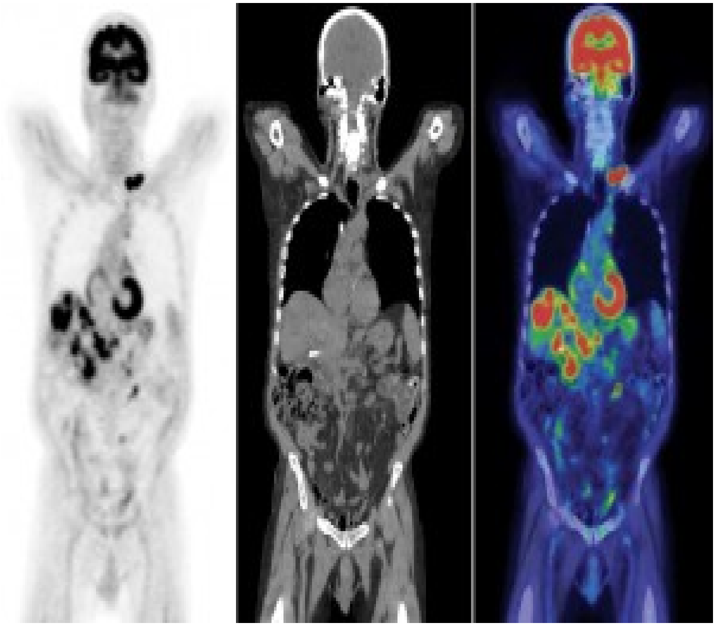
# RDCH 702 Lecture 11 Part 1
# Applications of nuclear material

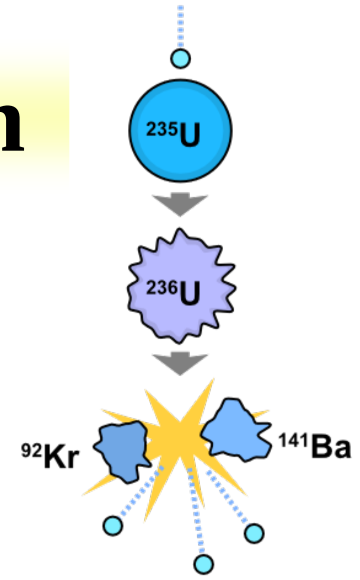
- Readings: Nuclear and Radiochemistry Chapter 11.D
- Modern Nuclear Chemistry Chapter 4.10

Outline

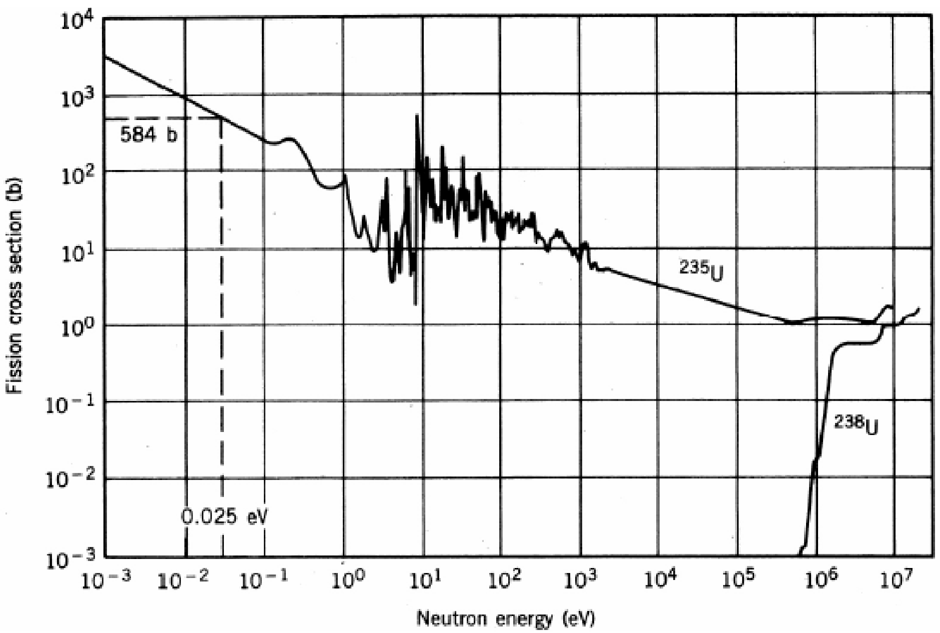
- Isotope production methods
- Neutron generators
- Ionization sources
- Heat source
- Radiopharmaceuticals
  - Diagnostic
    - → Gamma emission
      - * Positron emission tomography
  - Therapeutic
    - → Auger electron, Beta Decay, Alpha Decay



# Isotope production: Fission

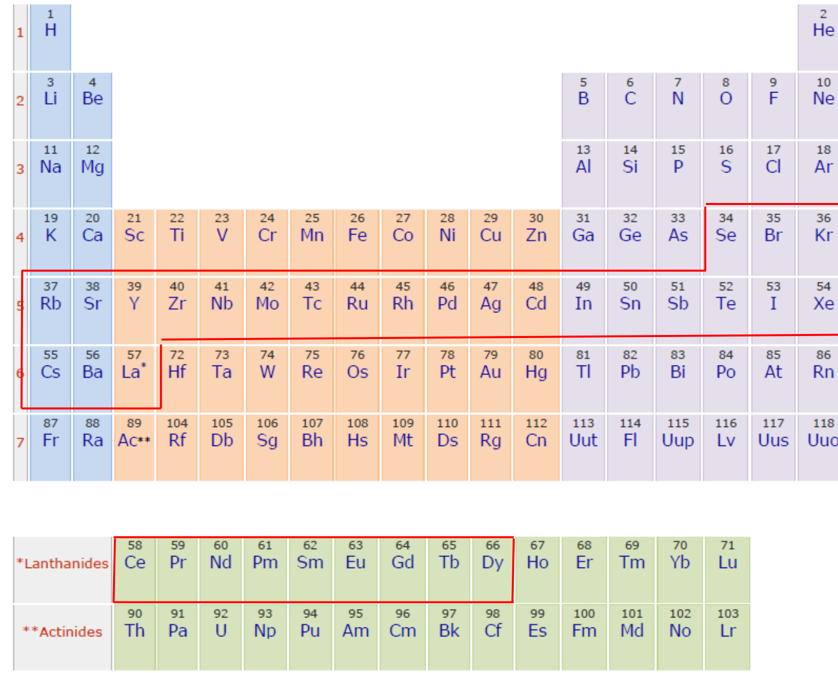


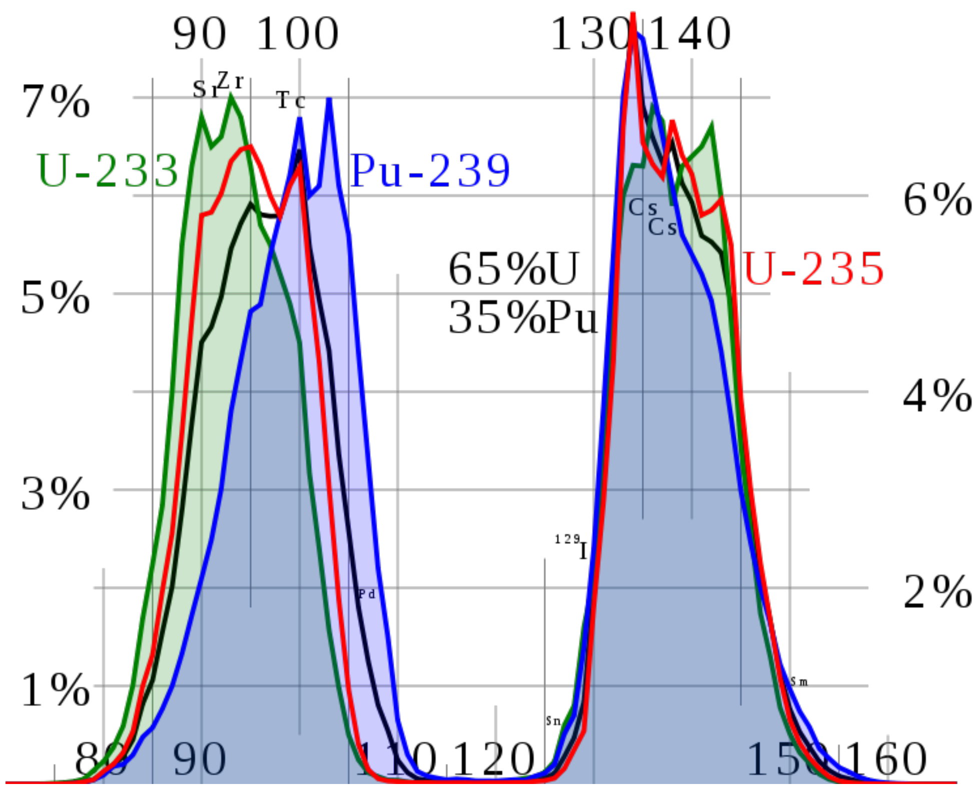

- **Fission**
  - **Direct production of fission products**
  - **Neutron reactions to form actinides**
  - **$^{238}$U+n→$^{239}$U→$^{239}$Np+β⁻→ $^{239}$Pu+β⁻**
    - → **Can go up to $^{252}$Cf**
- **Production of radioisotopes**
  - **Fission products**
  - **Neutrons for neutron capture**
    - → **$^{238}$Pu: $^{237}$Np(n,γ)**
    - → **$^{241}$Am**
      - * **Neutron capture on Pu isotopes, beta decay of $^{241}$Pu**



