Chem 30A

Ch 17. Radioactivity and Nuclear Chemistry

Nuclear Activity

- The nucleus does not strongly affect the *chemistry* of the atom (bond making/ breaking).

- HOWEVER, the nucleus can undergo changes, which usually cause an element to change into another element.

Implications of Nuclear Activity for Humans

- Hazardous effects of radiation
- Medical applications of radioactivity
- Dating by radioactivity
- Nuclear energy
- Nuclear weapons

Radioactivity

Radioactivity (Radioactive Decay)

Radioactivity: the spontaneous decomposition of atomic nuclei, which releases high-energy particles or rays

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$

- Radioactive decay results in a different nucleus.
- Nuclide: a nucleus with a specified number of protons and neutrons (= a specific isotope)

Isotope Symbol

Mass Number
(number of protons +
neutrons

$$^{A}_{Z}\mathrm{X}$$

Element Symbol

Atomic Number
(number of protons)
Identifies element

Similar notation for subatomic particles

Proton $^{1}_{1}p$ Neutron $^{1}_{0}n$ Electron $^{0}_{-1}e$

Radioactivity

- Every element has at least one isotope whose nucleus spontaneously decomposes (radioisotope).
- A certain level of radiation naturally occurs all around us, even in our bodies (potassium-40).

Parent nuclide

Daughter nuclides

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

Nuclear Equations

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$

In a balanced nuclear equation, both the atomic number and the mass number must be conserved.

Types of Radioactivity

1. Alpha Particle (α) Emission

$$^{222}_{88}\mathrm{Ra} \rightarrow \, ^{4}_{2}\mathrm{He} + \, ^{218}_{86}\mathrm{Rn}$$

$$^{230}_{90}\mathrm{Th} \rightarrow \, ^{4}_{2}\mathrm{He} + \, ^{226}_{88}\mathrm{Ra}$$

- α particle = helium nucleus $^{4}_{2}\mathrm{He}$
- Net effect: loss of 4 in mass number, loss of 2 in atomic number

Types of Radioactivity

2. Beta Particle (β) Emission

$$^{234}_{90}\mathrm{Th} \rightarrow \, ^{234}_{91}\mathrm{Pa} + \, ^{0}_{-1}\mathrm{e}$$

- β particle: an electron $^{0}_{-1}\mathrm{e}$
- Net effect: A neutron is changed into a proton.

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

Types of Radioactivity

3. Gamma Ray (γ) Emission

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + 2\,^{0}_{0}\gamma$$

- Gamma ray: high-energy photon of light (no charge or mass)
- Often accompanies different types of nuclear decays
- Net effect: no change in mass or atomic number

4. Positron Emission

$$^{22}_{11}\text{Na} \rightarrow {}^{0}_{1}\text{e} + {}^{22}_{10}\text{Ne}$$

- Positron (β^+): a particle with same mass as electron but opposite charge $^{0}_{1}\text{e}$

- Net effect: A proton is changed into a neutron.

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

Types of Radioactivity

Electron Capture

$$^{201}_{80}\text{Hg} + {}^{0}_{-1}\text{e} \rightarrow {}^{201}_{79}\text{Au} + {}^{0}_{0}\gamma$$

↑

Inner-orbital electron

- One of the inner-orbital electrons is captured by the nucleus.
- Net result: Changes proton into neutron.
- A way to make gold? Impractical

Summary: Radioactivity

TABLE 11.2 A Summary of Radioactive Decay Processes

Process	Symbol	Change in Atomic Number	Change in Mass Number	Change in Number of Neutrons
α emission	$^{4}_{2}He$ or α	−2	−4	−2
β emission	$^{0}_{-1}e$ or β^{-}*	+1	0	−1
γ emission	$^{0}_{0}\gamma$ or γ	0	0	0
Positron emission	$^{0}_{1}e$ or β^{+}*	−1	0	+1
Electron capture	E.C.	−1	0	+1

*Superscripts are used to indicate the charge associated with the two forms of beta decay; β^{-}, or a beta particle, carries a −1 charge, while β^{+}, or a positron, carries a +1 charge.

