

Lecture Outlines

Chapter 32

Physics, 3rd Edition

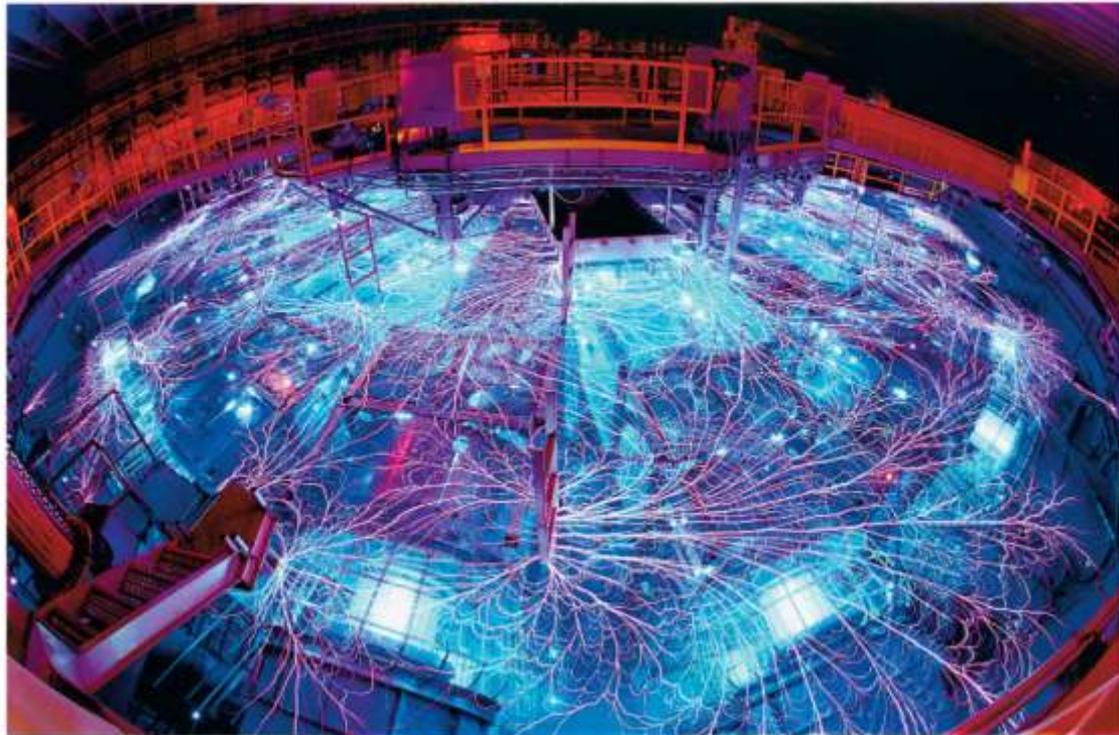
James S. Walker

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Chapter 32

Nuclear Physics and Nuclear Radiation



Units of Chapter 32

- **The Constituents and Structure of Nuclei**
- **Radioactivity**
- **Half-Life and Radioactive Dating**
- **Nuclear Binding Energy**
- **Nuclear Fission**
- **Nuclear Fusion**
- **Practical Applications of Nuclear Physics**

Units of Chapter 32

- **Elementary Particles**
- **Unified Forces and Cosmology**

32-1 The Constituents and Structure of Nuclei

Nuclei contain positively charged protons and neutral neutrons. Nuclei are characterized by the number of protons and neutrons they contain.

TABLE 32-1

Numbers That Characterize a Nucleus

Z	Atomic number = number of protons in nucleus
N	Neutron number = number of neutrons in nucleus
A	Mass number = number of nucleons in nucleus

$$A = Z + N$$

32-1 The Constituents and Structure of Nuclei

The notation for a particular nucleus of element X is written:



Examples: ${}^{14}_6\text{C}$ ${}^{27}_{13}\text{Al}$

Masses and charges of atomic particles:

TABLE 32–2 Mass and Charge of Particles in the Atom

Particle	Mass (kg)	Mass (MeV/c ²)	Mass (u)	Charge (C)
Proton	1.672623×10^{-27}	938.28	1.007276	$+1.6022 \times 10^{-19}$
Neutron	1.674929×10^{-27}	939.57	1.008665	0
Electron	9.109390×10^{-31}	0.511	0.0005485799	-1.6022×10^{-19}

32-1 The Constituents and Structure of Nuclei

The atomic mass unit, u , is defined so that the mass of $^{12}_6\text{C}$ is exactly 12 u .

Definition of Atomic Mass Unit, u

$$1 u = 1.660540 \times 10^{-27} \text{ kg}$$

SI unit: kg

This mass may also be written in terms of MeV/c^2 , using $E = mc^2$:

$$1 u = 931.5 \text{ MeV}/c^2$$

32-1 The Constituents and Structure of Nuclei

Careful measurements have related the size of the nucleus to its atomic number:

$$r = (1.2 \times 10^{-15} \text{ m})A^{1/3}$$

By contrast, the radius of an atom is on the order of 10^{-10} m. This means that the density of the nucleus is extremely high.

For convenience, we define:

Definition of the Fermi, fm

$$1 \text{ fermi} = 1 \text{ fm} = 10^{-15} \text{ m}$$

SI unit: m

32-1 The Constituents and Structure of Nuclei

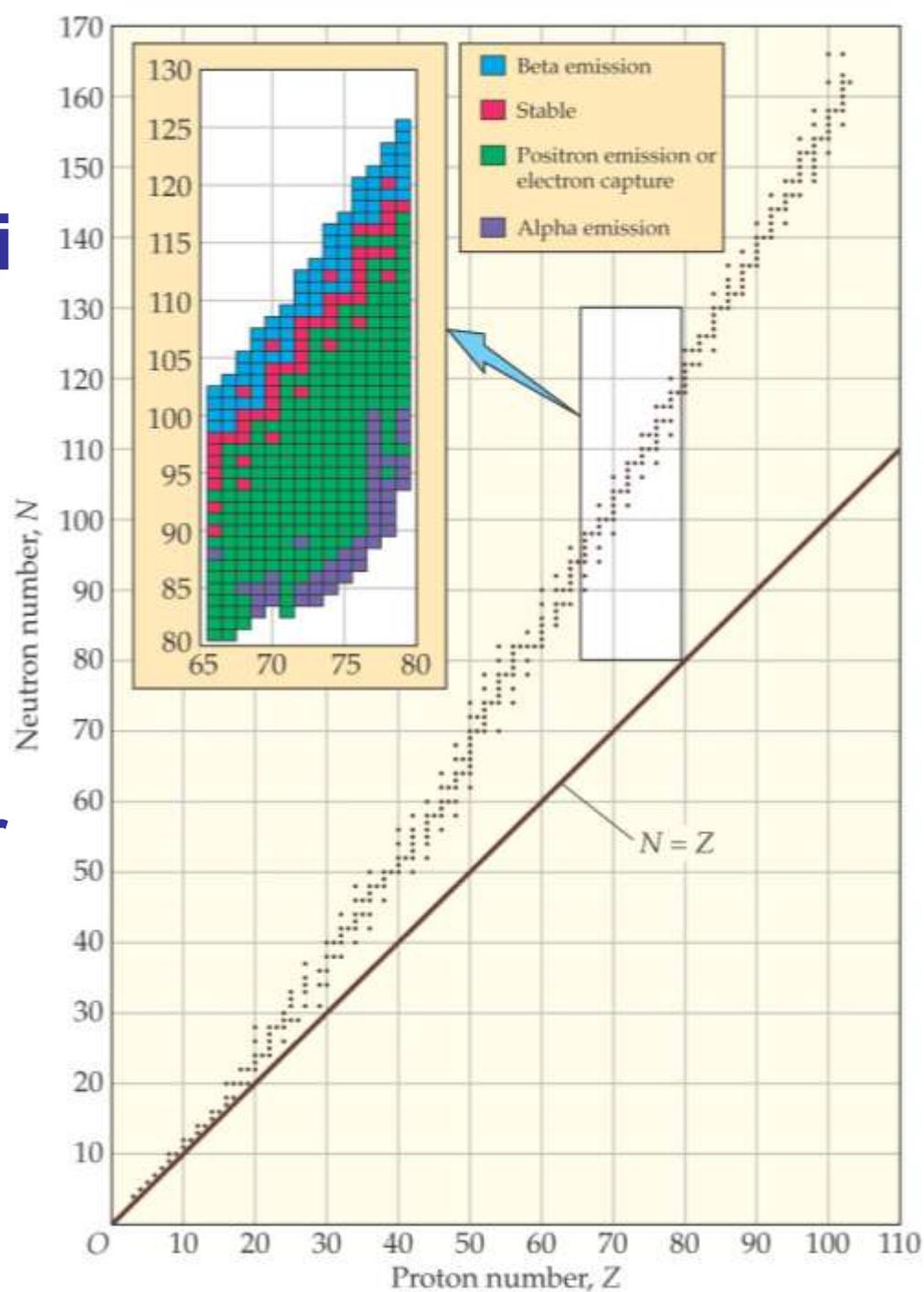
If the nucleus contains only positive charges, why doesn't it fly apart due to their mutual repulsion?

