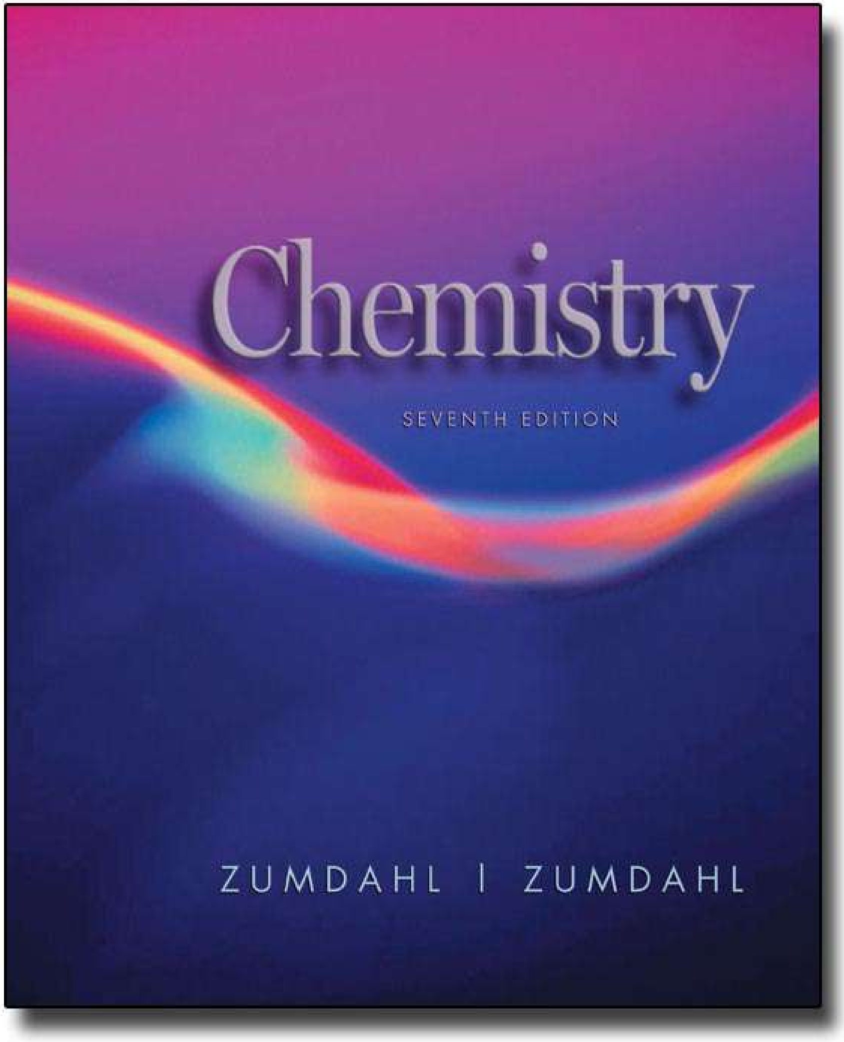
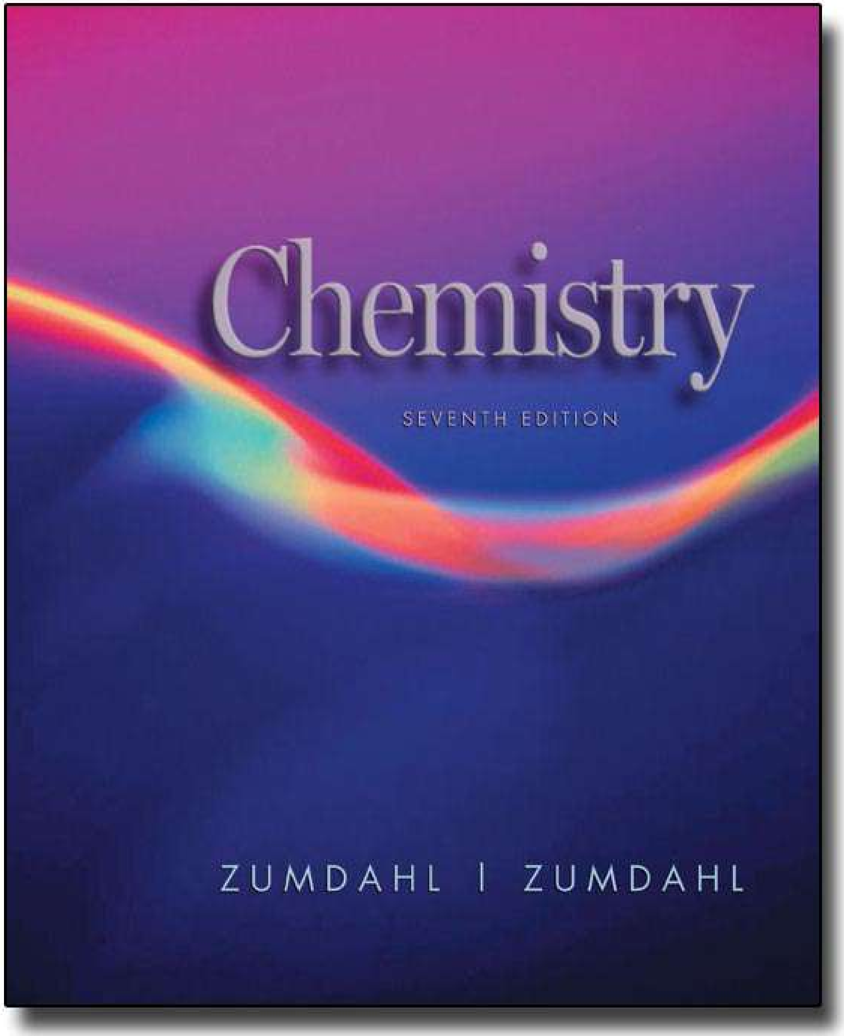


Chapter Eighteen:

THE NUCLEUS: A CHEMIST'S VIEW



Nuclear Stability and Radioactive Decay

Nuclear Particles

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The Zone of Stability

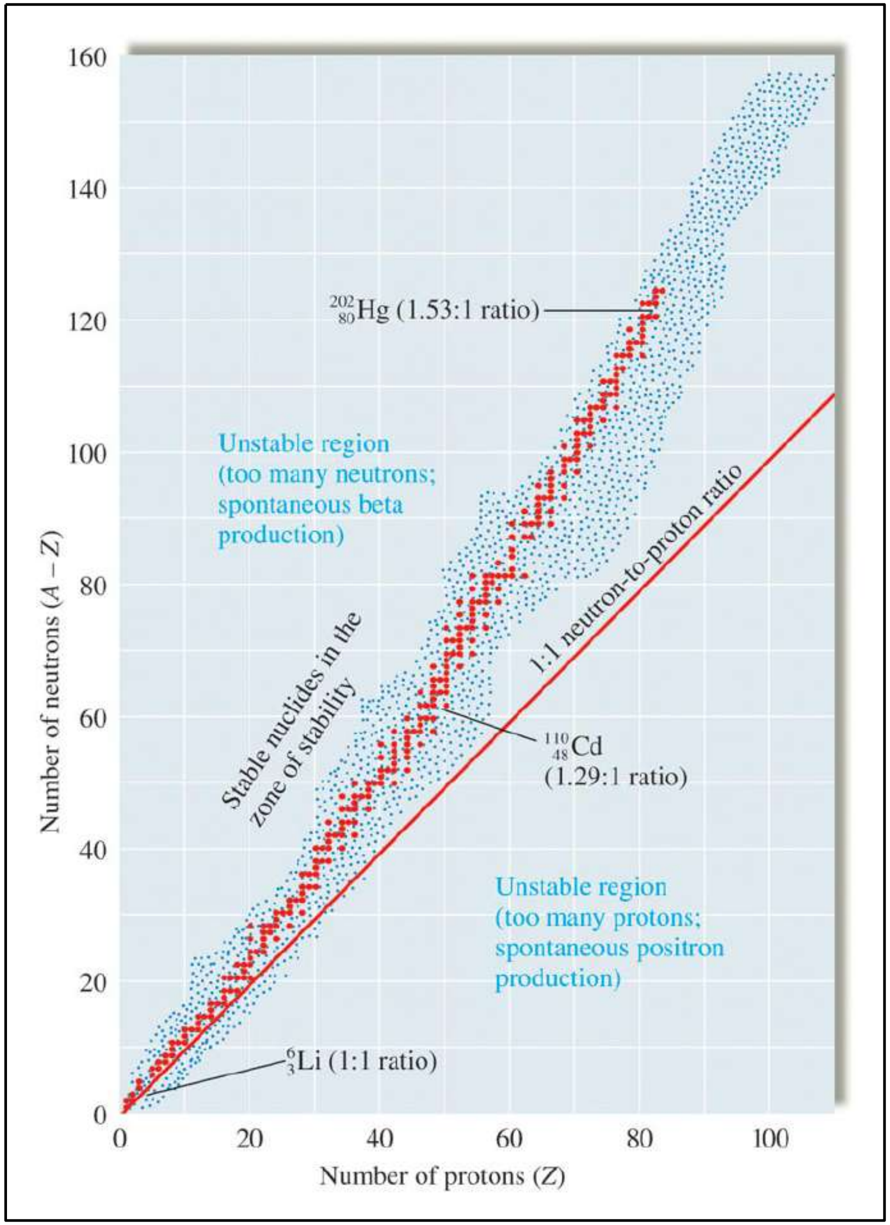

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Table 18.1 Number of Stable Nuclides Related to Numbers of Protons and Neurons

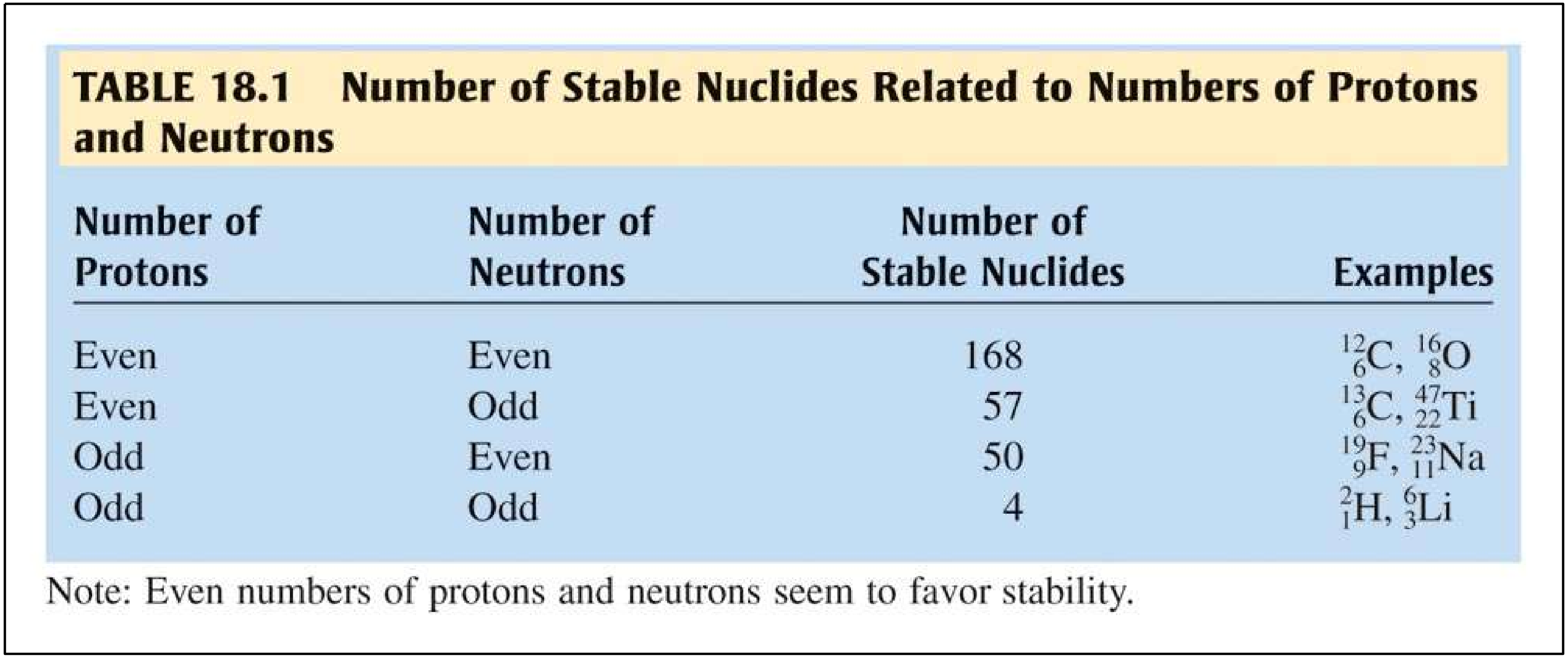

TABLE 18.1 Number of Stable Nuclides Related to Numbers of Protons and Neutrons

Number of Protons	Number of Neutrons	Number of Stable Nuclides	Examples
Even	Even	168	$^{12}_{6}C$, $^{16}_{8}O$
Even	Odd	57	$^{13}_{6}C$, $^{47}_{22}Ti$
Odd	Even	50	$^{19}_{9}F$, $^{23}_{11}Na$
Odd	Odd	4	$^{2}_{1}H$, $^{6}_{3}Li$

Note: Even numbers of protons and neutrons seem to favor stability.

