Material particles and light have both wave properties and particle properties.
Atomic structure is revealed by analyzing light. Light has a dual nature, which in turn radically alters our understanding of the atomic world.
Through the centuries there have been two primary models of light: the particle model and the wave model.
38 The Atom and the Quantum

38.1 Models

Nobody knows what an atom’s internal structure looks like, for there is no way to see it with our eyes. To visualize the processes that occur in the subatomic realm, we construct models.

The planetary model in which electrons orbit the nucleus was suggested by the Danish physicist Niels Bohr in 1913. It is still useful for understanding the emission of light.
38.1 Models

The planetary model has been replaced by a more complex model in which the electrons are represented as clouds.
38.1 Models

Models help us to understand processes that are difficult to visualize.

A useful model of the atom must be consistent with a model for light.

Most of what we know about atoms we learn from the light and other radiations they emit.

Most light comes from the motion of electrons within the atom.
There have been two primary models of light: the particle model and the wave model.

- Isaac Newton believed light was composed of tiny particles.
- Christian Huygens believed that light was a wave phenomenon.
38.1 Models

The wave model was reinforced when Thomas Young demonstrated constructive and destructive interference of light.

Later, James Clerk Maxwell proposed that light is an electromagnetic wave.

The wave model gained further support when Heinrich Hertz produced radio waves that behaved as Maxwell had predicted.

In 1905, Albert Einstein resurrected the particle theory of light.
What are the two primary models of light?
38.2 Light Quanta

The energy of a photon is directly proportional to the photon’s frequency.
38.2 Light Quanta

Einstein visualized particles of light as concentrated bundles of electromagnetic energy. Max Planck had proposed that atoms do not emit and absorb light continuously, but do so in little chunks. Each chunk was considered a quantum, or a fundamental unit.
38.2 Light Quanta

Planck believed that light existed as continuous waves, but that emission and absorption occurred in quantum chunks. Einstein went further and proposed that light itself is composed of quanta.

One quantum of light energy is now called a photon.
38 The Atom and the Quantum

38.2 Light Quanta

Matter is quantized, equal to some whole-number multiple of the mass of a single atom.
Electric charge is quantized as a multiple of the charge of a single electron.
Other quantities such as energy and angular momentum are quantized.
38.2 Light Quanta

The energy in a light beam is quantized and comes in packets, or quanta; only a whole number of quanta can exist.

- The quanta of electromagnetic radiation are the photons.
- Photons have no rest energy.
- They move at the speed of light so the total energy of a photon is the same as its kinetic energy.
38.2 Light Quanta

The energy of a photon of light is proportional to its vibrational frequency.

- When the energy $E$ of a photon is divided by its frequency $f$, the quantity that results is known as Planck’s constant, $h$.
- This quantity is always the same, no matter what the frequency.
- The energy of every photon is therefore $E = hf$.
- This equation gives the smallest amount of energy that can be converted to light of frequency $f$. 

![Diagram showing red and blue photons with captions: 
RED PHOTON—LONG WAVELENGTH LOW FREQUENCY 
BLUE PHOTON—SHORT WAVELENGTH HIGH FREQUENCY]
38.2 Light Quanta

How is the energy of a photon related to its frequency?
The photoelectric effect suggests that light interacts with matter as a stream of particle-like photons.
38.3 The Photoelectric Effect

Einstein found support for his quantum theory of light in the photoelectric effect.

The **photoelectric effect** is the ejection of electrons from certain metals when light falls upon them. These metals are said to be *photosensitive*. 
38.3 The Photoelectric Effect

Explanation of the Photoelectric Effect

Energy from the light shining on a metal plate gives electrons bound in the metal enough energy to escape.

- High-frequency light, even from a dim source, is capable of ejecting electrons from a photosensitive metal surface.
- Low-frequency light, even from a very bright source, cannot dislodge electrons.
- Since bright light carries more energy than dim light, it was puzzling that dim blue light could dislodge electrons when bright red light could not.
38.3 The Photoelectric Effect

Einstein explained the photoelectric effect in terms of photons.

• The absorption of a photon by an atom in the metal surface is an all-or-nothing process.
• Only one photon is absorbed by each electron ejected from the metal.
• The *number* of photons that hit the metal has nothing to do with whether a given electron will be ejected.
• If the energy in the photon is large enough, the electron will be ejected from the metal.
38.3 The Photoelectric Effect

The intensity of light does not matter. From $E = hf$, the critical factor is the frequency, or color, of the light.

- Each blue or violet light photon carries enough energy to free an electron from the metal.
- A few photons of blue or violet light can eject a few electrons. Many red or orange photons cannot eject a single electron.
- Only high-frequency photons have the energy needed to pull loose an electron.
38.3 The Photoelectric Effect

Support for the Particle Model of Light

The energy of a wave is spread out along a broad front. For the energy of a light wave to be concentrated enough to eject a single electron from a metal surface is unlikely. The photoelectric effect suggests that light interacts with matter as a stream of particle-like photons.
The number of photons in a light beam controls the brightness of the *whole* beam.

