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Chapter 19

Radioactivity and Nuclear Energy

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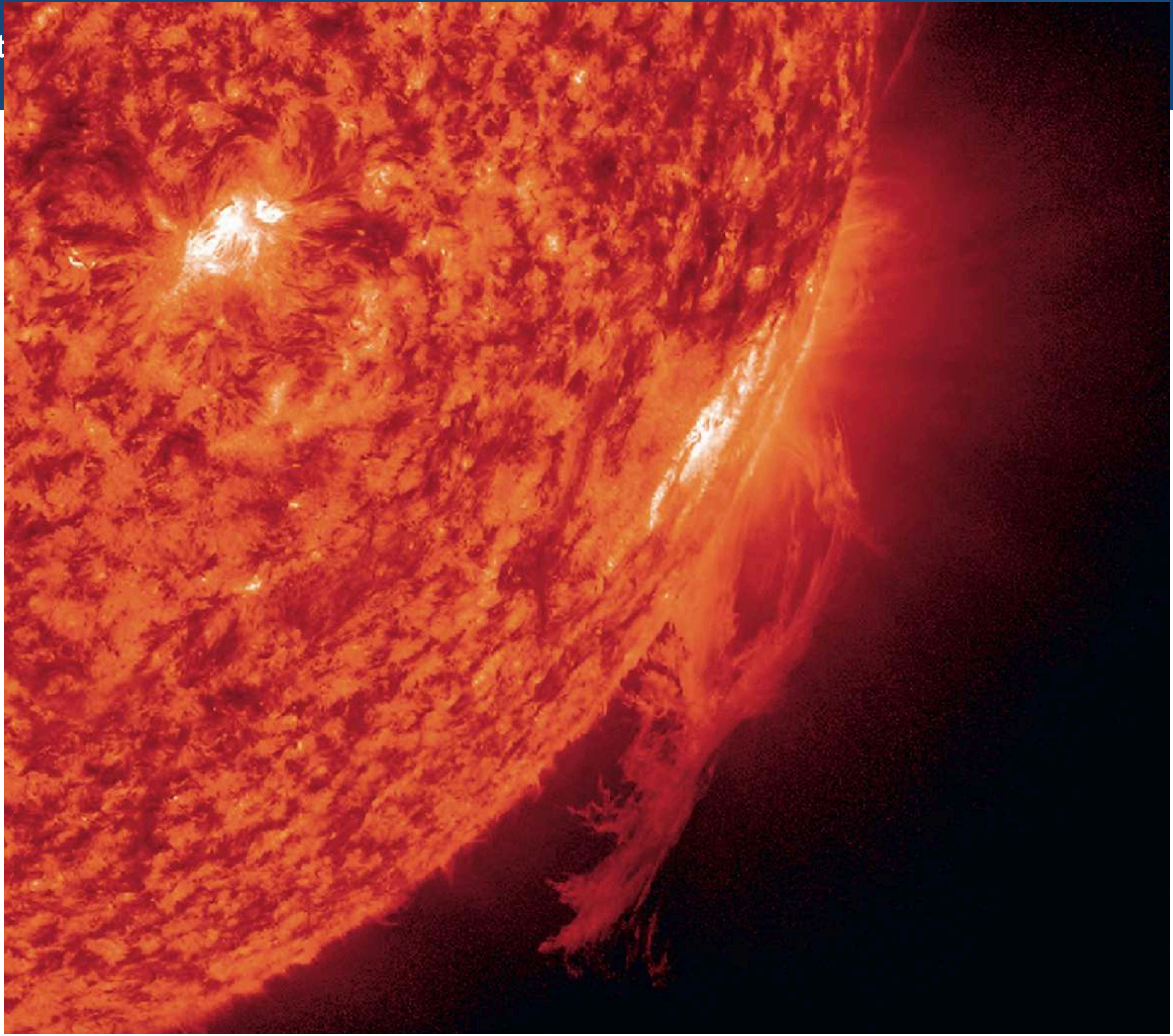
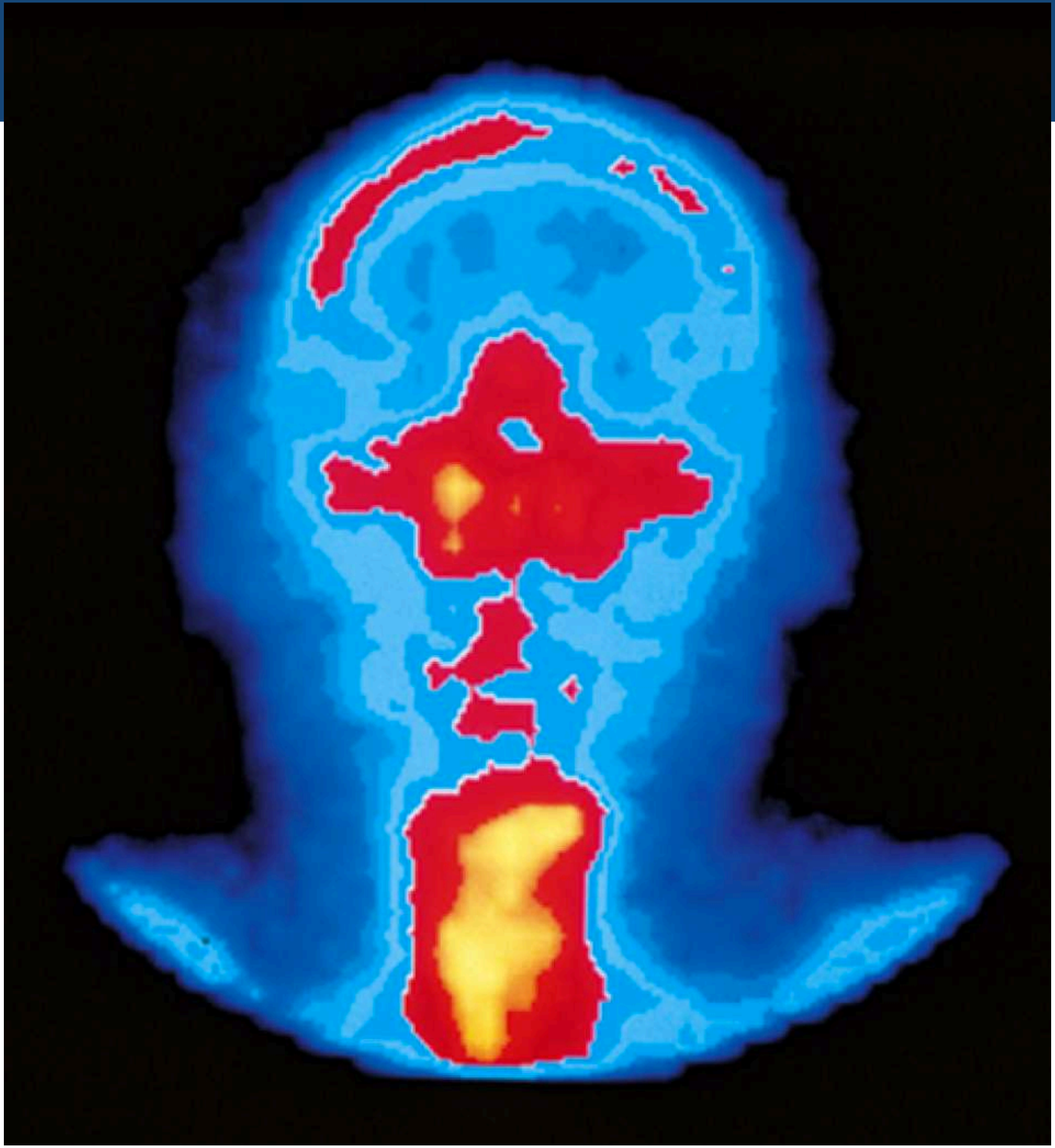
Objectives

1. To learn the types of radioactive decay
2. To learn to write nuclear equations for radioactive decay
3. To learn how one element may be changed to another by particle bombardment
4. To learn about radiation detection instruments
5. To understand half-life

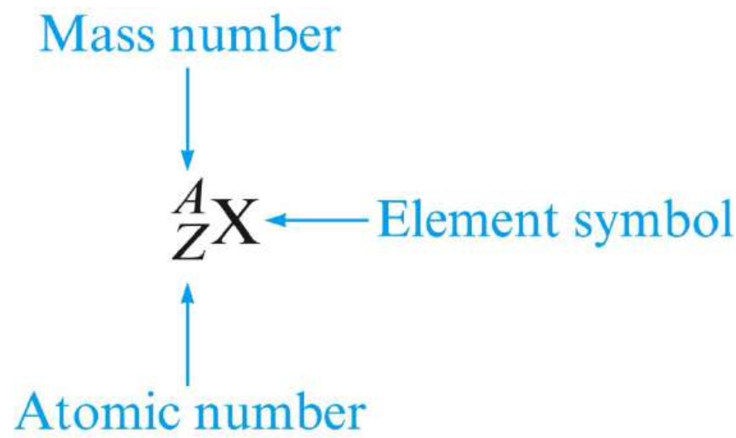
Radioact





A Review of Atomic Terms

- nucleons – particles found in the nucleus of an atom
  - neutrons
  - protons
- atomic number (Z) – number of protons in the nucleus
- mass number (A) – sum of the number of protons and neutrons
- isotopes – atoms with identical atomic numbers but different mass numbers
- nuclide – each unique atom



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A. Radioactive Decay

- radioactive – nucleus which spontaneously decomposes forming a different nucleus and producing one or more particles
- nuclear equation – shows the radioactive decomposition of an element

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

A. Radioactive Decay

Types of Radioactive Decay

- Alpha-particle production
- Alpha particle – helium nucleus
  - Examples

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

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

Net effect is loss of 4 in mass number and loss of 2 in atomic number.

