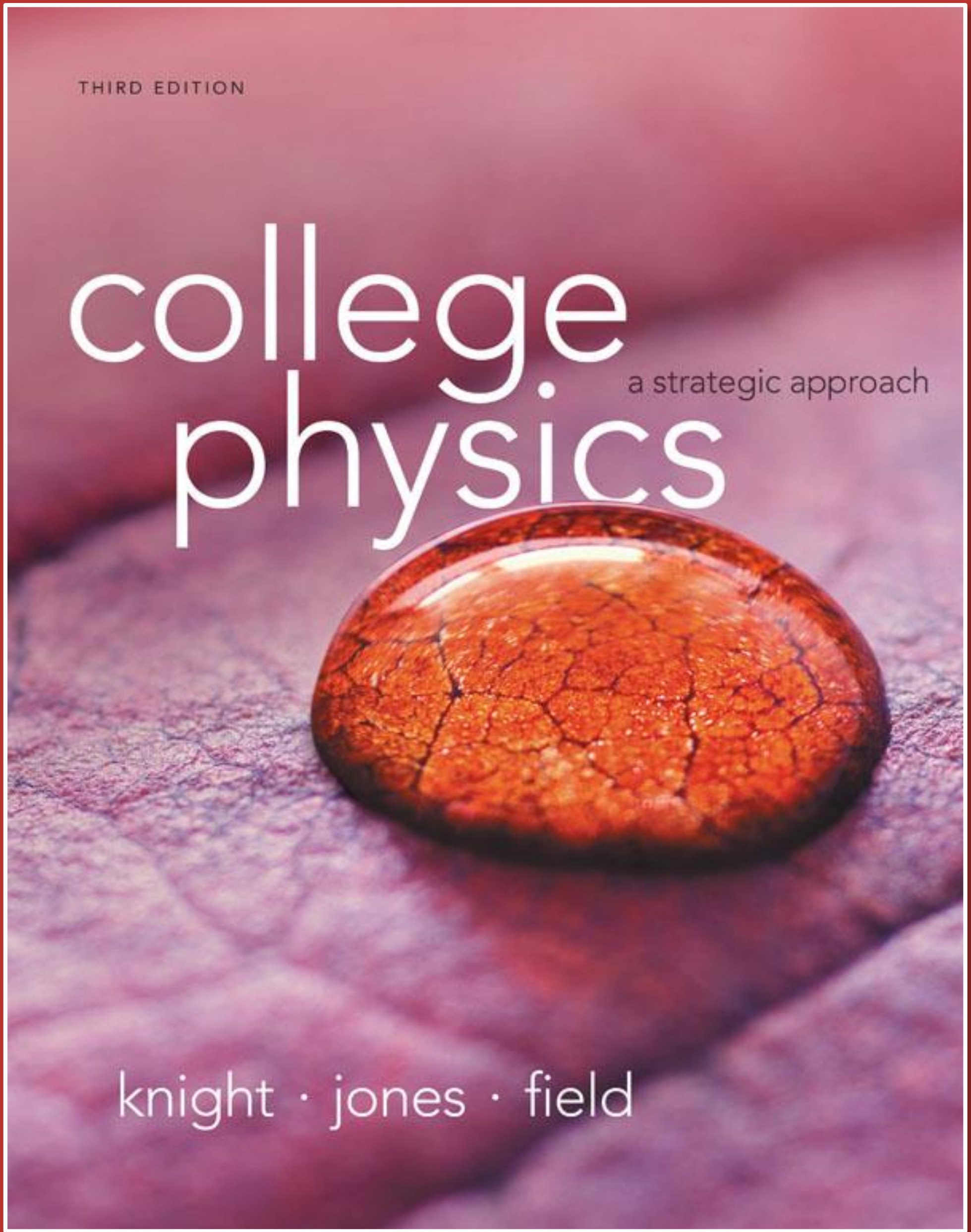


Lecture Presentation

Chapter 30

Nuclear Physics

Suggested Videos for Chapter 30

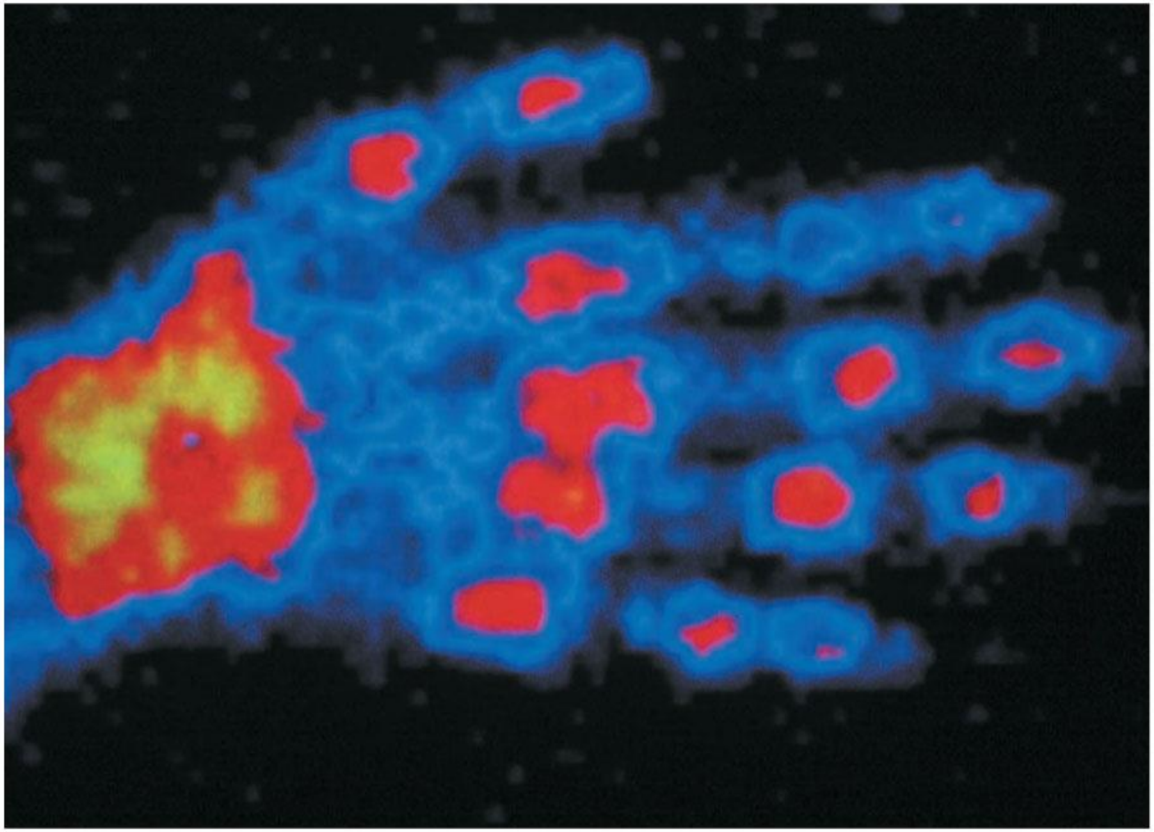
- **Prelecture Videos**
  - *Nuclei, Stability, and Radioactivity*
  - *Radioactive Decay and Half-Lives*
- **Class Videos**
  - *Nuclear Physics Notation*
  - *Radioactive Decay*
  - *Positron Emission Tomography*
- **Video Tutor Solutions**
  - *Nuclear Physics*

Suggested Simulations for Chapter 30

- **ActivPhysics**
  - *19.2–19.5*

- **PhETs**
  - *Alpha Decay*
  - *Beta Decay*
  - *Radioactive Dating Game*

Chapter 30 Nuclear Physics



Chapter Goal: To understand the physics of the nucleus and some of the applications of nuclear physics.

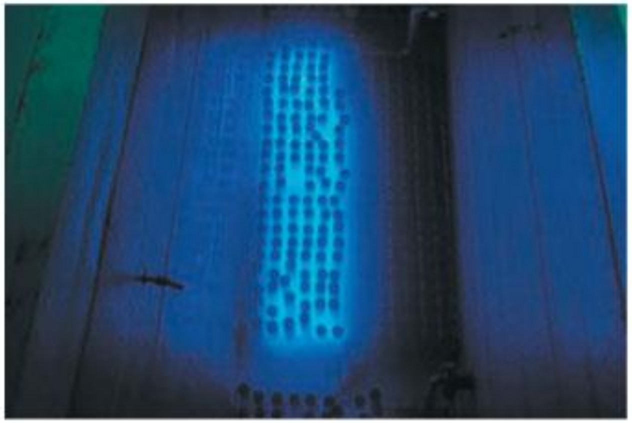
Chapter 30 Preview
Looking Ahead: Nuclei and Isotopes

- The ratio of two stable **isotopes** of oxygen in artic ice gives us a record of past temperatures.

- You'll learn about nuclear structure. The number of protons determines the element; the number of neutrons, the isotope.

Chapter 30 Preview
Looking Ahead: Radioactivity and Radiation

- These **radioactive** nuclei in this tank are unstable. They decay, emitting high-energy particles—**radiation**—that ionize the water.



- You'll learn about different nuclear decay models (alpha, beta, and gamma) and the resulting radiation for each.

Chapter 30 Preview
Looking Ahead: Decay and Half-Life

- Measurements of carbon isotopes in these cave drawings show that they are 30,000 years old.

- In any sample of ^{14}C, half the nuclei decay in 5700 years. You'll see how to use this half-life to calculate an object's age.

Chapter 30 Preview
Looking Ahead

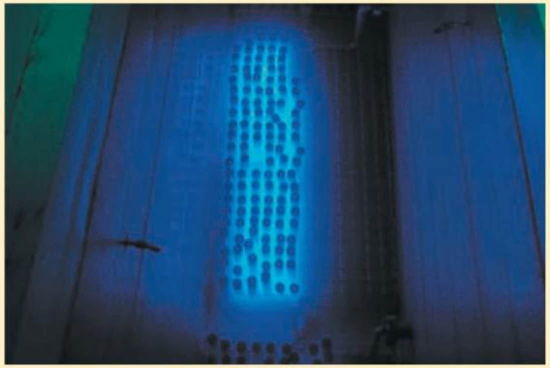
Nuclei and Isotopes

The ratio of two stable **isotopes** of oxygen in arctic ice gives us a record of past temperatures.

You'll learn about nuclear structure. The number of protons determines the element; the number of neutrons, the isotope.

Radioactivity and Radiation

These **radioactive** nuclei in this tank are unstable. They decay, emitting high-energy particles—**radiation**—that ionize the water.



You'll learn about different nuclear decay modes (alpha, beta, and gamma) and the resulting radiation for each.

Decay and Half-Life

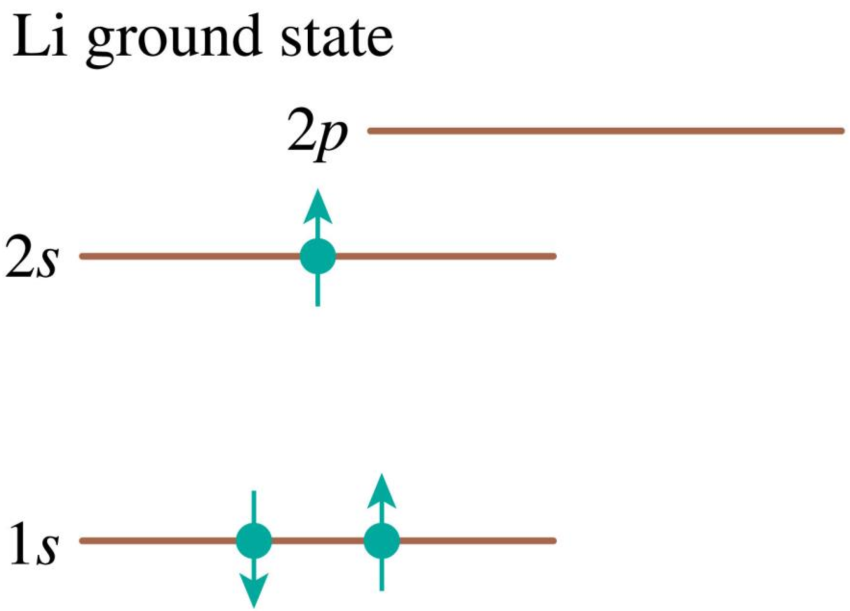
Measurements of carbon isotopes in these cave drawings show that they are 30,000 years old.

In any sample of ^{14}C, half the nuclei decay in 5700 years. You'll see how to use this half-life to calculate an object's age.

Text: p. 975

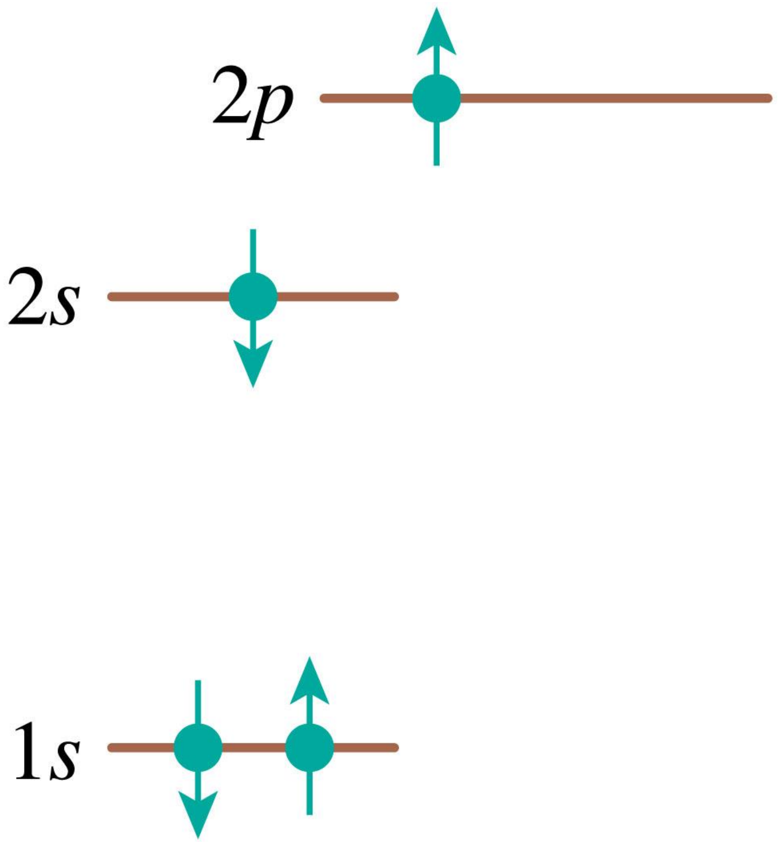
Chapter 30 Preview
Looking Back: Energy levels in atoms

- In Chapter 29, you learned how the periodic table of the elements is based on the energy levels of multielectron atoms.
- The protons and neutrons in nuclei also have energy levels. Understanding these energy levels will allow you to understand nuclear decay modes.



Chapter 30 Preview
Stop to Think

This energy-level diagram represents an atom with four electrons. What element is this? And is this the ground state of the atom or an excited state?



A. Lithium, ground state
B. Lithium, excited state
C. Beryllium, ground state
D. Beryllium, excited state
E. Boron, ground state
F. Boron, excited state

Reading Question 30.1

The mass of an atom, measured in atomic mass units, is

A. Exactly equal to the atomic mass number A.
B. Always slightly more than the atomic mass number A.
C. Always slightly less than the atomic mass number A.
D. Always very close to the atomic mass number A but could be a little more or a little less.

Reading Question 30.1

The mass of an atom, measured in atomic mass units, is

A. Exactly equal to the atomic mass number A.
B. Always slightly more than the atomic mass number A.
C. Always slightly less than the atomic mass number A.
✔ D. Always very close to the atomic mass number A but could be a little more or a little less.

Reading Question 30.2

MeV/c^2 is a unit of

A. Energy.
B. Momentum.
C. Mass.
D. Acceleration.

Reading Question 30.2

MeV/c^2 is a unit of

A. Energy.

B. Momentum.

✔ C. Mass.

D. Acceleration.

Reading Question 30.3

The binding energy of a nucleus is the amount of energy needed to

A. Remove a proton from the nucleus.
B. Remove a neutron from the nucleus.
C. Disassemble the nucleus.
D. Fragment the nucleus.
E. Fuse or join two of the nuclei together.

Reading Question 30.3

The binding energy of a nucleus is the amount of energy needed to

A. Remove a proton from the nucleus.
B. Remove a neutron from the nucleus.
✔ C. Disassemble the nucleus.
D. Fragment the nucleus.
E. Fuse or join two of the nuclei together.

Reading Question 30.4

For two nucleons 2 fm apart, the strong force is

A. Strongest for two interacting protons.
B. Strongest for two interacting neutrons.
C. Strongest for a proton interacting with a neutron.
D. Equally strong for any combination of protons and neutrons.

Reading Question 30.4

For two nucleons 2 fm apart, the strong force is

A. Strongest for two interacting protons.
B. Strongest for two interacting neutrons.
C. Strongest for a proton interacting with a neutron.
✔ D. Equally strong for any combination of protons and neutrons.

Reading Question 30.5

What is the decay mode of the following decay?

$$^{137}\text{Cs} \rightarrow {}^{137}\text{Ba} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

Reading Question 30.5

What is the decay mode of the following decay?

$$^{137}\text{Cs} \rightarrow {}^{137}\text{Ba} + ?$$

A. Alpha decay

✔ B. Beta-minus decay

C. Beta-plus decay

D. Gamma decay

Reading Question 30.6

What is the decay mode of the following decay?

$$^{222}\text{Rn} \rightarrow {}^{218}\text{Po} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

Reading Question 30.6

What is the decay mode of the following decay?

$$^{222}\text{Rn} \rightarrow {}^{218}\text{Po} + ?$$

✔ A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

Reading Question 30.7

What is the decay mode of the following decay ?

$$^{60}\text{Ni}^* \rightarrow {}^{60}\text{Ni} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

Reading Question 30.7

What is the decay mode of the following decay ?

$$^{60}\text{Ni}^* \rightarrow {}^{60}\text{Ni} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
✔ D. Gamma decay

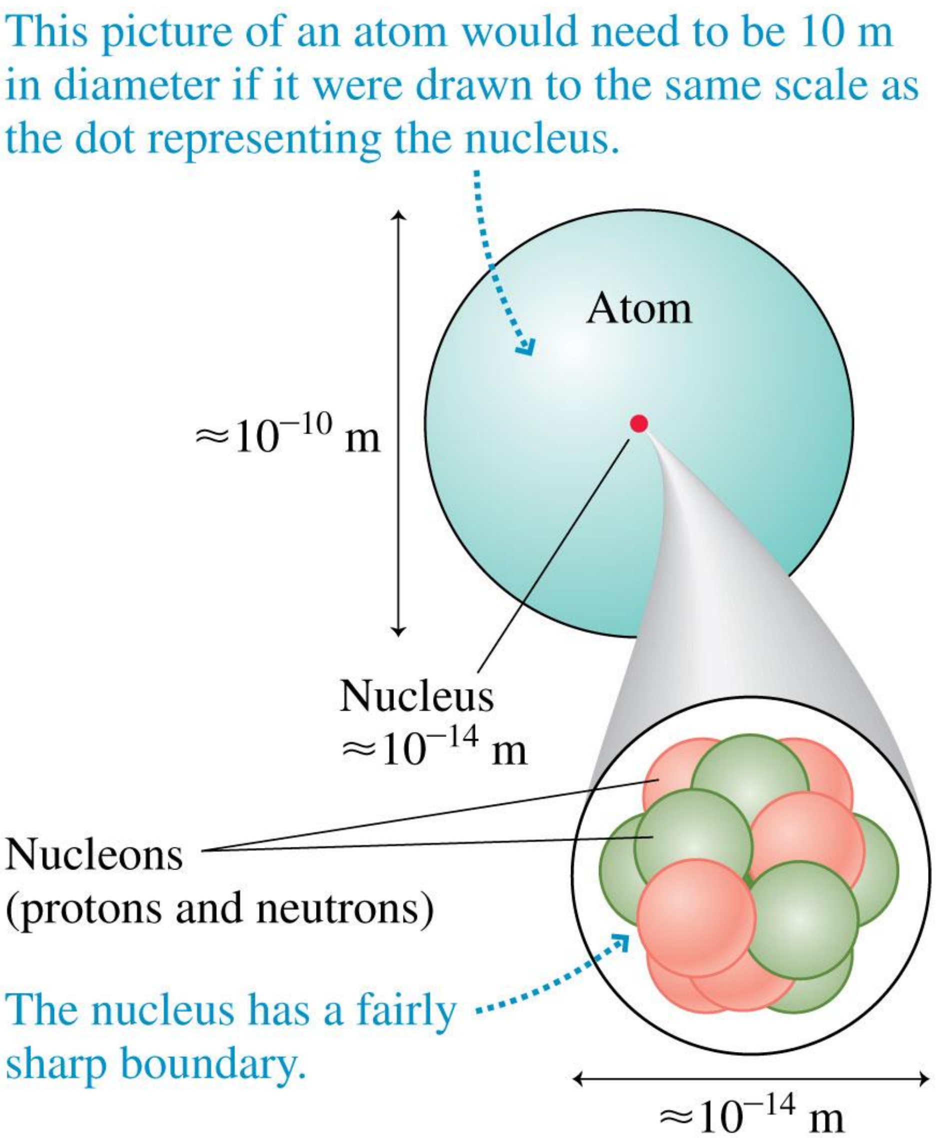
Section 30.1 Nuclear Structure

Nuclear Structure

- **Nuclear physics** explores the following questions:
  - What is nuclear matter? What are its properties?
  - What holds the nucleus together? Why doesn't the electrostatic force blow it apart?
  - What is the connection between the nucleus and radioactivity?

Nuclear Structure

- The nucleus is composed of protons and neutrons. Together they are referred to as nucleons.