The frequency of the light controls the energy of each *individual* photon.

Experimental verification of Einstein’s explanation was made 11 years later by the American physicist Robert Millikan. Every aspect of Einstein’s interpretation was confirmed, including the direct proportionality of photon energy to frequency.
38.3 The Photoelectric Effect

think!

Will high-frequency light eject a greater number of electrons than low-frequency light?
38.3 The Photoelectric Effect

**think!**

Will high-frequency light eject a greater number of electrons than low-frequency light?

**Answer:**

Not necessarily. The answer is yes if electrons are ejected by the high-frequency light but not by the low-frequency light, because its photons do not have enough energy. If the light of both frequencies can eject electrons, then the number of electrons ejected depends on the brightness of the light, not on its frequency.
What does the photoelectric effect suggest about the way light interacts with matter?
38 The Atom and the Quantum

38.4 Waves as Particles

Light behaves like waves when it travels in empty space, and like particles when it interacts with solid matter.
38.4 Waves as Particles

A photograph taken with exceedingly feeble light provides a striking example of the particle nature of light. The image progresses photon by photon. Photons seem to strike the film in an independent and random manner.
38.4 Waves as Particles

What causes light to behave like a wave? Like a particle?
38.5 Particles as Waves

De Broglie suggested that all matter could be viewed as having wave properties.
If waves can have particle properties, cannot particles have wave properties?

This question was posed by the French physicist Louis de Broglie and his answer later won the Nobel Prize in physics. De Broglie suggested that all matter could be viewed as having wave properties.

38.5 Particles as Waves

Light quanta, electrons, and other particles all behave in some ways as if they were lumps and in other ways as if they were waves.
38.5 Particles as Waves

All particles—electrons, protons, atoms, marbles, and even humans—have a wavelength:

\[
\text{wavelength} = \frac{h}{\text{momentum}}
\]

where \( h \) is Planck’s constant.
The wavelength of a particle is called the \textit{de Broglie wavelength}.

- A particle of large mass and ordinary speed has too small a wavelength to be detected by conventional means.
- A tiny particle—such as an electron—moving at typical speed has a detectable wavelength.
38.5 *Particles as Waves*

The wavelength of electrons is smaller than the wavelength of visible light but large enough for noticeable diffraction. A beam of electrons can be diffracted and undergoes wave interference under the same conditions that light does.
38.5 Particles as Waves

a. The diffraction of an electron beam produces an interference pattern.
38.5 **Particles as Waves**

a. The diffraction of an electron beam produces an interference pattern.

b. The fringes produced by a beam of light are very similar to those produced by the beam of electrons.

![Image a](image1.png) ![Image b](image2.png)
38.5 Particles as Waves

An electron microscope uses the wave nature of electrons.

- The wavelength of electron beams is typically thousands of times shorter than the wavelength of visible light.
- The electron microscope is able to distinguish details thousands of times smaller than is possible with optical microscopes.
What did de Broglie suggest about all matter?
According to de Broglie’s theory of matter waves, electron orbits exist only where an electron wave closes in on itself in phase.
38.6 **Electron Waves**

The planetary model of the atom was useful in explaining the atomic spectra of the elements and why elements emitted only certain frequencies of light.

- An electron has different amounts of energy when it is in different orbits around a nucleus.
- An electron is in a different *energy level* when it is in a different orbit.
- Electrons in an atom normally occupy the lowest energy levels available.
38.6 Electron Waves

In the Bohr model of the atom, the electron orbits correspond to different energy levels.
Bohr Model Explanation of Atomic Spectra

An electron can be boosted to a higher energy level.

- This occurs in gas discharge tubes such as neon signs.
- Electric current boosts electrons of the gas to higher energy levels.
- As the electrons return to lower levels, photons are emitted.
- The energy of a photon is exactly equal to the difference in the energy levels in the atom.
38.6 Electron Waves

The pattern of lines in the spectrum of an element corresponds to electron transitions between the energy levels of the atoms of that element.

By examining spectra, physicists were able to determine the various energy levels in the atom.
38.6 Electron Waves

Why were electrons at discrete distances from the atomic nucleus?

This was resolved by thinking of the electron not as a particle whirling around the nucleus but as a wave. According to de Broglie’s theory of matter waves, electron orbits exist only where an electron wave closes in on itself in phase.
38.6 Electron Waves

De Broglie’s Theory

The electron wave reinforces constructively in each cycle, like the standing wave on a music string.
The electron is visualized not as a particle located at some point in the atom.

