Nuclear Chemistry

- Up to now, we have been concerned mainly with the electrons in the elements—the nucleus has just been a positively charged things that attracts electrons
- The nucleus may also undergo changes
- Radioactivity results when the nucleus changes
- Radioactivity is the emission of particles or light by the nucleus

Nuclear Terminology

Nuclide—type of atom specified by its atomic number, atomic mass, and energy state, such as carbon-14

Nucleon—proton or neutron, especially as part of an atomic nucleus

Unstable isotope—natural or artificially created isotope having an unstable nucleus that decays, emitting alpha, beta, or gamma rays until stability is reached

Nuclear Chemistry

- We use a special notation to describe nuclear particles:

$$^{\text{mass \#}}_{\text{atomic \#}}X$$

X is elemental symbol

The mass number is total number of protons and neutrons in the nucleus

The atomic number is the total number of protons in the nucleus—determines identity of species

Nuclear Chemistry

- Examples:

  $^{12}_{6}C$: Carbon with 6 neutrons

  $^{13}_{6}C$: Carbon with 7 neutrons

  $^{235}_{92}U$: Uranium with 143 neutrons

  $^{238}_{92}U$: Uranium with 146 neutrons
- Neutrons act as glue to hold the nucleus together
  - for the smaller elements, the ratio of neutron to proton is ~1:1
  - as size increase, the ratio of neutron to proton increases to ~ 2:1

Types of Radioactivity

- There are three types of radioactive emissions

1. Alpha particles—alpha particles are simply the nucleus of helium, *i.e.*, 2 protons and 2 neutrons

   The symbol for an alpha particle is ${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$

2. Beta particles—beta particles are simply electrons

   The symbol for beta particles is ${}^{0}_{-1}\beta$

3. Gamma rays—gamma radiation consists of high energy photons

   The symbol for gamma radiation is ${}^{0}_{0}\gamma$

Nuclear Reactions

- We can express nuclear reactions as chemical equations just as we do other types of reactions
- Requirements:
  - Mass number and atomic number on each side of the equation must balance
  - Total charge must balance
- Differences:
  - The types of elements on each side need not be the same—nuclear reactions may change the identity of the nucleus, thus changing the elemental symbol

Nuclear Reactions

- Examples:

$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$ alpha decay

$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta$ beta decay

$^{234}_{91}Pa \longrightarrow {}^{234}_{92}U + {}^{0}_{-1}\beta$ beta decay

$^{230}_{90}Th \longrightarrow {}^{226}_{88}Ra + {}^{4}_{2}\alpha$ alpha decay

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

Nuclear Reactions

- Examples:

$^{239}_{93}Np \longrightarrow ? + {}^{0}_{-1}\beta$ $\quad {}^{239}_{94}Pu$

$^{232}_{89}Ac \longrightarrow {}^{228}_{87}Pa + ?$ $\quad {}^{4}_{2}\alpha$

$? \longrightarrow {}^{234}_{92}U + {}^{0}_{0}\gamma$ $\quad {}^{234}_{92}U$

Other Types of Radioactive Decay

- Positron emission—a positron is a positively charged electron: ${}^{0}_{+1}e$

  $${}^{207}_{84}Po \rightarrow {}^{207}_{83}Bi + {}^{0}_{+1}e$$

- Electron capture—

  $${}^{7}_{4}Be + {}^{0}_{-1}e \rightarrow {}^{7}_{3}Li$$

Band of Stability

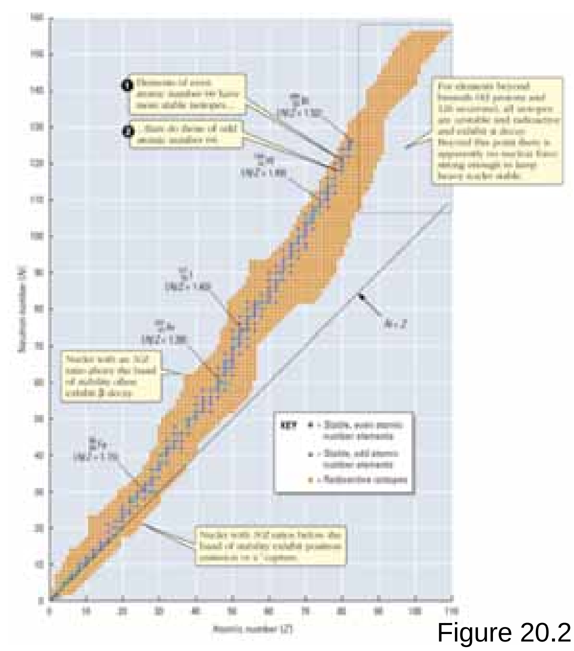


Figure 20.2

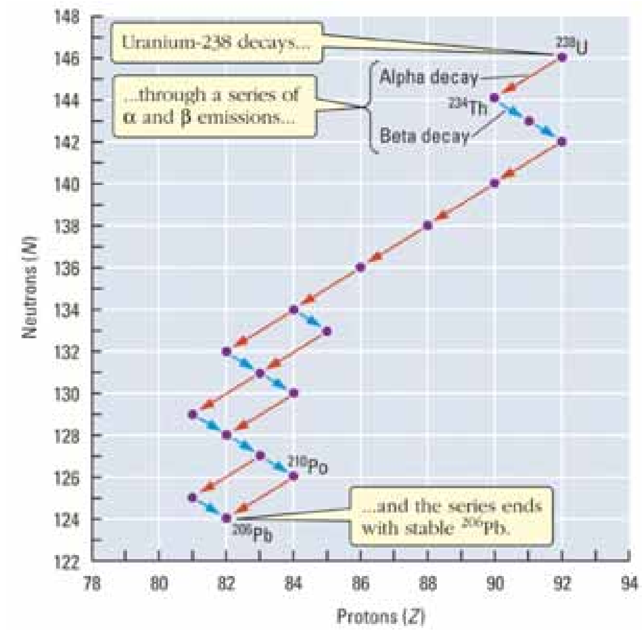
Nuclear Stability

- The number of neutrons is equal to or greater than the number of protons in a stable nucleus (exceptions H-1 and He-3)
- The number of protons and neutrons is nearly equal for low atomic number elements
- Usually the isotopes within the band of stability are stable

Nuclear Stability

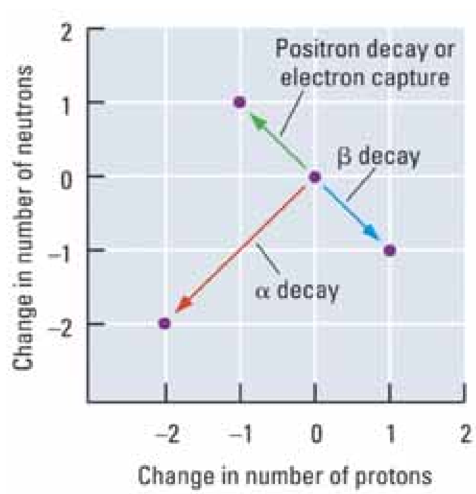
- Above Z = 20, the number of neutrons exceeds the number of protons in stable nuclides
- Usually nuclides with even numbers of protons, neutrons or both are stable
- Above Z = 83 the elements have no stable isotopes

Uranium Series



Predicting Decay Modes

- Beta decay for nuclides above zone of stability
- Positron decay for nuclides below zone of stability



Binding Energy

- Difference between the mass of a nuclide and the sum of the masses of the nucleons in the nucleus