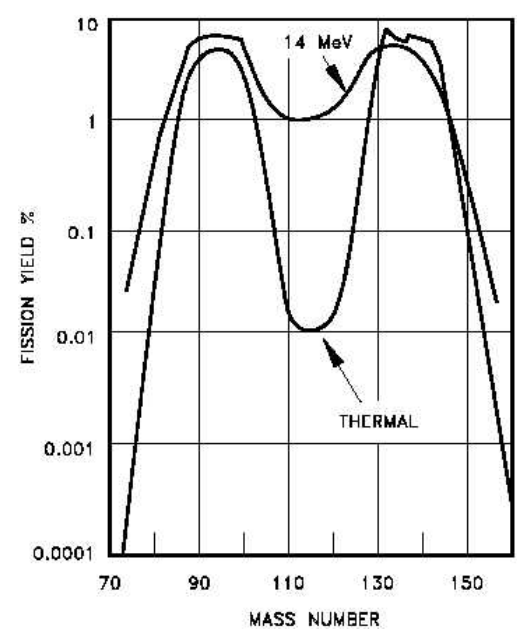
# Fission Products

- Fission yield curve varies with fissile isotope
    - Elements Se (Z=34) to Dy (Z=66)
- 2 peak areas for U and Pu thermal neutron induced fission
- Variation in light fragment peak
    - Higher peak stable due to magic numbers
- Influence of neutron energy observed
- Neutron rich isotopes, beta decay



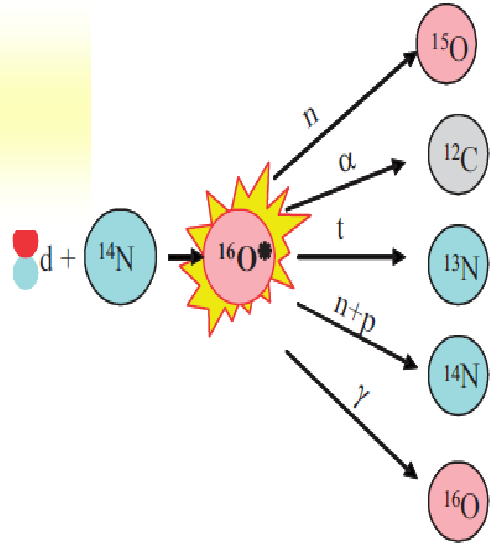



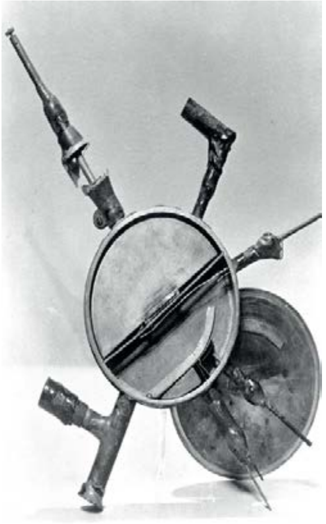

$^{235}$U fission yield



# Accelerator production

- Charged particle at high energy
  - Nuclear interactions between projectile and target
- Can vary target, projectile, separations
  - Amount of material
  - Energy
- Production of neutron poor isotopes
  - Positron emitters



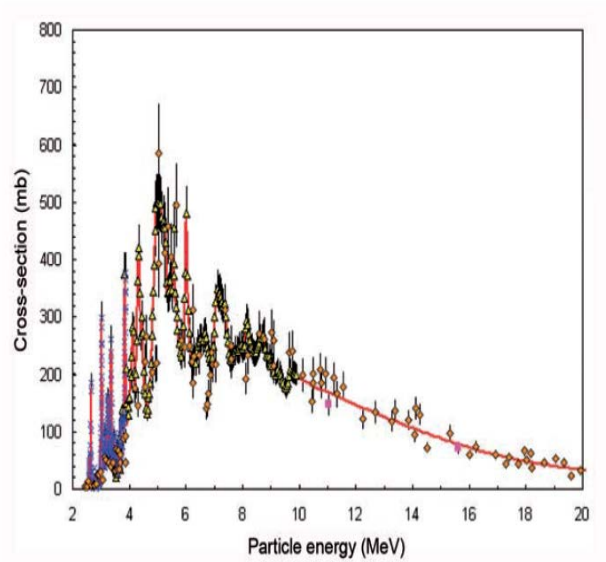
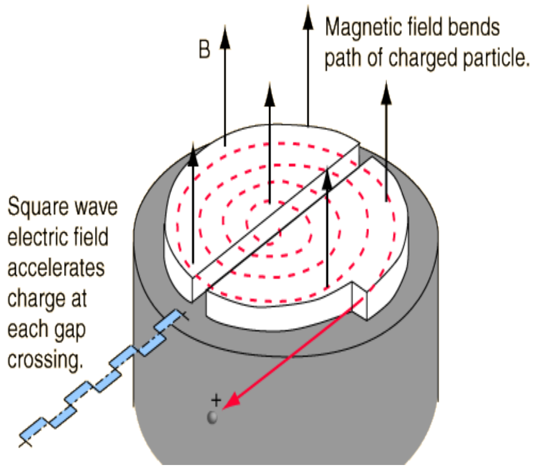



FIG. 4.3. Excitation function for the $^{18}O(p, n)^{18}F$ reaction, illustrating the energy dependence of the cross-section σ.

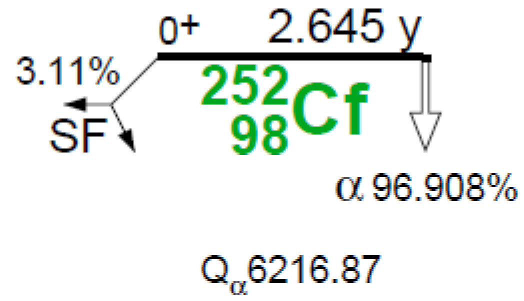


# Neutron emitters

- **Determine elements in samples based on reactions with neutrons**
  - **Na, Actinides**
- **Evaluation of subcritical amounts of fissile material**
- **Detect water or hydrogen by backscattering**
- **Explosives**
  - **utilizes cross-section resonances of N and O**
    - **→Explosives have characteristic N to O ratios**
      - *** Measurement of characteristic gammas from reaction or absorption of neutrons**

# Neutron emitters

- $^{252}$Cf as neutron source
- Reaction of alpha particle on Be
  - $^{9}Be(\alpha,n)^{12}C$
  - Can use different alpha source
    - → $^{241}$Am
    - → $^{239,240}$Pu
    - → $^{210}$Po



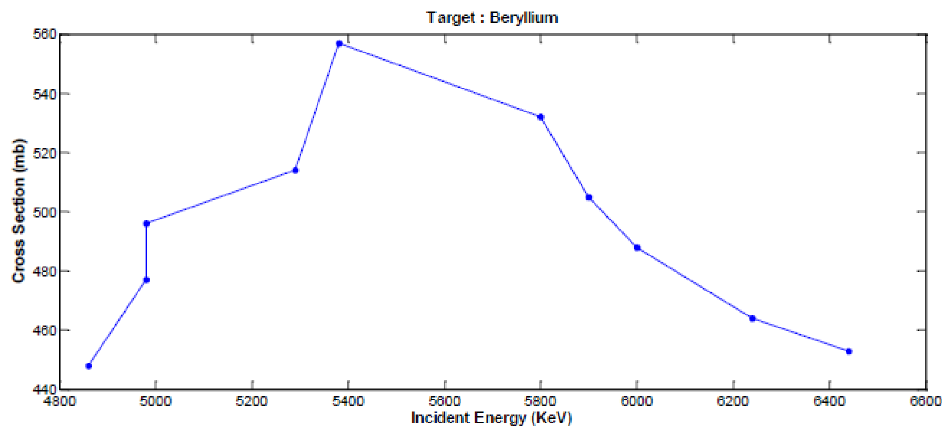




Fig.1. Cross section change for the reaction $^{9}Be(\alpha,n)^{12}C$ with respect to incident particles energy.

NEUTRON YIELD MEASUREMENTS FOR BERYLLIUM CHEMICAL COMBINATIONS

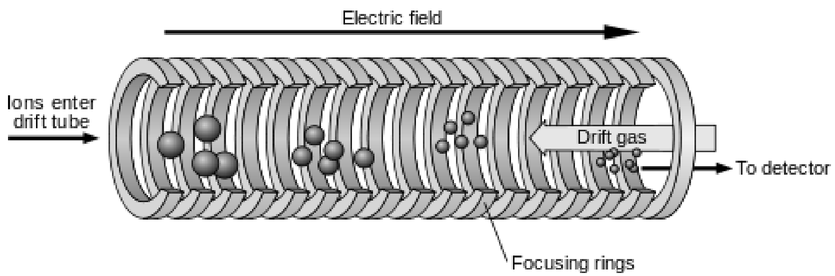
| Target | Yield n/α |
|---|---|
| BeO | 3.1006e-005 |
| $Be_2C$ | 3.0365e-005 |
| $BeH_2$ | 2.2866e-005 |
| $Be(OH)_2$ | 2.8363e-005 |
| $Be_3N_2$ | 3.0386e-005 |

# Emitted Particle Interaction

- **Smoke detectors**
  - $^{241}$Am alpha emission
  - $AmO_2$, 33 kBq of $^{241}$Am
  - Smoke detection by ionization chamber
    - →Alpha particles ionize air
      - * Ions detection through low level current in ionization chamber
    - →Smoke enters chamber between electrodes, drop in ion formation
      - * Ions will attach to smoke particles
    - →Decrease in electric current triggers alarm

