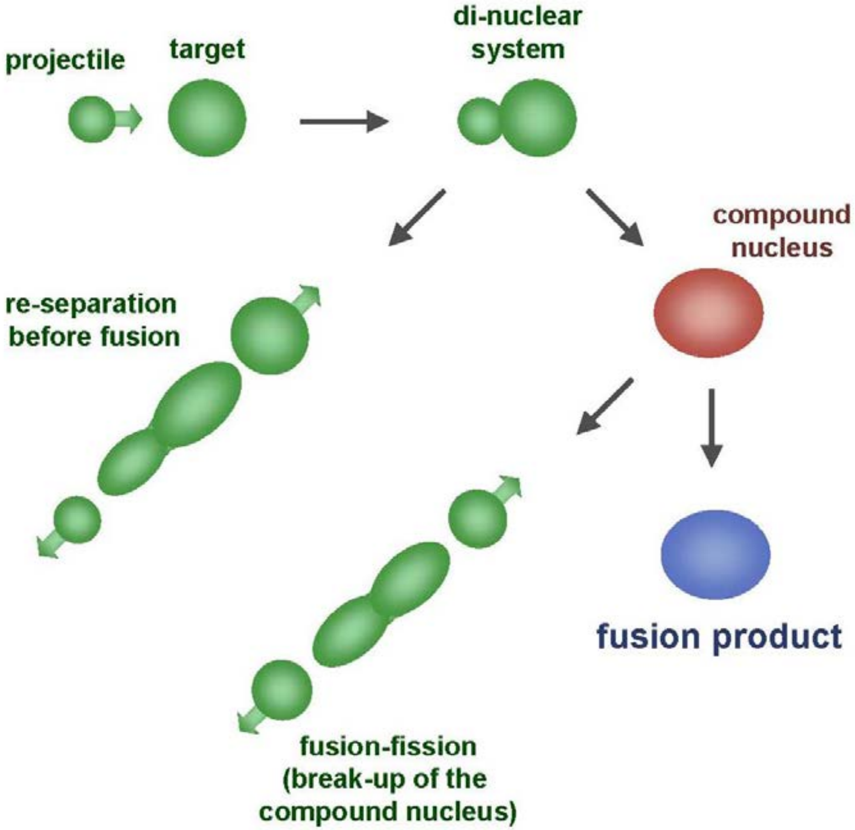
RDCH 702: Lecture 3, Nuclear Reactions

- Readings: Modern Nuclear Chemistry, Chapter 10; Nuclear and Radiochemistry, Chapter 4

- Notation
- Energetics of Nuclear Reactions
- Reaction Types and Mechanisms
    - Barriers
    - Scattering
- Nuclear Reaction Cross Sections
- Reaction Observables
- Scattering
- Direct Reactions
- Compound Nuclear Reactions
- Photonuclear Reactions
- Nucleosynthesis



Nuclear Reactions

- Nucleus reactions with a range of particles
  - Nucleus, subatomic particle, or photon to produce other nuclei
  - Short time frame (picosecond)
  - Energetics involved in reaction
- First nuclear reaction from Rutherford
  - What reaction was this?
- Number of terms conserved during nuclear reactions
  - Basis for understanding and evaluating reactions
    - → Number of nucleons
      - * except in reactions involving creation or annihilation of antinucleons
    - → Charge
    - → Energy/Mass
    - → Momentum
    - → Angular momentum
    - → Parity
- Q is the energy of the reaction
  - positive Q corresponds to energy release
  - negative Q to energy absorption
- Q terms given per nucleus transformed

$${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + Q$$

Shorthand: ${}^{14}N(\alpha, p){}^{17}O$

Energetics

- Energetically many orders of magnitude greater than chemical reactions
- $^{14}\text{N}(\alpha,p)^{17}\text{O}$; Q=-1.193 MeV
  - Convert energy to per molar basis
    - →1 eV = 1.60E-19 J
    - →=-7.18E23 MeV/mole= -7.18E29 eV/mole
    - →=-1.15E11 J/mole
- Reactions so large that mass change is observable
- Q value can be experimentally measured to provide a route to determine particle mass of reactants
  - Mass and energy balance
    - →Know Q value, determine unknown mass

Energetics

- Reaction Q values
  - Not necessarily equal to kinetic energy of bombarding particles for the reaction to occur
    - → Need more energy than Q value for reaction to occur
      - * Reaction products will have kinetic energy that needs to come from reaction
- Conservation of momentum
  - Some particles' kinetic energy must be retained by products as kinetic energy
- Amount retained as kinetic energy of products
  - Based on projectile mass
  - Retained kinetic energy becomes smaller with increasing target mass
    - →Equation for kinetic energy (T):

$$T = \frac{A_{Projectile}}{A_{Projectile} + A_{Target}} Q$$

- What does this mean about reaction
  - Heavier target or heavier projectile?
    - →^{248}Cm + ^{18}O→^{266}Rf

$$T = \frac{248}{248+18} Q = 0.932Q$$

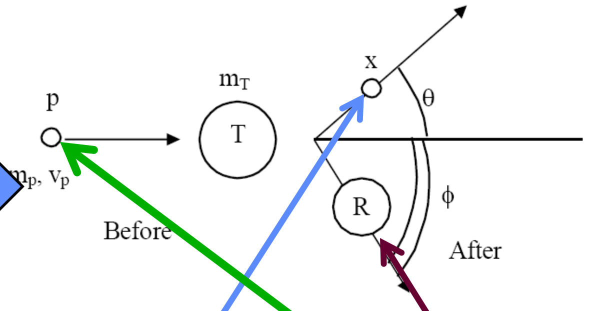
^{248}Cm Projectile

$$T = \frac{18}{248+18} Q = 0.068Q$$

^{18}O Projectile

Energetics: Reaction Barrier

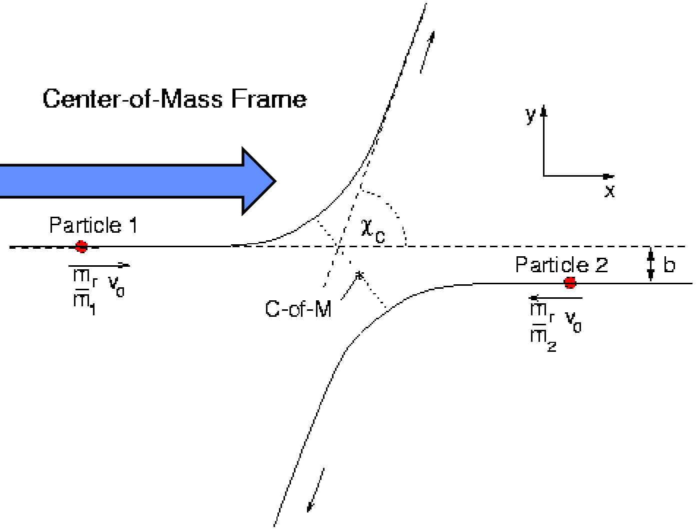
- **Need to consider laboratory and center of mass frame**
- **Laboratory frame**
  - **conservation of momentum considers angle of particles**



$$Q = T_x\left(1+\frac{m_x}{m_R}\right) - T_p\left(1+\frac{m_p}{m_R}\right) - \frac{2}{m_R}\sqrt{(m_p T_p m_x T_x)}\cos\theta$$

$$Q = T_x - T_p - T_R$$

- **Q value can be found if T_x and θ are measured and particles known**
  - **T_p from experiment**
- **Center of mass**
  - **Total particle angular momentum is zero**



$$T_{cm} = \frac{(m_p + m_T)v_{cm}^2}{2} \qquad v_{cm} = \frac{v_p m_p}{(m_p + m_T)}$$

- **Kinetic energy carried by projectile (T_{lab}) is not fully available for reaction**
  - **$T_{lab} - T_{cm} = T_0$**
  - **T_0 is energy to be dissipated in reaction**
- **For reaction to occur Q + T_0 must be achieved**
  - **Basis for threshold reaction**
  - **$Q + T_0 \geq 0$**

$$T_{cm} = T_{lab}\left(\frac{m_p}{m_p + m_T}\right)$$

Reaction Barrier

- **Threshold energy (minimum energy for reaction)**

$$Q + T_{lab} - T_{CM} \geq 0; \quad T_{cm} = T_{lab}\left(\frac{m_p}{m_p + m_T}\right)$$

Solve of laboratory T

$$T_{lab} - T_{lab}\left(\frac{m_p}{m_p + m_T}\right) \geq -Q$$

$$T_{lab}\left(1 - \left(\frac{m_p}{m_p + m_T}\right)\right) \geq -Q$$

$$T_{lab} \geq \frac{-Q}{\left(1 - \left(\frac{m_p}{m_p + m_T}\right)\right)} = \frac{-Q}{\left(\frac{m_p + m_T}{m_p + m_T} - \left(\frac{m_p}{m_p + m_T}\right)\right)} = \frac{-Q}{\frac{m_T}{m_p + m_T}}$$

A for mass

$$T \geq -Q\frac{A_{Projectile} + A_{Target}}{A_{Target}}\, MeV$$

- **Fraction of bombarding particle’s kinetic energy retained as kinetic energy of products becomes smaller with increasing mass of target**
  - **Heavier target or heavier projectile?**
  - **$^{248}Cm + {}^{18}O \rightarrow {}^{266}Rf$**

Reaction Barrier: Threshold Energy

- Consider the $^{14}N(\alpha,p)^{17}O$ reaction
  - Find threshold energy
    - → Q from mass excess
      - * Q=2.42[illegible] + 2.863 – 7.289 – (-0.809) = -1.19 MeV

$$T \geq -Q\frac{A_{Projectile}+A_{Target}}{A_{Target}}MeV$$

$$T \geq -(-)\text{[illegible]}19\frac{4+14}{14}MeV = 1.53MeV$$

- Reaction barrier also induced by Coulomb interaction
  - Need to have enough energy to react and overcome Coulomb barrier
    - → From charge repulse as particle approach each other
      - * R is radius
      - * r_o =1.1 to 1.6 fm

$$V_c = \frac{Z_1Z_2e^2}{R_1+R_2} \qquad R = r_oA^{1/3}$$

- Equation can vary due to r_o
- V_c can be above threshold energy

$$V_c = 0.96\frac{Z_1Z_2}{A_1^{1/3}+A_2^{1/3}}MeV$$

$$V_c = 0.96\frac{2*7}{4^{1/3}+14^{1/3}}MeV = 3.36MeV$$

- Center of mass, need to bring to laboratory frame
  - Consider kinetic energy carried by projectile
  - 3.36x ((14+4)/14) = 4.32 MeV alpha needed for reaction

Equations for production reactions: Cross Sections

- Probability of a nuclear process is generally expressed in terms of a cross section σ
  - dimensions of an area
- Originates from probability for reaction between nucleus and impinging particle is proportional to the cross-sectional target area presented by the nucleus
  - Doesn't hold for charged particles that have to overcome Coulomb barriers or for slow neutrons
- Total cross section for collision with fast particle is never greater than twice the geometrical cross-sectional area of the nucleus
  - cross section σ is close to 1 barn for this case
- 10^{-24} cm^2=1 barn

Cross sections

- **Accelerator: beam of particles striking a thin target with minimum beam attenuation**

$$R_i = I n x \sigma_i$$

- **When a sample is embedded in a uniform flux of particles incident on it from all direction, such as in a nuclear reactor, the cross section is defined:**

$$R_i = \phi N \sigma_i$$

  - **R_i= # of processes of type under consideration occurring in the target per unit time**
  - **I= # of incident particles per unit time**
  - **n= # of nuclei/cm^3**
  - **x=target thickness (cm)**
  - **ϕ=flux of particles/cm^2/sec**
  - **N=number of nuclei contained in sample**