- Its mass and charge are spread throughout a standing wave surrounding the nucleus.
- The wavelength of the electron wave must fit evenly into the circumferences of the orbits.
38.6 Electron Waves

De Broglie suggested electrons have a wavelength.

a. Electron orbits exist only when the circumference of the orbit is a whole-number multiple of the wavelength.
38.6 Electron Waves

De Broglie suggested electrons have a wavelength.

a. Electron orbits exist only when the circumference of the orbit is a whole-number multiple of the wavelength.

b. When the wave does not close in on itself in phase, it undergoes destructive interference.
38.6 Electron Waves

The circumference of the innermost orbit, according to this model, is equal to one wavelength of the electron wave. The second orbit has a circumference of two electron wavelengths, the third three, and so on.
38.6 Electron Waves

Orbit circumferences are whole-number multiples of the electron wavelengths, which differ for the various elements.

This results in discrete energy levels, which characterize each element.

Since the circumferences of electron orbits are discrete, the radii of these orbits, and hence the energy levels, are also discrete.

Both artists and scientists look for patterns in nature, finding connections that have always been there yet have been missed by the eye.
38.6 Electron Waves

In this simplified version of de Broglie’s theory of the atom, the waves are shown only in circular paths around the nucleus. In an actual atom, the standing waves make up spherical and ellipsoidal shells rather than flat, circular ones.
38.6 Electron Waves

This explains why electrons do not spiral closer and closer to the nucleus when photons are emitted. Since an orbit is described by a standing wave, the circumference of the smallest orbit can be no smaller than one wavelength.

In the modern wave model of the atom, electron waves also move in and out, toward and away from the nucleus. The electron wave is in three dimensions, an electron “cloud.”
38.6 Electron Waves

How did de Broglie’s theory of matter waves describe electron orbits?
38.7 Relative Sizes of Atoms

The radii of the electron orbits in the Bohr model of the atom are determined by the amount of electric charge in the nucleus.
38.7 Relative Sizes of Atoms

The single proton in the hydrogen atom holds one negatively charged electron in an orbit at a particular radius. In helium, the orbiting electron would be pulled into a tighter orbit with half its former radius since the electrical attraction is doubled. This doesn’t quite happen because the double-positive charge in the nucleus attracts and holds a second electron. The negative charge of the second electron diminishes the effect of the positive nucleus.
38.7 Relative Sizes of Atoms

This added electron makes the atom electrically neutral. The two electrons assume an orbit characteristic of helium. In a lithium atom, an additional proton pulls the electrons into an even closer orbit and holds a third electron in a second orbit.
38.7 Relative Sizes of Atoms

As the nuclear charge increases, the inner orbits shrink because of the stronger electrical attraction to the nucleus. This means that the heavier elements are not much larger in diameter than the lighter elements. The diameter of the uranium atom, for example, is only about three hydrogen diameters, even though it is 238 times more massive.
38.7 Relative Sizes of Atoms

Each element has a unique arrangement of electron orbits. The radii of orbits for the sodium atom are the same for all sodium atoms, but different from the radii of orbits for other kinds of atoms. Each element has its own distinct orbits.
38.7 Relative Sizes of Atoms

The Bohr model solved the mystery of the atomic spectra of the elements.

It accounted for X-rays that were emitted when electrons made transitions from outer orbits to innermost orbits.

Bohr was able to predict X-ray frequencies that were later experimentally confirmed.
38.7 Relative Sizes of Atoms

Bohr calculated the *ionization energy* of the hydrogen atom—the energy needed to knock the electron out of the atom completely.

This also was verified by experiment.

The model accounted for the chemical properties of the elements and predicted properties of hafnium, which led to its discovery.
38.7 Relative Sizes of Atoms

Bohr was quick to point out that his model was to be interpreted as a crude beginning. The picture of electrons whirling like planets about the sun was not to be taken literally. His discrete orbits were conceptual representations of an atom whose later description involved a wave description.
38.7 Relative Sizes of Atoms

a. In the Bohr model, the electrons orbit the nucleus like planets going around the sun.
38.7 Relative Sizes of Atoms

a. In the Bohr model, the electrons orbit the nucleus like planets going around the sun.

b. According to de Broglie’s idea, a wave follows along an orbit.
38.7 Relative Sizes of Atoms

a. In the Bohr model, the electrons orbit the nucleus like planets going around the sun.

b. According to de Broglie’s idea, a wave follows along an orbit.

c. The wave model—electrons are distributed in a “cloud” throughout the volume of the atom.
38.7 Relative Sizes of Atoms

think!

What fundamental force dictates the size of an atom?
38.7 Relative Sizes of Atoms

think!

What fundamental force dictates the size of an atom?

Answer:
The electrical force.
What determines the radii of the electron orbits in the Bohr model of the atom?
The subatomic interactions described by quantum mechanics are governed by laws of probability, not laws of certainty.
Physicists became convinced that the Newtonian laws that work so well for large objects do not apply to the microworld of the atom.

