Chapter 32

Ionizing Radiation, Nuclear Energy, and Elementary Particles

Ionizing radiation consists of photons and/or moving particles that have sufficient energy to knock and electron out of an atom or molecule, thus forming an ion.

Exposure is a measure of the ionizing radiation produced in air by X-rays or γ-rays.

In passing through the air, the beam produces positive ions whose total charge is *q*. Exposure is the charge per unit mass of the air.

$$\text{Exposure (in roentgens)} = \left(\frac{1}{2.58\times 10^{-4}}\right)\frac{q}{m}$$

For biological purposes, the ***absorbed dose*** is a more suitable quantity because it is the energy absorbed from the radiation per unit mass of the absorbing material:

$$\text{Absorbed dose} = \frac{\text{Energy absorbed}}{\text{Mass of absorbing material}}$$

gray

$$1\ \text{Gy} = 1\ \text{J/kg}$$

$$1\ \text{rad} = 0.01\ \text{gray}$$

To compare the damage produced by different types of radiation, the ***relative biological effectiveness*** (RBE) is used.

$$\text{RBE} = \frac{\begin{array}{l}\text{Dose of 200-keV X-rays that}\\ \text{pruduces a certain biological effect}\end{array}}{\begin{array}{l}\text{Dose of radiation that produces}\\ \text{the same biological effect}\end{array}}$$

Table 32.1 **Relative Biological Effectiveness (RBE) for Various Types of Radiation**

Type of Radiation	RBE
200-keV X-rays	1
γ rays	1
β^- particles (electrons)	1
Protons	10
α particles	10–20
Neutrons	
Slow	2
Fast	10

The product of the absorbed dose and the RBE is the ***biologically equivalent dose:***

Table 32.2 Average Biologically Equivalent Doses of Radiation Received by a U. S. Resident[a]

Source of Radiation	Biologically Equivalent Dose (mrem/yr)[b]
Natural background radiation	
Cosmic rays	28
Radioactive earth and air	28
Internal radioactive nuclei	39
Inhaled radon	≈200
Man-made radiation	
Consumer products	10
Medical/dental diagnostics	39
Nuclear medicine	14
Rounded total:	360

[a] National Council on Radiation Protection and Measurements, Report No. 93, "Ionizing Radiation Exposure of the Population of the United States," 1987.
[b] 1 mrem = 10^{-3} rem.

$$\text{Biologically equivalent dose} = \text{Absorbed dose} \times \text{RBE}$$

A ***nuclear reaction*** is said to occur whenever the incident nucleus, particle, or photon causes a change to occur in the target nucleus.

Nuclear Reaction	Notation
${}^{1}_{0}\mathrm{n} + {}^{10}_{5}\mathrm{B} \rightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\mathrm{He}$	${}^{10}_{5}\mathrm{B}\ (n, \alpha)\ {}^{7}_{3}\mathrm{Li}$
$\gamma + {}^{25}_{12}\mathrm{Mg} \rightarrow {}^{24}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}$	${}^{25}_{12}\mathrm{Mg}\ (\gamma, p)\ {}^{24}_{11}\mathrm{Na}$
${}^{1}_{1}\mathrm{H} + {}^{13}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \gamma$	${}^{13}_{6}\mathrm{C}\ (p, \gamma)\ {}^{14}_{7}\mathrm{N}$

Example 3 An Induced Nuclear Transmutation

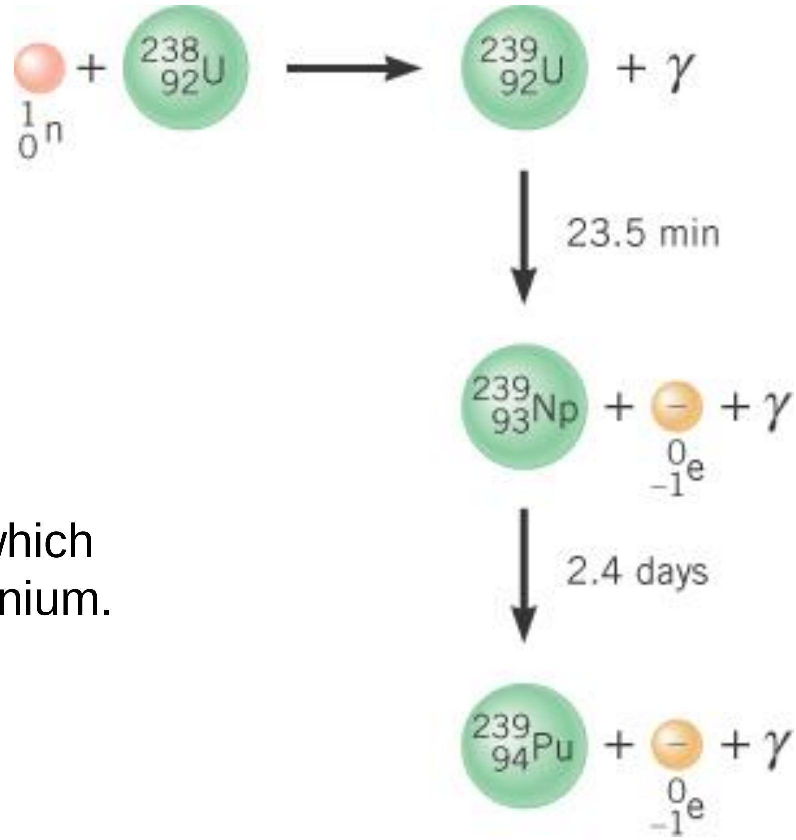
An alpha particle strikes an aluminum nucleus. As a result, an unknown nucleus and a neutron are produced.

$$ {}^{4}_{2}\mathrm{He} + {}^{27}_{13}\mathrm{D} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} $$