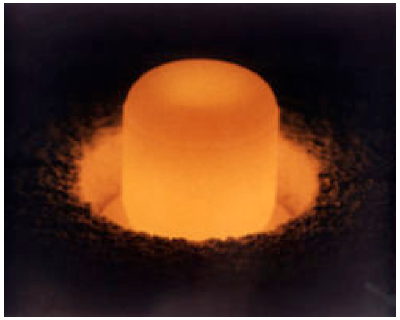
# Emitted particle interaction

- Explosive detection
  - $^{63}$Ni beta emission
  - Ion mobility detector
    - → Sample collected
      - * can determine pgram level
    - → Molecules ionized by beta particles
      - * Cross section related to ion size and shape
    - → Migration of molecules in chamber based on mass, size and shape
      - * Chamber filled with gas
      - * Detector at end
      - * Migration time characteristic for ion



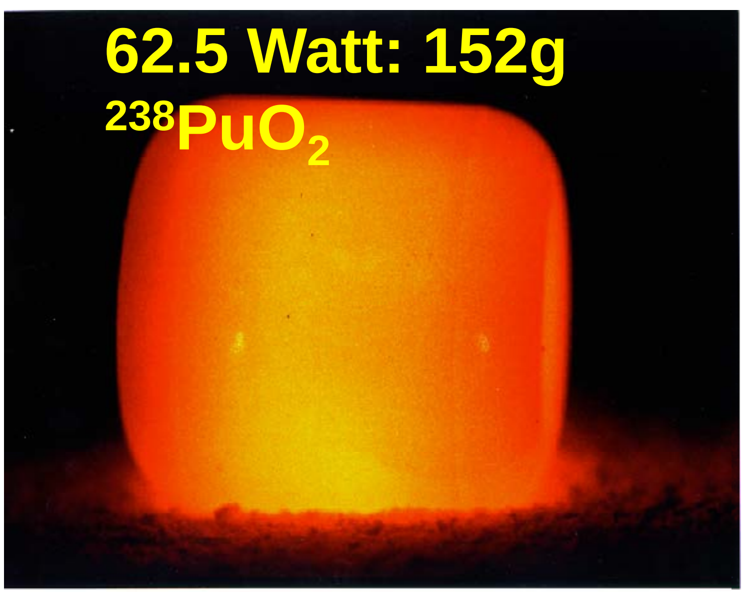
# $^{238}$Pu properties

- Half-life 87.7 a
- $^{237}Np(n,\gamma)^{238}Np$
  - $^{238}$Pu from beta decay of $^{238}$Np ($t_{1/2}$=2.12 d)
  - Separated from unreacted Np by ion exchange
- Decay of $^{242}$Cm
- 0.57 W/g
- Power source for space exploration
  - 83.5 % $^{238}$Pu, chemical form as dioxide
  - Enriched $^{16}$O to limit neutron emission
    - → 6000 n $s^{-1}g^{-1}$
    - → 0.418 W/g $PuO_2$
- 150 g $PuO_2$ in Ir-0.3 % W container



# $^{238}Pu$ production

- $^{238}Pu$ prepared at Savannah River by irradiating $NpO_2$ particles embedded in an aluminum matrix
- Anion exchange in nitric acid solution was used to separate the Np and Pu from the fission products
  - Then separate Pu from Np
- Irradiated aluminum targets dissolved in 10 M nitric acid containing small amounts of KF and mercuric nitrate
  - nitric acid solution was treated to give a nitric acid concentration of 8 M and ferrous sulfamate was used to adjust the valence of Np and Pu to the tetravalent state
- A first stage of anion exchange on a Dowex I type resin separated the Np(IV) and Pu(IV) (held on the resin as anionic nitrato complexes) from the aluminum and the bulk of the fission products
- In the second stage of anion exchange, Pu(IV) and Np(IV) were again bound to the column and the Pu selectively eluted as Pu(III) using 5.5 M nitric acid 0.05 M ferrous sulfamate and 0.05 M hydrazine.
- Np(IV) was eluted from the second column with 0.35 M nitric acid, precipitated as the oxalate complex, and then calcined to $NpO_2$ for reuse in new targets
- $^{238}Pu$ was purified in a third stage of anion exchange and the eluted $^{238}Pu$ nitrate solution sent on for further processing into $PuO_2$ or other compounds

