Useful Consequences of Radioactivity

1) Radiocarbon Dating

Radioactive ^{14}C produced in upper atm.

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

-provides constant source of ^{14}C

^{14}C undergoes β^- decay w. $t_{1/2} = 5715$ yrs

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

A steady-state is reached w. about 15 disintegrations/min-g of C

Assume that $^{14}C : ^{12}C$ has been constant for at least 50,000 yrs.

^{14}C is incorporated into CO_2

-becomes part of life cycle

The $^{14}C : ^{12}C$ is maintained as long as plant or animal is living.

Once dies, ^{14}C is not replenished
- lost by radioactive decay
  - ratio dec

Compare ^{14}C activity to that of growing plants (or in atm.) & determine how long it's been dead

a) Ex: A wooden object is measured to undergo 9.0 disintegrations of ^{14}C per second. An ordinary sample containing the natural abundance of ^{14}C undergoes 15.2 disint. of ^{14}C per sec. For ^{14}C $t_{1/2} = 5715$ yr. How old is the object?

Ex: A rock contains 0.257 mg of ^{206}Pb for every mg of ^{238}U. The half-life for the decay of ^{238}U to ^{206}Pb is 4.5×10^9 yr. How old is the rock?

2) Uses in Chemistry

Radioisotopes can be used to follow an element through chemical rx's – **tracer**

e.g. determine mech. of photosynthesis

$$6\underset{\uparrow\,{}^{14}C}{C^{*}}O_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

Analyze leaves after various periods of time. Process was broken down into sequence of steps.

Nuclear Fission, Binding Energy, Fusion

Fission

Process in which a nucleus splits into 2 major pieces

Induced when nucleus is hit by a slow-moving (thermal) neutron.

$$^{235}U + {}^{1}_{0}n \rightarrow {}^{94}_{38}Sr + {}^{139}_{54}Xe + 3\,{}^{1}_{0}n$$

$$^{235}U + {}^{1}_{0}n \rightarrow {}^{96}_{39}Y + {}^{136}_{53}I + 4\,{}^{1}_{0}n$$

$$^{235}U + {}^{1}_{0}n \rightarrow {}^{97}_{40}Zr + {}^{137}_{52}Te + 2\,{}^{1}_{0}n$$

Over 200 diff. isotopes of 35 diff. elements have been found among fission products of ^{235}U

- most are radioactive

Nuclear fission is the energy-producing process used in nuclear weapons & reactors.

- Where does the energy come from & why is there so much of it?

Look at Eienstein Eq.

$$\boxed{E = mc^2}$$

- mass + energy are interconvertible

In nuclear fission there is a significant loss of mass

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{94}_{38}Sr + {}^{139}_{54}Xe + 3\,{}^{1}_{0}n$$

235.0439 1.0087 93.9154 138.9178 1.0087

$$\Delta m = \sum_{prod}(mass) - \sum_{react}(mass) = -0.1933 \text{ amu}$$

System loses 0.1933 amu/atom U

or

0.1933 g/mol U

mass $\Longrightarrow$ energy

$$\Delta E = \Delta m c^2 = -1.933 \times 10^{-4} kg\,(2.9979 \times 10^{8} m/s)^2$$
$$= -1.737 \times 10^{13} J/mol$$

Greater by factor of 10^6 than energy released in a highly exothermic ordinary chem. process