Production of radionuclides

- σ=cross section
- ϕ=neutron flux
- t=time of irradiation

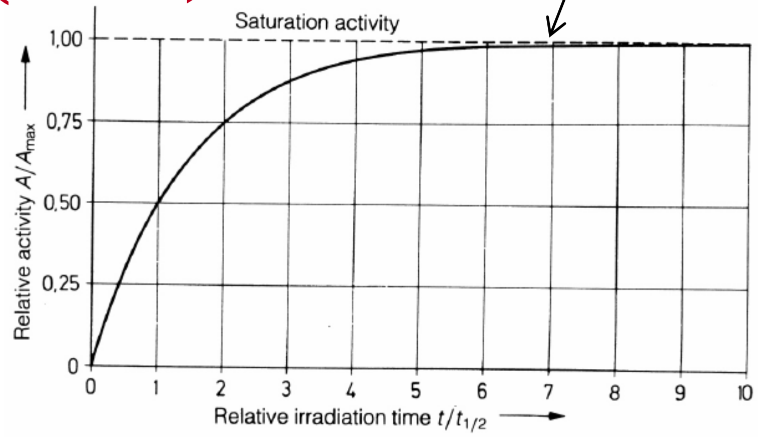
$$N_1 = \frac{N_0 \sigma \phi}{\lambda_1}(1-e^{-\lambda_1 t})$$

$$N_1\lambda_1 = A_1 = N_0 \sigma \phi (1-e^{-\lambda_1 t})$$

→$(1-e^{-(\lambda t)})$

* maximum level (saturation factor)

- Activity of radioactive product at end bombardment is divided by saturation factor, formation rate is obtained
  - $R=A/(1-e^{-(\lambda t)})$



half life	%
1	50
2	75
3	87.5
4	93.75
5	96.875

Nuclei production: Short irradiation compared to half-life

- **Find amount of ^{59}Fe ($t_{1/2}$=44.5 d, λ = 1.803E-7 s^{-1}) from irradiation of 1 g of Fe in a neutron flux of 1E13 n/cm^2/s for 1 hour**
  - **^{58}Fe(n,γ)^{59}Fe: ^{58}Fe+ n →γ + ^{59}Fe σ=1.3E-24 cm^2**
  - **N_o= 1g/55.845 g/mol *6.02E23 atom/mol*0.00282**
  - **N_o=3.04E19 atom**
- **R= 1E13 n/cm^2/s *1.3E-24 cm^2 * 3.04E21 atom**
- **R=3.952E8 atoms/sec**
- **1.423E12 atoms ^{59}Fe in 1 hour**

$$R_i = \phi N \sigma_i$$

$$N_1 = \frac{3.04\text{E}19(1.3\text{E}-24)(1E13)}{1.803\text{E}-7}(1-e^{-1.803\text{E-}7*3600})$$

$$N_1 = \frac{3.952E8}{1.803\text{E}-7}(1-9.994E-1)$$

$$N_1 = 2.192E15(6.489E-4) = 1.422E12\,atoms$$

$$N_1 = \frac{N_0 \sigma \phi}{\lambda_1}(1-e^{-\lambda_1 t})$$

Nuclei production: Long irradiation compared to half-life

- **Find amount of ^{56}Mn ($t_{1/2}$=2.578 hr, λ = 7.469E-5 s^{-1}) from irradiation of 1 g of Mn in a neutron flux of 1E13 n/cm^2/s for 1 hour**
  - **^{55}Mn(n,γ)^{56}Mn: ^{55}Mn+ n → γ + ^{56}Mn σ=13.3E-24 cm^2**
  - **N_o= 1g/54.93804 g/mol *6.02E23 atom/mol**
  - **N_o=1.096E22 atom**
- **R= 1E13 n/cm^2/s *13.3E-24 cm^2 * 1.096E22 atom**

$$R_i = \phi N \sigma_i$$

- **R=1.457E12 atoms/sec**
- **5.247E15 atoms ^{56}Mn in 1 hour (does not account for decay)**

$$N_1 = \frac{1.096\mathrm{e}22(13.3\mathrm{E}-24)(1E13)}{7.469\mathrm{E}-5}(1-e^{-7.469\mathrm{E}\text{-}5*3600}) \quad N_1 = \frac{N_0 \sigma \phi}{\lambda_1}(1-e^{-\lambda_1 t})$$

$$N_1 = \frac{1.458E12}{7.469\mathrm{E}-5}(1-7.642E-1)$$

$$N_1 = 1.952E16(2.358E-1) = 4.603E15\,atoms$$

Formation rate from activity

- $R=A/(1-e^{-(\lambda t)})$
- 4.603E15 atoms ^{56}Mn ($t_{1/2}$=2.578 hr, λ = 7.469E-5 s^{-1}) from 1 hour irradiation
- $A=\lambda N$= 4.603E15* 7.469E-5 =3.436E11 Bq
- $R=A/(1-e^{-(\lambda t)})$
- R= 3.436E11/(1-exp(- 7.469E-5 *3600))
- R=1.457E12 atom/sec

Cross Section Values and Limits

- Reaction cross section of πR^2 is approximated at high energies
  - Wave nature of incident particle causes upper limit of reaction cross section to include de Broglie wavelength
    - →So cross section can be larger than area due to incoming particle wavelength
    - →Expressed as an increase in R, quantum in nature

$$\sigma_r = \pi(R + \bar{\lambda})^2$$

- Collision between neutron and target nucleus characterized by distance of closest approach
  - B is impact parameter

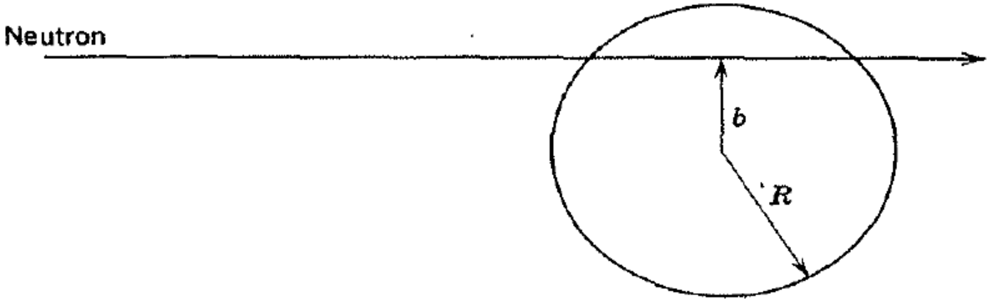
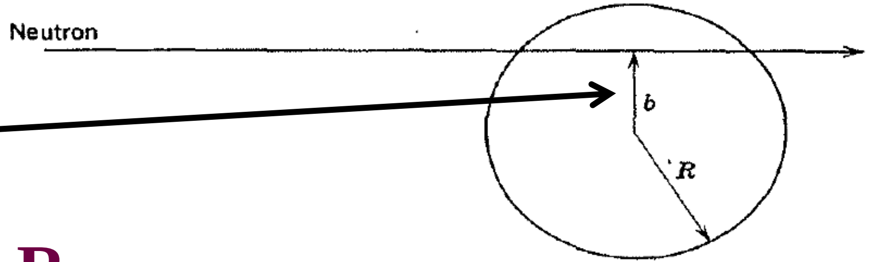


Fig. 4-1 Collision with impact parameter *b* between a neutron and target nucleus with interaction radius *R*.

Cross sections

- Angular momentum of system is normal to the relative momentum p

$$L = pb = \frac{\hbar b}{\bar{\lambda}} = l\hbar \qquad b = l\bar{\lambda}$$



- b any value between 0 and R

$$l\bar{\lambda} < b < (l+1)\bar{\lambda}$$

- l =0,1,2,…b angular momentum
  - lħ

$$\sigma_r = \pi(R+\bar{\lambda})^2$$

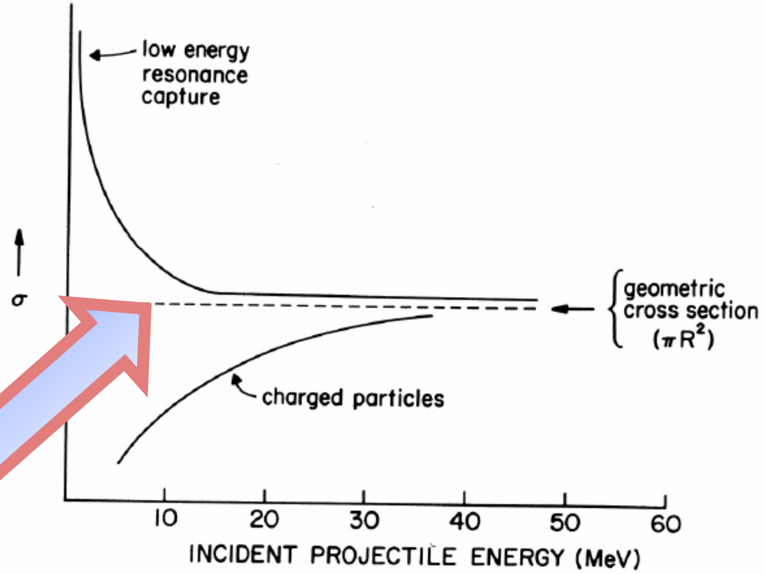
- Sum all l from 0 to l_{max}
- Cross section based on summation of l cross sections
- For this reason nuclear reaction cross sections can be several orders of magnitude larger than the nuclear geometrical cross section
  - Manifest by slow-neutron reactions

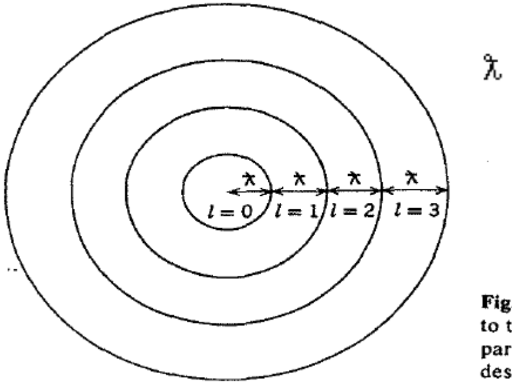
Cross section

$$\sigma_l = \pi\bar{\lambda}^2[(l+1)^2 - l^2] = \pi\bar{\lambda}^2(2l+1)$$

σ_l is partial cross section of given angular momentum l

- Quantum-mechanical treatment T_ℓ is the transmission coefficient for reaction of a neutron with angular momentum ℓ
  - Represents fraction of incident particles with angular momentum ℓ that penetrate within range of nuclear forces
    - → Provides summing term to increase cross section
    - → Reason why cross section can be larger than physical size of nucleus





$$\sigma_r = \pi\bar{\lambda}^2 \sum_{l=0}^{\infty} (2l+1) T_l$$

Fig. 4-2 The incident beam is perpendicular to the plane of the figure. The particles with a particular *l* are considered to strike within the designated ring.