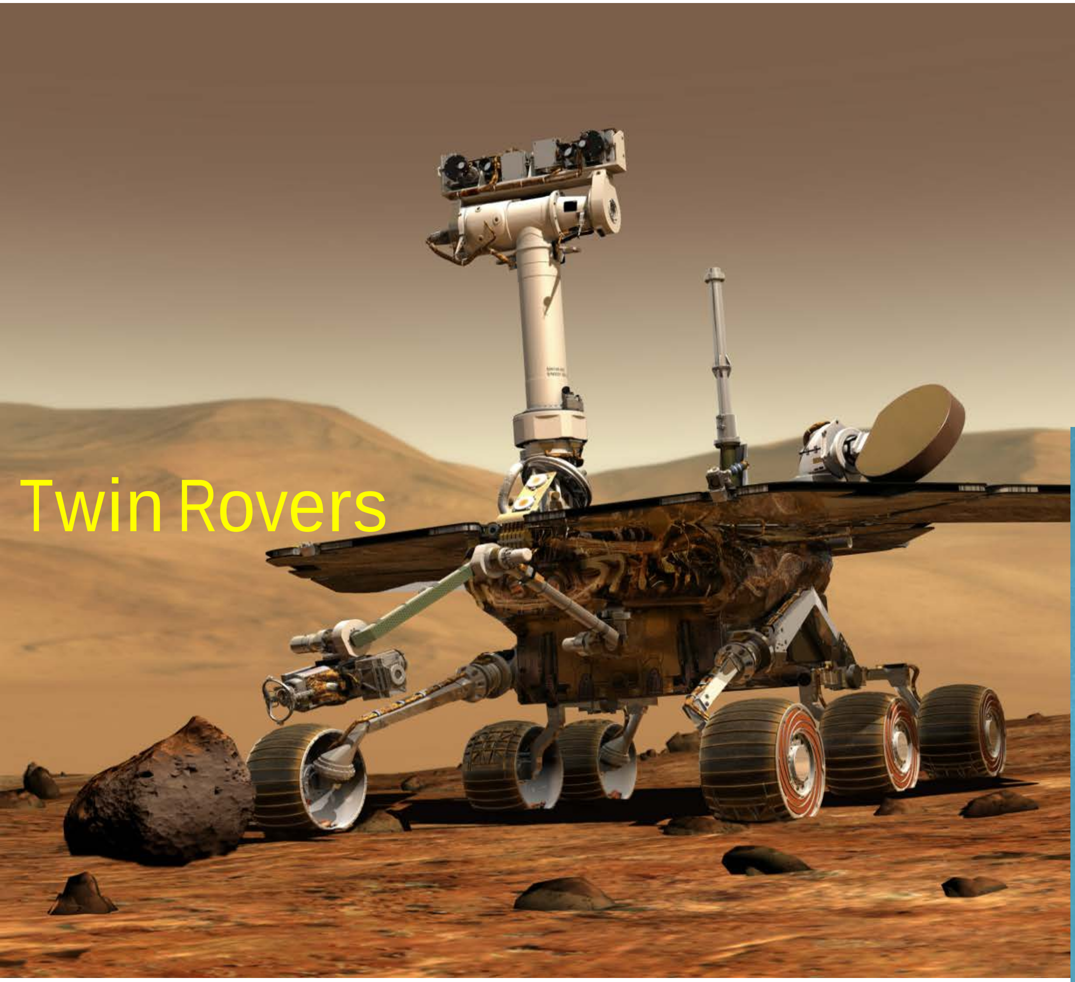



**General Purpose Heat Source - GPHS**

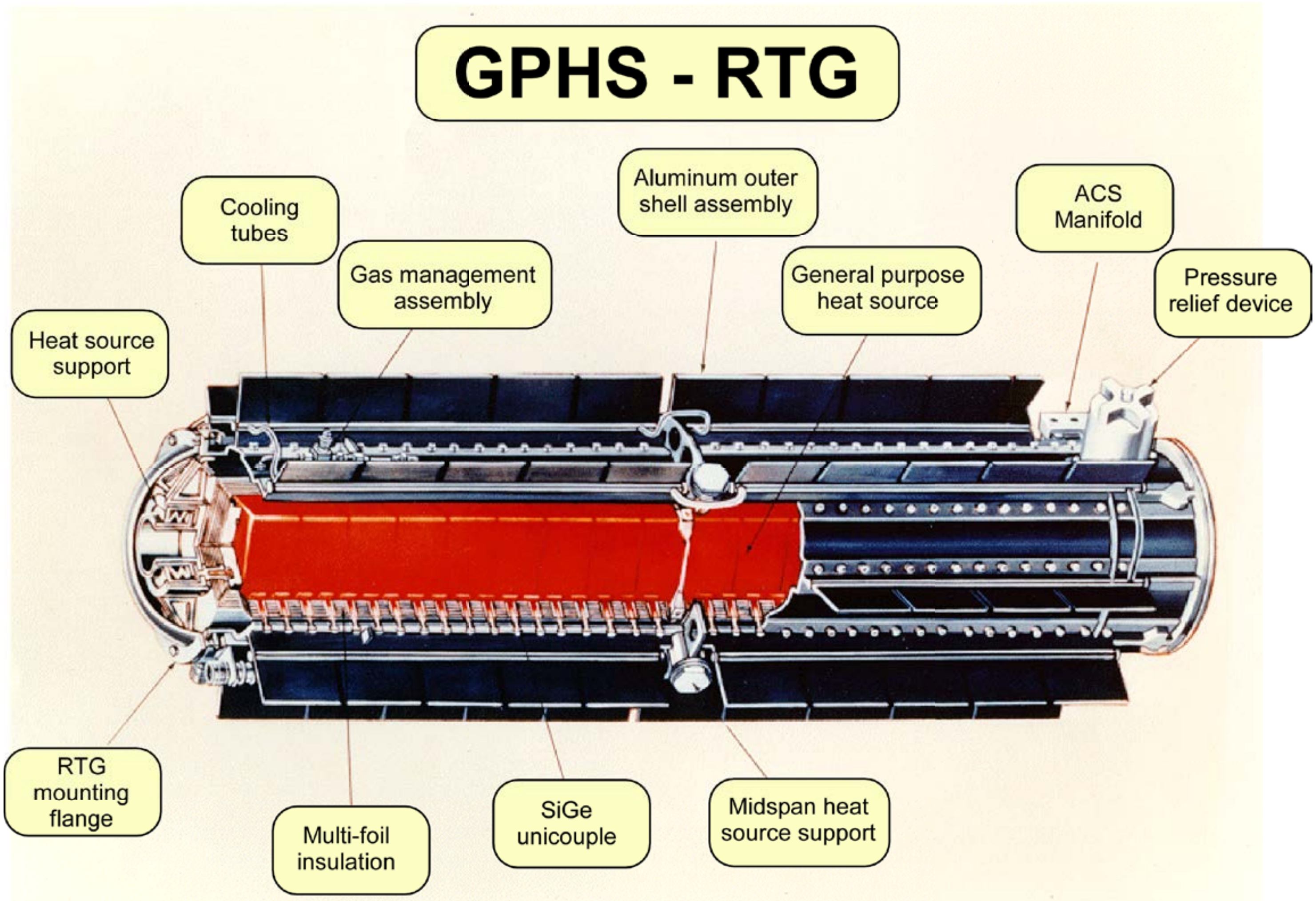
**Equatorial tungsten arc weld**

**Iridium-clad capsule**

# Planetary Exploration – Heat for Mars Rovers



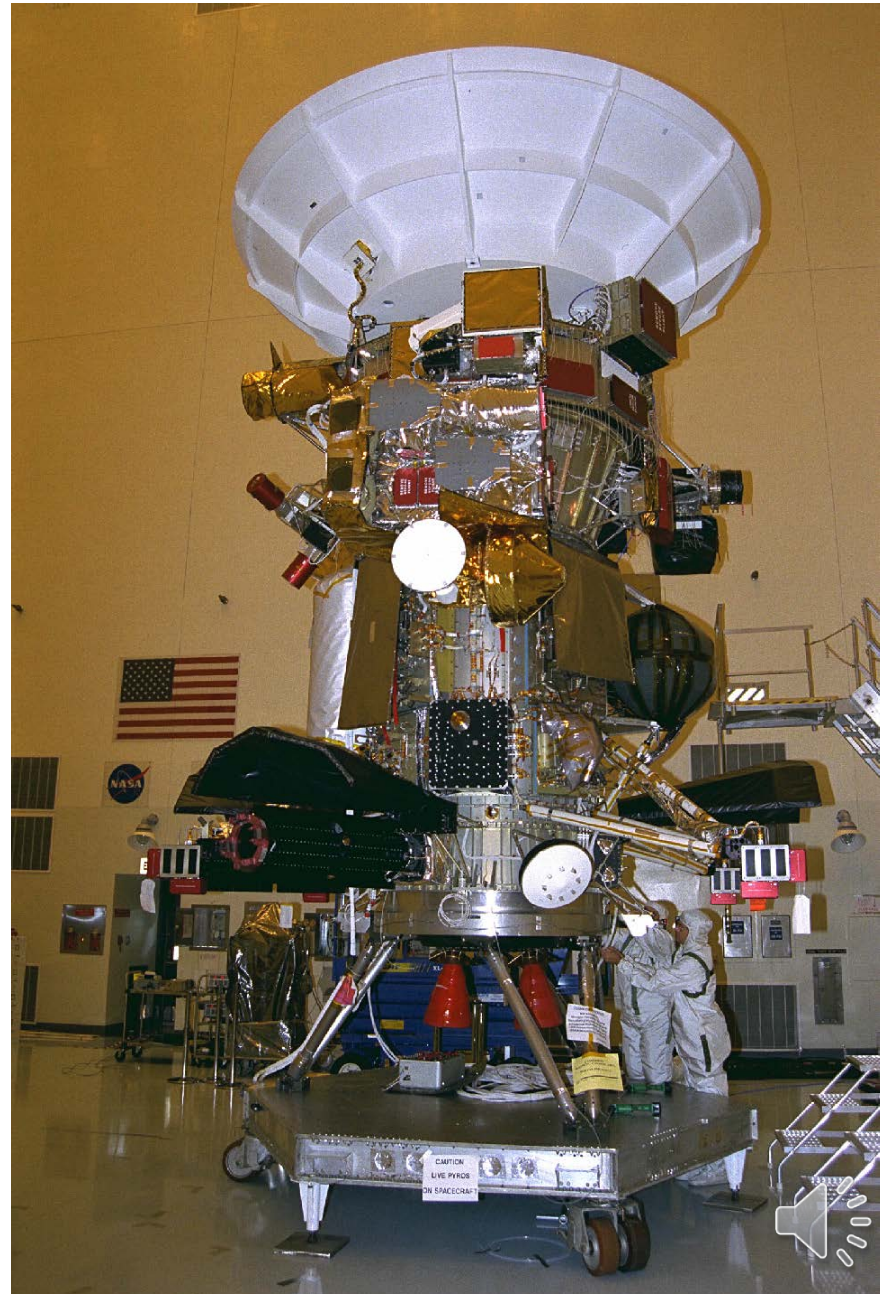

# Radioisotope Thermoelectric Generator




- 2 GPHS pellets per impact shell
- 2 impact shells per module
- 18 modules per RTG
- Total 72 GPHS pellets per RTG
- 11 kg Pu
- 200 Watts power

# Cassini Heat and Power Sources

- 333 LANL Heat Sources
- 117 RHUs (0.3 kg)
  - heat for spacecraft components
- 216 GPHS pellets (32 kg)
  - electrical power



# New Horizons Pluto-Kuiper Belt Mission

- 61 GPHS pellets
- 1 RTG, 170 Watts
- 10 kg plutonium
- Arrival 2015

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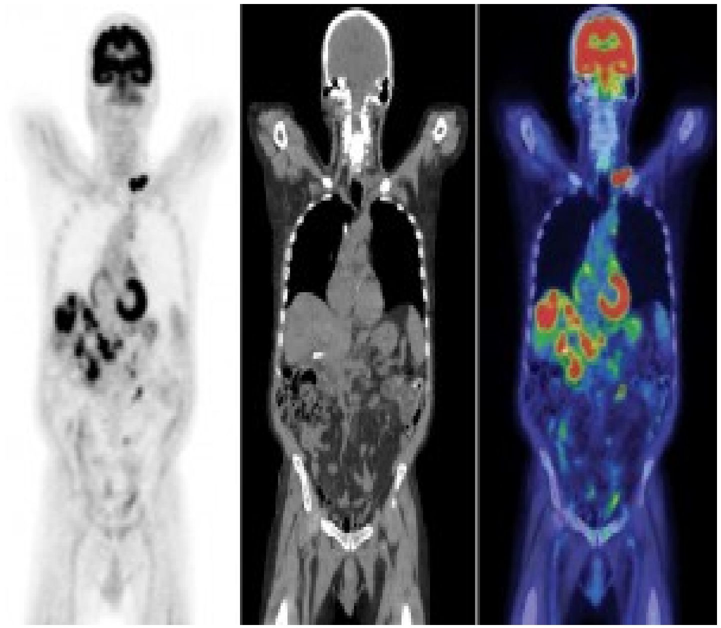

# RDCH 702 Lecture 11
# Part 2 Applications of nuclear material

- Readings: Nuclear and Radiochemistry Chapter 11.D
- Modern Nuclear Chemistry Chapter 4.10