Energy evolved reflects the diff. in binding energy of product & reactant nuclei

Nuclear Binding Energy

Mass of atomic nucleus is less than masses of individual nucleons

$^{57}_{27}Co$ $27p + 30n = 57.4564$ amu

mass of $^{57}_{27}Co = \underline{56.9215 \text{ amu}}$

$\Delta m = 0.5349$ amu

mass defect - "missing mass"
- measure of the binding energy

Binding Energy

energy required to separate a nucleus into its individual nucleons

greater b.e. ⇒ greater stability

Relative stability of nuclei is expressed in terms of binding energy per nucleon

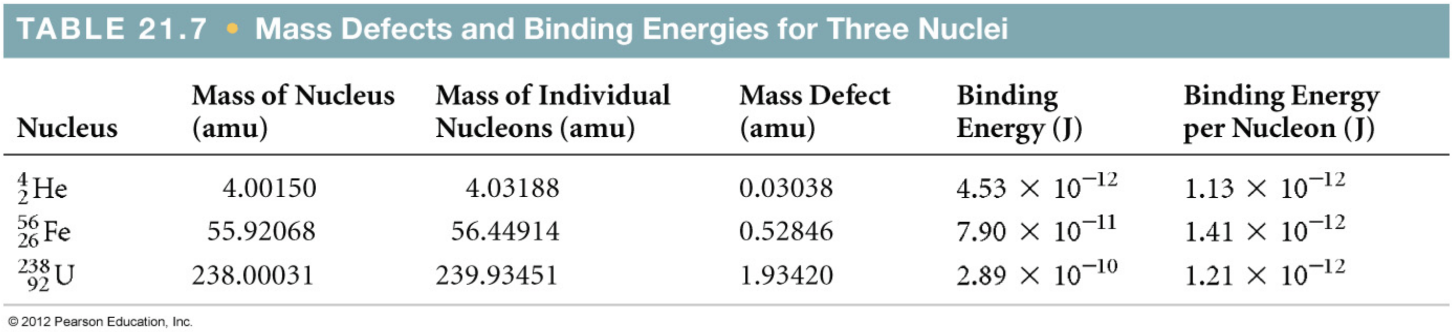
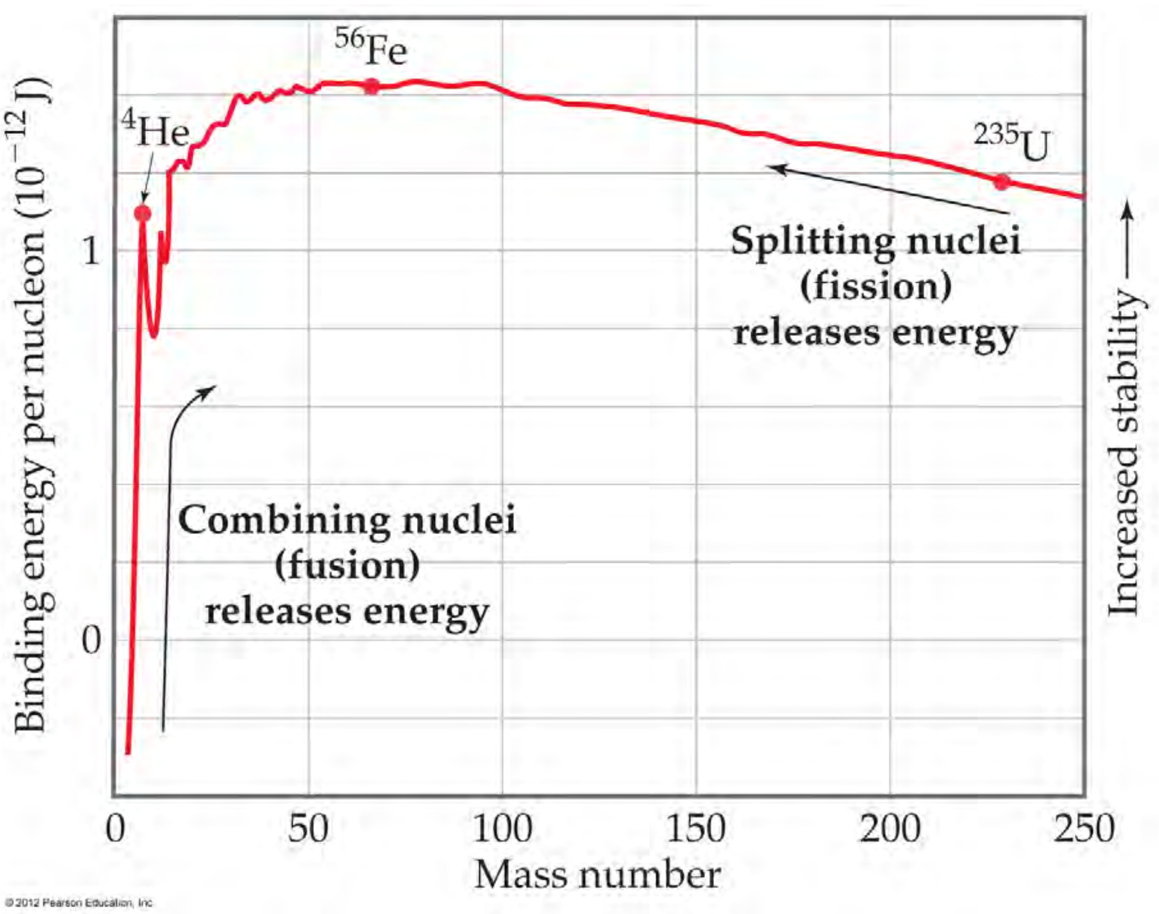