- General trends for neutron and charged particles
  - Charged particle cross section minimal at low energy
  - Neutron capture cross section maximum at low energy

Measuring Cross Section: Excitation Functions

- Variation of reaction cross section with incident energy
- Shape can be determined by exposing several target foils in same beam with energy-degrading
    - Simultaneous measurement of multiple particle energies
- Provide information about probabilities for emission of various kinds and combination of particles in nuclear reactions
    - formation of given product implies what particles were ejected from target nuclide
- Range of cross sections can be evaluated
    - Detection limit of product can influence cross section limit measurement

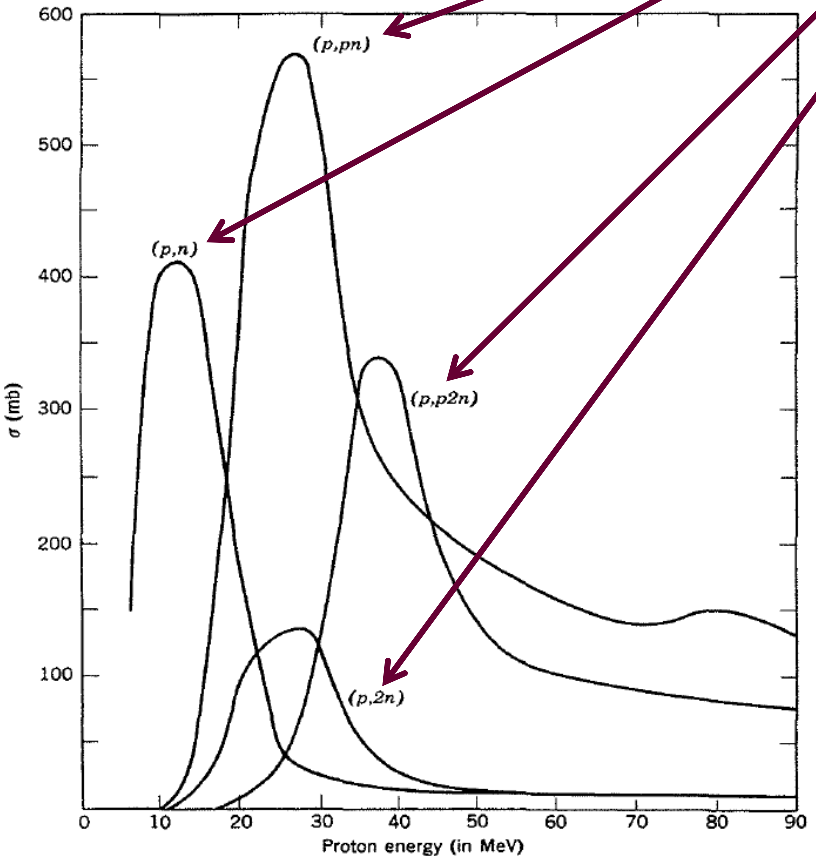


Fig. 4-5 Excitation functions for proton-induced reactions on ^{63}Cu. [From J. W. Meadows, *Phys. Rev.* **91**, 885 (1953).]

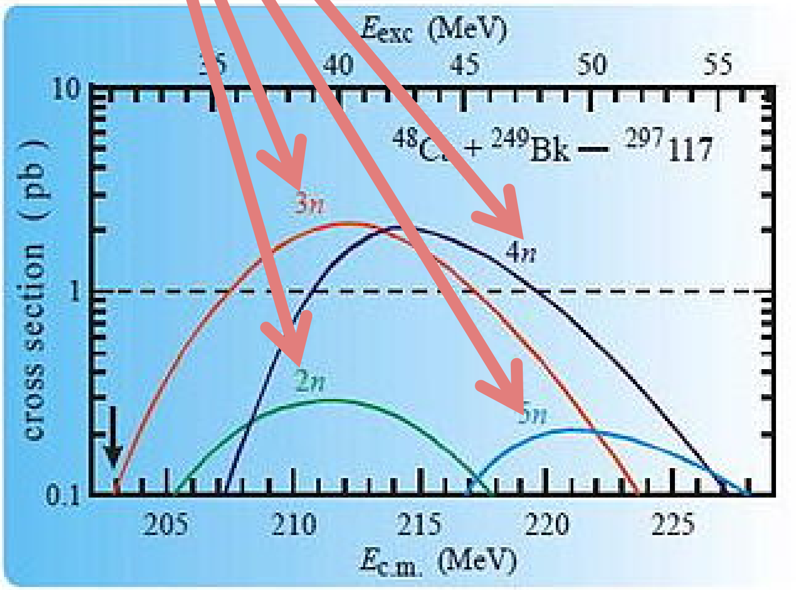
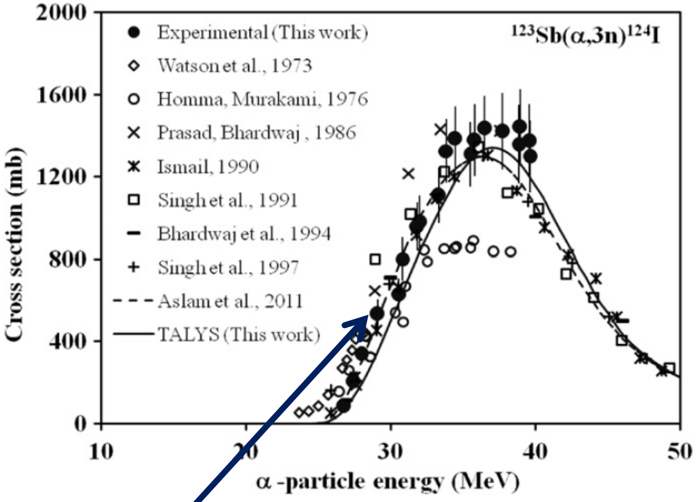
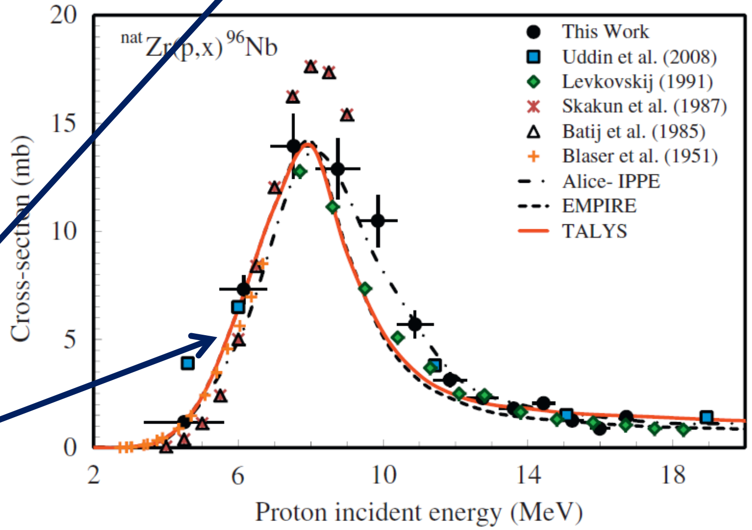


Fig. 2. The ^{249}Bk(^{48}Ca, *xn*) excitation functions calculated in the framework of the model of Zagrebaev.

Barriers for Charged Particles

- Coulomb repulsion between charged bombarding particles and nucleus
    - Repulsion increases with decreasing distance of separation until charged particle comes within range of nuclear forces
    - Probability of tunneling through barrier drops rapidly as energy of particle decreases
    - Coulomb barriers affect charged particles both entering and leaving the nucleus
        - →Charged particles emitted from nuclei experience Coulomb repulsion during emission
        - →greater than 1 MeV
        - →seen with position emission
- Related to change in cross section with energy for charged particle reactions
    - Maximum cross section dependent upon energy





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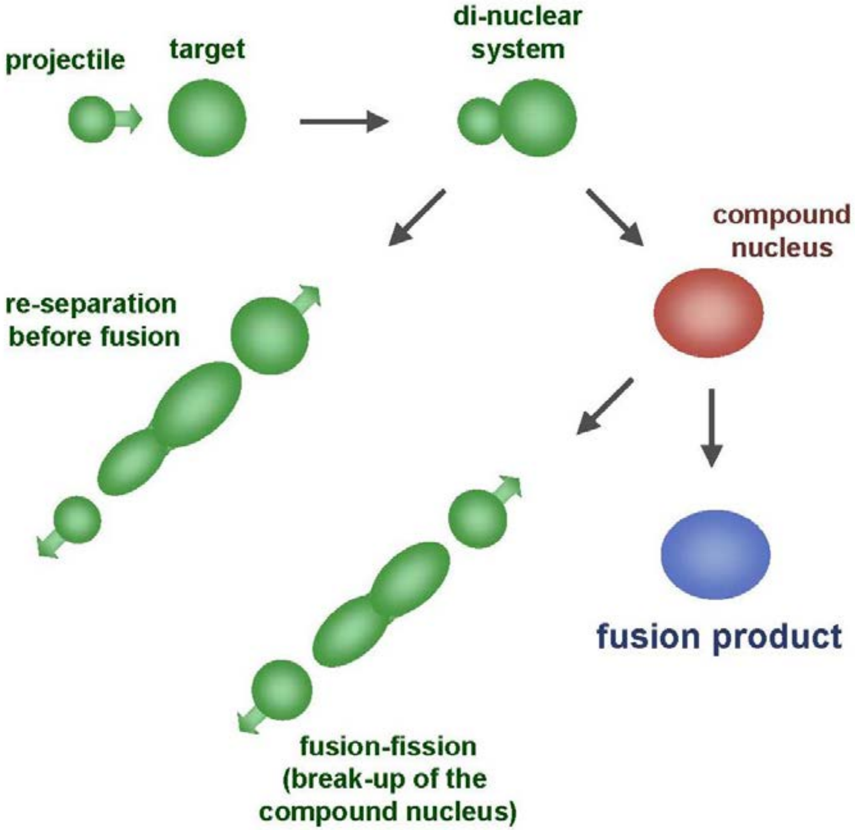


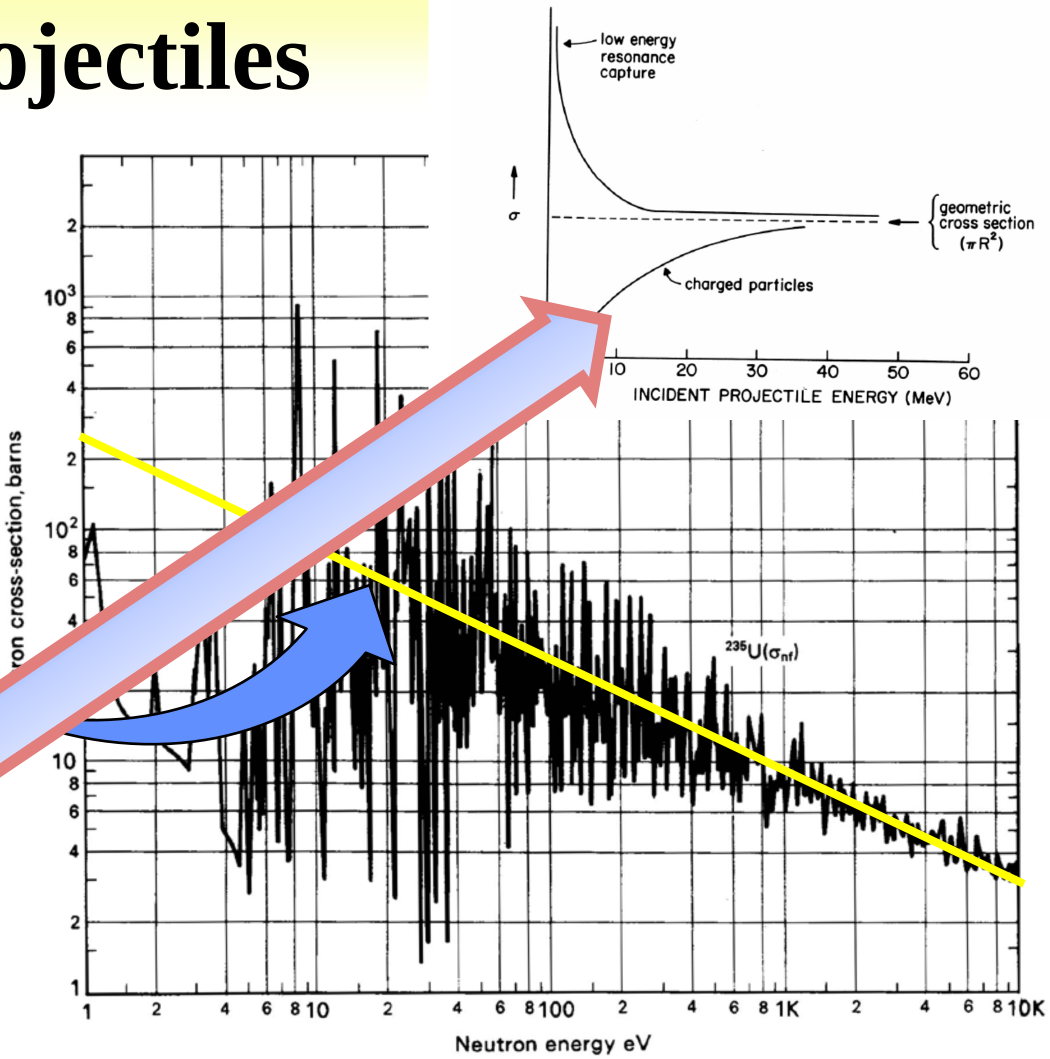
Reactions: Elastic Scattering

- Elastic scattering
  - kinetic energy conserved
  - Particles do not change
- Simplest consequence of a nuclear collision
  - Not a “reaction”

