 312	14.910
Tm-169	168.934 213 250	100.
Yb-168	167.933 896 895	0.13
Yb-170	169.934 761 837	3.04
Yb-171	170.936 325 799	14.28
Yb-172	171.936 381 469	21.83
Yb-173	172.938 210 787	16.13
Yb-174	173.938 862 089	31.83
Yb-176	175.942 571 683	12.76
Lu-175	174.940 771 819	97.41
Lu-176	175.942 686 310	2.59
Hf-174	173.940 046 178	0.16
Hf-176	175.941 408 631	5.26
Hf-177	176.943 220 651	18.60
Hf-178	177.943 698 766	27.28
Hf-179	178.945 816 145	13.62
Hf-180	179.946 549 953	35.08
Ta-180	179.947 464 831	0.012
Ta-181	180.947 995 763	99.988
W-180	179.946 704 459	0.12
W-182	181.948 204 156	26.50
W-183	182.950 222 951	14.31
W-184	183.950 931 188	30.64
W-186	185.954 364 127	28.43
Re-185	184.952 954 982	37.40
Re-187	186.955 753 109	62.60
Os-184	183.952 489 071	0.02
Os-186	185.953 838 158	1.59
Os-187	186.955 750 458	1.96
Os-188	187.955 838 228	13.24
Os-189	188.958 147 470	16.15
Os-190	189.958 447 048	26.26
Os-192	191.961 480 690	40.78
Ir-191	190.960 594 046	37.3
Ir-193	192.962 926 430	62.7
Pt-190	189.959 931 655	0.014
Pt-192	191.961 038 005	0.782
Pt-194	193.962 680 253	32.967
Pt-195	194.964 791 134	33.832
Pt-196	195.964 951 521	25.242
Pt-198	197.967 892 790	7.163
Au-197	196.966 568 662	100.
Hg-196	195.965 832 649	0.15
Hg-198	197.966 769 032	9.97
Hg-199	198.968 279 932	16.87
Hg-200	199.968 326 004	23.10
Hg-201	200.970 302 268	13.18
Hg-202	201.970 643 011	29.86
Hg-204	203.973 493 933	6.87
Tl-203	202.972 344 220	29.52
Tl-205	204.974 427 541	70.48
Pb-204	203.973 043 589	1.4
Pb-206	205.974 465 278	24.1
Pb-207	206.975 896 887	22.1
Pb-208	207.976 652 071	52.4
Bi-209	208.980 398 734	100.
Th-232	232.038 055 325	100.
Pa-231	231.035 883 990	100.
U-234	234.040 952 088	0.0054
U-235	235.043 929 918	0.7204
U-238	238.050 788 247	99.2742