Conserved Quantity	Before Reaction		After Reaction
Total electric charge (number of protons)	2 + 13	=	Z + 0
Total number of nucleons	4 + 27	=	A + 1

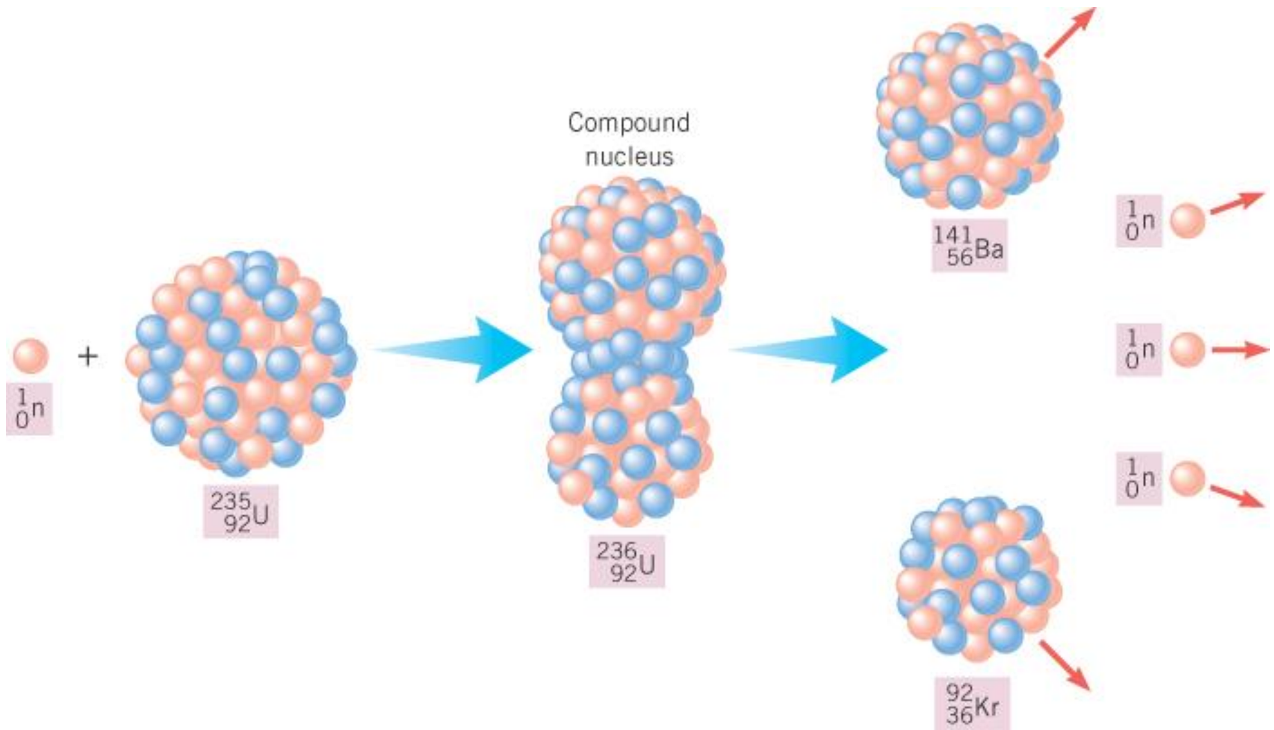
$$ {}^{30}_{15}\mathrm{P} $$

32.2 Induced Nuclear Reactions



An induced nuclear reaction in which uranium is transmuted into plutonium.

