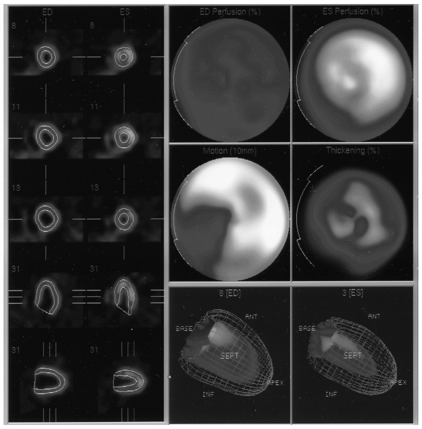
Nuclear Chemistry

Chapter 21

Chemistry 222
Professor Michael Russell



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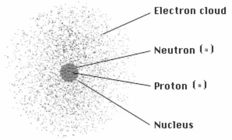
Last update: 4/29/24

Nuclear Chemistry: *the study of the nucleus*



Nucleus = neutrons and protons
Differs from "normal" electron chemistry

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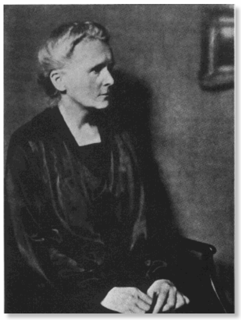
Early Nuclear Chemistry Pioneers:

Marie Curie
Pierre Curie
Henri Becquerel

Noticed beams of light on photographic plates

Danger (and potential) of nuclear chemistry poorly understood

Marie Curie



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Atomic Number, Z

All atoms of the same element have the same number of protons in the nucleus, Z.

13 ⟵ atomic number
Al ⟵ symbol
26.9815 ⟵ atomic weight

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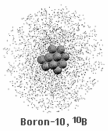
Mass Number, A

Mass Number
= # protons + # neutrons

A boron atom can have
A = 5 p + 5 n = 10 *and*
Z = 5 protons = 5

$$\begin{matrix} A \rightarrow 10 \\ Z \rightarrow 5 \end{matrix} B$$



Boron-10, ^{10}B

Isotopes of boron have **different # of neutrons** but **same # of protons** *(Boron-10, Boron-11)*

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Radioactive Particles

ALPHA	helium nucleus	$^{4}_{2}He$ *or* $^{4}_{2}\alpha$
BETA	electron	$^{0}_{-1}e$ *or* $^{0}_{-1}\beta$
GAMMA	*energy (massless)*	γ
PROTON	proton	$^{1}_{1}p$ *or* $^{1}_{1}H$
NEUTRON	neutron	$^{1}_{0}n$
POSITRON	antielectron	$^{0}_{+1}e$ *or* $^{0}_{+1}\beta$

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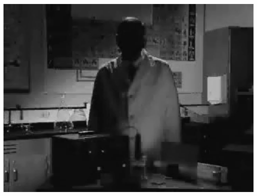
see: Nuclear Chemistry Guide

Radioactive Particles

Each particle has different properties



Alpha **- stopped by clothes**
Beta **- stopped by skin**
Gamma **- stopped by lead**

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Balancing Nuclear Reactions

*** Number of *reactant* protons must equal the number of *product* protons**

*** Number of *reactant* neutrons must equal the number of *product* neutrons**

Example:

$${}^{226}_{88}\text{Ra} \longrightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$$

$$\text{A: } 226 = 4 + 222$$
$$\text{Z: } 88 = 2 + 86$$

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Balancing Nuclear Reactions

Problem: Uranium-235 decomposes through beta decay to a new product. Find the identity of the new product.