A. Radioactive Decay

Types of Radioactive Decay

- Beta-particle production

Beta particle – electron

- Examples

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

$$^{131}_{53}\text{I} \rightarrow {}^{0}_{-1}\text{e} + {}^{131}_{54}\text{Xe}$$

Net effect is to change a neutron to a proton.

A. Radioactive Decay

Types of Radioactive Decay

- Gamma ray release

Gamma ray – high energy photon

  - Examples

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

Net effect is no change in mass number or atomic number.

A. Radioactive Decay

Types of Radioactive Decay

- Positron production

Positron – particle with same mass as an electron but with a positive charge

  - Examples

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

Net effect is to change a proton to a neutron.

A. Radioactive Decay

Types of Radioactive Decay

- Electron capture
  - Example

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

↑ Inner-orbital electron

A. Radioactive Decay

Table 19.1 Various Types of Radioactive Processes

Process	Example
β-particle (electron) production	$^{227}_{89}Ac \rightarrow ^{227}_{90}Th + ^{0}_{-1}e$
positron production	$^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{1}e$
electron capture	$^{73}_{33}As + ^{0}_{-1}e \rightarrow ^{73}_{32}Ge$
α-particle production	$^{210}_{84}Po \rightarrow ^{206}_{82}Pb + ^{4}_{2}He$
γ-ray production	excited nucleus → ground-state nucleus + $^{0}_{0}\gamma$ excess energy lower energy

Concept Check

Which of the following produces a beta particle?

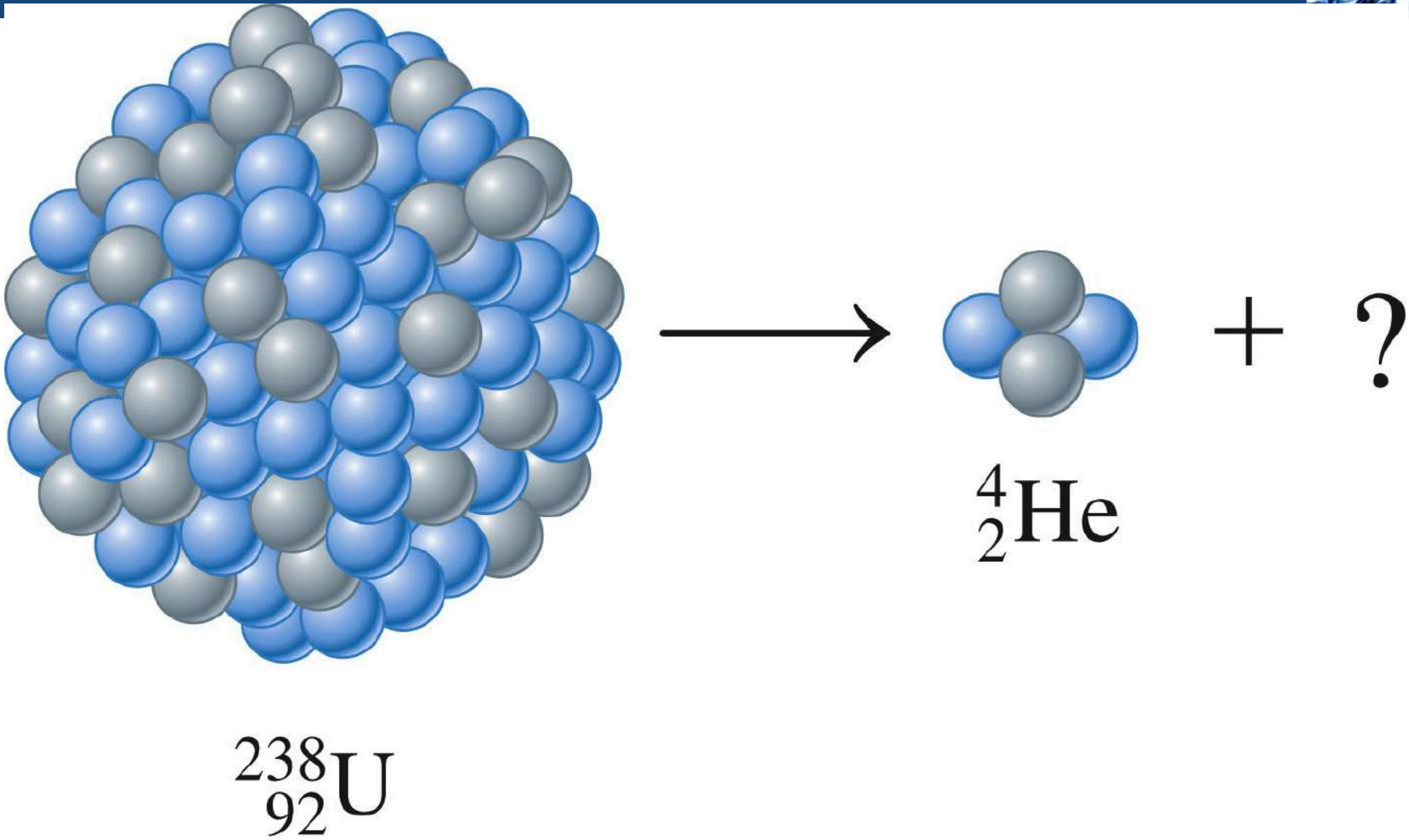
a) $^{68}_{31}Ga + ^{0}_{-1}e \rightarrow ^{68}_{30}Zn$ electron capture

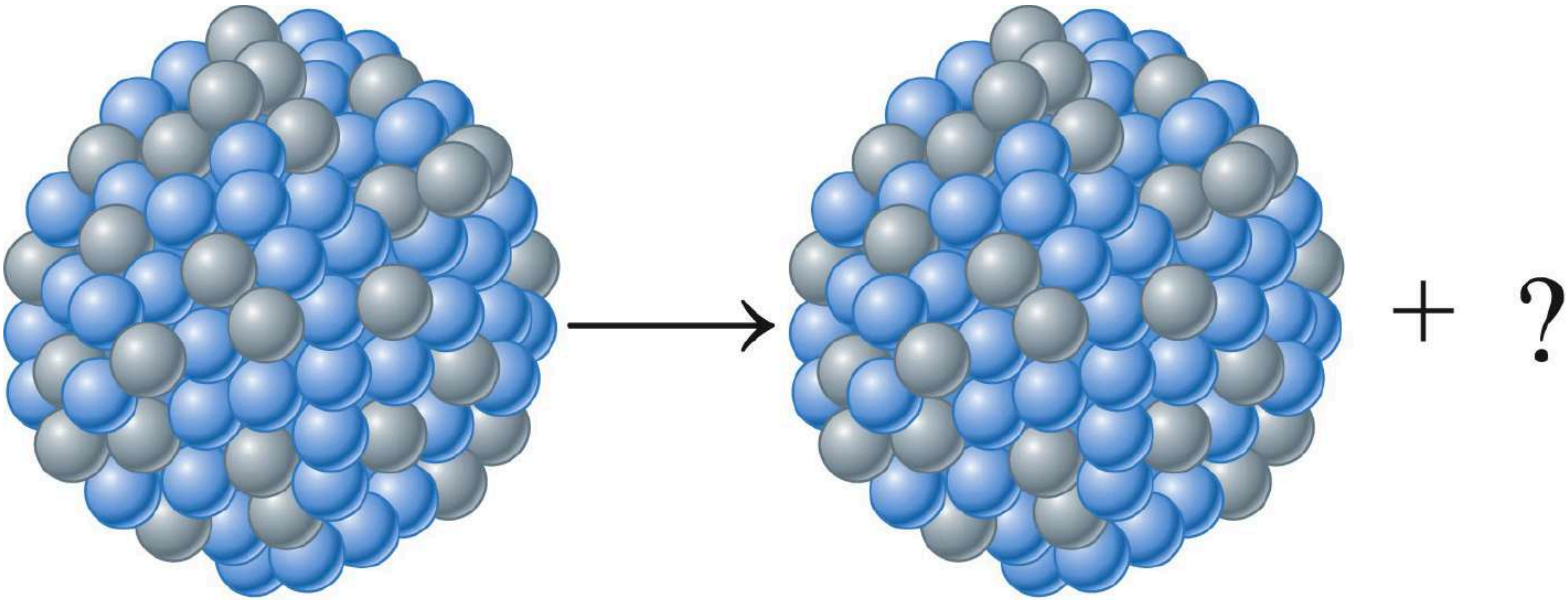
b) $^{62}_{29}Cu \rightarrow ^{0}_{+1}e + ^{62}_{28}Ni$ positron