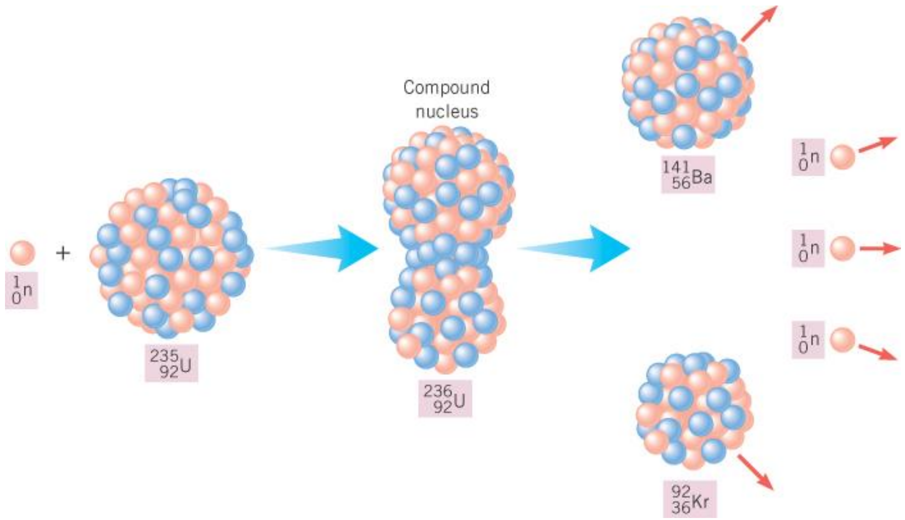
32.3 Nuclear Fission



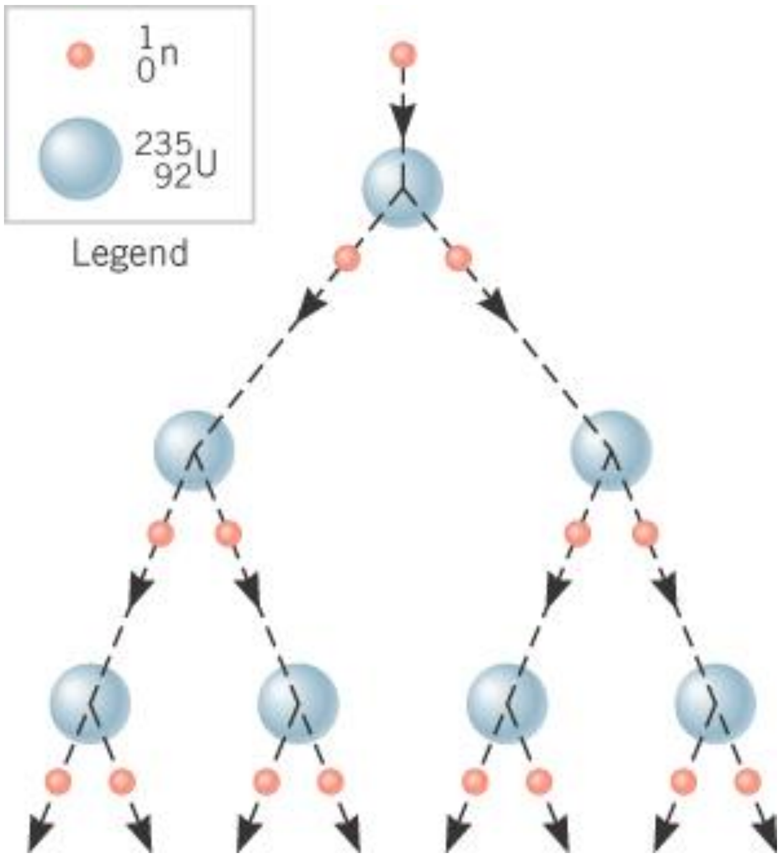
A slowly moving neutron causes the uranium nucleus to fission into barium, krypton, and three neutrons.

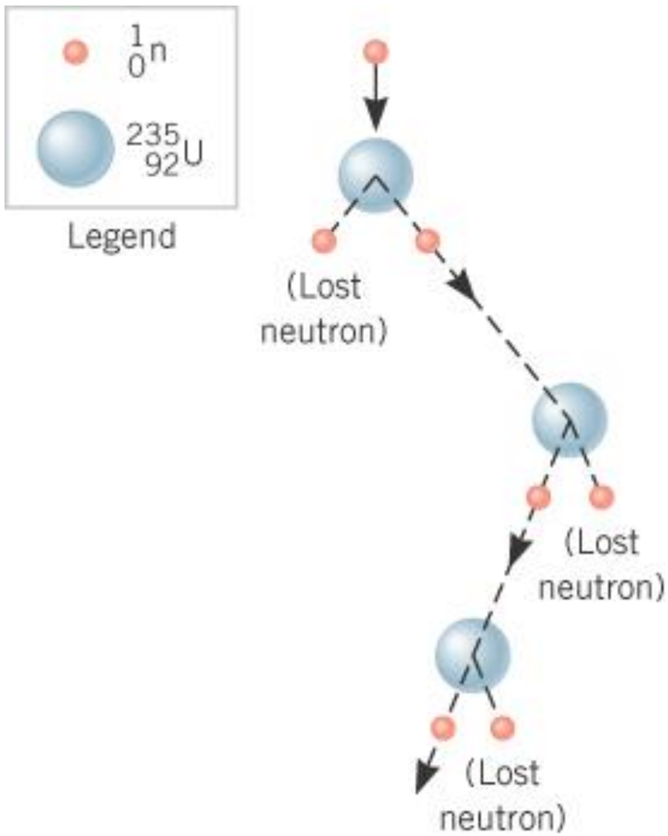
Conceptual Example 5 **Thermal Neutrons Versus Thermal Protons or Alpha Particles**

Why is it possible for a thermal neutron to penetrate a nucleus, whereas a proton or alpha particle would need a much larger amount of energy?