In the macroworld, the study of motion is called *mechanics*, or sometimes classical mechanics. The study of the motion of particles in the microworld of atoms and nuclei is called *quantum mechanics*. The branch of physics that is the general study of the microworld of photons, atoms, and nuclei is simply called *quantum physics*. 
38.8 Quantum Physics

There are fundamental uncertainties in the measurements of the atomic domain.

For the measurement of macroscopic quantities, such as the temperature of materials or the speeds of light and sound, there is no limit to the accuracy with which the experimenter can measure.
38.8 Quantum Physics

Subatomic measurements, such as the momentum and position of an electron or the mass of an extremely short-lived particle, are entirely different. In this domain, the uncertainties in many measurements are comparable to the magnitudes of the quantities themselves. The subatomic interactions described by quantum mechanics are governed by laws of probability, not laws of certainty.
What laws govern the interactions described by quantum mechanics?
Predictability in orderly systems, both Newtonian and quantum, depends on knowledge of initial conditions.
38.9 Predictability and Chaos

When we know the initial conditions of an orderly system we can make predictions about it.

Knowing the initial conditions lets us state where a planet will be after a certain time or where a launched rocket will land.

In the quantum microworld, we give odds where an electron is likely to be. We calculate the probability that a radioactive particle will decay in a given time interval.
Some systems, however, whether Newtonian or quantum, are not orderly—they are inherently unpredictable. These are called “chaotic systems.”

A feature of chaotic systems is that slight differences in initial conditions result in wildly different outcomes later.
38.9 Predictability and Chaos

Weather is chaotic. Small changes in one day’s weather can produce big (and largely unpredictable) changes a week later.

This barrier to good prediction first led the scientist Edward Lorenz to ask, “Does the flap of a butterfly’s wings in Brazil set off a tornado in Texas?”

Now we talk about the butterfly effect when dealing with situations where very small effects can amplify into very big effects.
38.9 Predictability and Chaos

What determines predictability in orderly systems?
Assessment Questions

1. A model of an atom is useful when it
   a. shows exactly what an atom looks like.
   b. magnifies what the eye can't see.
   c. helps to visualize processes that cannot be seen with our eyes.
   d. is shown only as the planetary model.
Assessment Questions

1. A model of an atom is useful when it
   a. shows exactly what an atom looks like.
   b. magnifies what the eye can’t see.
   c. helps to visualize processes that cannot be seen with our eyes.
   d. is shown only as the planetary model.

Answer: C
Assessment Questions

2. In the equation $E = hf$, $f$ stands for the
   a. frequency of a photon with energy $E$.
   b. wavelength of a photon with energy $E$.
   c. Planck’s constant with energy $h$.
   d. quantum of energy.
Assessment Questions

2. In the equation $E = hf$, $f$ stands for the
   a. frequency of a photon with energy $E$.
   b. wavelength of a photon with energy $E$.
   c. Planck’s constant with energy $h$.
   d. quantum of energy.

Answer: A
Assessment Questions

3. Which of these photons is more likely to initiate the photoelectric effect?
   a. red
   b. green
   c. blue
   d. violet
Assessment Questions

3. Which of these photons is more likely to initiate the photoelectric effect?
   a. red
   b. green
   c. blue
   d. violet

Answer: D
Assessment Questions

4. Which of these best illustrates the dual nature of light?

a. Light travels as a wave and interacts with solid matter like a particle.

b. Light travels as a particle and interacts with solid matter like a wave.

c. Light can interact in empty spaces as do particles, and travel around solid matter as do waves.

d. Light does not have a dual nature.
Assessment Questions

4. Which of these best illustrates the dual nature of light?
   a. Light travels as a wave and interacts with solid matter like a particle.
   b. Light travels as a particle and interacts with solid matter like a wave.
   c. Light can interact in empty spaces as do particles, and travel around solid matter as do waves.
   d. Light does not have a dual nature.

Answer: A
Assessment Questions

5. The wavelength of a matter wave is
   a. directly proportional to its momentum.
   b. inversely proportional to its momentum.
   c. equal to its momentum.
   d. theoretical only.
Assessment Questions

5. The wavelength of a matter wave is
   a. directly proportional to its momentum.
   b. inversely proportional to its momentum.
   c. equal to its momentum.
   d. theoretical only.

Answer: B
6. The view of radii of electrons about the atomic nucleus is nicely understood by thinking of the electrons as
   a. standing waves.
   b. discrete particles.
   c. resonating vibrations.
   d. reflections.
Assessment Questions

6. The view of radii of electrons about the atomic nucleus is nicely understood by thinking of the electrons as
   a. standing waves.
   b. discrete particles.
   c. resonating vibrations.
   d. reflections.

Answer: A
Assessment Questions

7. The greater the number of protons in a nucleus, the
   a. larger the orbits of the outermost electron.
   b. tighter the orbits of all electrons.
   c. looser inner orbits become.
   d. more electrically neutral the atom becomes.
Assessment Questions

7. The greater the number of protons in a nucleus, the
   a. larger the orbits of the outermost electron.
   b. tighter the orbits of all electrons.
   c. looser inner orbits become.
   d. more electrically neutral the atom becomes.