c) $^{212}_{87}Fr \rightarrow ^{4}_{2}He + ^{208}_{85}At$ alpha particle

d) $^{129}_{51}Sb \rightarrow ^{0}_{-1}e + ^{129}_{52}Te$ beta particle

Radioactivity





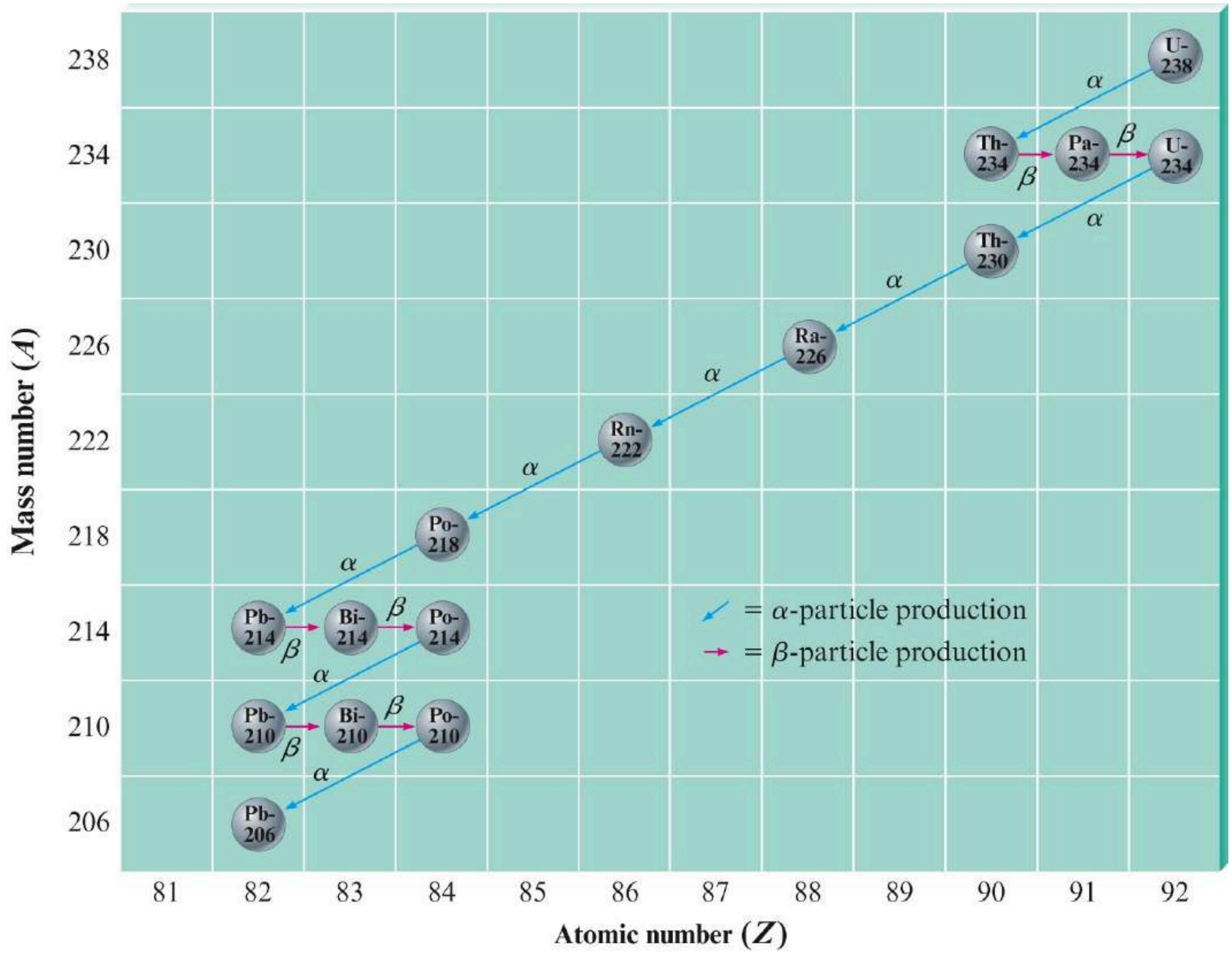
$$^{234}_{90}\text{Th} \longrightarrow \, ^{234}_{91}\text{Pa} + ?$$

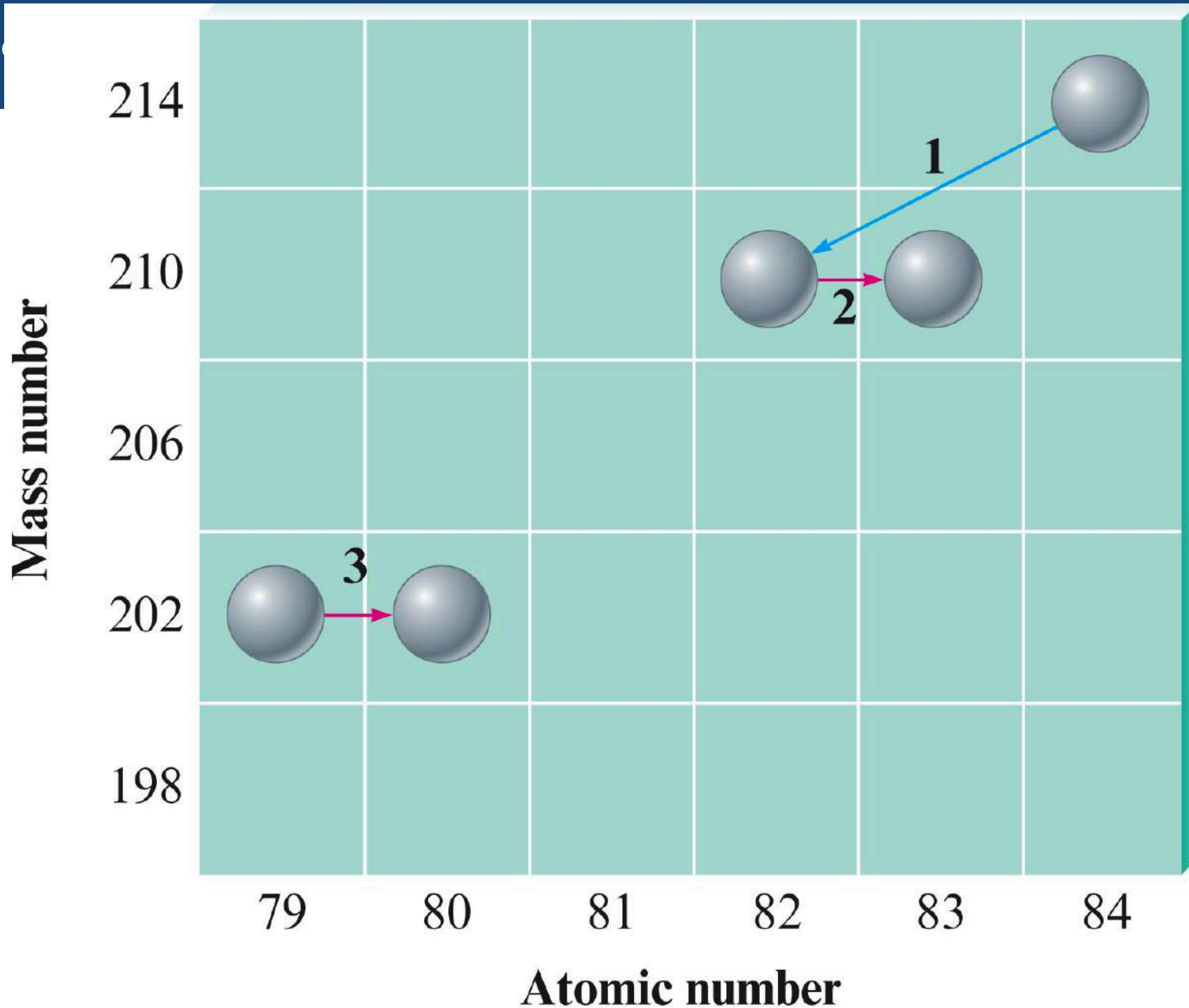
$$^{11}_{6}\mathrm{C} \longrightarrow {}^{0}_{1}\mathrm{e} + {}^{A}_{Z}\mathrm{X}$$