Outline

- Isotope production methods
- Neutron generators
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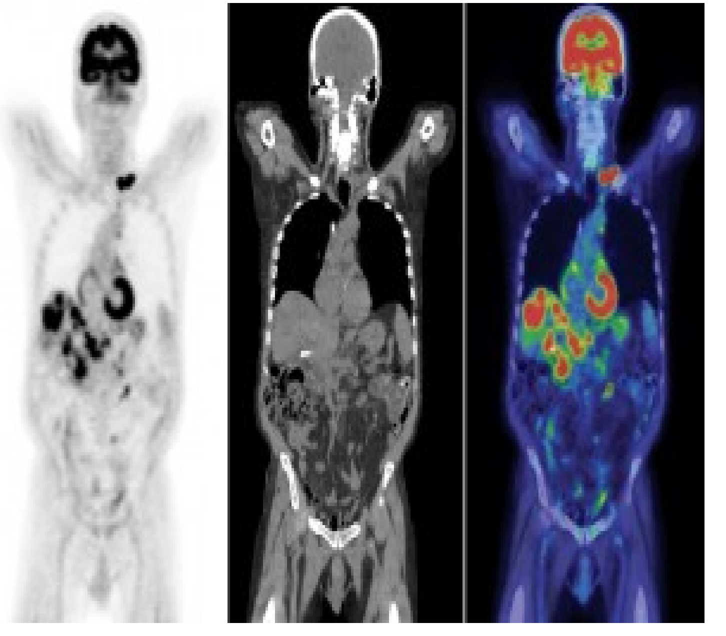
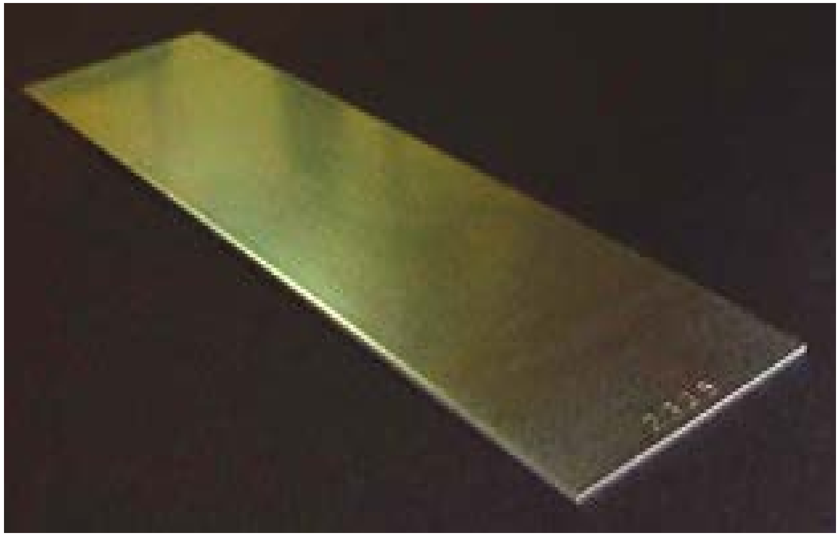
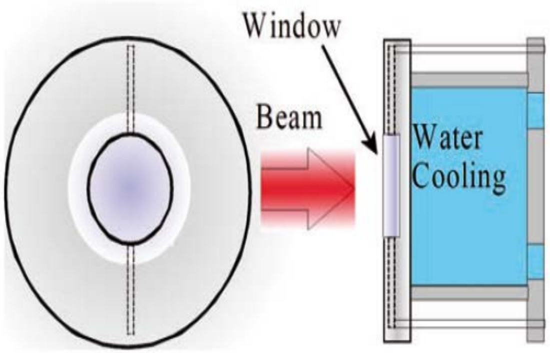
- Heat source
- Radiopharmaceuticals
  - Diagnostic
    - → Gamma emission
      - * Positron emission tomography
  - Therapeutic
    - → Auger electron, Beta Decay, Alpha Decay



# Medical Isotope Production Methods

- **Neutron reactions**
  - **Fission of uranium to make fission products**
  - **Addition of neutron to target**
  - **Products are neutron rich, neutron tends to transform to proton**
    - → **Beta decay**
    - → **Alpha decay**
- **Particle interactions with accelerators**
  - **Tends to form proton rich isotopes, proton transforms to neutron**
    - → **Positron decay**
    - → **Auger emission isotopes**



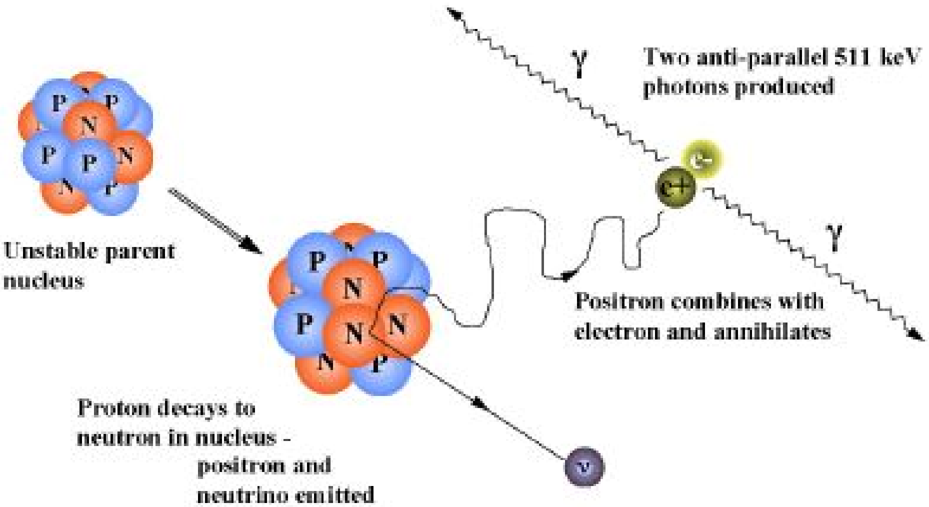


# Decay Modes

- Alpha and beta can deposit high amount of energy in cell
  - Alpha travels about 1 cell length, beta around 7-8 cells
  - Therapeutic, can kill tumor cells
    - → Includes Auger electron
- Gamma decay and positron decay for imaging
  - Photon emission
  - Positron produces 2 photons when interaction with electron
    - → matter-antimatter interaction

# Positrons

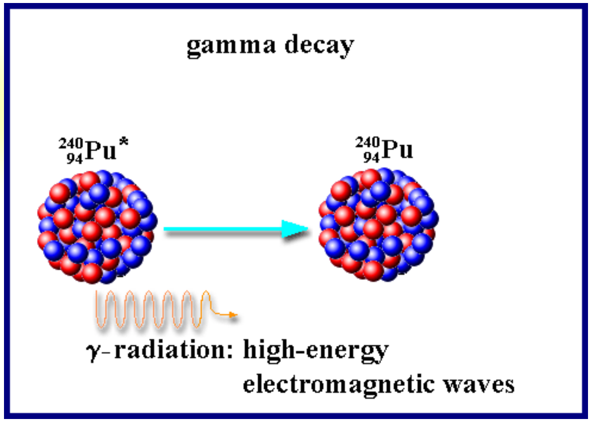
- Postulated in 1931
  - Relativistic equations could be solved for electrons with positive energy states
  - Require energies greater than electron mass
  - Creation of positive hole with electron properties
- Pair production process involves creation of a positron-electron pair by a photon in nuclear field
  - Nucleus carries off some momentum and energy
- Positron-electron annihilation
  - Conversion of mass to energy when positron and electron interact
  - simultaneous emission of corresponding amount of energy in form of radiation
  - Responsible for short lifetime of positrons

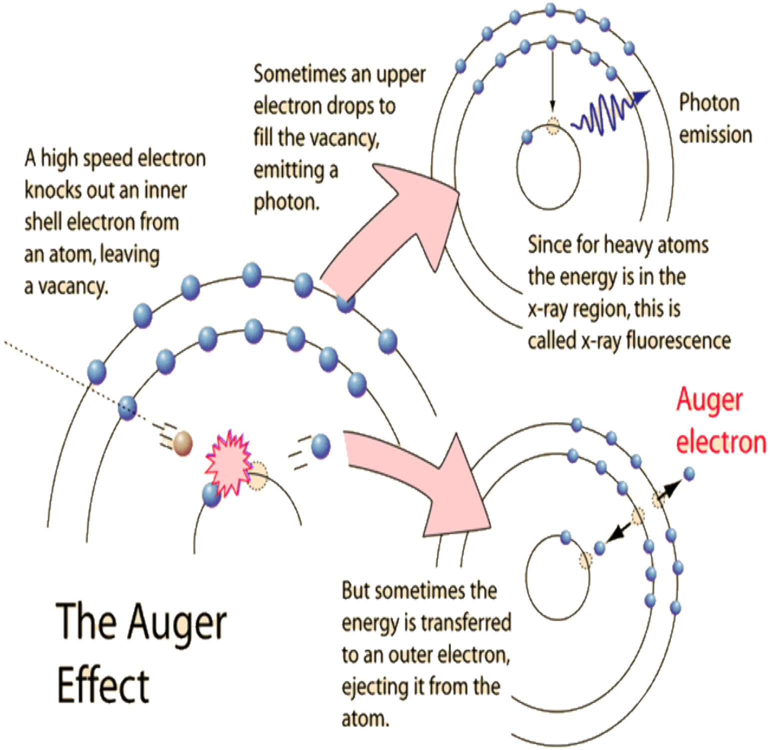



- Annihilation radiation
  - energy carried off by two γ quanta of opposite momentum
  - Annihilation conserves momentum
  - Exploited in Positron Emission Tomography

# Photon and Auger emission electron

- Gamma decay
  - Emission of photon from excited nucleus
    - → Metastable nuclide (i.e., $^{99m}Tc$)
    - → Following decay to excited daughter state
- X-ray
  - Electron from a lower level is removed
    - → electrons from higher levels occupy resulting vacancy with photon emission
- Auger emission
  - Similar to x-ray, energy transferred to outer electrons