Nuclear Structure

TABLE 30.1 Protons and neutrons

	Proton	Neutron
Number	Z	N
Charge q	$+e$	0
Mass, in u	1.00728	1.00866

Isotopes

- There is a *range* of neutron numbers that can form a nucleus with Z protons, creating a series of nuclei having the same Z-value (so they are the same chemical element) but with a different mass number A.
- Each A-value in a series of nuclei with the same Z-value is called an *isotope*.

Isotopes

The leading superscript gives the total number of nucleons, which is the mass number *A*.

$^{12}_{6}\text{C}$ $^{13}_{6}\text{C}$ $^{14}_{6}\text{C}$

The leading subscript (if included) gives the number of protons.

The three nuclei all have the same number of protons, so they are isotopes of the same element, carbon.

Isotopes

- **Deuterium** is the isotope form of hydrogen; its nucleus has a proton and a neutron.
- For each element, the fraction of naturally occurring nuclei represented by one particular isotope is called the **natural abundance** of that isotope.
- More than 3,000 isotopes are known. The majority of these are **radioactive**, meaning that the nucleus is not stable and, after some period of time, will fragment or emit a subatomic particle to reach a more stable state.
- Only 266 isotopes are **stable** and occur in nature.

Atomic Mass

- The atomic masses are specified in terms of the *atomic mass unit* u, defined such that the atomic mass of isotope ^{12}C is exactly 12 u.
- $1\ \text{u} = 1.6605 \times 10^{-27}\ \text{kg}$
- The energy equivalent of 1 u of mass is

$$E_0 = (1.6605 \times 10^{-27}\ \text{kg})(2.9979 \times 10^8\ \text{m/s})^2$$

$$= 1.4924 \times 10^{-10}\ \text{J} = 931.49\ \text{MeV}$$

- To find the energy equivalent of any atom or particle whose mass is given in atomic mass units we can use

$$E_0\ (\text{in MeV}) = m(\text{in u}) \times (931.49\ \text{MeV/u})$$

Atomic Mass

- We can write 1 u in the following form as well:

$$1\ \text{u} = \frac{E_0}{c^2} = 931.49\left(\frac{\text{MeV}}{c^2}\right)$$

- MeV/c^2 are units of mass. The energy equivalent of 1 MeV/c^2 is 1 MeV.

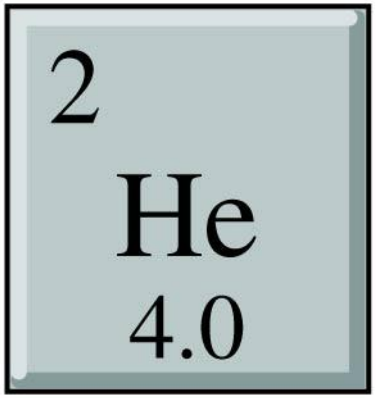
Atomic Mass

- The mass of a hydrogen atom is equal to the sum of the masses of a proton and an electron.
- The mass of a helium atom is *less* than the sum of the masses of its protons, neutrons, and electrons due to the *binding energy* of the nucleus.
- The *chemical* atomic mass shown on the periodic table is the *weighted average* of the atomic masses of all naturally occurring isotopes.

QuickCheck 30.1

The isotope ^{3}He has ___ neutrons.

A. 0
B. 1
C. 2
D. 3
E. 4



QuickCheck 30.1

The isotope ^{3}He has ___ neutrons.

He is the second element with 2 protons.

3 nucleons

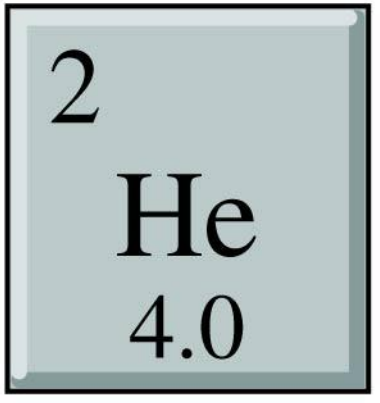
A. 0

B. 1

C. 2

D. 3

E. 4



QuickCheck 30.2

How many neutrons are in each of the following isotopes? (Some of these are uncommon or unstable.)

$$^{11}_{3}\text{Li},\ ^{11}_{4}\text{Be},\ ^{11}_{5}\text{B},\ ^{11}_{6}\text{C}$$

A. 8
B. 7
C. 6
D. 5
E. 4

QuickCheck 30.2

How many neutrons are in each of the following isotopes? (Some of these are uncommon or unstable.)

$$^{11}_{3}\text{Li},\ ^{11}_{4}\text{Be},\ ^{11}_{5}\text{B},\ ^{11}_{6}\text{C}$$

A. 8
B. 7
C. 6
D. 5
E. 4

The number of neutrons is given by A–Z, so:

$^{11}_{3}\text{Li}$: 8 neutrons

$^{11}_{4}\text{Be}$: 7 neutrons

$^{11}_{5}\text{B}$: 6 neutrons

$^{11}_{6}\text{C}$: 5 neutrons

QuickCheck 30.7

Boron, with atomic number $Z = 5$, has two stable isotopes, with atomic mass numbers $A = 10$ and $A = 11$. Boron's chemical atomic mass is 10.81. What are the approximate fractions of the two stable boron isotopes found in nature?

A. 92% ^{11}B, 8% ^{10}B
B. 80% ^{11}B, 20% ^{10}B
C. 50% ^{11}B, 50% ^{10}B
D. 20% ^{11}B, 80% ^{10}B
E. 8% ^{11}B, 92% ^{10}B

QuickCheck 30.7

Boron, with atomic number $Z = 5$, has two stable isotopes, with atomic mass numbers $A = 10$ and $A = 11$. Boron's chemical atomic mass is 10.81. What are the approximate fractions of the two stable boron isotopes found in nature?

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✔ B. 80% ^{11}B, 20% ^{10}B
C. 50% ^{11}B, 50% ^{10}B
D. 20% ^{11}B, 80% ^{10}B
E. 8% ^{11}B, 92% ^{10}B

Example Problem

Magnesium has three stable isotopes, with the following natural abundances:

79% of naturally occurring magnesium is 24 Mg, with u = 23.99.

10% of naturally occurring magnesium is 25 Mg, with u = 24.99.

11% of naturally occurring magnesium is 26 Mg, with u = 25.98.

What is the chemical atomic mass of magnesium?

Example Problem

There are several elements for which there is only one stable isotope, or for which one stable isotope dominates the natural abundance. Three examples are:

All but 0.00013% of naturally occurring helium is the stable isotope ^{4}He.

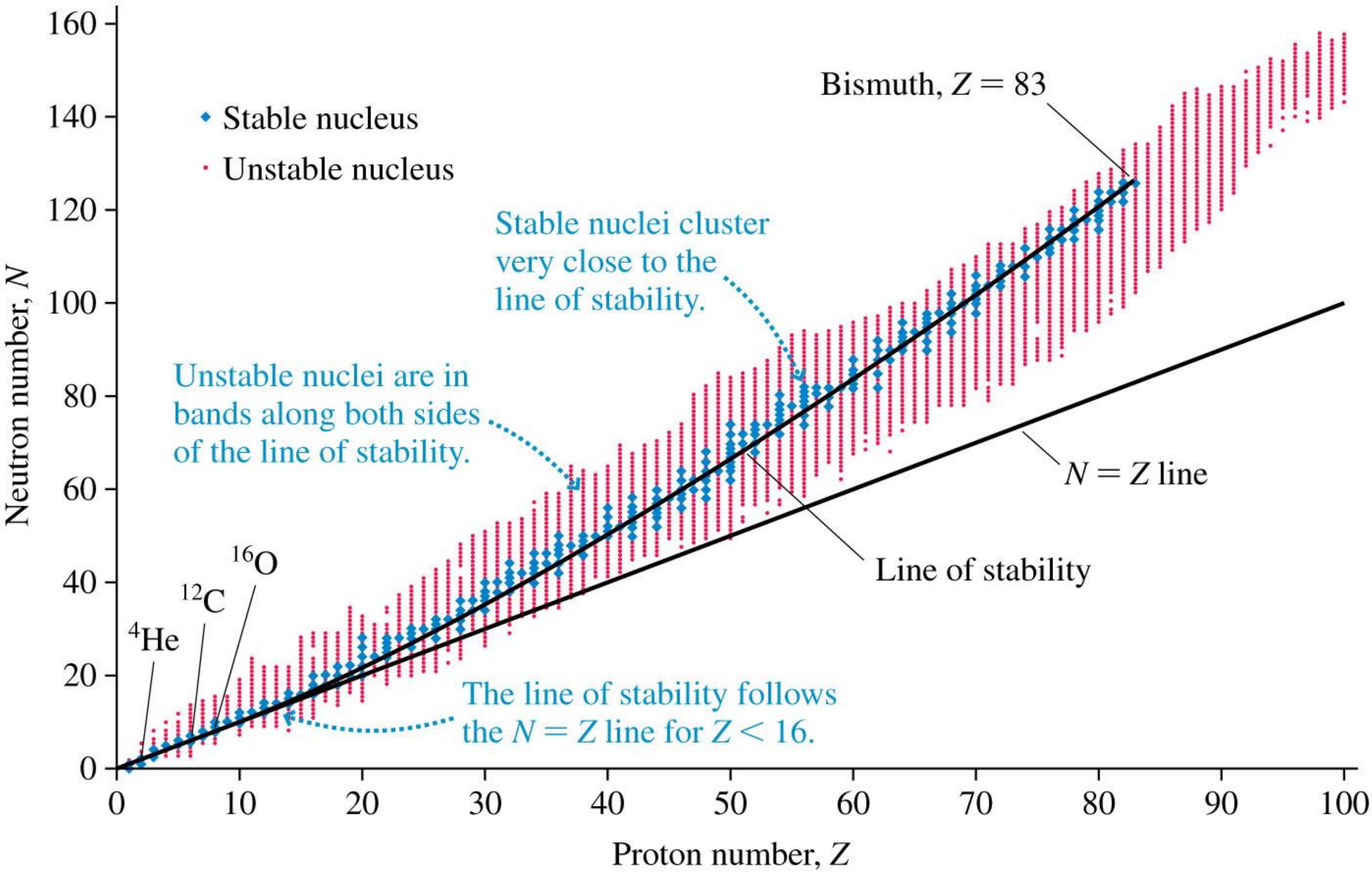
100% of naturally occurring niobium is the stable isotope ^{93}Nb.

100% of naturally occurring bismuth is the stable isotope ^{209}Bi.

What is the ratio of neutrons to protons for these three isotopes?

Section 30.2 Nuclear Stability

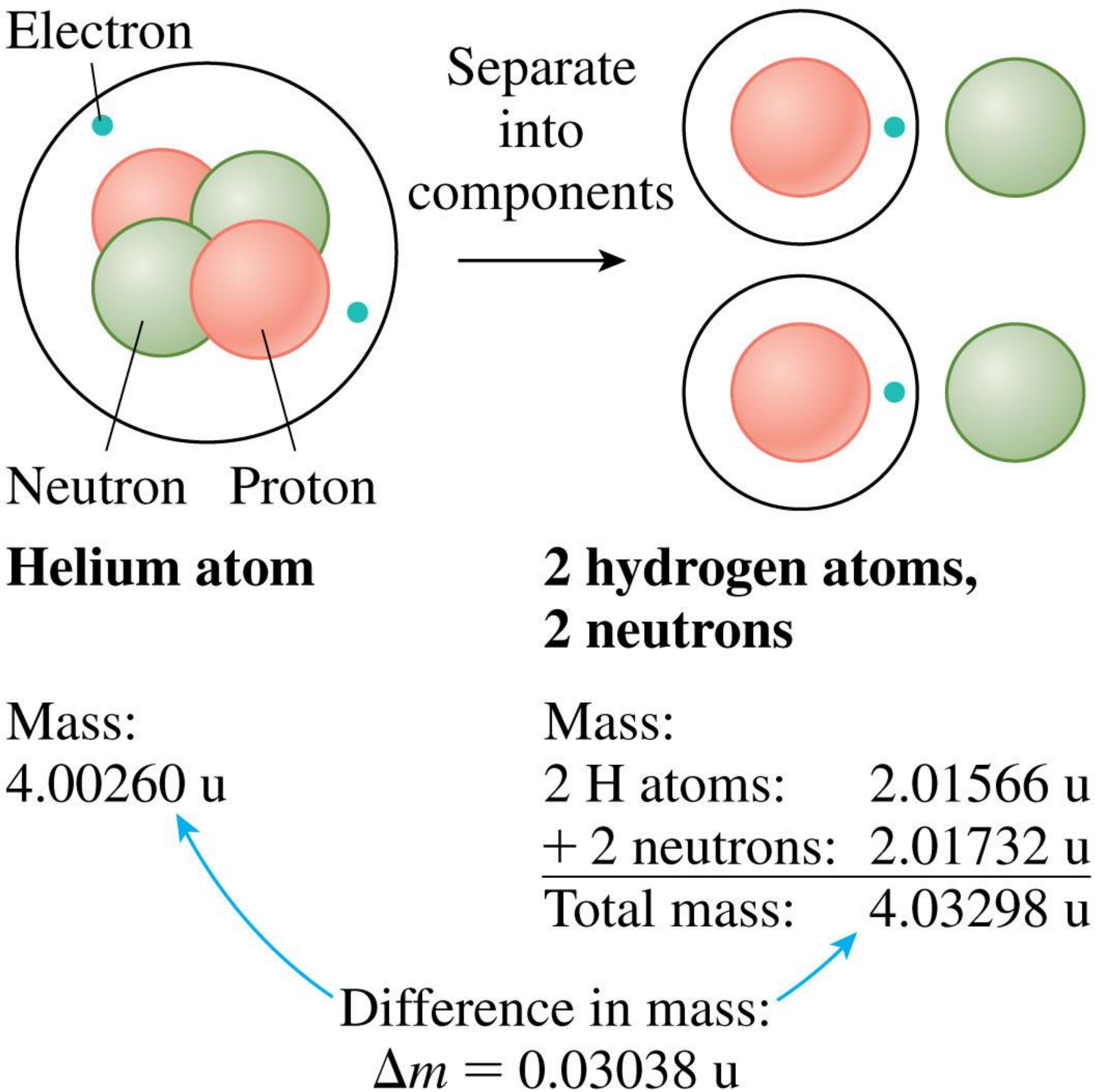
Nuclear Stability



Nuclear Stability

- Graphically, the stable nuclei cluster very close to the **line of stability**.
- There are no stable nuclei with $Z > 83$ (bismuth). Heavier elements (up to $Z = 92$, uranium) are found in nature but they are radioactive.
- Unstable nuclei are in the bands along both sides of the line of stability.
- The lightest elements with $Z < 16$ are stable when $N \approx Z$.
- As Z increases, the number of neutrons needed for stability grows increasingly larger than the number of protons.

Binding Energy



Binding Energy

- The nuclear binding energy is computed by considering the mass difference between the atom and its separate components, Z hydrogen atoms and N neutrons:

$$B = (Zm_{\text{H}} + Nm_{\text{n}} - m_{\text{atom}}) \times (931.49\ \text{MeV/u})$$

Nuclear binding energy for an atom of mass m_{atom} with Z protons and N neutrons

Example 30.1 Finding the binding energy of iron

What is the nuclear binding energy of ^{56}Fe to the nearest MeV?

PREPARE Appendix D gives the atomic mass of ^{56}Fe as 55.934940 u. Iron has atomic number 26, so an atom of ^{56}Fe could be separated into 26 hydrogen atoms and 30 neutrons. The mass of the separated components is more than that of the iron nucleus; the difference gives us the binding energy.

Example 30.1 Finding the binding energy of iron (cont.)

SOLVE We solve for the binding energy using Equation 30.4. The masses of the hydrogen atom and the neutron are given in Table 30.2. We find

$$B = (26(1.007825\ \text{u}) + 30(1.008665\ \text{u}) - 55.934940\ \text{u})(931.49\ \text{MeV/u})$$
$$= (0.52846\ \text{u})(931.49\ \text{MeV/u}) = 492.26\ \text{MeV} \simeq 492\ \text{MeV}$$

Example 30.1 Finding the binding energy of iron (cont.)

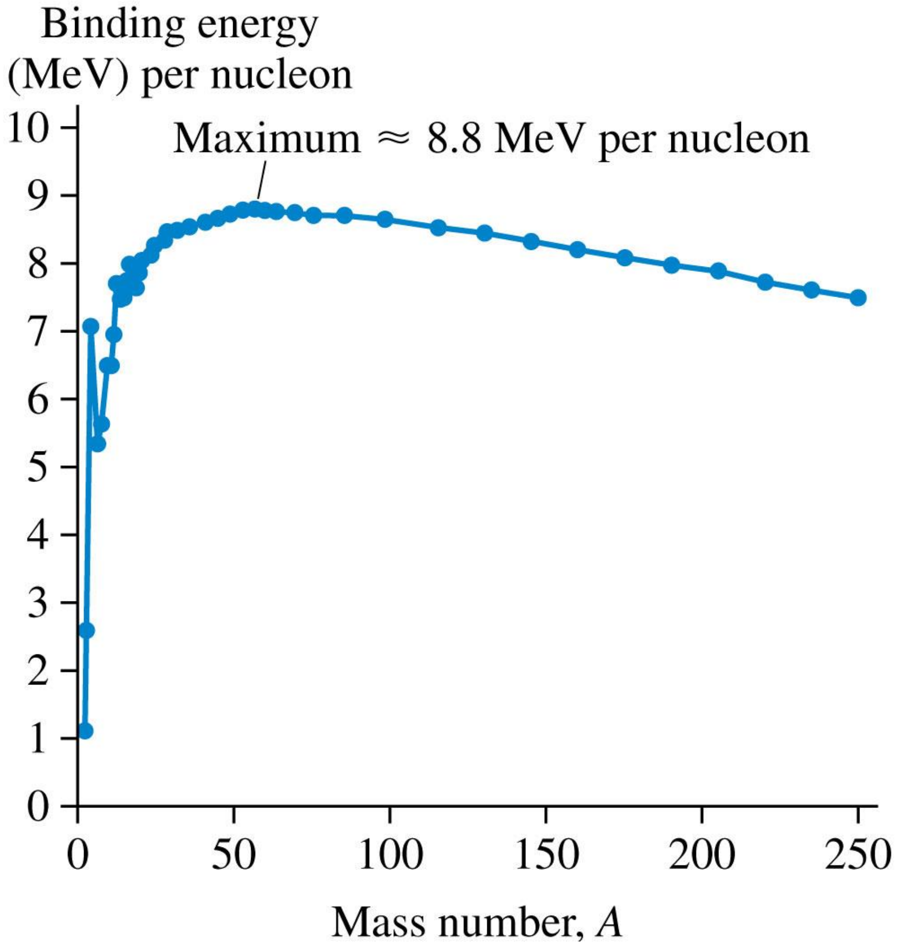
ASSESS The difference in mass between the nucleus and its components is a small fraction of the mass of the nucleus, so we must use several significant figures in our mass values. The mass difference is small—about half that of a proton—but the energy equivalent, the binding energy, is enormous.

Binding Energy

- As A increases, the nuclear binding energy increases because there are more nuclear bonds.
- A useful measure for comparing one nucleus to another is the quantity B/A called the *binding energy per nucleon*.

Binding Energy

- The line connecting the points on this graph is called the **curve of binding energy**



Binding Energy

- If two light nuclei can be joined together to make a single, larger nucleus, the final nucleus will have a higher binding energy per nucleon.
- Because the final nucleus is more tightly bound, energy will be released in this *nuclear fusion* process.
- Nuclear fusion of hydrogen to helium is the basic reaction that powers the sun.

Binding Energy

- Nuclei with $A > 60$ become less stable as their mass increases because adding nucleons *decreases* the binding energy per nucleon.
- *Alpha decay* is a basic type of radioactive decay that occurs when a heavy nucleus becomes more stable by ejecting a small group of nucleons in order to decrease its mass, releasing energy in the process.
- *Nuclear fission* is when very heavy nuclei are so unstable that they can be induced to fragment into two lighter nuclei.

Binding Energy

- The collision of a slow-moving neutron with a ^{235}U nucleus causes the reaction

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow {}^{90}Sr + {}^{144}Xe + 2n$$

- ^{236}U is so unstable that it immediately fragments, in this case into two nuclei and two neutrons. A great deal of energy is released in this reaction.

Example Problem

^{16}O, with u = 15.994915, is stable; ^{19}O, with u = 19.003577, is not. What is the binding energy per nucleon for each of these nuclei?

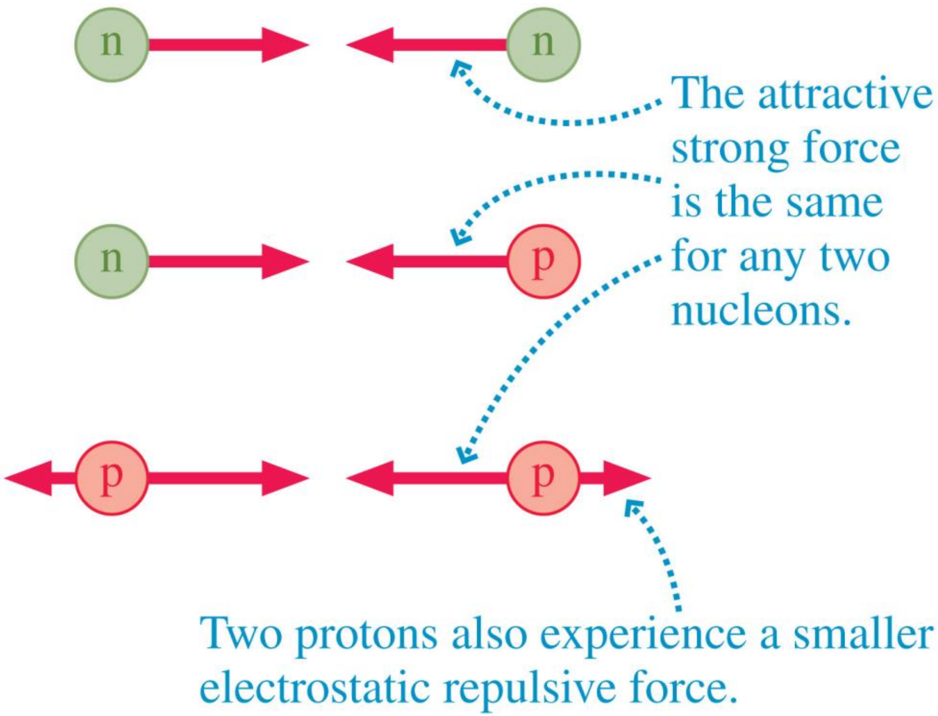
Section 30.3 Forces and Energy in the Nucleus

Forces and Energy in the Nucleus

- The **strong nuclear force** is the force that keeps the nucleus together.
  1. It is an *attractive* force between any two nucleons.
  2. It does not act on electrons.
  3. It is a *short-range* force, acting only over nuclear distances. We see no evidence for the nuclear forces outside the nucleus.
  4. Over the range where it acts, it is *stronger* than the electrostatic force that tries to push two protons apart.