There is another force acting, called the strong nuclear force, which keeps it together. Its properties:

- The strong force is short range, acting only to distances of a couple fermis.**
- The strong force is attractive and acts with nearly equal strength between protons and protons, protons and neutrons, and neutrons and neutrons.**

32-1 The Constituents and Structure of Nuclei

Since the strong nuclear force is short range, atoms with more protons must have proportionally more neutrons in order to remain stable.



32-2 Radioactivity

Unstable nuclei can either decay into a stable nucleus of different N and Z , or can return to the ground state. Three different types of particles may be emitted:

1. Alpha particles, which consist of two neutrons and two protons, and are nuclei of ${}^4_2\text{He}$
2. Electrons and positrons, also called (for historical reasons) beta rays. Positrons have the same mass as electrons but are positively charged.
3. Gamma rays, which are high-energy photons.

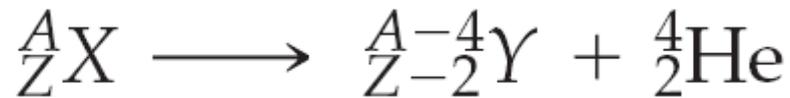
32-2 Radioactivity

Penetrating abilities:

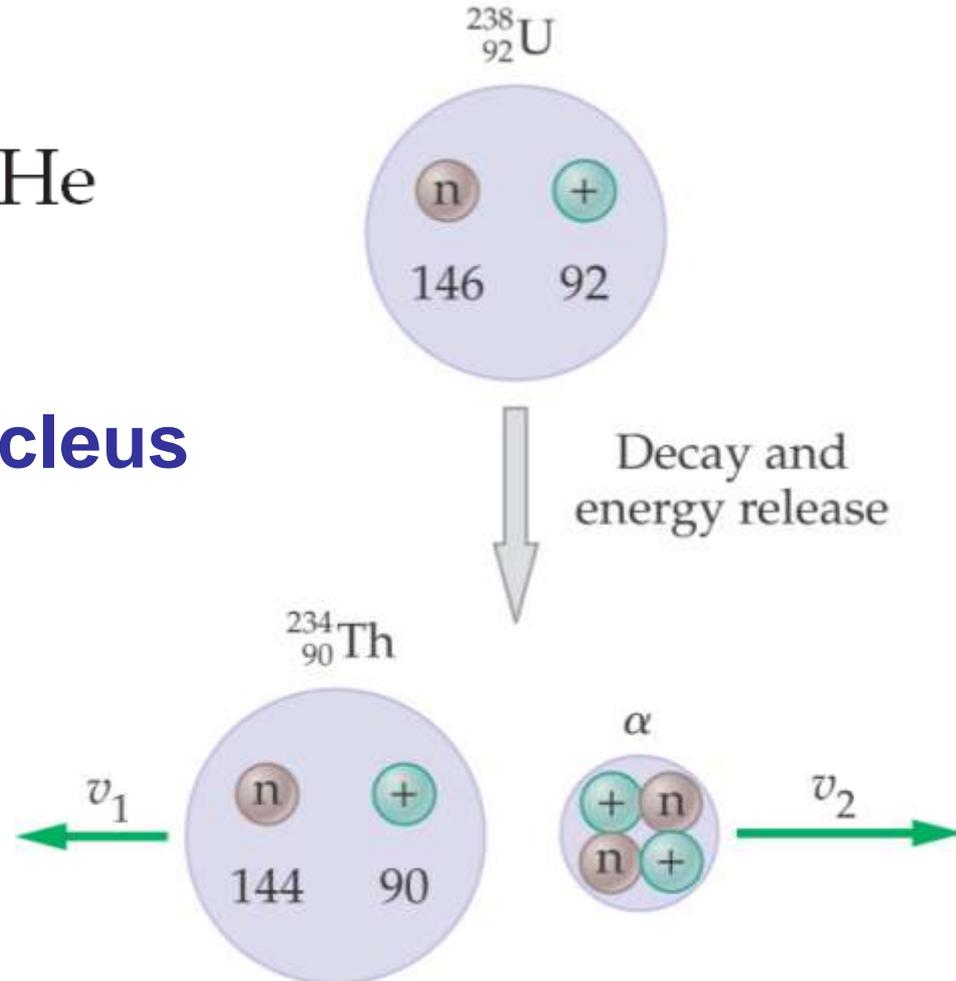
- α rays can barely penetrate a sheet of paper.
- β rays (both β^- and β^+) can penetrate a few millimeters of aluminum.
- γ rays can penetrate several centimeters of lead.

32-2 Radioactivity

When a nucleus decays by emitting an alpha particle, it loses two protons and two neutrons, Symbolically:

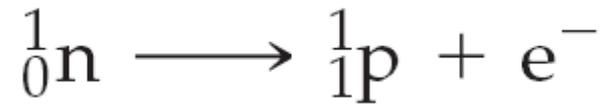


Here, X is the parent nucleus and Y is the daughter.

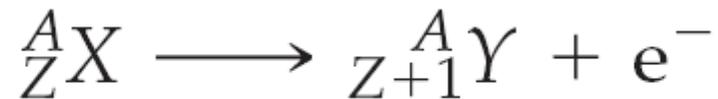


32-2 Radioactivity

The basic process in beta decay converts a neutron into a proton and an electron:



Therefore, a nucleus that decays via beta decay loses a neutron and gains a proton.