Answer: B
Assessment Questions

8. Subatomic interactions described by quantum mechanics are governed by
   a. the same laws of classical physics.
   b. laws of certainty.
   c. laws of probability.
   d. exact measurements.
Assessment Questions

8. Subatomic interactions described by quantum mechanics are governed by
   a. the same laws of classical physics.
   b. laws of certainty.
   c. laws of probability.
   d. exact measurements.

Answer: C
A feature of chaotic systems is that small changes in initial conditions

a. lead to small differences later.
b. lead to big differences later.
c. may lead to big differences later.
d. have little or no relation to small or big differences later.
Assessment Questions

9. A feature of chaotic systems is that small changes in initial conditions
   a. lead to small differences later.
   b. lead to big differences later.
   c. may lead to big differences later.
   d. have little or no relation to small or big differences later.

Answer: C
Certain elements radiate particles and turn into other elements.
The idea that atoms are indivisible changed in 1896 when the French physicist Henri Becquerel discovered that some unused photographic plates had been exposed by particles coming from a piece of uranium. Understanding how atoms can change requires looking deep into the structure of the atom—into the atomic nucleus.
The principal role of the neutrons in an atomic nucleus is to act as a sort of nuclear cement to hold the nucleus together.
39.1 The Atomic Nucleus

It would take 30,000 carbon nuclei to stretch across a single carbon atom.

The nucleus is composed of particles called nucleons—electrically charged protons and electrically neutral neutrons.

Neutrons and protons have close to the same mass, with the neutron’s being slightly greater.

Nucleons have nearly 2000 times the mass of electrons. The mass of an atom is practically equal to the mass of its nucleus alone.
39.1 The Atomic Nucleus

The positively charged protons in the nucleus hold the negatively charged electrons in their orbits. The number of protons in the nucleus therefore determines the chemical properties of that atom. The positive nuclear charge determines the possible structures of electron orbits that can occur. The number of neutrons has no direct effect on the electron structure, and hence does not affect the chemistry of the atom.
39.1 The Atomic Nucleus

The number of electrons that surround the atomic nucleus is matched by the number of protons in the nucleus.
39.1 The Atomic Nucleus

Nucleons are bound together by an attractive nuclear force appropriately called the **strong force**.

- The nuclear force of attraction is strong only over a very short distance (large force vectors).
39.1 The Atomic Nucleus

Nucleons are bound together by an attractive nuclear force appropriately called the \textbf{strong force}.

- The nuclear force of attraction is strong only over a very short distance (large force vectors).
- When two nucleons are just a few nucleon diameters apart, the nuclear force they exert on each other is nearly zero (small force vectors).
39.1 The Atomic Nucleus

Nucleons are bound together by an attractive nuclear force appropriately called the **strong force**.

- The nuclear force of attraction is strong only over a very short distance (large force vectors).
- When two nucleons are just a few nucleon diameters apart, the nuclear force they exert on each other is nearly zero (small force vectors).
- This means that if nucleons are to be held together by the strong force, they must be held in a very small volume.
- Nuclei are tiny because the nuclear force is very short-range.

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![Diagram of nucleons bound together by strong force]
39.1 The Atomic Nucleus

Meanwhile, the electrical force acts as a repulsive force between protons that are not in direct contact with one another.

Stability is due to a tension between the strong force’s tendency to hold the nucleus together and the electrical force’s tendency to blow it apart.

A nucleus needs a certain balance of neutrons and protons for stability.
39.1 The Atomic Nucleus

Although the nuclear force is strong, it is only barely strong enough to hold a pair of nucleons together.

- For a pair of protons, which repel each other electrically, the nuclear force is not quite strong enough to keep them together.

- When neutrons are present, the attractive strong force is increased relative to the repulsive electrical force.

- The presence of neutrons adds to the nuclear attraction and keeps protons from flying apart.
39.1 The Atomic Nucleus

The more protons there are in a nucleus, the more neutrons are needed to hold them together.

- For light elements, it is sufficient to have about as many neutrons as protons.
- For heavy elements, extra neutrons are required.
- For elements with more than 83 protons, even the addition of extra neutrons cannot completely stabilize the nucleus.
39.1 The Atomic Nucleus

A strong attractive nuclear force acts between nearby protons A and B, but not significantly between A and C. The longer-range electrical force repels protons A and C as well as A and B.
What is the role of neutrons in the nucleus?
39.2 Radioactive Decay

The atoms of radioactive elements emit three distinct types of radiation called *alpha particles*, *beta particles*, and *gamma rays*.
39.2 Radioactive Decay

One factor that limits how many stable nuclei can exist is the instability of the neutron.

A lone neutron will decay into a proton plus an electron (and also an antineutrino, a tiny particle we will not discuss here).

About half of a bunch of lone neutrons will decay in 11 minutes.