Solution:

Uranium has 92 protons, so: ${}^{235}_{92}\text{U}$

Beta decay **means "losing a beta particle", or generating a beta particle as a product, so:**

$${}^{235}_{92}\text{U} \longrightarrow {}^{0}_{-1}\text{e} + {}^{A}_{Z}\text{X}$$

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Balancing Nuclear Reactions

Problem: Uranium-235 decomposes through beta decay to a new product. Find the identity of the new product.

$${}^{235}_{92}\text{U} \longrightarrow {}^{0}_{-1}\text{e} + {}^{A}_{Z}\text{X}$$

Solution:

235 = 0 + A, therefore A = 235
92 = -1 + Z, therefore Z = 93
If Z = 93, X = Neptunium (Np), and

$$\boxed{{}^{235}_{92}\text{U} \longrightarrow {}^{0}_{-1}\text{e} + {}^{235}_{93}\text{Np}}$$

The "inner reaction":

$${}^{1}_{0}\text{n} \longrightarrow {}^{0}_{-1}\text{e} + {}^{1}_{1}\text{p}$$

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Emission, Decay and Capture

Emission and Decay imply a *product* particle

An example of positron emission:

$$\boxed{{}^{207}_{84}\text{Po} \longrightarrow {}^{0}_{+1}\beta + {}^{207}_{83}\text{Bi}}$$

Capture implies a *reactant* particle

An example of neutron capture:

$$\boxed{{}^{19}_{9}\text{F} + {}^{1}_{0}\text{n} \longrightarrow {}^{20}_{9}\text{F}}$$

Many types of "particles" and "decays"

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Positrons and Antimatter

Paul Dirac first predicted antimatter in 1928, identical to "regular" matter except for opposite charge

Positrons are antielectrons; combining with electrons leads to annihilation *(gamma)*

$$\boxed{{}^{0}_{-1}\text{e} + {}^{0}_{+1}\text{e} \longrightarrow 2\gamma}$$

electron + positron ---> gamma radiation
Used in Positron Emission Tomography (PET)

Many examples of annihilation reactions are known:

$$\boxed{\nu + \bar{\nu} \longrightarrow 2\gamma}$$

neutrino + antineutrino ---> gamma radiation

Neutrino first postulated by Pauli (CH 221)

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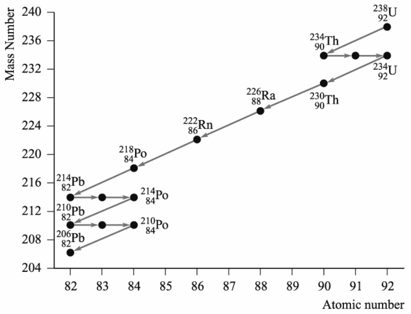
Decay Scheme for Uranium-238



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Metastable Nuclei

When *electrons* are excited in an atom, they relax and emit UV, IR and visible radiation

A metastable nuclei is created when a *nucleus* is excited. Relaxation results in high energy gamma ray emission

$$^{99m}_{43}\text{Tc} \longrightarrow {}^{99}_{43}\text{Tc} + \gamma$$

metastable Tc ---> "regular" Tc + gamma ray
Note the "m" for "metastable" and no change in atomic or mass numbers

Metastable nuclei (*especially Technetium-99m*) used extensively in medical imaging

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The Four Forces of Nature

Gravitation: weak, long range force

Weak nuclear: short range, gives beta decay

Electromagnetic (E/M): long range, keeps electrons around nucleus, 10^{36} times more powerful than gravity (*aka* electrostatic, Coulombic, etc.)

Strong nuclear: 10^{6} times more powerful than E/M, *very* short range (10^{-15} m); overpowers E/M repulsion between protons. Strong keeps (protons + neutrons) and (neutrons + neutrons) together. "Glue" that keeps nucleus together

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Nuclear Stability

Why are nuclei unstable? E/M Force (long range) begins overpowering strong force (short range)

Magnetic dilution* (more neutral neutrons than positive protons) helps stabilize nuclei - *to a point

Up to calcium (Z = 20), most stable nuclei occur when # protons = # neutrons

***Exceptions:* helium-3 and hydrogen-1**

Up to lead (Z = 82), most stable nuclei occur when # protons < # neutrons

Beyond lead, all isotopes unstable and radioactive

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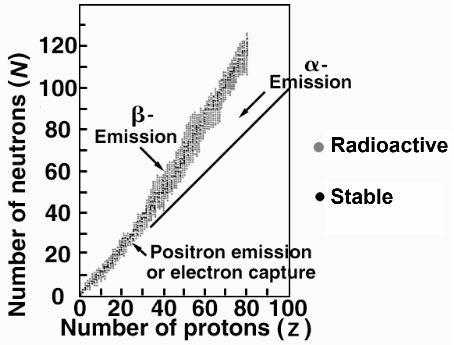

A "peninsula of stability" (black dots) in a "sea of instability" (red dots)

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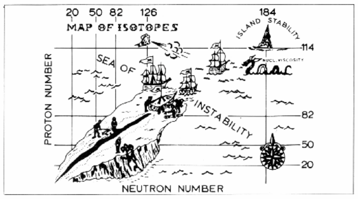
An "Island of Stability"?