Alphabetical List of the Elements

Name	Symbol	Z	Naturally Occurring Isotopes*	Atomic Weight (u)**	Name	Symbol	Z	Naturally Occurring Isotopes*	Atomic Weight (u)**
actinium	Ac	89		…	meitnerium	Mt	109		…
aluminum	Al	13	1	26.981 5386(8)	mendelevium	Md	101		…
americium	Am	95		…	mercury	Hg	80	7	200.59(2)
antimony	Sb	51	2	121.760(1)	molybdenum	Mo	42	7	95.94(2)
argon	Ar	18	3	39.948(1)	neodymium	Nd	60	7	144.242(3)
arsenic	As	33	1	74.921 60(2)	neon	Ne	10	3	20.1797(6)
astatine	At	85		…	neptunium	Np	93		…
barium	Ba	56	7	137.327(7)	nickel	Ni	28	5	58.6934(2)
berkelium	Bk	97		…	niobium	Nb	41	1	92.906 38(2)
beryllium	Be	4	1	9.012 182(3)	nitrogen	N	7	2	14.0067(2)
bismuth	Bi	83	1	208.980 40(1)	nobelium	No	102		…
bohrium	Bh	107		…	osmium	Os	76	7	190.23(3)
boron	B	5	2	10.811(7)	oxygen	O	8	3	15.9994(3)
bromine	Br	35	2	79.904(1)	palladium	Pd	46	6	106.42(1)
cadmium	Cd	48	8	112.411(8)	phosphorus	P	15	1	30.973 762(2)
calcium	Ca	20	6	40.078(4)	platinum	Pt	78	6	195.084(9)
californium	Cf	98		…	plutonium	Pu	94		…
carbon	C	6	2	12.0107(8)	polonium	Po	84		…
cerium	Ce	58	4	140.116(1)	potassium	K	19	3	39.0983(1)
cesium	Cs	55	1	132.905 4519(2)	praseodymium	Pr	59	1	140.907 65(2)
chlorine	Cl	17	2	35.453(2)	promethium	Pm	61		…
chromium	Cr	24	4	51.9961(6)	protactinium	Pa	91	1	231.035 88(2)
cobalt	Co	27	1	58.933 195(5)	radium	Ra	88		…
copernicium	Cn	112		…	radon	Rn	86		…
copper	Cu	29	2	63.546(3)	rhenium	Re	75	2	186.207(1)
curium	Cm	96		…	rhodium	Rh	45	1	102.905 50(2)
darmstadtium	Ds	110		…	roentgenium	Rg	111		…
dubnium	Db	105		…	rubidium	Rb	37	2	85.4678(3)
dysprosium	Dy	66	7	162.500(1)	ruthenium	Ru	44	7	101.07(2)
einsteinium	Es	99		…	rutherfordium	Rf	104		…
erbium	Er	68	6	167.259(3)	samarium	Sm	62	7	150.36(2)
europium	Eu	63	2	151.964(1)	scandium	Sc	21	1	44.955 912(6)
fermium	Fm	100		…	seaborgium	Sg	106		…
fluorine	F	9	1	18.998 4032(5)	selenium	Se	34	6	78.96(3)
francium	Fr	87		…	silicon	Si	14	3	28.0855(3)
gadolinium	Gd	64	7	157.25(3)	silver	Ag	47	2	107.8682(2)
gallium	Ga	31	2	69.723(1)	sodium	Na	11	1	22.989 769 28(2)
germanium	Ge	32	5	72.64(1)	strontium	Sr	38	4	87.62(1)
gold	Au	79	1	196.966 569(4)	sulfur	S	16	4	32.065(5)
hafnium	Hf	72	6	178.49(2)	tantalum	Ta	73	2	180.947 88(2)
hassium	Hs	108		…	technetium	Tc	43		…
helium	He	2	2	4.002 602(2)	tellurium	Te	52	8	127.60(3)
holmium	Ho	67	1	164.930 32(2)	terbium	Tb	65	1	158.925 35(2)
hydrogen	H	1	2	1.007 94(7)	thallium	Tl	81	2	204.3833(2)
indium	In	49	2	114.818(3)	thorium	Th	90	1	232.038 06(2)
iodine	I	53	1	126.904 47(3)	thulium	Tm	69	1	168.934 21(2)
iridium	Ir	77	2	192.217(3)	tin	Sn	50	10	118.710(7)
iron	Fe	26	4	55.845(2)	titanium	Ti	22	5	47.867(1)
krypton	Kr	36	6	83.798(2)	tungsten	W	74	5	183.84(1)
lanthanum	La	57	2	138.905 47(7)	uranium	U	92	3	238.028 91(3)
lawrencium	Lr	103		…	vanadium	V	23	2	50.9415(1)
lead	Pb	82	4	207.2(1)	xenon	Xe	54	9	131.293(6)
lithium	Li	3	2	6.941(2)	ytterbium	Yb	70	7	173.04(3)
lutetium	Lu	71	2	174.967(1)	yttrium	Y	39	1	88.905 85(2)
magnesium	Mg	12	3	24.3050(6)	zinc	Zn	30	5	65.409(4)
manganese	Mn	25	1	54.938 045(5)	zirconium	Zr	40	5	91.224(2)

* The number of naturally-occurring isotopes.

** The numbers in parentheses following the atomic weights are the uncertainties in the atomic weights.

Fundamental General Physics Constants

This set of fundamental constants is excerpted from a self-consistent set prepared by P.J. Mohr, B.N. Taylor, and D.B. Newell published in Rev. Mod. Phys. **80** 633 (2008). The values can also be found on the Internet at http://physics.nist.gov/cuu/Constants/index.html.

The values given in parentheses after the stated value of the constants are the one sigma uncertainties in the last digit(s) given. The first value of each constant given is in SI units. Following values are in non-SI units. Where no value is given in parentheses for the error, it may be assumed that the value is exact, except where trailing "..." are indicated.