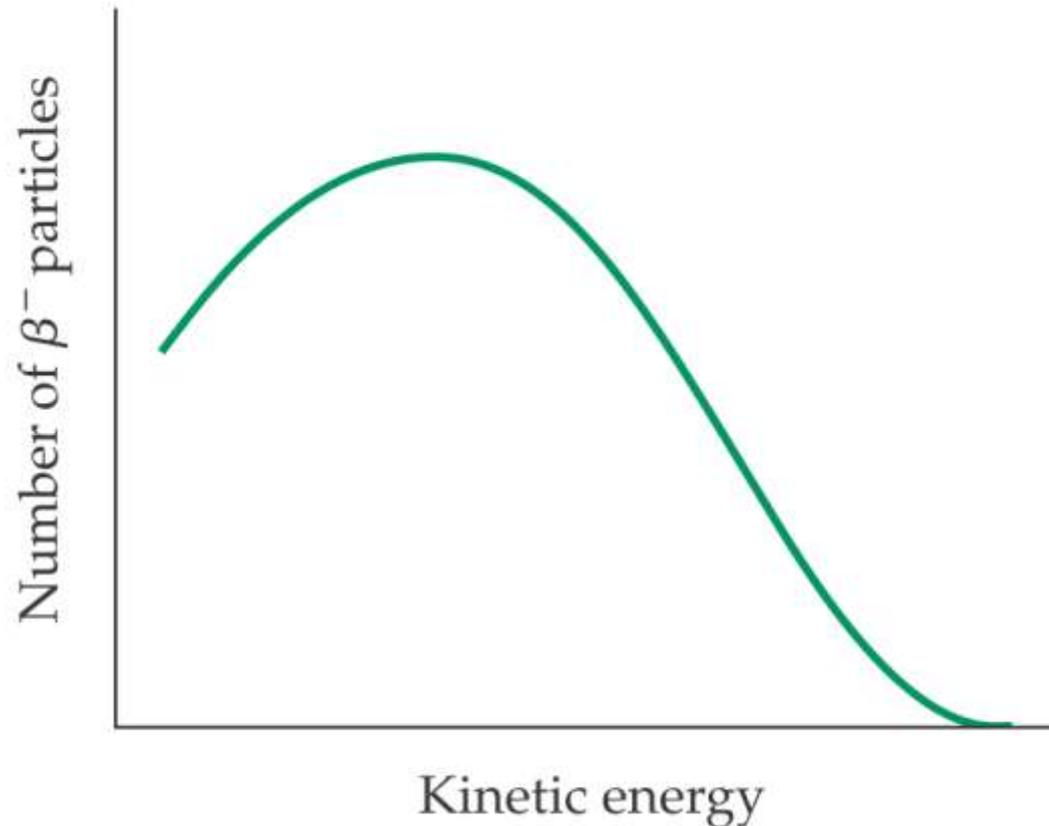


If a nucleus emits a positron, a proton has become a neutron:



32-2 Radioactivity

Analysis of the energy spectrum of the emitted electron in beta decay showed that it was not monoenergetic, as would be expected from a two-body decay.



32-2 Radioactivity

In fact, there is a third particle emitted, which has no electric charge and little, if any, mass, called the neutrino. With the neutrino, beta decay is more correctly written:



32-2 Radioactivity

A gamma ray is emitted when an excited nucleus returns to its ground state. Nuclei may become excited through alpha or beta decay, leading to a sequence such as this one:



The asterisk indicates the excited nucleus.

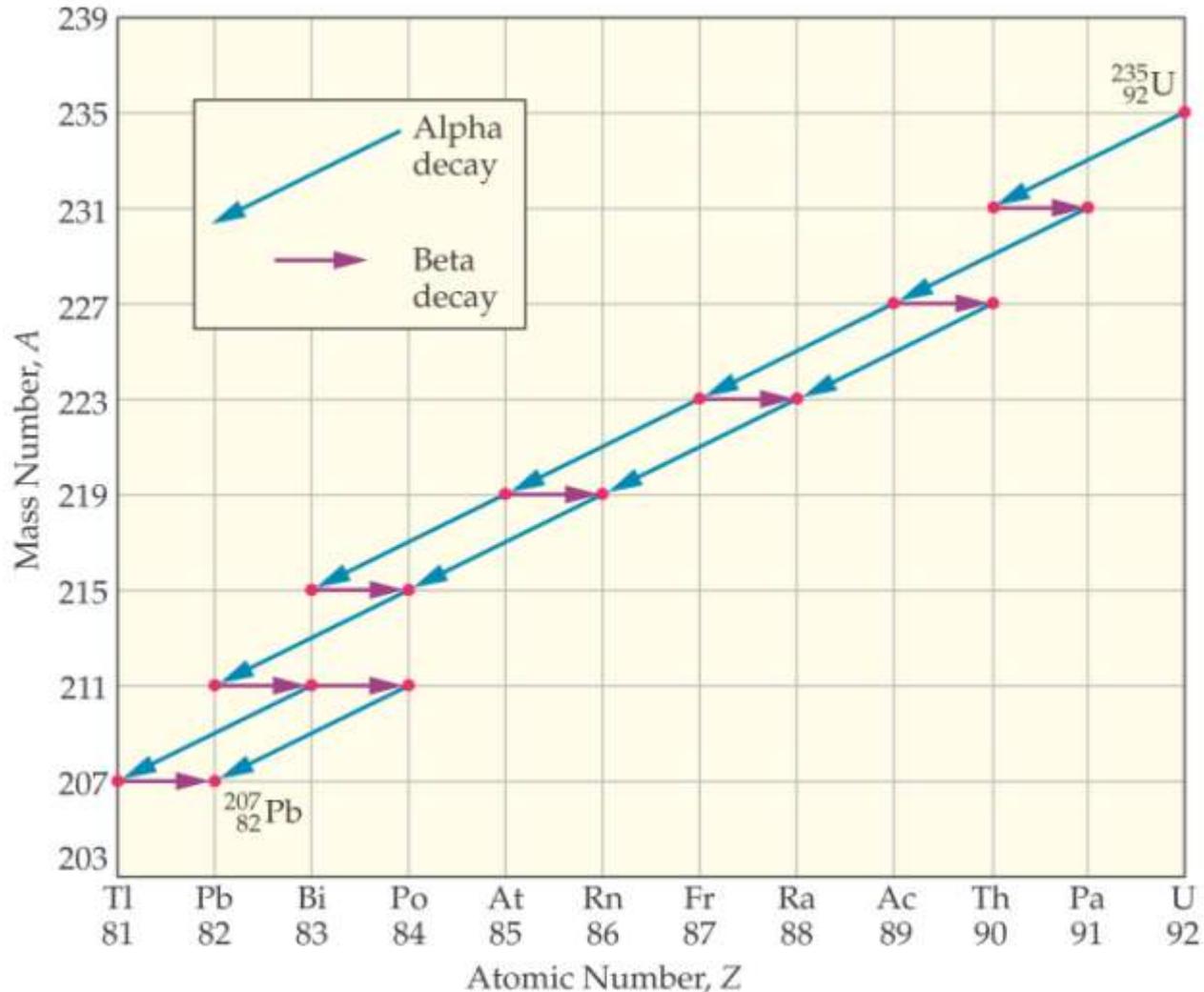
32-2 Radioactivity

Heavy nuclei decaying via alpha emission may very well decay to a daughter nucleus which is also unstable, and so on. The decays will continue until a stable nucleus is reached.

For example, one isotope of uranium, ${}_{92}^{235}\text{U}$, goes through a decay series that finally ends up at a stable isotope of lead, ${}_{82}^{207}\text{Pb}$.

32-2 Radioactivity

This is a diagram of the series of alpha and beta decays in the decay chain.



32-2 Radioactivity

Some nuclei decay more rapidly than others. The rate of decay – the number of decays per second – is called the activity.

Two units of activity:

$$1 \text{ curie} = 1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/s}$$

$$1 \text{ becquerel} = 1 \text{ Bq} = 1 \text{ decay/s}$$

The curie (and the millicurie and microcurie) are most commonly used.