Particles that decay by spontaneously emitting charged particles and energy are said to be radioactive.
39.2 Radioactive Decay

Radioactivity is governed by mass-energy equivalence.

- Particles decay spontaneously only when their combined products have less mass after decay than before.
- The mass of a neutron is slightly greater than the total mass of a proton plus electron (and the antineutrino).
- When a neutron decays, there is less mass.
- Decay will not spontaneously occur for reactions where more mass results. A proton decaying into a neutron can occur only with external energy input.
39.2 Radioactive Decay

All elements heavier than bismuth (atomic number 83) decay in one way or another, so these elements are radioactive. **Radiation** is the name given to the charged particles and energy emitted by an unstable nucleus or particle.
39.2 Radioactive Decay

The atoms of radioactive elements emit three distinct types of radiation called *alpha particles*, *beta particles*, and *gamma rays*.

- alpha particles have a positive electric charge
- beta particles are negative
- gamma rays are electrically neutral
39.2 Radioactive Decay

A magnetic field separates alpha and beta particles and gamma rays, all of which come from a radioactive source placed at the bottom of a hole drilled in a lead block.
39.2 Radioactive Decay

An alpha particle is made of two protons and two neutrons and is identical to the nucleus of a helium atom.

A beta particle is simply an electron ejected from the nucleus when a neutron is transformed into a proton.

An electron does not exist in a neutron. The electron that pops out of the neutron is produced during an interaction.
39.2 Radioactive Decay

A gamma ray is massless energy. Like visible light, gamma rays are simply photons, but of much higher frequency and energy.

- Visible light is emitted when electrons jump from one atomic orbit to another of lower energy.
- Gamma rays are emitted when nucleons do a similar sort of thing inside the nucleus.
- There are great energy differences in nuclear energy levels, so the photons emitted carry a large amount of energy.
39.2 Radioactive Decay

A gamma ray is simply electromagnetic radiation, much higher in frequency and energy per photon than light and X-rays.
39.2 Radioactive Decay

think!

The electrical force of repulsion between the protons in a heavy nucleus acts over a greater distance than the attractive forces among the neutrons and protons in the nucleus. Given this fact, explain why all of the very heavy elements are radioactive.
The electrical force of repulsion between the protons in a heavy nucleus acts over a greater distance than the attractive forces among the neutrons and protons in the nucleus. Given this fact, explain why all of the very heavy elements are radioactive.

**Answer:**
In a large nucleus, where protons such as those on opposite sides are far apart, electrical repulsion can exceed nuclear attraction. This instability makes all the heaviest atoms radioactive.
What types of radiation are emitted by the atoms of radioactive elements?
The penetrating power of radiation depends on its speed and its charge.
39.3 Radiation Penetrating Power

There is a great difference in the penetrating power of the three types of radiation.

- Alpha particles are the easiest to stop. They can be stopped by a few sheets of thin paper.
- Beta particles go right through paper but are stopped by several sheets of aluminum foil.
- Gamma rays are the most difficult to stop and require lead or other heavy shielding to block them.
39.3 Radiation Penetrating Power

Alpha particles penetrate least and can be stopped by a few sheets of paper; beta particles by a sheet of aluminum; gamma rays by a thick layer of lead.
39.3 Radiation Penetrating Power

An alpha particle is easy to stop because it is relatively slow and its charge interacts with the molecules it encounters along its path. It slows down as it shakes many of these molecules apart and leaves positive and negative ions in its wake.

Even when traveling through nothing but air, an alpha particle will come to a stop after only a few centimeters. It soon grabs up a couple of stray electrons and becomes nothing more than a harmless helium atom.
39 The Atomic Nucleus and Radioactivity

39.3 **Radiation Penetrating Power**

A beta particle normally moves at a faster speed than an alpha particle and carries only a single negative charge. It is able to travel much farther through the air. Most beta particles lose their energy during the course of a large number of glancing collisions with atomic electrons. Beta particles slow down until they become a part of the material they are in, like any other electron.
Gamma rays are the most penetrating of the three because they have no charge.

A gamma ray photon interacts with the absorbing material only via a direct hit with an atomic electron or a nucleus. Unlike charged particles, a gamma ray photon can be removed from its beam in a single encounter.

Dense materials such as lead are good absorbers mainly because of their high electron density.
39.3 Radiation Penetrating Power

think!

Pretend you are given three radioactive cookies—one alpha, one beta, and the other gamma. Pretend that you must eat one, hold one in your hand, and put the other in your pocket. Which would you eat, hold, and pocket if you were trying to minimize your exposure to radiation?
39.3 Radiation Penetrating Power

Think!

Pretend you are given three radioactive cookies—one alpha, one beta, and the other gamma. Pretend that you must eat one, hold one in your hand, and put the other in your pocket. Which would you eat, hold, and pocket if you were trying to minimize your exposure to radiation?