Types of Radioactive Decay

- alpha production (α):

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

- beta production (β):

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

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Types of Radioactive Decay

gamma ray production (γ):

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

positron production:

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

electron capture:

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

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Table 18.2 Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

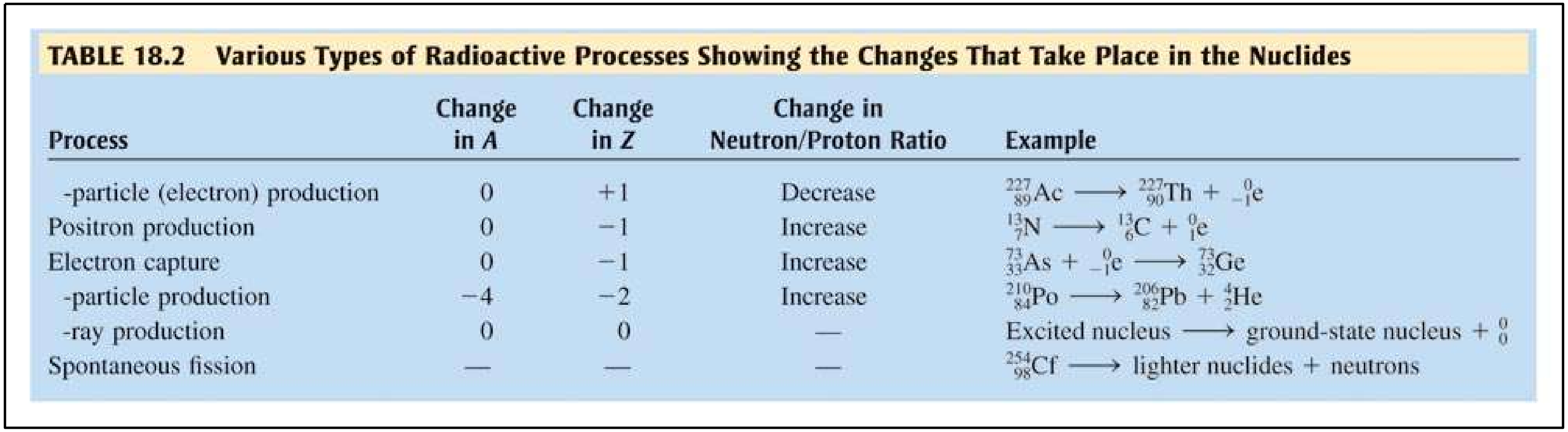

TABLE 18.2 Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

Process	Change in *A*	Change in *Z*	Change in Neutron/Proton Ratio	Example
-particle (electron) production	0	+1	Decrease	$^{227}_{89}\mathrm{Ac} \longrightarrow\ ^{227}_{90}\mathrm{Th} +\ ^{0}_{-1}\mathrm{e}$
Positron production	0	−1	Increase	$^{13}_{7}\mathrm{N} \longrightarrow\ ^{13}_{6}\mathrm{C} +\ ^{0}_{1}\mathrm{e}$
Electron capture	0	−1	Increase	$^{73}_{33}\mathrm{As} +\ ^{0}_{-1}\mathrm{e} \longrightarrow\ ^{73}_{32}\mathrm{Ge}$
-particle production	−4	−2	Increase	$^{210}_{84}\mathrm{Po} \longrightarrow\ ^{206}_{82}\mathrm{Pb} +\ ^{4}_{2}\mathrm{He}$
-ray production	0	0	—	Excited nucleus $\longrightarrow$ ground-state nucleus + $^{0}_{0}$
Spontaneous fission	—	—	—	$^{254}_{98}\mathrm{Cf} \longrightarrow$ lighter nuclides + neutrons

Decay Series

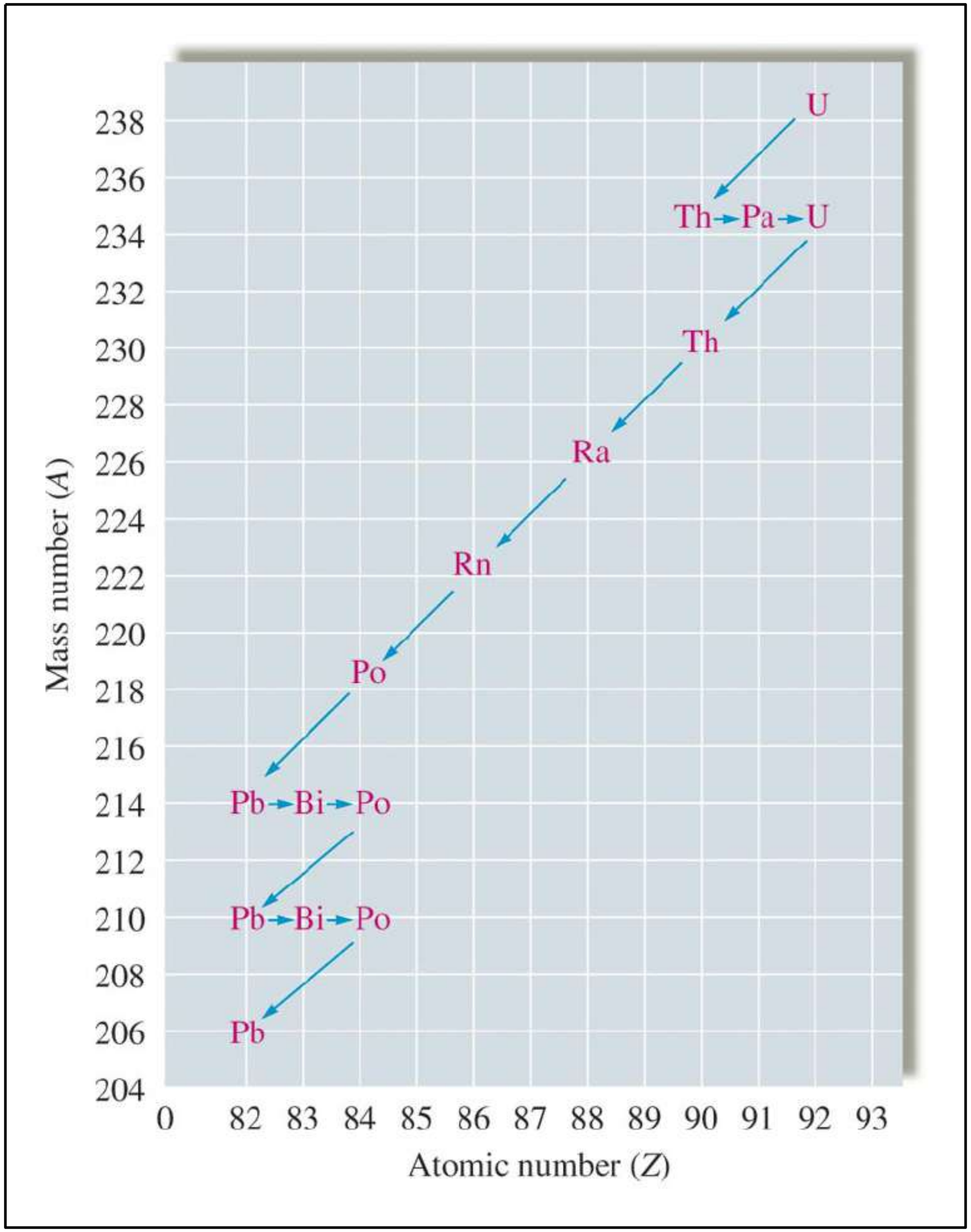

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Table 18.3 The Half-Lives of Nuclides in the $^{238}_{92}U$ Decay Series

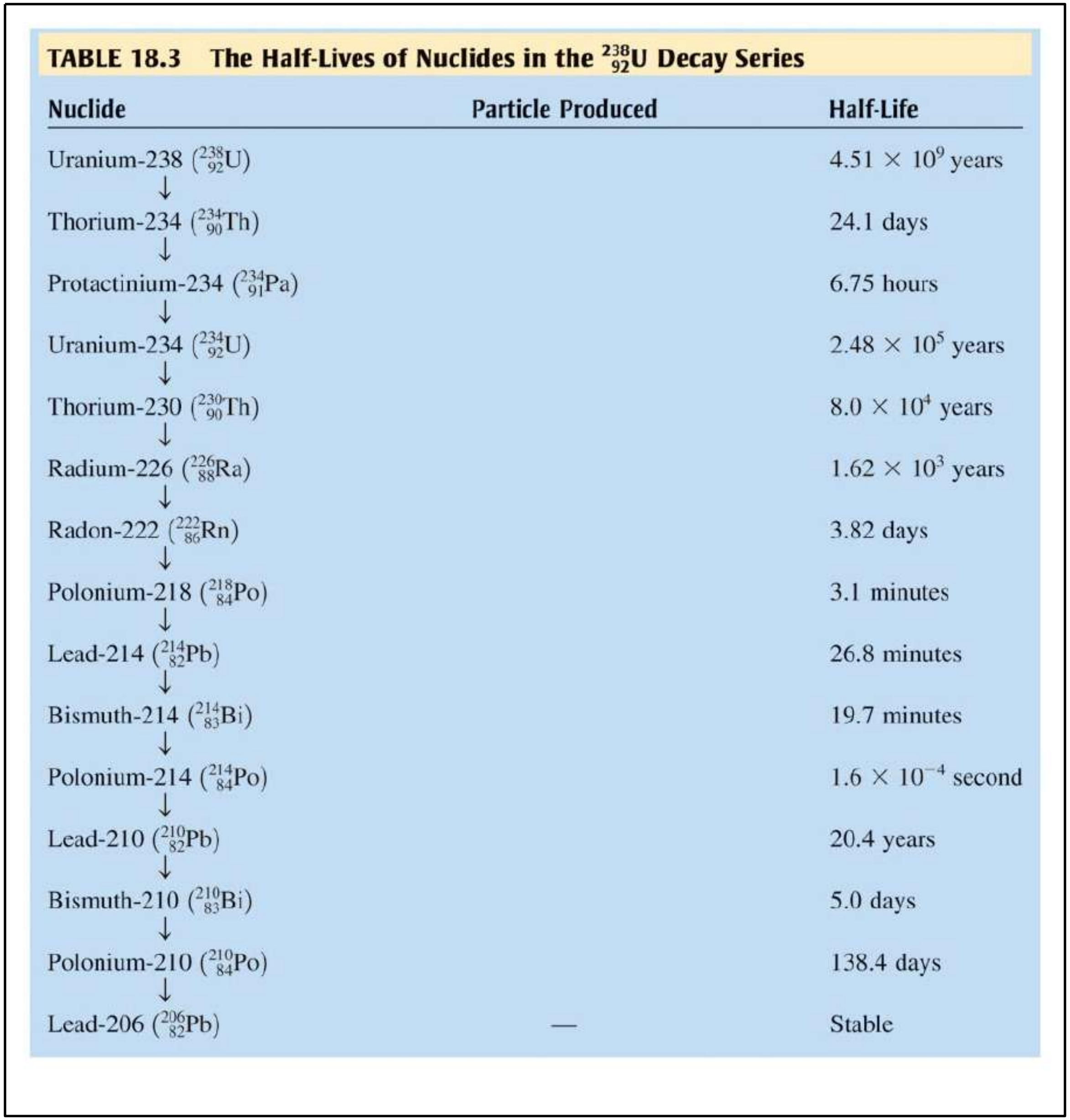
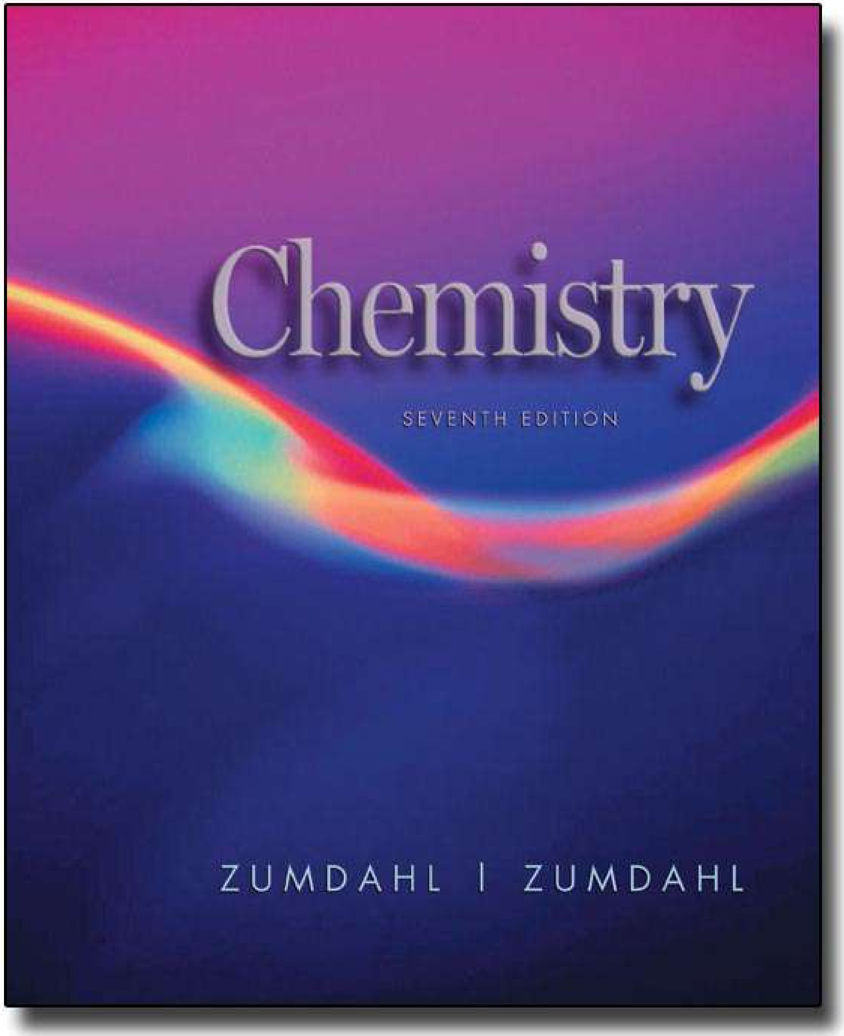


TABLE 18.3 The Half-Lives of Nuclides in the $^{238}_{92}U$ Decay Series

Nuclide	Particle Produced	Half-Life
Uranium-238 ($^{238}_{92}U$)		4.51×10^9 years
↓		
Thorium-234 ($^{234}_{90}Th$)		24.1 days
↓		
Protactinium-234 ($^{234}_{91}Pa$)		6.75 hours
↓		
Uranium-234 ($^{234}_{92}U$)		2.48×10^5 years
↓		
Thorium-230 ($^{230}_{90}Th$)		8.0×10^4 years
↓		
Radium-226 ($^{226}_{88}Ra$)		1.62×10^3 years
↓		
Radon-222 ($^{222}_{86}Rn$)		3.82 days
↓		
Polonium-218 ($^{218}_{84}Po$)		3.1 minutes
↓		
Lead-214 ($^{214}_{82}Pb$)		26.8 minutes
↓		
Bismuth-214 ($^{214}_{83}Bi$)		19.7 minutes
↓		
Polonium-214 ($^{214}_{84}Po$)		1.6×10^{-4} second
↓		
Lead-210 ($^{210}_{82}Pb$)		20.4 years
↓		
Bismuth-210 ($^{210}_{83}Bi$)		5.0 days
↓		
Polonium-210 ($^{210}_{84}Po$)		138.4 days
↓		
Lead-206 ($^{206}_{82}Pb$)	—	Stable



The Kinetics of Radioactive Decay

Rate of Decay

$$\text{rate} = kN$$

The rate of decay is proportional to the number of nuclides. This represents a first-order process.