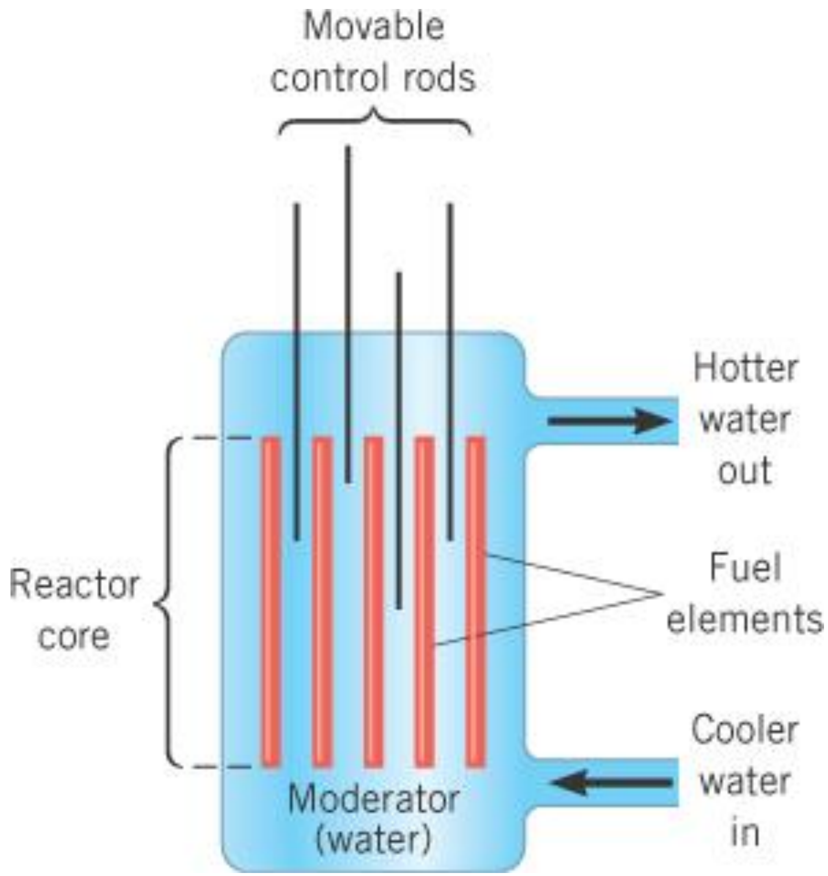
A chain reaction



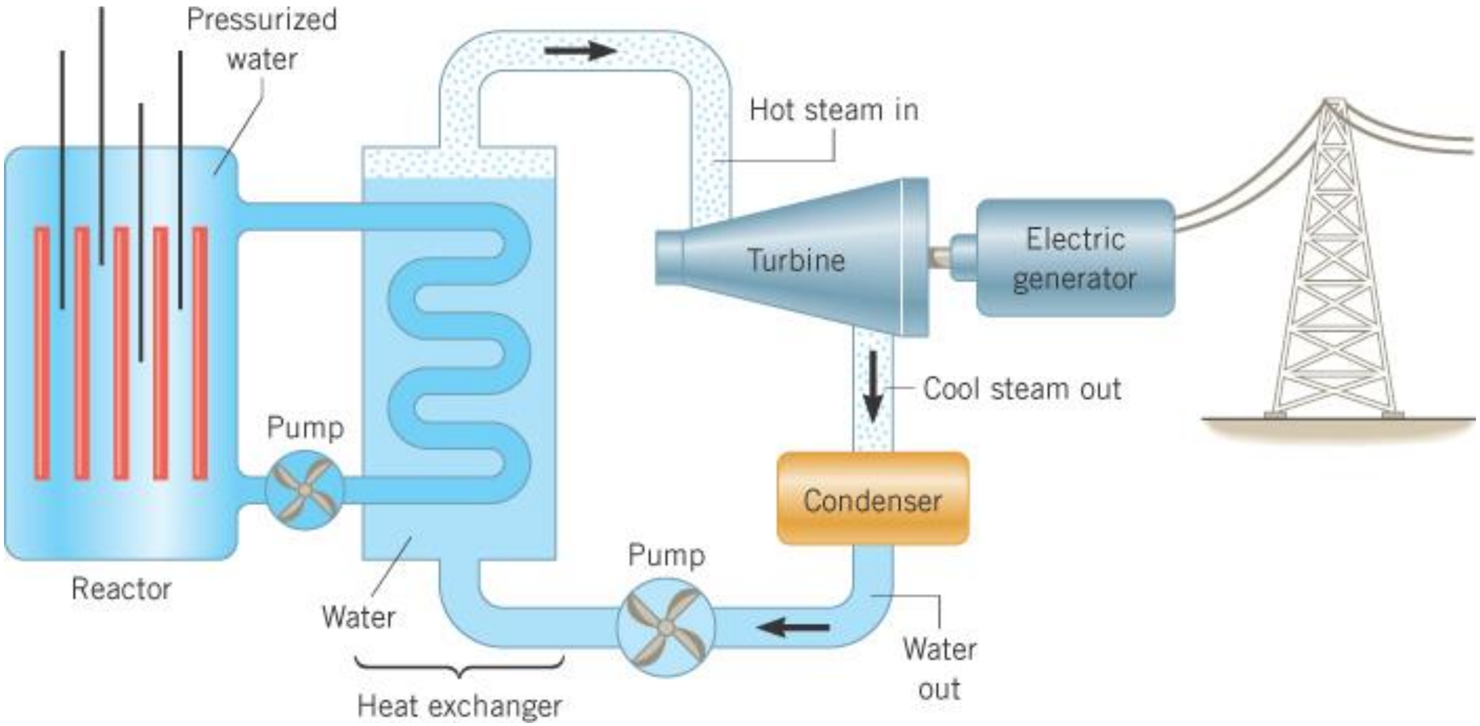


In a controlled chain reaction, only one neutron, on average, causes another neutron to fission.