    →no exchange of nucleons or creation of particles
- Particles do not change their identity during the process and the sum of their kinetic energies remains constant
- Elastic scattering will also have a contribution from nuclear forces

Low-Energy Reactions with Light Projectiles

- Slow-Neutron Reactions
  - Purest example of compound-nucleus behavior
    - →1/v law governs most neutron cross sections in region of th mal energies
  - neutrons availabl only from nuclear reac ons
    - →Range of energi can be obtained
- Reaction Cross Sections
  - Coulomb barrier preven study of nuclear reacti with charged particles below 1 MeV
    - →resonances no longer observable
    - →with increasing energy, increasing variety of reactions possible

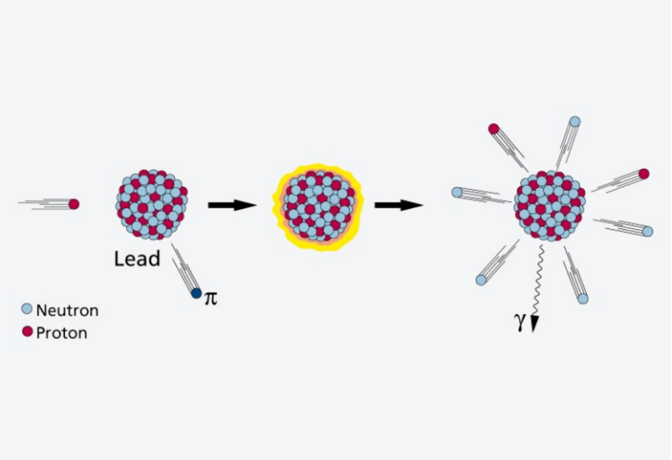


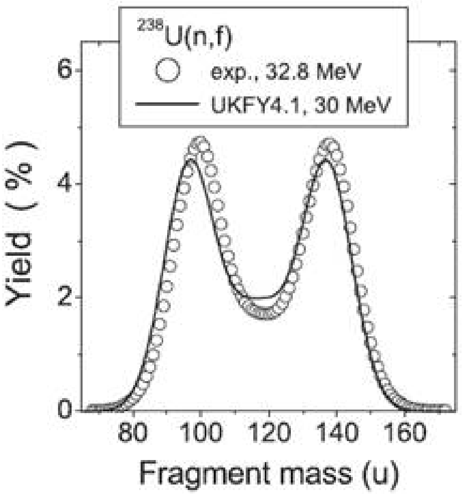
Low-Energy Reactions

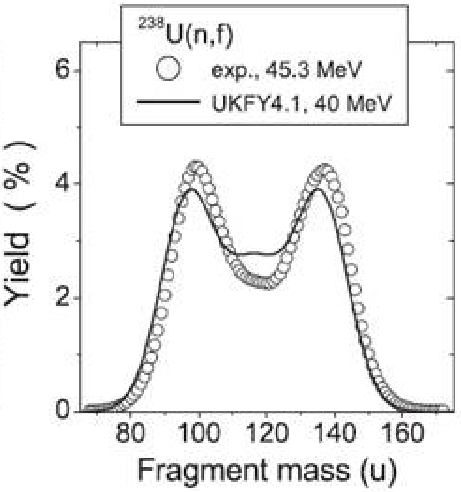
- **Deuteron Reactions**
  - **Prevalence of one nucleon stripping**
    - **→large size and loose binding of deuteron**
    - **→Only proton and neutron in deuteron nucleus**
      - *** Proton charge carries both nucleons**
  - **Neutron comes within range of nuclear forces while proton is still outside most of Coulomb barrier**
    - **→Inherent in large neutron-proton distance in deuteron**
    - **→weakly bound deuteron can be broken up**
      - *** proton outside barrier**
- **Competition among Reactions**
  - **depends on relative probabilities for emission of various particles from compound nucleus**
    - **→determined by number of factors**
      - *** energy available**
      - *** Coulomb barrier**
      - *** density of final states in product nucleus**

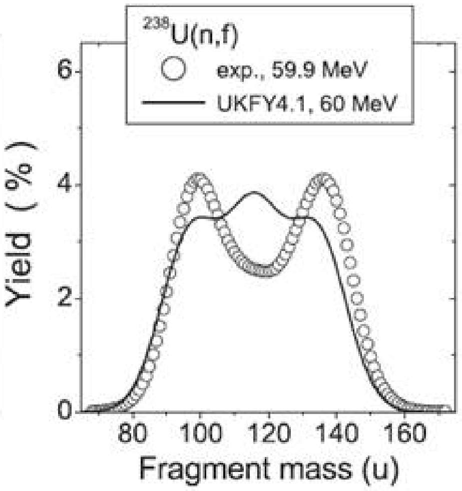
High Energy Reactions

- Spallation Products
  - products in immediate neighborhood of target element found in highest yields
    - → within 10 to 20 mass numbers
  - yields tend to form in two regions
  - β stability for medium-weight products
  - neutron-deficient side of stability with increasing Z of products
  - Used to produce beam of neutrons at spallation neutron source
    - → Heavy Z will produce 20-30 neutrons
    - → Basis of Spallation neutron source (http://neutrons.ornl.gov/facilities/SNS/)
- High-Energy Fission
  - single broad peak in mass-yield curve instead of double hump seen in thermal-neutron fission
  - many neutron-deficient nuclides
    - → especially among heavy products
    - → originate from processes involving higher deposition energies
    - → lower kinetic energies
    - → do not appear to have partners of comparable mass
    - → arise from spallation-like or fragmentation reactions



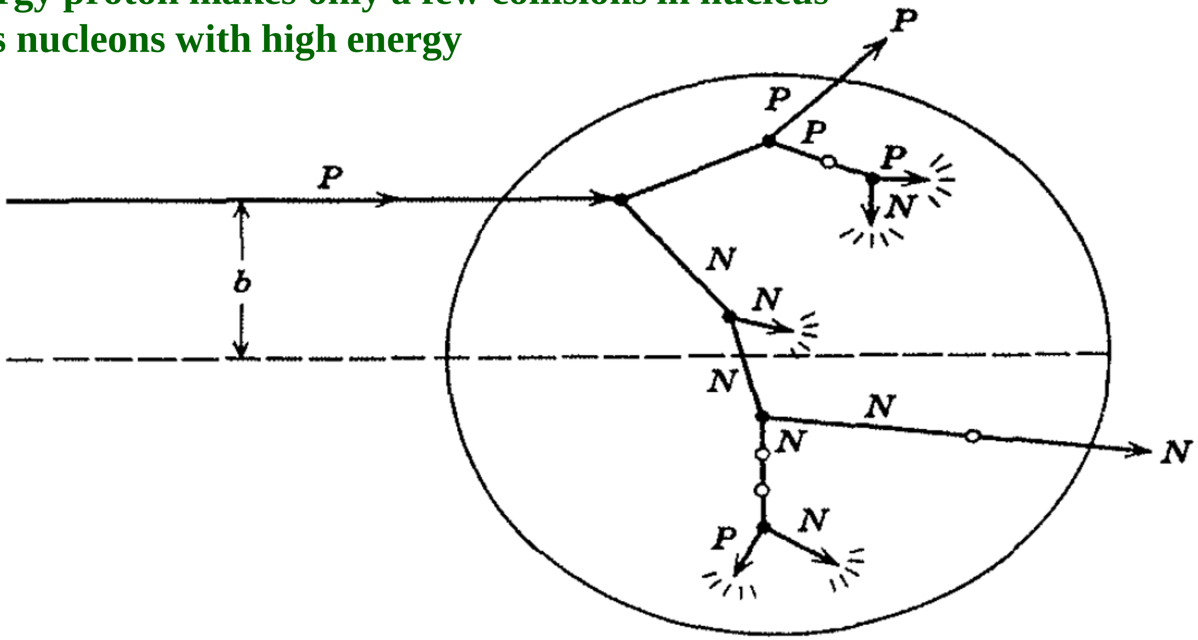






High-Energy Reactions

- **Mass-Yield Curves**
  - at low energies, compound-nucleus picture dominates
    - → as energy increases importance of direct reactions and preequilibrium (pre-compound nucleus) emission increase
    - → above 100 MeV, nuclear reactions proceed nearly completely by direct interactions
  - products down to mass number 150 are spallation products
  - those between mass numbers 60 and 140 are fission products
- **Cascade-Evaporation Model**
  - Above 100 MeV reactions
  - energy of the incident proton larger than interaction energy between the nucleons in the nucleus
  - Wavelength less than average distance between nucleons
    - → proton will collide with one nucleon at a time within the nucleus
      - * high-energy proton makes only a few collisions in nucleus
      - * Produces nucleons with high energy



Heavy-Ion Reactions

- **Range of heavy ion reactions**
  - **elastic and inelastic scattering**
  - **compound-nucleus formation,**
  - **direct interactions**
  - **deeply inelastic reaction**
- **Reactions influence by parameter**
  - **impact parameter of collision**
  - **kinetic energy of projectile**
  - **masses of target**
  - **projectile nuclei**

$$R = r_o\left(A_1^{1/3} + A_2^{1/3}\right)$$

- **Elastic and Inelastic Scattering, Coulomb Excitation**
  - **elastic-scattering measurements used to obtain information on interaction radii**
  - **$R=R_1+R_2$ between mass numbers A_1 and A_2**

Heavy Ion Reactions

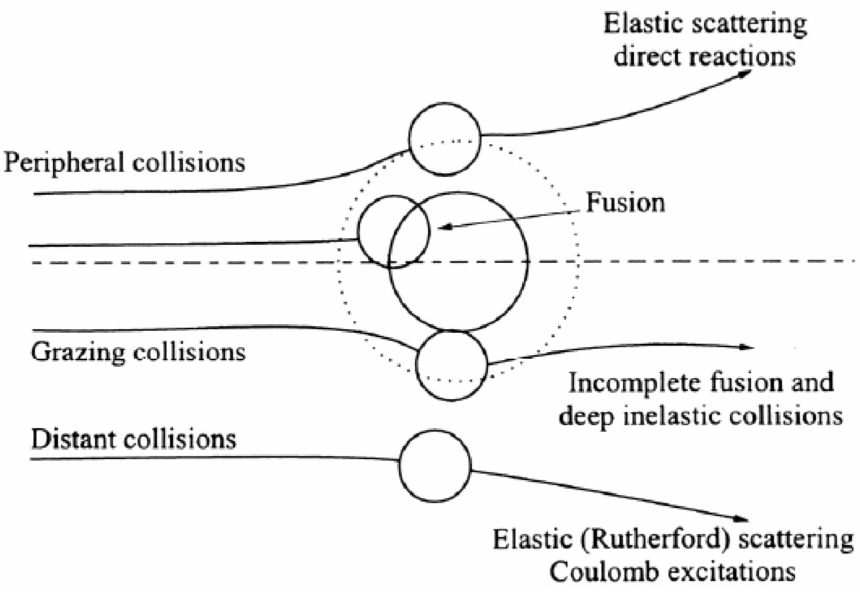
- Inelastic scattering
  - scattering in which some of projectile's kinetic energy transformed into excitation of target nucleus
    - →greatest importance at large impact parameters
  - heavy ions valuable
    - →can excite high-spin states in target nuclei because of large angular momenta
- Can experience Coulomb excitation
  - high charges
  - below Coulomb barrier heights and excite nuclei by purely electromagnetic interactions
- Transfer Reactions
  - stripping and pickup reactions prevalent with heavy ions
    - →take place at impact parameters just below those at which interactions are purely Coulombic
  - angular distributions show oscillatory, diffraction-like pattern when transfer reaction to single, well-defined state observed