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Half-Life of Nuclear Decay

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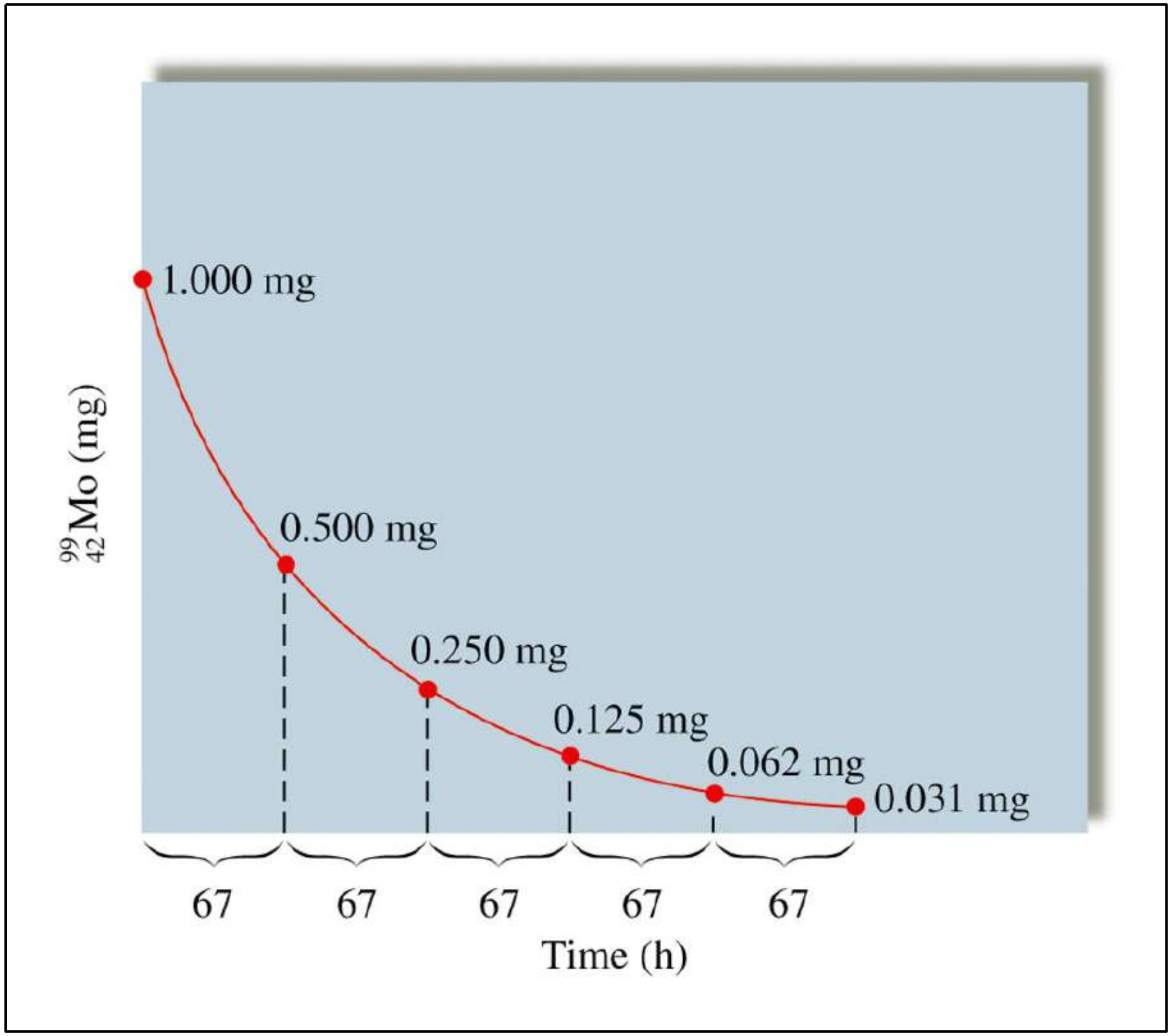
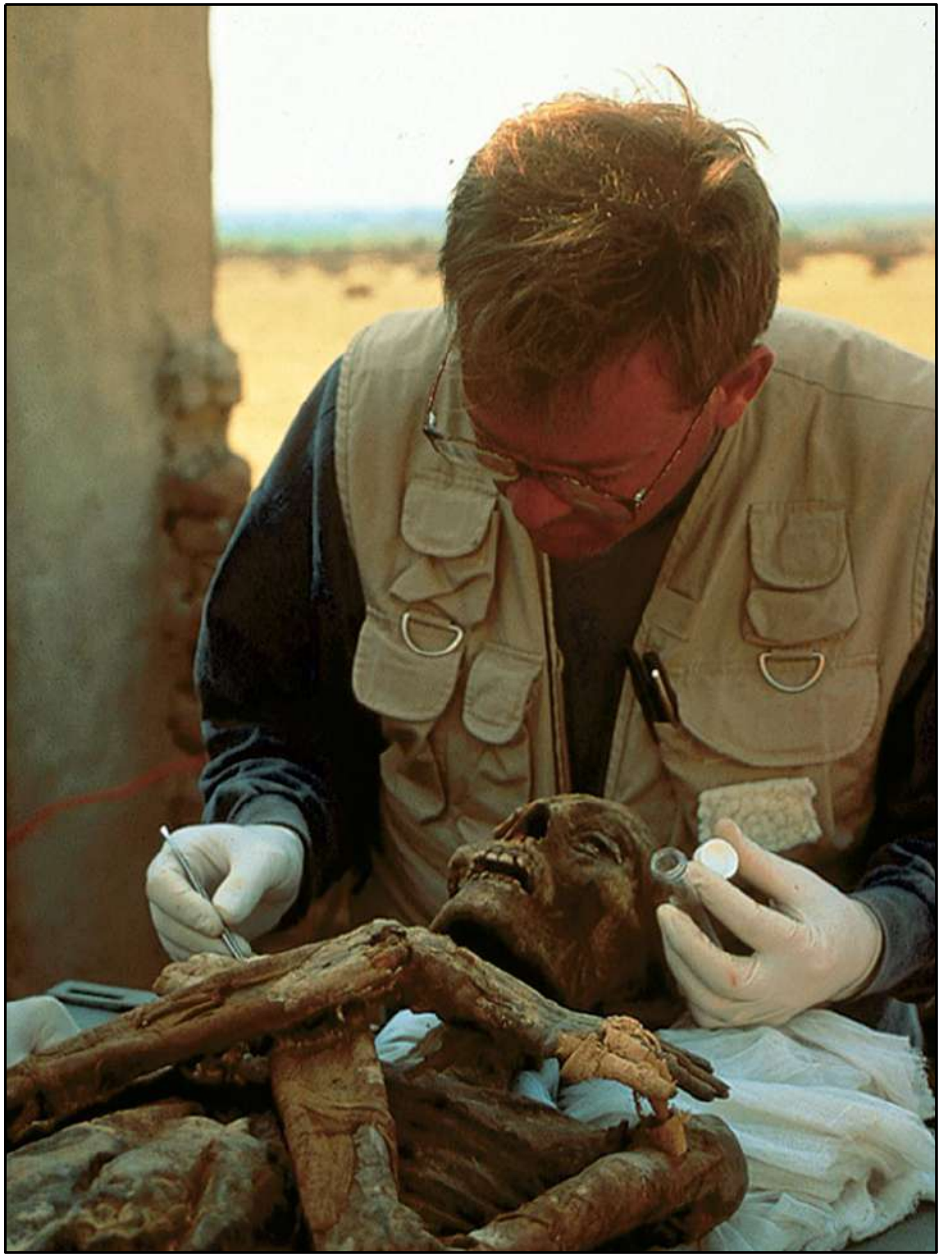
Figure 18.4 The Half-Lives of Radioactive Nuclides

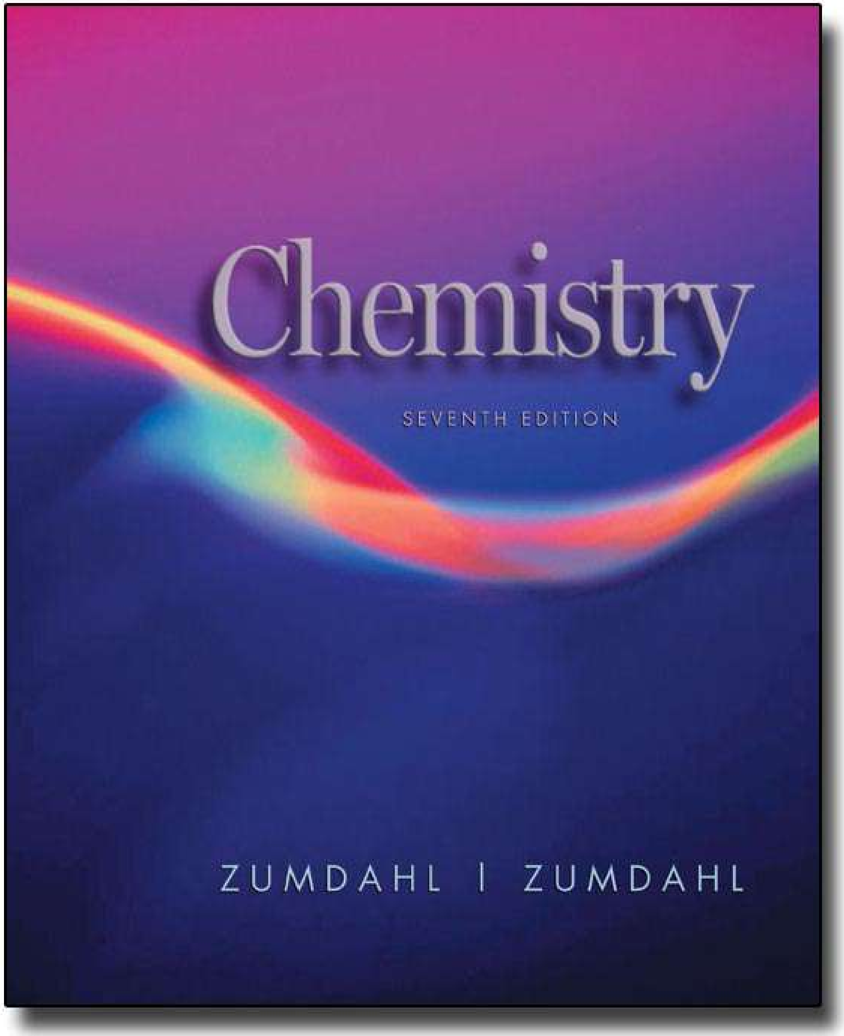


Brigham Young Researcher Scott Woodward Taking a Bone Sample



A Dendrochronologist Cutting a Section from a Dead Tree

Nuclear Transformation



Nuclear Transformation

The change of one element into another.

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

$$ {}^{249}_{98}\mathrm{Cf} + {}^{18}_{8}\mathrm{O} \rightarrow {}^{263}_{106}\mathrm{X} + 4\,{}^{1}_{0}\mathrm{n} $$

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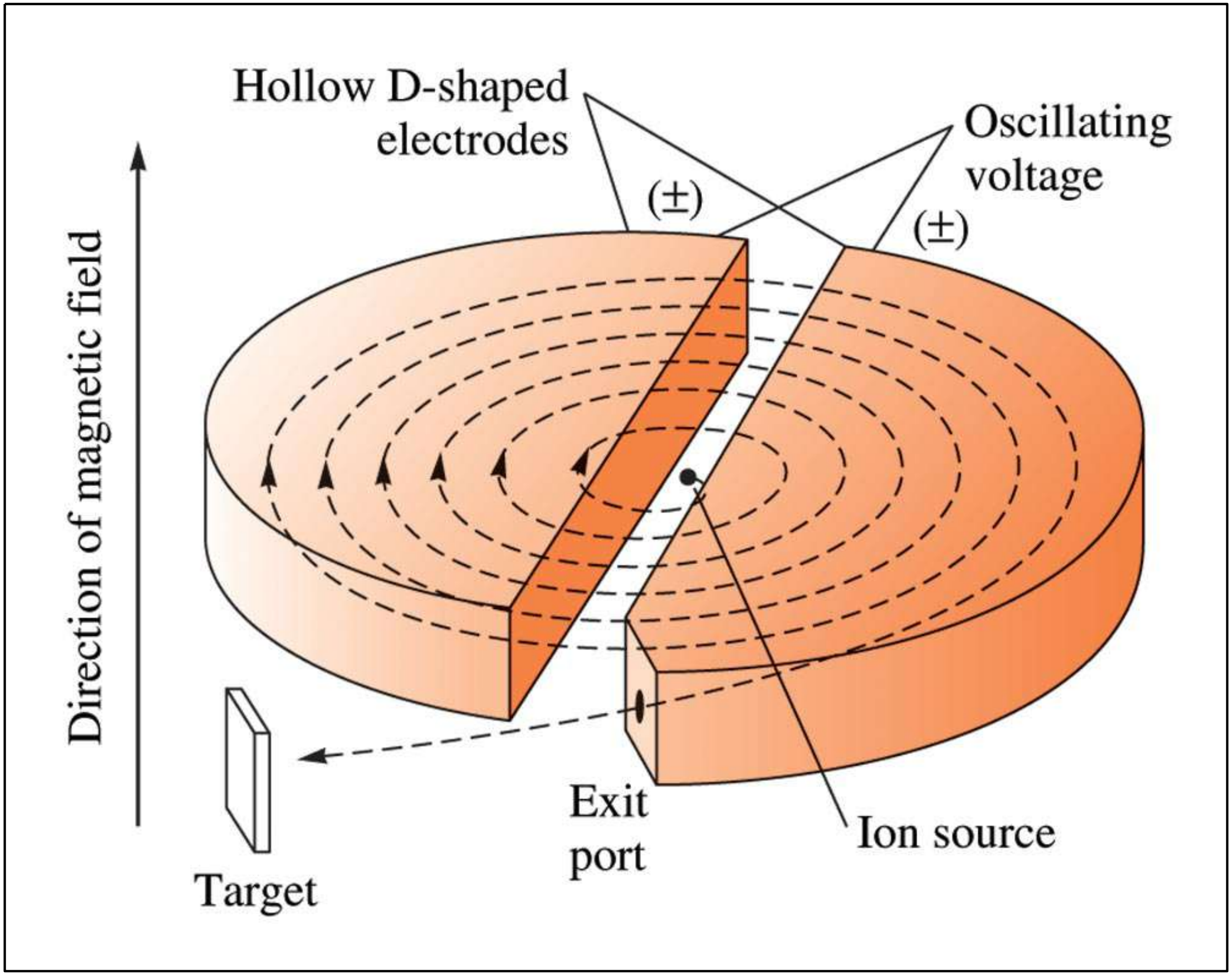
An Aerial View of Fermilab, a High Energy Particle Accelerator

