Nuclear Reactions

- **Result from transformations in the nucleus**
- **Involve protons and neutrons**
- **Often result in *transmutation* into more stable elements**

- **Participants:**

Energy	Type	Symbol(s)	Charge	Mass (g/particle)
Low	Alpha	${}^{4}_{2}\mathrm{He}$, ${}^{4}_{2}\alpha$	+2	6.65×10^{-24}
Intermediate	Beta	${}^{0}_{-1}\mathrm{e}$, ${}^{0}_{-1}\beta$	-1	9.11×10^{-28}
High	Gamma	${}^{0}_{0}\gamma$, γ	0	0
Intermediate	Positron	${}^{0}_{+1}\beta$	+1	9.11×10^{-28}

Nuclear Reactions

How the heck do we get an electron (β-particle) out of (or in to) the nucleus???

- Conversion of a neutron to a proton → β emission

$$ {}^{1}_{0}\mathrm{n} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{1}_{1}\mathrm{p} $$

- Conversion of a proton to a neutron → e^- capture

$$ {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{1}_{0}\mathrm{n} $$

Balancing Nuclear Reactions:

- Total number of **nucleons** (protons and neutrons) remains the same on both sides of the arrow.
- Total mass remains the same (matter isn't created or destroyed)

Examples:

Alpha emission from ${}^{226}\mathrm{Ra}$:
Beta emission from ${}^{214}\mathrm{Pb}$:
Electron Capture by ${}^{41}\mathrm{Ca}$:

Why Do Nuclear Reactions Occur?

- Reactions occur as the nucleus tries to reach a stable neutron:proton ratio
  - “Peninsula of Stability”
- Ratio depends on "size" of nucleus
  - Balance between proton repulsion and size
  - Reactions continue until stable n:p ratio is reached

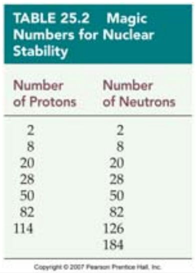


TABLE 25.2 Magnic Numbers for Nuclear Stability

Number of Protons	Number of Neutrons
2	2
8	8
20	20
28	28
50	50
82	82
114	126
	184

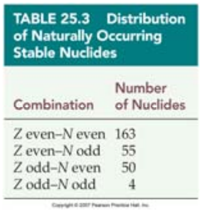
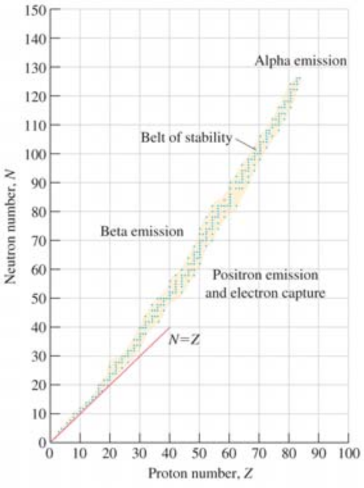


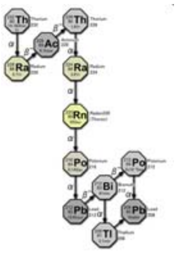
TABLE 25.3 Distribution of Naturally Occurring Stable Nuclides

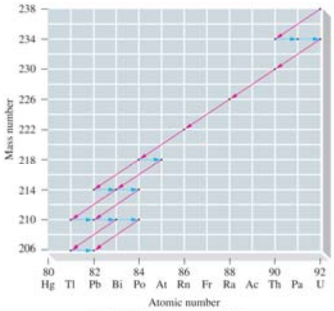
Combination	Number of Nuclides
Z even–N even	163
Z even–N odd	55
Z odd–N even	50
Z odd–N odd	4

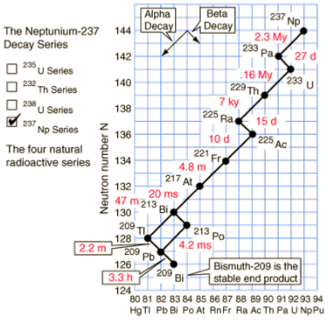


Radioactive Decay

- All nucleii of atomic number > 83 are unstable
  - Undergo spontaneous decay
  - Merge into one of three (four?) decay series
    - Uranium, thorium, actinium (*neptunium?)*
    - ^{238}U, ^{232}Th, ^{235}U, *^{237}Np*







Energy Changes in Nuclear Reactions

Something must hold the nucleus together.