Glenn Seaborg and Ken Moody believe that heavier elements can be made - *exciting!*

Interested? See: http://www.pbs.org/wgbh/nova/sciencenow/3313/02.html

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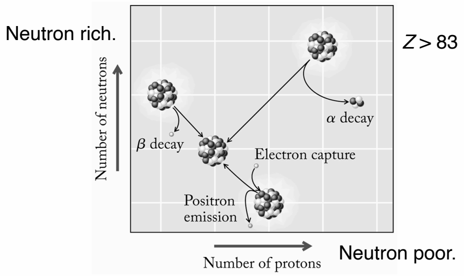
Nuclear Stability

Isotopes *often* decay based on their number of neutrons:



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Nuclear Stability

β-decay occurs in isotopes with a high neutron to proton ratio. *Result:* higher atomic number, same mass number

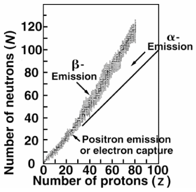
$$^{235}_{92}\mathrm{U} \longrightarrow {}^{0}_{-1}\mathrm{e} + {}^{235}_{93}\mathrm{Np}$$

Low neutron to proton ratio: **positron emission** or **electron capture**. *Result:* lower atomic number, same mass number

$$^{13}_{7}\mathrm{N} \longrightarrow {}^{0}_{+1}\mathrm{e} + {}^{13}_{6}\mathrm{C}$$

All elements beyond Bi decay, usually by **α-decay**

$$^{226}_{88}\mathrm{Ra} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{222}_{86}\mathrm{Rn}$$



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Nuclear Stability

Energy required to overcome positive-positive repulsion of protons is substantial - use strong *(and weak)* forces

- *Strong and weak forces much stronger than electromagnetic force or gravity*

Nuclear binding energy, E_b, used to estimate force contribution

- **E_b is the negative of the energy change if nucleus formed directly from individual protons and neutrons**

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Nuclear Stability

Problem: Calculate the binding energy, E_b, for deuterium (hydrogen-2).

Solution:

The process: $^{1}_{1}\mathrm{p} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{2}_{1}\mathrm{H}$

Note that: $\mathrm{mass}_p + \mathrm{mass}_n \neq \mathrm{mass}_D$

$$1.007825 + 1.00865 \neq 2.01410$$

$$2.016475 \neq 2.01410$$

$$\Delta m = -0.00239 \text{ g/mol}$$

mass is *not* conserved!

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Nuclear Stability

Problem: Calculate the binding energy, E_b, for deuterium (hydrogen-2). $\Delta m = -0.00239$ g/mol

Solution:

Now use <u>Einstein's equation</u>: $\Delta E = \Delta mc^2$

$\Delta E = (-2.39 \times 10^{-6} \text{ kg mol}^{-1})(2.998 \times 10^{8} \text{ m s}^{-1})^2$

$\Delta E = -2.15 \times 10^{11}$ J mol^{-1}, ***and***

$E_b = -\Delta E$, **so**

$E_b = 2.15 \times 10^{8}$ kJ mol^{-1}

E very negative (exothermic) - lots of energy produced. E_b very positive - lots of energy saved through stabilization

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Nuclear Stability

Problem: **Calculate the binding energy, E_b, for deuterium (hydrogen-2). $\Delta m = -0.00239$ g/mol**

Solution:

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$\Delta E = -2.15 \times 10^{11}$ J mol^{-1}, ***and***

$E_b = -\Delta E$, **so**

$E_b = 2.15 \times 10^{8}$ kJ mol^{-1}

<u>E_b per nucleon</u> $= 2.15 \times 10^{8} / (1 \text{ p} + 1 \text{ n})$ ***nucleons***

$= 1.08 \times 10^{8}$ kJ mol^{-1} nucleon^{-1}

This is the strong force contribution in the nucleus!