The Accelerator Tunnel at Fermilab

A Schematic Diagram of a Cyclotron



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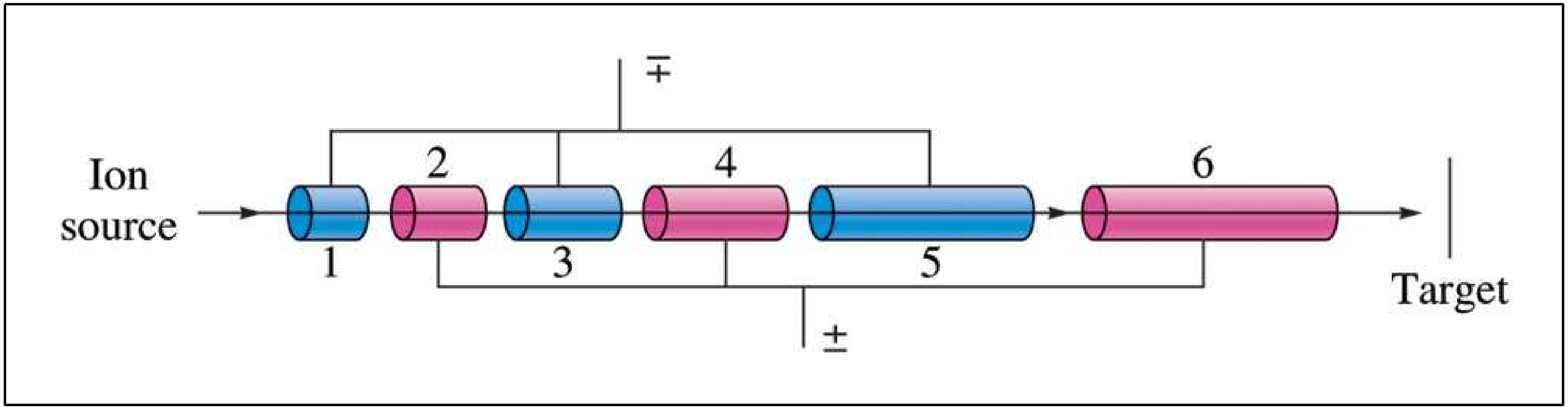
A Schematic Diagram of a Linear Accelerator



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A Physicist Works with a Small Cyclotron at the University of California Berkley

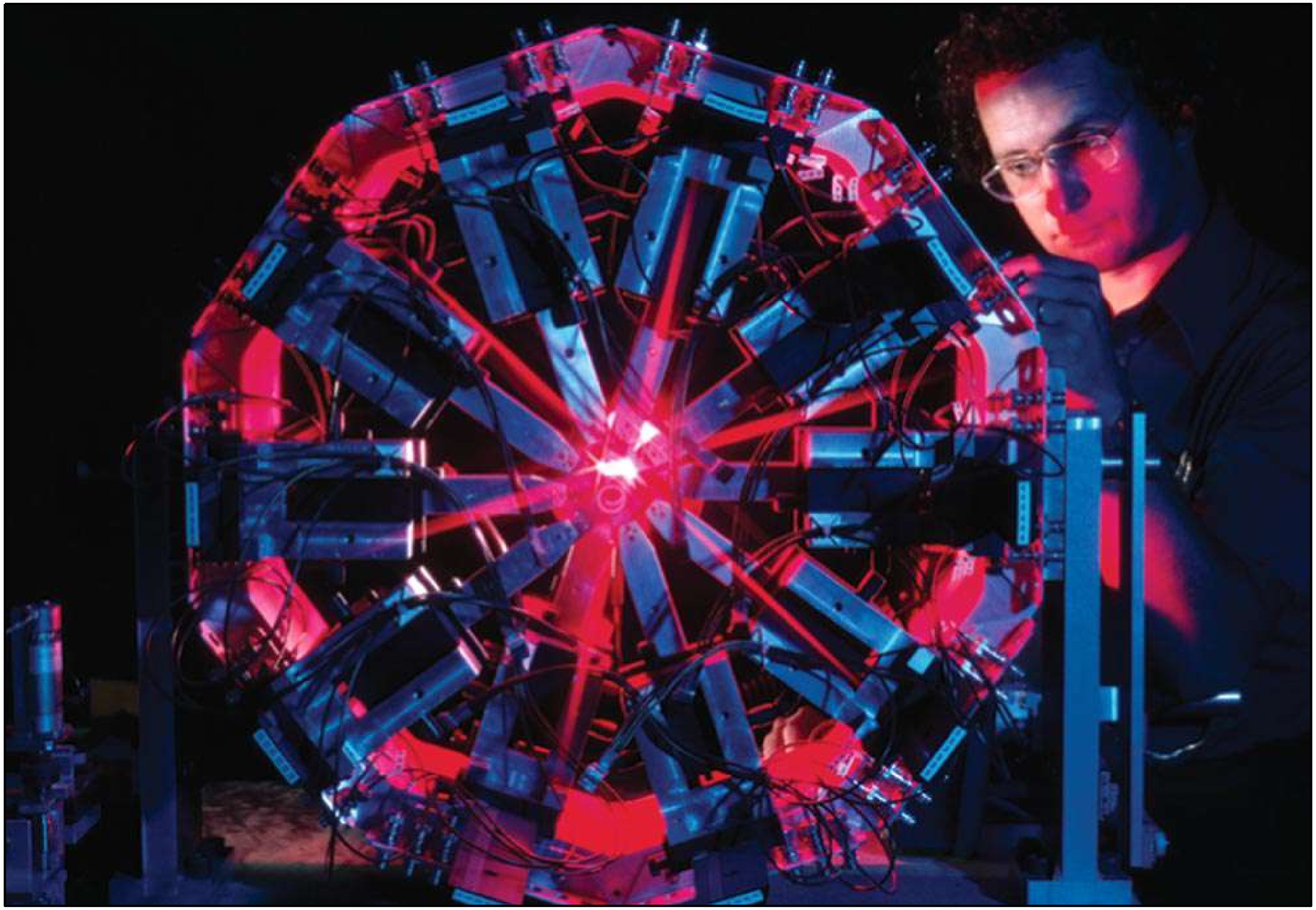


Table 18.4 Syntheses of Some of the Transuranium Elements

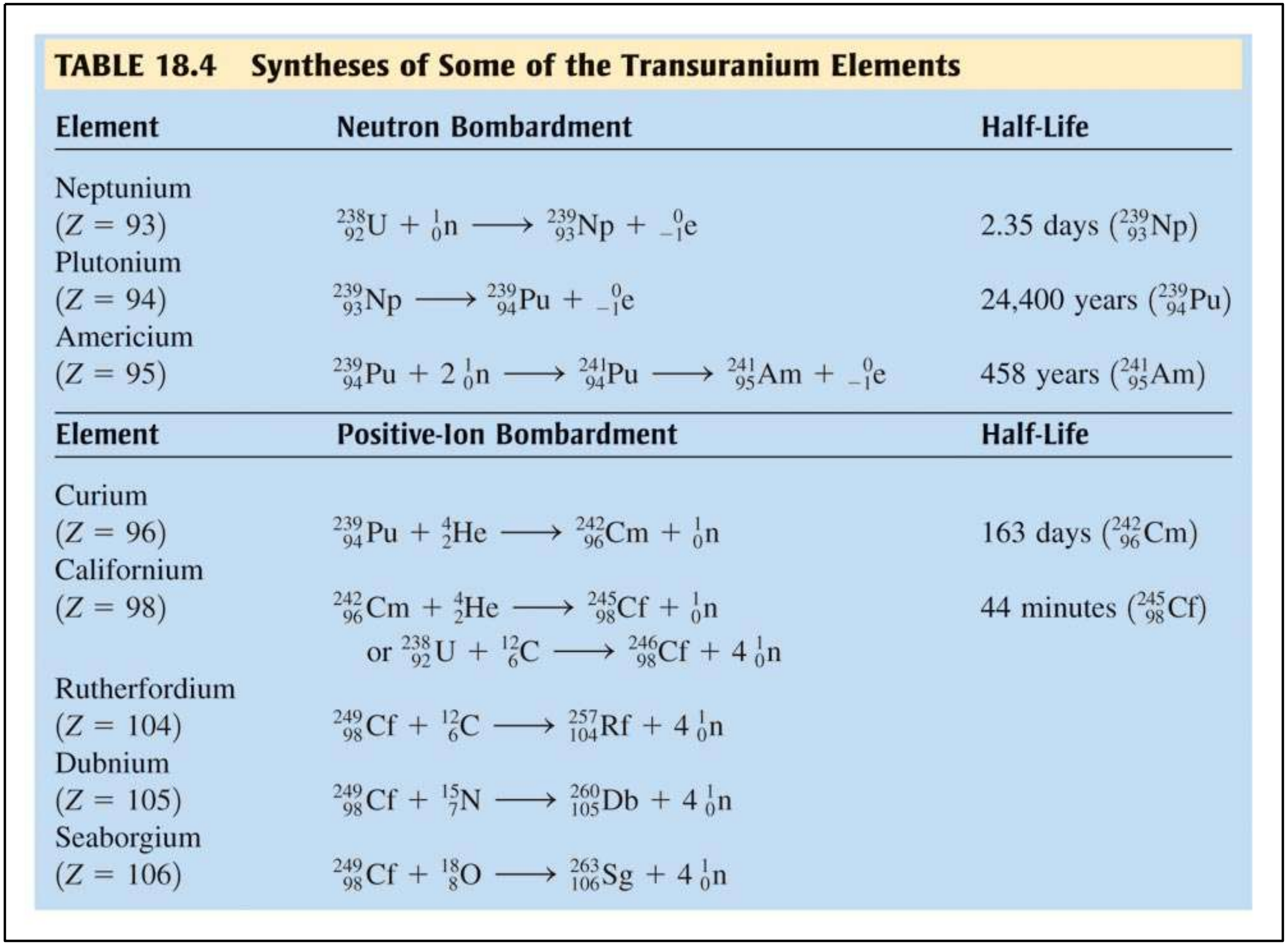
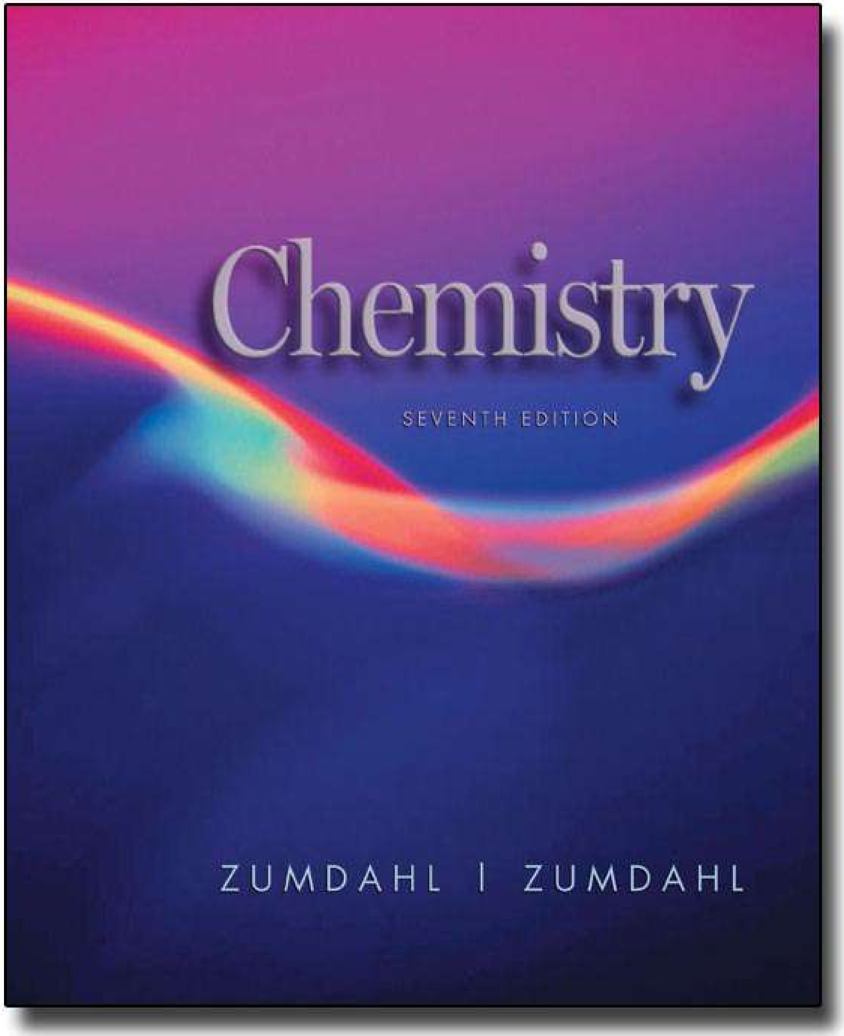


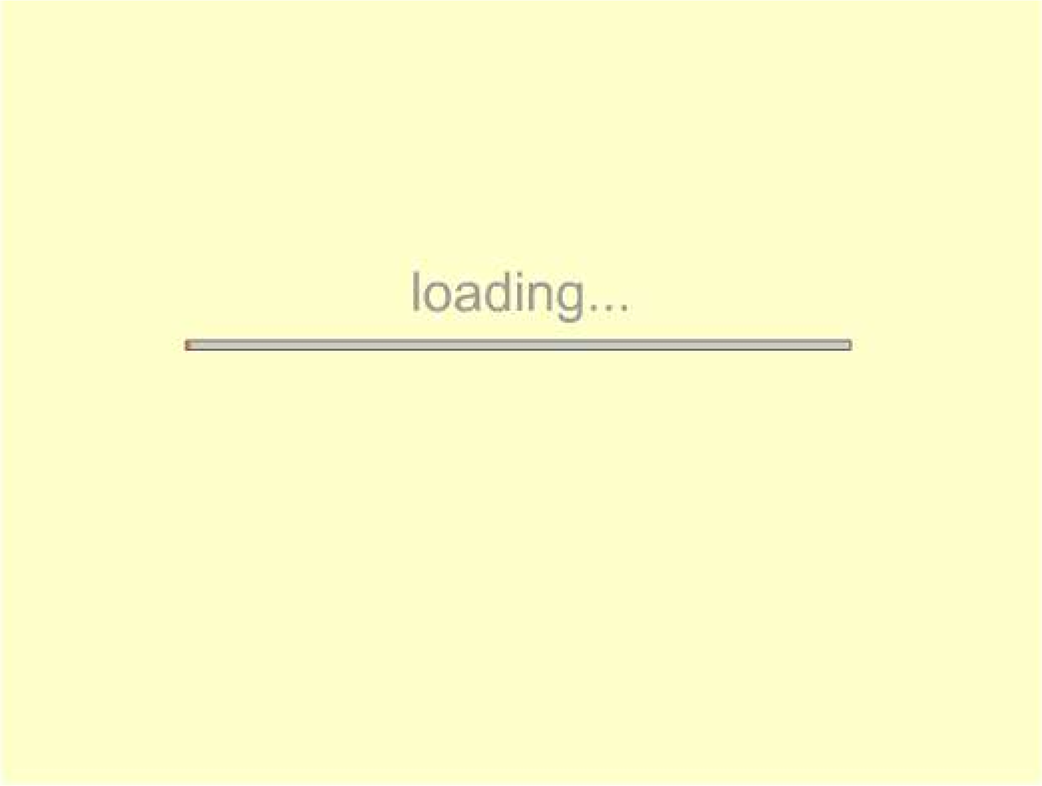
TABLE 18.4 Syntheses of Some of the Transuranium Elements