Acceleration due to gravity (standard)
g = 9.806 65 E+00 meters per second squared
= 3.217 405 ... E+01 feet per second squared

Alpha particle rest mass
m_α = 6.644 656 20(33) E−27 kilogram
= 4.001 506 179 127(62) E+00 u

Alpha particle rest mass equivalent energy
$m_\alpha c^2$ = 3.727 379 109(93) E+03 MeV

Atomic mass unit = $(10^{-3}$ kg mol$^{-1})/N_A$
u = 1.660 538 782(83) E−27 kilogram

Atomic mass unit-electron volt relationship
1 uc^2 = 9.314 940 28 (23) E+02 MeV

Avogadro constant
N_A = 6.022 141 79(30) E+23 "entities" (molecules, atoms, etc.) per mole

Bohr magneton = $e\hbar/2m_e$
μ_B = 9.274 009 15(23) E−24 joule per tesla

Boltzmann constant = R/N_A
k = 1.380 6504(24) E−23 joule per kelvin
= 8.617 343(15) E−05 electron volt per kelvin

Characteristic impedance of vacuum = $(\mu_0/\varepsilon_0)^{1/2}$
Z_0 = 3.767 303 134 61 ... E+02 ohms

Classical electron radius = $\alpha^2\alpha_0$
r_e = 2.817 940 2894(58) E−15 meter

Deuteron rest mass
m_d = 3.343 583 20(17) E−27 kilogram
= 2.013 553 212 724(78) E+00 u

Deuteron rest mass equivalent energy
$m_d c^2$ = 1.875 612 793(47) E+03 MeV

Electric constant = $1/\mu_0 c^2$
ε_0 = 8.854 187 817 ... E−12 coulomb squared per joule per meter
= 8.854 187 817 ... E−12 farad per meter

Electron charge to mass ratio
$-e/m_e$ = −1.758 820 150(44) E+11 coulombs per kilogram

Electron rest mass
m_e = 9.109 382 15(45) E−31 kilogram
= 5.485 799 0943(23) E−04 u

Electron rest mass equivalent energy
$m_e c^2$ = 5.109 989 10(13) E−01 MeV

Elementary charge
e = 1.602 176 487(40) E−19 coulomb

Faraday constant
F = 9.648 533 99(24) E+04 coulombs per mole

Fine-structure constant (dimensionless)
α = 7.297 352 5376(50) E−03

First Bohr radius = $\alpha/4\pi R_\infty$
α_0 = 5.291 772 0859(36) E−11 meter

Gravitational constant
G = 6.674 28(67) E−11 newton meter squared per kilogram squared
= 6.674 28(67) E−08 centimeter cubed per gram per second squared, or dyne centimeter squared per gram squared

Molar gas constant
R = 8.314 472(15) E+00 joules per mole per kelvin

Magnetic constant
μ_0 = (4π) E−07 henry per meter
= (4π) E−07 newton per ampere squared
= 1.256 637 061 4 ...E−06 henry per meter

Neutron rest mass
m_n = 1.674 927 211(84) E−27 kilogram
= 1.008 664 915 97(43) E+00 u

Neutron rest mass equivalent energy
$m_n c^2$ = 9.395 653 46(23) E+02 MeV

Nuclear magneton = $e\hbar/2m_p$
μ_N = 5.050 783 24(13) E−27 joule per tesla

Planck constant
h = 6.626 068 96(33) E−34 joule second or joule per Hertz
= 4.135 667 33(10) E−21 MeV second

Proton mass to electron mass ratio
m_p/m_e = 1.836 152 672 47(80) E+03

Proton rest mass
m_p = 1.672 621 637(83) E−27 kilogram
= 1.007 276 466 77(10) E+00 u

Proton rest mass equivalent energy
$m_p c^2$ = 9.382 720 13(23) E+02 MeV

Rydberg constant
R_∞ = 1.097 373 156 8527(73) E+07 per meter

Speed of light
c = 2.997 924 58 E+08 meters per second
= 2.997 924 58 E+10 centimeters per second

Stefan-Boltzmann constant
σ = 5.670 400(40) E−08 watt per meter squared per kelvin to fourth power