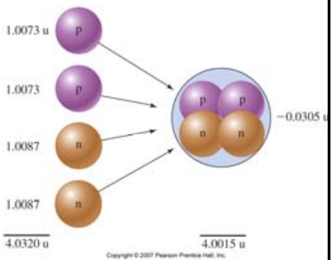
- Nuclear Binding Energy: generally huge!
- Nucleus + Nucleon → New Nucleus reaction is typically exothermic.

Energy comes as a result of the *mass defect:*

- During nuclear synthesis, the mass of the new nucleus is always smaller than the masses of the component nucleons.
- This small, "missing mass" is apparently converted to energy ($E = mc^2$).
- Because c is so large (3×10^8 m/s) even a small mass defect gives rise to tremendous energy.

  1MeV = 1.6022×10^{-13}J

  ~10^{-10}J per amu mass defect



Kinetics of Radioactive Decay:

Nucleus → New Nucleus + Radiation

- Decay follows first-order rate law

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

- Often talk about *half-life,* $t_{1/2} = 0.693/\lambda$
  - Time needed for half of the material to undergo decay. (Time for $N \rightarrow \frac{1}{2}N_0$)
- Half-Lives vary from fractions of a second to millions of years.

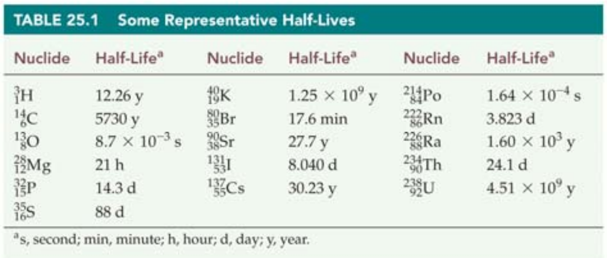


TABLE 25.1 Some Representative Half-Lives

Nuclide	Half-Life[a]	Nuclide	Half-Life[a]	Nuclide	Half-Life[a]
$^{3}_{1}\text{H}$	12.26 y	$^{40}_{19}\text{K}$	1.25×10^{9} y	$^{214}_{84}\text{Po}$	1.64×10^{-4} s
$^{14}_{6}\text{C}$	5730 y	$^{80}_{35}\text{Br}$	17.6 min	$^{222}_{86}\text{Rn}$	3.823 d
$^{13}_{8}\text{O}$	8.7×10^{-3} s	$^{90}_{38}\text{Sr}$	27.7 y	$^{226}_{88}\text{Ra}$	1.60×10^{3} y
$^{28}_{12}\text{Mg}$	21 h	$^{131}_{53}\text{I}$	8.040 d	$^{234}_{90}\text{Th}$	24.1 d
$^{32}_{15}\text{P}$	14.3 d	$^{137}_{55}\text{Cs}$	30.23 y	$^{238}_{92}\text{U}$	4.51×10^{9} y
$^{35}_{16}\text{S}$	88 d				

[a] s, second; min, minute; h, hour; d, day; y, year.

Radiocarbon Dating: Application of Decay Kinetics

- ${}^{14}C$ concentration (activity) in living material is essentially constant. (15 dpm/g carbon)
  - ${}^{14}C$ is continually being produced in the upper atmosphere.
  - ${}^{14}C$ is continually being consumed by living organisms in the carbon cycle.

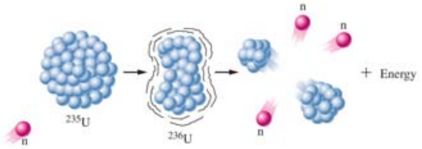
- Once the living organism dies, β-decay causes the activity to decrease. ($t_{1/2}$ = 5730 years).
  - First-order kinetics tells us how long the decay process has been occurring.

- **Example**: A wooden Japanese garden statue from the Kamakura period had a carbon-14 activity of 12.9 dpm/g in 1990. What is the approximate age of the statue?

Alternative Energy Sources: Fission

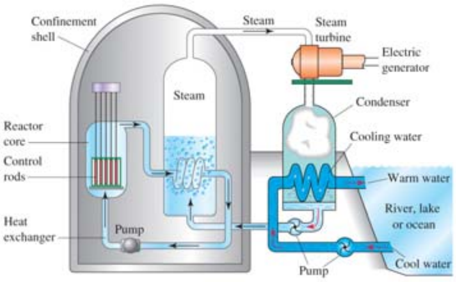
- **Fission Reactions:** "Splitting" the nucleus.