Answer:

If you must, then hold the alpha; the skin on your hand will shield you. Put the beta in your pocket; your clothing will likely shield you. Eat the gamma; it will penetrate your body anyway. (In real life, always use appropriate safeguards when near radioactive materials.)
What factors determine the penetrating power of radiation?
39.4 Radioactive Isotopes

Isotopes of an element are chemically identical but differ in the number of neutrons.
39.4 Radioactive Isotopes

In a neutral atom, the number of protons in the nucleus determines the number of electrons surrounding the nucleus.
39.4 Radioactive Isotopes

In a neutral atom, the number of protons in the nucleus determines the number of electrons surrounding the nucleus. If there is a difference in the number of electrons and protons, the atom is charged and is called an \textit{ion}.

An ionized atom is one that has a different number of electrons than nuclear protons.
39.4 Radioactive Isotopes

The number of neutrons has no bearing on the number of electrons the atom may have or on the chemistry of an atom. The common form of hydrogen has a bare proton as its nucleus.

There can be different kinds, or *isotopes*, of hydrogen, however, because there can be different numbers of neutrons in the nucleus.

An *isotope* is a form of an element having a particular number of neutrons in the nuclei of its atoms.
39.4 Radioactive Isotopes

In one isotope of hydrogen, the nucleus consists of a single proton.

In a second isotope of hydrogen, the proton is accompanied by a neutron.

In a third isotope of hydrogen, there are two neutrons.

All the isotopes of hydrogen are chemically identical. The orbital electrons are affected only by the positive charge in the nucleus.
We distinguish between the different isotopes of hydrogen with the symbols $^1\text{H}$, $^2\text{H}$, and $^3\text{H}$.
39.4 Radioactive Isotopes

We distinguish between the different isotopes of hydrogen with the symbols $\text{ }^1\text{H}$, $\text{ }^2\text{H}$, and $\text{ }^3\text{H}$. The lower number in each notation is the atomic number or the number of protons.
39 The Atomic Nucleus and Radioactivity

39.4 Radioactive Isotopes

We distinguish between the different isotopes of hydrogen with the symbols $^1\text{H}$, $^2\text{H}$, and $^3\text{H}$.

The lower number in each notation is the atomic number or the number of protons.

The upper number is the atomic mass number or the total number of nucleons in the nucleus.
39.4 Radioactive Isotopes

The common isotope of hydrogen, $^1_1\text{H}$, is a stable element.
The isotope $^2_1\text{H}$, called \textit{deuterium}, is also stable.
The triple-weight hydrogen isotope $^3_1\text{H}$, called \textit{tritium}, however, is unstable and undergoes beta decay.
This is the radioactive isotope of hydrogen.
39.4 Radioactive Isotopes

The three isotopes of hydrogen have different numbers of neutrons in the nucleus. The varying number of neutrons changes the mass of the atom, but not its chemical properties.
39.4 Radioactive Isotopes

The common isotope of uranium is $^{238}_{92}U$, or U-238 for short.

- It has 92 protons and 146 neutrons in its nucleus.
- It is radioactive, with a smaller decay rate than $^{235}_{92}U$, or U-235, with 92 protons and 143 neutrons in its nucleus.
- Any nucleus with 92 protons is uranium, by definition.
- Nuclei with 92 protons but different numbers of neutrons are simply different isotopes of uranium.
All isotopes of uranium are unstable and undergo radioactive decay.
think!

The nucleus of beryllium-8, \(^{8}_{4}\text{Be}\), undergoes a special kind of radioactive decay: it splits into two equal halves. What nuclei are the products of this decay? Why is this a form of alpha decay?
The nucleus of beryllium-8, $^8_4\text{Be}$, undergoes a special kind of radioactive decay: it splits into two equal halves. What nuclei are the products of this decay? Why is this a form of alpha decay?

**Answer:**

When beryllium-8 splits into equal halves, a pair of nuclei with 2 protons and 2 neutrons is created. These are nuclei of helium-4, $^4_2\text{He}$, also called alpha particles. So this reaction is a form of alpha decay.
How are the isotopes of an element similar? How do they differ?
Rates of radioactive decay appear to be absolutely constant, unaffected by any external conditions.
39.5 Radioactive Half-Life

Since some radioactive nuclei are more stable than others, they decay at different rates. A relatively stable isotope will decay slowly, while an unstable isotope will decay in a shorter period of time. The radioactive decay rate is measured in terms of a characteristic time, the *half-life*. The *half-life* of a radioactive material is the time needed for half of the radioactive atoms to decay.
39.5 Radioactive Half-Life

Graphing Decay Rates

Radium-226, for example, has a half-life of 1620 years.
39.5 Radioactive Half-Life

- This means that half of any given specimen of Ra-226 will have undergone decay by the end of 1620 years.
- In the next 1620 years, half of the remaining radium decays, leaving only one fourth the original of radium atoms.
39.5 Radioactive Half-Life

- The rest are converted, by a succession of disintegrations, to lead.
39.5 Radioactive Half-Life

- After 20 half-lives, an initial quantity of radioactive atoms will be diminished to about one millionth of the original quantity.
39.5 Radioactive Half-Life

The isotopes of some elements have a half-life of less than a millionth of a second.

