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	$6.65\text{x}10^{-24}$
Intermediate	Beta	${}^{0}_{-1}\mathrm{e},\ {}^{0}_{-1}\beta$	-1	$9.11\text{x}10^{-28}$
High	Gamma	${}^{0}_{0}\gamma,\ \gamma$	0	0
Intermediate	Positron	${}^{0}_{+1}\beta$	+1	$9.11\text{x}10^{-28}$

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

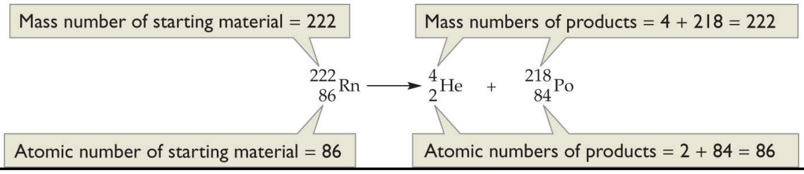
$${}^{1}_{0}\mathrm{n} \rightarrow {}^{0}_{-1}\mathrm{e} + {}^{1}_{1}\mathrm{p}$$

- 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.
- A balanced nuclear equation is one where the sum of the mass numbers (the top number in notation) and the sum of the atomic numbers balance on either side of an equation.



Mass number of starting material = 222

Mass numbers of products = 4 + 218 = 222

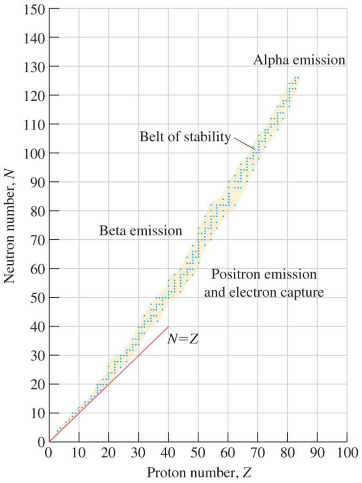
$${}^{222}_{86}\mathrm{Rn} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{218}_{84}\mathrm{Po}$$

Atomic number of starting material = 86

Atomic numbers of products = 2 + 84 = 86

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



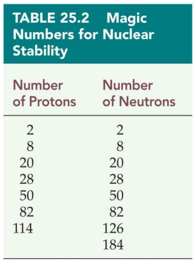


TABLE 25.2 Magic Numbers for Nuclear Stability

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

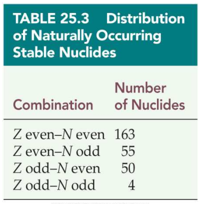
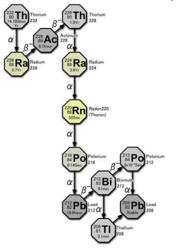


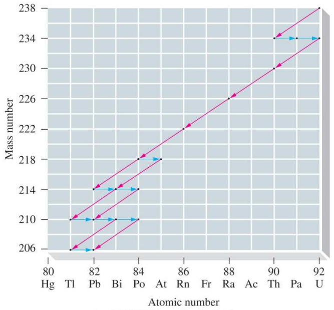
TABLE 25.3 Distribution of Naturally Occurring Stable Nuclides

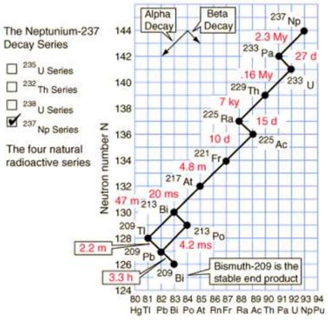
Combination	Number of Nuclides
Z even–N even	163
Z even–N odd	55
Z odd–N even	50
Z odd–N odd	4

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.

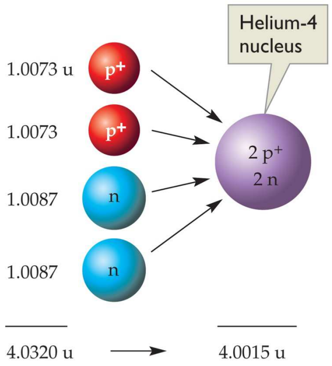
- Nuclear Binding Energy: generally huge!
- Nucleus + Nucleon → New Nucleus reaction is typically exothermic.

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

- Often talk about *half-life*
  - 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.