Element	Neutron Bombardment	Half-Life
Neptunium (Z = 93)	$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \longrightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e}$	2.35 days ($^{239}_{93}\text{Np}$)
Plutonium (Z = 94)	$^{239}_{93}\text{Np} \longrightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}$	24,400 years ($^{239}_{94}\text{Pu}$)
Americium (Z = 95)	$^{239}_{94}\text{Pu} + 2\,^{1}_{0}\text{n} \longrightarrow ^{241}_{94}\text{Pu} \longrightarrow ^{241}_{95}\text{Am} + ^{0}_{-1}\text{e}$	458 years ($^{241}_{95}\text{Am}$)
Element	**Positive-Ion Bombardment**	**Half-Life**
Curium (Z = 96)	$^{239}_{94}\text{Pu} + ^{4}_{2}\text{He} \longrightarrow ^{242}_{96}\text{Cm} + ^{1}_{0}\text{n}$	163 days ($^{242}_{96}\text{Cm}$)
Californium (Z = 98)	$^{242}_{96}\text{Cm} + ^{4}_{2}\text{He} \longrightarrow ^{245}_{98}\text{Cf} + ^{1}_{0}\text{n}$ or $^{238}_{92}\text{U} + ^{12}_{6}\text{C} \longrightarrow ^{246}_{98}\text{Cf} + 4\,^{1}_{0}\text{n}$	44 minutes ($^{245}_{98}\text{Cf}$)
Rutherfordium (Z = 104)	$^{249}_{98}\text{Cf} + ^{12}_{6}\text{C} \longrightarrow ^{257}_{104}\text{Rf} + 4\,^{1}_{0}\text{n}$	
Dubnium (Z = 105)	$^{249}_{98}\text{Cf} + ^{15}_{7}\text{N} \longrightarrow ^{260}_{105}\text{Db} + 4\,^{1}_{0}\text{n}$	
Seaborgium (Z = 106)	$^{249}_{98}\text{Cf} + ^{18}_{8}\text{O} \longrightarrow ^{263}_{106}\text{Sg} + 4\,^{1}_{0}\text{n}$	



Detection and Uses of Radioactivity

Geiger Counter



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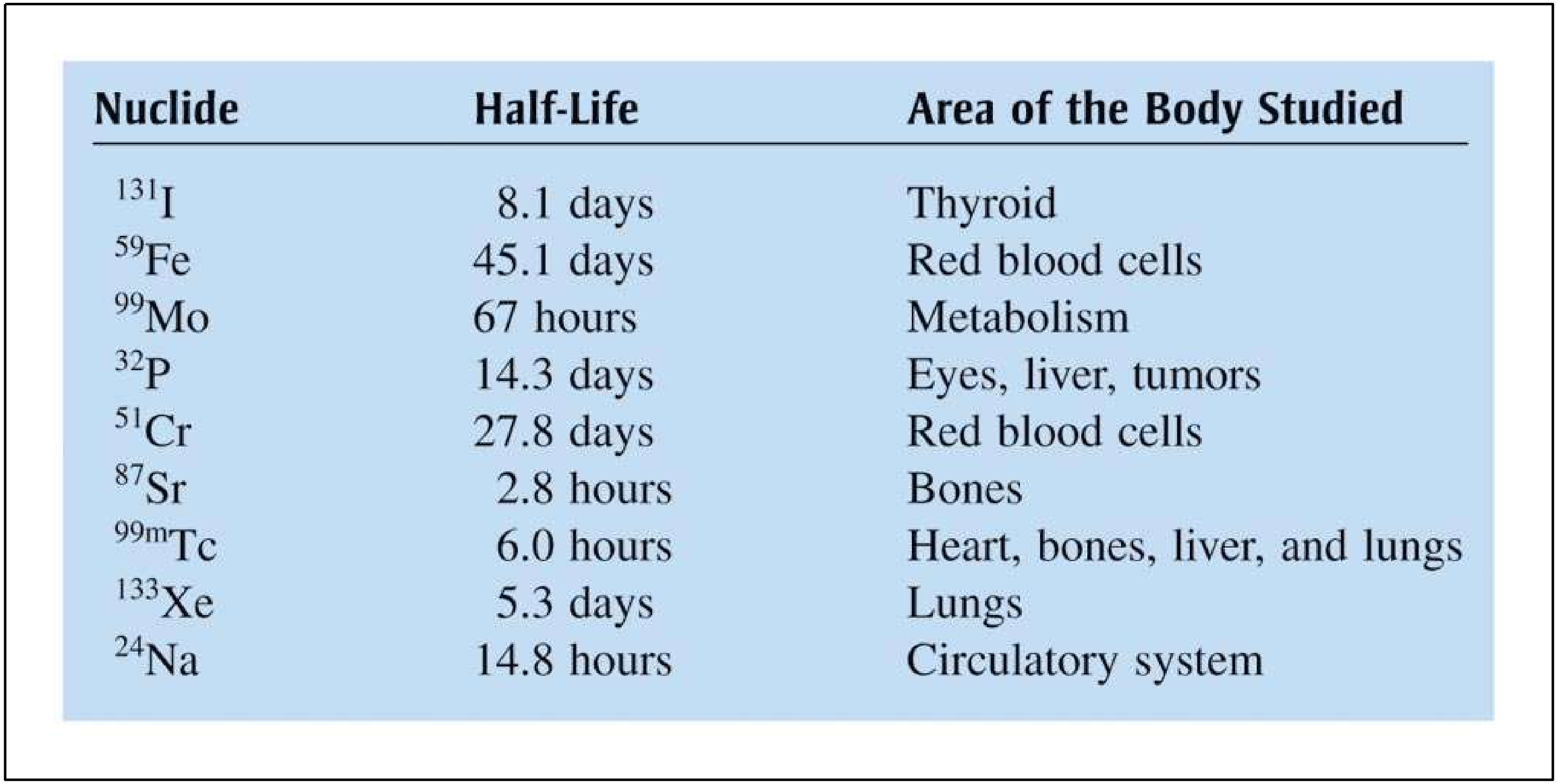
Radiotracers



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
^{99m}Tc	6.0 hours	Heart, bones, liver, and lungs
^{133}Xe	5.3 days	Lungs
^{24}Na	14.8 hours	Circulatory system

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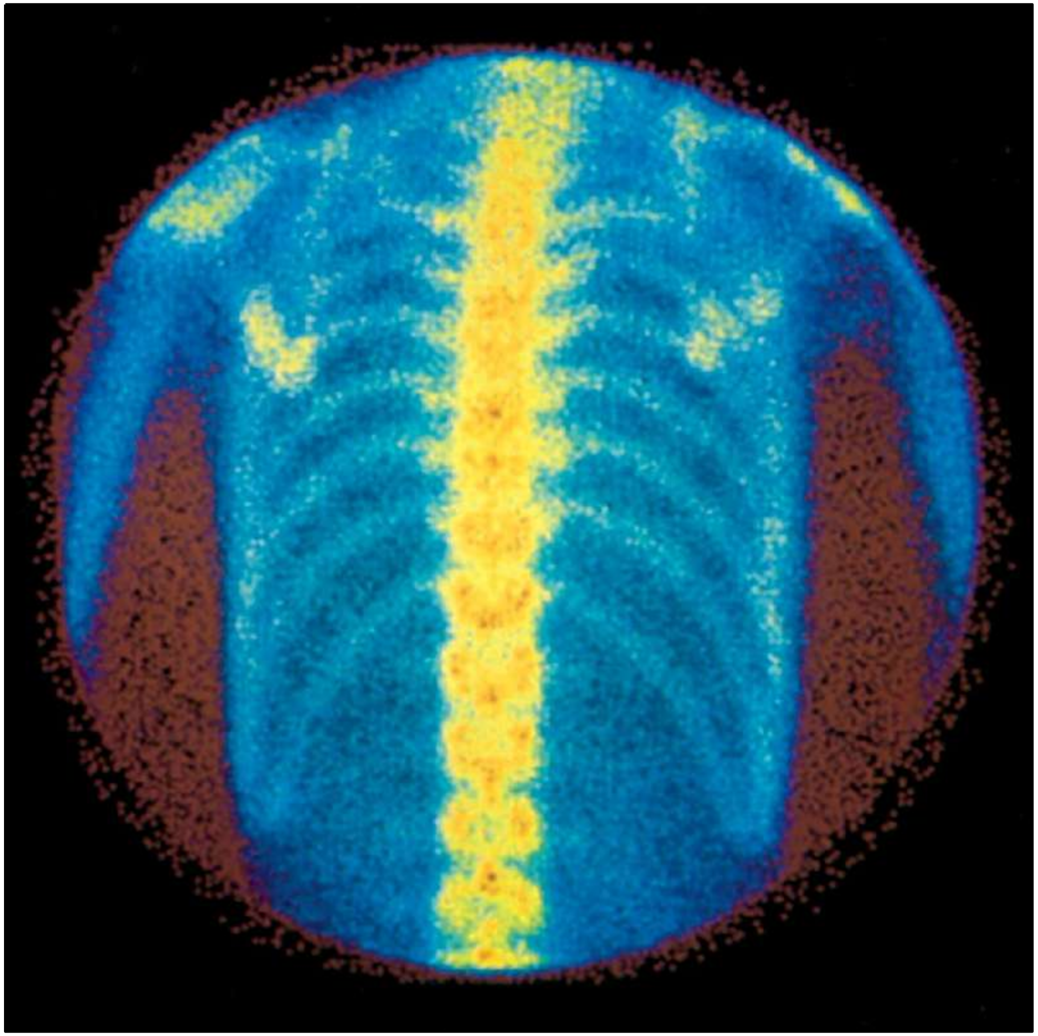
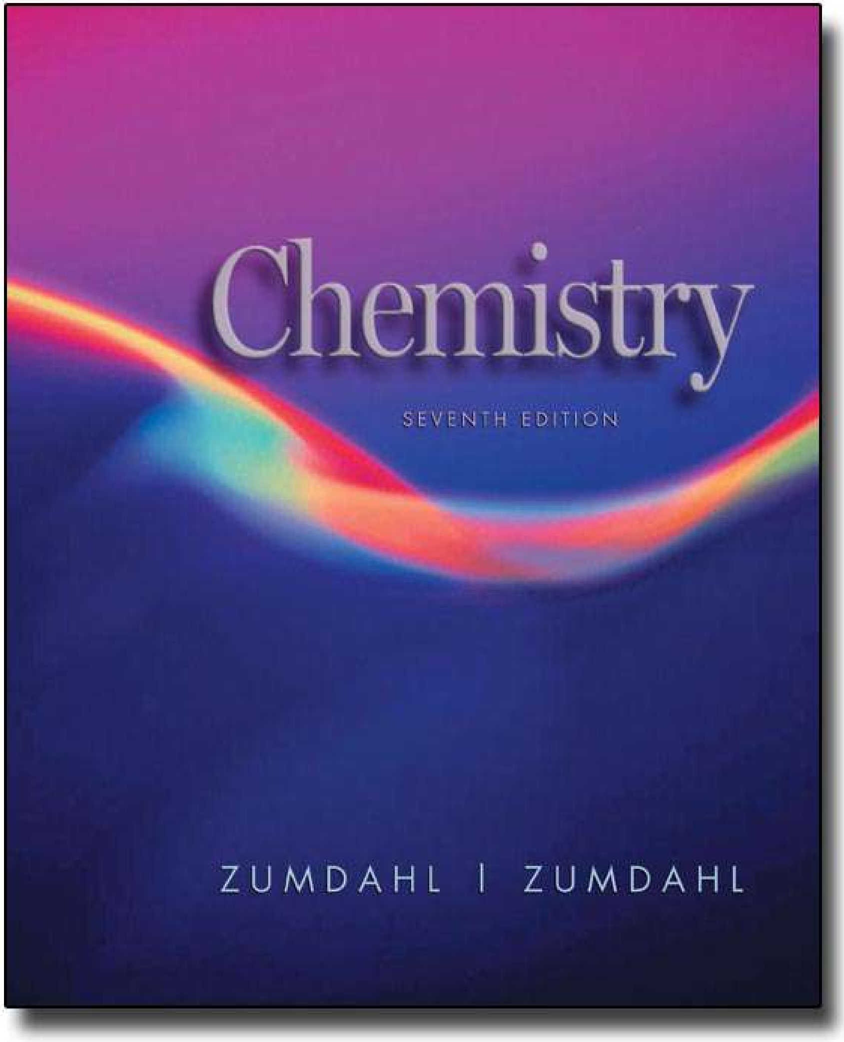
A Pellet Containing Radioactive ^{131}I

The Image of a Bone Scan of a Normal Chest





Thermodynamic Stability of the Nucleus

Uranium Oxide (refined uranium)

Energy and Mass

When a system gains or loses energy it also gains or loses a quantity of mass.

$$\Delta E = \Delta mc^2$$

Δm = mass defect

ΔE = change in energy

If ΔE is negative(exothermic), mass is lost from the system.

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Binding Energy

- The energy required to decompose the nucleus into its components.
- Iron-56 is the most stable nucleus and has a binding energy of 8.97 MeV.