  Δm = mass of nuclide - sum of mass of nucleons

  $E = -\Delta mc^2$

Binding Energy

<u>Example:</u> Binding energy of ${}^{4}_{2}He$

$\Delta m = 4.00260 – 2(1.00867 + 1.00783)$

$= -0.03040$ amu

$= -5.0480 \times 10^{-29}$ kg

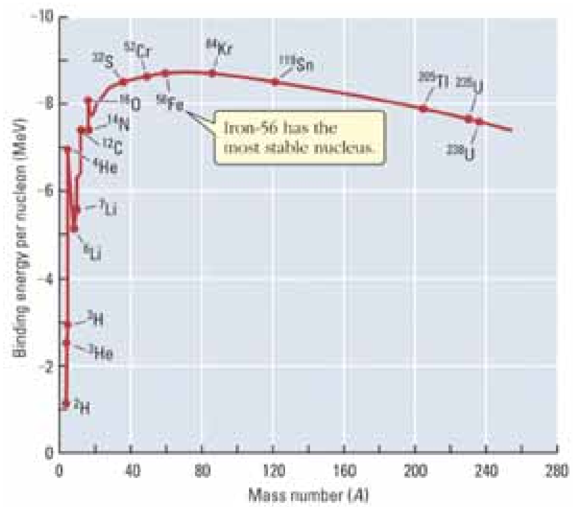
1 amu $= 1.66054 \times 10^{-27}$ kg

$E = -(-5.0480 \times 10^{-29}\ \text{kg})(2.99792 \times 10^{8}\ \text{m/s})^2$

$= 4.5369 \times 10^{-12}$ J

$= 2.7321 \times 10^{9}$ kJ/mol

Binding Energy per Nucleon



Half-life of Radioactive Nuclei

- The decay of radioactive nuclei follow 1st order kinetics
- The half-life of a radioactive nucleus is defined as the time required for one half of the radioactive nuclide to decay to products

  $[A]_t = ½[A]_o$
- Half-life is designated by $t_{1/2}$

Rates of Radioactive Decay

- For 1st order kinetics, the relationship between concentration and rate is:

  $[A(t)] = [A]_o \exp\{-kt\}$

- Taking ln of both sides and rearranging gives:

  $\ln([A]_t) = \ln([A]_o) - kt$

  $\ln([A]_o/[A]_t) = kt$

Rates of Radioactive Decay

$\ln([A]_o/[A]_t) = kt$

- When $[A]_t = ½[A]_o$, we get:

  $\ln([A]_o/½[A]_o) = kt_{1/2}$

  $\ln(2) = kt_{1/2}$

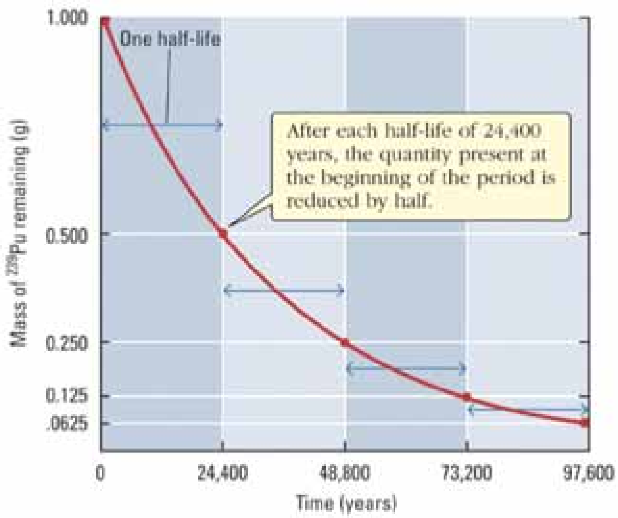
  $t_{1/2} = 0.693/k$

Selected Half Lives

TABLE 20.2 Half-Lives of Some Common Radioactive Isotopes

Isotope	Decay process	Half-life
$^{238}_{92}U$	$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$	4.15×10^9 y
$^{3}_{1}H$ (tritium)	$^{3}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{-1}e$	12.3 y
$^{14}_{6}C$ (carbon-14)	$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$	5730 y
$^{131}_{53}I$	$^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e$	8.04 d
$^{123}_{53}I$	$^{123}_{53}I + ^{0}_{-1}e \rightarrow ^{123}_{52}Te$	13.2 h
$^{57}_{24}Cr$	$^{57}_{24}Cr \rightarrow ^{57}_{25}Mn + ^{0}_{-1}e$	21 s
$^{28}_{15}P$	$^{28}_{15}P \rightarrow ^{28}_{14}Si + ^{0}_{+1}e$	0.270 s
$^{90}_{38}Sr$	$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}e$	28.8 y
$^{60}_{27}Co$	$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e$	5.26 y

Decay of Plutonium-239



Relationships of Concentrations

$$\ln\left\{\frac{[A]_{time=t}}{[A]_{time=0}}\right\} = -k_{1/2}\,t$$

k = rate constant for decay of nuclide

Dating Artifacts by Radioactivity

Carbon-14 Dating

- $t_{1/2}$ = 5730 yr
- While alive, plants constantly replace carbon-14
- After death, the carbon-14 will decay at a known rate