Positron

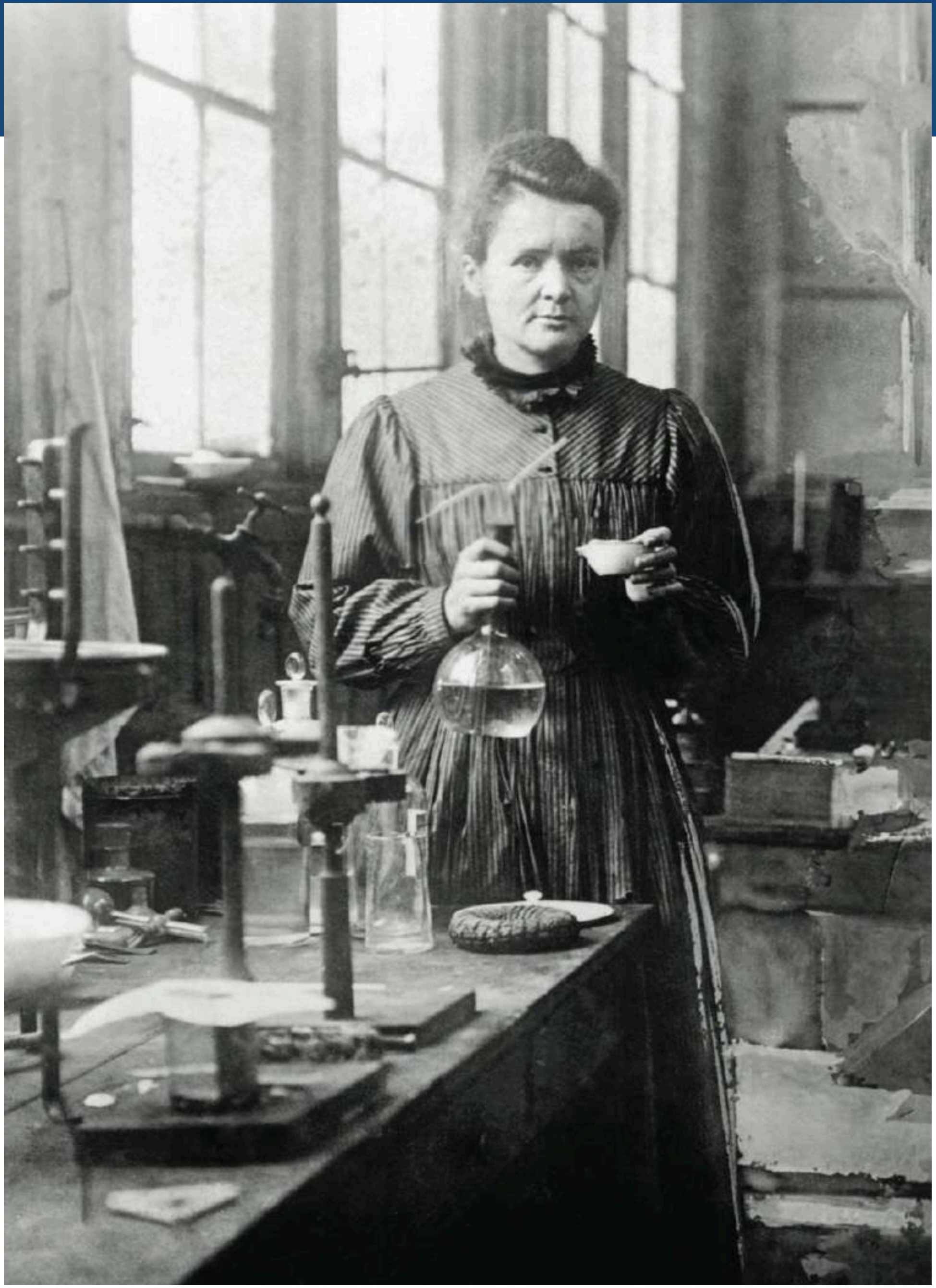
A. Radioactive Decay

Decay series




214
210
206
202
198
Mass number
1
2
3
79
80
81
82
83
84
Atomic number

Radioactivity



B. Nuclear Transformations

- Nuclear transformation – change of one element to another
- Bombard elements with particles
    - Examples

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

B. Nuclear Transformations

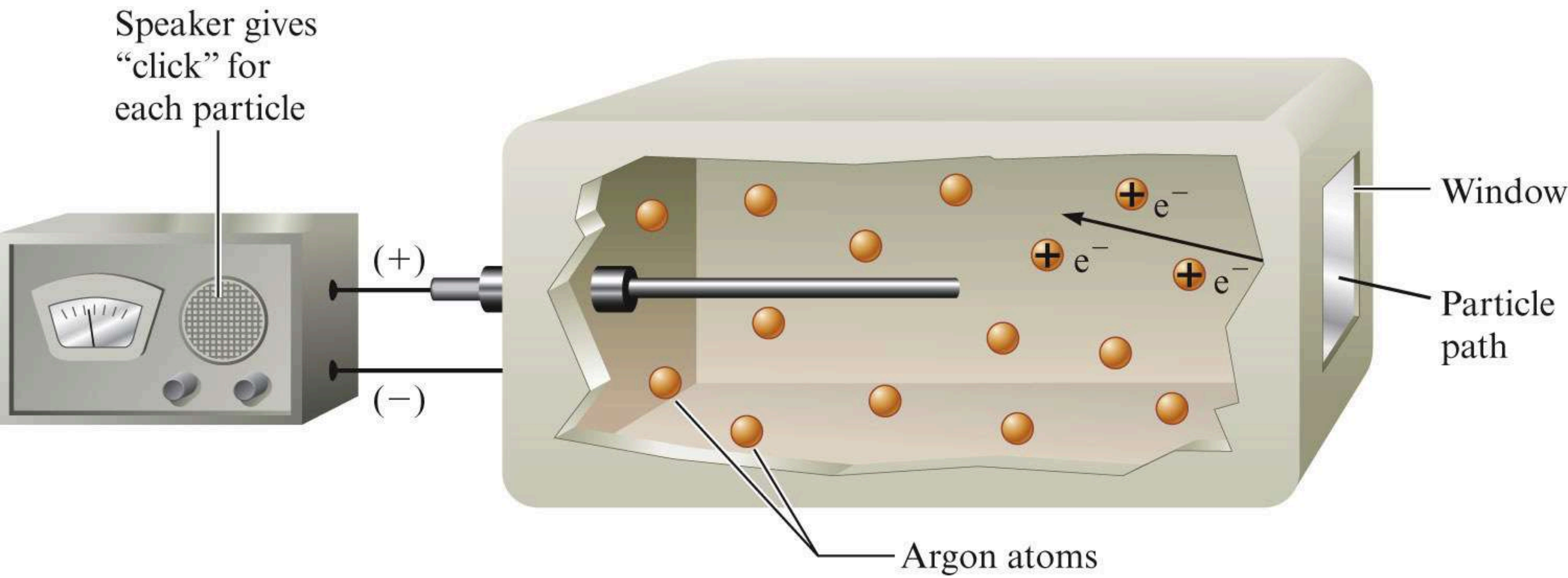
- Transuranium elements – elements with atomic numbers greater than 92 which have been synthesized

Table 19.2 Syntheses of Some of the Transuranium Elements

Neutron Bombardment	neptunium ($Z = 93$)	${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$
	americium ($Z = 95$)	${}^{239}_{94}Pu + 2\,{}^{1}_{0}n \rightarrow {}^{241}_{94}Pu \rightarrow {}^{241}_{95}Am + {}^{0}_{-1}e$
Positive-Ion Bombardment	curium ($Z = 96$)	${}^{239}_{94}Pu + {}^{4}_{2}He \rightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$
	californium ($Z = 98$)	${}^{242}_{96}Cm + {}^{4}_{2}He \rightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$ or
		${}^{238}_{92}U + {}^{12}_{6}C \rightarrow {}^{246}_{98}Cf + 4\,{}^{1}_{0}n$
	rutherfordium ($Z = 104$)	${}^{249}_{98}Cf + {}^{12}_{6}C \rightarrow {}^{257}_{104}Rf + 4\,{}^{1}_{0}n$
	dubnium ($Z = 105$)	${}^{249}_{98}Cf + {}^{15}_{7}N \rightarrow {}^{260}_{105}Db + 4\,{}^{1}_{0}n$
	seaborgium ($Z = 106$)	${}^{249}_{98}Cf + {}^{18}_{8}O \rightarrow {}^{263}_{106}Sg + 4\,{}^{1}_{0}n$

C. Detection of Radioactivity and the Concept of Half-life

- Geiger-Muller counter – instrument which measures radioactive decay by registering the ions and electrons produced as a radioactive particle passes through a gas-filled chamber



C. Detection of Radioactivity and the Concept of Half-life

- Scintillation counter – instrument which measures the rate of radioactive decay by sensing flashes of light that the radiation produces in the detector

$$100\text{ million } {}^{234}_{91}\text{Pa} \xrightarrow[\substack{\text{minutes} \\ \text{(50 million decays)}}]{1.2} 50\text{ million } {}^{234}_{91}\text{Pa} \xrightarrow[\substack{\text{minutes} \\ \text{(25 million decays)}}]{1.2} 25\text{ million } {}^{234}_{91}\text{Pa}$$

C. Detection of Radioactivity and the Concept of Half-life

- Half-life – time required for half of the original sample of radioactive nuclides to decay

Table 19.3 The Half-lives for Some of the Radioactive Nuclides of Radium

Nuclide	Half-life
$^{223}_{88}Ra$	12 days
$^{224}_{88}Ra$	3.6 days
$^{225}_{88}Ra$	15 days
$^{226}_{88}Ra$	1600 years
$^{228}_{88}Ra$	6.7 years

$$1.00\ \text{mol}\ {}^{223}_{88}\text{Ra} \xrightarrow[\text{12 days}]{} 0.50\ \text{mol}\ {}^{223}_{88}\text{Ra} \xrightarrow[\text{12 days}]{} 0.25\ \text{mol}\ {}^{223}_{88}\text{Ra}$$


93
237.05
Np
Neptunium
94
(244)
95
(243)
Am
96
(247)
Cm
Curium
97
Bk
Berkelium
(252)
100
(257)
Fm
Fermium
101
(260)
Md
(262)
104
(261)
Rf
(266)

Objectives

1. To learn how objects can be dated by radioactivity
2. To understand the use of radiotracers in medicine

A. Dating by Radioactivity

Radiocarbon dating

- Originated in 1940s by Willard Libby
  - Based on the radioactivity of carbon-14

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

Used to date wood and artifacts

B. Medical Applications of Radioactivity

Radiotracers

- Radioactive nuclides that can be introduced into organisms and traced for diagnostic purposes.