Forces and Energy in the Nucleus

- A nucleus with too many protons will be unstable because the repulsive electrostatic forces will overcome the attractive strong forces.
- Because neutrons participate in the strong force but exert no repulsive forces, **the neutrons provide the extra "glue" that holds the nucleus together.**



Forces and Energy in the Nucleus

- In small nuclei, one neutron per proton is sufficient for stability, so small nuclei have $N \approx Z$.
- As the nucleus grows, the repulsive force increases faster than the binding energy, so more neutrons are needed for stability.

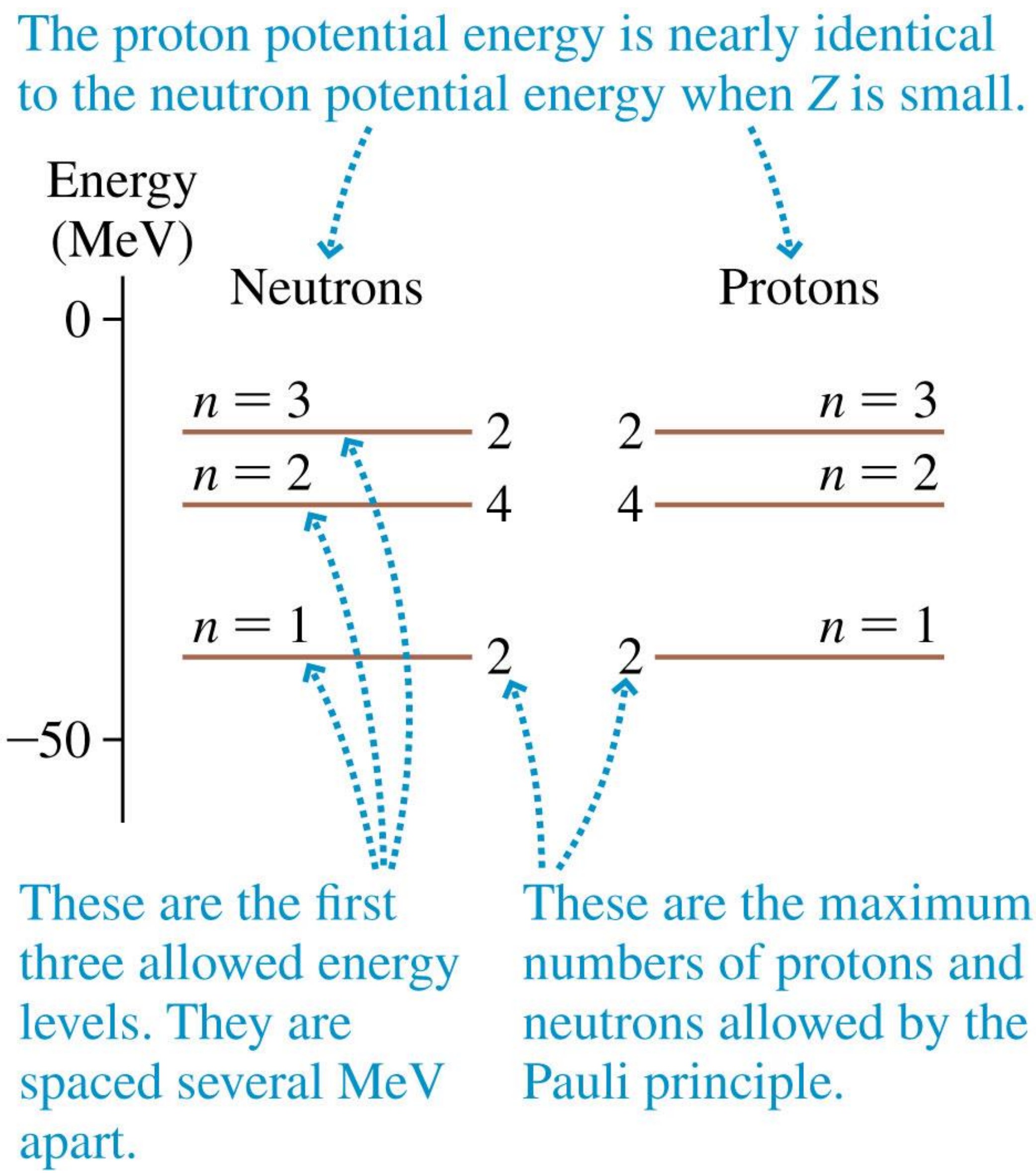
Forces and Energy in the Nucleus

- Protons and neutrons have quantized energy levels like electrons. They have spin and follow the Pauli exclusion principle.
- The proton and neutron energy levels are separated by a million times more energy than the energy separation of electron energy levels.

Low-*Z* Nuclei

- Low-*Z* nuclei ($Z < 8$) have few protons, so we can neglect the electrostatic potential energy due to proton-proton repulsion.
- In this case, the energy levels of protons and neutrons are essentially identical.

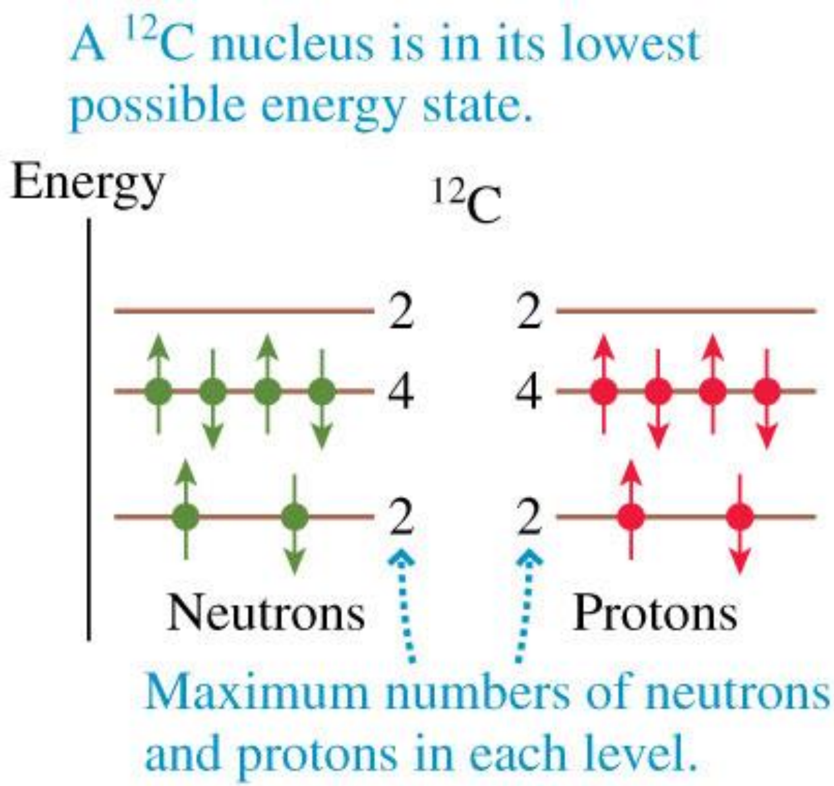
Low-*Z* Nuclei



The proton potential energy is nearly identical to the neutron potential energy when Z is small.
Energy (MeV)
0
−50
Neutrons
Protons
n = 3
n = 2
n = 1
2
4
2
2
4
2
n = 3
n = 2
n = 1
These are the first three allowed energy levels. They are spaced several MeV apart.
These are the maximum numbers of protons and neutrons allowed by the Pauli principle.

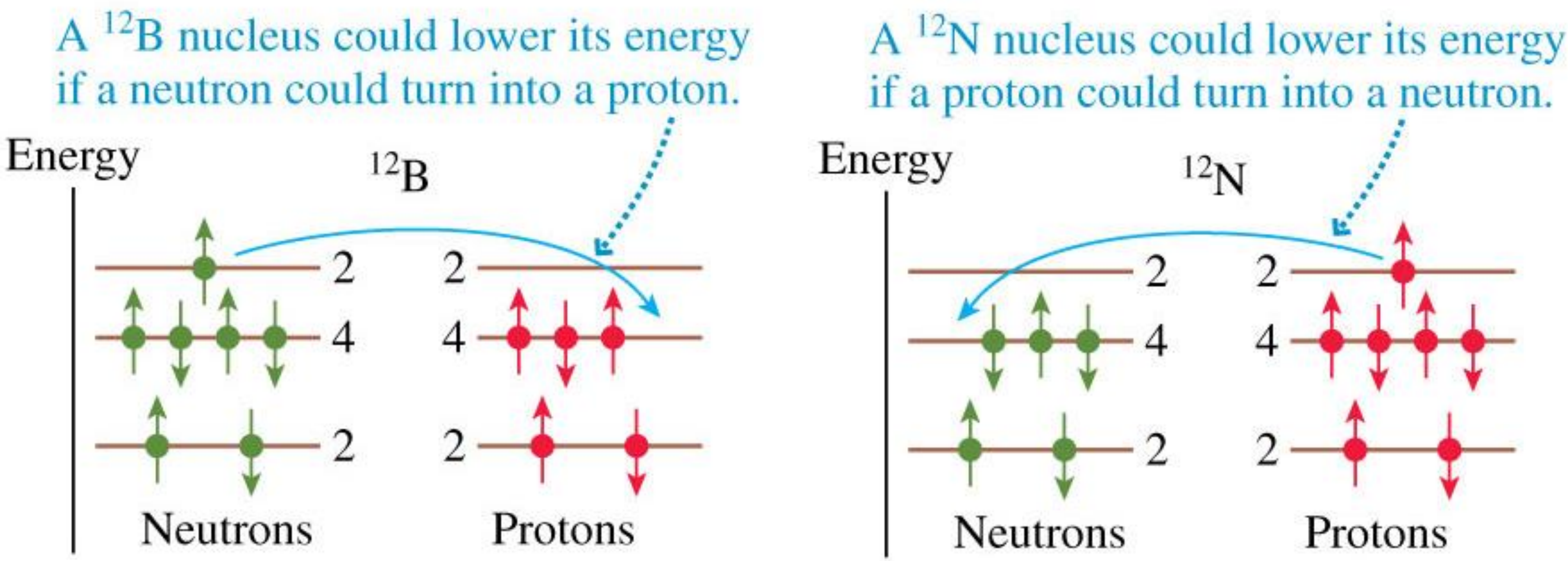
Low-*Z* Nuclei

- The nuclear energy-level diagram of ^{12}C, which has 6 protons and 6 neutrons, shows that it is in its lowest possible energy state



Low-Z Nuclei

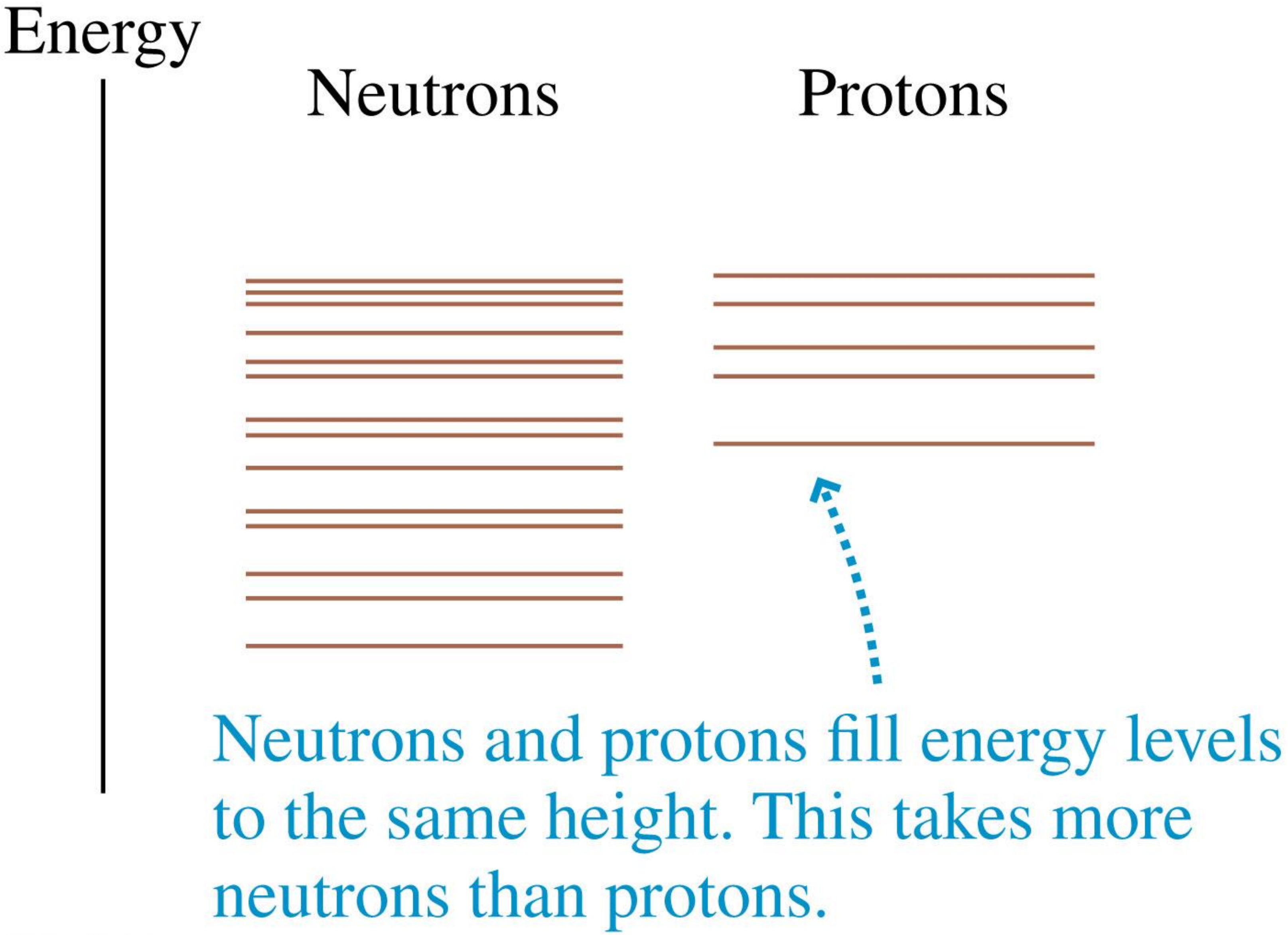
- ^{12}B and ^{12}N could lower their energies in a process known as *beta decay*—where a proton turns into a neutron or vice versa.



High-Z Nuclei

- In a nucleus with many protons, the increasing electrostatic potential energy raises the proton energy levels but not the neutron energy levels.
- If there were neutrons in energy levels above vacant proton levels, the nucleus would lower its energy by changing neutrons into protons, and vice versa.
- **The net result is that the filled levels for protons and neutrons are at just about the same height.**
- Because neutron energy levels start at a lower energy, *more neutron states* are available.

High-Z Nuclei



Section 30.4 Radiation and Radioactivity

Alpha Decay

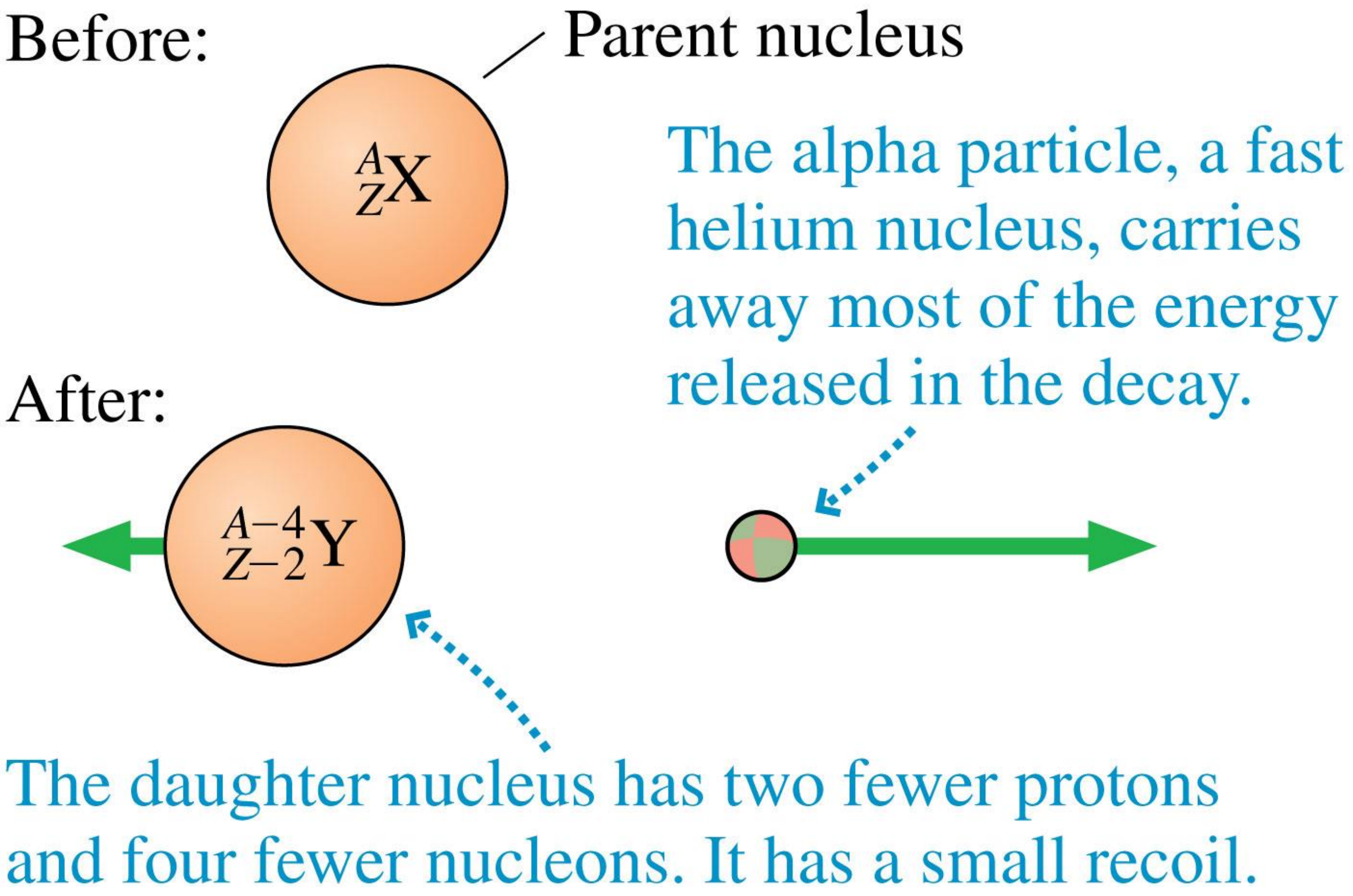
- When a large nucleus spontaneously decays by breaking into two smaller fragments, one of the fragments is almost always a stable ^{4}He nucleus—an alpha particle. An alpha particle is symbolized by α.
- An unstable nucleus that ejects an alpha particle loses two protons and two neutrons, so we write the decay as

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + \alpha + \text{energy}$$

Alpha decay of a nucleus

Alpha Decay

- The original nucleus X is called the **parent nucleus** and the decay-product nucleus Y is the **daughter nucleus.**



Alpha Decay

- The daughter nucleus, which is much more massive than an alpha particle, undergoes a slight recoil, so **the energy released in an alpha decay ends up mostly as the kinetic energy of the alpha particle**.

$$K_\alpha \approx \Delta E = (m_{\mathrm{X}} - m_{\mathrm{Y}} - m_{\mathrm{He}})c^2$$

Example 30.2 Analyzing alpha decay in a smoke detector

Americium, atomic number 95, doesn't exist in nature; it is produced in nuclear reactors. An isotope of americium, ^{241}Am, is part of the sensing circuit in most smoke detectors. ^{241}Am decays by emitting an alpha particle. What is the daughter nucleus?

Example 30.2 Analyzing alpha decay in a smoke detector (cont.)

SOLVE Equation 30.6 shows that an alpha decay causes the atomic number to decrease by 2 and the atomic weight by 4. Let's write an equation for the decay showing the alpha particle as a helium nucleus, including the atomic weight superscript and the atomic number subscript for each element.

Example 30.2 Analyzing alpha decay in a smoke detector (cont.)

There is no change in the total number of neutrons or protons, so the subscripts and superscripts must “balance” in the reaction:

$$^{241}_{95}\text{Am} \longrightarrow {}^{237}_{93}? + {}^{4}_{2}\text{He} + \text{energy}$$

A quick glance at the periodic table reveals the unknown element in this equation, the daughter nucleus, to be an isotope of neptunium, $^{237}_{93}\text{Np}$.

Example 30.2 Analyzing alpha decay in a smoke detector (cont.)