Dating Artifacts by Radioactivity

Example: Determine the date of a fossil when the relative ^{14}C abundance is .038 compared to living tissues

$k = .693/t_{1/2} = .693/5730 \text{ yrs} = 1.21 \times 10^{-4} \text{ yrs}^{-1}$

$\ln\{[A]_t/[A]_o\} = -kt$

$t = -\ln\{[A]_t/[A]_o\} / k$

$= -\ln\{.038/1.000\}/1.21 \times 10^{-4} \text{ yrs}^{-1}$

$= 2.70 \times 10^{4} \text{ yrs}$

Fission Reactions

- Nuclear reaction in which an atomic nucleus splits into two fragments with nearly equal masses accompanied by the evolution of a tremendous amount of energy

Nuclear Fission

Figure 20.6

$^{235}_{92}U$ Fission

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

masses:

^{235}U:	235.043924 amu
^{92}Kr:	91.926270 amu
^{141}Ba:	140.914363 amu
$^{1}_{0}n$:	1.008665 amu

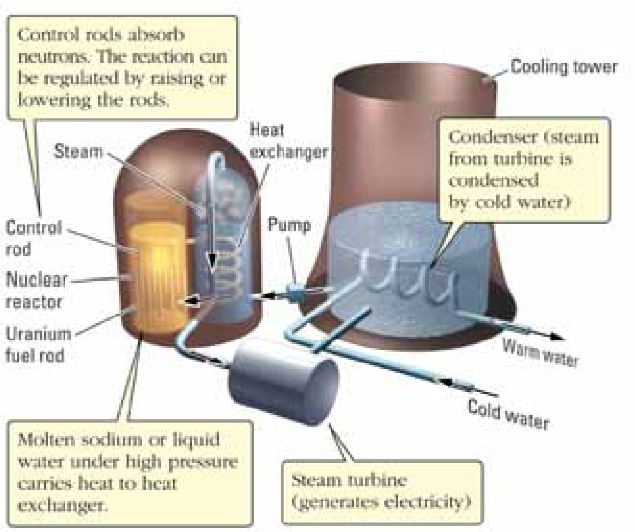
$\Delta m = -.185961\ \text{amu} = -3.08740 \times 10^{-28}\ \text{kg}$

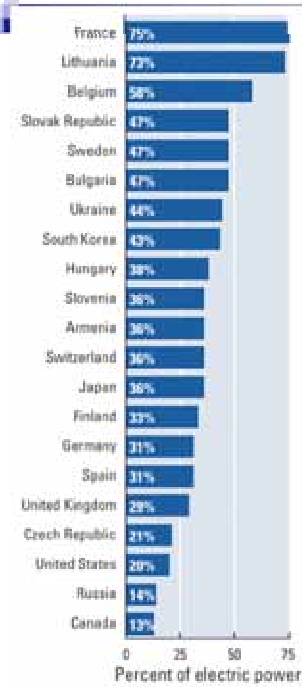
$E = 2.775 \times 10^{-11}\ \text{J} = 1.671 \times 10^{10}\ \text{kJ/mol}$

Nuclear Fission

Figure 20.7

Nuclear Power Plant





Percent Electricity Generated from Nuclear Energy

Reactor Terminology

Critical Mass

- The smallest mass of a fissionable material that will sustain a nuclear chain reaction at a constant level.

Breeder Reactor

- A nuclear reactor that produces as well as consumes fissionable material, especially one that produces more fissionable material than it consumes.

Nuclear Fusion

- Nuclear reaction where smaller particles are joined together to form larger particles