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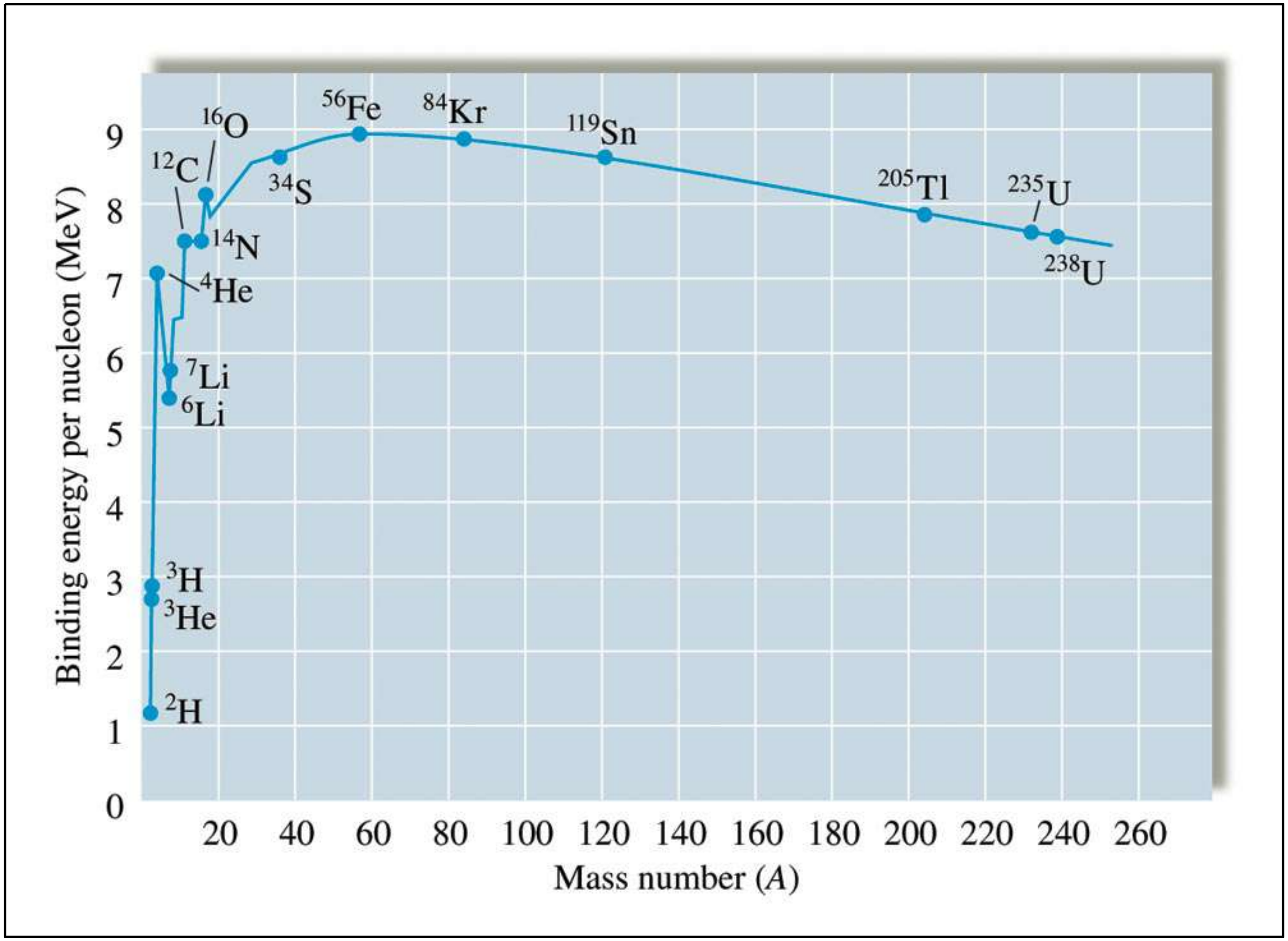
Binding Energy per Nucleon vs. Mass Number



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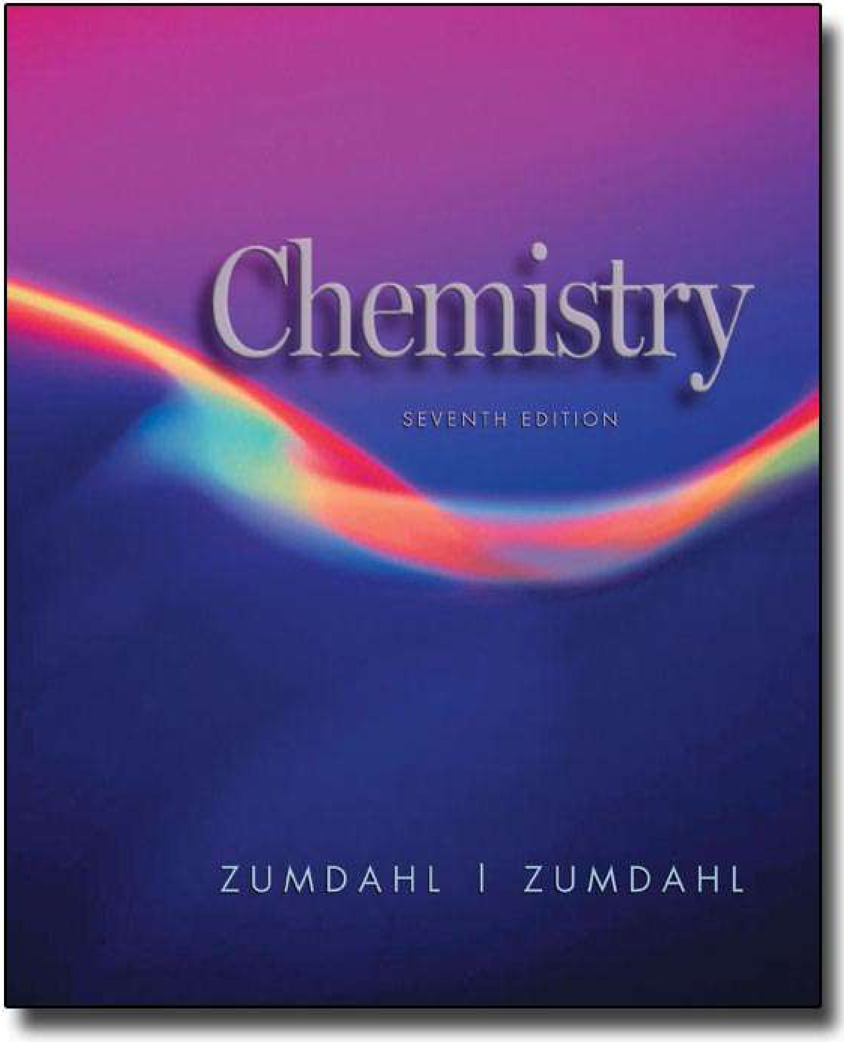
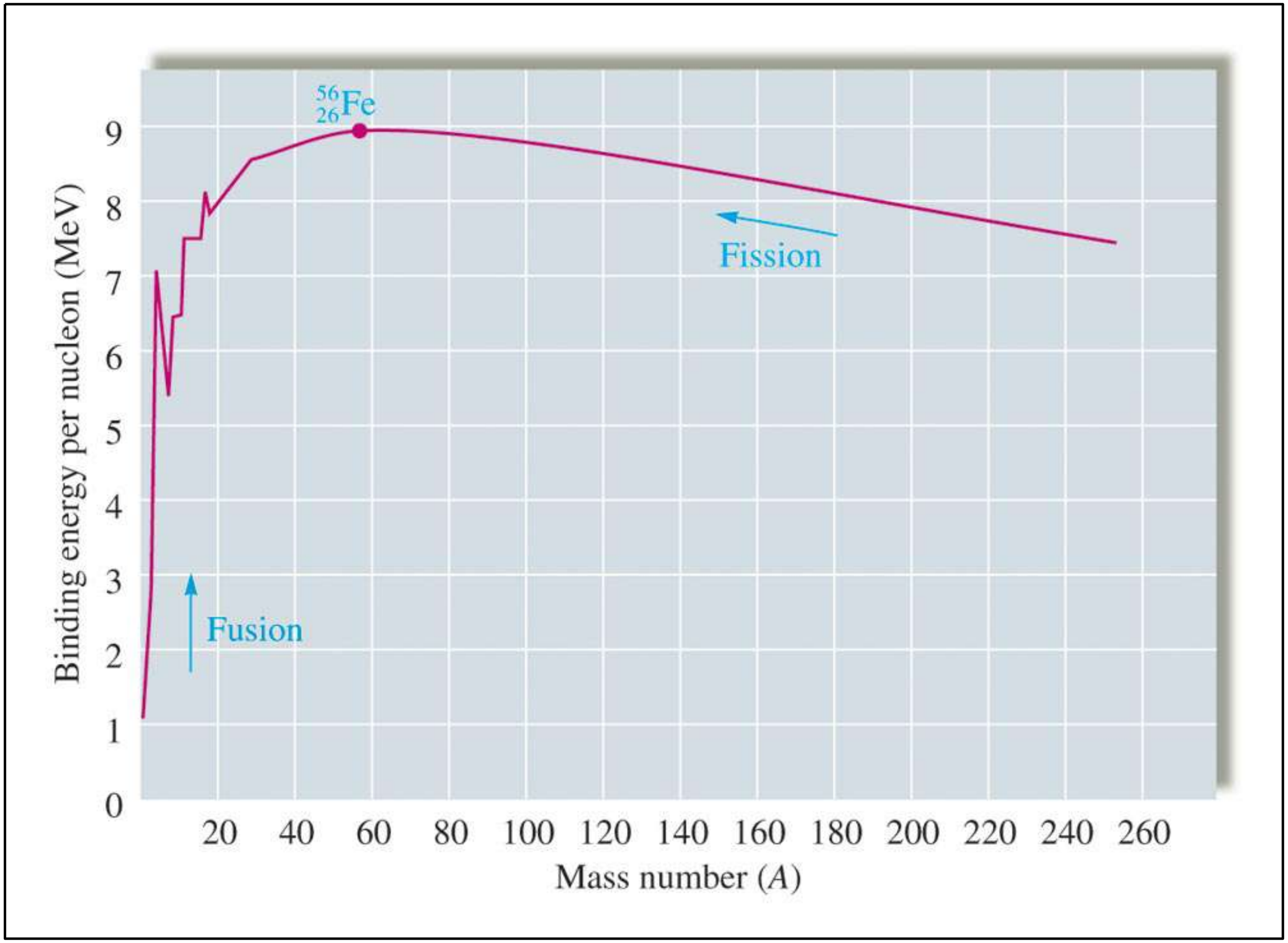


Nuclear Fission and Nuclear Fusion

Figure 18.10 Both Fission and Fusion Produce More Stable Nuclides and are thus Exothermic



Nuclear Fission and Fusion

- **Fusion:** Combining two light nuclei to form a heavier, more stable nucleus.

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

- **Fission:** Splitting a heavy nucleus into two nuclei with smaller mass numbers.