ASSESS Balancing the two sides of the above reaction is similar to balancing the equation for a chemical reaction.

Beta Decay

- In beta decay, a nucleus decays by emitting an electron.
- The neutron changes itself into a proton by emitting an electron:

$$n \rightarrow p + e^-$$

- The electron is ejected from the nucleus but the proton is not. The beta-decay process is

$${}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + e^- + \text{energy}$$

Beta-minus decay of a nucleus

- **Beta decay occurs only if** $m_X > m_Y$.

Beta Decay

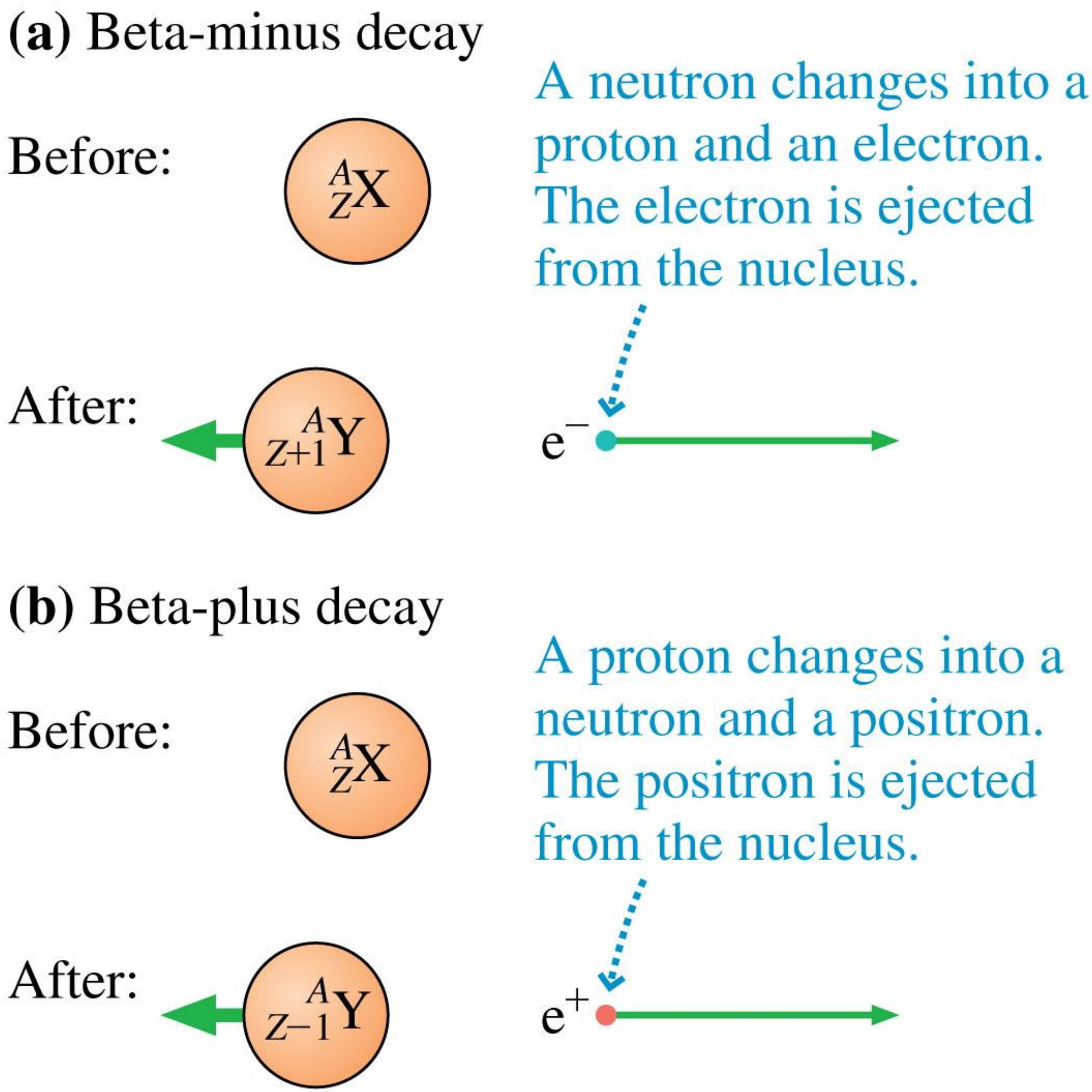
- Some nuclei emit a *positron*. A positron, e^+, is identical to an electron except that it has a positive charge. It is the *antiparticle* of the electron.
- To distinguish between the two forms of beta decay, we call the emission of an electron *beta-minus decay* and the emission of a positron *beta-plus decay*.

$$p^+ \rightarrow n + e^+$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \text{energy}$$

Beta-plus decay of a nucleus

Beta Decay


(a) Beta-minus decay
Before:
$^{A}_{Z}X$
After:
$^{A}_{Z+1}Y$
A neutron changes into a proton and an electron. The electron is ejected from the nucleus.
e^-
(b) Beta-plus decay
Before:
$^{A}_{Z}X$
After:
$^{A}_{Z-1}Y$
A proton changes into a neutron and a positron. The positron is ejected from the nucleus.
e^+

Example 30.4 Analyzing beta decay in the human body

Your body contains several radioactive isotopes. Approximately 20% of the radiation dose you receive each year comes from the radioactive decay of these atoms. Most of this dose comes from one potassium isotope, ^{40}K, which most commonly decays by beta-minus emission. What is the daughter nucleus?

Example 30.4 Analyzing beta decay in the human body

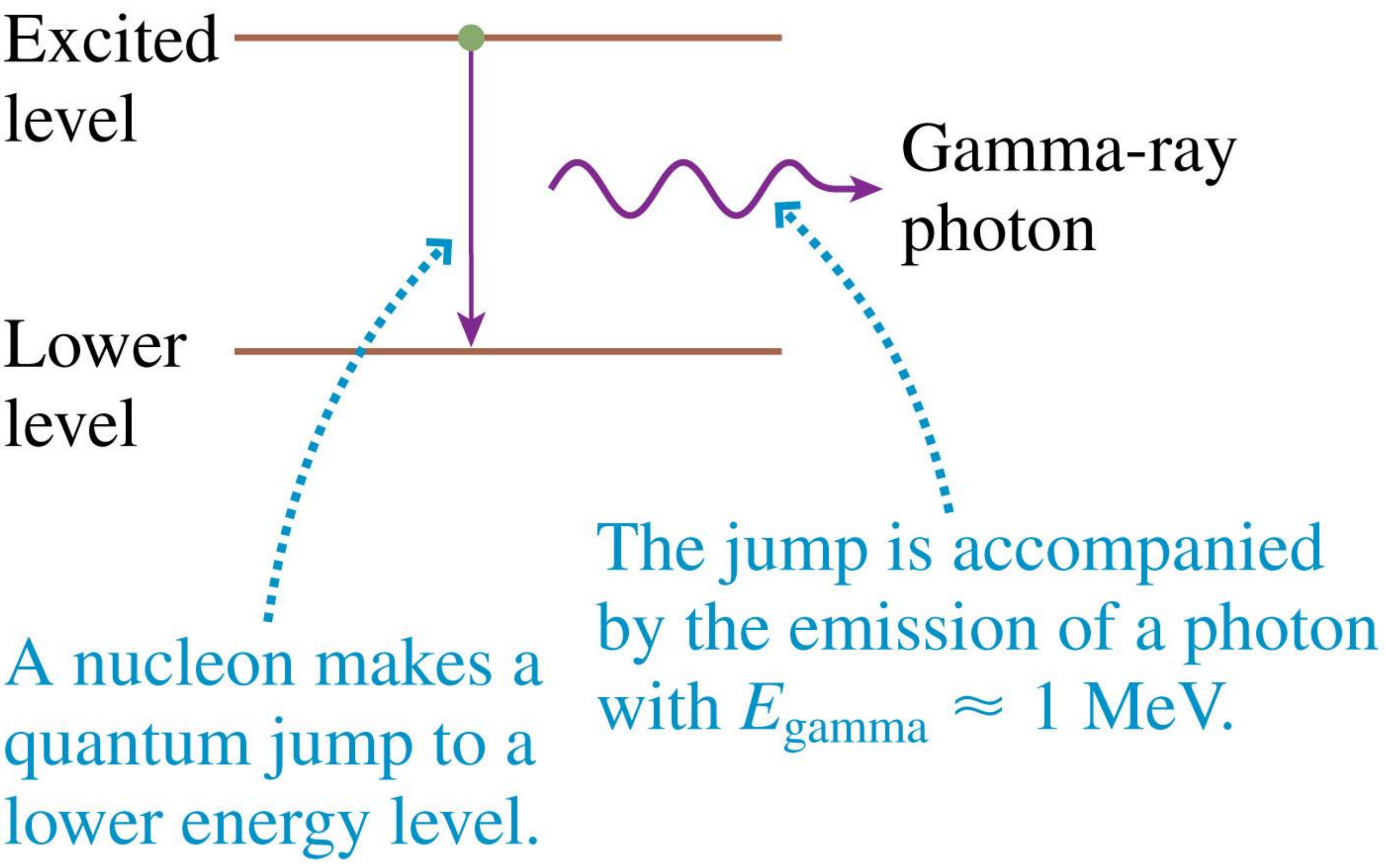
SOLVE Rewriting Equation 30.9 as

$$^{40}_{19}\text{K} \rightarrow {}^{40}_{20}? + e^{-} + \text{energy}$$

we see that the daughter nucleus must be the calcium isotope $^{40}_{20}\text{Ca}$.

Gamma Decay

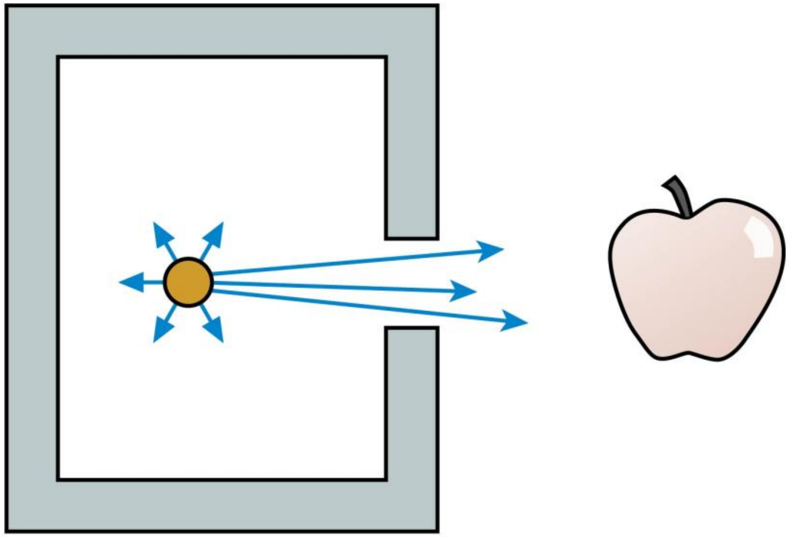
- Gamma decay occurs when a proton or neutron undergoes a quantum jump.



QuickCheck 30.3

The apple is irradiated for 2 hours by a very strong radioactive source. Is the apple now radioactive?

A. Yes
B. No
C. It depends on what kind of radiation it is.



QuickCheck 30.3

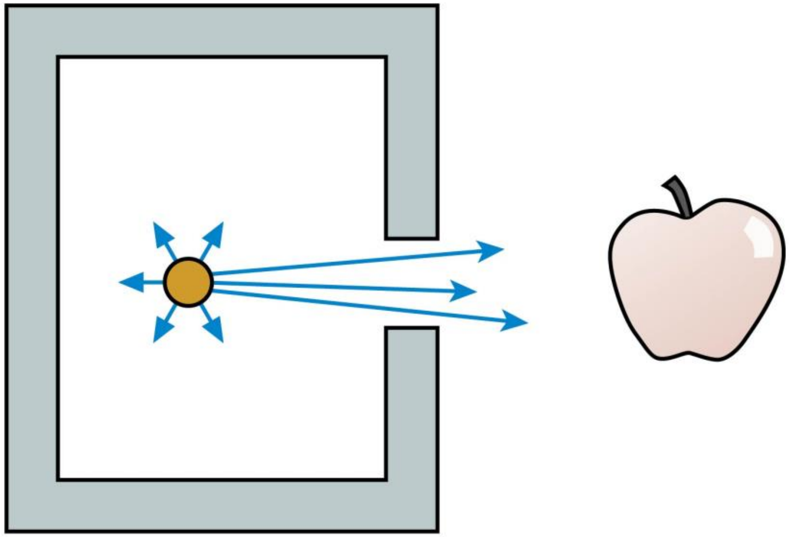
The apple is irradiated for 2 hours by a very strong radioactive source. Is the apple now radioactive?

A. Yes

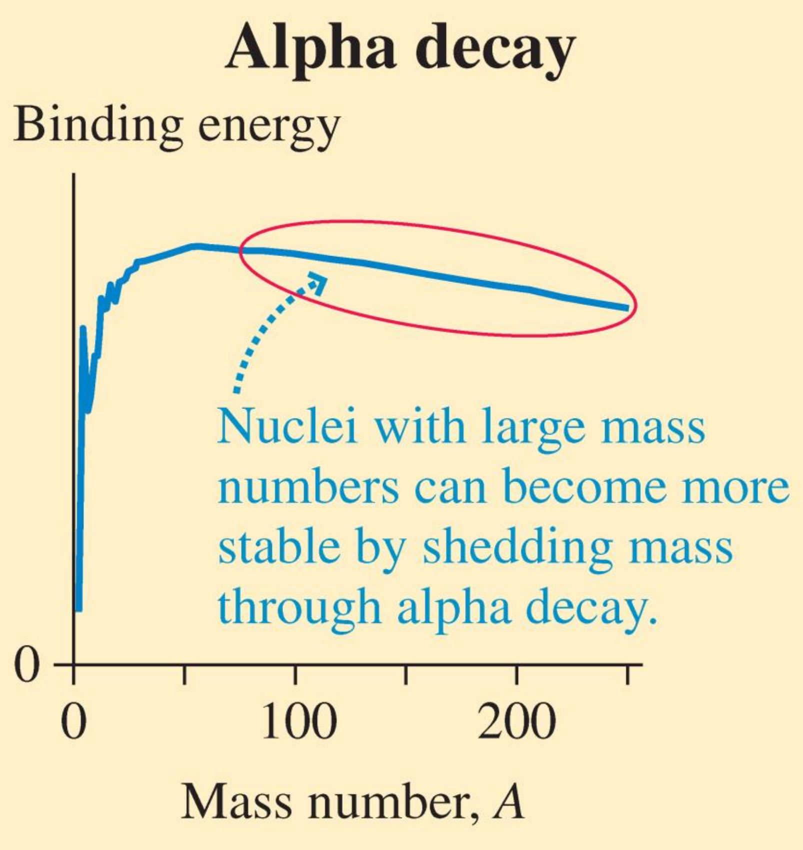
✔ B. No

C. It depends on what kind of radiation it is.

The radiation is ionizing molecules and breaking bonds but not changing the nuclei in the apple.



SYNTHESIS 30.1 Nuclear decay modes



Text: p. 985

SYNTHESIS 30.1 Nuclear decay modes

The nucleus loses 4 nucleons . . .

$$^{A}_{Z}X \rightarrow\, ^{A-4}_{Z-2}Y + \alpha + \text{energy}$$

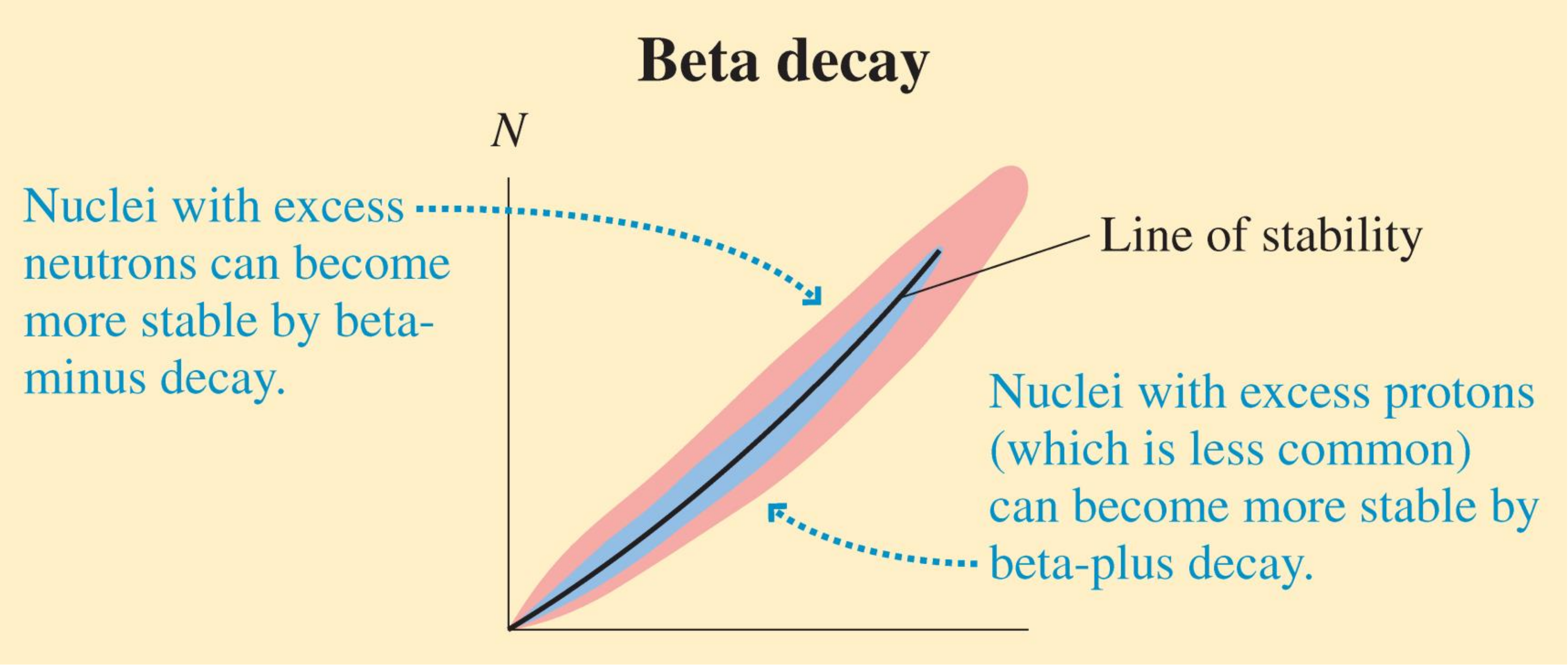
. . . of which 2 are protons.

Radium is a heavy element that is produced by decay of uranium.

$$^{226}_{88}Ra \rightarrow\, ^{222}_{86}Rn + \alpha + \text{energy}$$

Text: p. 985

SYNTHESIS 30.1 Nuclear decay modes



Text: p. 985

SYNTHESIS 30.1 Nuclear decay modes

Beta-minus decay

A neutron turns into a proton, so:

The number of nucleons stays the same . . .

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \text{energy}$$

. . . and the nucleus gains a proton.

This chlorine isotope is present at low levels in the environment.

$$^{36}_{17}Cl \rightarrow {}^{36}_{18}Ar + e^{-} + \text{energy}$$

Beta-plus decay

A proton turns into a neutron, so:

The number of nucleons stays the same . . .

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \text{energy}$$

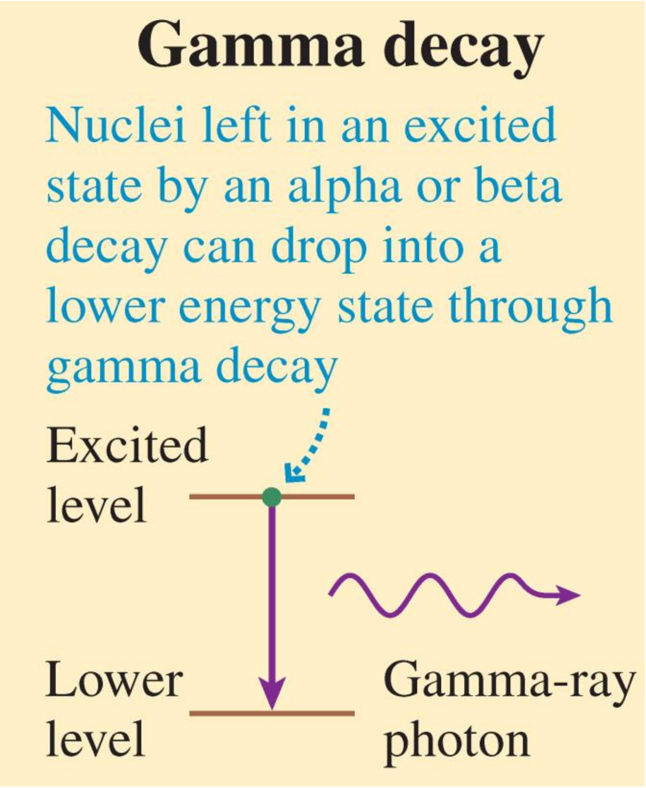
. . . and the nucleus loses a proton.

This carbon isotope is produced in cyclotrons.

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + e^{+} + \text{energy}$$

Text: p. 985

SYNTHESIS 30.1 Nuclear decay modes



Text: p. 985

SYNTHESIS 30.1 Nuclear decay modes

No change in the number of neutrons or protons means no change of element or isotope.

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

This excited form of nickel is produced in the beta-minus decay of ^{60}Co.

$$^{60}_{28}Ni^{*} \rightarrow {}^{60}_{28}Ni + \gamma$$

Text: p. 985

Example 30.5 What type of decay?

Phosphorus has one stable isotope, ^{31}P. The isotope ^{32}P is a neutron-rich radioactive isotope that is used in nuclear medicine. What is the likely daughter nucleus of ^{32}P decay?

Example 30.5 What type of decay? (cont.)