TABLE 21.7 • Mass Defects and Binding Energies for Three Nuclei

Nucleus	Mass of Nucleus (amu)	Mass of Individual Nucleons (amu)	Mass Defect (amu)	Binding Energy (J)	Binding Energy per Nucleon (J)
$^{4}_{2}\text{He}$	4.00150	4.03188	0.03038	4.53×10^{-12}	1.13×10^{-12}
$^{56}_{26}\text{Fe}$	55.92068	56.44914	0.52846	7.90×10^{-11}	1.41×10^{-12}
$^{238}_{92}\text{U}$	238.00031	239.93451	1.93420	2.89×10^{-10}	1.21×10^{-12}



nuclei of intermediate mass numbers are more stable than those w. either smaller or larger mass numbers

Ex: What is the b.e. & b.e./nucleon for ^{57}Co?

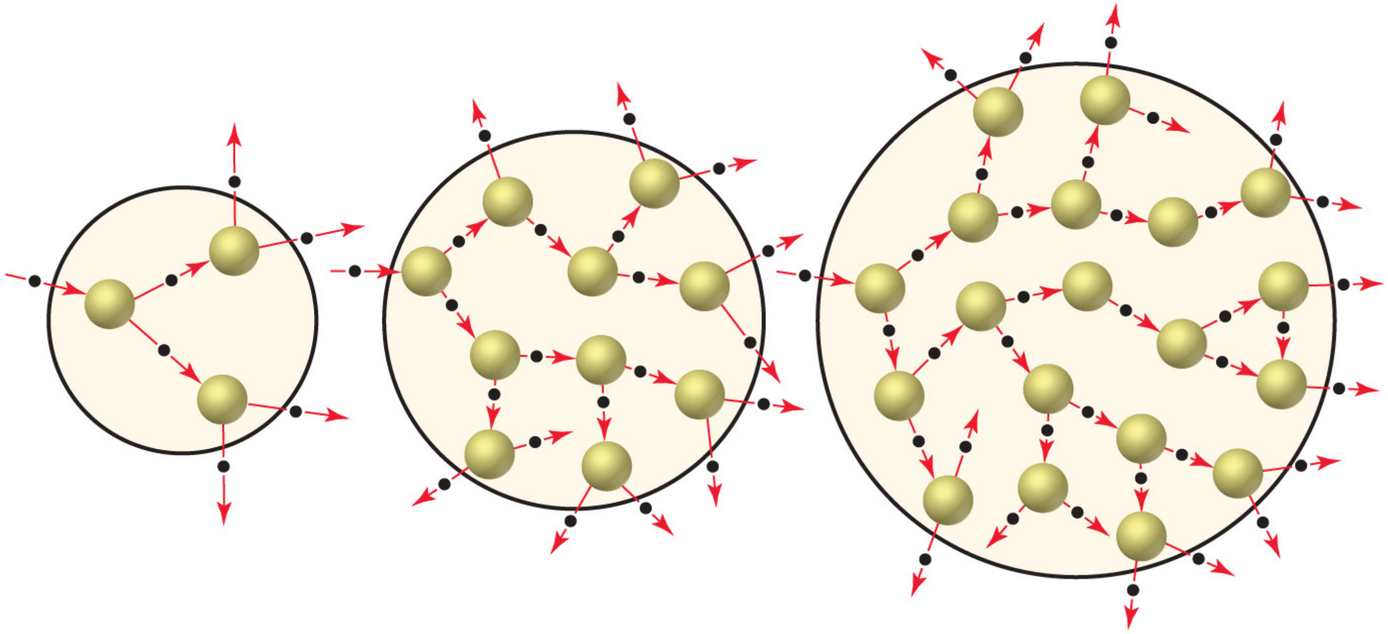
When ^{235}U undergoes fission to produce two lighter nuclei the b.e./nucleon inc.

This is the energy released in the fission process.

Note: When a neutron induces fission not only is a tremendous amt. of energy released but also 2 or 3 more neutrons.

If mass of ^{235}U is small, most of product neutrons escape (subcritical mass).