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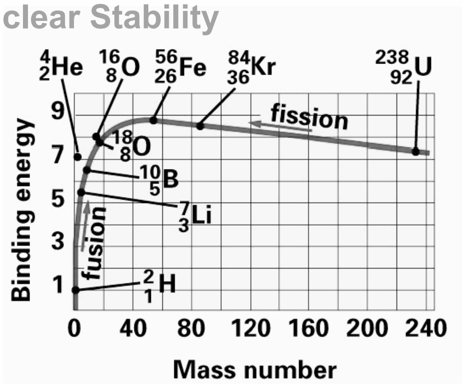
Nuclear Stability

Can use Binding energy (E_b) to calculate stability of nuclei:



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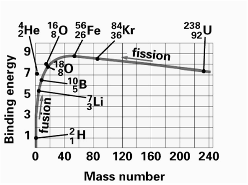
Nuclear Stability

Note that iron-56 is the most stable element *thermodynamically* - end of solar cycles, etc.

Elements with Z < 26 can use fusion to become more like iron-56

Elements with Z > 26 can use fission to become more like iron-56

***Kinetics* of nuclear reactions important - half life, rate of decay, etc.**



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Tremendous amounts of energy are generated when light nuclei combine to form heavier nuclei - nuclear fusion

"Clean" energy, used in stars and bombs, requires *plasma* and/or high temperatures - high activation energy barrier

No "meltdown" - reaction just stops, no waste

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \longrightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

$E = -1.7 \times 10^{9}$ kJ/mol

Fusion

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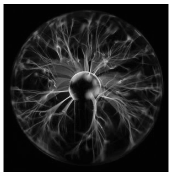
Plasma



Plasma is the fourth state of matter - along with solids, liquids and gases

Plasma is an electrically conducting fluid composed of freely roaming electrons and ions; strong magnetic and electric fields; hot!

Plasmas comprise the vast majority of the apparent universe, and only in occasional "islands" (like the planet Earth) is matter found in condensed forms (solids, liquids, gases)!

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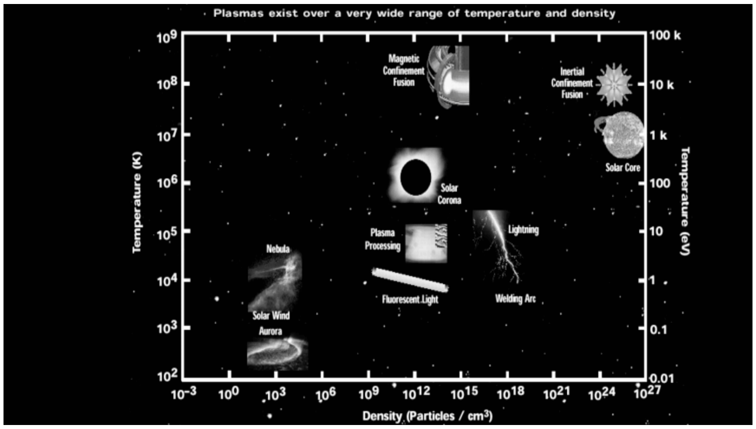

Plasma - *in your microwave?*

Video by Sergiu and Ben Todor 2010

Grape microwave "plasma" - ?!?

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Fusion - *Tokamak Reactor*

Tokamak reactor uses magnetic fields to constrict plasma for fusion in "donut" shape; most promising "future" magnetic fusion device

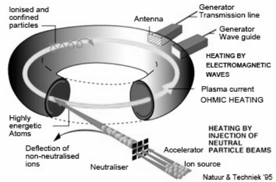

Figure 2: Various tokamak plasma heating techniques

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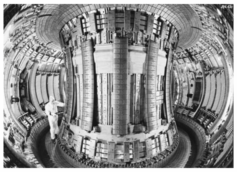
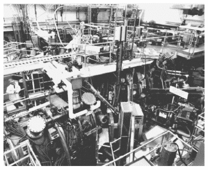
Fusion - *Tokamak Reactor*