PREPARE Synthesis 30.1 contains details of when different decay modes are expected. $A = 32$ isn't an especially large mass number, so alpha decay is unlikely. But ^{32}P is neutron rich; it has one more neutron than the only stable phosphorus isotope, so it is likely to undergo beta-minus decay.

Example 30.5 What type of decay? (cont.)

SOLVE Phosphorus has atomic number 15. When $^{32}_{15}P$ undergoes beta-minus decay, the daughter nucleus has the same number of nucleons and one more proton. Following the details in Synthesis 30.1, we can write the decay as

$$^{32}_{15}P \rightarrow \, ^{32}_{16}S + e^{-}$$

The daughter nucleus of this decay is ^{32}S.

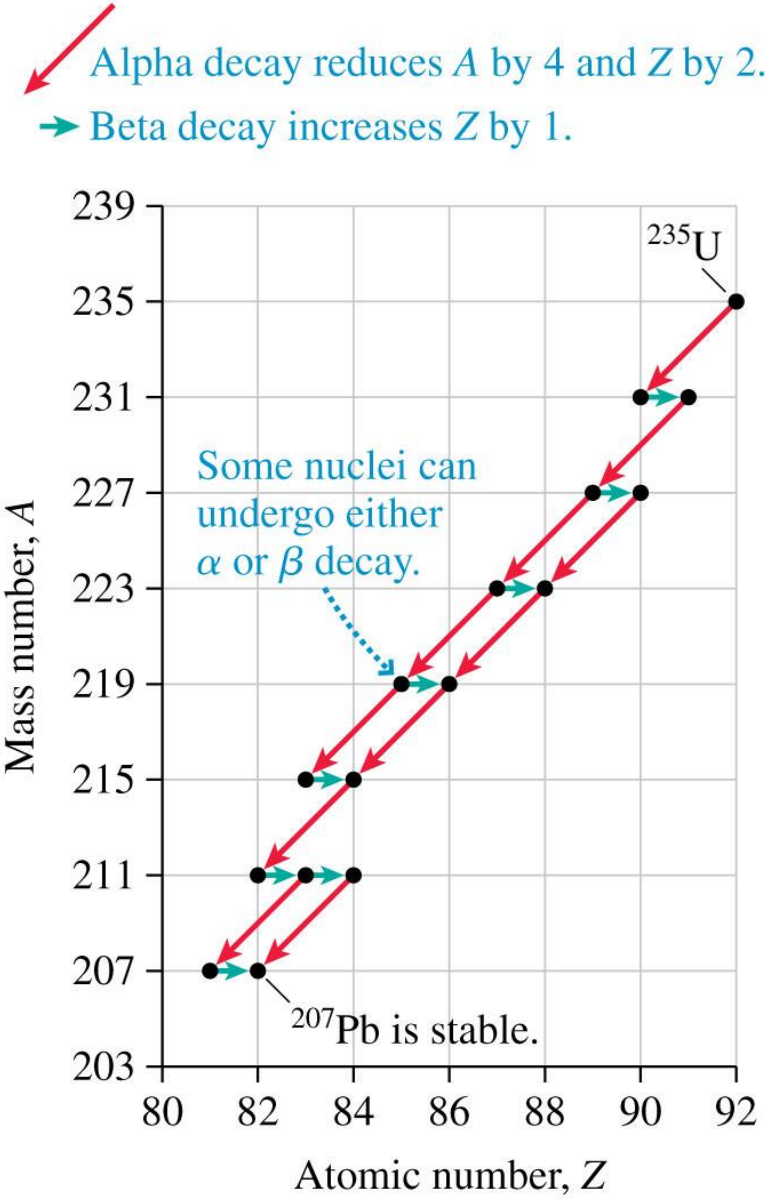
Example 30.5 What type of decay? (cont.)

ASSESS $^{32}_{16}S$ is a stable isotope of sulfur, so our solution has a radioactive isotope decaying to a more stable state. This gives us confidence in our result.

Decay Series

- The sequence of isotopes, starting with the original unstable isotope and ending with the stable isotope, is called the **decay series**.

^{235}U decay series.



Nuclear Radiation Is a Form of Ionizing Radiation

- The energies of alpha and beta particles and the gamma-ray photons have energies much higher than the ionization energies of atoms and molecules.
- They interact with matter, *ionizing* atoms and *breaking* molecular bonds.
- Ionizing radiation causes damage to the body by driving chemical reactions that would not otherwise occur. Ionizing radiation can also damage DNA molecules by ionizing them and breaking bonds, which can create a mutation or a tumor.

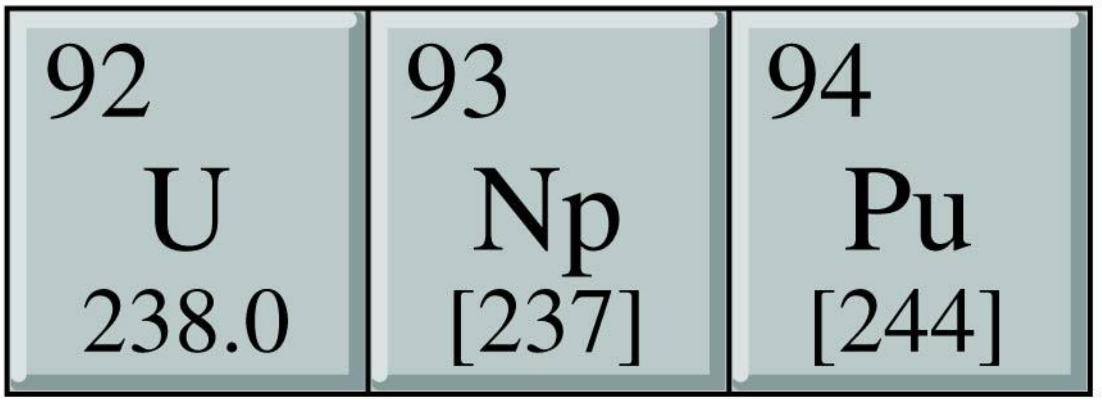
QuickCheck 30.6

Is $^{238}\text{Pu} \rightarrow {}^{236}\text{U} + \alpha$ a possible decay mode?

A. Yes

B. No

C. It depends on the energy of the alpha particle.



QuickCheck 30.6

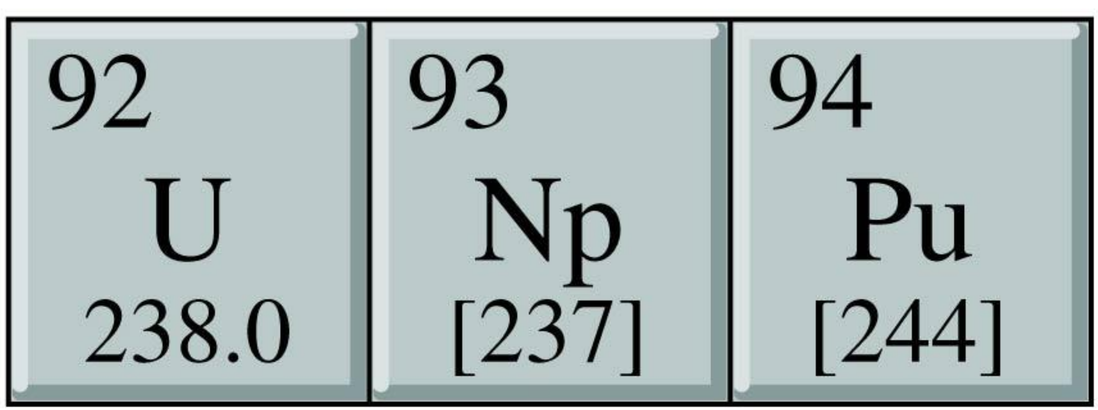
Is ^{238}Pu $\rightarrow$ ^{236}U + α a possible decay mode?

A. Yes

B. No

In alpha decay, *Z* must decrease by 2 (it does) and *A* must decrease by 4 (it doesn't).

C. It depends on the energy of the alpha particle.

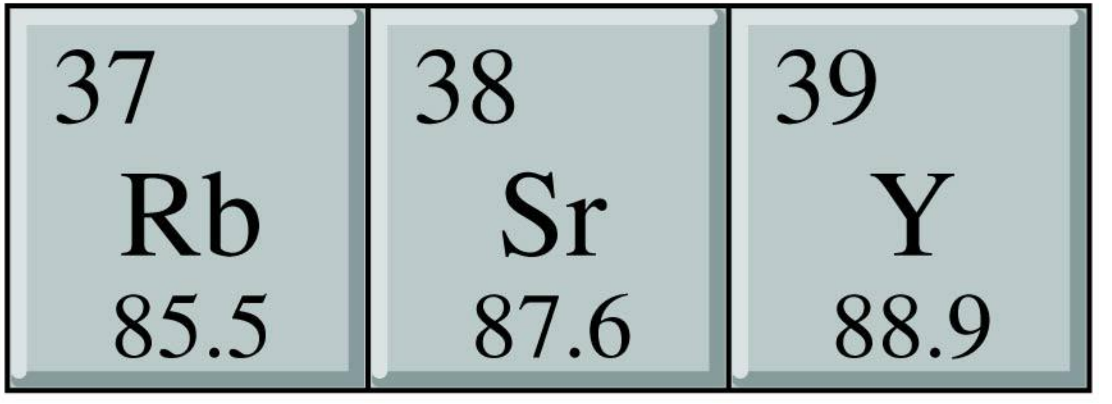


QuickCheck 30.8

What is the daughter nucleus for the following decay?

$$^{90}\text{Sr} \rightarrow {}^{?}\text{X} + e^{-}$$

A. ^{90}Y
B. ^{89}Y
C. ^{90}Rb
D. ^{89}Rb



QuickCheck 30.8

What is the daughter nucleus for the following decay?

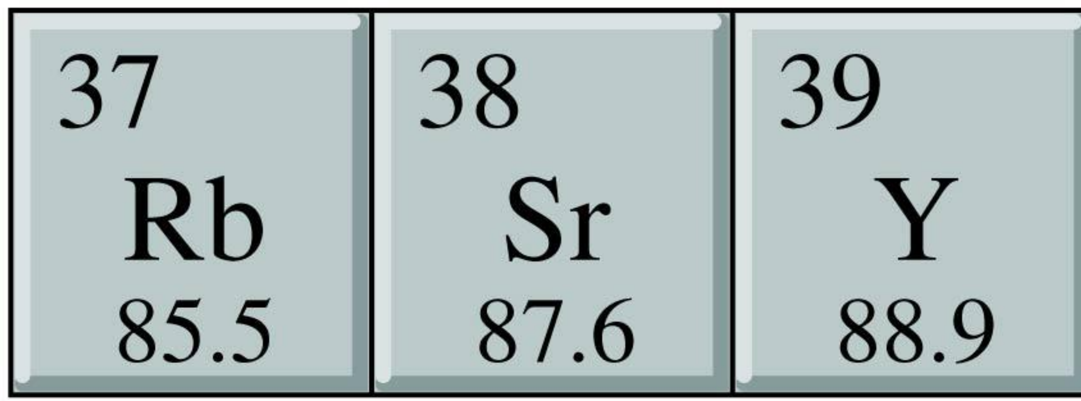
$$^{90}\text{Sr} \rightarrow {}^{?}\text{X} + e^{-}$$

✔ A. ^{90}Y

B. ^{89}Y

C. ^{90}Rb

D. ^{89}Rb



QuickCheck 30.9

What is the daughter nucleus for the following decay?

$$^{222}\text{Rn} \rightarrow {}^{?}\text{X} + \alpha$$

A. ^{220}Po

B. ^{218}Po

C. ^{220}Ra

D. ^{218}Ra

84	85	86	87	88
Po	At	Rn	Fr	Ra
[209]	[210]	[222]	[223]	[226]

QuickCheck 30.9

What is the daughter nucleus for the following decay?

$$^{222}\text{Rn} \rightarrow {}^{?}\text{X} + \alpha$$

A. ^{220}Po

✔ B. ^{218}Po

C. ^{220}Ra

D. ^{218}Ra

84	85	86	87	88
Po	At	Rn	Fr	Ra
[209]	[210]	[222]	[223]	[226]

QuickCheck 30.10

What is the daughter nucleus for the following decay?

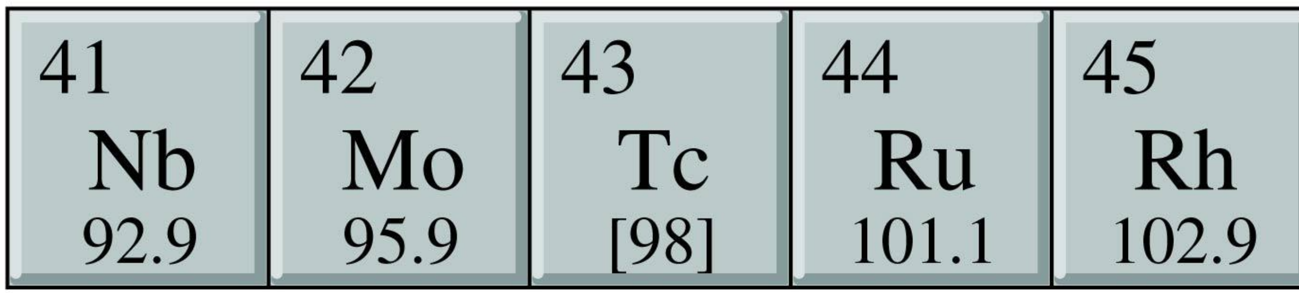
$$^{99}\text{Tc} \rightarrow {}^{?}\text{X} + \gamma$$

A. ^{99}Tc

B. ^{99}Mo

C. ^{99}Nb

D. ^{100}Ru



QuickCheck 30.10

What is the daughter nucleus for the following decay?

$$^{99}\text{Tc} \rightarrow {}^{?}\text{X} + \gamma$$

- A. ^{99}Tc
- B. ^{99}Mo
- C. ^{99}Nb
- D. ^{100}Ru

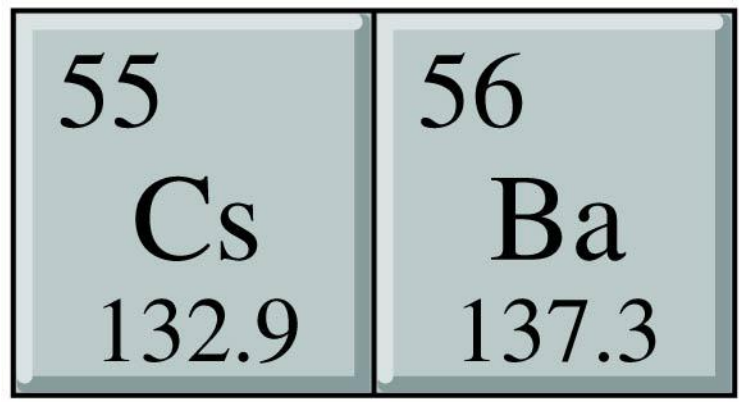
41	42	43	44	45
Nb	Mo	Tc	Ru	Rh
92.9	95.9	[98]	101.1	102.9

QuickCheck 30.11

What is the decay mode of the following decay?

$$^{137}\text{Cs} \rightarrow {}^{137}\text{Ba} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay



QuickCheck 30.11

What is the decay mode of the following decay?

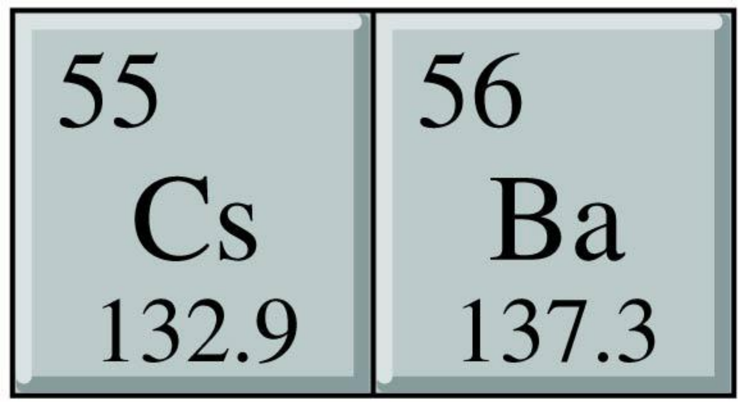
$$^{137}Cs \rightarrow {}^{137}Ba + ?$$

A. Alpha decay

✔ B. Beta-minus decay

C. Beta-plus decay

D. Gamma decay

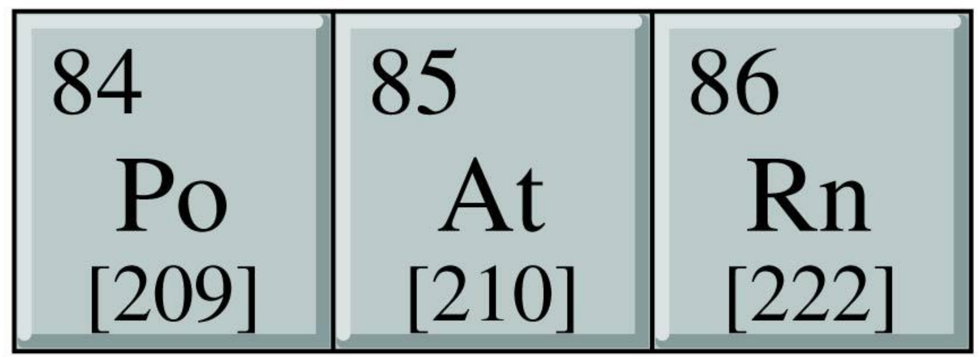


QuickCheck 30.12

What is the decay mode of the following decay?

$$^{222}\text{Rn} \rightarrow {}^{218}\text{Po} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay



QuickCheck 30.12

What is the decay mode of the following decay?

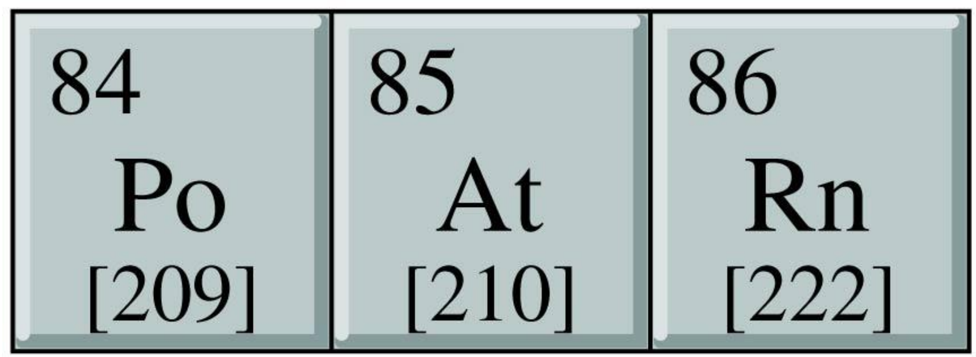
$$^{222}\text{Rn} \rightarrow {}^{218}\text{Po} + ?$$

✔ A. Alpha decay

B. Beta-minus decay

C. Beta-plus decay

D. Gamma decay

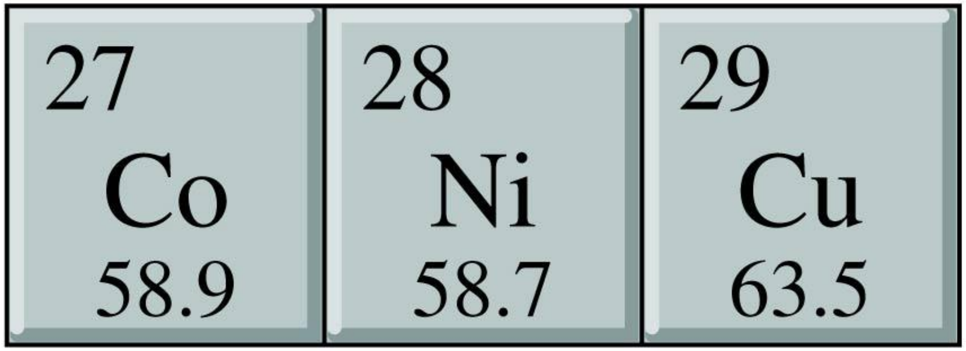


QuickCheck 30.13

What is the decay mode of the following decay?

$$^{60}\text{Ni}^* \rightarrow {}^{60}\text{Ni} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay



QuickCheck 30.13

What is the decay mode of the following decay?