Heavy Ion Reactions: Deep Inelastic Reactions

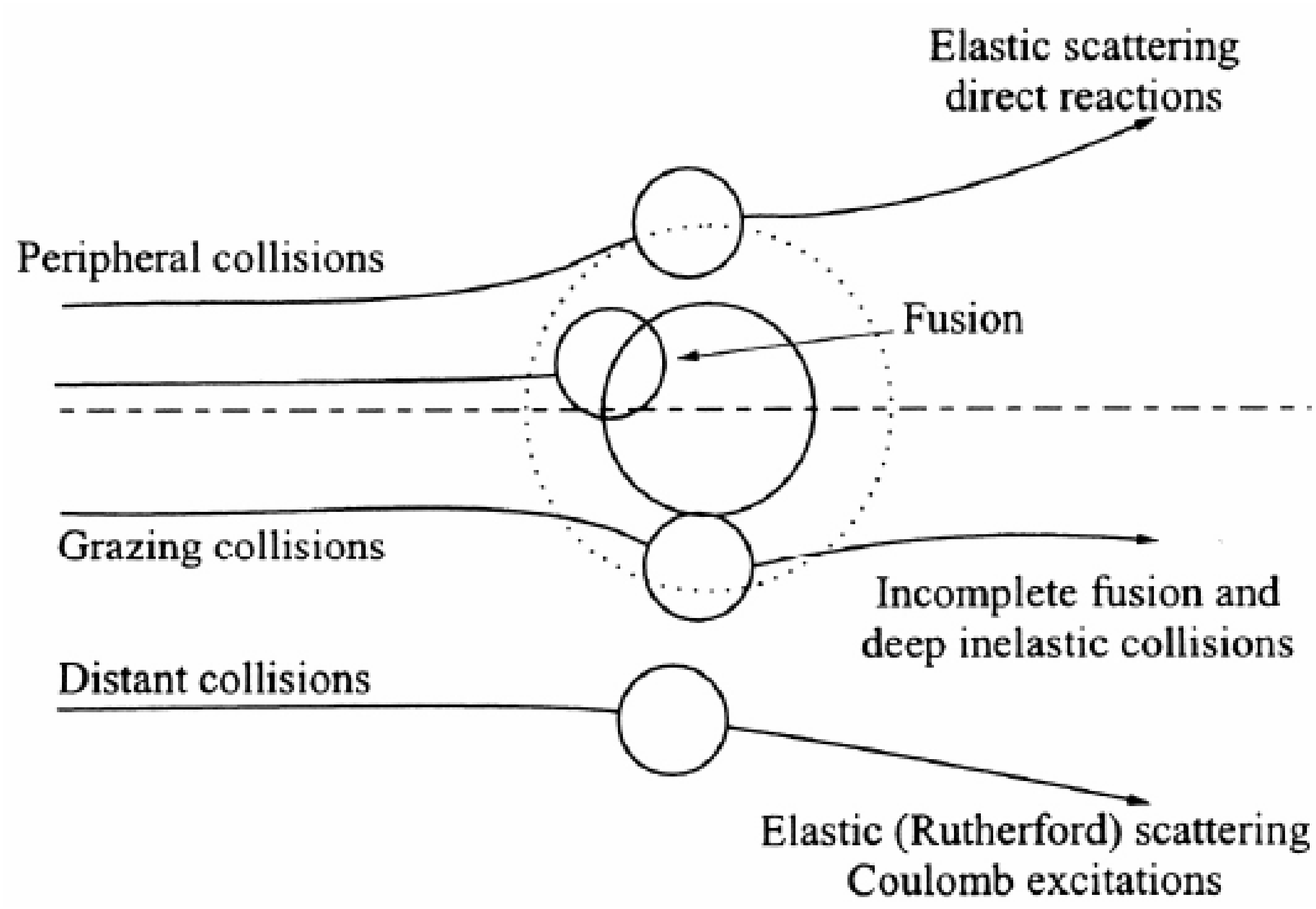
- Relatively large amounts of nuclear matter transferred between target and projectile
  - Show strongly forward-peaked angular distributions
  - "Grazing contact mechanism"
- Products with masses in vicinity of projectile mass appear at angles other than classical grazing angle
  - Relatively small kinetic energies
- Total kinetic energies of products strongly correlated with amount of mass transfer
  - Increasing mass difference of product and projectile lowers kinetic energy
- Product will dissociate into two fragments
  - Appreciable fraction of incident kinetic energy dissipated and goes into internal excitation

Compound-Nucleus Reactions

- Compound-nucleus formation can only take place over a restricted range of small impact parameters
  - can define critical angular momentum above which complete fusion cannot occur
  - σ_{cf}/σ_R decreases with increasing bombarding energy
- Neutron deficient heavy ions produce compound nuclei on neutron-deficient side of β stability belt
- Heavy ion of energy above Coulomb barrier brings enough excitation energy to evaporate several nucleons
  - 5-10 MeV deexcitation for neutron evaporation
- heavy-ion reactions needed for reaching predicted island of stability around Z=114 to N=184
- U is excitation energy, M_A and M_a masses of target and projectile, T_a is projectile kinetic energy, S_a is projectile binding energy in compound nucleus

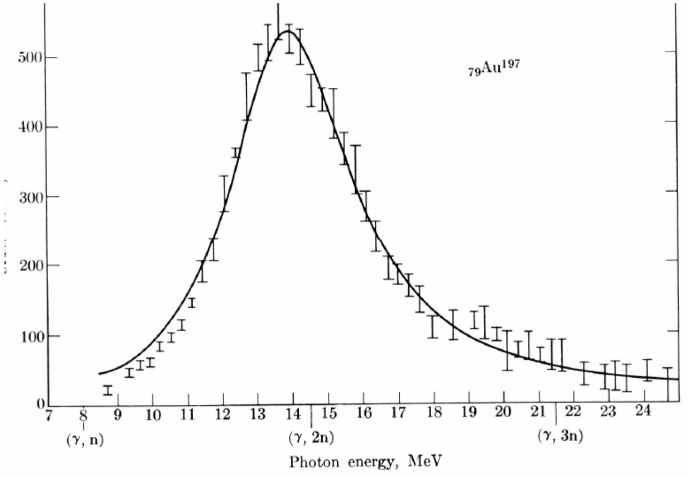


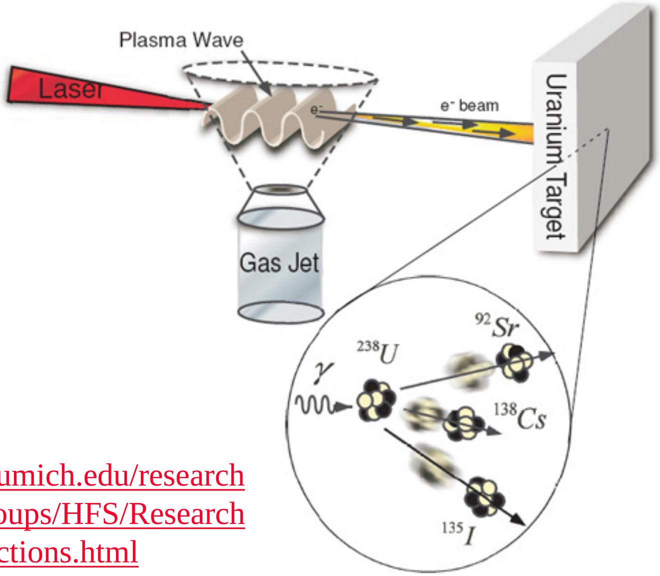
$$U = \frac{M_A}{M_A + M_a} T_a + S_a$$


Elastic scattering
direct reactions
Peripheral collisions
Fusion
Grazing collisions
Incomplete fusion and
deep inelastic collisions
Distant collisions
Elastic (Rutherford) scattering
Coulomb excitations

Photonuclear reactions

- Reactions between nuclei and low- and medium-energy photons dominated by giant resonance
  - Excitation function for photon absorption goes through a broad maximum a few MeV wide
    - → Due to excitation of dipole vibrations of protons against neutrons in the nucleus
- Resonance peak varies smoothly with A
  - 24 MeV at ^{16}O
  - 13 MeV at ^{209}Bi
- Peak cross sections are 100-300 mb
- (γ, p), (γ, n), (γ,α) reactions

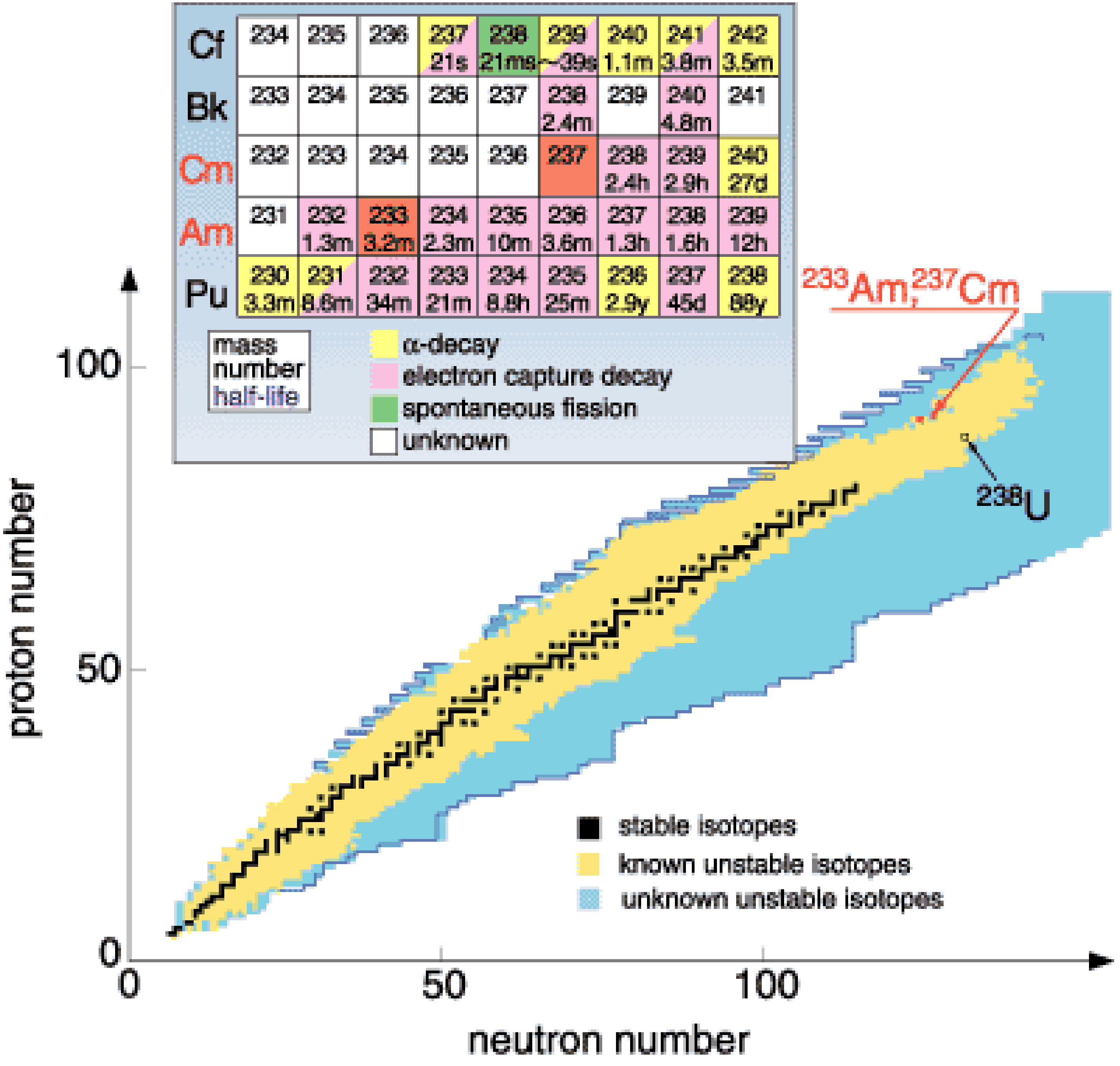




http://www.engin.umich.edu/research/cuos/ResearchGroups/HFS/Research/photonuclear_reactions.html