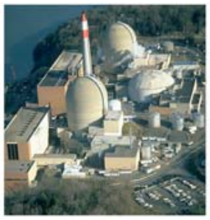
$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$$



- **Tremendous** energy release (2×10^{10} kJ/mol!!)
  - This energy is transferred to heat in nuclear power plant.
- Production of 3 neutrons/mol leads to **chain reaction**
  - Provided *critical mass* is retained.

Fission Reactor – Based Power





- Control rods (neutron absorbers) are used to regulate reaction.

- Requires uranium that is enriched in ^{235}U (<1% naturally)
  - Breeder Reactors: convert abundant, nonfissile ^{238}U to fissile material.
- Produces highly radioactive waste.
  - Much with long half-life

Alternative Energy Sources: Fusion

- Several potential reactions, such as

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

- Potential for a tremendous amount of energy
  - Lots of deuterium in the ocean!
  - Enough potential energy for 1,000,000 years!
  - So what’s the holdup?!?

- Requires tremendous amount of heat and pressure to sustatin
  - ~10,000,000 K (hot!)
  - Need to maintain and contain plasma

- Not radiation-free. Neutrons have to go somewhere!
  - But much less waste than fusion

Monitoring Exposure to Radiation

rad = "radiation absorbed dose": energy absorbed per gram of material.

rem = “radiation equivalent man": accounts for varying effects of α, β and γ radiation.

rem = rad x quality factor

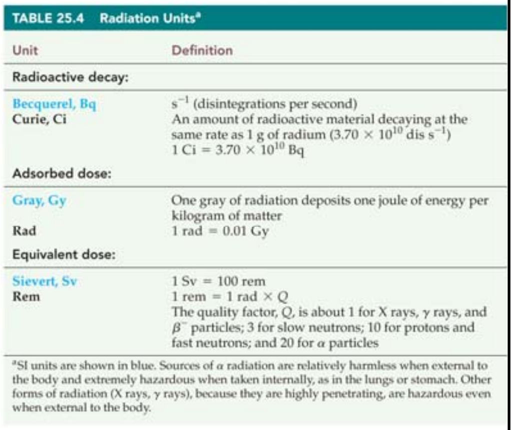
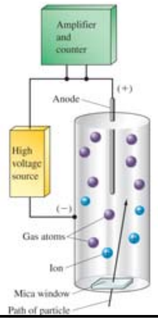


TABLE 25.4 Radiation Units[a]

Unit	Definition
Radioactive decay:	
Becquerel, Bq	s^{-1} (disintegrations per second)
Curie, Ci	An amount of radioactive material decaying at the same rate as 1 g of radium (3.70×10^{10} dis s^{-1}) 1 Ci = 3.70×10^{10} Bq
Adsorbed dose:	
Gray, Gy	One gray of radiation deposits one joule of energy per kilogram of matter
Rad	1 rad = 0.01 Gy
Equivalent dose:	
Sievert, Sv	1 Sv = 100 rem
Rem	1 rem = 1 rad × Q The quality factor, Q, is about 1 for X rays, γ rays, and β^- particles; 3 for slow neutrons; 10 for protons and fast neutrons; and 20 for α particles

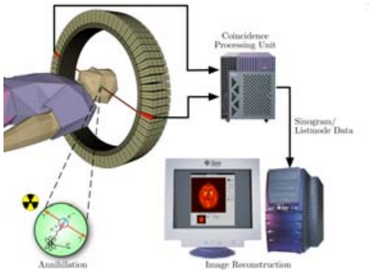
[a] SI units are shown in blue. Sources of α radiation are relatively harmless when external to the body and extremely hazardous when taken internally, as in the lungs or stomach. Other forms of radiation (X rays, γ rays), because they are highly penetrating, are hazardous even when external to the body.



Applications of Nuclear Chemistry

Medical Applications

- PET Scans
- Radiotracers
- Cancer therapy



Fundamental Applications

- Reaction mechanisms
- Chemical structures
- Chemical analysis
  - Neutron activation analysis: http://www.metmuseum.org/special/set_in_stone/index.asp