At a certain critical mass, enough neutrons come in contact w. other fissionable nuclei so a chain reaction can be sustained (constant rate of fission).



Subcritical mass
Rate of neutron loss
> rate of neutron
creation by fission

Critical mass
Rate of neutron loss
= rate of neutron
creation by fission

Supercritical mass
Rate of neutron loss
< rate of neutron
creation by fission

In atomic bombs, a supercritical mass is suddenly brought together. Most product neutrons cause another fission.

=> branched chain

Tremendous amts. of energy released in short period of time

In a nuclear reactor, no more than ONE of the product neutrons is allowed to come in contact w. another fissionable nucleus.

- Control rods of Cd or B are used to absorb some neutrons

Fusion

Refer to curve of nuclear b.e.

Conversion of very light nuclei into heavier ones results in an even greater inc. in b.e./nucleon

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

2.01345 2.01345 3.01493 1.00867

$\Delta m = 4.0236 - 4.0269 = -\ 0.0033$ amu

$\Delta E = (-3.3 \text{ x } 10^{-6}\ \text{kg})(2.9979 \text{ x } 10^{8}\ \text{m/s})^{2}$

$= -2.9 \text{ x } 10^{8}\ \text{kJ}$

Can provide large amt's of energy & fusion products are generally not radioactive

One problem w. fusion rxns
is getting them started

- Requires extremely high energies to force 2 nuclei close enough to fuse
  - in terms of temp. ~ 10^{8} °C

Thermonuclear rxn (H-bomb)

- fission rxn used to provide high energies needed for fusion

- have achieved sustained fusion for < 1 sec.

Biological Effects of Radiation

Radiation is generally harmful:

- Energies of radiation are far in excess of chem. bond energies
- As radiation travels through matter, it gives up its energy to molecules it encounters
  - leaves a trail of ions & molecular fragments (radicals)

living tissue + α, β, γ radiation (high energy) ⟶ ions & radicals

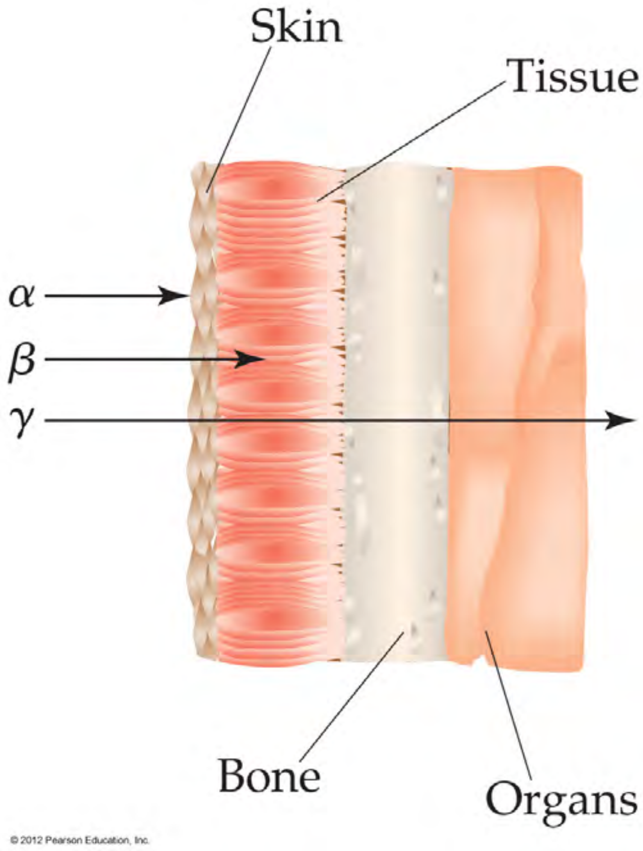
Ions & radicals are very reactive & disrupt the normal operations of the cell

Damage from a source outside the body depends on penetrating ability of the radiation.

γ-rays penetrate very effectively

α & β emitters dangerous w/in body

- a lot of damage in a localized area



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Radiation Doses

Gray (Gy)

SI unit of absorbed dose

absorption of 1 J/kg tissue

rad (radiation absorbed dose)

absorption of 1 x 10^{-2} J/kg tissue

1 Gy = 100 rad

RBE (relative biological effectiveness)

- multiplication factor to account for relative damage by different forms of radiation.