32.4 Nuclear Reactors

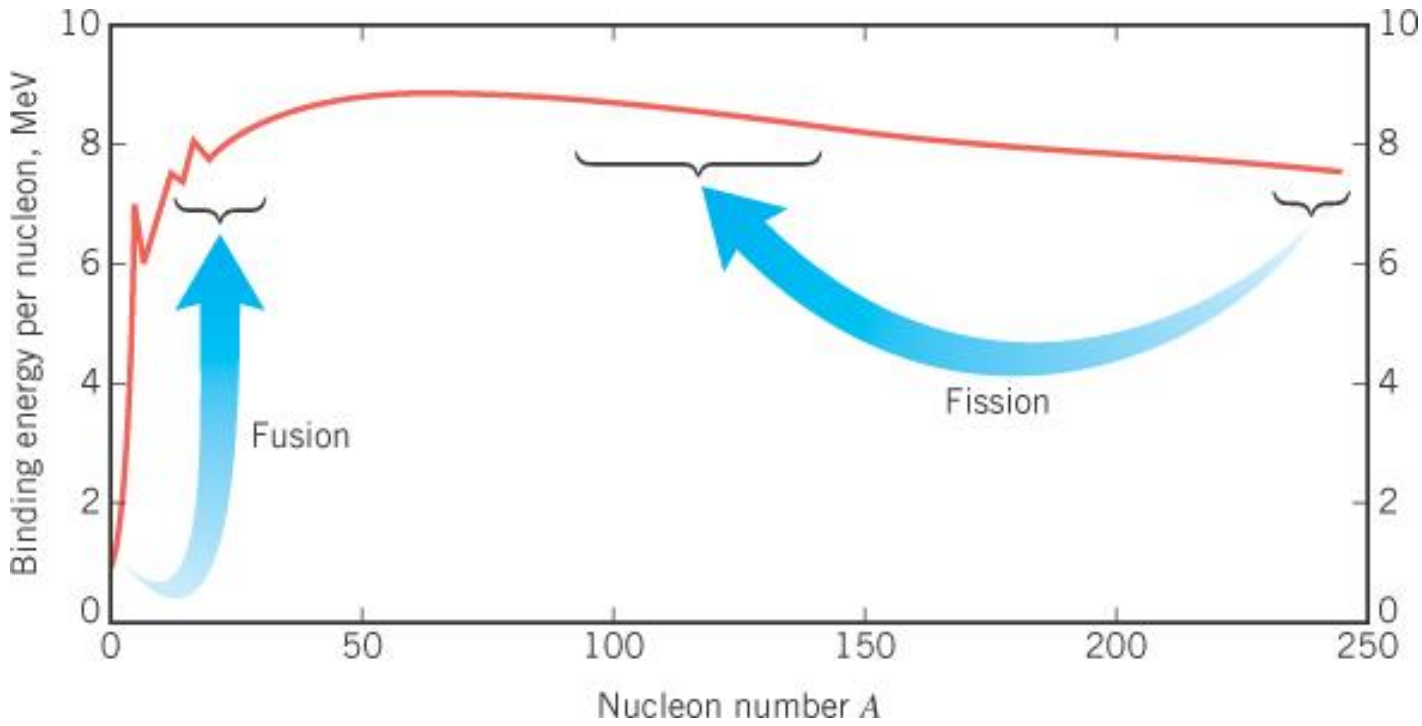


A nuclear reactor consists of fuel elements, control rods, and a moderator.



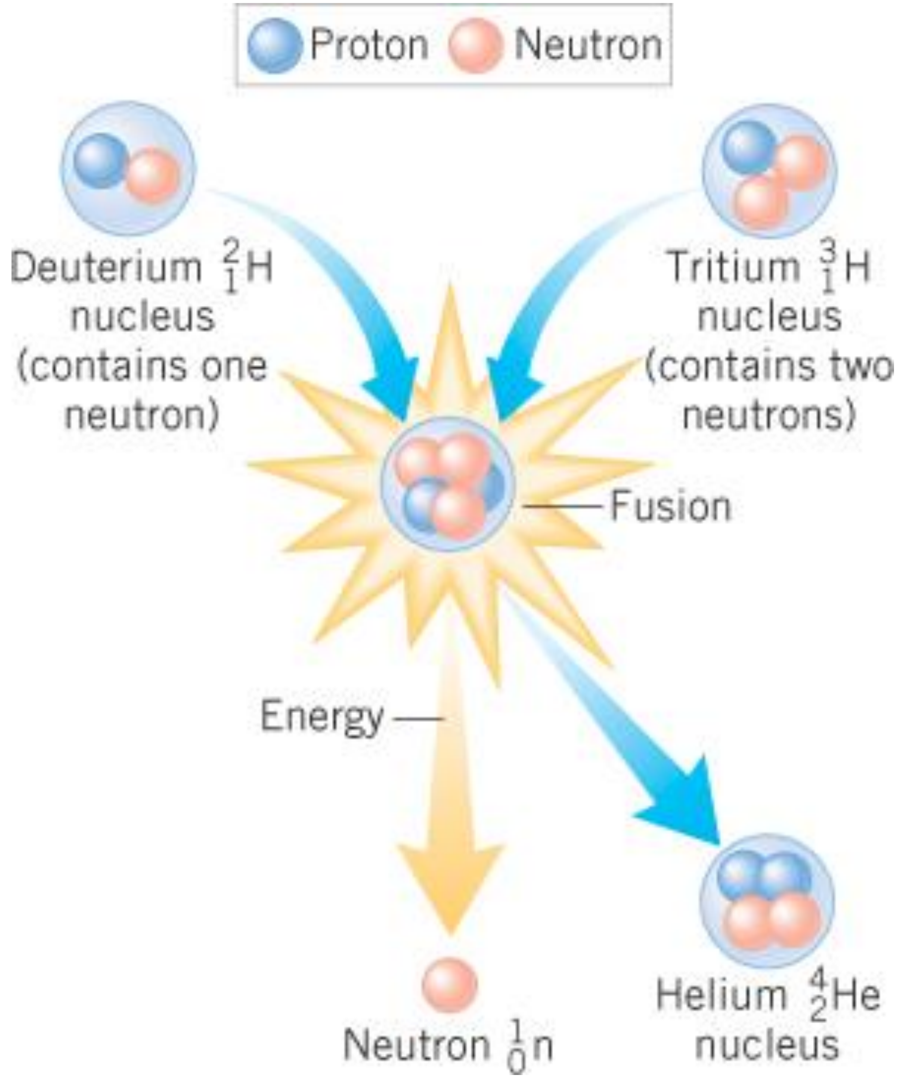
The moderator slows neutrons and the control rods absorb neutrons.

32.5 Nuclear Fusion



Two nuclei of very low mass can combine to generate energy. This process is called ***nuclear fusion.***