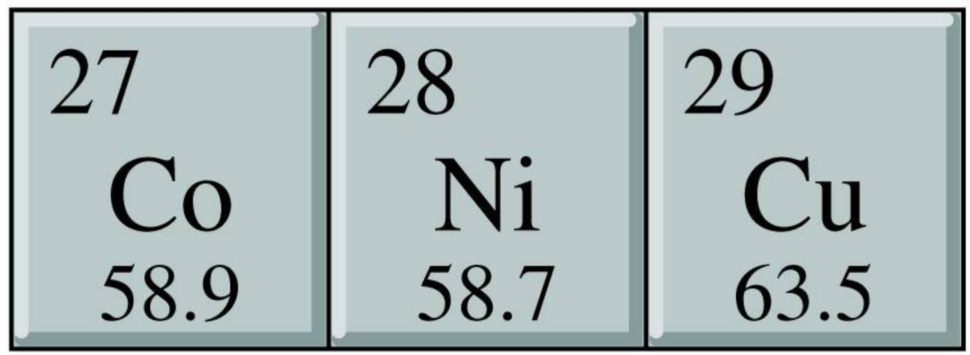
$$^{60}Ni^{*} \rightarrow {}^{60}Ni + ?$$

A. Alpha decay

B. Beta-minus decay

C. Beta-plus decay

D. Gamma decay



Section 30.5 Nuclear Decay and Half-Lives

Nuclear Decay and Half-Lives

- If you start with N_0 unstable nuclei, after an interval of time called the *half-life*, you'll have ½ N_0 nuclei remaining.
- The **half-life** $t_{1/2}$ is the average time required for one-half the nuclei to decay.
- The number of nuclei N remaining at time t is

$$N = N_0 \left(\frac{1}{2}\right)^{t/t_{1/2}}$$

Number of atoms remaining after time t (N)

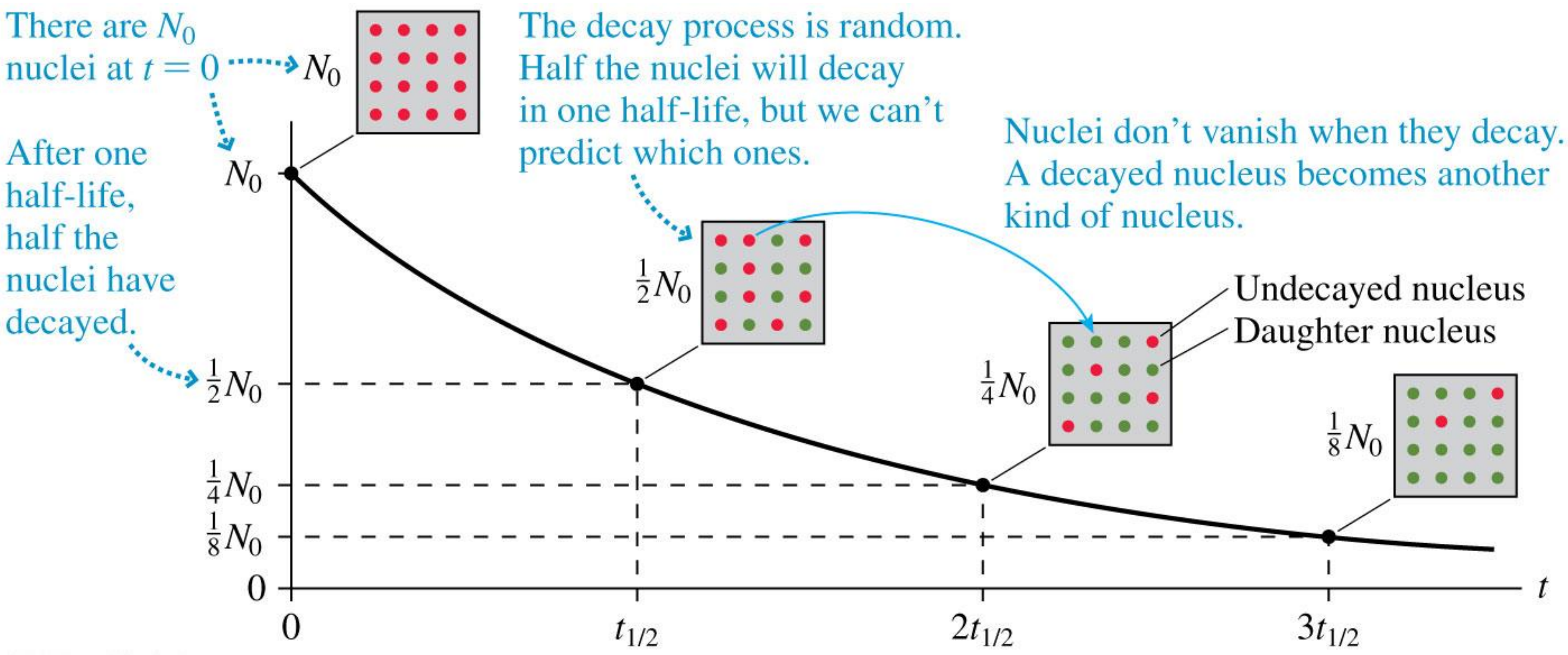
Number of atoms at the start, $t = 0$ (N_0)

The units for t and $t_{1/2}$ must be the same.

- **No matter how many nuclei there are at any point in time, the number decays by half during the next half-life.**

Nuclear Decay and Half-Lives

- The figure shows the decay of a sample of radioactive nuclei.



Nuclear Decay and Half-Lives

- The decay of radioactive nuclei is an exponential decay.
- The equation for the number of atoms after a half-life can be written in terms of a *time constant* τ that is related to the half-life:

$$N = N_0 e^{-t/\tau}$$

The time constant τ is proportional to the half-life $t_{1/2}$

$$\tau = \frac{t_{1/2}}{\ln 2} = (1.44)t_{1/2}$$

Nuclear Decay and Half-Lives

- The relationship between the time constant and the half life can be demonstrated by applying $N = N_0/2$ at $t = t_{1/2}$ to the equation for exponential decay:

$$\frac{N_0}{2} = N_0 e^{-t_{1/2}/\tau}$$

$$\ln\left(\frac{1}{2}\right) = -\ln 2 = -\frac{t_{1/2}}{\tau}$$

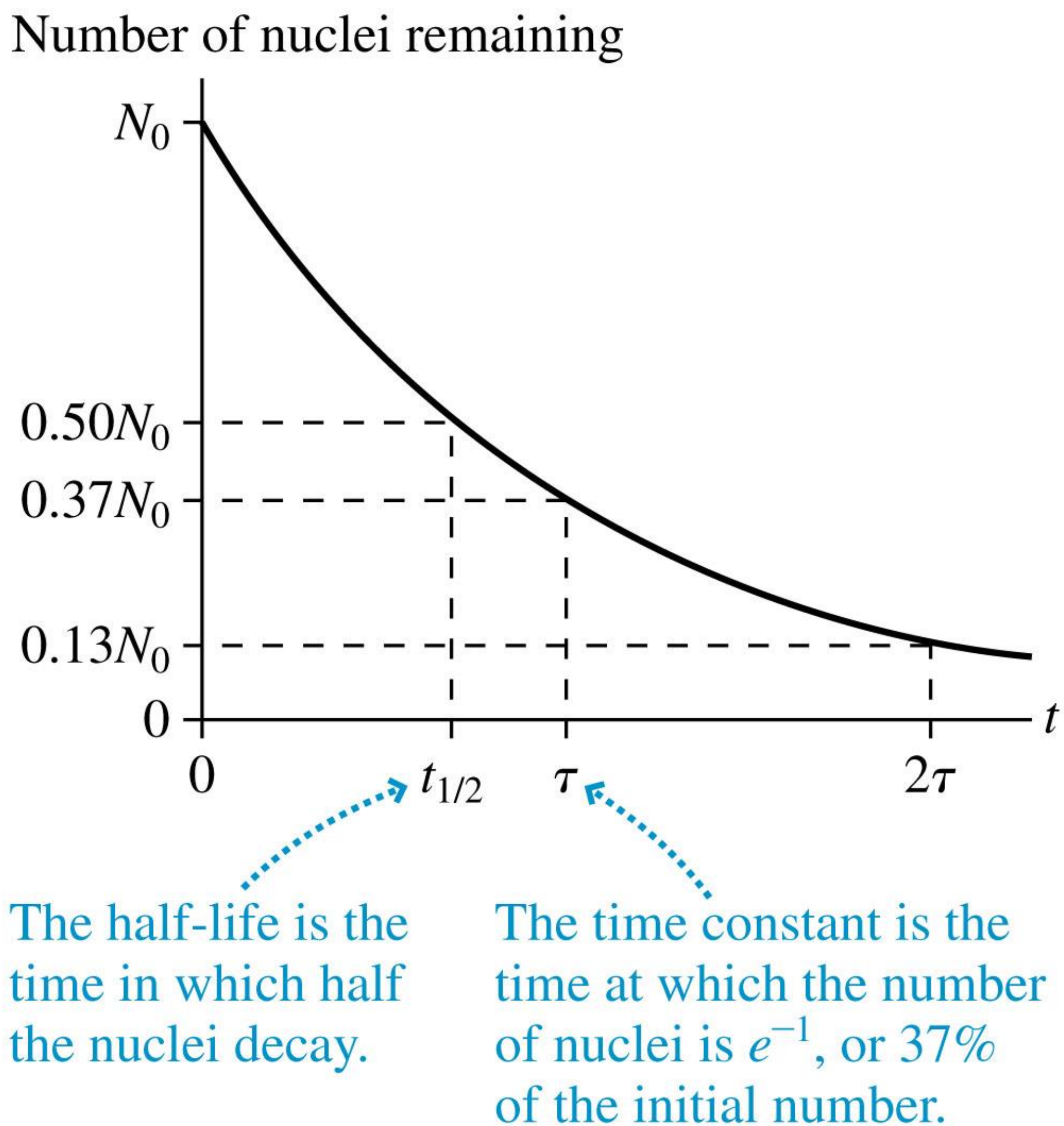
- We find that the time constant in terms of the half-life and the half-life in terms of the time constant are

$$\tau = \frac{t_{1/2}}{\ln 2} = 1.44 t_{1/2}$$

$$t_{1/2} = \tau \ln 2 = 0.693\tau$$

Nuclear Decay and Half-Lives

- The number of radioactive atoms decreases exponentially with time.



QuickCheck 30.4

A sealed box is completely evacuated (perfect vacuum), then 1,000,000 radioactive atoms are added. Their half-life is 2 days. After 4 days have passed, how many atoms are in the box?

A. 1,000,000
B. 500,000
C. 250,000
D. 0

QuickCheck 30.4

A sealed box is completely evacuated (perfect vacuum), then 1,000,000 radioactive atoms are added. Their half-life is 2 days. After 4 days have passed, how many atoms are in the box?

✔ A. 1,000,000

B. 500,000

C. 250,000

D. 0

QuickCheck 30.5

100 g of radioactive element X are placed in a sealed box. The half-life of this isotope of X is 2 days. After 4 days have passed, what is the mass of element X in the box?

A. 100 g
B. 50 g
C. 37 g
D. 25 g
E. 0 g

QuickCheck 30.5

100 g of radioactive element X are placed in a sealed box. The half-life of this isotope of X is 2 days. After 4 days have passed, what is the mass of element X in the box?

A. 100 g
B. 50 g
C. 37 g
✔ D. 25 g
E. 0 g

$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ left after 2 half-lives

Example 30.6 Determining the decay of radioactive iodine

Patients with Graves disease have an overactive thyroid gland. A common treatment uses radioactive iodine, which is taken up by the thyroid. The radiation emitted in its decay will damage the tissues of the gland. A single pill is produced with 4.0×10^{14} atoms of the isotope ^{131}I, which has a half-life of 8.0 days.

Example 30.6 Determining the decay of radioactive iodine (cont.)

a. How many atoms remain 24 hours after the pill's creation, when the pill is delivered to a hospital?

b. Although the iodine in the pill is constantly decaying, it is still usable as long as it contains at least 1.1×10^{14} ^{131}I atoms. What is the maximum delay before the pill is no longer usable?

Example 30.6 Determining the decay of radioactive iodine (cont.)

PREPARE The atoms in the sample undergo exponential decay, decreasing steadily in number.

SOLVE a. The half-life is $t_{1/2} = 8.0$ days $= 192$ h. Using Equation 30.12, we can find the number of atoms remaining after 24 h have elapsed:

$$N = (4.0 \times 10^{14})\left(\frac{1}{2}\right)^{24/192} = 3.7 \times 10^{14} \text{ atoms}$$

Example 30.6 Determining the decay of radioactive iodine (cont.)

b. The time after which 1.1 × 1014 atoms remain is given by

$$1.1 \times 10^{14} = (4.0 \times 10^{14})\left(\frac{1}{2}\right)^{t/192}$$

To solve for *t*, we write this as

$$\frac{1.1 \times 10^{14}}{4.0 \times 10^{14}} = \left(\frac{1}{2}\right)^{t/192}$$

or

$$0.275 = \left(\frac{1}{2}\right)^{t/192}$$

Example 30.6 Determining the decay of radioactive iodine (cont.)

Now, we take the natural logarithm of both sides:

$$\ln(0.275) = \ln\left(\left(\frac{1}{2}\right)^{t/192}\right)$$

We can solve for t by using the fact that $\ln(a^x) = x\ln(a)$. This allows us to "pull out" the $t/192$ exponent to find

$$\ln(0.275) = \left(\frac{t}{192}\right)\ln\left(\frac{1}{2}\right)$$

Example 30.6 Determining the decay of radioactive iodine (cont.)

Solving for t, we find that the pill ceases to be useful after

$$t = 192\frac{\ln(0.275)}{\ln(1/2)} = 360 \text{ h} = 15 \text{ days}$$

ASSESS The weakest usable concentration of iodine is approximately one-fourth of the initial concentration. This means that the decay time should be approximately equal to two half-lives, which is what we found.

Activity

- The **activity** R of a radioactive sample is the number of decays per second. Each decay corresponds to an alpha, beta, or gamma emission.
- The activity of a sample N nuclei with a time constant τ or half-life $t_{1/2}$ is

$$R = \frac{N}{\tau} = \frac{0.693N}{t_{1/2}}$$

- **The activity is inversely proportional to the half-life.**

Activity

- We can find the variation of activity with time:

$$R = \frac{N}{\tau} = \frac{N_0}{\tau}\left(\frac{1}{2}\right)^{t/t_{1/2}} = \frac{N_0}{\tau}e^{-t/\tau}$$

- N_0/τ is the initial activity R_0 so the decay of activity is

Activity after time t

Activity at the start, $t = 0$

$$R = R_0\left(\frac{1}{2}\right)^{t/t_{1/2}} = R_0 e^{-t/\tau}$$

- The SI unit of activity is the **becquerel**:

1 becquerel = 1 Bq = 1 decay/second or 1 s^{-1}

- The **curie** is also used:

1 curie = 1 Ci = 3.7×10^{10} Bq

Conceptual Example 30.7 Relative activities of isotopes in the body

^{40}K ($t_{1/2} = 1.3 \times 10^9$ yr) and ^{14}C ($t_{1/2} = 5.7 \times 10^3$ yr) are two radioactive isotopes found in measurable quantities in your body. Suppose you have 1 mole of each. Which is more radioactive—that is, which has a greater activity?

REASON Equation 30.15 shows that the activity of a sample is proportional to the number of atoms and inversely proportional to the half-life. Because both samples have the same number of atoms, the sample of ^{14}C, with its much shorter half-life, has a much greater activity.

Radioactive Dating

- **Radiocarbon dating** is a dating technique that uses the radioactive carbon isotope ^{14}C.
- ^{14}C is present in atmospheric carbon dioxide because it is created from collisions of high-energy rays with gas molecules high in the atmosphere. The creation and decay of ^{14}C (5730 years) has reached a steady state, with a $^{14}C/^{12}C$ ratio of 1.3×10^{-12}. This is also the ratio found in living organisms.
- When an organism dies, the ^{14}C begins to decay, and no new ^{14}C is added. Since we know the decay rate, we can determine the time since the organism died.

Radioactive Dating

- Carbon dating can be used to date anything made of organic matter (bones, wood, paper, fur, etc.). It is very accurate for ages to about 15,000 years, or three half-lives.
- Isotopes with longer half-lives, like ^{40}K with a half life of 1.25 billion years, are useful for dating geological samples like rocks of volcanic origin.

Example 30.9 Carbon dating a tooth

A rear molar from a mammoth skeleton is dated using a measurement of its ^{14}C content. Carbon from the tooth is chemically extracted and formed into benzene. The benzene sample is placed in a shielded chamber. Decays from the sample come at an average rate of 11.5 counts per minute. A modern benzene sample of the exact same size gives 54.9 counts per minute. What is the age of the skeleton?

Example 30.9 Carbon dating a tooth (cont.)

PREPARE We can assume that, thousands of years ago, the sample had an initial activity of 54.9 counts per minute—identical to the activity of a modern sample. The present activity is lower due to the decay of the ^{14}C since the death of the mammoth.

Example 30.9 Carbon dating a tooth (cont.)

SOLVE Equation 30.16 gives the decrease of the activity as a function of time as $R = R_0\,(1/2)^{t/t_{1/2}}$. The current activity is R = 11.5 counts per minute, and we assume that the initial activity was R_0 = 54.9. t is the time since the mammoth stopped growing—the age of the skeleton.

Example 30.9 Carbon dating a tooth (cont.)

We solve for t by rearranging terms and computing a natural logarithm, as in Example 30.6:

$$\frac{R}{R_0} = \left(\frac{1}{2}\right)^{t/t_{1/2}}$$

$$\ln\left(\frac{R}{R_0}\right) = \left(\frac{t}{t_{1/2}}\right)\ln\left(\frac{1}{2}\right)$$

We then solve for the time t:

$$t = \frac{t_{1/2}}{\ln(1/2)}\ln\left(\frac{R}{R_0}\right) = \frac{5730\ \text{yr}}{\ln(1/2)}\ln\left(\frac{11.5}{54.9}\right) = 12{,}900\ \text{yr}$$

Example 30.9 Carbon dating a tooth (cont.)

ASSESS The final time is in years, the same unit we used for the half-life. This is a realistic example of how such radiocarbon dating is done; the numbers and details used in this example come from an actual experimental measurement. The age of the sample places it at the end of the last ice age, when mammoths last roamed the earth, so our result seems reasonable.

Example Problem

A scrap of parchment from the Dead Sea Scrolls was found to have a $^{14}C/^{12}C$ ratio that is 79.5% of the modern value. Determine the age of this parchment.

Section 30.6 Medical Applications of Nuclear Physics

Radiation Dose

- The biological effects of radiation depend on how much energy was absorbed by the body and how tissue reacts to different forms of radiation.
- We define the radiation **dose** as the energy from ionizing radiation absorbed by 1 kg of tissue.
- The SI unit of a dose is the **gray**, abbreviated Gy.
- 1 Gy = 1.00 J/kg of absorbed energy.

Radiation Dose

- The **relative biological effectiveness** (RBE) is defined as the biological effect of a given dose relative to the biological effect of an equal dose of x rays.
- The radiation **dose equivalent** is the product of the energy dose in Gy and the relative biological effectiveness. It is measured in **sieverts**, Sv.
- Dose equivalent in Sv = dose in Gy × RBE
- One Sv of radiation produces the same biological damage regardless of the type of radiation.

Radiation Dose

TABLE 30.3 Relative biological effectiveness of radiation

Radiation type	RBE
X rays	1
Gamma rays	1
Beta particles	1
Protons	5
Neutrons	5–20
Alpha particles	20

Radiation Dose

- What is a safe exposure?
- We can weigh the significance of the exposure in relation to the *natural background*.
- We are exposed to radiation from cosmic rays, radioactive atoms in the ground, the atmosphere, and the food we eat.

TABLE 30.4 Radiation exposure

Radiation source	Typical exposure (mSv)
PET scan	7.0
Natural background (1 year)	3.0
Mammogram	0.70
Chest x ray	0.30
Transatlantic airplane flight	0.050
Dental x ray	0.030

Example 30.11 Finding energy deposited in radiation exposure

A 75 kg patient is given a bone scan. A phosphorus compound containing the gamma-emitter ^{99}Tc is injected into the patient. It is taken up by the bones, and the emitted gamma rays are measured. The procedure exposes the patient to 3.6 mSv (360 mrem) of radiation. What is the total energy deposited in the patient's body, in J and in eV?

Example 30.11 Finding energy deposited in radiation exposure (cont.)

PREPARE The exposure is given in Sv, so it is a dose equivalent, a combination of deposited energy and biological effectiveness. The RBE for gamma rays is 1. Gamma rays are penetrating, and the source is distributed throughout the body, so this is a whole-body exposure. Each kg of the patient's body will receive approximately the same energy.

Example 30.11 Finding energy deposited in radiation exposure (cont.)

SOLVE The dose in Gy is the dose equivalent in Sv divided by the RBE. In this case, because RBE = 1, the dose in Gy is numerically equal to the equivalent dose in Sv. The dose is thus 3.6 mGy = 3.6×10^{-3}J/kg. The radiation energy absorbed in the patient's body is

$$\text{absorbed energy} = (3.6 \times 10^{-3}\ \text{J/kg})(75\ \text{kg}) = 0.27\ \text{J}$$

In eV, this is

$$\text{absorbed energy} = (0.27\ \text{J})(1\ \text{eV}/1.6 \times 10^{-19}\ \text{J}) = 1.7 \times 10^{18}\ \text{eV}$$

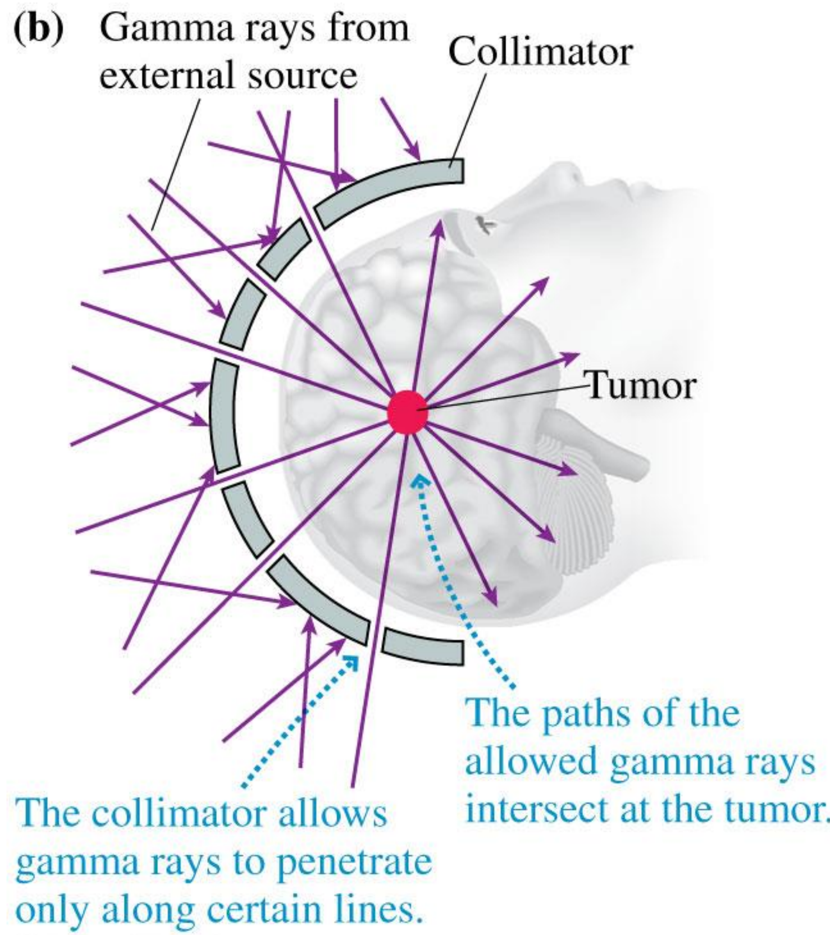
Example 30.11 Finding energy deposited in radiation exposure (cont.)