~1 for γ and β ~10 for α

RBE varies with dose rate, total dose and type of tissue affected.

rem (roentgen equivalent for man):

- effective dosage

rem = (# rad) (RBE)

- used in medicine

SI unit: sievert (Sv) 1 Sv = 100 rem

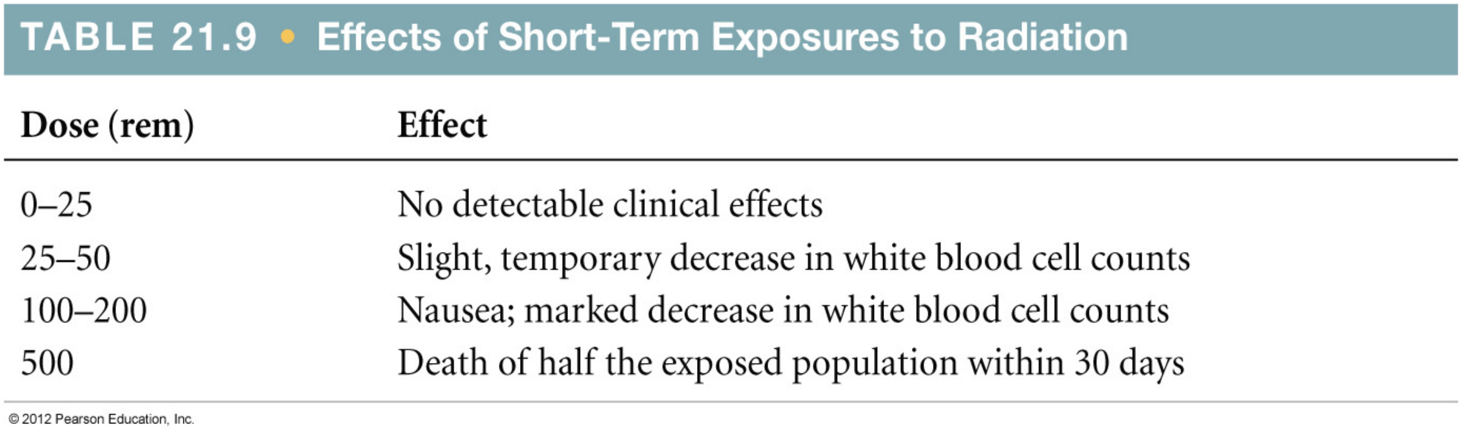
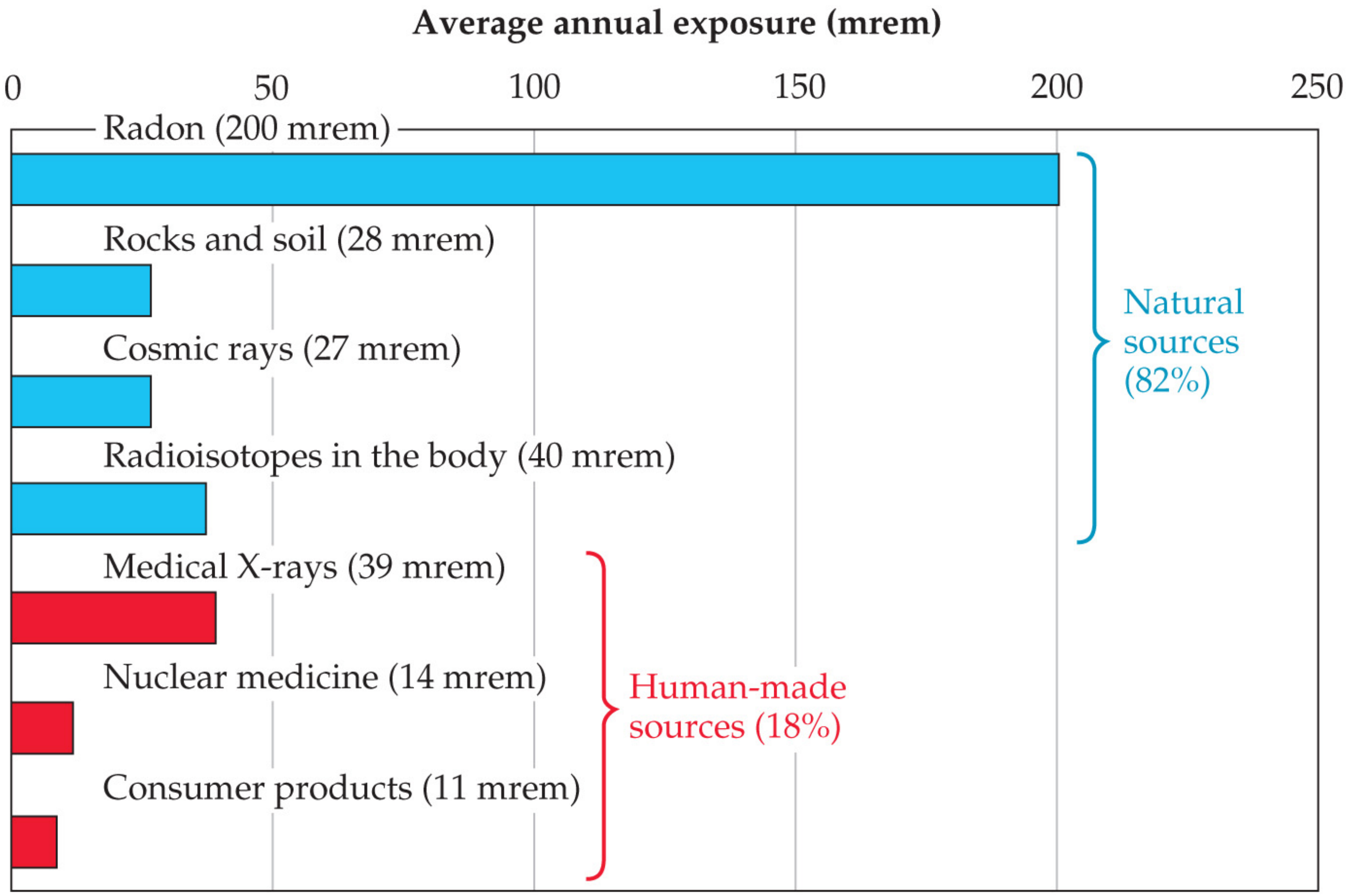