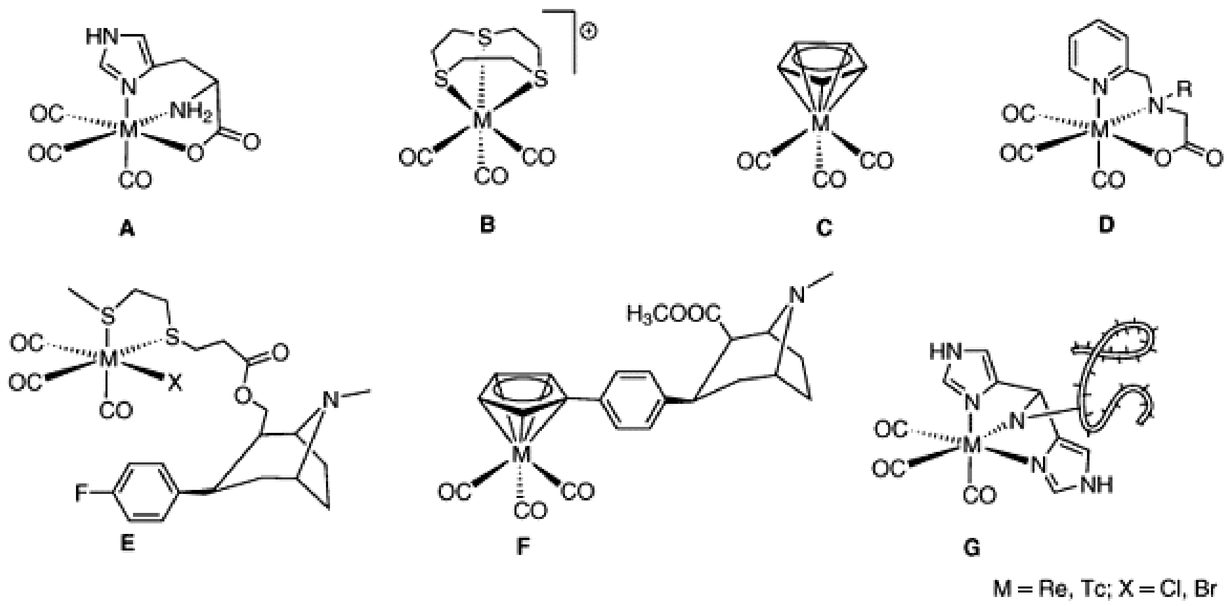


# Radiopharmaceutical research

- Chemical species and coordination chemistry
  - Exploiting chemistry of radionuclide
- Radionuclide introduced and used for imaging or therapy
  - Gamma emission for imaging
  - Alpha, beta, Auger electron for therapy
- Example with $^{99m}$Tc
  - Produced from $^{99}$Mo via generator
  - 80 % of radiopharmaceutical applications use $^{99m}$Tc
- Linked with Tc coordination chemistry
- Synthesis and characterization of $Tc(CO)_3^+$

  Alberto, J. Organomet. Chem., 493, 119 (1995)
  - Used in variety of $^{99m}$Tc compounds

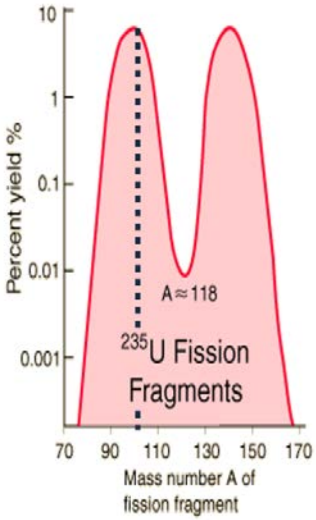


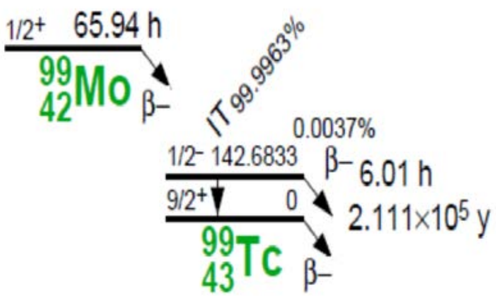
# $^{99m}$Tc medical isotope usage

- **Limited production facilities**
- **Produced from fission of uranium in reactors**
- **Target dissolved and Mo separated from uranium and fission products**
  - **Based on Mo chemistry**
  - **Forms anionic species in solution**

    **→$MoO_4^{2-}$**
- **$^{99}$Mo decays into $^{99m}$Tc**

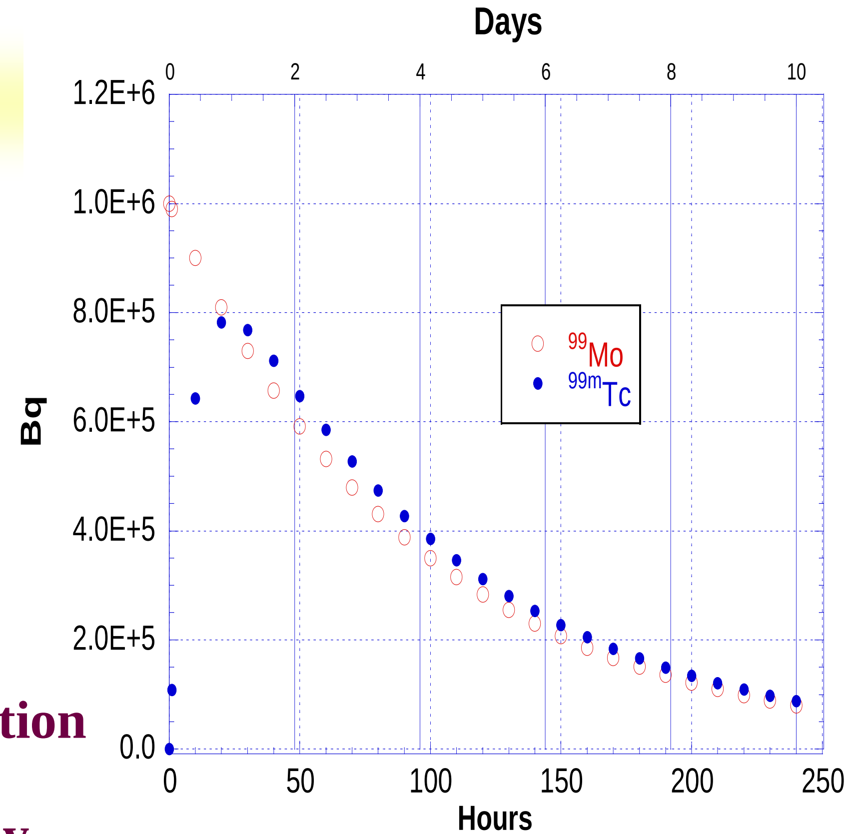
| Country | Name | Thermal power, MW |
| --- | --- | --- |
| Canada | NRU | 135 |
| Netherlands | HFR | 45 |
| Belgium | BR-2 | 100 |
| South Africa | Safari-1 | 20 |
| France | OSIRIS | 70 |
| *Australia* | *OPAL* | *20* |
| *Poland* | *MARIA* | *30* |



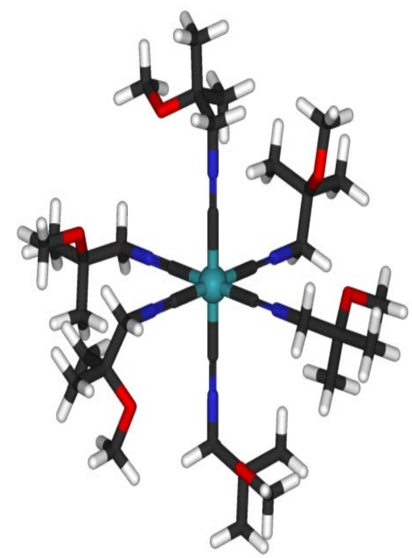



# $^{99m}$Tc generators

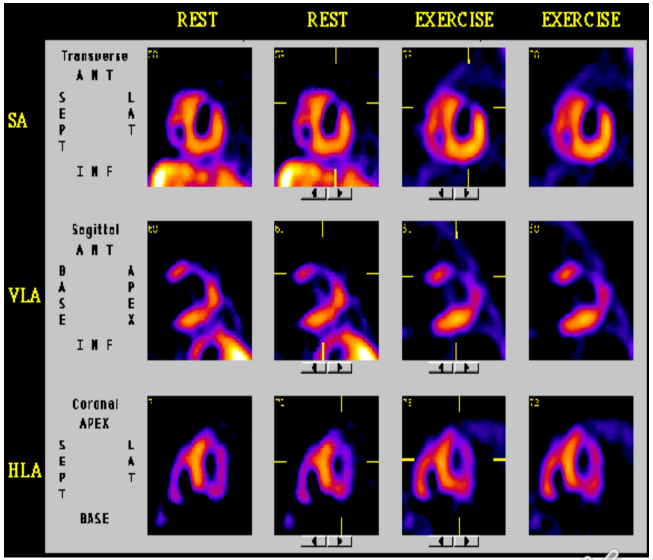
- Commercial $^{99}$Mo/$^{99m}$Tc generators used $Al_2O_3$ chromatography
  - $MoO_4^{2-}$ sorbed to column
- Formed $TcO_4^-$ is less tightly bound
  - Mono anionic
  - Normal saline solution elutes soluble $^{99m}$Tc
  - saline solution containing $^{99m}$Tc
- Added to kit with appropriate concentration to the organ-specific pharmaceutical
- sodium pertechnetate can be used directly without pharmaceutical tagging for specific procedures
- Large percentage of the $^{99m}$Tc generated by a $^{99}$Mo/$^{99m}$Tc generator is produced in the first 3 parent half-lives
  - One week