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.

Application of Radioactivity

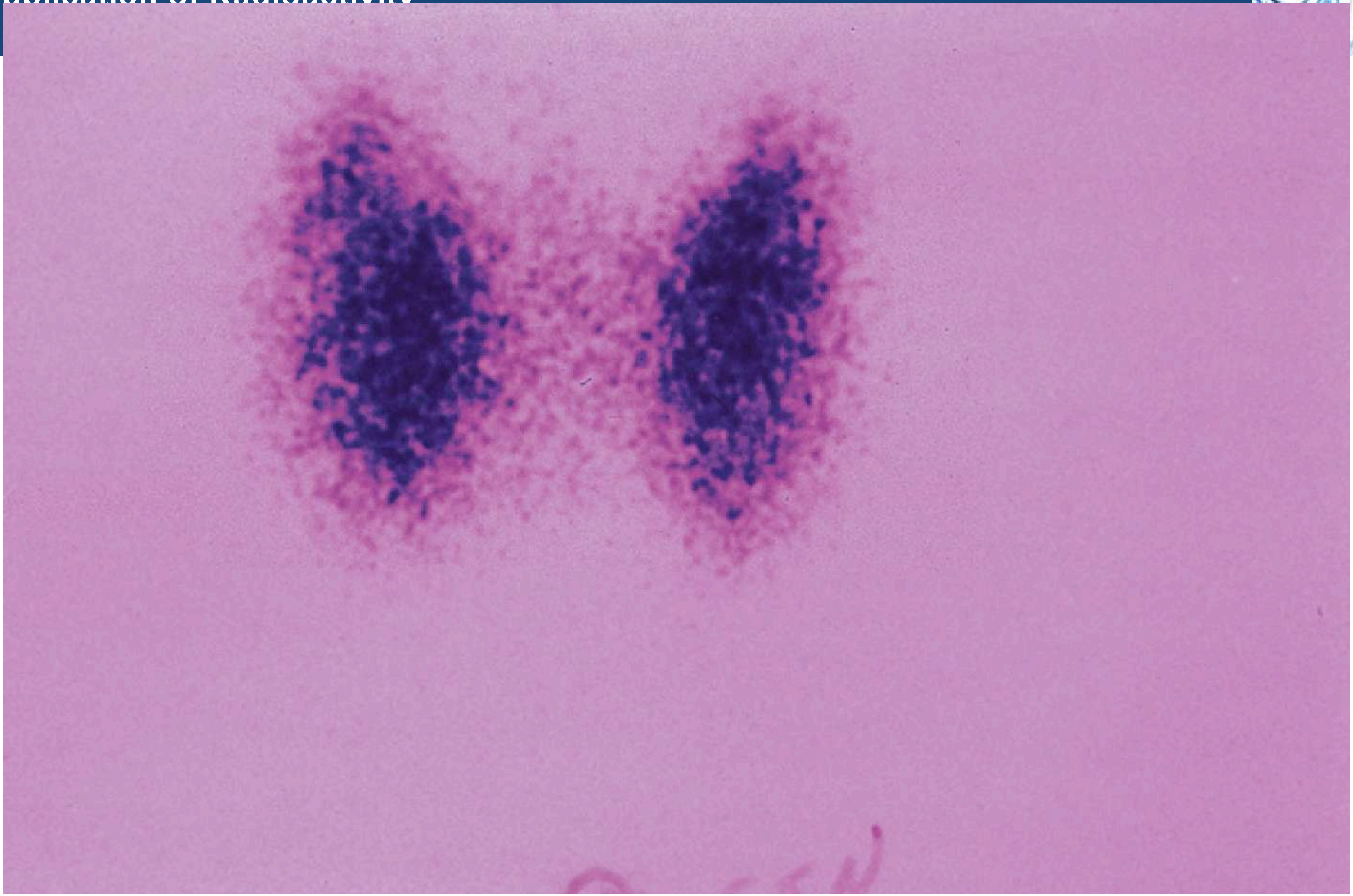


Figure 19-3a p723

Application of Radioactivity

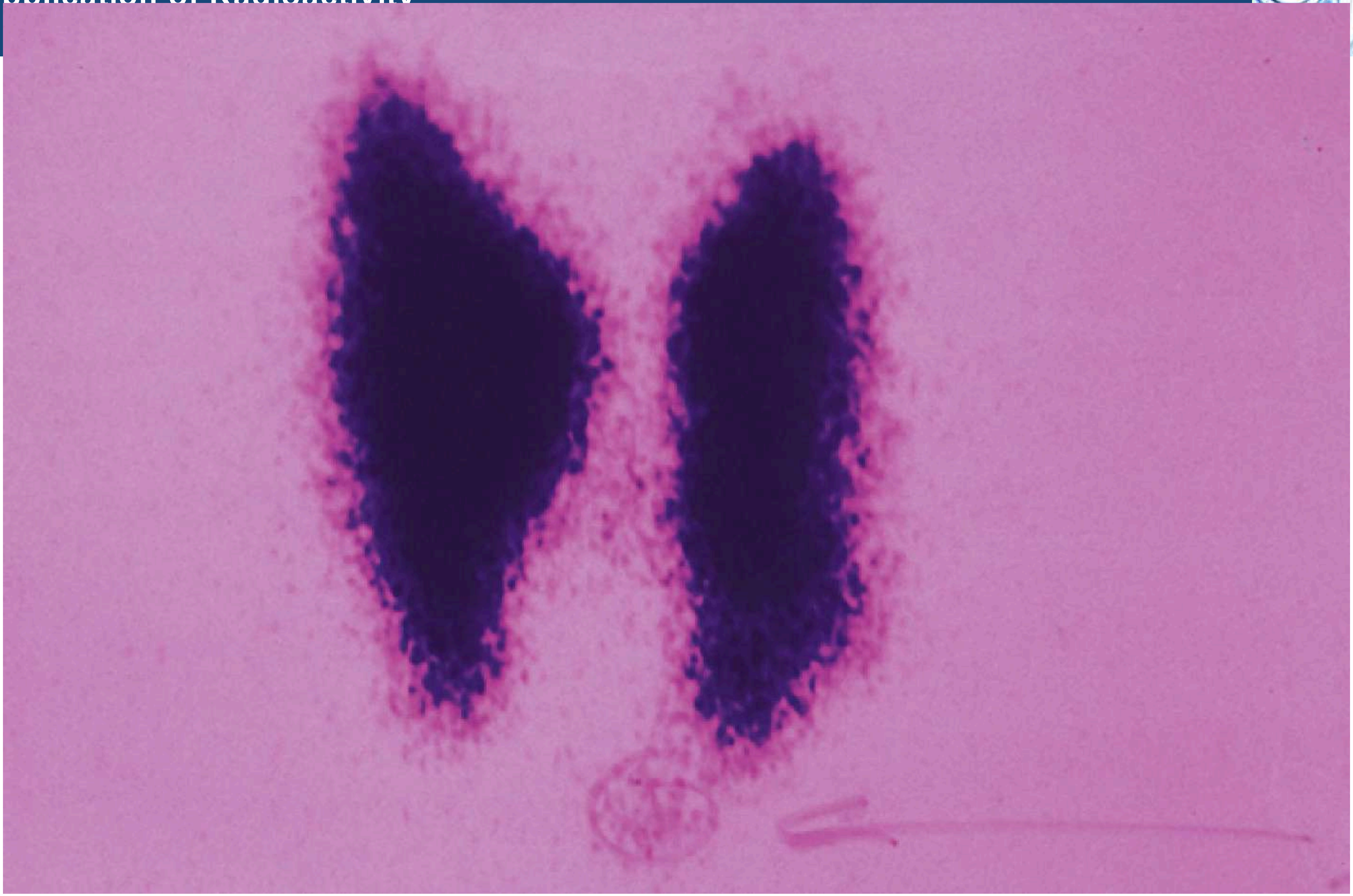
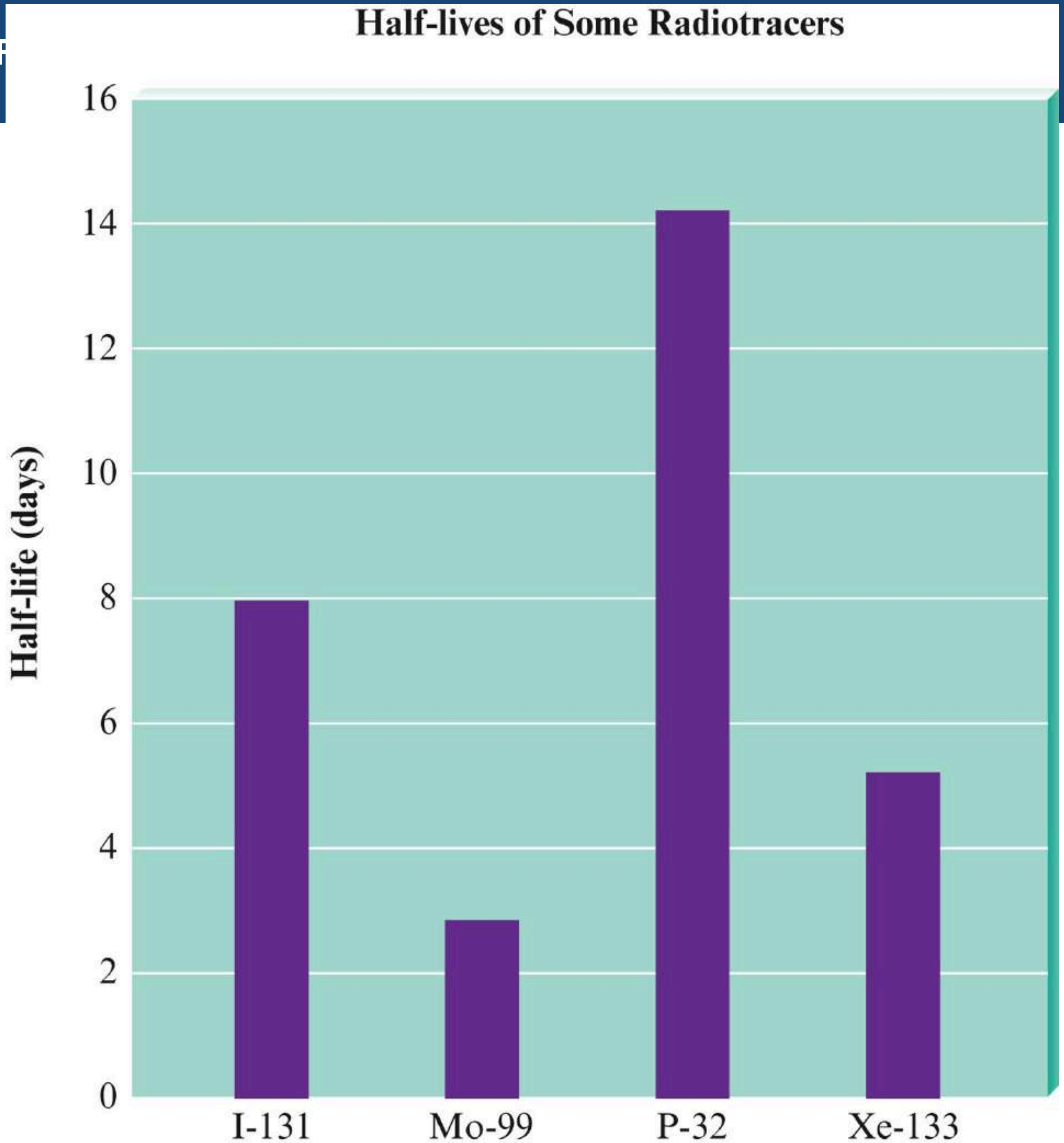