Natural Element Production

- Nuclear Astrophysics
  - fundamental information on the properties of nuclei and their reactions to the
  - perceived properties of astrological objects
  - processes that occur in space
- Nuclear reactions responsible for production of elements
  - Occurs in stars
- At temperatures and densities
  - light elements are ionized and have high enough thermal velocities to induce a nuclear reaction
  - heavier elements were created by a variety of nuclear processes in massive stellar systems
- systems must explode to disperse the heavy elements
  - distribution of isotopes here on earth
- underlying information on the elemental abundances
- nuclear processes to produce the primordial elements

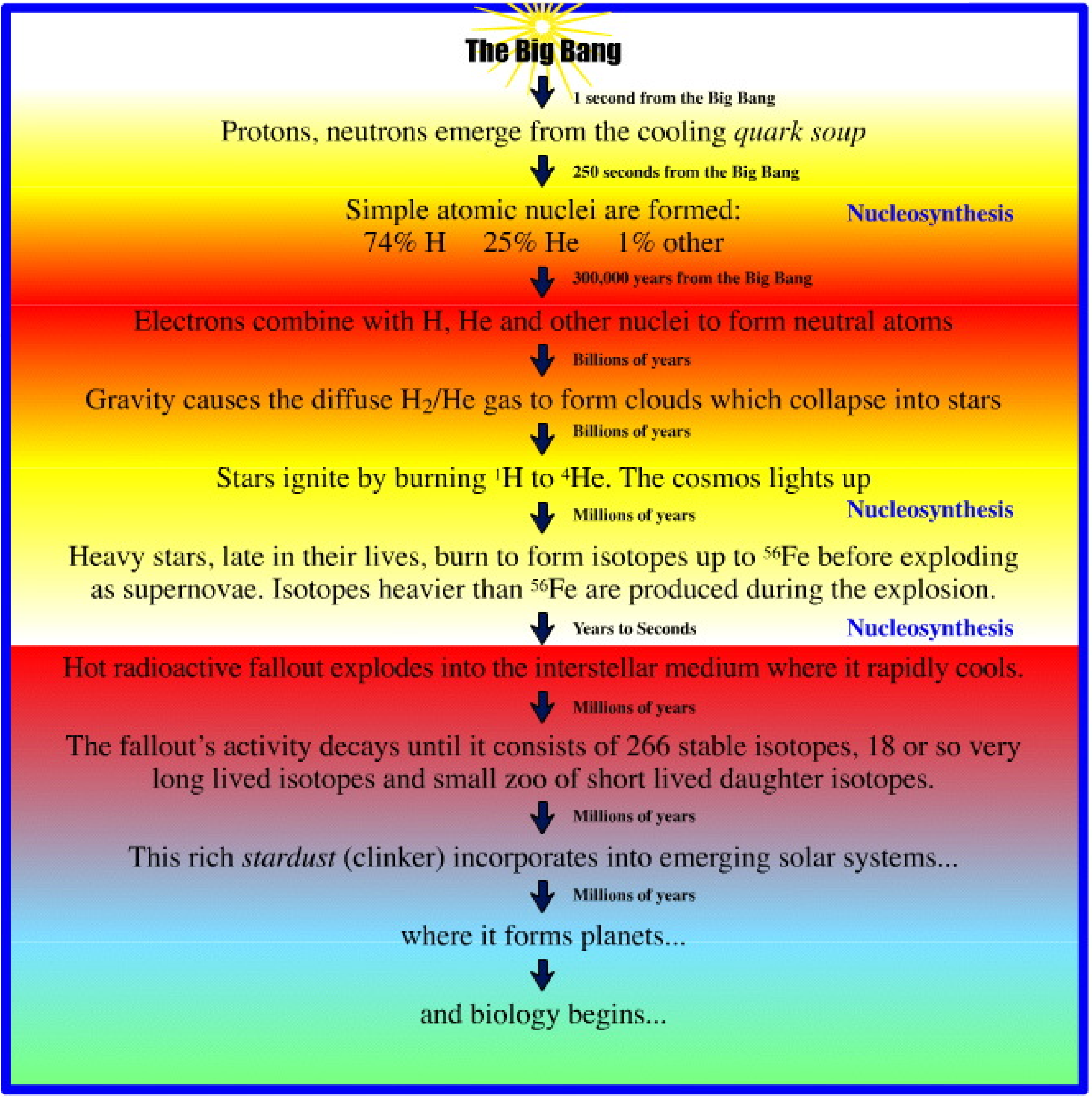


Cf	234	235	236	237 21s	238 21ms	239 ~39s	240 1.1m	241 3.8m	242 3.5m
Bk	233	234	235	236	237	238 2.4m	239	240 4.8m	241
Cm	232	233	234	235	236	237	238 2.4h	239 2.9h	240 27d
Am	231	232 1.3m	233 3.2m	234 2.3m	235 10m	236 3.6m	237 1.3h	238 1.6h	239 12h
Pu	230 3.3m	231 8.6m	232 34m	233 21m	234 8.8h	235 25m	236 2.9y	237 45d	238 88y

- Chart of the nuclide trends
- Actinides some distance from stable elements

Timeline

- **Big bang 15E9 years ago**
- **Temperature 1E9 K**
- **Upon cooling influence of forces felt**
  - **2 hours**
    - **→ H (89 %) and He (11 %)**
  - **Free neutrons decay**



The Big Bang

1 second from the Big Bang

Protons, neutrons emerge from the cooling *quark soup*

250 seconds from the Big Bang

Simple atomic nuclei are formed:
74% H 25% He 1% other

Nucleosynthesis

300,000 years from the Big Bang

Electrons combine with H, He and other nuclei to form neutral atoms

Billions of years

Gravity causes the diffuse H_2/He gas to form clouds which collapse into stars

Billions of years

Stars ignite by burning ^{1}H to ^{4}He. The cosmos lights up

Millions of years

Nucleosynthesis

Heavy stars, late in their lives, burn to form isotopes up to ^{56}Fe before exploding as supernovae. Isotopes heavier than ^{56}Fe are produced during the explosion.

Years to Seconds

Nucleosynthesis

Hot radioactive fallout explodes into the interstellar medium where it rapidly cools.

Millions of years

The fallout's activity decays until it consists of 266 stable isotopes, 18 or so very long lived isotopes and small zoo of short lived daughter isotopes.

Millions of years

This rich *stardust* (clinker) incorporates into emerging solar systems...

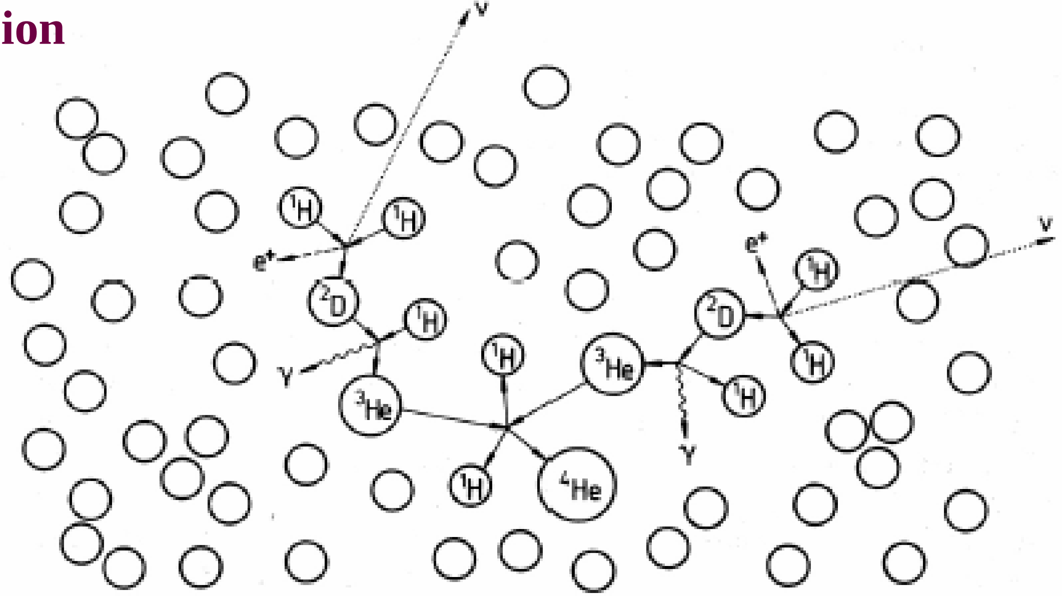
Millions of years

where it forms planets...

and biology begins...