# Cardiolite

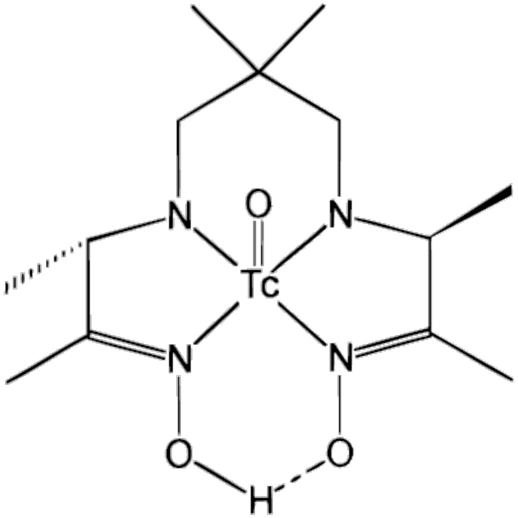


- $[^{99m}Tc(CNCH_2C(Me)_2OMe)_6]^+$
  - 40 million applications since 1990s
- Cation accumulate in mitochondrial membrane
- Complex lipophilicity important for uptake into heart
  - Used in cardiac stress
  - Compare rest and exercise

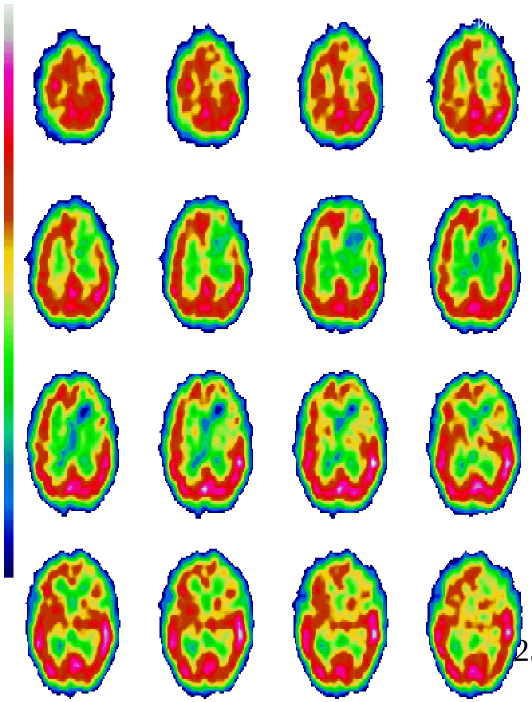


# *Ceretec*

- **Can cross blood-brain barrier**
  - **detected defects in the brain**
    - **→Dementia**
    - **→Strokes**
    - **→Artery issues**

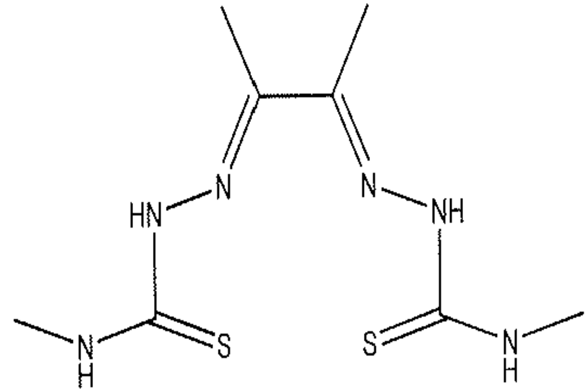



hexamethylpropyleneamineoxime

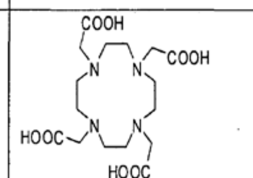
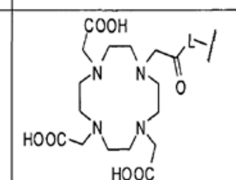
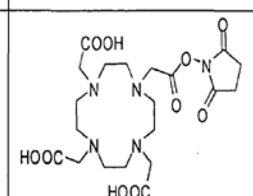
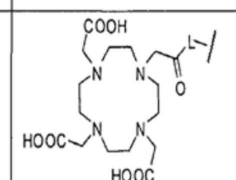
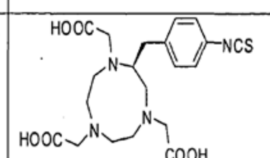
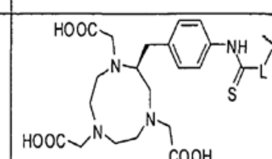


# Other ligands

- **ATSM Characterization**
  - **diacetyl-di-methylthiosemicarbazone**
  - **New radioimaging drug designed to image ischemic tissues**
  - **Examine complexation with Tc**
- **For other metal ions**
  - **DOTA**
    - **→ 1,4,7,10-tetrakis(carboxymethyl)-1,4,7,10-tetraazacyclododecane**
  - **Ligand can be bound to monoclonal antibody**

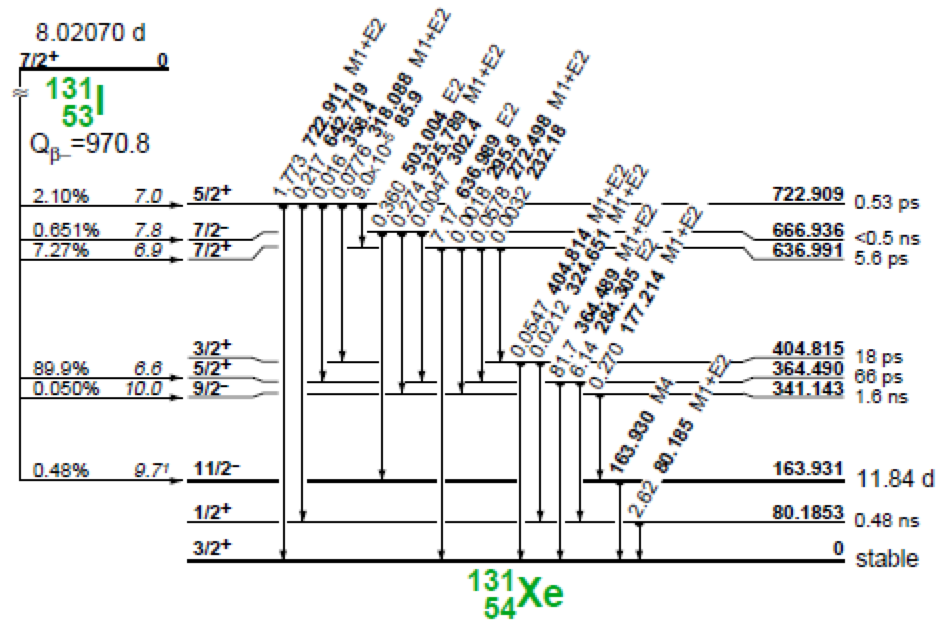


ATSM2

| Chelator | Structure | R |
|---|---|---|
| DOTA |  |  |
| DOTA-NHS |  |  |
| *p*-SCN-Bn-NOTA |  |  |

# $^{131}$I therapy

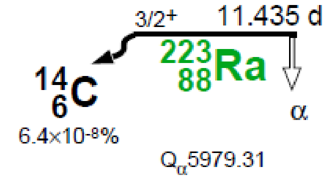
- Based on iodine uptake by thyroid
- $Na^{131}I$
  - No ligand needed
  - Limitation of iodine intake prior to therapy
- $^{131}$I major fission product
  - Cannot use fission I due to presence of other isotopes
- Neutron irradiation of Te
  - $^{131}$Te 25 minute half life
    - → Ion exchange separation of I
    - → Distillation of I and dissolution



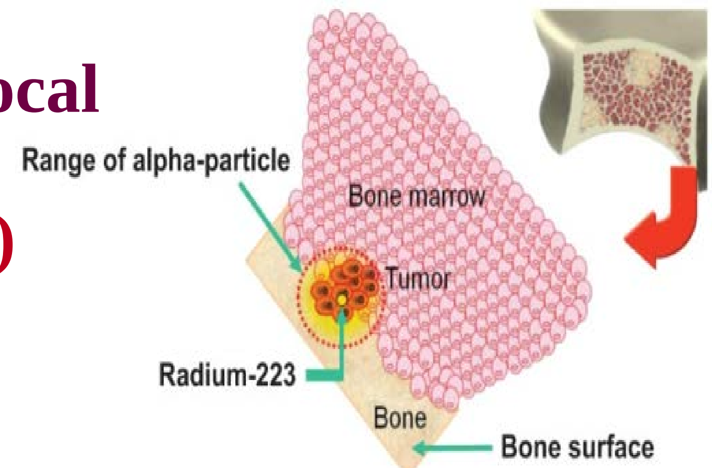

**Gammas from $^{131}$I (8.02070 d *11*)**

| Eγ (keV) | Iγ (%) | Decay mode |
|---|---|---|
| 284.305 *5* | 6.14 *5* | $\beta^-$ |
| 364.489 *5* | 81.7 *6* | $\beta^-$ |
| 636.989 *4* | 7.17 *9* | $\beta^-$ |
| 722.911 *5* | 1.773 *25* | $\beta^-$ |

# Therapeutic: $^{223}RaCl_2$




- Ra is divalent, as is Ca
  - Will go to bone
- Extremely simple chemistry
- Produced from neutron irradiation of $^{226}Ra$
  - $^{227}Ra \rightarrow {}^{227}Ac \rightarrow {}^{227}Th \rightarrow {}^{223}Ra$
    - $\rightarrow$ Decay to $^{219}Rn$
- Treat pain associated with multifocal bone metastases
  - Around 180 µCi (1.35 µCi/kg)
  - First U.S. Food and Drug Administration-approved unsealed α-emitting radiopharmaceutical