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

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Nuclear Fission

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Figure 18.11 Fission

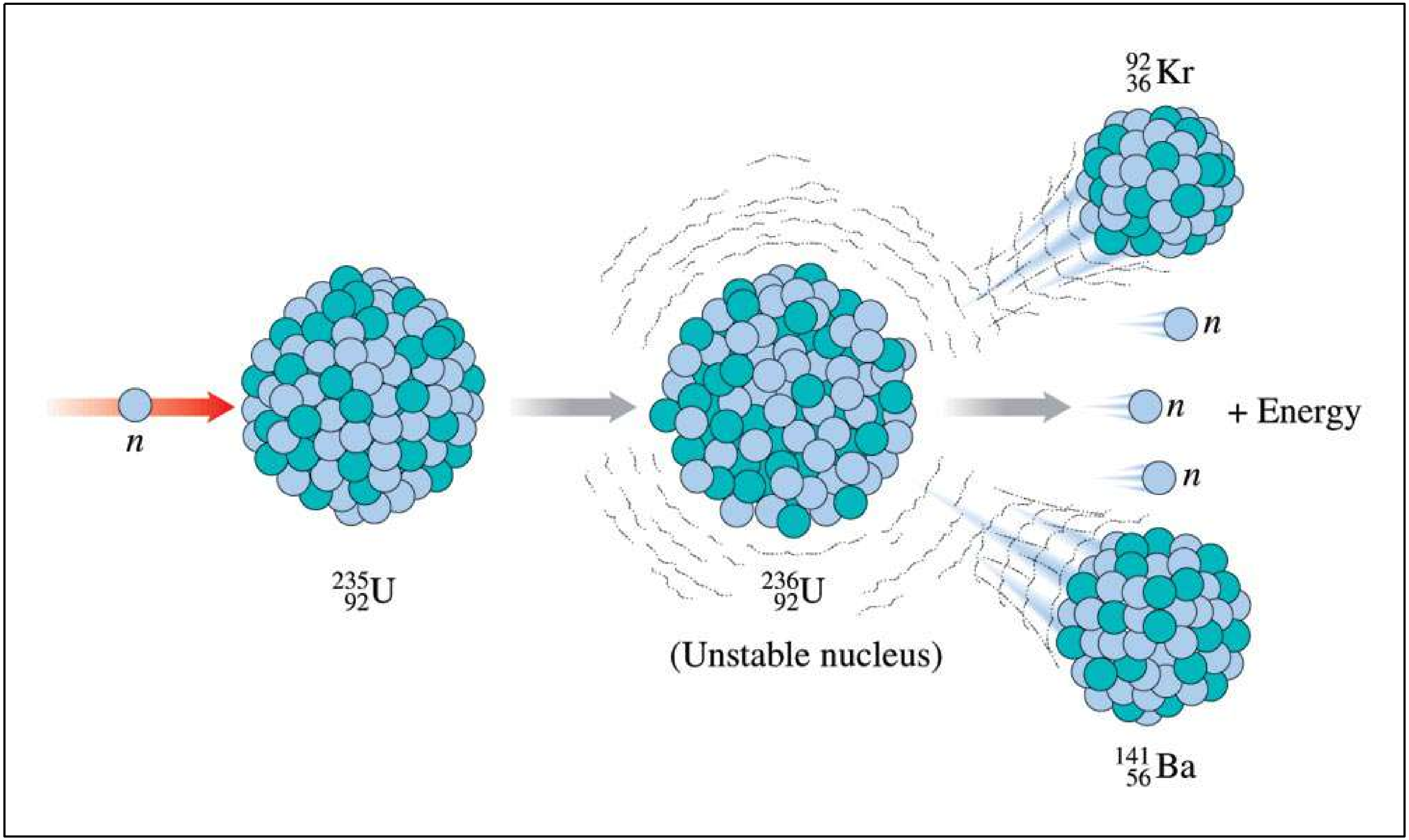


Figure 18.12 Fission Process in which each Event Produces Two Neutrons

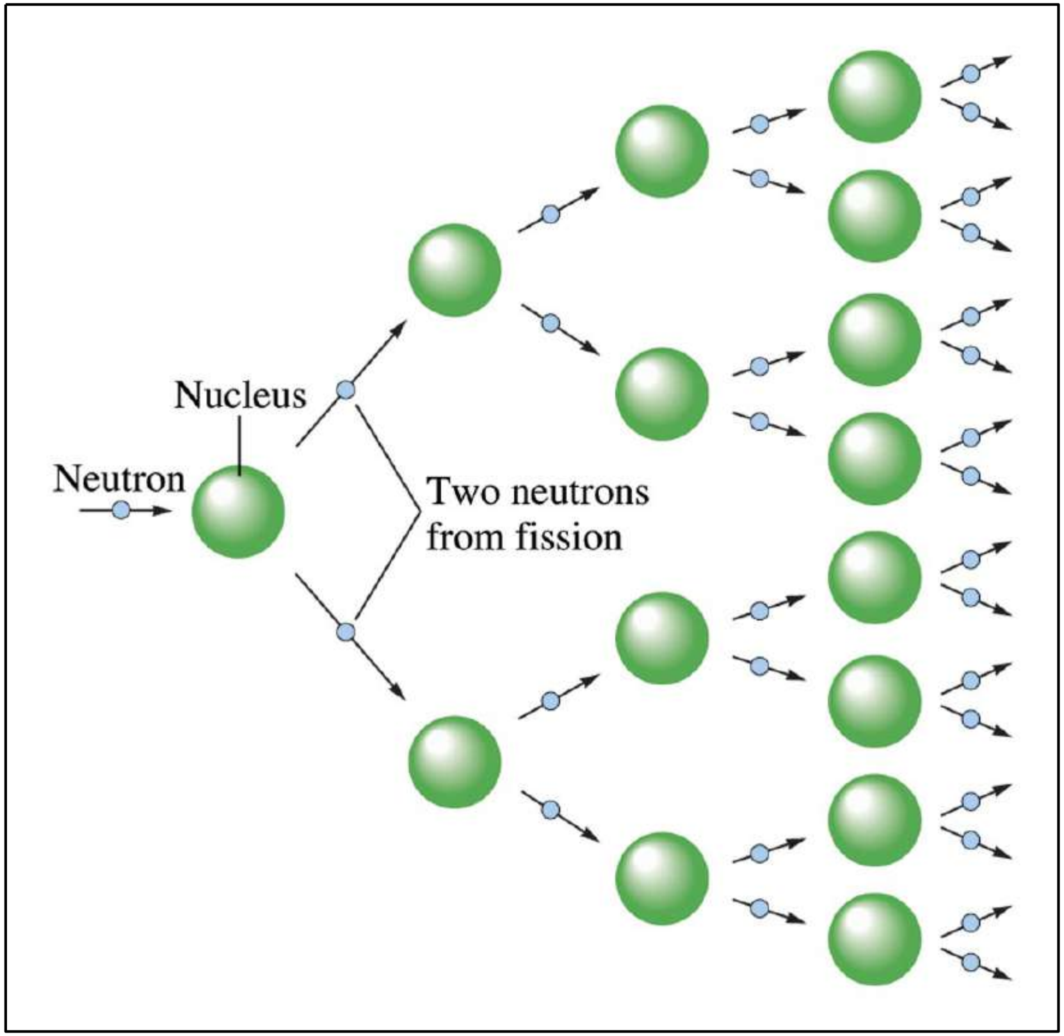
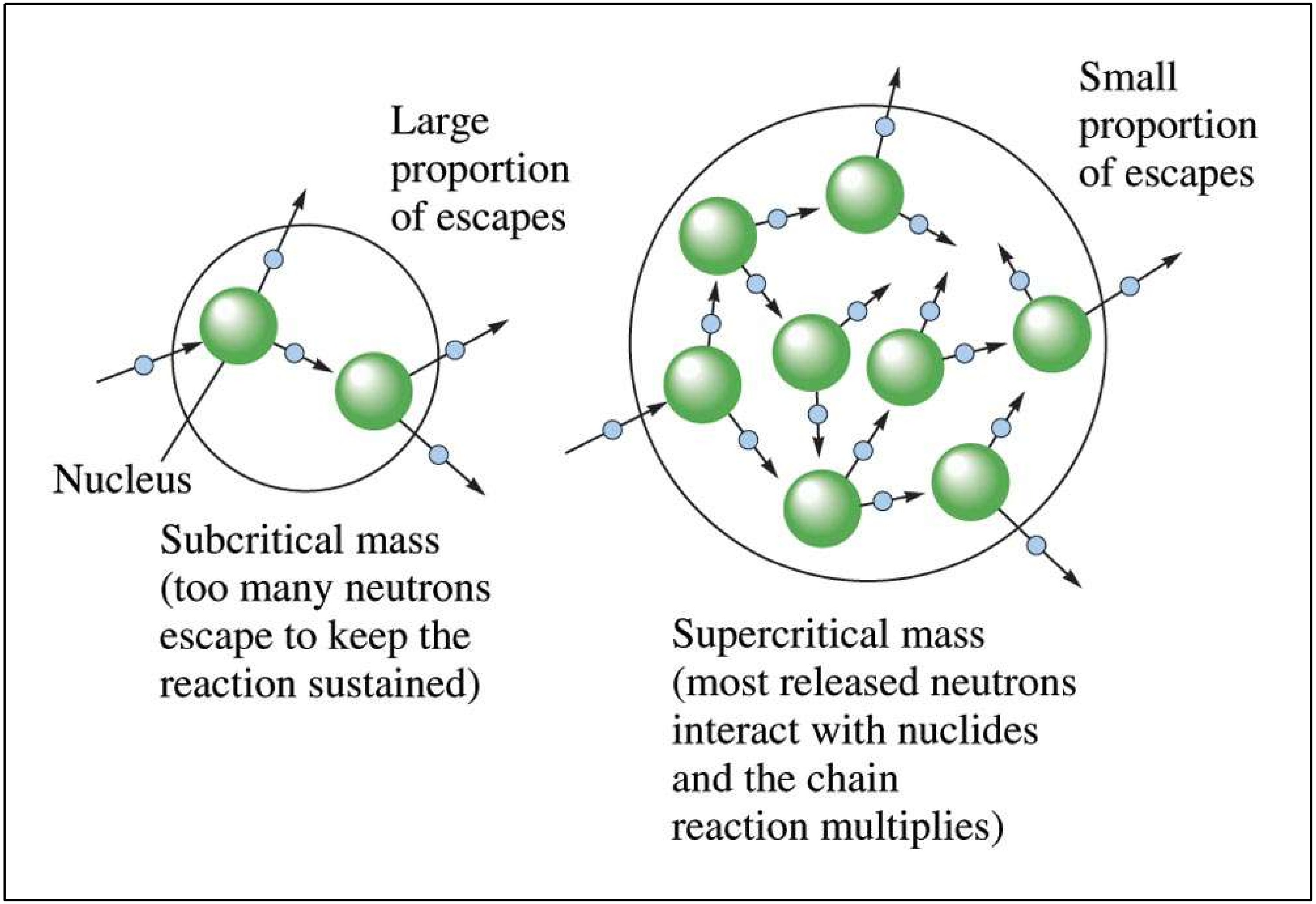


Figure 18.13 Result of Too Small a Mass of Fissionable Material



Fission Processes

A self-sustaining fission process is called a chain reaction.

Event	Neutrons Causing Fission	Result
subcritical	< 1	reaction stops
critical	= 1	sustained reaction
supercritical	> 1	violent explosion

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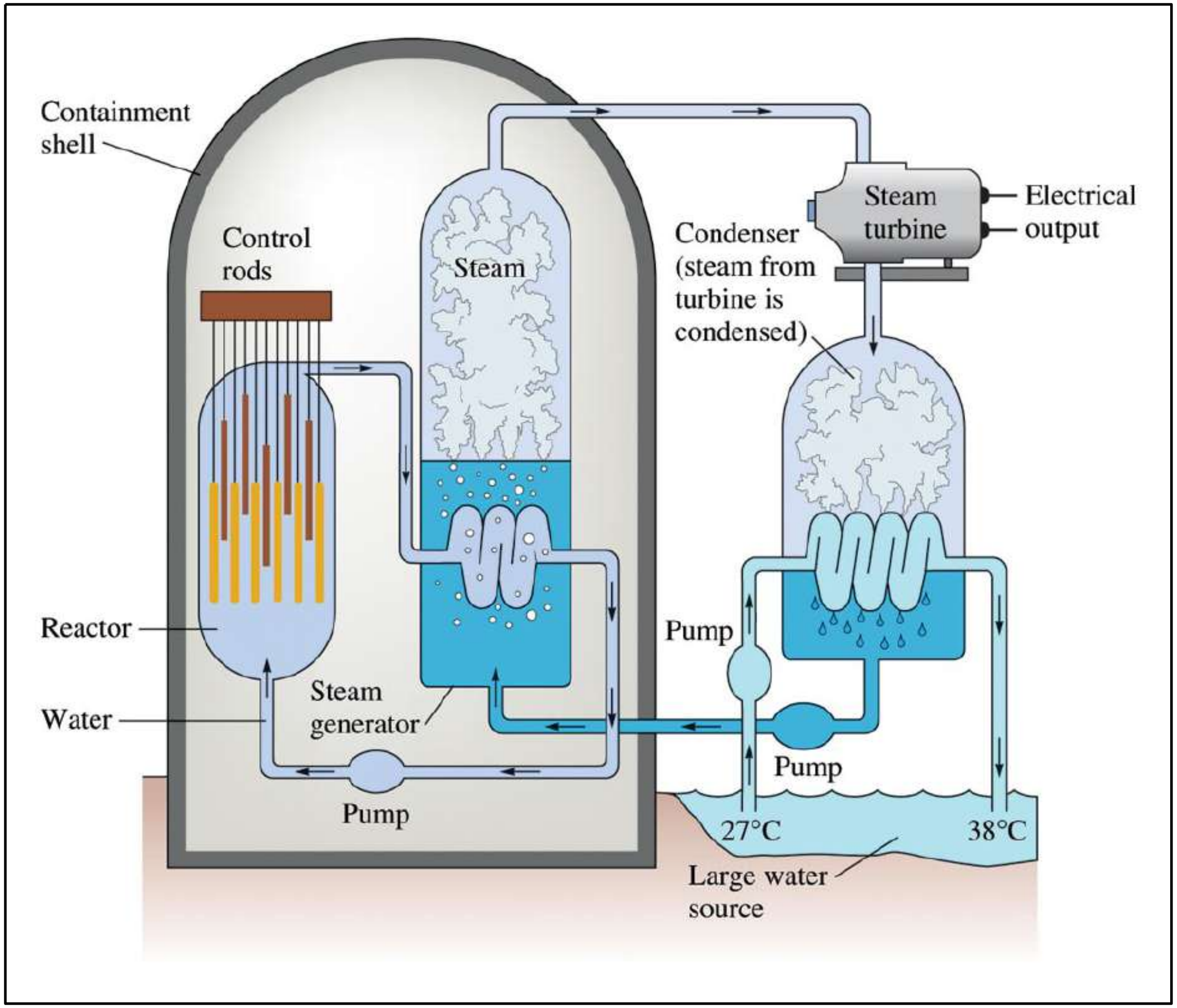
Schematic Diagram of a Nuclear Power Plant



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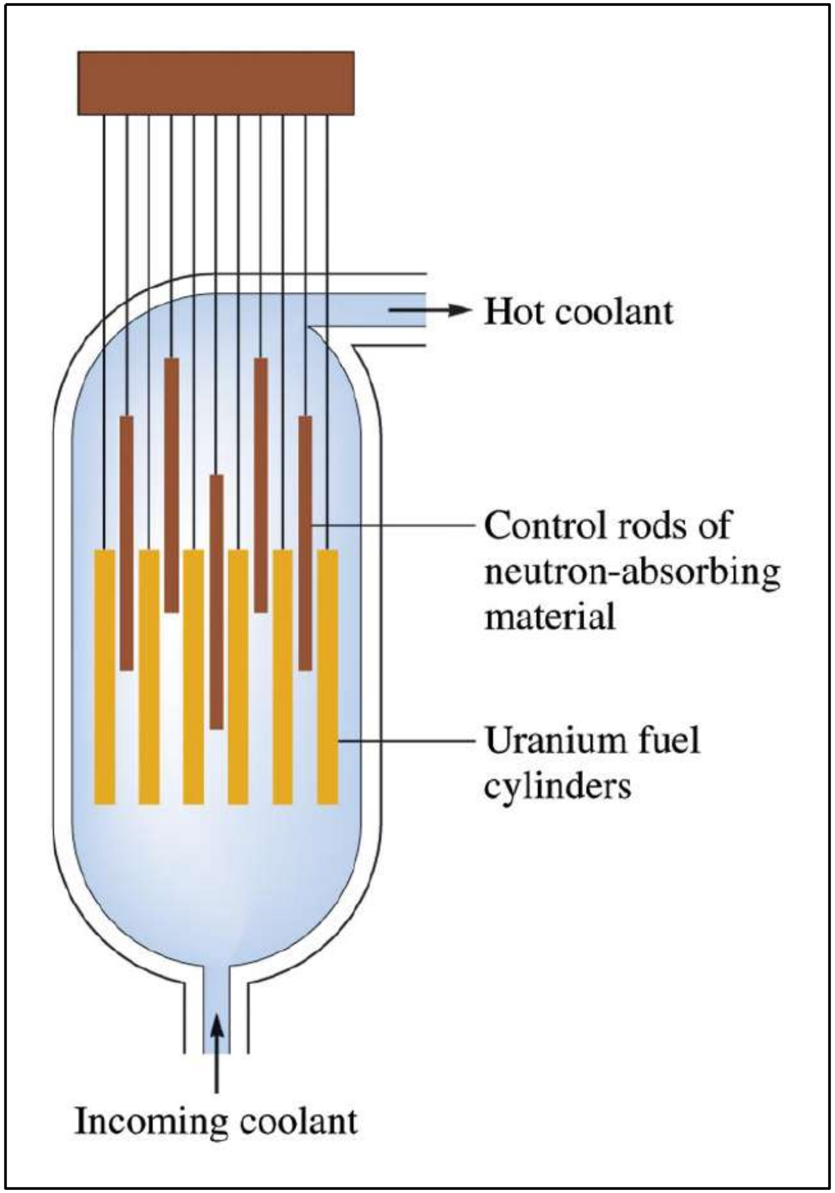
Schematic Diagram of a Reactor Core