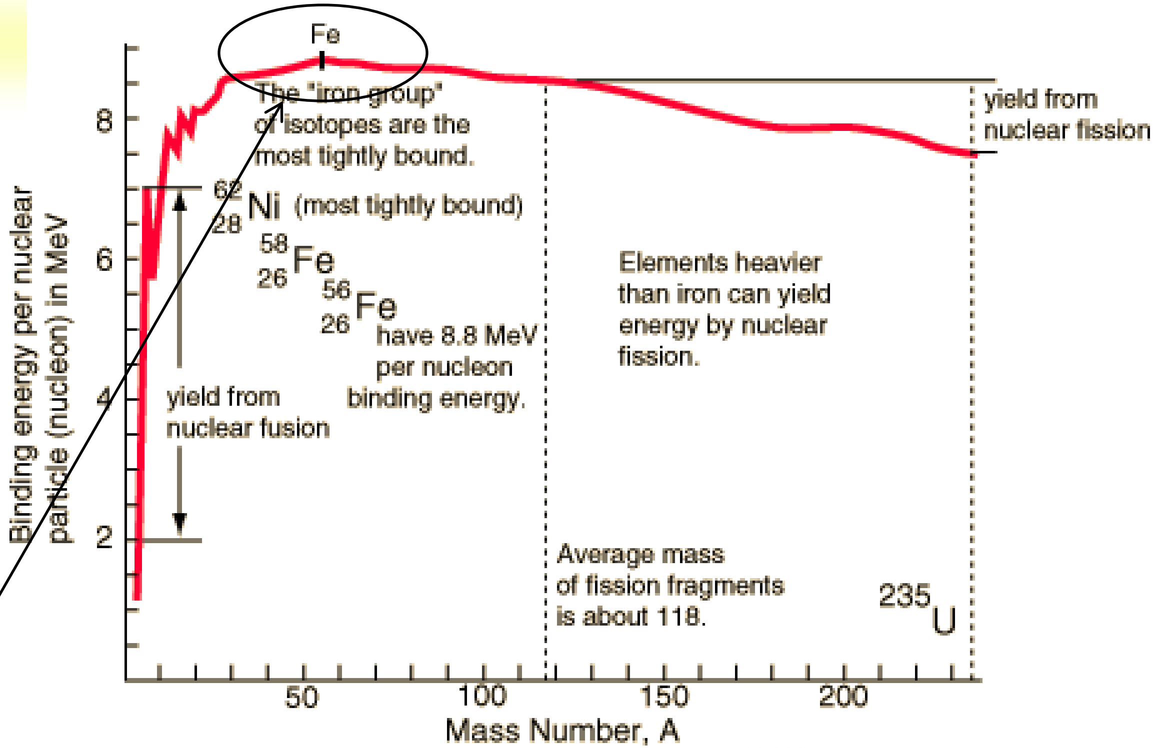
Origin of Elements

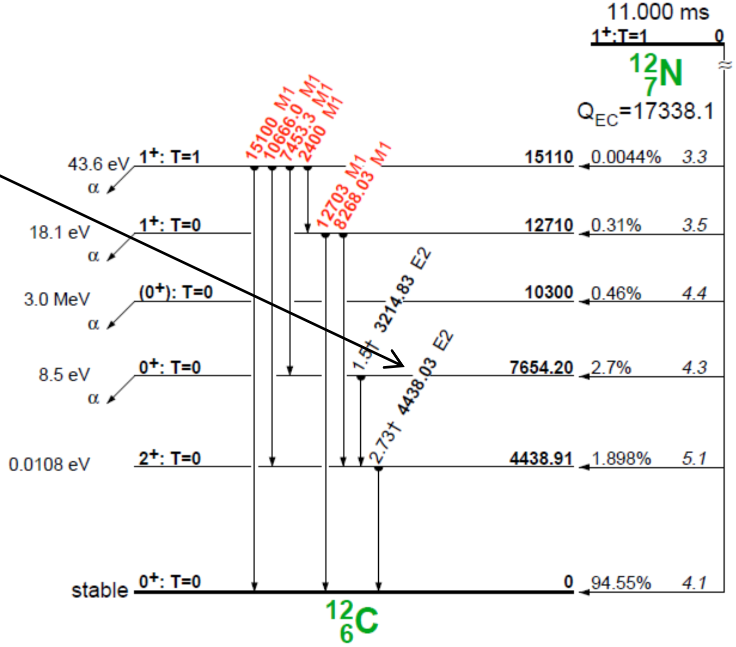
- **Gravitational coalescence of H and He into clouds**
- **Increase in temperature to fusion**
- **Proton reaction**
  - $^{1}H + n \rightarrow {}^{2}H + \gamma$
  - $^{2}H + {}^{1}H \rightarrow {}^{3}He$
  - $^{2}H + n \rightarrow {}^{3}H$
  - $^{3}H + {}^{1}H \rightarrow {}^{4}He + \gamma$
  - $^{3}He + n \rightarrow {}^{4}He + \gamma$
  - $^{3}H + {}^{2}H \rightarrow {}^{4}He + n$
  - $^{2}H + {}^{2}H \rightarrow {}^{4}He + \gamma$
  - $^{4}He + {}^{3}H \rightarrow {}^{7}Li + \gamma$
  - $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
    - → **^{7}Be short lived**
    - → **Initial nucleosynthesis lasted 30 minutes**
      - * **Consider neutron reaction and free neutron half life**
- **Further nucleosynthesis in stars**
  - **No EC process in stars**



Stellar Nucleosynthesis

- He burning
  - $^{4}He + {}^{4}He \leftrightarrow {}^{8}Be + \gamma - 91.78$ keV
    - → Too short lived
  - $3\ {}^{4}He \rightarrow {}^{12}C + \gamma + 7.367$ MeV
  - $^{12}C + {}^{4}He \rightarrow {}^{16}O$
  - $^{16}O + {}^{4}He \rightarrow {}^{20}Ne$
- Formation of ^{12}C based on Hoyle state
  - Excited nuclear state
    - → Somewhat different from ground state ^{12}C
  - Around 7.6 MeV above ground state
  - 0+
- Fusion up to Fe
  - From binding energy curve
  - Maximum at Fe





Stellar Nucleosynthesis

- **CNO cycle**
  - **$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$**
  - **$^{13}N \rightarrow {}^{13}C + e^{+} + \nu e$**
  - **$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$**
  - **$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$**
  - **$^{15}O \rightarrow {}^{15}N + e^{+} + \nu e$**
  - **$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$**
  - **Net result is conversion of 4 protons to alpha particle**

    → $4\ {}^{1}H \rightarrow {}^{4}He + 2\ e^{+} + 2\ \nu e + 3\ \gamma$

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$$

$$^{12}C + {}^{12}C \rightarrow {}^{23}Na + p$$

$$^{12}C + {}^{12}C \rightarrow {}^{23}Mg + n$$

$$^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$$

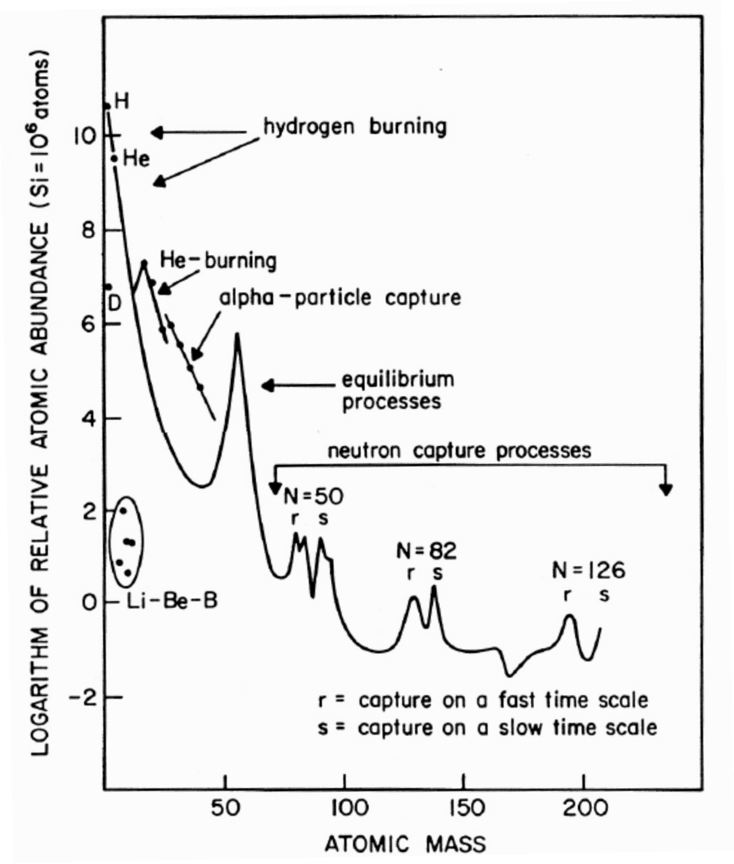
$$^{16}O + {}^{16}O \rightarrow {}^{24}Mg + 2\ {}^{4}He$$

$$^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^{4}He$$

$$^{16}O + {}^{16}O \rightarrow {}^{31}P + p$$

$$^{16}O + {}^{16}O \rightarrow {}^{31}S + n$$

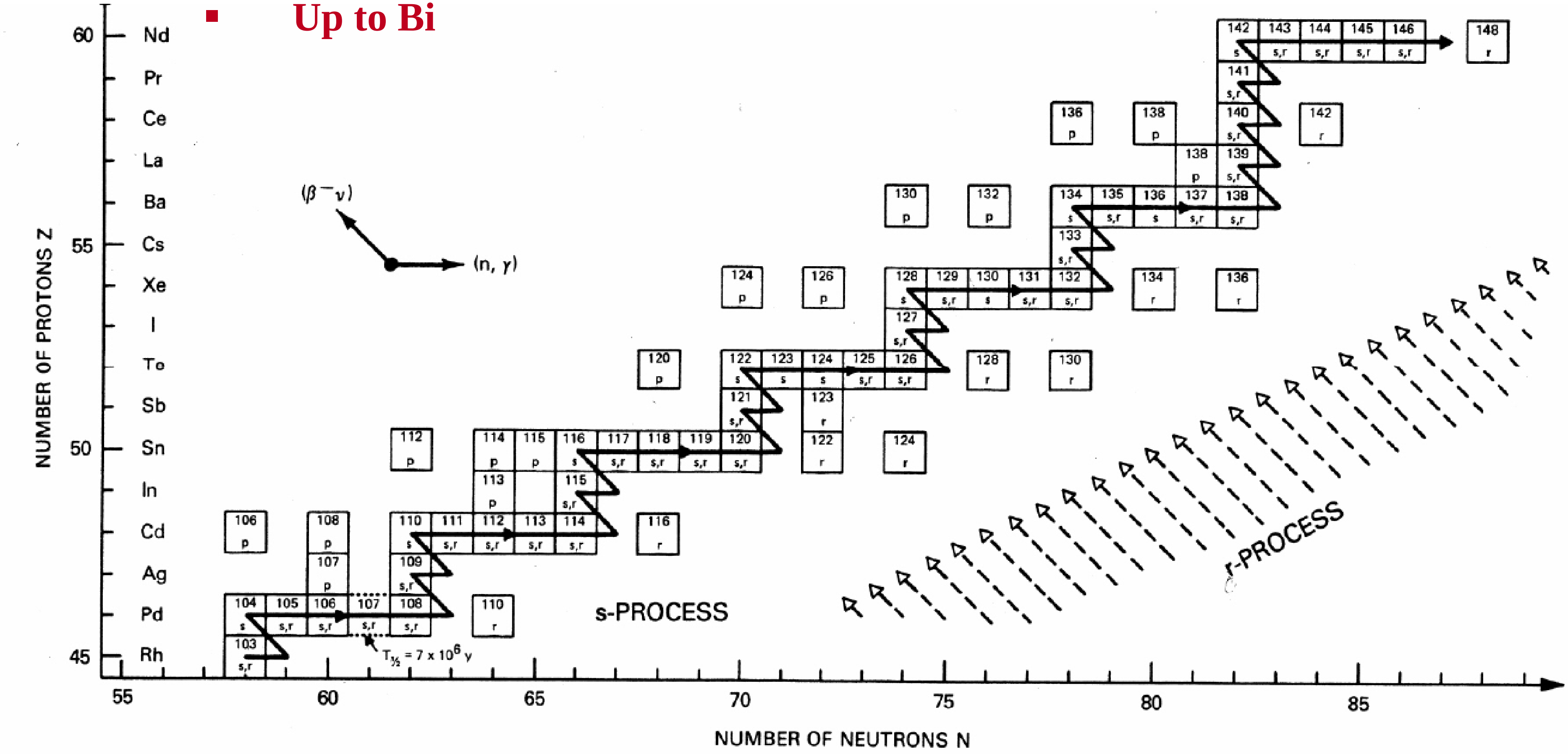
$$^{16}O + {}^{16}O \rightarrow {}^{32}S + \gamma$$