Tokamak reactors - *inside* and *outside* views

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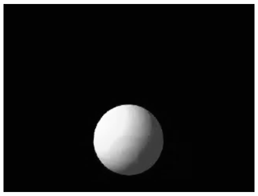
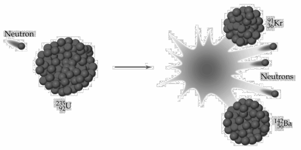
Fission

- **Tremendous amounts of energy *(electricity)* generated when heavy nuclei split to form lighter nuclei - *nuclear fission***
- **Generally requires a "neutron trigger"**





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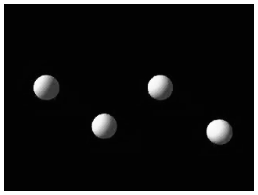
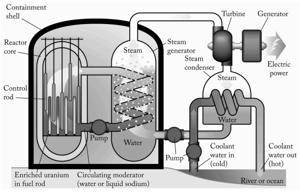
Fission

- **Excess neutrons *must* be controlled! *Supercritical chain reactions* can result without proper caution**
- **Waste products from fission messy and virtually perpetual**
- ***More than 400 nuclear fission plants in 30 different countries!***





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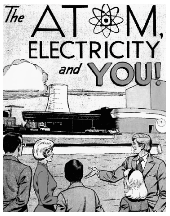
Uses for Nuclear Chemistry

Energy: Fission (commercial) *and* Fusion (coming!)

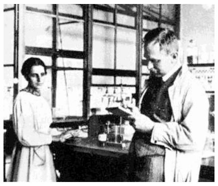


Nuclear fission "problem events":

- SL-1, Idaho Falls (1961)
- Three Mile Island, Pennsylvania (1979)
- Chernobyl, Ukraine (1986)
- Fukushima Daiichi, Japan (2011)
- Hanford, Washington (ongoing!)

LISE MEITNER - *unsung hero*

With Otto Hahn



- **Meitner and colleagues Otto Hahn, Fritz Strassmann & Otto Frisch explained the process of fission (1938)**
- **Meitnerium (Mt, #109) named after her**
- **Forced to work in basement, never got Nobel Prize (but Hahn did!)**
- **Pioneering woman in a male-dominated field; deserves more credit for her work**

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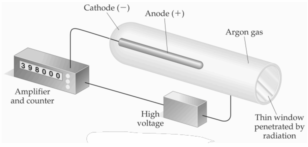
Radiation and Health

Some radiation is around us all of the time



Geiger counters measure the amount of radioactive activity present in a sample. The radiation creates ions which conduct a detectable current.

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Radiation and Health

Many units for radiation exposure - röntgen (R), curie (Ci), rad, rem, *others*

The röntgen is a measure of radiation exposure proportional to air ionization (*X*- and γ-rays)

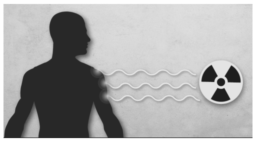
***Ex:* chest X-ray = 0.1 R**

rem = röntgen equivalent man

One curie = quantity of any isotope that undergoes $3.7 * 10^{10}$ *dps* (disintegrations per second)

One rad = $1.00 * 10^{-5}$ J absorbed per gram of material.

A whole-body dose of 450 rad = LD_{50} for humans



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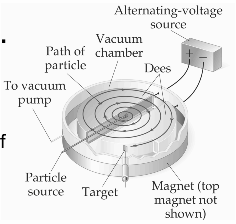
Nuclear Transformations

Nuclear transformations can be induced by accelerating a particle and colliding it with the nuclide.

- **Linear accelerator**—uses alternating electric fields to accelerate particle.
- **Cyclotron**—uses combination of electric and magnetic fields to accelerate particles in spiral pathway.



Cyclotron

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Particle Accelerators

These particle accelerators are *enormous*, having circular tracks with radii that are miles long. New elements created by "smashing" smaller nuclei together.