Ex Probs

Nuclear Transmutation

- Nuclear transmutation: the change of one element into another by particle bombardment (neutron, α particle, proton, nucleus)
- Most of the ~3300 known radioisotopes are made through artificial nuclear transmutation in particle accelerators.

$$^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

$$^{238}_{92}U + {}^{4}_{2}He \rightarrow {}^{241}_{94}Pu + {}^{1}_{0}n$$

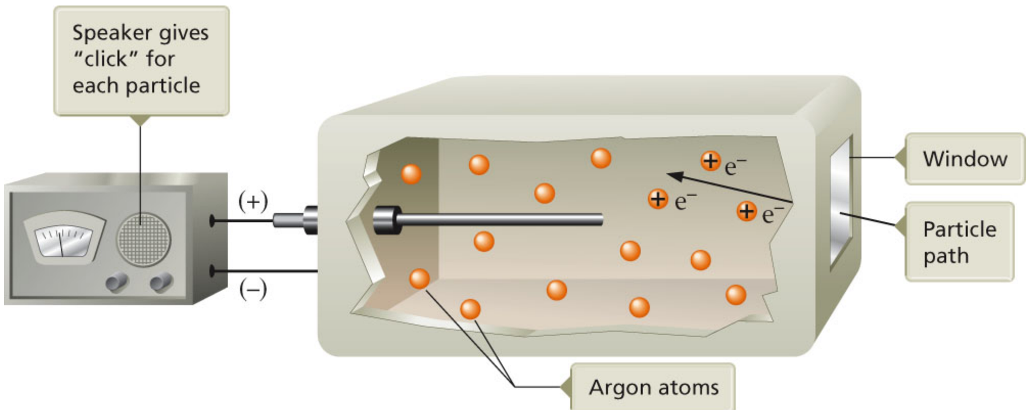
Nuclear Transformation, cont'd

- All elements with atomic numbers greater than 92 (transuranium elements) have been artificially made.

Half Life

Detection of Radioactivity

- Geiger-Müller counter: High-energy particles ionize argon; argon ions can conduct electricity



- Scintillation counter: Uses a substance that gives off light when struck by high-energy particles

- Thermoluminescent dosimeters: Electrons excited by high-energy particles are trapped in crystals, then heated to relax into ground state and emit light