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Nuclear Fusion

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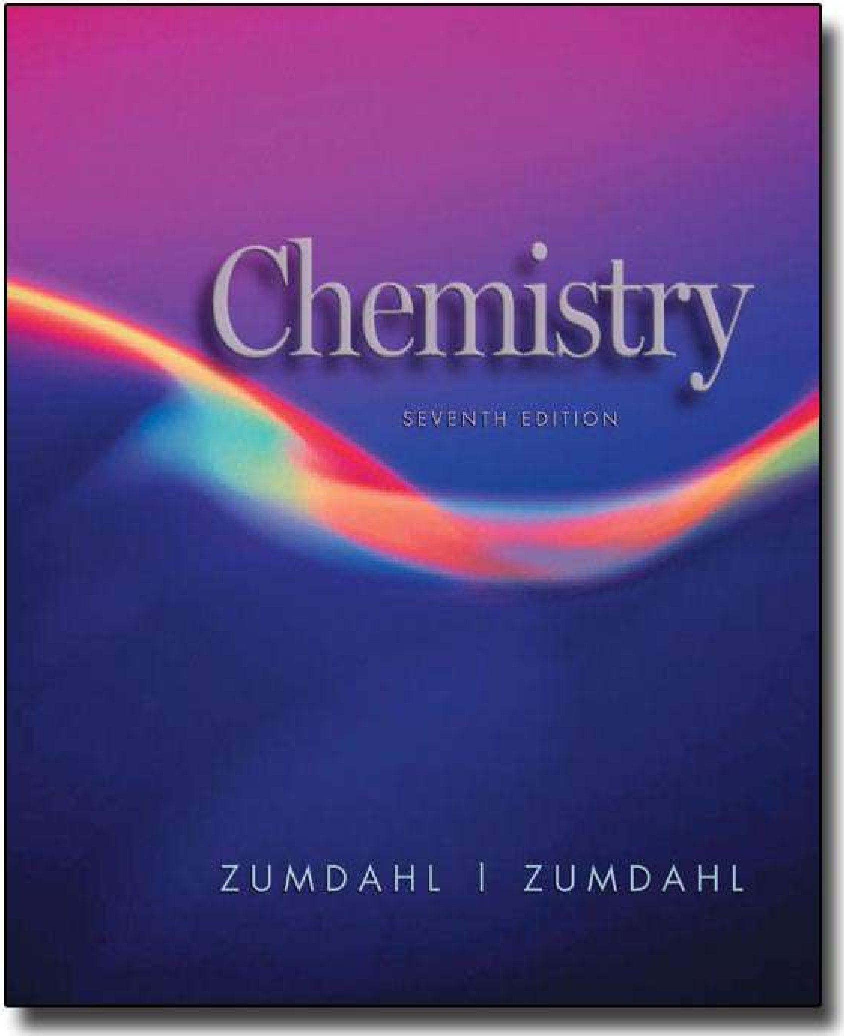
Image of a Portion of the Cygnus Loop Supernova Remnant



Effects of Radiation

Biological Effects of Radiation

… depend on:

1. Energy of the radiation
2. Penetration ability of the radiation
3. Ionizing ability of the radiation
4. Chemical properties of the radiation source

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Figure 18.16 A Plot of Energy versus the Separation Distance

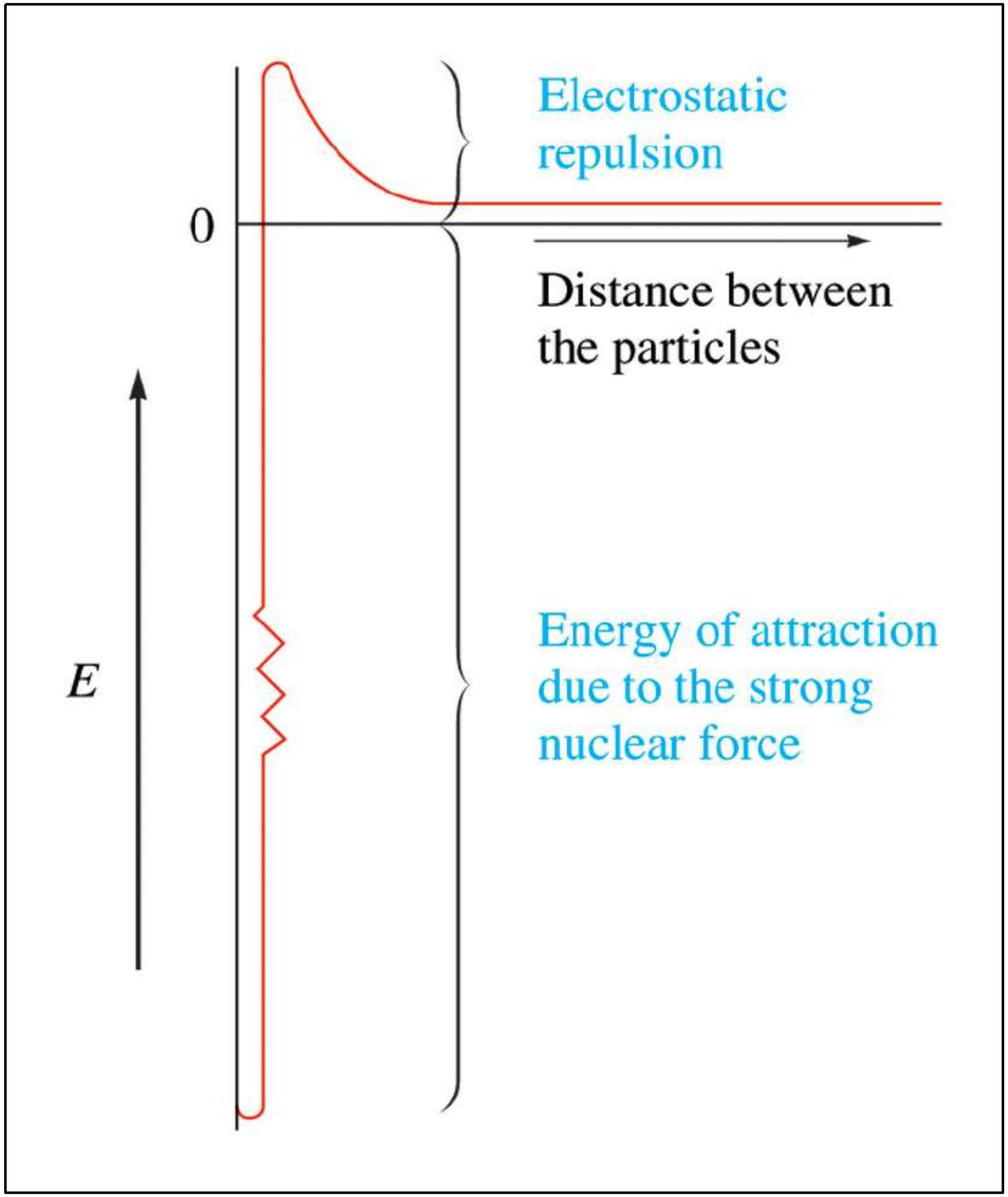
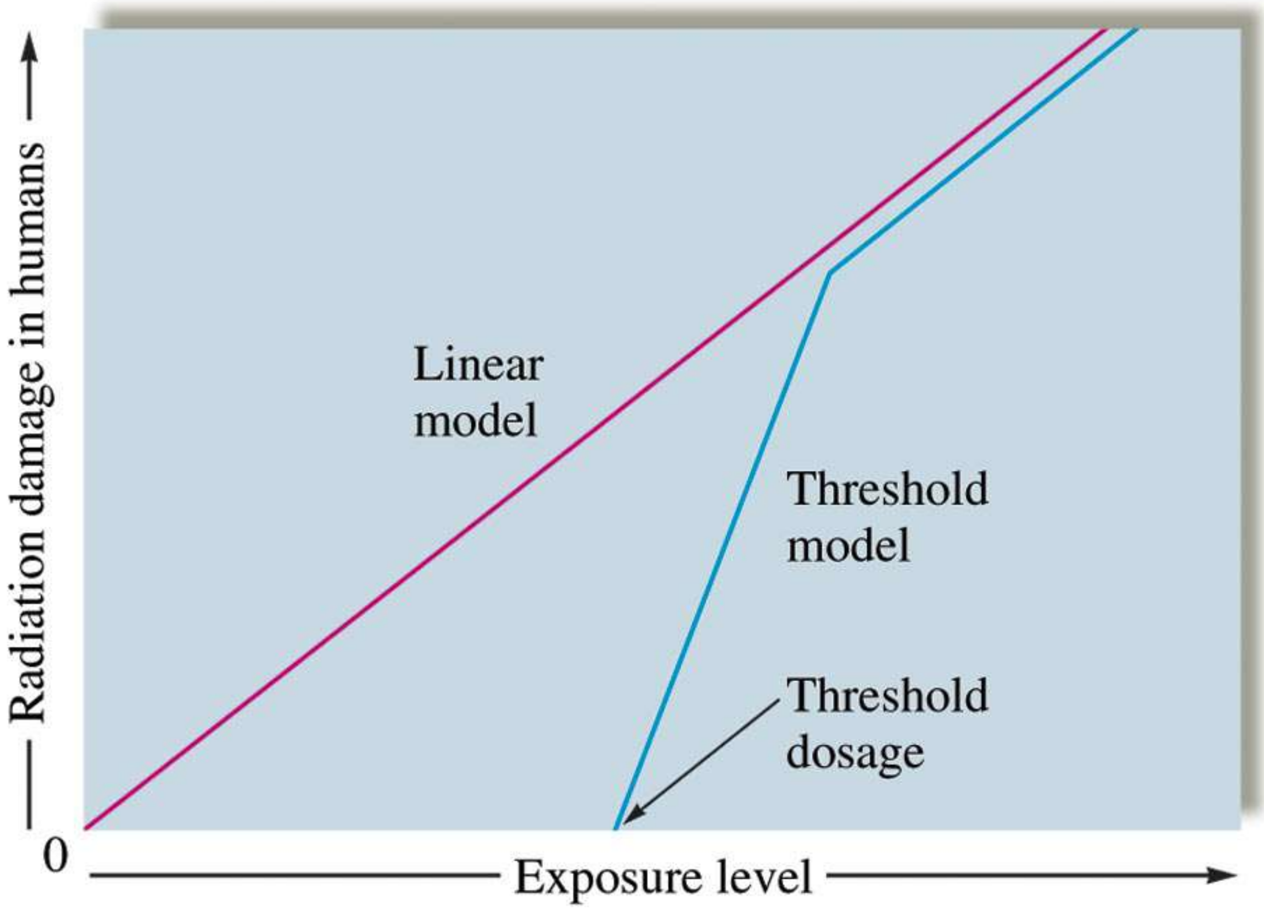
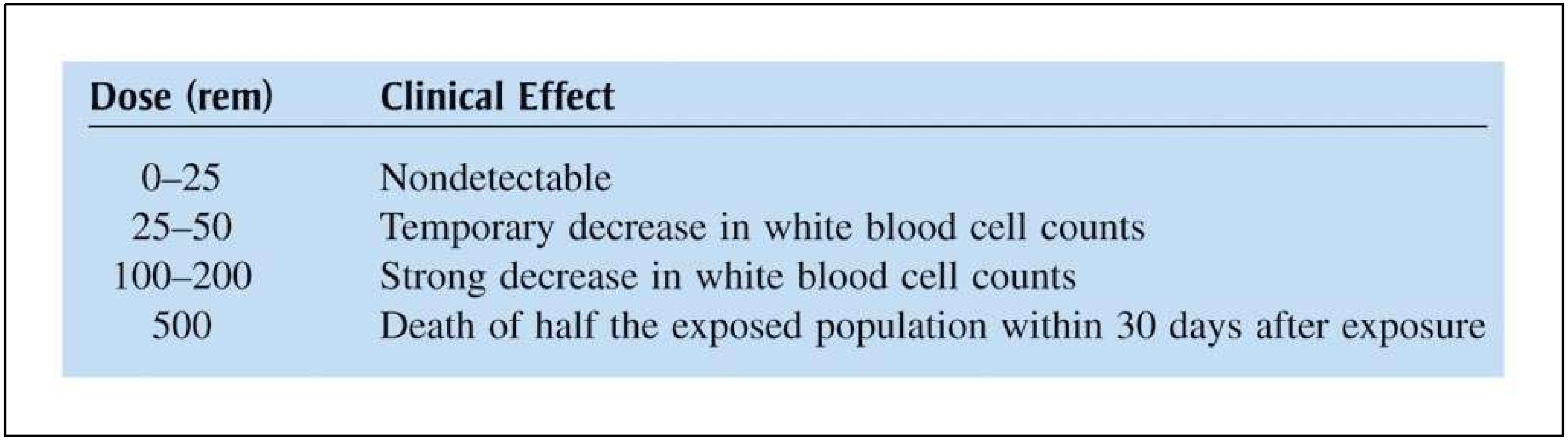


Figure 18.17 The Two Models for Radiation Damage



Effects of Short-Term Exposures on 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

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Table 18.7 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

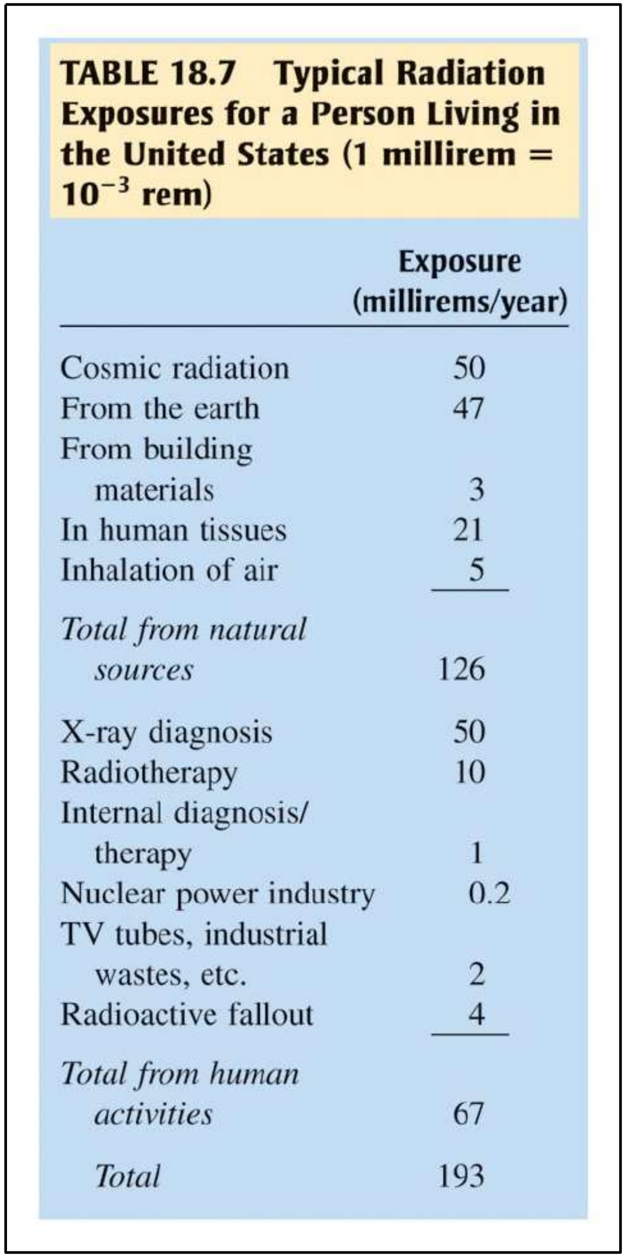

TABLE 18.7 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

	Exposure (millirems/year)
Cosmic radiation	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	10
Internal diagnosis/therapy	1
Nuclear power industry	0.2
TV tubes, industrial wastes, etc.	2
Radioactive fallout	4
Total from human activities	67
Total	193