TABLE 21.9 • Effects of Short-Term Exposures to Radiation

Dose (rem)	Effect
0–25	No detectable clinical effects
25–50	Slight, temporary decrease in white blood cell counts
100–200	Nausea; marked decrease in white blood cell counts
500	Death of half the exposed population within 30 days

Background Radiation

Average exposure for a person in
1 year due to all natural sources
of ionizing radiation.



Radon

Radon-222, ^{222}Rn

one decay product of ^{238}U

accounts for ~ half backgrd radiation

Noble gas - unreactive, readily inhaled

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

($t_{1/2}$ = 3.82 days)

Po-218

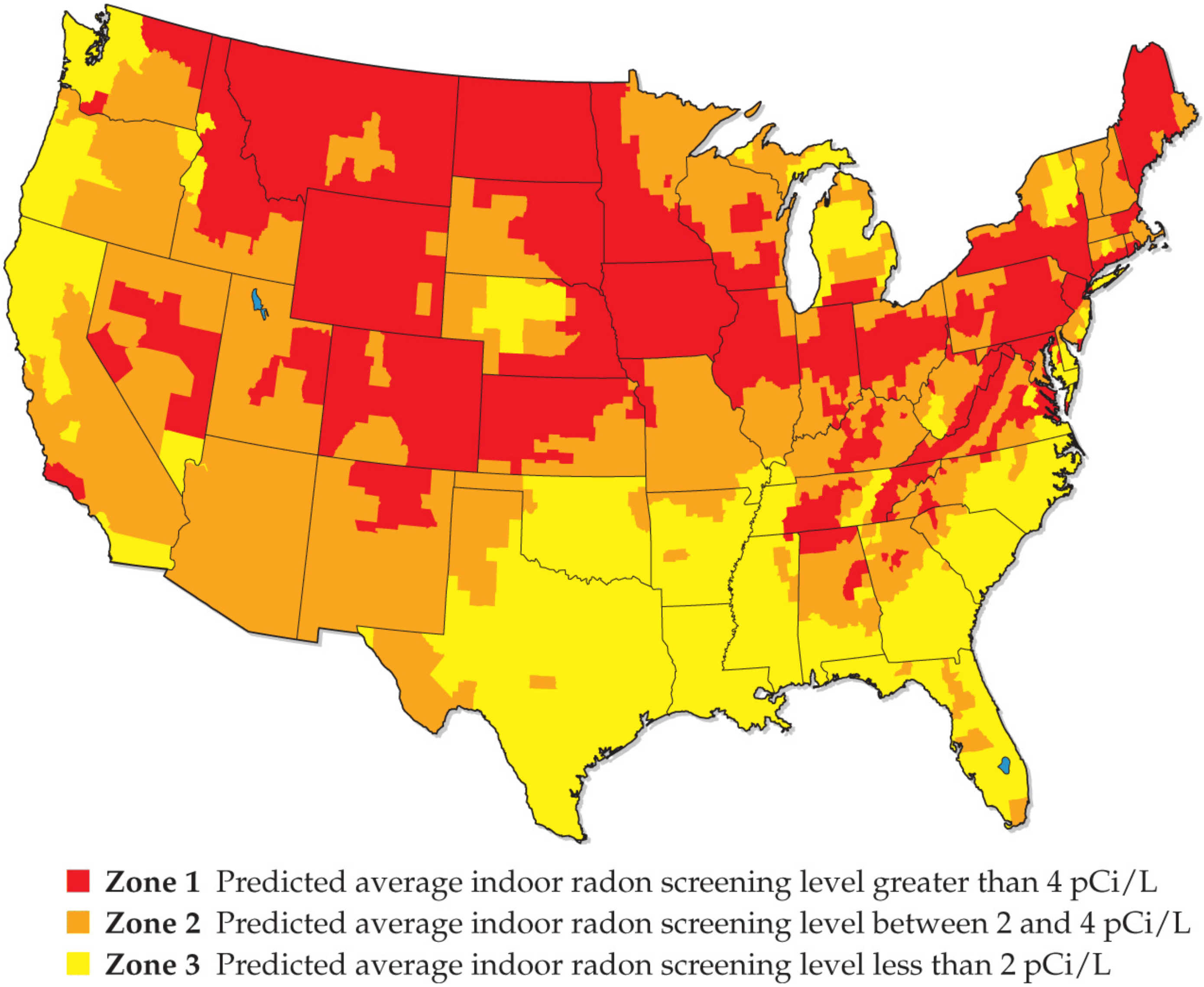
chemically active (trapped in lungs)

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

($t_{1/2}$ = 3.11 min)

Causes ~ 10% lung cancer deaths

Radon-222 levels should not exceed 4 pCi/L air in homes (EPA)



🟥 **Zone 1** Predicted average indoor radon screening level greater than 4 pCi/L

🟧 **Zone 2** Predicted average indoor radon screening level between 2 and 4 pCi/L

🟨 **Zone 3** Predicted average indoor radon screening level less than 2 pCi/L

Medical Uses

Diagnosis

1) Must be effective at low conc.

2) Short half-life

3) Readily eliminated

4) Emit γ-rays - detected outside body