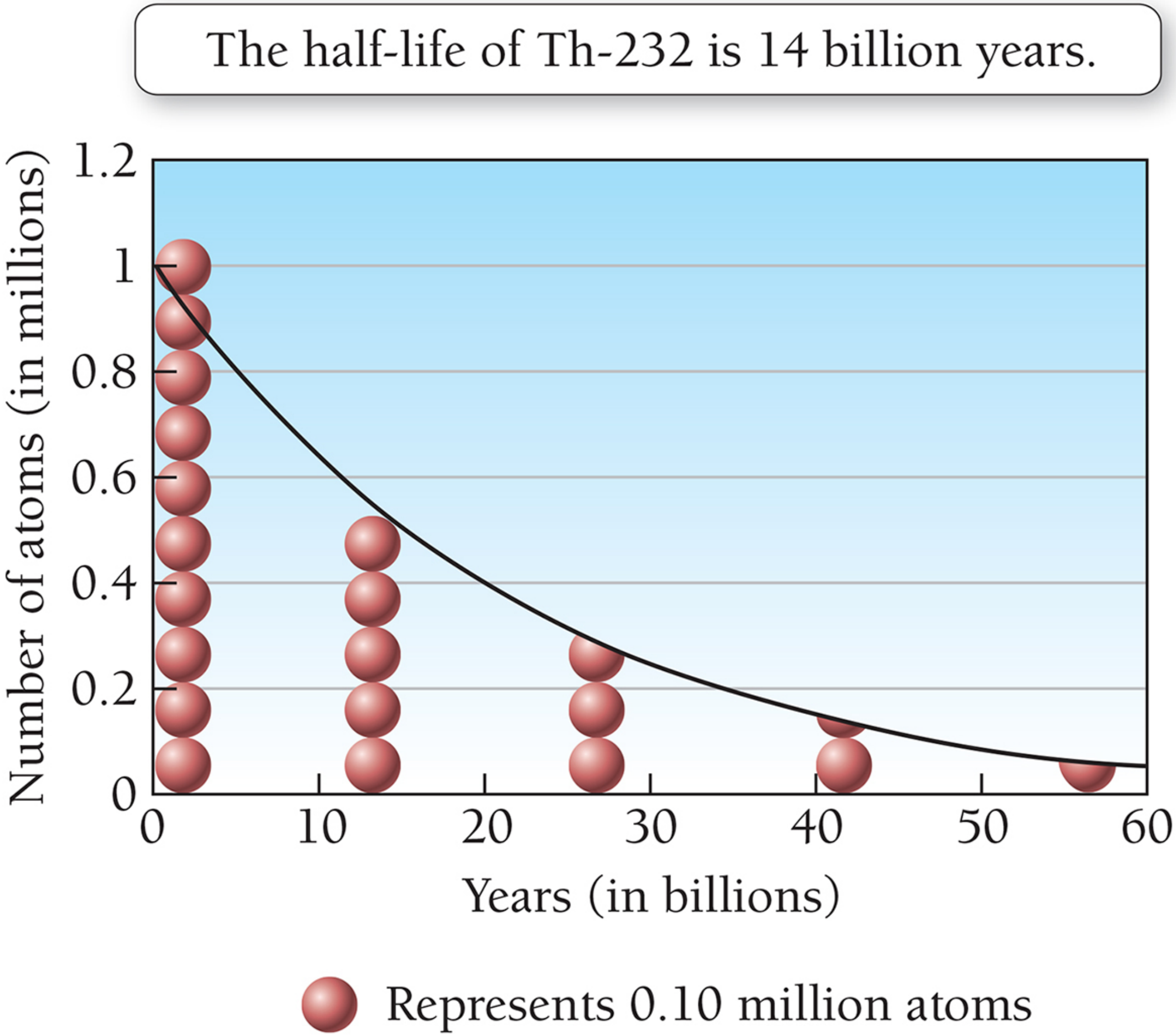
Half-Life

Half-life: Time required for half of the original sample of nuclei to decay

1 mil $^{220}_{86}Rn$ $\xrightarrow{\text{1 min}}$ 1/2 mil $^{220}_{86}Rn$ $\xrightarrow{\text{1 min}}$ 1/4 mil $^{220}_{86}Rn$