ASSESS The total energy deposited, 0.27 J, is quite small; there will be negligible heating of tissue. But radiation produces its effects in other ways, as we have seen. Because it takes only ≈10 eV to ionize an atom, this dose is enough energy to ionize over 10^{17} atoms, meaning it can cause significant disruption to the cells of the body.

Nuclear Medicine

- The tissues in the body that are most susceptible to radiation are those that are rapidly proliferating, including tumors.
- *Radiation therapy* applies a large dose of radiation to destroy or shrink a tumor while attempting to produce minimal damage to the surrounding healthy tissue.

Nuclear Medicine



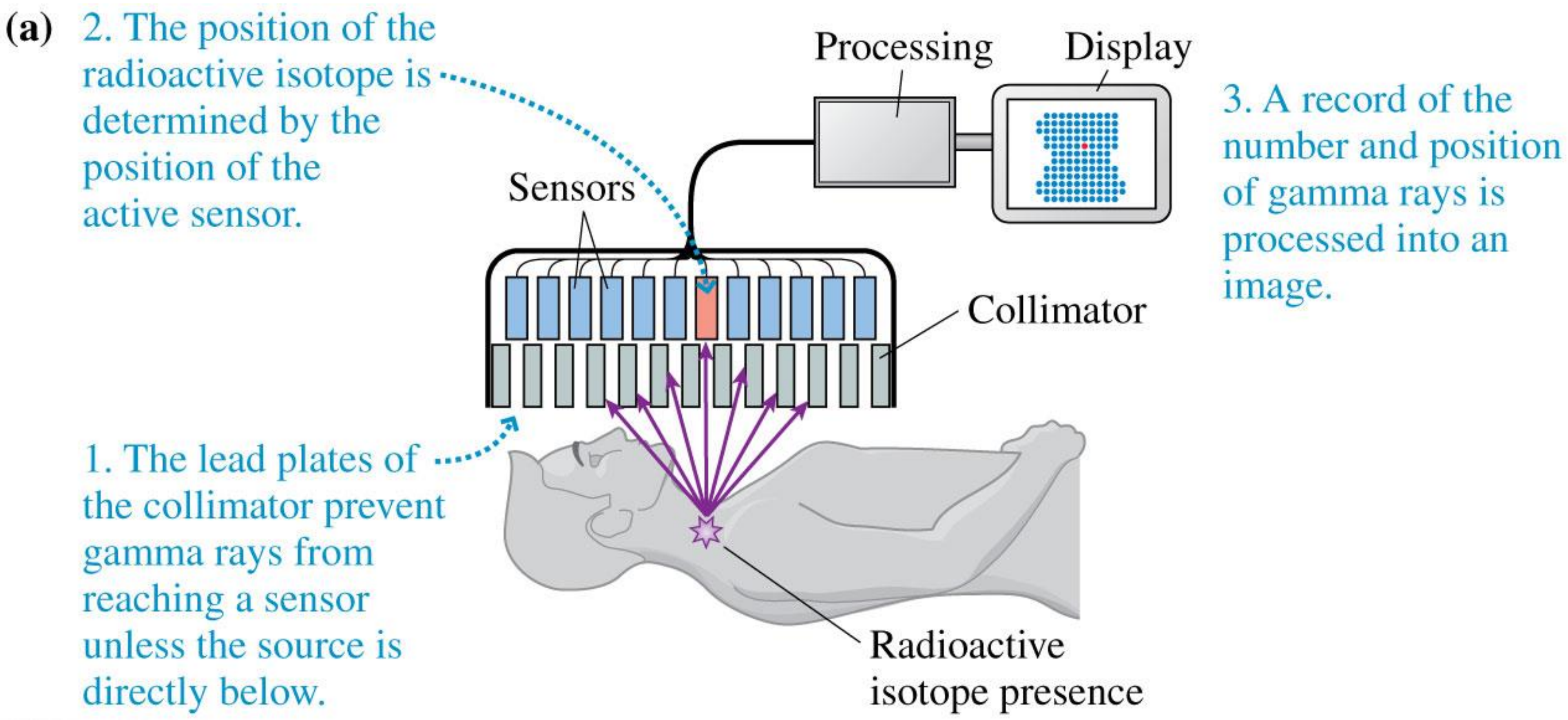
Nuclear Medicine

- Other tumors are treated by surgically implanting low-energy radioactive “seeds” within a tumor.
- Some tissues preferentially take up certain isotopes, allowing treatment by isotope ingestion. A common treatment for hyperthyroidism is to damage the gland with isotope ^{131}I, resulting in a reduction of the gland’s activity with minimal disruption of surrounding tissue.

Nuclear Imaging

- *Nuclear imaging* uses radiation from isotopes from within the body to produce an image of the tissues in the body.
- **An x ray is an image of the anatomical structure while nuclear imaging produces an image of the biological activity of tissues in the body.**
- A **gamma ray camera** can measure and produce an image from gamma rays emitted within the body.
- To use a gamma ray camera, a patient is given a compound with the gamma-emitting ^{99}Tc, which is taken up by bone tissue where active growth is occurring. The camera can then pinpoint the location of the gamma-emitting isotopes.

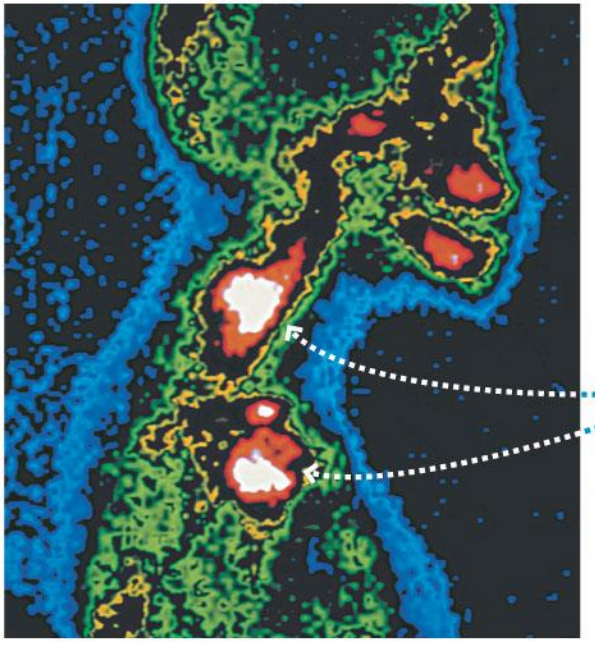
Nuclear Imaging



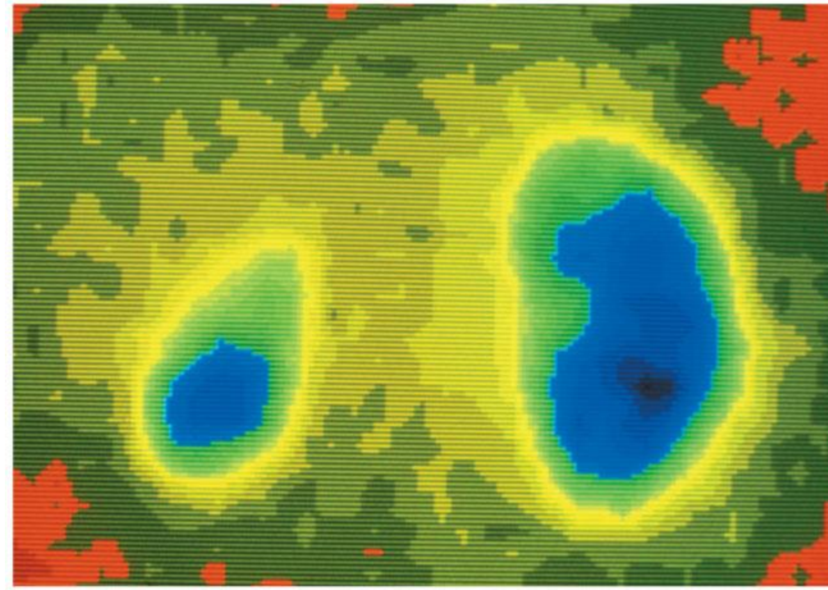
Nuclear Imaging

- The image produced by a gamma ray camera highlights areas of active growth.

(b)

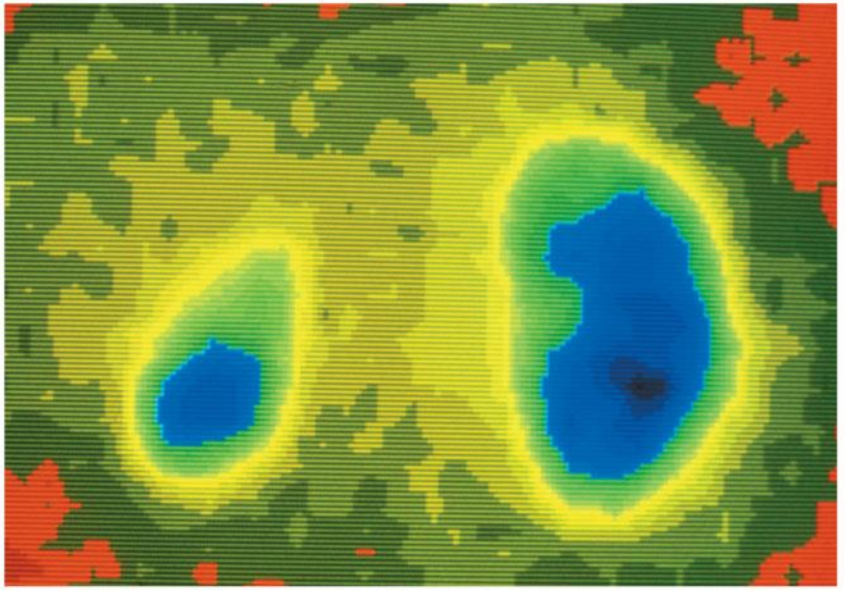


Conceptual Example 30.13 Using radiation to diagnose disease



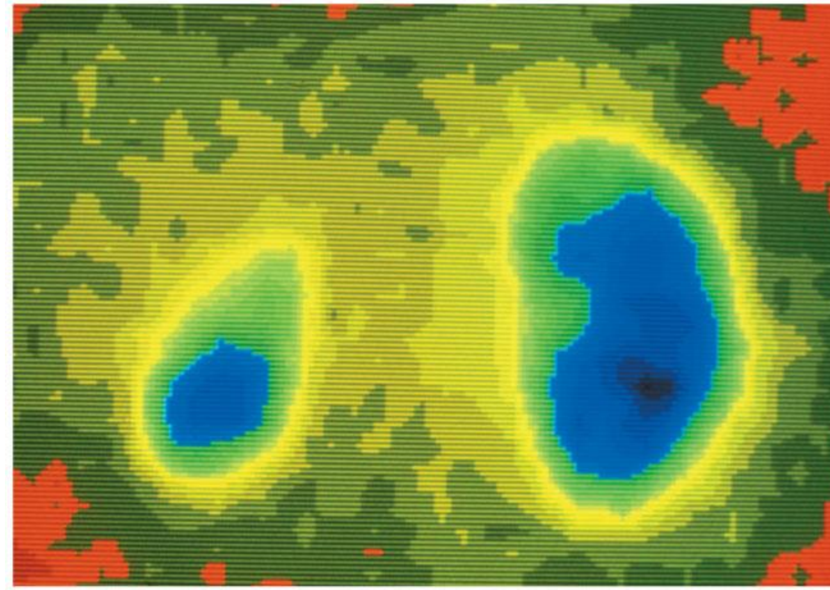
A patient suspected of having kidney disease is injected with a solution containing molecules that are taken up by healthy kidney tissue. The molecules have been "tagged" with radioactive ^{99}Tc. A gamma camera scan of the patient's abdomen gives the image in FIGURE 30.20. In this image, blue corresponds to the areas of highest activity. Which of the patient's kidneys has reduced function?

Conceptual Example 30.13 Using radiation to diagnose disease (cont.)



REASON Healthy tissue should show up in blue on the scan because healthy tissue will absorb molecules with the ^{99}Tc attached and will thus emit gamma rays. The kidney imaged on the right shows normal activity throughout; the kidney imaged on the left appears smaller, so it has a smaller volume of healthy tissue. The patient is ill; the problem is with the kidney imaged on the left.

Conceptual Example 30.13 Using radiation to diagnose disease (cont.)

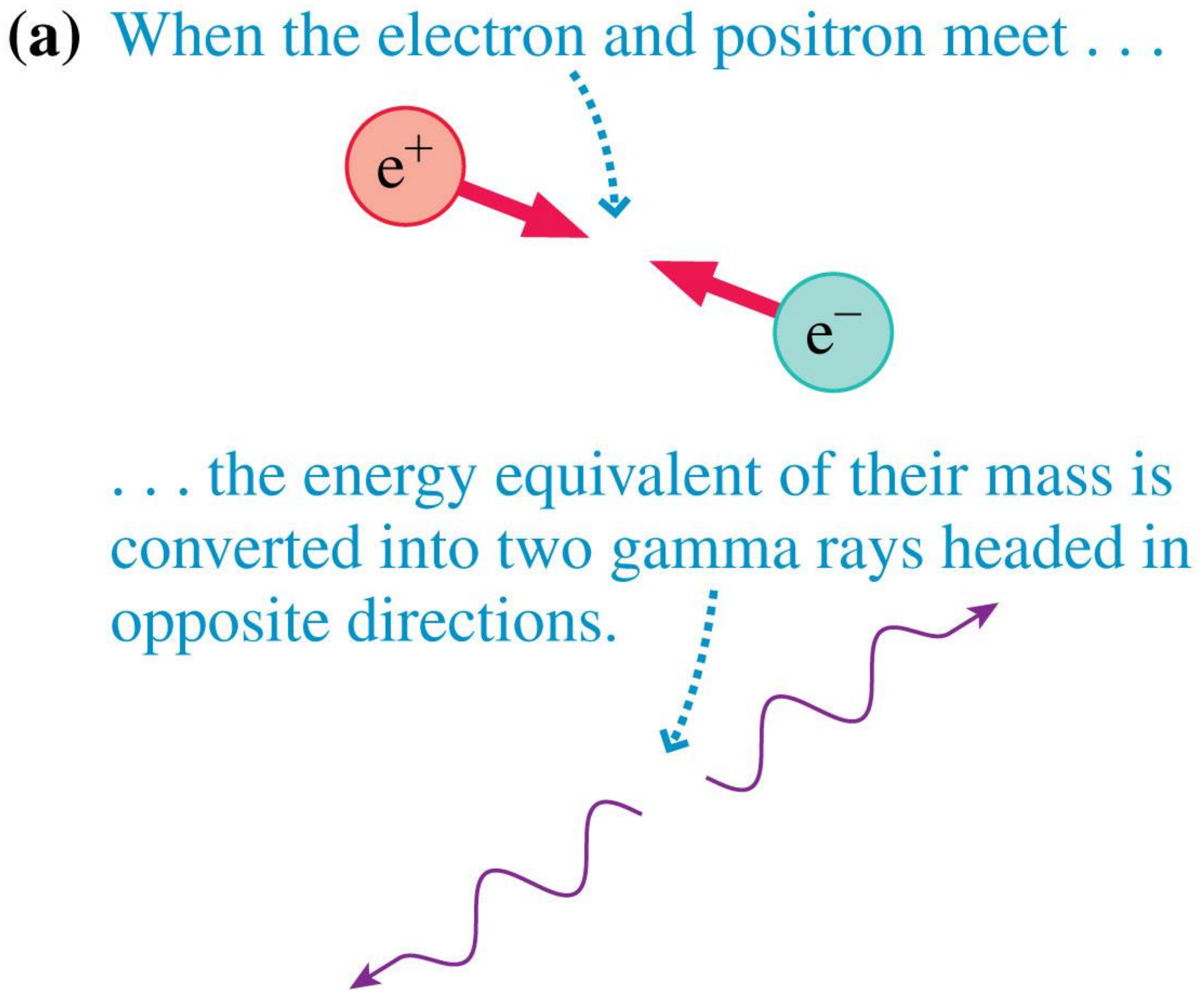


ASSESS Depending on the isotope and how it is taken up by the body, either healthy tissue or damaged tissue could show up on a gamma camera scan.

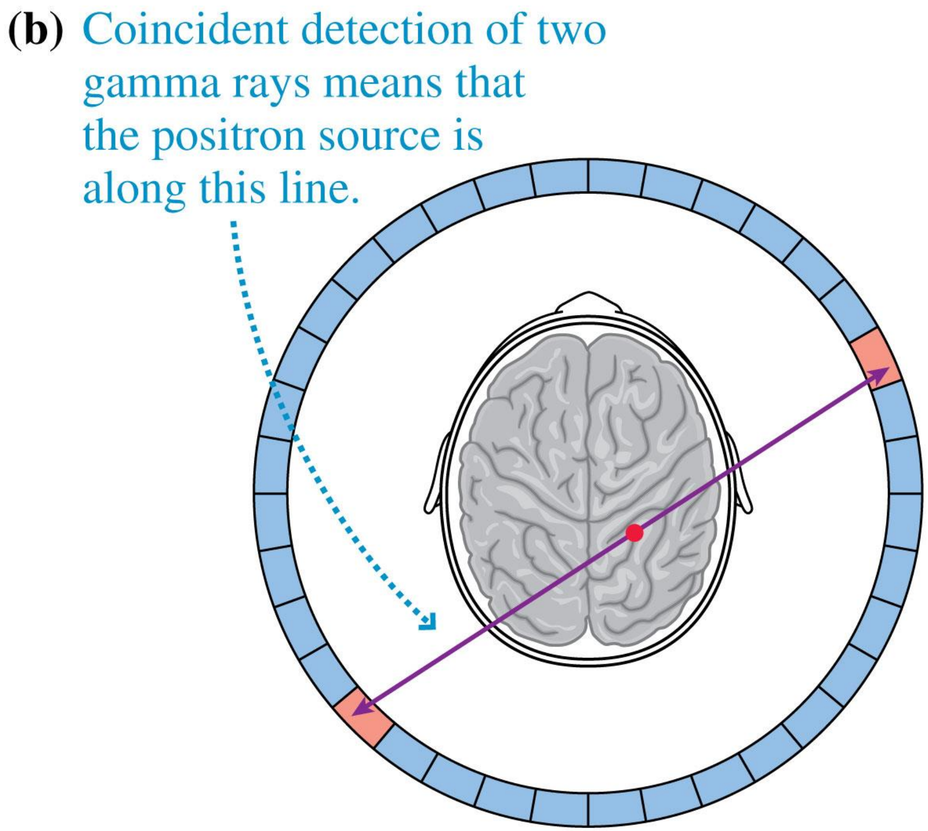
Positron-Emission Tomography

- Isotopes that decay by the emission of a positron can be used in positron-emission tomography (PET).
- Most PET scans use the fluorine isotope ^{18}F which emits a positron as it undergoes beta-plus decay to ^{18}O with a half-life of 110 minutes.
- ^{18}F is used to create an analog of glucose, which gets taken up by the brain. It gets concentrated in active brain regions.

Positron-Emission Tomography

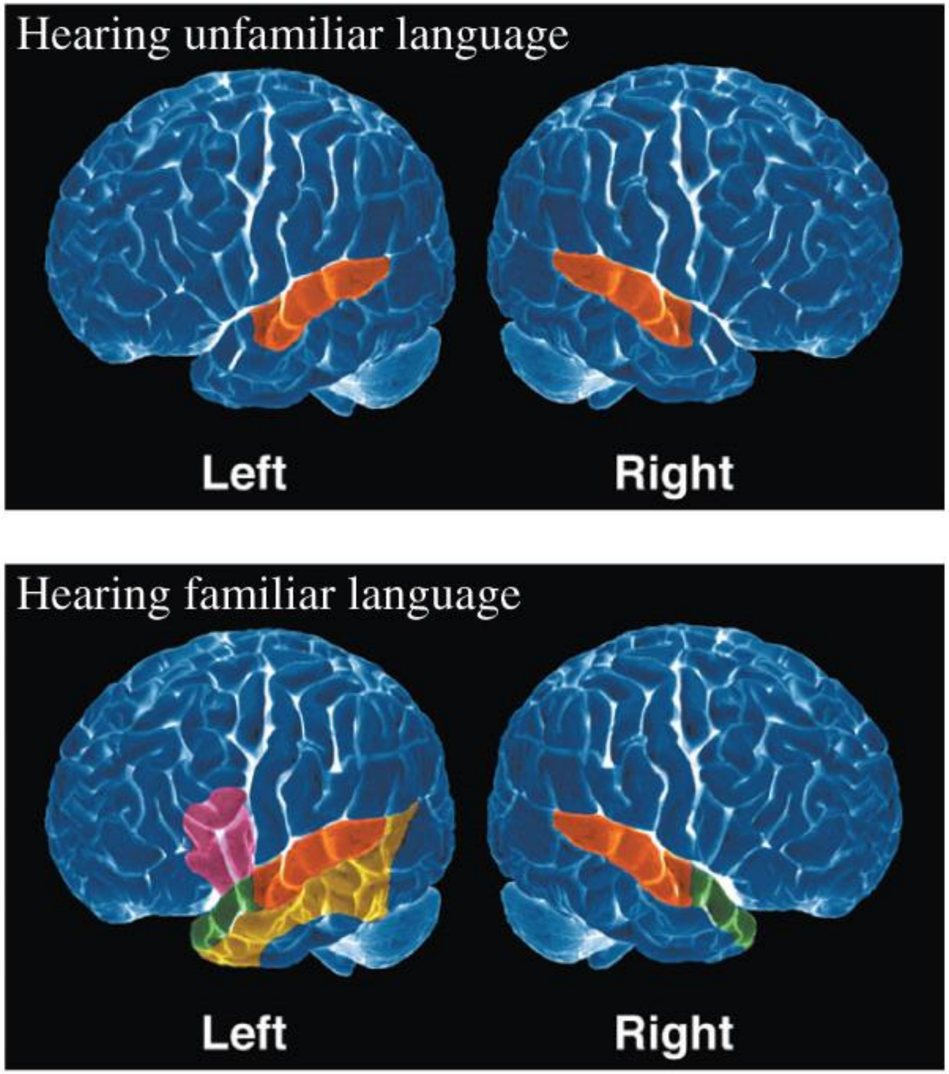


Positron-Emission Tomography



- An analysis of these scans can provide a conclusive diagnosis of stroke, injury, or Alzheimer's disease.