5) Selectively go to part of body desired

I-131	diagnosing thyroid activity
Na-24	detecting problems in circulating system - NaCl soln injected into blood stream
Tc-99	concentrates in abnormal heart tissue - survey extent of damage from heart disease and locating brain tumors

TABLE 21.6 • Some Radionuclides Used as Radiotracers

Nuclide	Half-Life	Area of the Body Studied
Iodine-131	8.04 days	Thyroid
Iron-59	44.5 days	Red blood cells
Phosphorus-32	14.3 days	Eyes, liver, tumors
Technetium-99	6.0 hours	Heart, bones, liver, and lungs
Thallium-201	73 hours	Heart, arteries
Sodium-24	14.8 hours	Circulatory system

TABLE 21.10 • Some Radioisotopes Used in Radiation Therapy

Isotope	Half-Life	Isotope	Half-Life
^{32}P	14.3 days	^{137}Cs	30 yr
^{60}Co	5.27 yr	^{192}Ir	74.2 days
^{90}Sr	28.8 yr	^{198}Au	2.7 days
^{125}I	60.25 days	^{222}Rn	3.82 days
^{131}I	8.04 days	^{226}Ra	1600 yr

Treatment

Must be an α or β emitter (internal)

- do not have great penetrating power

- cells are damaged in a localized area

Works because radiation is most damaging to rapidly dividing cells

- cancer cells

Ir-192 taken internally as “seeds”

Co-60 β & γ emitter (external)
Used for high intensity cancer treatment from outside body

- beamed directly at affected area