32-3 Half-Life and Radioactive Dating

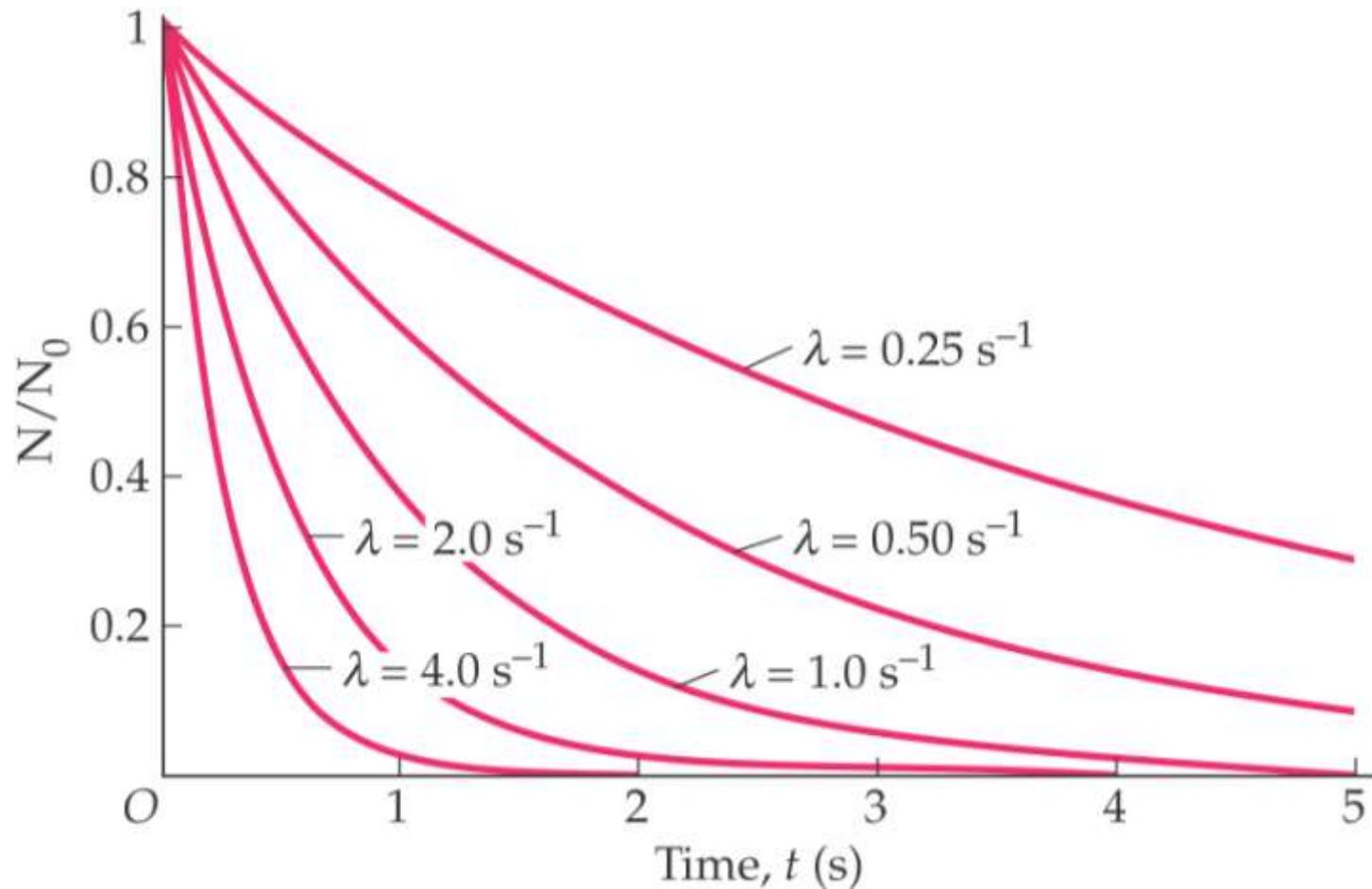
Nuclear decay is a random process, in that we do not know which nucleus will decay at what time. However, if we have a large number of similar nuclei, we can predict the rate at which they decay quite well.

The number that decay within a given time interval is always the same fraction of the total number at the beginning of the interval; this is exponential decay.

$$N = N_0 e^{-\lambda t}$$

32-3 Half-Life and Radioactive Dating

Different nuclei have different decay constants λ . A larger decay constant means the material decays away more rapidly.



32-3 Half-Life and Radioactive Dating

Nuclear decay can also be characterized by the half-life, which is the time it takes for half a sample to decay away.

The half-life is related to the decay constant:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

The decay rate, or activity, is also related to the decay constant:

$$R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N$$

32-3 Half-Life and Radioactive Dating

The activity as a function of time:

$$R = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$

This change in activity can be used in carbon-14 dating of organic materials.

In the Earth's atmosphere, carbon-12 and carbon-14 are in equilibrium; as the carbon-14 decays away, more is formed. It is in equilibrium within living plants and animals as well, as there is a constant exchange of carbon with the atmosphere.