32.5 Nuclear Fusion

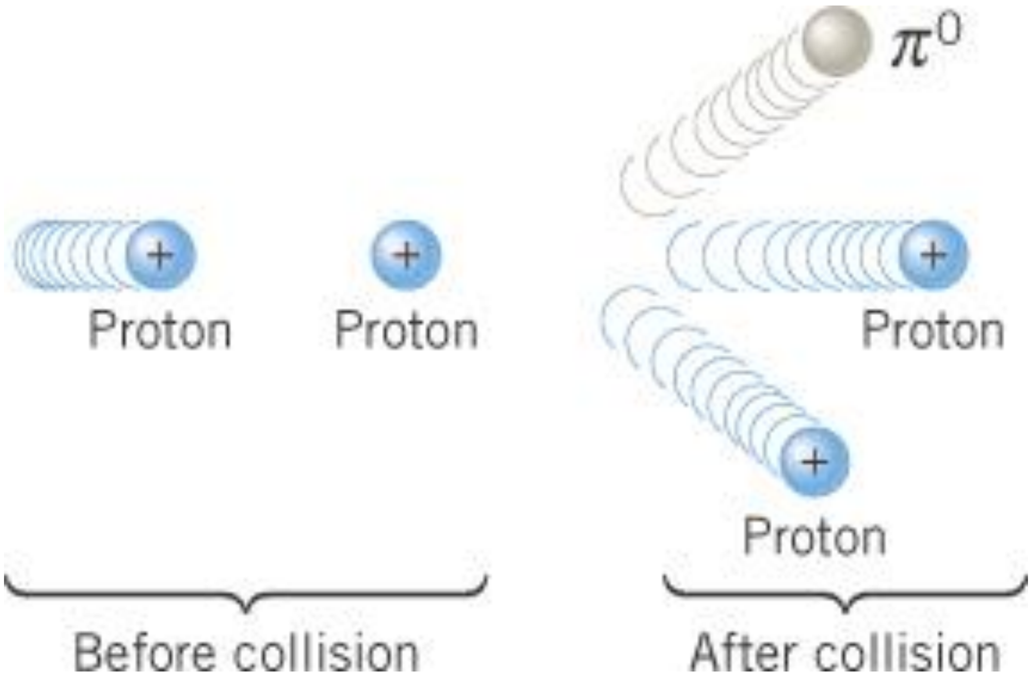


32.6 Elementary Particles

Table 32.3 Some Particles and Their Properties

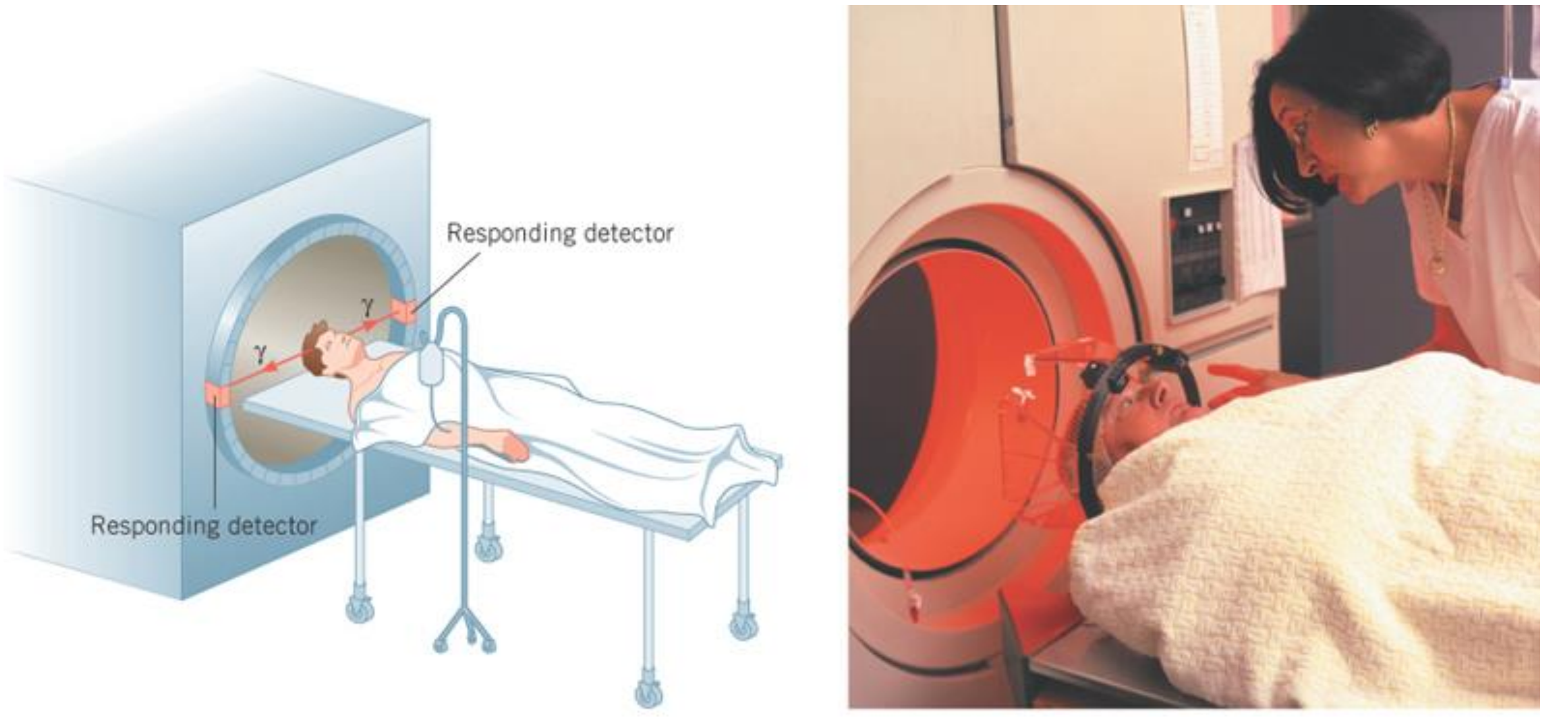
Family	Particle	Particle Symbol	Antiparticle Symbol	Rest Energy (MeV)	Lifetime (s)
Photon	Photon	γ	Self[a]	0	Stable
Lepton	Electron	e^- or β^-	e^+ or β^+	0.511	Stable
	Muon	μ^-	μ^+	105.7	2.2×10^{-6}
	Tau	τ^-	τ^+	1777	2.9×10^{-13}
	Electron neutrino	ν_e	$\bar{\nu}_e$	$<3 \times 10^{-6}$	Stable
	Muon neutrino	ν_μ	$\bar{\nu}_\mu$	<0.19	Stable
	Tau neutrino	ν_τ	$\bar{\nu}_\tau$	<18.2	Stable
Hadron					
Mesons					
	Pion	π^+	π^-	139.6	2.6×10^{-8}
		π^0	Self[a]	135.0	8.4×10^{-17}
	Kaon	K^+	K^-	493.7	1.2×10^{-8}
		K_S^0	$\bar{K}_S^0$	497.7	8.9×10^{-11}
		K_L^0	$\bar{K}_L^0$	497.7	5.2×10^{-8}
	Eta	η^0	Self[a]	547.3	$<10^{-18}$
Baryons					
	Proton	p	$\bar{p}$	938.3	Stable
	Neutron	n	$\bar{n}$	939.6	886
	Lambda	Λ^0	$\bar{\Lambda}^0$	1116	2.6×10^{-10}
	Sigma	Σ^+	$\bar{\Sigma}^-$	1189	8.0×10^{-11}
		Σ^0	$\bar{\Sigma}^0$	1193	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	1197	1.5×10^{-10}
	Omega	Ω^-	Ω^+	1672	8.2×10^{-11}

[a] The particle is its own antiparticle.