Figure 19-3b p723


Half-lives of Some Radiotracers
Half-life (days)
16
14
12
10
8
6
4
2
0
I-131
Mo-99
P-32
Xe-133

p723

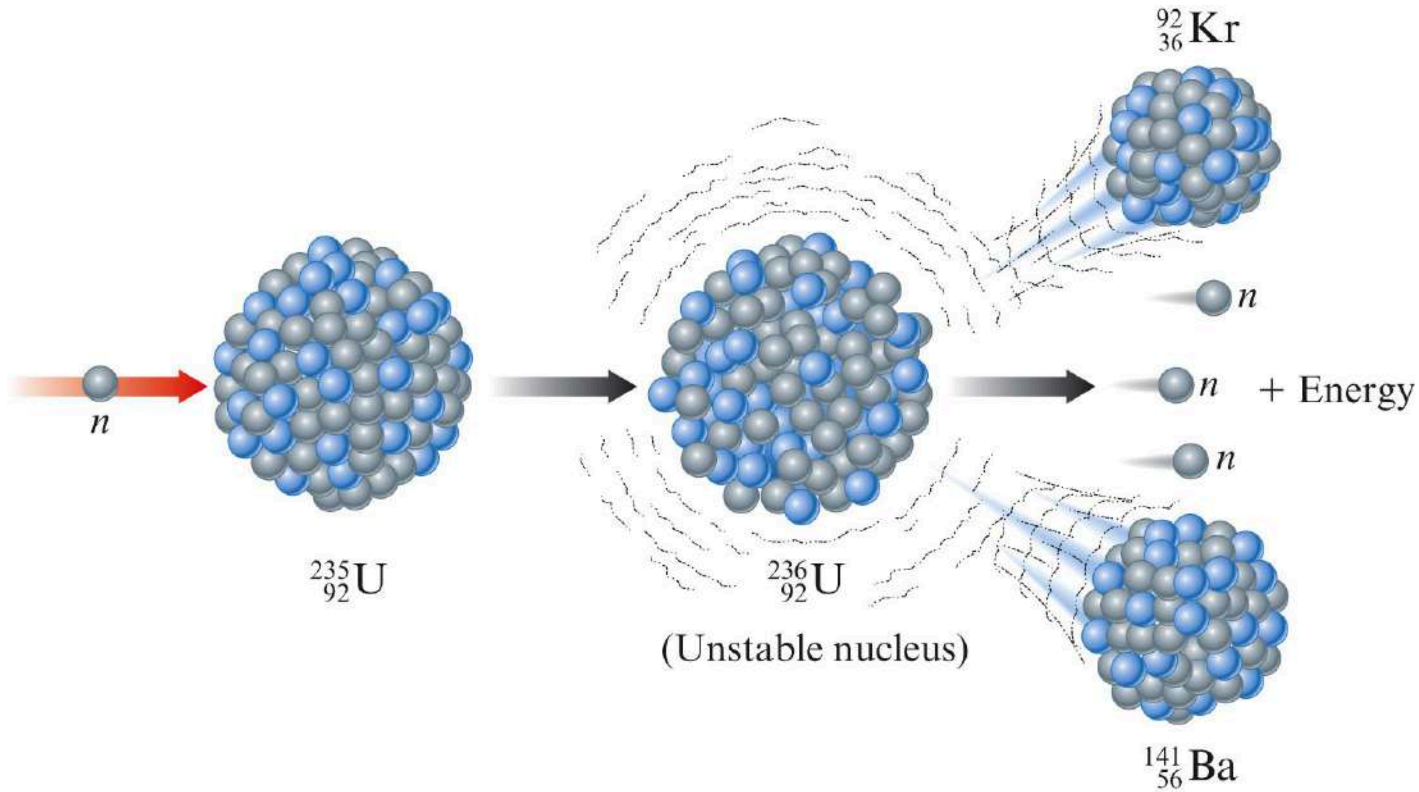
Objectives

1. To introduce fusion and fission as sources of energy
2. To learn about nuclear fission
3. To understand how a nuclear reactor works
4. To learn about nuclear fusion
5. To see how radiation damages human tissue

A. Nuclear Energy

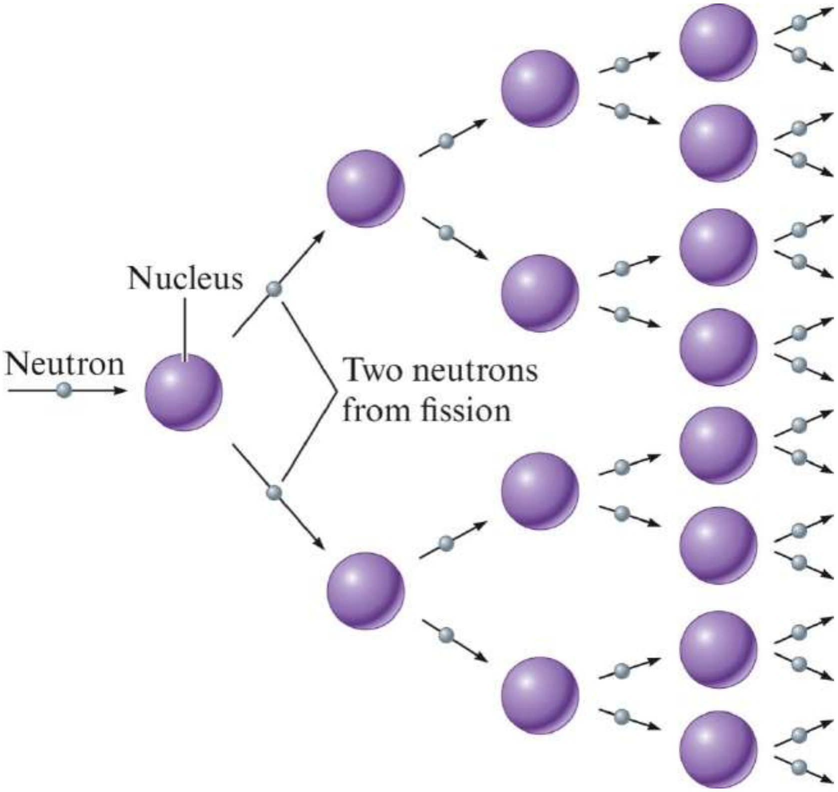
- Two types of nuclear processes can produce energy
  - Combining 2 light nuclei to form a heavier nucleus - fusion
  - Splitting a heavy nucleus into 2 nuclei with smaller mass numbers - fission