Periodic Table of the Elements
Knolls Atomic Power Laboratory

Symbol ↓

	6,5,4	← Oxidation States—most common in red
Atomic Number →	92 U 1.7	← Electronegativity (Pauling scale)
	238.02891	← Atomic Mass
	uranium	← Name
Melting Point (°C) →	1135 138.5	← Atomic Radius (pm)
Boiling Point (°C) →	4131 13.612	← K or L α X-ray energy (keV)
Specific Gravity–(density g/l for gases at 0°C) →	18.95 17.217	← K or L β X-ray energy (keV)
Thermal Conductivity [W/(m K)] →	27.6 2.7	← crustal abundance (ppm by mass)

Note: Color of Symbol and Name indicates gas, liquid, **solid** (at 20°C) or **artificially prepared**;
"d" on C (Z=6) represents "diamond" and "w" on P (Z=15) represents "white phosphorus"

Group

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1,−1 1 H 2.20 1.00794 hydrogen −259.34 78 −252.87 0.08988 0.1815 1400																	2 He – 4.002602 helium <−272.2 128 −268.93 0.1785 0.152 0.008
1 3 Li 0.98 6.941 lithium 180.5 152 1342 0.534 84.7 20	2 4 Be 1.57 9.012182 beryllium 1287 113.3 2471 1.848 200 2.8											3 5 B 2.04 10.811 boron 2075 83 4000 2.35 27.0 10	2,4,−4 6 C 2.55 12.0107 carbon 3550 d 77 3800 subl 0.277 1.8–3.5 5–2300 200	−3, 5 7 N 3.04 14.0067 nitrogen −210.0 71 −195.79 0.392 1.2506 0.02598 19	−2 8 O 3.44 15.9994 oxygen −218.79 66 −182.95 0.525 1.429 0.2674 461000	−1 9 F 3.98 18.9984032 fluorine −219.67 70.9 −188.12 0.677 1.696 0.0279 585	10 Ne – 20.1797 neon −248.59 −246.08 0.848 0.89990 0.0493 0.005
1 11 Na 0.93 22.98976928 sodium 97.80 153.7 883 1.041 0.971 1.071 141 23600	2 12 Mg 1.31 24.3050 magnesium 650 160 1090 1.253 1.738 1.302 156 23300											3 13 Al 1.61 26.9815386 aluminum 660.32 143.1 2519 1.486 2.6989 1.557 237 82300	2,4,−4 14 Si 1.90 28.0855 silicon 1414 117 3265 1.739 2.33 1.836 148 282000	5,3,−3 15 P 2.19 30.973762 phosphorus 44.15 w 93 280.5 w 2.013 1.82 w 2.137 0.235 w 1050	6,4,2,−2 16 S 2.58 32.065 sulfur 115.21 104 444.60 2.307 2.07 2.465 0.269 350	7,5,1,−1 17 Cl 3.16 35.453 chlorine −101.5 99 −34.4 2.621 3.214 2.815 0.0089 145	18 Ar – 39.948 argon −189.35 174 −185.85 2.957 1.784 3.190 0.0177 3.5
1 19 K 0.82 39.0983 potassium 63.38 227 759 3.312 0.862 3.589 102.4 20900	2 20 Ca 1.00 40.078 calcium 842 197.3 1484 3.690 1.55 4.012 200 41500	3 21 Sc 1.36 44.955912 scandium 1541 160.6 2836 4.088 2.989 4.460 15.8 22	4,3,2 22 Ti 1.54 47.867 titanium 1668 144.8 3287 4.508 4.54 4.931 21.9 5650	5,4,3,2 23 V 1.63 50.9415 vanadium 1910 132.1 3407 4.949 6.11 5.426 30.7 120	6,3,2 24 Cr 1.66 51.9961 chromium 1907 124.9 2671 5.411 7.19 5.946 93.7 102	7,4,3,2 25 Mn 1.55 54.938045 manganese 1246 124 2061 5.894 7.3 6.489 7.82 950	3,2 26 Fe 1.83 55.845 iron 1538 124.1 2861 6.398 7.874 7.057 80.2 56300	3,2 27 Co 1.88 58.933195 cobalt 1495 125.3 2927 6.924 8.9 7.648 100 25	3,2 28 Ni 1.91 58.6934 nickel 1455 124.6 2913 7.471 8.902 8.263 90.7 84	2,1 29 Cu 1.90 63.546 copper 1084.6 127.8 2562 8.040 8.96 8.904 401 60	2 30 Zn 1.65 65.409 zinc 419.5 133.2 907 8.630 7.133 9.570 116 70	3 31 Ga 1.81 69.723 gallium 29.76 122.1 2204 9.241 5.904 10.262 40.6 19	4,2 32 Ge 2.01 72.64 germanium 938.25 122.5 2833 9.874 5.323 10.979 59.9 1.5	5,3,−3 33 As 2.18 74.92160 arsenic ~817 125 603 subl 10.530 5.7 11.722 50.0 1.8	6,4,−2 34 Se 2.55 78.96 selenium 220.5 117 685 11.207 4.7 12.492 0.5–4.5 0.05	5,1,−1 35 Br 2.96 79.904 bromine −7.2 115 58.8 11.907 3.12 13.286 0.122 2.4	36 Kr – 83.798 krypton −157.38 189 −153.22 12.631 3.733 14.107 0.00949 trace