CERN Particle Accelerator, Geneva, Switzerland

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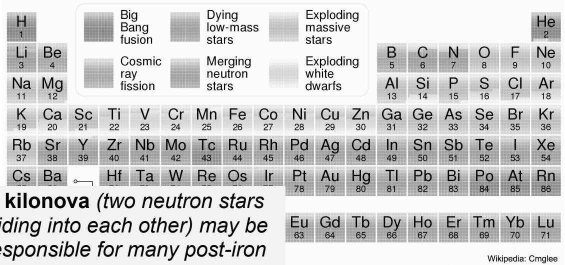
Uses for Nuclear Chemistry

Astronomers and chemists work together to define the origin of elements. Many made through fusion, some via fission, much not understood



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

*A **kilonova** (two neutron stars sliding into each other) may be responsible for many post-iron elements on the Earth*

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NSCL = *National Superconducting Cyclotron Laboratory at Michigan State University (http://www.nscl.msu.edu/)*

Full video *available here:* **https://youtu.be/677ZmPEFIXE**

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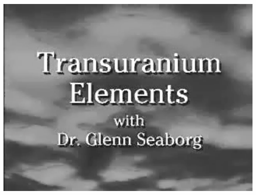
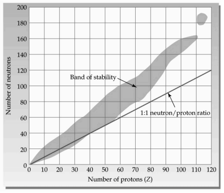
Uses for Nuclear Chemistry

Uses for Nuclear Chemistry

Expanding the Frontiers of Science





Dr. Glenn Seaborg (1912 - 1999)

Uses for Nuclear Chemistry

Radiocarbon Dating

$t_{1/2}$ = 5730 years for carbon-14
Accurate up to 60,000 years old!

Uses for Nuclear Chemistry

Medicine: PET *and* MRI

Tc (in PET) not found in nature, created via Mo:

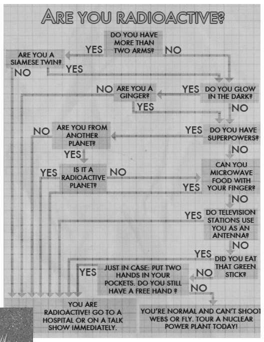
$$^{99}_{42}\text{Mo} \longrightarrow {}^{0}_{-1}\text{e} + {}^{99\text{m}}_{43}\text{Tc}$$

- Tc-99*m*: metastable; $t_{1/2}$ = 6.0 hrs.
- Can be incorporated into variety of compounds to target specific organs (heart, etc.).

PET = Positron Emission Tomography
MRI = Magnetic Resonance Imaging

End of Chapter 21

See:
- *Chapter Twenty-one Study Guide*
- *Chapter Twenty-one Concept Guide*
- *Important Equations (following this slide)*
- *End of Chapter Problems (following this slide)*



Important Equations, Constants, and Handouts from this Chapter:

- **all** *of the* **first order kinetics** *equations apply. See the* **Nuclear Chemistry Guide** *(handout)*
- **decay** *or* **emission = product**
- **capture = reactant**
- **know how to balance nuclear reactions**

$$-E_b = \Delta E = \Delta mc^2$$

c *= speed of light =*
2.998 x 10^8 m/s
use **kg/mol** *for* Δ**m**

1st Order Integrated Rate Law;

$$ln\frac{[R]}{[R_0]} = -kt$$

$$t_{\frac{1}{2}} = \frac{0.693}{k}$$

End of Chapter Problems: *Test Yourself*

1. What particle is emitted when Gold-198 decays to mercury-198?
2. What particle is emitted when radon-222 decays to polonium-218?
3. What particle is emitted when indium-110 decays to cadmium-110?
4. What is emitted when hafnium-178m decays?
5. Boron has two stable isotopes, ^{10}B and ^{11}B. Calculate the binding energies per nucleon of these two nuclei. The required masses (in grams per mole) are proton = 1.00783, neutron = 1.00867, boron-10 = 10.01294, and boron-11 = 11.00931.
6. Gold-198 is used in the diagnosis of liver problems. The half-life of ^{198}Au is 2.69 days. If you begin with 2.8 μg of this gold isotope, what mass remains after 10.8 days?

End of Chapter Problems: ***Answers***

1. beta particle
2. alpha particle
3. positron particle
4. hafnium-178
5. boron-10: 6.26 x 10^8 kJ/mol·nucleons; boron-11: 6.70 x 10^8 kJ/mol·nucleons
6. 0.17 µg

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