# Other Reactor Produced Isotopes

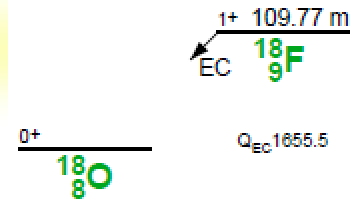
- **Bismuth-213 (46 min): Used for targeted alpha therapy (TAT), especially cancers, as it has a high energy (8.4 MeV).**
- **Chromium-51 (28 d): Used to label red blood cells and quantify gastro-intestinal protein loss.**
- **Dysprosium-165 (2 h): Used as an aggregated hydroxide for synovectomy treatment of arthritis.**
- **Erbium-169 (9.4 d): Use for relieving arthritis pain in synovial joints.**
- **Holmium-166 (26 h): Being developed for diagnosis and treatment of liver tumors.**
- **Iodine-125 (60 d): Used in cancer brachytherapy (prostate and brain), also diagnostically to evaluate the filtration rate of kidneys and to diagnose deep vein thrombosis in the leg. It is also widely used in radioimmuno-assays to show the presence of hormones in tiny quantities.**
- **Iodine-131 (8 d)*: Widely used in treating thyroid cancer and in imaging the thyroid; also in diagnosis of abnormal liver function, renal (kidney) blood flow and urinary tract obstruction.**
- **Iridium-192 (74 d): Supplied in wire form for use as an internal radiotherapy source for cancer treatment (used then removed). Beta emitter.**
- **Iron-59 (46 d): Used in studies of iron metabolism in the spleen.**
- **Lead-212 (10.6 h): Used in TAT for cancers or alpha radioimmunotherapy, with decay products Bi-212 and Po-212 delivering the alpha particles.**
- **Lutetium-177 (6.7 d): Lu-177 is increasingly important as it emits just enough gamma for imaging while the beta radiation does therapy**

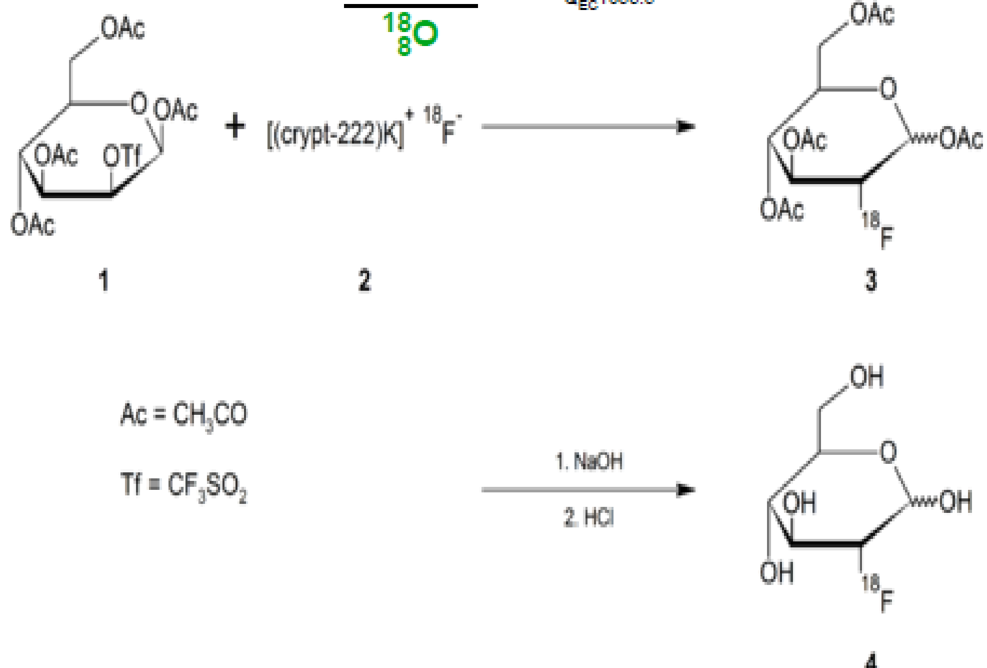
# Other reactor produced isotopes

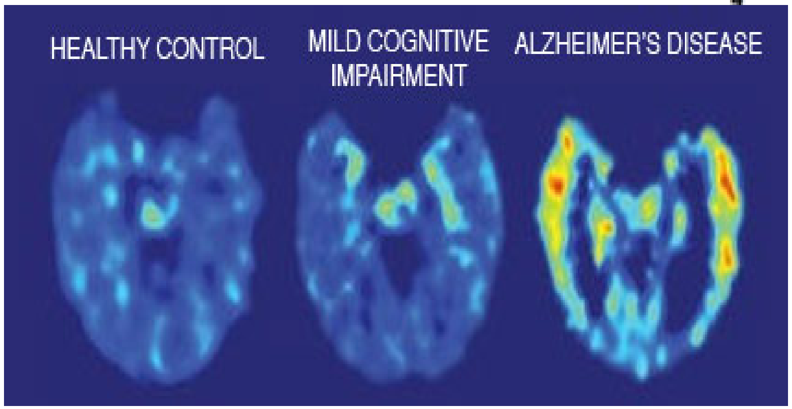
- **Palladium-103 (17 d): Used to make brachytherapy permanent implant seeds for early stage prostate cancer.**
- **Phosphorus-32 (14 d): Used in the treatment of polycythemia vera (excess red blood cells). Beta emitter.**
- **Potassium-42 (12 h): Used for the determination of exchangeable potassium in coronary blood flow.**
- **Rhenium-186 (3.8 d): Used for pain relief in bone cancer. Beta emitter with weak gamma for imaging.**
- **Rhenium-188 (17 h): Used to beta irradiate coronary arteries from an angioplasty balloon.**
- **Samarium-153 (47 h): Sm-153 is very effective in relieving the pain of secondary cancers lodged in the bone**
- **Selenium-75 (120 d): Used in the form of seleno-methionine to study the production of digestive enzymes.**
- **Sodium-24 (15 h): For studies of electrolytes within the body.**
- **Strontium-89 (50 d)*: Very effective in reducing the pain of prostate and bone cancer. Beta emitter.**
- **Xenon-133 (5 d)*: Used for pulmonary (lung) ventilation studies.**
- **Ytterbium-169 (32 d): Used for cerebrospinal fluid studies in the brain.**
- **Yttrium-90 (64 h)*: Used for cancer brachytherapy and as silicate colloid for the relieving the pain of arthritis in larger synovial joints. Pure beta emitter and of growing significance in therapy, especially liver cancer.**

# Positron: $^{18}$F Fluorodeoxyglucose

- $^{18}$F is cyclotron produced
  - $^{18}O(p,n)$ reaction, 11-17 MeV
    - → $H_2{}^{18}O$ as target
  - $^{Nat}Ne(d,\alpha)$, 8-14 MeV
  - Separate F from target and product
    - → from water by anion exchange ($F^-$)
- Half life 109.8 minutes
  - 97 % positron decay



# Cyclotron produced isotopes

- **Carbon-11, Nitrogen-13, Oxygen-15, Fluorine-18: These are positron emitters used in PET for studying brain physiology and pathology, in particular for localizing epileptic focus, and in dementia, psychiatry and neuropharmacology studies. They also have a significant role in cardiology.**
- **Cobalt-57 (272 d): Used as a marker to estimate organ size and for in-vitro diagnostic kits.**
- **Copper-64 (13 h): Used to study genetic diseases affecting copper metabolism, such as Wilson's and Menke's diseases, and for PET imaging of tumors, and therapy.**
- **Copper-67 (2.6 d): Beta emitter, used in therapy.**
- **Gallium-67 (78 h): Used for tumor imaging and localization of inflammatory lesions (infections).**
- **Gallium-68 (68 min): Positron emitter used in PET and PET-CT units. Derived from germanium-68 in a generator.**
- **Germanium-68 (271 d): Used as the 'parent' in a generator to produce Ga-68.**
- **Indium-111 (2.8 d): Used for specialist diagnostic studies, eg brain studies, infection and colon transit studies.**
- **Iodine-123 (13 h): Increasingly used for diagnosis of thyroid function, it is a gamma emitter without the beta radiation of I-131.**
- **Iodine-124: tracer.**
- **Krypton-81m (13 sec) from Rubidium-81 (4.6 h): Kr-81m gas can yield functional images of pulmonary ventilation, e.g. in asthmatic patients, and for the early diagnosis of lung diseases and function.**
- **Rubidium-82 (1.26 min): Convenient PET agent in myocardial perfusion imaging.**
- **Strontium-82 (25 d): Used as the 'parent' in a generator to produce Rb-82.**
- **Thallium-201 (73 h): Used for diagnosis of coronary artery disease other heart conditions such as heart muscle death and for location of low-grade lymphomas. It is the most commonly used substitute for technetium-99 in cardiac-stress tests.**

# Review

- Combination of chemistry and nuclear reactions can be applied isotope utilization
  - All nuclear reactions possible for producing useful isotopes
  - Can isolate from natural decay chains
- Interaction of particle used for evaluating material
  - Particles
  - Presence of water
- Radionuclide can be used for therapeutic and diagnostic applications in radiopharmaceuticals
  - Radionuclide can be free or bound to ligand
  - Dependent upon the
- Research needed to extend use of other isotopes

# Questions

- What nuclear reaction is used to make $^{131}$I for therapy?

Neutron capture on Te
$^{130}$Te(n,$\gamma$)$^{131}$Te
34.08 % of Te is $^{130}$Te
$^{131}$Te beta decay to $^{131}$I

- What is the role of $^{241}$Am in a smoke detector?

Alpha decay of $^{241}$Am ionization source. Decrease in ionization indicates smoke

- What Ra isotope is used as in a radiopharmaceutical?

$^{223}$Ra, half life 11.4 d

- Are $^{99m}$Tc radiopharmaceuticals therapeutic or diagnostic?

$^{99m}$Tc only gamma emission, diagnostic.

# PDF Quiz

- **Comment on blog**
- **Respond to PDF Quiz 11**