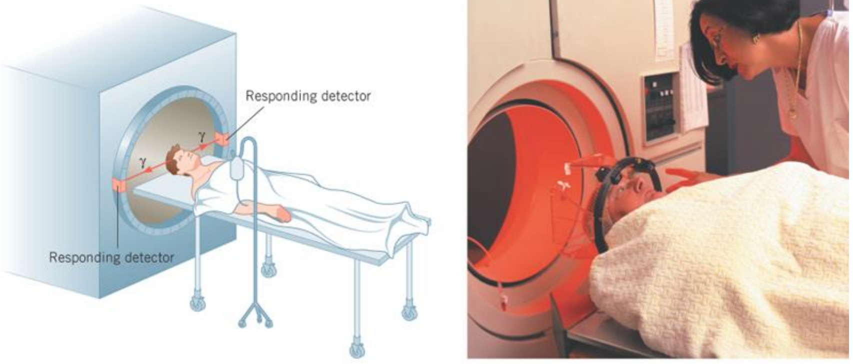
Pion production through p-p collision.

Antiparticles, like positrons, can be used in positron emission tomography, or PET scans.

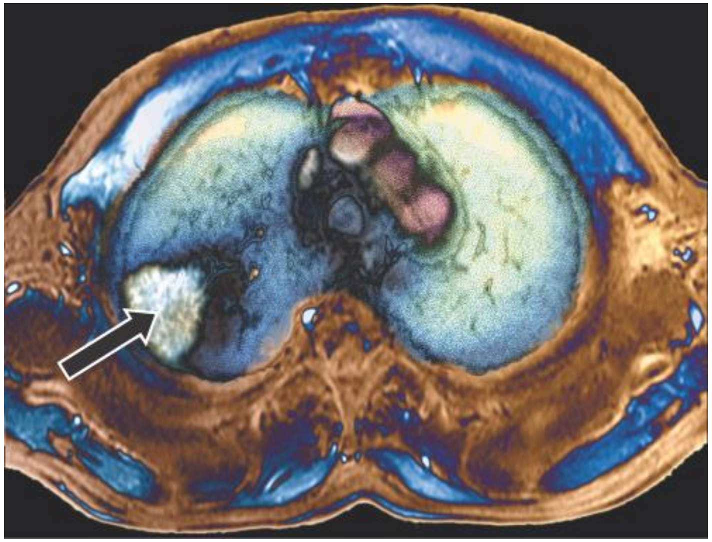


(a) (b)

32.6 Elementary Particles



(a) (b)



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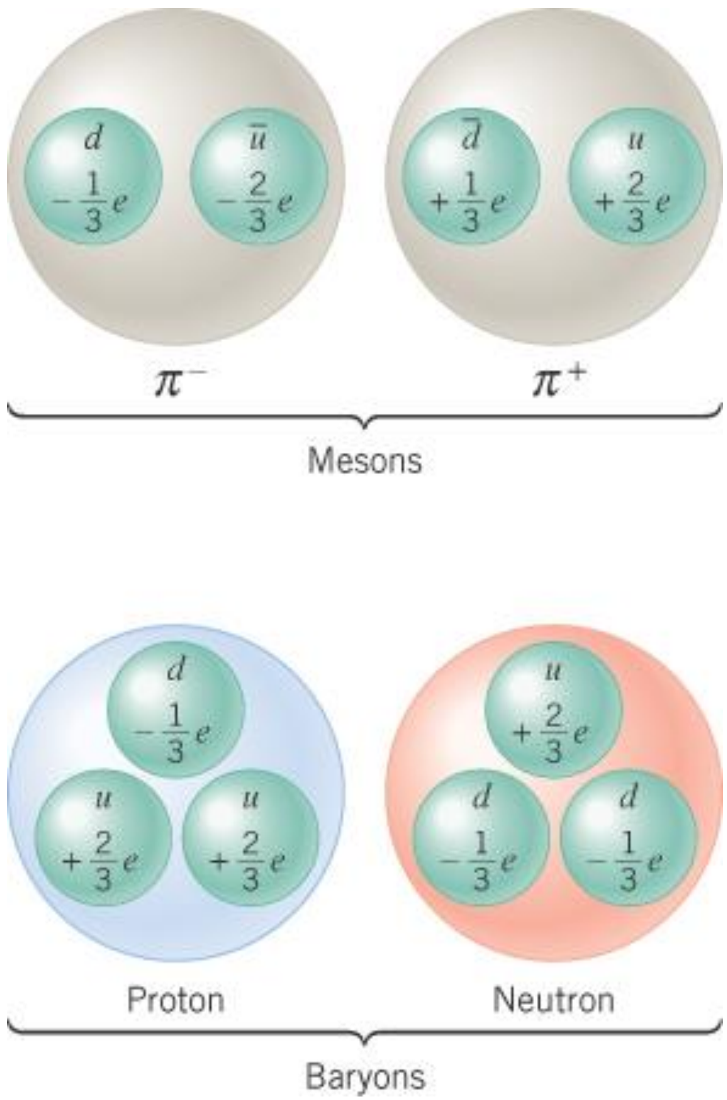
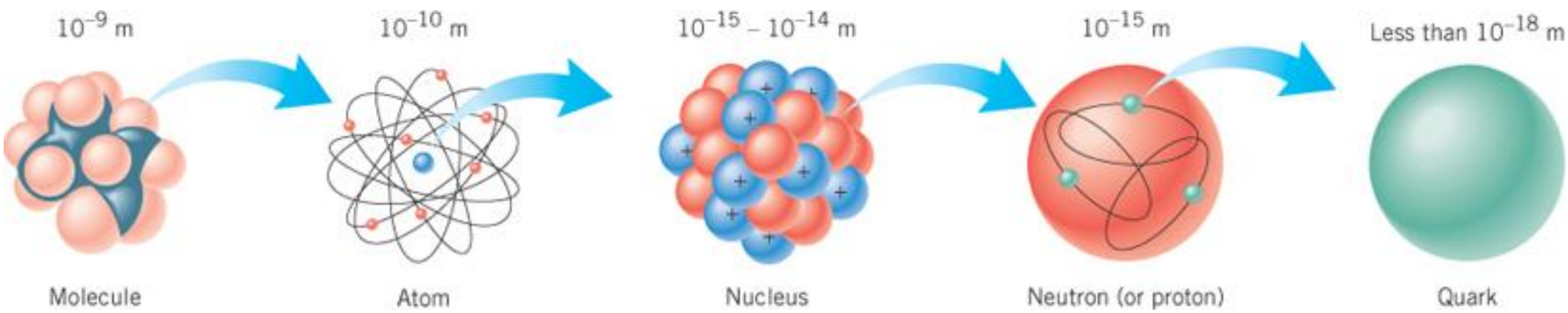