Positron-Emission Tomography



Example Problem

A passenger on an airplane flying across the Atlantic will receive an extra radiation dose of about 5 microsieverts per hour from cosmic rays. How many hours of flying would it take in one year for a person to double her yearly radiation dose? Assume there are no other significant radiation sources besides natural background.

Section 30.7 The Ultimate Building Blocks of Matter

The Ultimate Building Blocks of Matter

- **Particle physics** is the branch of physics that deals with the basic constituents of matter and the relationships between them. It starts with the atom, the proton, the neutron, and the electron.
- **Subatomic particles** are particles below the scale of the atom.

Antiparticles

- Every subatomic particle discovered has an antiparticle twin that has the same mass with the same spin but opposite charge.
- There are positrons, antiprotons, antineutrons (also neutral, but not the same as regular neutrons), and antimatter versions of the various subatomic particles we will discuss.
- A proton is represented as p, an antiproton as $\bar{p}$.

Antiparticles

- When a particle and its antiparticle meet, the two annihilate, leaving nothing but energy behind.
- Sometimes the energy is emitted as gamma rays and sometimes it is used to create other particles.
- A *particle collider* uses electric and magnetic fields to accelerate particles and their antiparticles to speeds close to the speed of light. When they collide and annihilate, they produce exotic particles, many of which do not live more than a trillionth of a second.
- These subatomic particles include pions, kaons, lambda particles, and more, as well as their antiparticles.

Example 30.14 Determining a possible outcome of a proton-antiproton collision

When a proton and an antiproton annihilate, the resulting energy can be used to create new particles. One possibility is the creation of electrically neutral particles called *neutral pions*. A neutral pion has a rest mass of 135 MeV/c^2. How many neutral pions could be produced in the annihilation of a proton and an antiproton? Assume the proton and antiproton are moving very slowly as they collide.

Example 30.14 Determining a possible outcome of a proton-antiproton collision (cont.)

PREPARE The mass of a proton is given in Table 30.2 as 938 MeV/c^2. The mass of an antiproton is the same. Because the proton and antiproton are moving slowly, with essentially no kinetic energy, the total energy available for creating new particles is the energy equivalent of the masses of the proton and the antiproton.

Example 30.14 Determining a possible outcome of a proton-antiproton collision (cont.)

SOLVE The total energy from the annihilation of a proton and an antiproton is the energy equivalent of their masses:

$$E = (m_{\text{proton}} + m_{\text{antiproton}})c^2$$

$$= (938\ \text{MeV}/c^2 + 938\ \text{MeV}/c^2)c^2 = 1876\ \text{MeV}$$

Example 30.14 Determining a possible outcome of a proton-antiproton collision (cont.)

It takes 135 MeV to create a neutral pion. The ratio

$$\frac{\text{energy available}}{\text{energy required to create a pion}} = \frac{1876\ \text{MeV}}{135\ \text{MeV}} = 13.9$$

tells us that we have enough energy to produce 13 neutral pions from this process, but not quite enough to produce 14.

Example 30.14 Determining a possible outcome of a proton-antiproton collision (cont.)

ASSESS Because the mass of a pion is much less than that of a proton or an antiproton, the annihilation of a proton and antiproton can produce many more pions than the number of particles at the start. Though the production of 13 neutral pions is a possible outcome of a proton-antiproton interaction, it is not a likely one. In addition to the conservation of energy, there are many other physical laws that determine what types of particles, and in what quantities, are likely to be produced.

Neutrinos

- The **neutrino** is the most abundant particle in the universe. It is *nearly* massless and interacts weakly with matter.
- The neutrino is represented by v.
- There are three types of neutrinos. The type involved in beta decay is the *electron neutrino* v_e. It shows up in processes involving electrons and positrons.
- The full descriptions of the beta-minus and beta-plus decays, including neutrinos, are

$$n \longrightarrow p^+ + e^- + \bar{\nu}_e$$

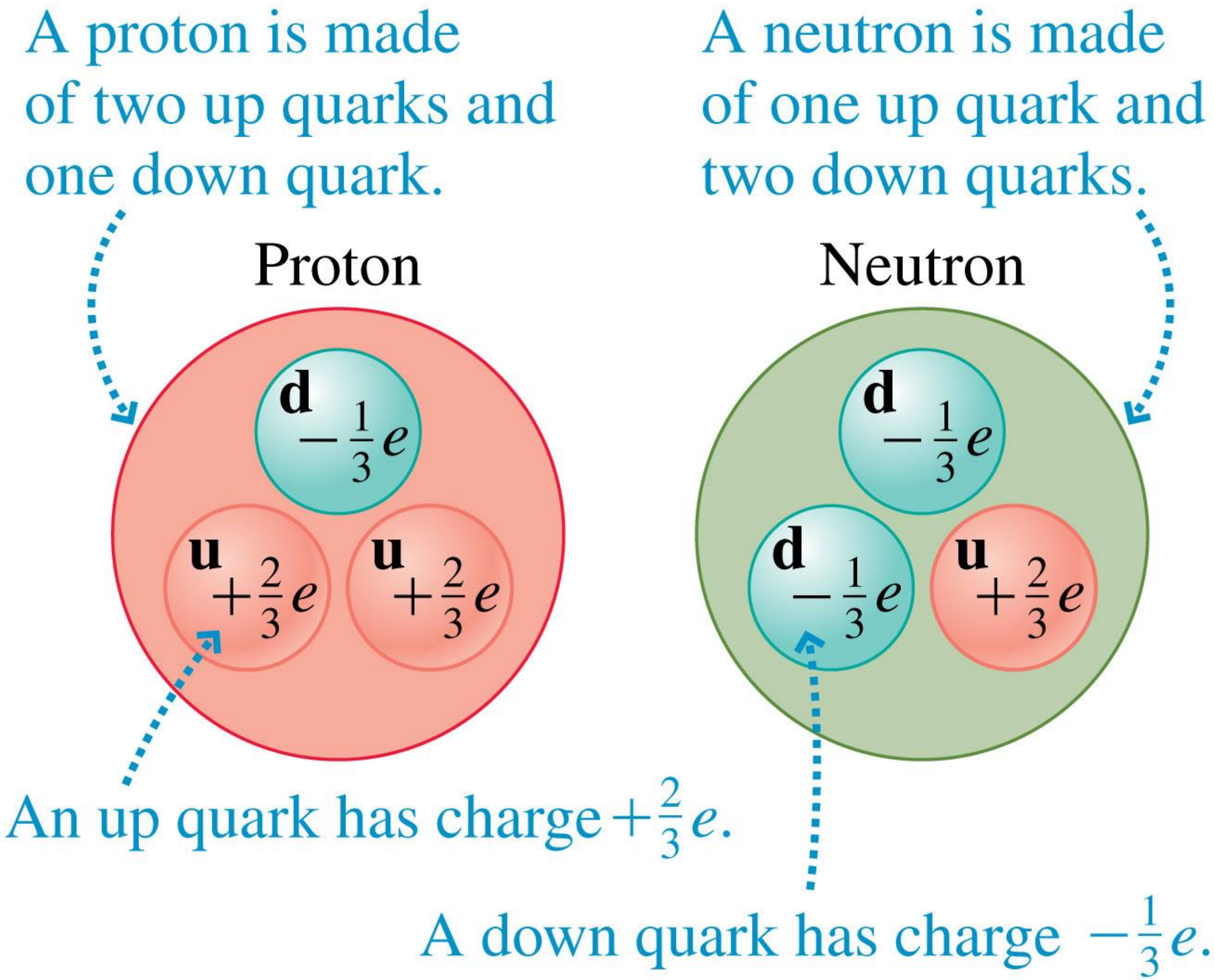
$$p^+ \longrightarrow n + e^+ + \nu_e$$

Quarks

- Protons and neutrons are composed of smaller charged particles named **quarks**. The quarks that form the protons and neutrons are called **up quarks** and **down quarks**, symbolized as u and d, respectively.
- A neutron and a proton differ by one quark.
- Beta decay can then be understood as a process in which a down quark changes to an up quark, or vice versa.
- Beta-minus decay can then be written as

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Quarks



The quark content of the proton and neutron.

Conceptual Example 30.15 Quarks and beta-plus decay

What is the quark description of beta-plus decay?

REASON with the emission of a positron and an electron neutrino. To turn a proton into a neutron requires the conversion of an up quark into a down quark; the total reaction is thus

$$u \rightarrow d + e^{+} + \nu_e$$

Fundamental Particles

- Our understanding of the truly *fundamental particles*—the ones that cannot be broken down into subunits—is that they come in two types: **leptons** and quarks.
- Leptons are particles like the electron and neutrino.
- Quarks combine to make particles like protons and neutrons.

TABLE 30.5 Leptons and quarks

Leptons		Antileptons	
Electron	e^-	Positron	e^+
Electron neutrino	ν_e	Electron antineutrino	$\bar{\nu}_e$
Muon	μ^-	Antimuon	μ^+
Muon neutrino	ν_μ	Muon antineutrino	$\bar{\nu}_\mu$
Tau	τ^-	Antitau	τ^+
Tau neutrino	ν_τ	Tau antineutrino	$\bar{\nu}_\tau$

Quarks		Antiquarks	
Up	u	Antiup	$\bar{u}$
Down	d	Antidown	$\bar{d}$
Strange	s	Antistrange	$\bar{s}$
Charm	c	Anticharm	$\bar{c}$
Bottom	b	Antibottom	$\bar{b}$
Top	t	Antitop	$\bar{t}$

Fundamental Particles

- Important features of leptons and quarks include:
  - Each particle has an associated antiparticle.
  - There are three *families* of leptons. The first is the electron and its associated neutrino, and their antiparticles. The other families are based on the muon and the tau, heavier siblings to the electron. Only the electron and positron are stable.
  - There are also three families of quarks. The first is the up-down family that makes all "normal" matter. The other families are pairs of heavier quarks that form more exotic particles.

Fundamental Particles

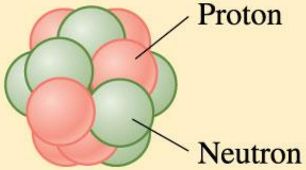
- Quarks and electrons seem to be truly fundamental.
- However, new tools such as the next generation of particle colliders will provide new discoveries and new surprises.

Summary: General Principles

The Nucleus

The nucleus is a small, dense, positive core at the center of an atom.

Z protons, charge $+e$, spin $\frac{1}{2}$
N neutrons, charge 0, spin $\frac{1}{2}$



The **mass number** is

$$A = Z + N$$

Isotopes of an element have the same value of Z but different values of N.

The strong force holds nuclei together:

- It acts between any two nucleons.
- It is short range.

Adding neutrons to a nucleus allows the strong force to overcome the repulsive Coulomb force between protons.

The **binding energy** B of a nucleus depends on the mass difference between an atom and its constituents:

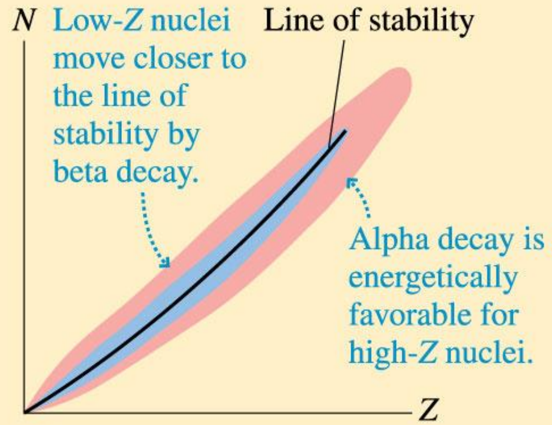
$$B = (Zm_{\mathrm{H}} + Nm_{\mathrm{n}} - m_{\mathrm{atom}}) \times (931.49 \text{ MeV/u})$$

Text: p. 1001

Summary: General Principles

Nuclear Stability

Most nuclei are not **stable.** Unstable nuclei undergo **radioactive decay.** Stable nuclei cluster along the **line of stability** in a plot of the isotopes.



Mechanisms by which unstable nuclei decay:

Decay	Particle
alpha	^{4}He nucleus
beta-minus	e^-
beta-plus	e^+
gamma	photon

Alpha and beta decays change the nucleus; the daughter nucleus is a different element.

Alpha decay:

$$^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + \alpha + \text{energy}$$

Beta-minus decay:

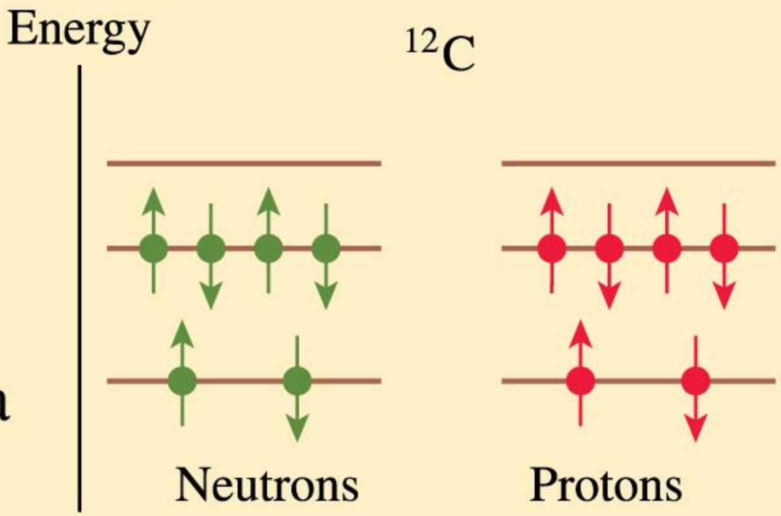
$$^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + \beta + \text{energy}$$

Text: p. 1001

Summary: Important Concepts

Energy levels

Nucleons fill nuclear energy levels, similar to filling electron energy levels in atoms. Nucleons can often jump to lower energy levels by emitting beta particles or gamma photons.



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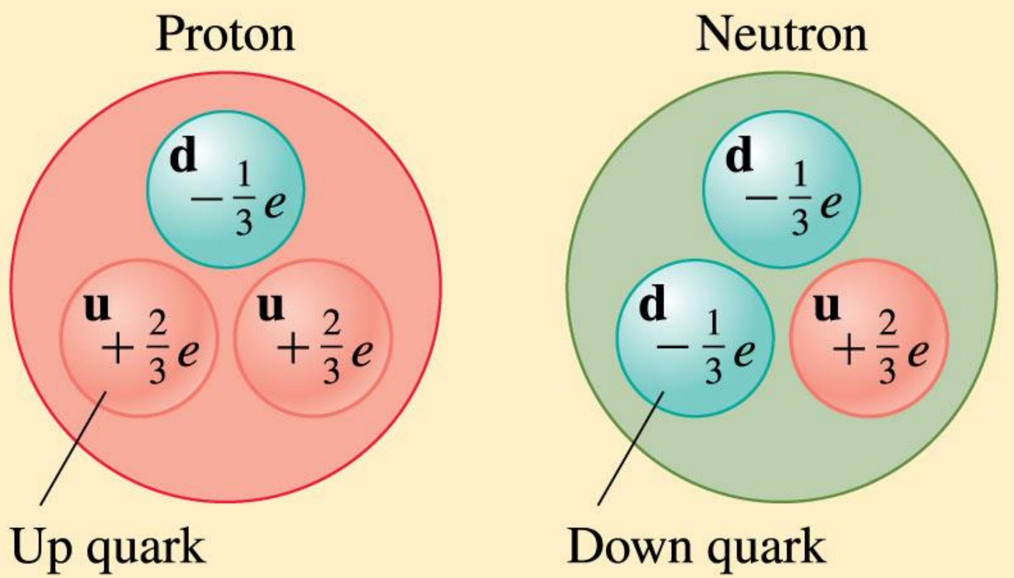
Summary: Important Concepts

Quarks

Nucleons (and other particles) are made of quarks. Quarks and leptons are fundamental particles.



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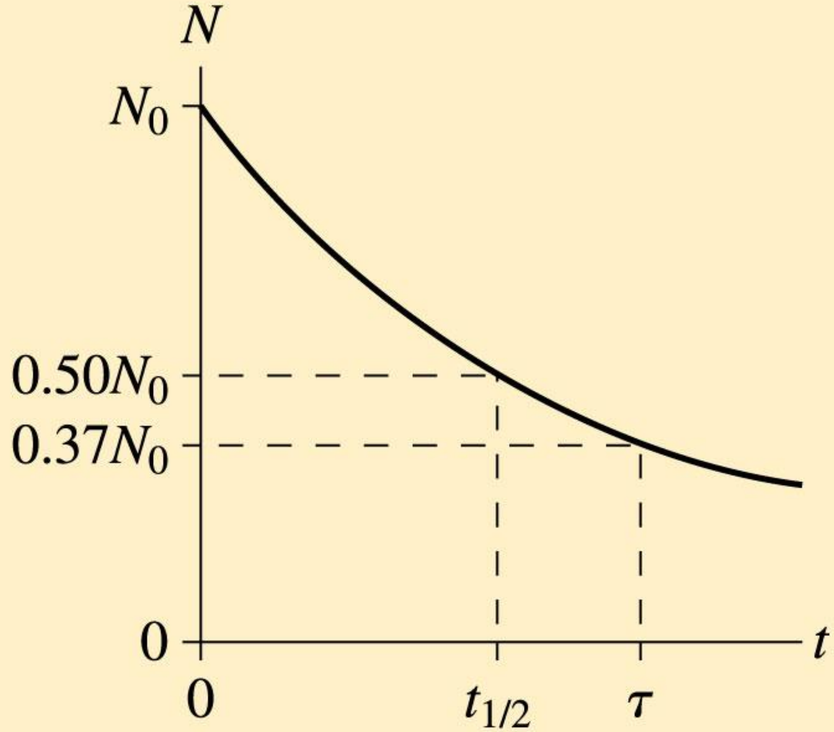
Summary: Applications

Radioactive decay

The number of undecayed nuclei decreases exponentially with time t:

$$N = N_0 e^{-t/\tau}$$

$$N = N_0\left(\frac{1}{2}\right)^{t/t_{1/2}}$$



The **half-life**

$$t_{1/2} = \tau \ln 2 = 0.693\tau$$

is the time in which half of any sample decays.

Text: p. 1001

Summary: Applications

Measuring radiation

The **activity** of a radioactive sample is the number of decays per second. Activity is related to the half-life as

$$R = \frac{0.693N}{t_{1/2}} = \frac{N}{\tau}$$

The radiation **dose** is measured in grays, where

$$1 \text{ Gy} = 1.00 \text{ J/kg of absorbed energy}$$

The **relative biological effectiveness** (RBE) is the biological effect of a dose relative to the biological effects of x rays. The **dose equivalent** is measured in sieverts, where

$$\text{dose equivalent in Sv} = \text{dose in Gy} \times \text{RBE}$$

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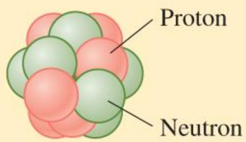

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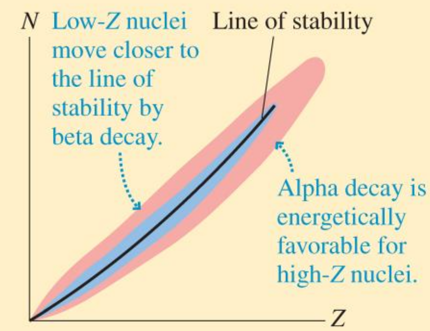

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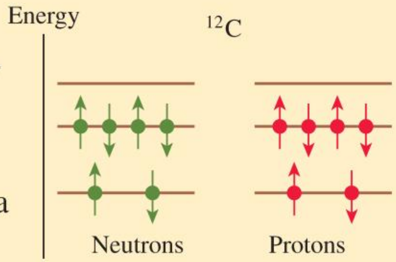

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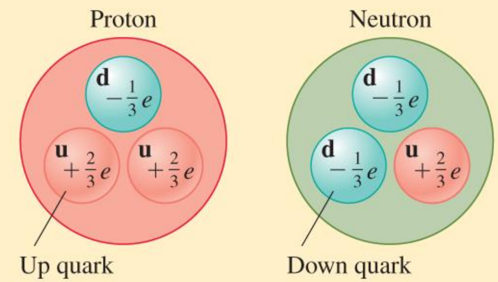

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Summary

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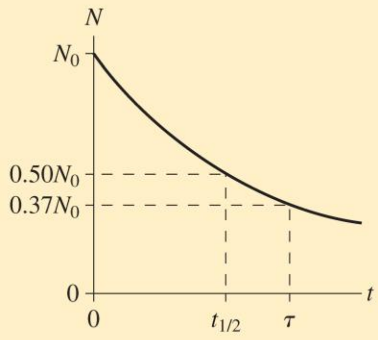

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