B. Nuclear Fission



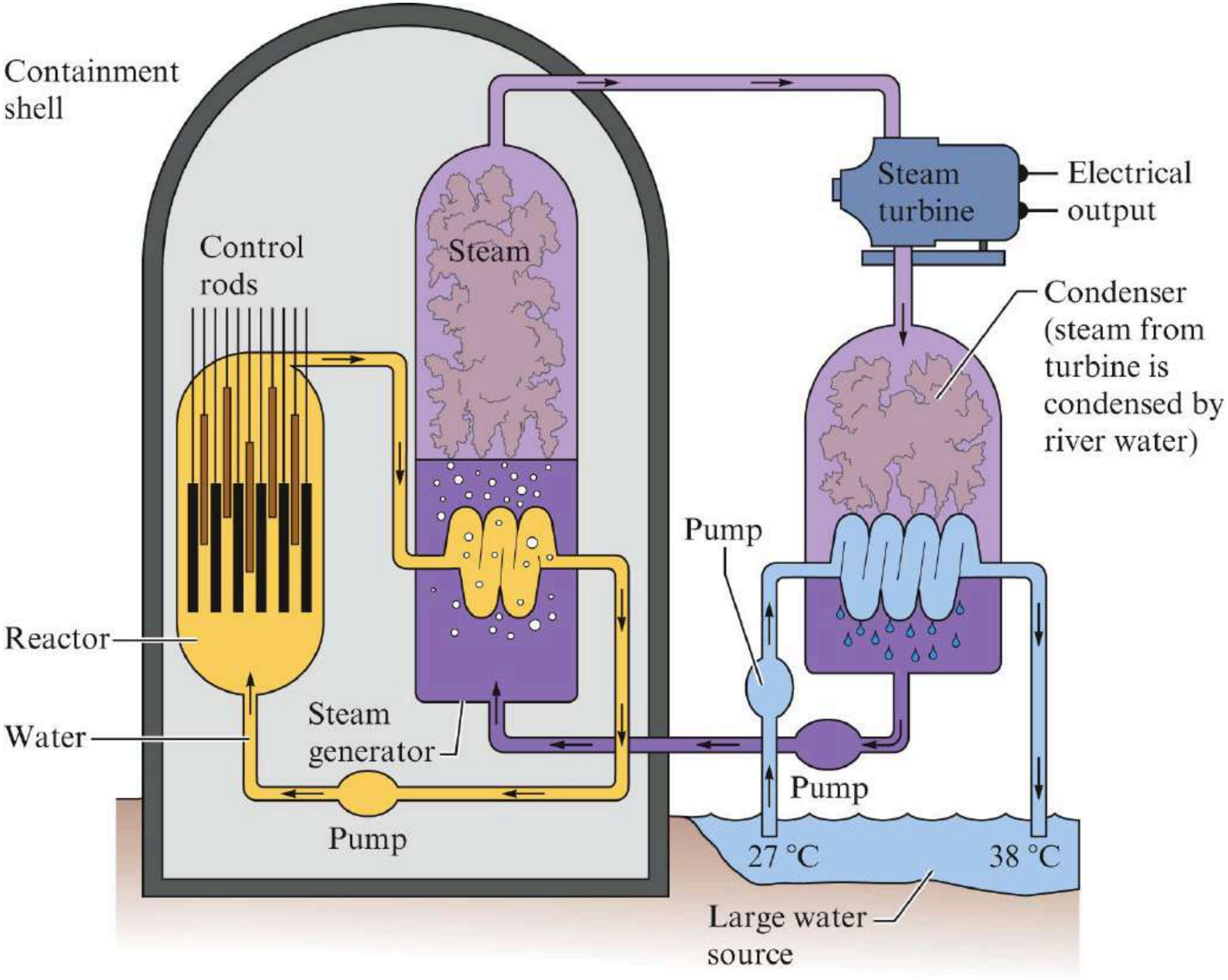
- Releases 2.1×10^{13} J/mol uranium-235
- Each fission produces 3 neutrons.

B. Nuclear Fission



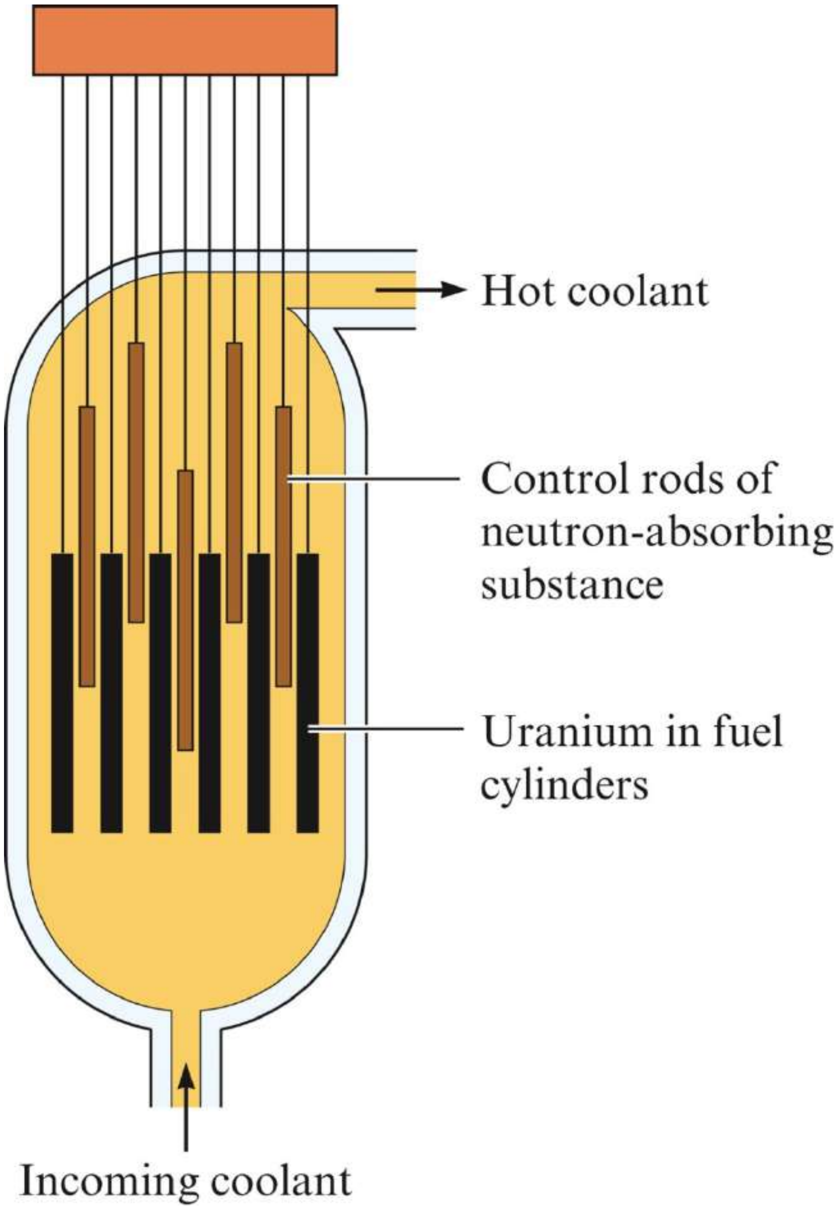
- Chain reaction – self sustaining fission process caused by the production of neutrons that proceed to split other nuclei
- Critical mass – mass of fissionable material required to produce a chain reaction