1 mil $^{238}_{92}U$ $\xrightarrow{\text{4.5 bil yrs}}$ 1/2 mil $^{238}_{92}U$ $\xrightarrow{\text{4.5 bil yrs}}$ 1/4 mil $^{238}_{92}U$

Half Life of Th-232



Half-lives of Radium Nuclides

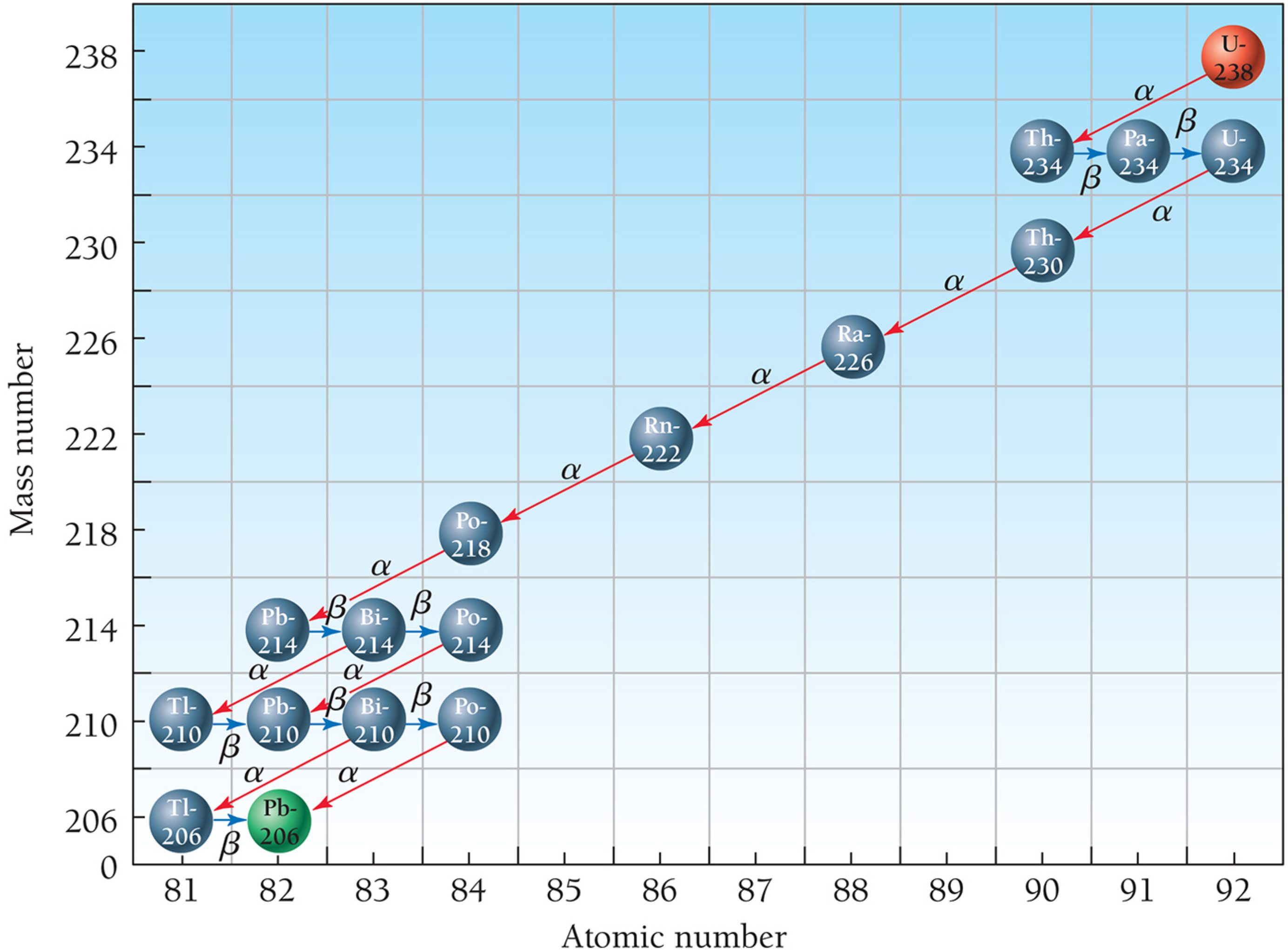
TABLE 17.2 Selected Nuclides and Their Half-Lives