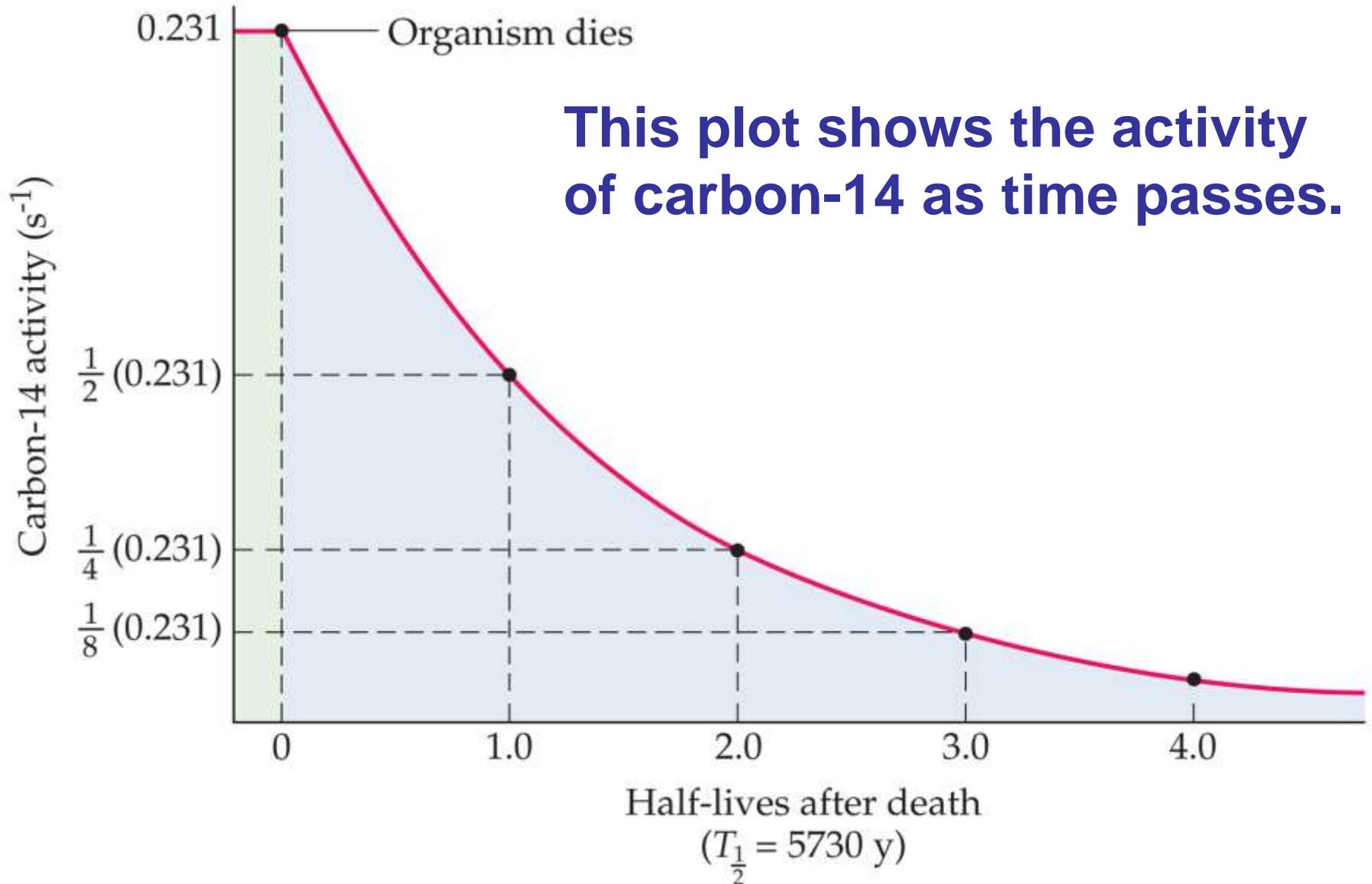
32-3 Half-Life and Radioactive Dating

However, at death, this exchange stops, and the carbon-14 decays without being replenished, with a half-life of 5730 years.

We can use this to date the material, as we know the ratio of carbon-12 to carbon-14 in the atmosphere and therefore the activity of 1 gram of natural carbon. If we compare that with the present activity of a sample, we know how old it is.

This technique only works for a few half-lives; after that the activity is too low to measure reliably.

32-3 Half-Life and Radioactive Dating

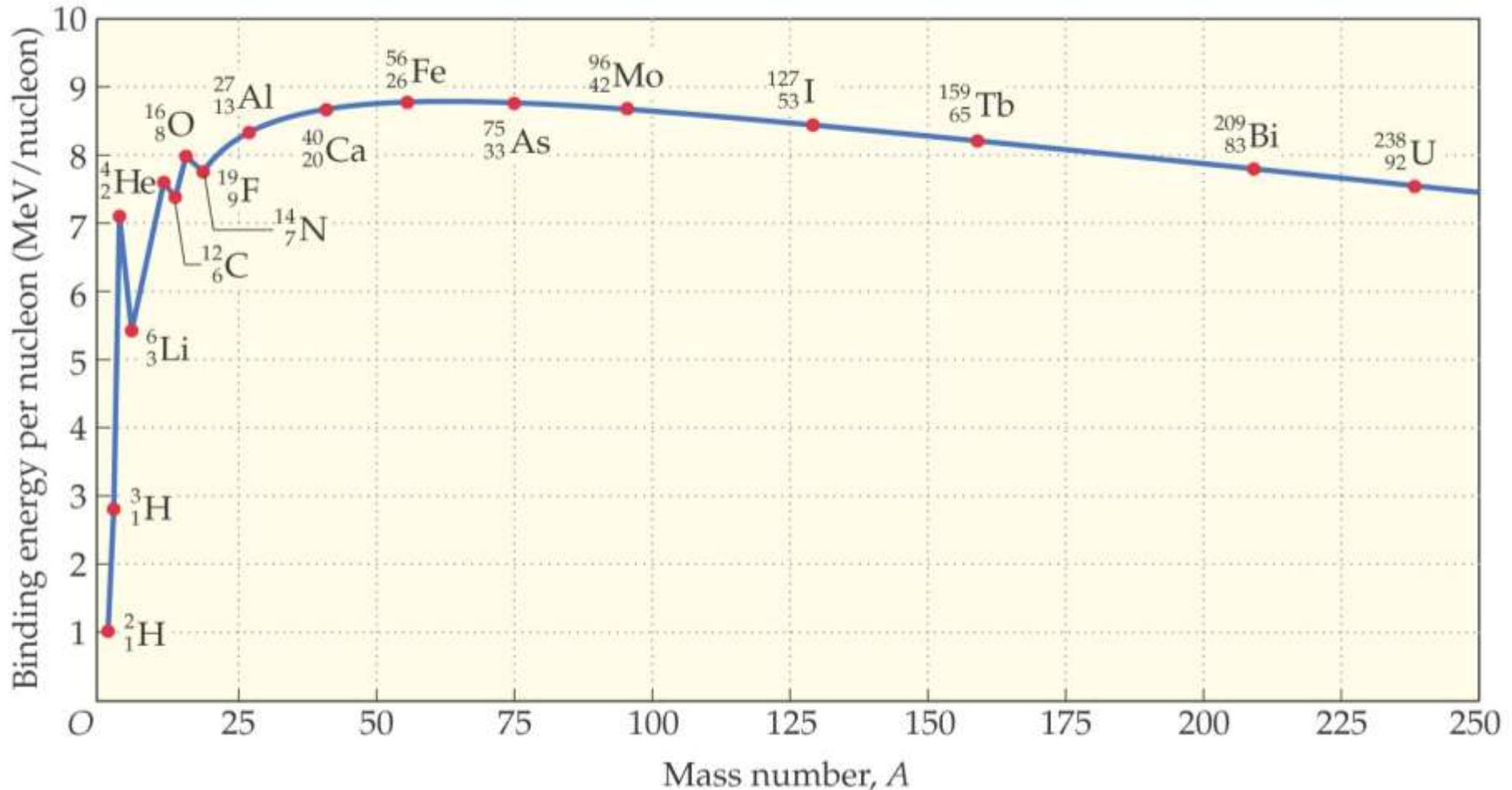


32-4 Nuclear Binding Energy

The mass of any stable nucleus is less than the sum of the masses of the protons and neutrons it contains. This difference, multiplied by c^2 , is called the binding energy, and is another consequence of relativity.