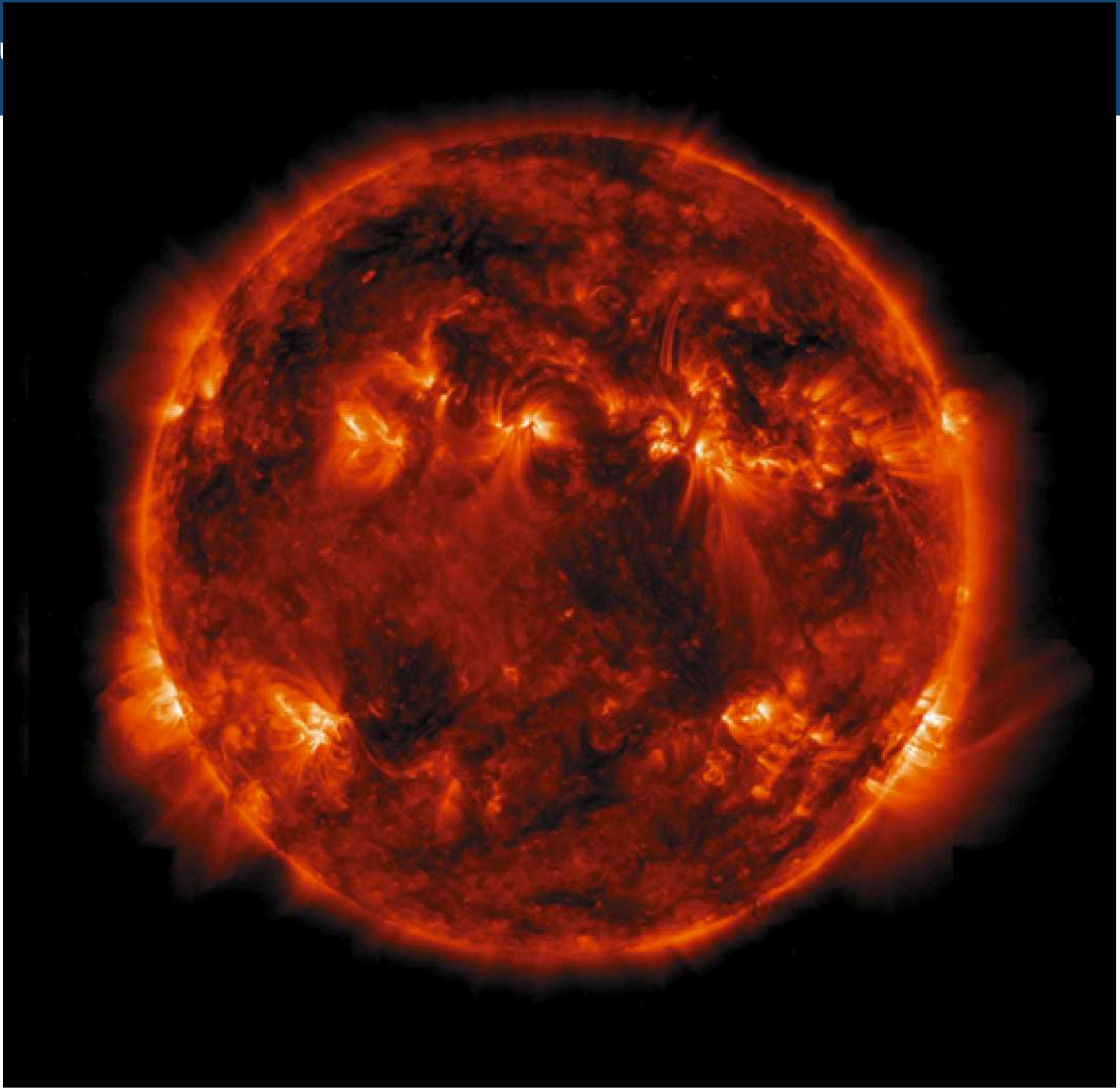
C. Nuclear Reactors



C. Nuclear Reactors

Reactor core





D. Nuclear Fusion

- Process of combining 2 light nuclei
- Produces more energy per mole than fission
- Powers the stars and sun

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e + \text{energy}$$

$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \text{energy}$$

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2\,^{1}_{1}H + \text{energy}$$

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

D. Nuclear Fusion

- Requires extremely high temperatures

Currently not technically possible for us to use as an energy source

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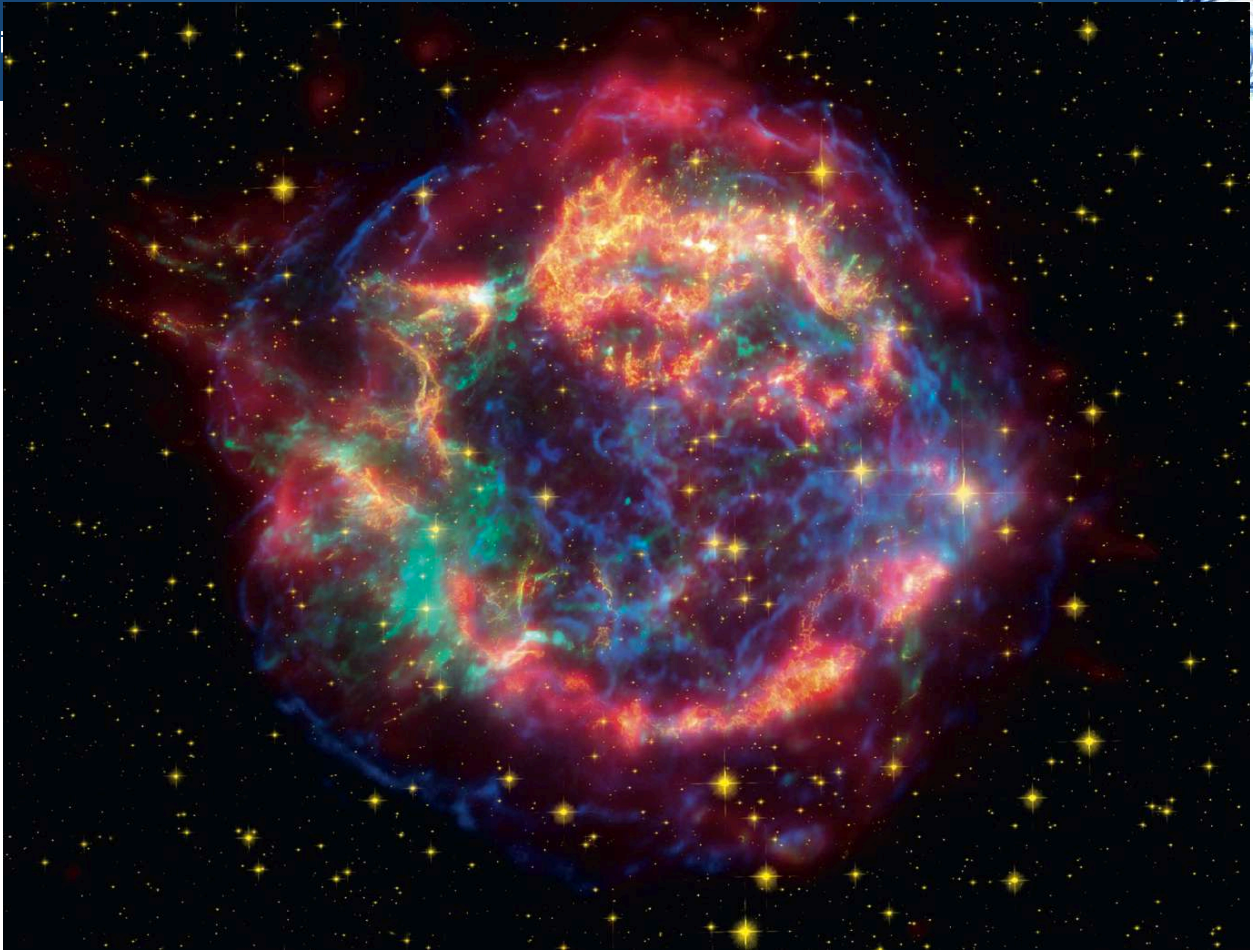
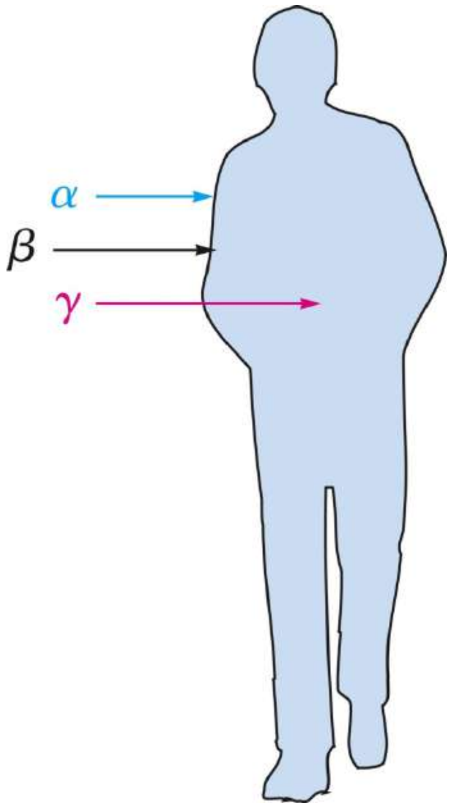


E. Effects of Radiation

Factors Determining Biological Effects of Radiation

- Energy of the radiation
- Penetrating ability of the radiation
- Ionizing ability of the radiation
- Chemical properties of the radiation source



E. Effects of Radiation

Table 19.5 Effects of Short-Term Exposures to Radiation

Dose (rem)	Clinical Effect
0–25	nondetectable
25–50	temporary decrease in white blood cell counts
100–200	strong decrease in white blood cell counts
500	death of half the exposed population within 30 days after exposure

E. Effects of Radiation

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	97
Total	193 = 0.193 rems