Nuclide	Half-Life	Type of Decay
$^{232}_{90}Th$	1.4×10^{10} yr	alpha
$^{238}_{92}U$	4.5×10^{9} yr	alpha
$^{14}_{6}C$	5715 yr	beta
$^{220}_{86}Rn$	55.6 s	alpha
$^{219}_{90}Th$	1.05×10^{-6} s	alpha

Ex Probs

U-238 Decay Series

In many cases, daughter nuclides are also radioactive.



Application: Radiocarbon Dating (C-14 Dating)

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$ C-14 Made

$$^{14}_{6}C \longrightarrow ^{0}_{-1}e + ^{14}_{7}N$$ C-14 Broken down

Half-life of ^{14}C = 5715 years

- Atmosphere has constant amount of ^{14}C.
- ^{14}C content in a living plant is constant due to constant uptake of $^{14}CO_2$ by plant.
- At moment of death, plant ^{14}C decays without replenishment.
- So ^{14}C content of fossil tells how much time has passed since the plant died (age).

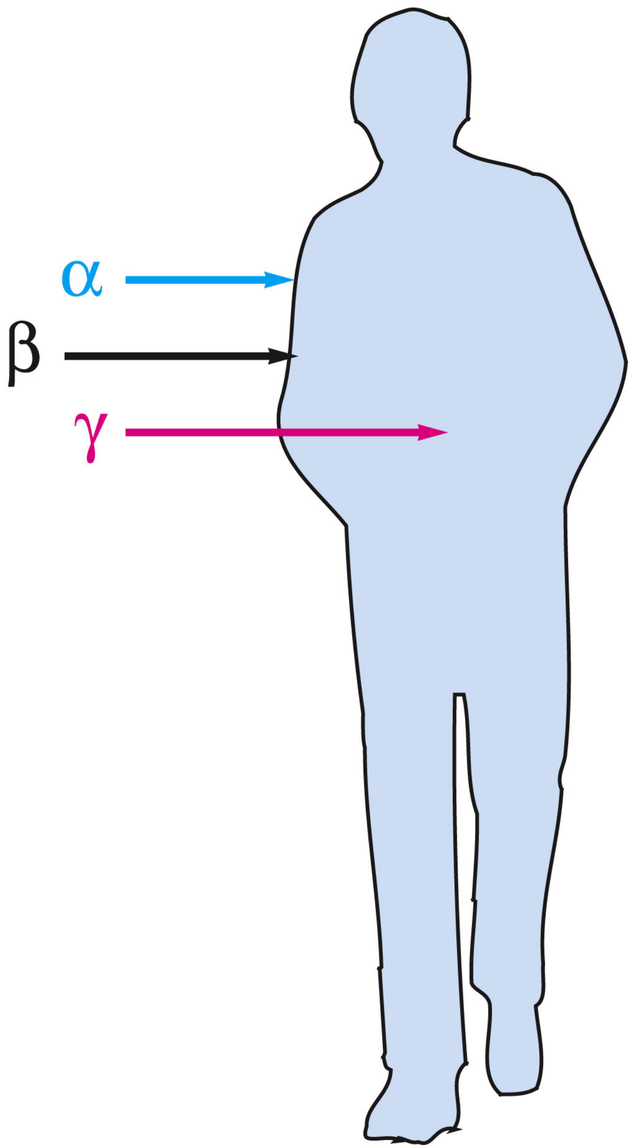
Effect of Radiation on Life

Effect of Radiation on Life

Damaging Effects of Radiation

- Ionizing power: ability of radiation to ionize molecules and atoms. More massive particles have more potential to interact with and ionize other molecules.
- Penetrating power: ability of radiation to penetrate matter. Smaller particles can penetrate more deeply.

Effects of Different Types of Radiation



s	Ionizing Power	Penetrating Power	Stopped By
$^{4}_{2}He$ α particle	High	Low	Sheet of paper, clothing
on becomes proton $^{0}_{-1}e$ β particle	Moderate	Moderate	Sheet of metal, thick wood
$^{0}_{0}γ$ γ ray Photon	Low	High	Thick lead or concrete
ton becomes a neutron $^{0}_{+1}e$ Positron	Moderate	Moderate	Sheet of metal, thick wood (also for gamma ray)

Types of Radiation Damages

- Acute radiation damage: damage to cells resulting from exposures to large amounts of radiation in short period of time
- Increased cancer risk: Lower radiation doses over a longer period of time can cause damage to somatic cells and increase cancer risk.
- Genetic defects: damage to DNA in reproductive cells that shows effect in offspring

Effects of Short-Term Radiation Exposure

Rem: A unit that indicates biological damage of radiation

TABLE 17.4 Effects of Radiation Exposure

Dose (rem)	Probable Outcome
20–100	decreased white blood cell count; possible increase in cancer risk
100–400	radiation sickness; skin lesions; increase in cancer risk
500	death

Biological Effects of Radiation

Typical Radiation Exposure in U.S.

Table 19.6 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

Source	Exposure (millirems/year)
cosmic	50
from the earth	47
from building materials	3
in human tissues	21
inhalation of air	5
Total from natural sources	126
X-ray diagnosis	50
radiotherapy X rays, radioisotopes	10
internal diagnosis and therapy	1
nuclear power industry	0.2
luminous watch dials, TV tubes, industrial wastes	2
radioactive fallout	4
Total from human activities	67
Total	193 = 0.193 rem

Nuclear Medicine Application: Radiotracers

- Radiotracers: radioactive nuclides that can be put into organisms through food or drugs, and be traced for medical diagnostics

Table 19.4 Some Radioactive Nuclides, Their Half-lives, and Their Medical Applications as Radiotracers*

Nuclide	Half-life	Area of the Body Studied
^{131}I	8.1 days	thyroid
^{59}Fe	45.1 days	red blood cells
^{99}Mo	67 hours	metabolism
^{32}P	14.3 days	eyes, liver, tumors
^{51}Cr	27.8 days	red blood cells
^{87}Sr	2.8 hours	bones
^{99}Tc	6.0 hours	heart, bones, liver, lungs
^{133}Xe	5.3 days	lungs
^{24}Na	14.8 hours	circulatory system

*Z is sometimes not written when listing nuclides.

Radiotracers in PET Scans

- PET: positron emission tomography
- Examples of positron-producing isotopes: ^{18}F, ^{11}C
- These radioactive isotopes are attached to glucose.
- Areas of brain rapidly consuming these radiotracers “light up” on PET screen.
- Short half-lives (110 min for ^{18}F, 20 min for ^{11}C) require speedy synthesis.

Nuclear Medicine Application: Radiotherapy

- Gamma rays are used to kill rapidly dividing cancer cells.
- Patients undergoing radiotherapy develop symptoms of radiation sickness (vomiting, hair loss, skin burns).