1 37 Rb 0.82 85.4678 rubidium 39.3 247.5 688 13.373 1.532 14.956 58.2 90	2 38 Sr 0.95 87.62 strontium 777 215.1 1382 14.140 2.54 15.830 35.3 370	3 39 Y 1.22 88.90585 yttrium 1522 181 3345 14.931 4.469 16.734 17.2 33	4 40 Zr 1.33 91.224 zirconium 1855 160 4409 15.744 6.506 17.663 22.7 165	5,3 41 Nb 1.6 92.90638 niobium 2477 142.9 4744 16.581 8.57 18.700 53.7 20	6 42 Mo 2.16 95.94 molybdenum 2623 136.2 4639 17.441 10.22 19.599 138 1.2	7,6,4 43 Tc 2.10 technetium 2157 135.8 4265 18.325 11.50 20.608 50.6 0	3 44 Ru 2.2 101.07 ruthenium 2334 134 4150 19.233 12.41 21.646 117 0.001	3 45 Rh 2.28 102.90550 rhodium 1964 134.5 3695 20.165 12.41 22.712 150 0.001	3,2 46 Pd 2.20 106.42 palladium 1554.9 138 2963 21.121 12.02 23.807 71.8 0.015	1 47 Ag 1.93 107.8682 silver 961.78 144 2162 22.101 10.50 24.921 429 0.075	2 48 Cd 1.69 112.411 cadmium 321.07 148.9 767 23.106 8.65 26.091 96.8 0.15	3 49 In 1.78 114.818 indium 156.6 162.6 2072 24.136 7.31 27.271 81.6 0.25	4,2 50 Sn 1.96 118.710 tin 231.93 140.5 2602 25.191 5.7–7.3 28.481 66.5 2.3	5,3,−3 51 Sb 2.05 121.760 antimony 630.63 142 1587 26.271 6.691 29.721 24.3 0.2	6,4,−2 52 Te 2.1 127.60 tellurium 449.5 143.2 988 27.377 6.24 30.990 2.3 0.001	5,7,−1 53 I 2.66 126.90447 iodine 113.7 133.3 184.4 28.508 4.93 32.289 0.449 0.45	54 Xe 2.60 131.293 xenon −111.79 218 −108.12 29.666 5.887 33.619 0.00569 trace
1 55 Cs 0.79 132.9054519 cesium 28.5 265.4 671 30.851 1.873 34.981 35.9 3	2 56 Ba 0.89 137.327 barium 727 217.3 1897 32.062 3.5 36.372 18.4 425	3 57 La* 1.10 138.90547 lanthanum 918 187.7 3464 33.299 6.145 37.795 13.5 39	4 72 Hf 1.3 178.49 hafnium 2233 156.4 4603 7.898 13.31 9.021 23.0 3	5 73 Ta 1.5 180.94788 tantalum 3017 143 5458 8.145 16.654 9.342 57.5 2	6 74 W 1.7 183.84 tungsten 3422 137.0 5555 8.396 19.3 9.671 174 1.25	7,6,4 75 Re 1.9 186.207 rhenium 3186 137.0 5596 8.651 21.02 10.008 47.9 0.0007	3,4 76 Os 2.2 190.23 osmium 3033 135 5012 8.910 22.57 10.354 87.6 0.0015	3,4 77 Ir 2.2 192.217 iridium 2446 135.7 4428 9.174 22.42 10.706 147 0.001	2,4 78 Pt 2.2 195.084 platinum 1768.4 138 3825 9.441 21.45 11.069 71.6 0.005	3,1 79 Au 2.4 196.966569 gold 1064.18 144 2856 9.712 ~19.3 11.440 317 0.004	2,1 80 Hg 1.9 200.59 mercury −38.83 160 356.73 9.987 13.546 11.821 8.34 0.085	3,1 81 Tl 1.8 204.3833 thallium 304 170.4 1473 10.267 11.85 12.211 46.1 0.85	4,2 82 Pb 1.8 207.2 lead 327.46 175.0 1749 10.550 11.35 12.612 35.3 14	5,3 83 Bi 1.9 208.98040 bismuth 271.4 155 1564 10.837 9.747 13.021 7.87 0.0085	6,4,2 84 Po 2.0 polonium 254 167 962 11.129 9.32 13.445 20 –	7,5,3,1,−1 85 At 2.2 astatine 302 – ~340 11.425 – 13.874 1.7 –	86 Rn – radon −71 – −61.7 11.725 9.73 14.313 0.00364 trace
1 87 Fr 0.7 francium 27 270 677 12.029 – 14.768 ~15 –	2 88 Ra 0.9 radium 700 223 1140 12.338 5 15.233 18.6 –	3 89 Ac* 1.1 actinium 1051 187.8 3198 12.650 10.07 15.710 12 –	4 104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113	114	115	116		118