32-4 Nuclear Binding Energy

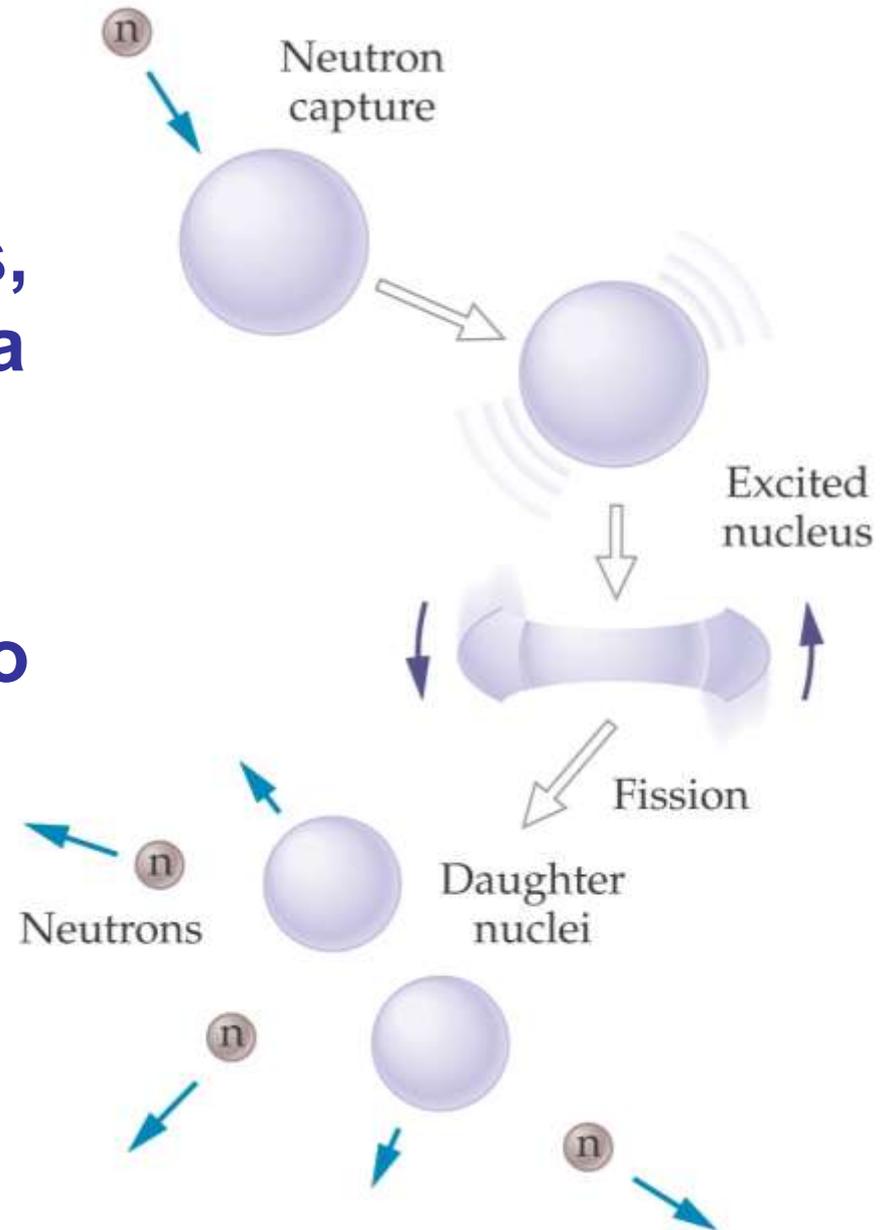
The curve of binding energy is the binding energy per nucleon:



32-5 Nuclear Fission

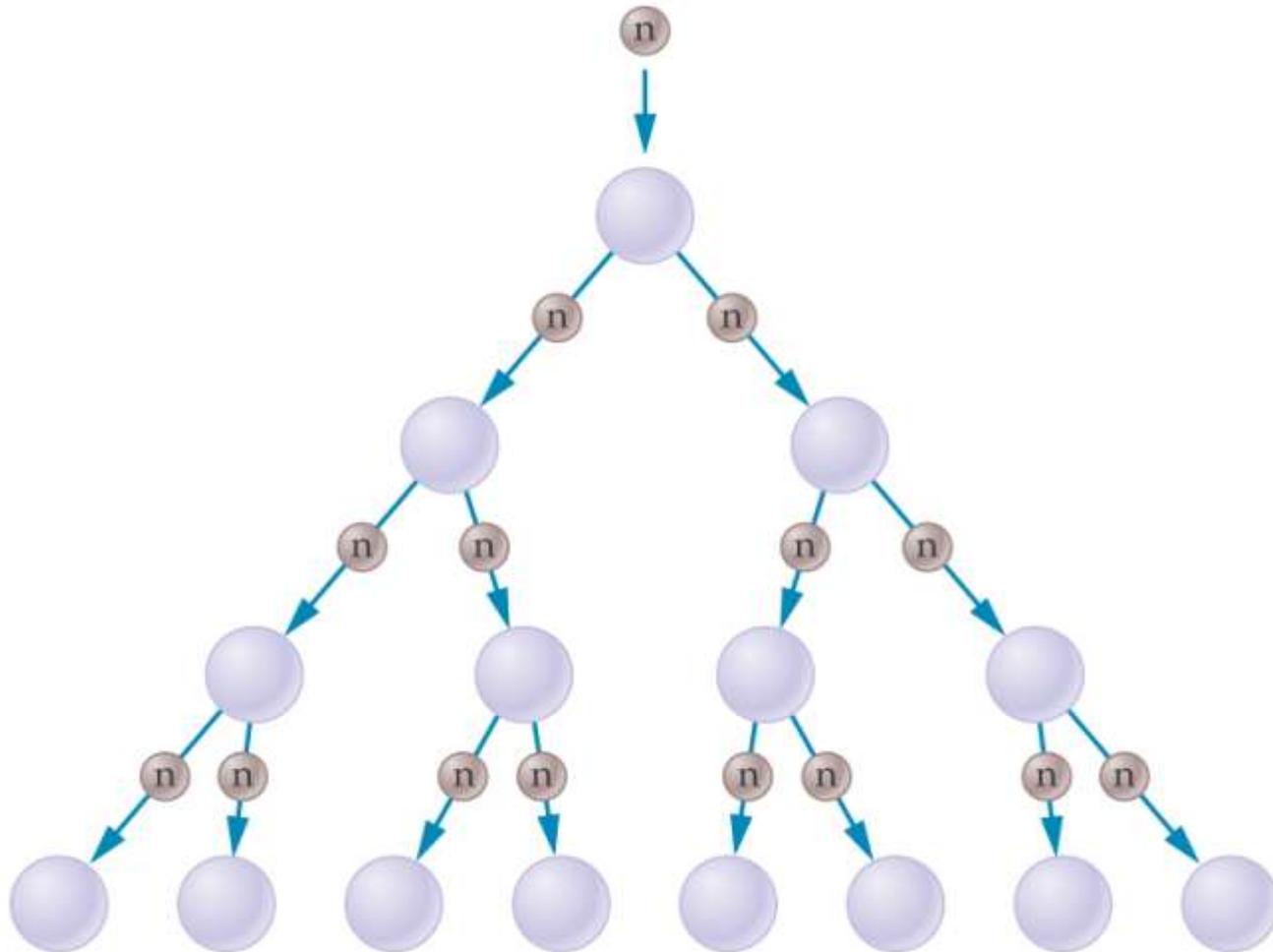
Nuclear fission occurs when a heavy nucleus splits into two lighter ones, especially after capturing a neutron.

The lighter nuclei do not need so many neutrons, so there are typically extra neutrons emitted from the reaction.



32-5 Nuclear Fission

This emission of multiple neutrons can lead to a chain reaction, either controlled or uncontrolled.



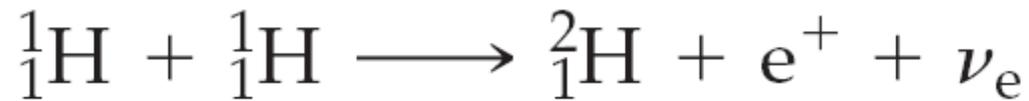
32-6 Nuclear Fusion

Very light nuclei can combine to form a heavier nucleus with greater binding energy; energy is therefore released. This can only occur at extremely high temperatures, as the nuclei must be moving fast enough to overcome the electrical repulsion.

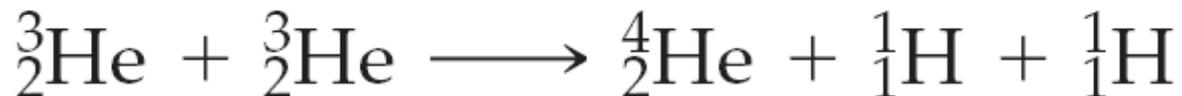
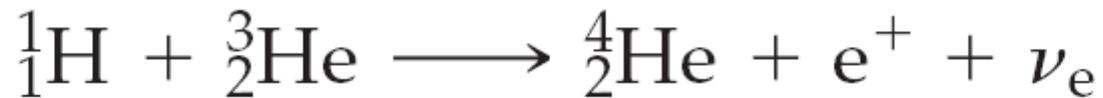
Such temperatures are available in the center of the Sun and other stars; nuclear fusion is what powers them.