Formation of elements A>60

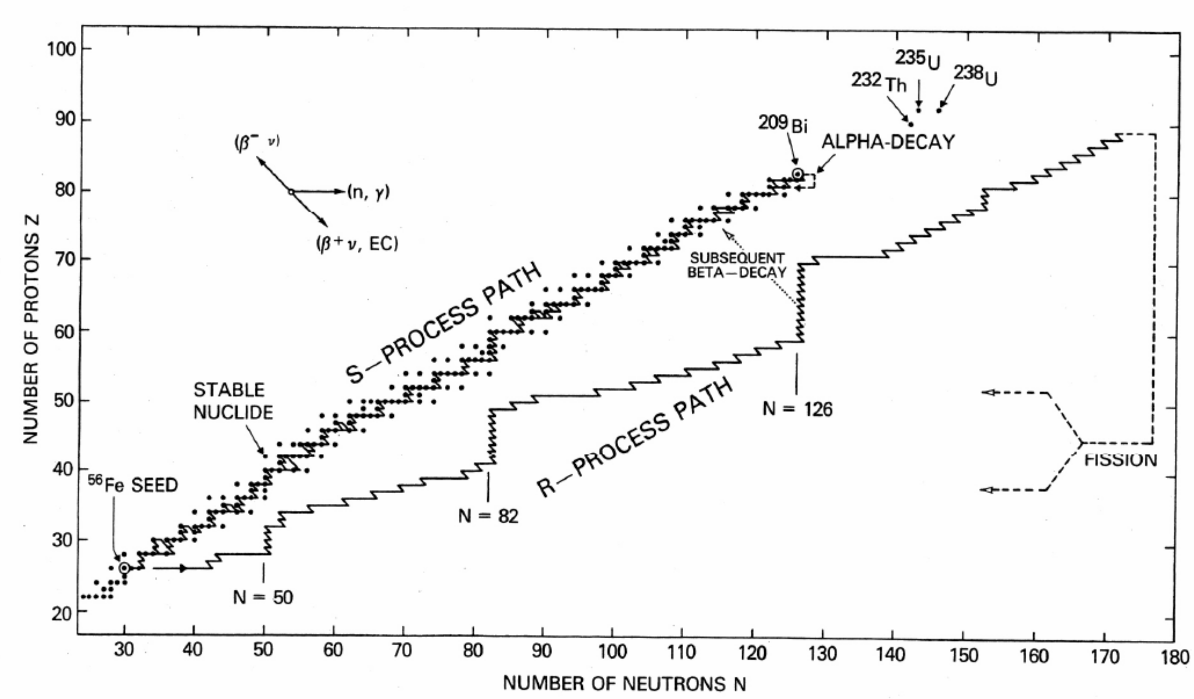
Neutron Capture; S-process

- A>60
- $^{68}Zn(n, \gamma)\ ^{69}Zn,\ ^{69}Zn \rightarrow\ ^{69}Ga + \beta^- + \nu$
- mean times of neutron capture reactions longer than beta decay half-life
  - → Isotope can beta decay before another capture
- Up to Bi



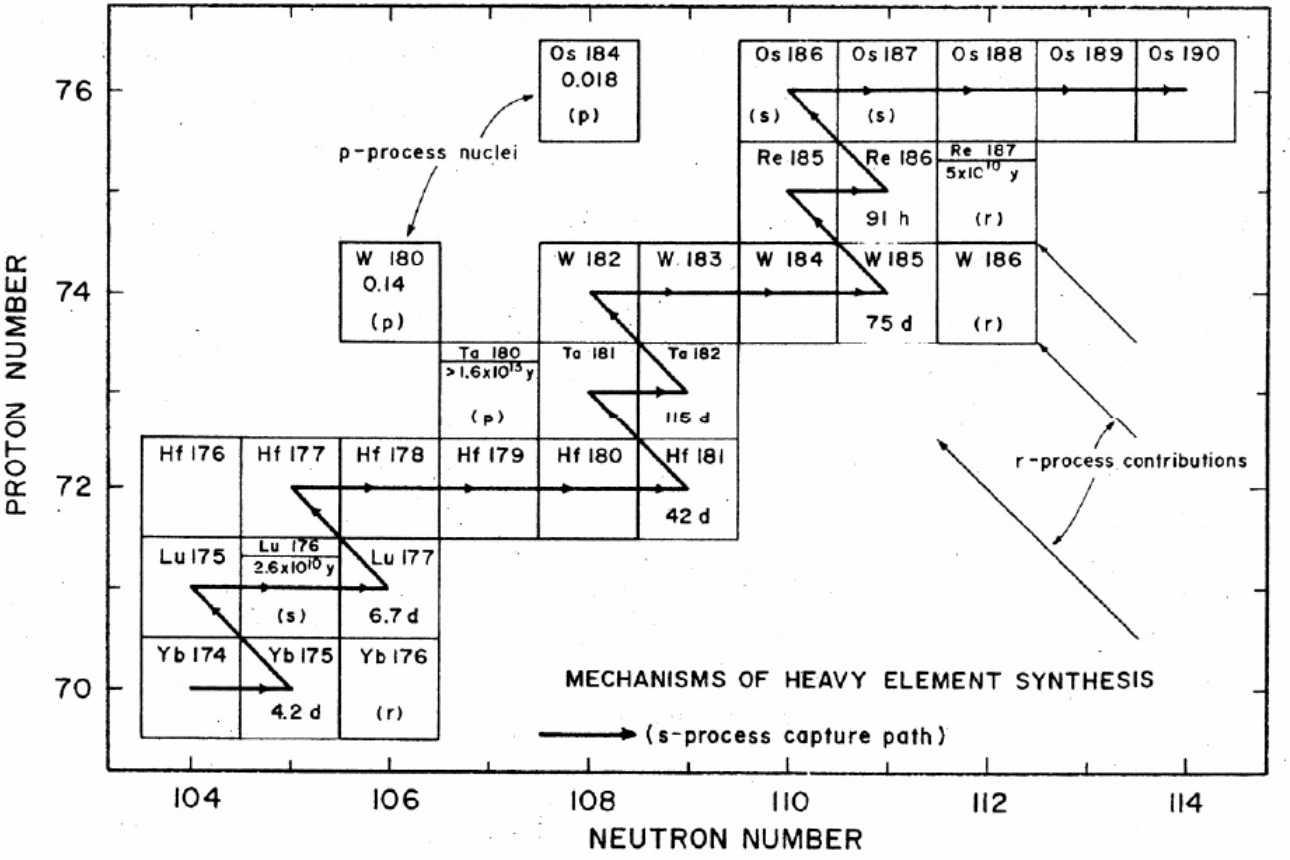
Nucleosynthesis: R process

- Neutron capture time scale very much less than β- decay lifetimes
- Neutron density $10^{28}/m^3$
  - Extremely high flux
  - capture times of the order of fractions of a second
  - Unstable neutron rich nuclei
- rapidly decay to form stable neutron rich nuclei
- all A<209 and peaks at N=50,82, 126 (magic numbers)



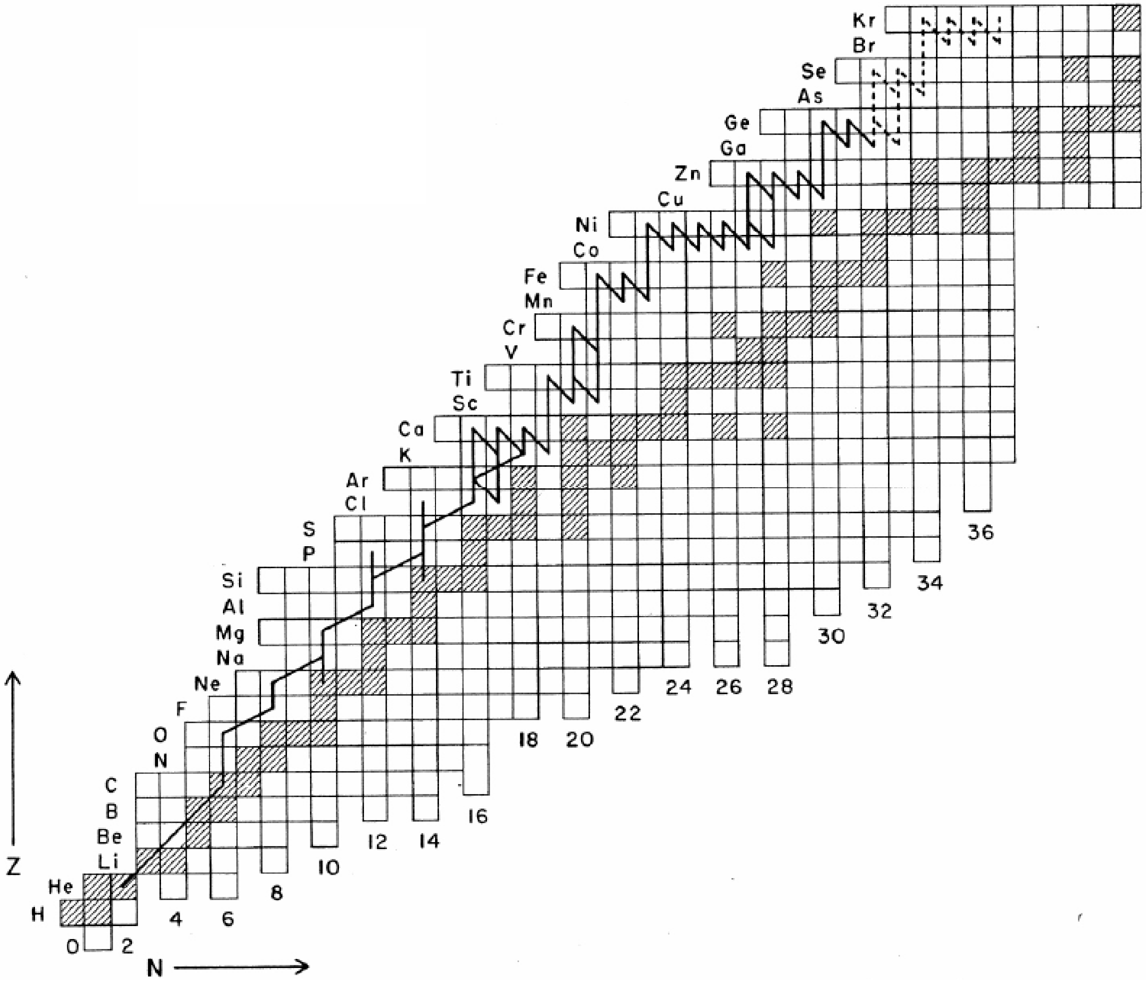
P process

- Formation of proton rich nuclei
- Proton capture process
- 70<A<200
- Photonuclear process, at higher Z (around 40)
  - (γ, p), (γ, α), (γ, n)
  - ^{190}Pt and ^{168}Yb from p process
- Also associated with proton capture process (p,γ)
- Variation on description in the literature



rp process (rapid proton capture)

- **Proton-rich nuclei with Z = 7-26**
  - **Forms a small number of nuclei with A< 100**
- **(p,γ) and β^+ decays that populate the p-rich nuclei**
  - **Also associated with rapid proton capture process**
- **Initiates as a side chain of the CNO cycle**
  - **^{21}Na and ^{19}Ne**



Review Notes

- Understand Reaction Notation
- Understand Energetics of Nuclear Reactions
  - Q values and barriers
- Understand the Different Reaction Types and Mechanisms
  - Particles
  - Energy
- Relate cross sections to energy
- Describe Photonuclear Reactions
- Routes and reactions in nucleosynthesis
- Influence of reaction rate and particles on nucleosynthesis

Questions

- Describe the different types of nuclear reactions for heavy ions.
- Provide notations for the following
  - Reaction of ^{16}O with ^{208}Pb to make stable Au
  - Formation of Pu from Th and a projectile
- Find the threshold energy for the reaction of ^{59}Co and an alpha that produces a neutron and a product nuclei
- What are the differences between low and high energy reactions?
- How does a charged particle reaction change with energy? A neutron reaction?
- How are actinides made in nucleosynthesis?
- What is the s-process?
- What elements were produced in the big bang?
- Which isotopes are produced by photonuclear reactions?
- What is interesting about the production of ^{12}C

Question

- **Respond to PDF Quiz**
- **Comment in blog**