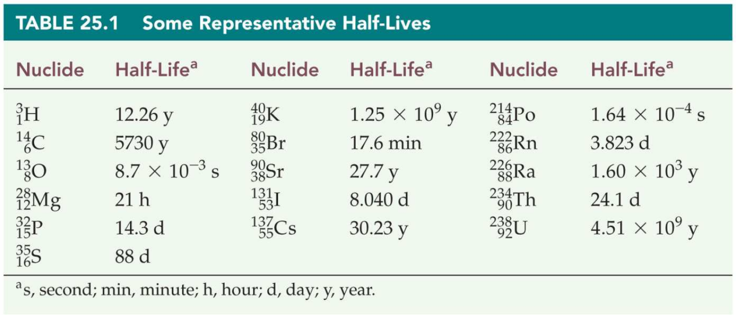


TABLE 25.1 Some Representative Half-Lives

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

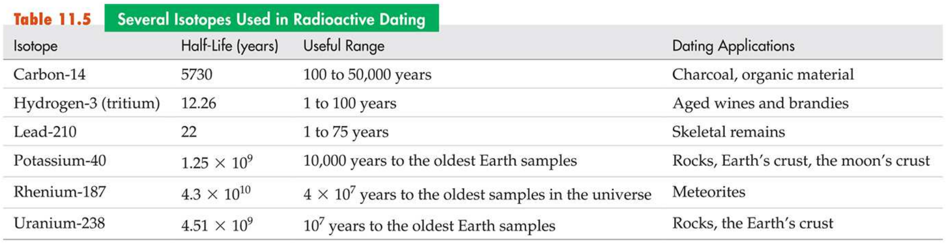


Table 11.5 Several Isotopes Used in Radioactive Dating

Isotope	Half-Life (years)	Useful Range	Dating Applications
Carbon-14	5730	100 to 50,000 years	Charcoal, organic material
Hydrogen-3 (tritium)	12.26	1 to 100 years	Aged wines and brandies
Lead-210	22	1 to 75 years	Skeletal remains
Potassium-40	1.25×10^9	10,000 years to the oldest Earth samples	Rocks, Earth’s crust, the moon’s crust
Rhenium-187	4.3×10^{10}	4×10^7 years to the oldest samples in the universe	Meteorites
Uranium-238	4.51×10^9	10^7 years to the oldest Earth samples	Rocks, the Earth’s crust

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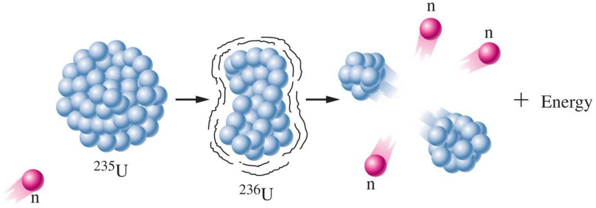
Alternative Energy Sources: Fission

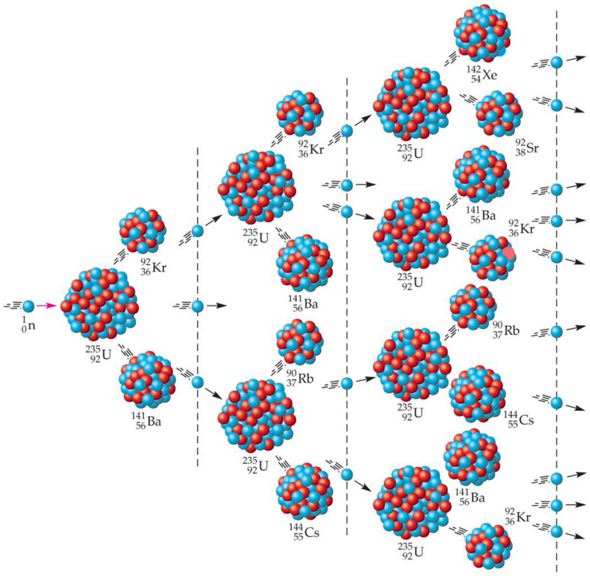
- **Fission Reactions:** "Splitting" the nucleus.

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

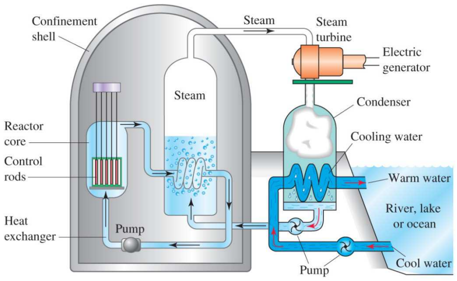


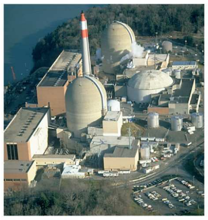
- **Tremendous** energy release (2x10^{10} kJ/mol!!)
  - This energy is transferred to heat in nuclear power plant.
- Production of 3 neutrons/mol leads to **chain reaction**
  - Provided *critical mass* is retained.

Nuclear Chain Reaction



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

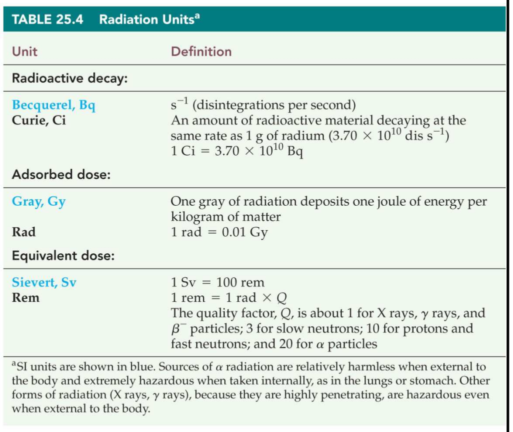
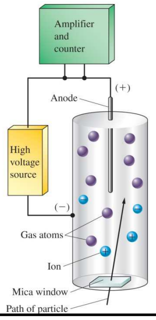


TABLE 25.4 Radiation Units[a]

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

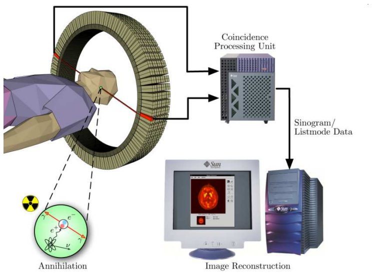
[a] SI units are shown in blue. Sources of α radiation are relatively harmless when external to the body and extremely hazardous when taken internally, as in the lungs or stomach. Other forms of radiation (X rays, γ rays), because they are highly penetrating, are hazardous even when external to the body.



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