32-6 Nuclear Fusion

The nuclear fusion process in the Sun begins with two protons fusing to form deuterium, and then fusing with a third proton to form helium-3.



After that, a helium-4 nucleus is formed in one of the following two ways:



Considerable energy is emitted in this interaction.

32-7 Practical Applications of Nuclear Physics

Nuclear radiation can be beneficial if used properly, but can also cause tissue damage. There are different ways of measuring this damage.

The first is by measuring the amount of ionization; the roentgen is the dosage that creates 2.58×10^{-4} C when passing through 1 kg of matter.

Definition of the Roentgen, R

$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$ (X-rays or γ rays in dry air at STP)

SI unit: C/kg

32-7 Practical Applications of Nuclear Physics

Another measure is the amount of energy absorbed by the irradiated material:

Definition of the Rad

1 rad = 0.01 J/kg (any type of radiation)

SI unit: J/kg

However, the same amount of energy of different types of radiation can have different biological effects.

32-7 Practical Applications of Nuclear Physics

In order to quantify these differences, we define the relative biological effectiveness:

Definition of Relative Biological Effectiveness, RBE

$$\text{RBE} = \frac{\text{the dose of 200-keV X-rays necessary to produce a given biological effect}}{\text{the dose of a particular type of radiation necessary to produce the same biological effect}}$$

SI unit: dimensionless

32-7 Practical Applications of Nuclear Physics

The RBE for different types of radiation:

TABLE 32-3

Relative Biological Effectiveness, RBE, for Different Types of Radiation

Type of radiation	RBE
Heavy ions	20
α rays	10–20
Protons	10
Fast neutrons	10
Slow neutrons	4–5
β rays	1.0–1.7
γ rays	1
200-keV X-rays	1

32-7 Practical Applications of Nuclear Physics

This can be combined with the dose to give the biologically equivalent dose, measured in rem (**r**oentgen **e**quivalent in **m**an).

Definition of Roentgen Equivalent in Man, rem

$$\text{dose in rem} = \text{dose in rad} \times \text{RBE}$$

SI unit: J/kg

32-7 Practical Applications of Nuclear Physics

We receive some radiation from natural and manufactured sources every year.

TABLE 32–4 Typical Radiation Dosages

Source of radiation	Radiation dose (rem/y)
Inhaled radon	~0.200
Medical/dental examinations	0.040
Cosmic rays	0.028
Natural radioactivity in the Earth and atmosphere	0.028
Nuclear medicine	0.015

32-7 Practical Applications of Nuclear Physics

There are a number of medical applications for radioactivity:

- Radioactive tracers are useful in diagnoses**
- PET scans (positron-emission tomography) are useful in looking at the brain, including normal activity, abnormalities, and tumors**
- Magnetic resonance imaging (MRI) is particularly good at imaging soft tissue**

32-8 Elementary Particles

All forces of nature are manifestations of just four fundamental forces:

TABLE 32–5 The Fundamental Forces

Force	Relative Strength	Range
Strong	1	≈ 1 fm
Electromagnetic	10^{-2}	Infinite ($\propto 1/r^2$)
Weak	10^{-6}	$\approx 10^{-3}$ fm
Gravitational	10^{-43}	Infinite ($\propto 1/r^2$)

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The only one we have not discussed so far is the weak force; it is the one responsible for beta decay.

32-8 Elementary Particles

There are two kinds of fundamental particles, leptons and hadrons. Leptons interact only via the electromagnetic force (if charged) and the weak force. These are the known leptons:

TABLE 32-6 Leptons

Particle	Particle Symbol	Antiparticle Symbol	Rest Energy (MeV)	Lifetime (s)
Electron	e^- or β^-	e^+ or β^+	0.511	Stable
Muon	μ^-	μ^+	105.7	2.2×10^{-6}
Tau	τ^-	τ^+	1784	10^{-13}
Electron neutrino	ν_e	$\bar{\nu}_e$	≈ 0	Stable
Muon neutrino	ν_μ	$\bar{\nu}_\mu$	≈ 0	Stable
Tau neutrino	ν_τ	$\bar{\nu}_\tau$	≈ 0	Stable

32-8 Elementary Particles

Hadrons are particles that interact strongly. They come in two varieties, baryons and mesons. Protons and neutrons are baryons.

Particle	Particle Symbol	Antiparticle Symbol	Rest Energy (MeV)	Lifetime (s)
BARYONS				
Proton	p	\bar{p}	938.3	Stable
Neutron	n	\bar{n}	939.6	900
Sigma	Σ^+	$\bar{\Sigma}^-$	1189	0.8×10^{-10}
	Σ^0	$\bar{\Sigma}^0$	1192	6×10^{-20}
	Σ^-	$\bar{\Sigma}^+$	1197	1.6×10^{-10}
Omega	Ω^-	Ω^+	1672	0.8×10^{-10}

32-8 Elementary Particles

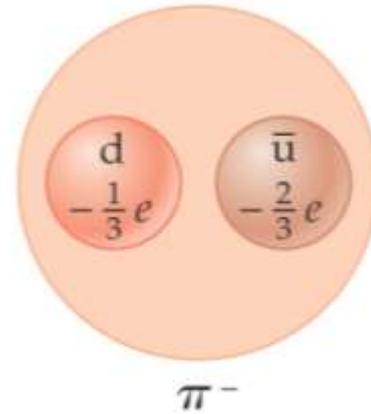
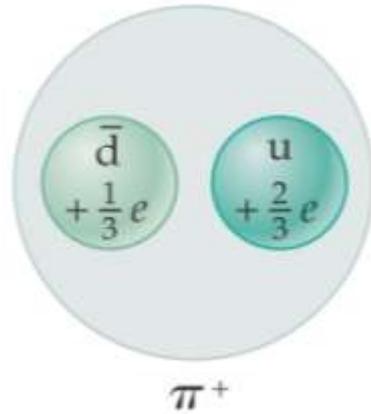
Mesons are created by cosmic rays and in particle accelerators.

Particle	Particle Symbol	Antiparticle Symbol	Rest Energy (MeV)	Lifetime (s)
MESONS				
Pion	π^+	π^-	139.6	2.6×10^{-8}
	π^0	π^0	135.0	0.8×10^{-16}
Kaon	K^+	K^-	493.7	1.2×10^{-8}
	K_S^0	\bar{K}_S^0	497.7	0.9×10^{-10}
	K_L^0	\bar{K}_L^0	497.7	5.2×10^{-8}
Eta	η^0	η^0	548.8	$<10^{-18}$

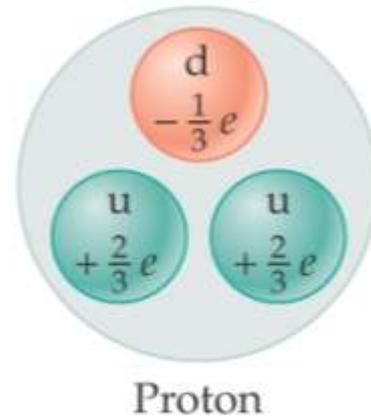
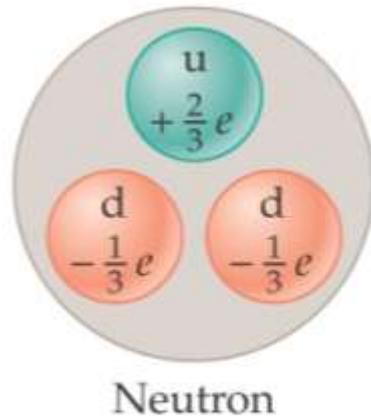
Leptons appear to have no internal structure. The same is not true of hadrons, however.