$4\ {}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\ {}^{0}_{-1}e$

${}^{2}_{1}H + {}^{2}_{1}H \rightarrow + {}^{1}_{0}n$

${}^{1}_{1}H + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{0}_{-1}e$

Radiation Units

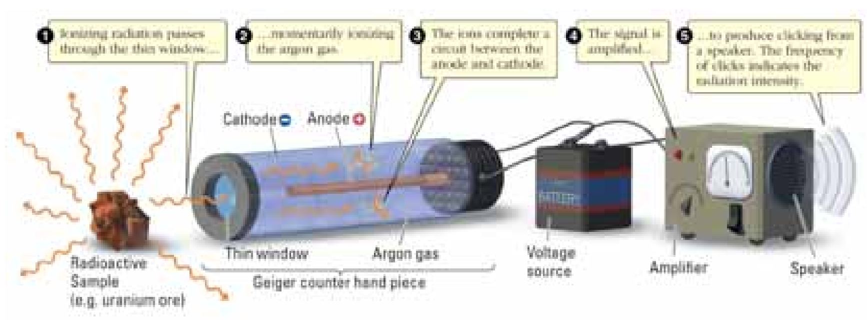
Roentgen—dosage of x-rays or γ-rays
- deposition of 93.3×10^{-7} J per gram of tissue

rad (*r*adiation *a*bsorbed *d*ose)—dose of 1.00×10^{-2} J absorbed per kilogram of material

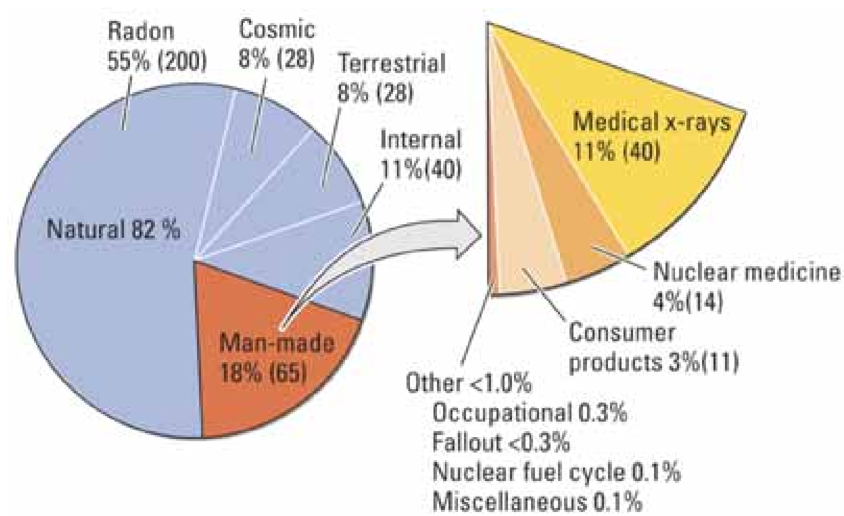
Gray—SI unit equal to the absorption of 1 J per kilogram of material

Detection of Radioactivity

- film badge
- scintillation counter
- Geiger counter → ionizes gas



Background Radiation



Radiation Sickness

Illness induced by ionizing radiation, ranging in severity from nausea, vomiting, headache, and diarrhea to loss of hair and teeth, reduction in red and white blood cell counts, extensive hemorrhaging, sterility, and death.

Radon

- Radioactive, noble gas produced by decomposition of naturally occurring uranium deposits in the soil
- Decays by alpha emission producing other alpha emitters
- Common household hazard where the home is built on a conventional foundation over soil containing trace amounts of uranium

Radon

- Inhalation hazard

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

$$^{218}_{84}Po \rightarrow {}^{4}_{2}He + {}^{214}_{82}Pb$$

Use of Isotopes as Tracers

- Radioactive isotope is introduced into a biological system to follow the course of a process
- Provides information on the process

Tracers

TABLE 20.3 Radioisotopes Used as Tracers

Isotope	Half-life	Use
^{14}C	5730 y	CO_2 for photosynthesis research
^{3}H	12.33 y	Tag hydrocarbons
^{35}S	87.2 d	Tag pesticides, measure air fl ow
^{32}P	14.3 d	Measure phosphorus uptake by plants

Diagnostic Radioisotopes

TABLE 20.4 Diagnostic Radioisotopes

Radioisotope	Name	Half-life (hours)	Site for diagnosis
^{99m}Tc*	Technetium-99m	6.0	As $^{99m}TcO_4^-$ to the thyroid
^{201}Tl	Thallium-201	72.9	To the heart
^{123}I	Iodine-123	13.2	To the thyroid
^{67}Ga	Gallium-67	78.2	To various tumors and abscesses

* The technetium-99m isotope is the radioisotope most commonly used for diagnostic purposes. The *m* stands for "metastable."