*Lanthanoids	4,3 58 Ce 1.12 140.116 cerium 798 182.5 3424 34.566 6.770 39.251 11.3 66.5	3 59 Pr 1.13 140.90765 praseodymium 931 182.8 3520 35.860 6.773 40.741 12.5 9.2	3 60 Nd 1.14 144.242 neodymium 1021 182.1 3074 37.182 7.008 42.264 16.5 41.5	3,2 61 Pm – promethium 1042 181.0 3000 38.532 7.264 43.818 ~17.9 –	3,2 62 Sm 1.17 150.36 samarium 1074 180.2 1794 39.911 7.520 45.405 13.3 7.05	3,2 63 Eu – 151.964 europium 822 204.2 1596 5.845 5.244 6.455 13.9 2	3 64 Gd 1.20 157.25 gadolinium 1313 180.2 3273 6.056 7.901 6.712 10.6 6.2	3 65 Tb – 158.92535 terbium 1356 178.2 3230 6.272 8.230 6.977 11.1 1.2	3 66 Dy 1.22 162.500 dysprosium 1413 177.3 2567 6.494 8.551 7.246 10.7 5.2	3 67 Ho 1.23 164.93032 holmium 1474 176.6 2700 6.719 8.795 7.524 16.2 1.3	3 68 Er 1.24 167.259 erbium 1529 175.7 2868 6.947 9.066 7.809 14.3 3.5	3,2 69 Tm 1.25 168.93421 thulium 1545 174.6 1950 7.179 9.321 8.100 16.8 0.52	3,2 70 Yb – 173.04 ytterbium 819 194 1196 7.414 6.903 8.400 35 3.2	3 71 Lu 1.0 174.967 lutetium 1663 173.4 3402 7.654 9.841 8.708 16.4 0.8
*Actinoids	4 90 Th 1.3 232.03806 thorium 1750 179.8 4788 12.967 11.72 16.199 54.0 9.6	5,4 91 Pa 1.5 231.03588 protactinium 1572 160.6 ~4000 13.288 15.37 16.699 ~47 trace	6,5,4 92 U 1.7 238.02891 uranium 1135 138.5 4131 13.612 18.95 17.217 27.6 2.7	6,5,4,3 93 Np 1.3 neptunium 644 131 3900 20.25 6.3 –	6,5,4,3 94 Pu 1.3 plutonium 640 151 3228 19.84 6.74 –	6,5,4,3 95 Am americium 1176 184 2011 13.67 ~10 –	3 96 Cm curium 1345 170 3100 13.5 ~10 –	4,3 97 Bk berkelium 105 – ~14 ~10	3 98 Cf californium 900 ~186 – – ~10	3,2 99 Es einsteinium 860 ~186 – – ~10	3,2 100 Fm fermium 1527 – – ~10	3,2 101 Md mendelevium 827 – – ~10	3,2 102 No nobelium 827 – – ~10	3 103 Lr lawrencium 1627 – – ~10

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