32-8 Elementary Particles

It is now known that hadrons are made of pointlike particles called quarks. A meson is a quark plus an antiquark; a baryon is three quarks.



Mesons



Baryons

32-8 Elementary Particles

These are the known quarks and antiquarks:

TABLE 32–8 Quarks and Antiquarks

Name	Rest Energy (MeV)	Quarks		Antiquarks	
		Symbol	Charge	Symbol	Charge
Up	360	u	$+\frac{2}{3}e$	\bar{u}	$-\frac{2}{3}e$
Down	360	d	$-\frac{1}{3}e$	\bar{d}	$+\frac{1}{3}e$
Charmed	1500	c	$+\frac{2}{3}e$	\bar{c}	$-\frac{2}{3}e$
Strange	540	s	$-\frac{1}{3}e$	\bar{s}	$+\frac{1}{3}e$
Top	173,000	t	$+\frac{2}{3}e$	\bar{t}	$-\frac{2}{3}e$
Bottom	5000	b	$-\frac{1}{3}e$	\bar{b}	$+\frac{1}{3}e$

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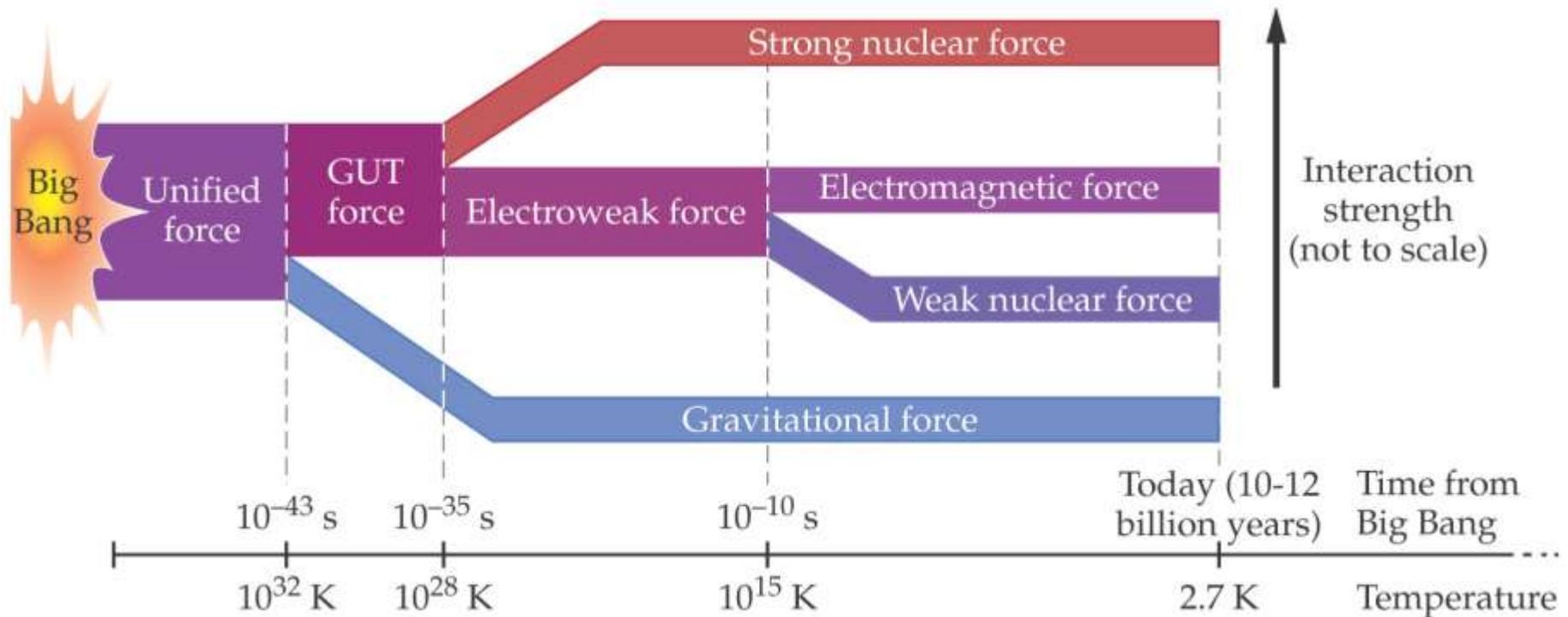
Quarks cannot exist on their own; they are always found as bound states, either baryons or mesons.

32-9 Unified Forces and Cosmology

Shortly after the Big Bang, the energy density of the universe was enormous. All four forces had the same strength, and comprised a single unified force. As the universe expanded and the energy density dropped, the forces “froze out” one by one, until we have the four forces we are familiar with today.

32-9 Unified Forces and Cosmology

This diagram illustrates the transitions since the Big Bang. Exactly how the gravitational force unifies with the other three is not well understood.



Summary of Chapter 32

- Nuclei are composed of protons and neutrons (nucleons).
- Number of protons in a nucleus (atomic number): Z
- Number of neutrons in a nucleus: N
- Mass number $A = N + Z$
- Designation: A_ZX
- Isotopes: same atomic number, different N

Summary of Chapter 32

- **Mass of $^{12}_6\text{C}$ is exactly 12 u.**
- $1 \text{ u} = 1.660540 \times 10^{-27} \text{ kg}$
 $= 931.5 \text{ MeV}/c^2$
- **Nuclear radius:** $r = (1.2 \times 10^{-15} \text{ m})A^{1/3}$
- **Nuclear density is approximately constant**
- **Strong nuclear force holds nuclei together**
- **Radioactivity is the emission from the decay of an unstable or excited nucleus**

Summary of Chapter 32

- An alpha particle (helium nucleus) is two protons and two neutrons.
- Alpha decay: ${}^A_Z X \longrightarrow {}^{A-4}_{Z-2} Y + {}^4_2 \text{He}$
- Beta decay: ${}_0^1 \text{n} \longrightarrow {}_1^1 \text{p} + \text{e}^- + \bar{\nu}$
- Gamma decay occurs when an excited nucleus decays to its ground state.
- Activity is the number of decays per second:

$$1 \text{ curie} = 1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/s}$$

$$1 \text{ becquerel} = 1 \text{ Bq} = 1 \text{ decay/s}$$

Summary of Chapter 32

- **Nuclear decay:** $N = N_0 e^{-\lambda t}$

- **Half-life related to decay constant:**

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

- **Decay rate:**

$$R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$

Summary of Chapter 32

- **The binding energy of a nucleus is the energy that must be supplied to separate it into its component nucleons.**
- **Nuclear fission is the splitting of a heavier nucleus into two or more lighter ones, plus extra neutrons.**
- **These extra neutrons can cause a chain reaction.**
- **Nuclear fusion occurs when two light nuclei join to make a single heavier one.**

Summary of Chapter 32

- There are several ways of measuring radiation dose.
- **Ionization charge:** $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$
- **Energy deposit:** $1 \text{ rad} = 0.01 \text{ J/kg}$
- **Relative biological effectiveness:**

$$\text{RBE} = \frac{\text{the dose of 200-keV X-rays necessary to produce a given biological effect}}{\text{the dose of a particular type of radiation necessary to produce the same biological effect}}$$

Summary of Chapter 32

- **Biological dose:** dose in rem = dose in rad \times RBE
- **There are four fundamental forces in nature: strong nuclear force, electromagnetic force, weak nuclear force, and gravity**
- **Leptons interact only electromagnetically and weakly**
- **Hadrons interact strongly**
- **Hadrons consist of quarks, either a quark-antiquark pair or three quarks**
- **The fundamental forces were unified at the time of the Big Bang**