Mesons consist of a quark-antiquark pair, while baryons consist of three quarks.

32.6 Elementary Particles



The current view of how matter is composed of basic units.

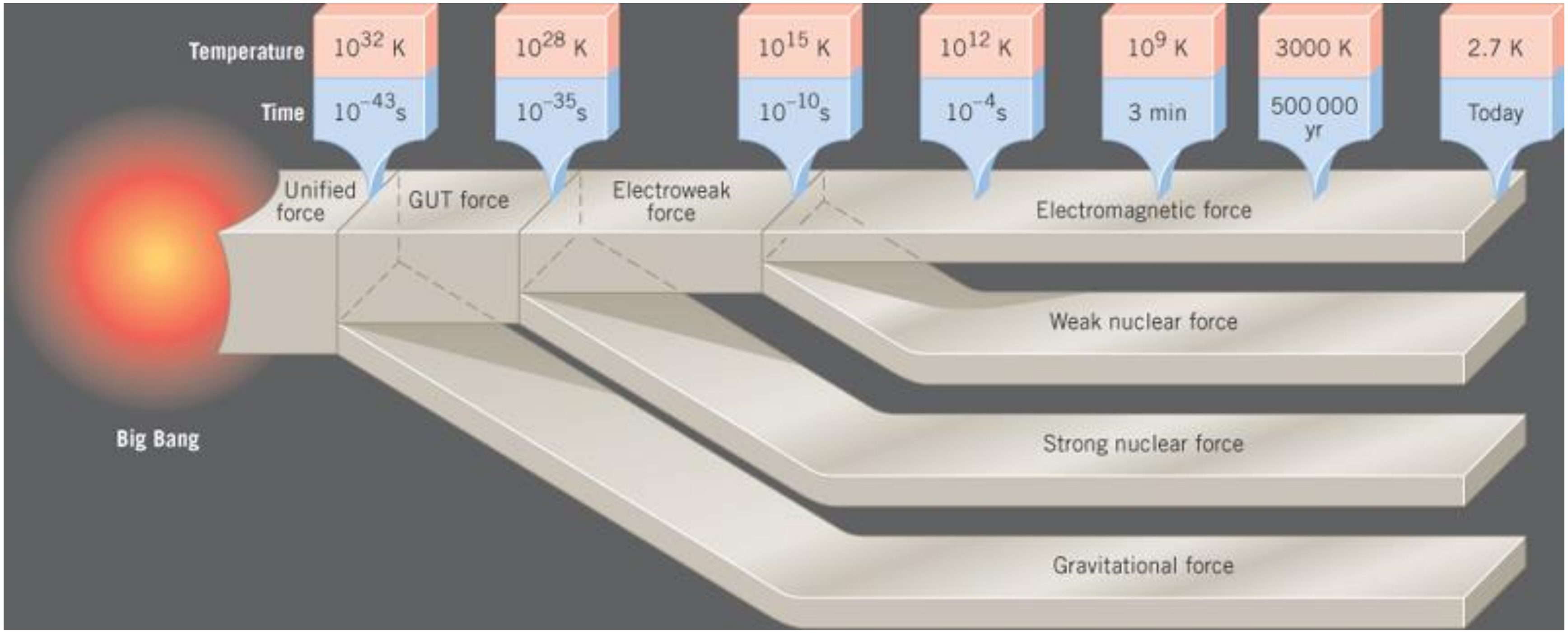
distance of
galaxy from earth

Hubble's law

$$v = Hd$$

speed of
galaxy

$$H = 0.022 \frac{\mathrm{m}}{\mathrm{s} \cdot \text{light-year}}$$


Temperature
Time
10^{32} K
10^{-43}s
10^{28} K
10^{-35}s
10^{15} K
10^{-10}s
10^{12} K
10^{-4}s
10^{9} K
3 min
3000 K
500 000 yr
2.7 K
Today
Unified force
GUT force
Electroweak force
Electromagnetic force
Weak nuclear force
Strong nuclear force
Gravitational force
Big Bang