U-238 has a half-life of 4.5 billion years.

Each isotope of a radioactive element has its own characteristic half-life.

Rates of radioactive decay appear to be absolutely constant, unaffected by any external conditions.
39.5 Radioactive Half-Life

Constancy of Decay Rates

High or low pressures, high or low temperatures, strong magnetic or electric fields, and even violent chemical reactions have no detectable effect on the rate of decay of an element.

Any of these stresses, however severe by ordinary standards, is far too mild to affect the nucleus deep in the interior of the atom.
39.5 Radioactive Half-Life

Measuring Decay Rates

The half-life is determined by calculating the number of atoms in a sample and the rate at which the sample decays. The half-life of an isotope is related to its rate of disintegration. The shorter the half-life of a substance, the faster it disintegrates, and the more active is the substance. The half-life can be computed from the rate of disintegration, which can be measured in the laboratory.
39.5 Radioactive Half-Life

a. A Geiger counter detects incoming radiation by its ionizing effect on enclosed gas in the tube.
39.5 **Radioactive Half-Life**

a. A Geiger counter detects incoming radiation by its ionizing effect on enclosed gas in the tube.

b. Lab workers wear film badges to measure their accumulated radiation exposure.
39.5 Radioactive Half-Life

think!

If a sample of a radioactive isotope has a half-life of 1 year, how much of the original sample will be left at the end of the second year? What happens to the rest of the sample?
39.5 Radioactive Half-Life

think!

If a sample of a radioactive isotope has a half-life of 1 year, how much of the original sample will be left at the end of the second year? What happens to the rest of the sample?

Answer:

One quarter of the original sample will be left. The three quarters that underwent decay became other elements.
How do external conditions affect rates of radioactive decay?
When a radioactive isotope undergoes alpha or beta decay, it changes to an isotope of a different element.
The changing of one element to another is called transmutation. Consider common uranium.

- Uranium-238 has 92 protons and 146 neutrons. The nucleus loses two protons and two neutrons—an alpha particle.
- The 90 protons and 144 neutrons left behind are the nucleus of a new element.
- This element is thorium.

\[ ^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He \]
39.6 Natural Transmutation of Elements

Alpha Decay

An arrow is used to show that the $^{238}_{92}U$ changes into the other elements.

Energy is released in three forms: gamma radiation, kinetic energy of the alpha particle, and kinetic energy of the thorium atom.

In the nuclear equation, the mass numbers at the top balance and the atomic numbers at the bottom also balance.
39.6 Natural Transmutation of Elements

Beta Decay

Thorium-234 is also radioactive.

- When it decays, it emits a beta particle, an electron ejected from the nucleus.
- When a beta particle is ejected, a neutron changes into a proton.
- The new nucleus then has 91 protons and is no longer thorium.
- It is the element protactinium.

\[ ^{234}\text{Th} \rightarrow ^{234}\text{Pa} + ^{0}\text{e} \]
39.6 Natural Transmutation of Elements

The atomic number has increased by 1 in this process but the mass number remains the same.

The beta particle (electron) is written as $^0_{-1}e$.

- The -1 is the charge of the electron.
- The 0 indicates that its mass is insignificant when compared with the mass of nucleons.
- Beta emission has hardly any effect on the mass of the nucleus; only the charge changes.
39.6 Natural Transmutation of Elements

Transmutation and the Periodic Table

When an atom ejects an alpha particle, the mass number of the resulting atom decreases by 4, and the atomic number by 2. The resulting atom belongs to an element two spaces back in the periodic table.

When an atom ejects a beta particle from its nucleus, it loses no nucleons, its atomic number \textit{increases} by 1. The resulting atom belongs to an element one place forward in the periodic table.

Thus, radioactive elements decay backward or forward in the periodic table.
39.6 Natural Transmutation of Elements

A nucleus may emit gamma radiation along with an alpha particle or a beta particle. Gamma emission does not affect the mass number or the atomic number.
39.6 Natural Transmutation of Elements

Radioactive Decay Series

The radioactive decay of $^{238}_{92}U$ to an isotope of lead, $^{206}_{82}Pb$, occurs in steps. On a graph of the decay series, each arrow that slants downward toward the left shows an alpha decay. Each arrow that points to the right shows a beta decay. Some of the nuclei in the series can decay either way.
39.6 Natural Transmutation of Elements

**think!**

Complete the following nuclear reactions.

a. \( ^{228}_{88}\text{Ra} \rightarrow ??? + ^{\phantom{0}}_{-1}\text{e} \)

b. \( ^{209}_{84}\text{Po} \rightarrow ^{205}_{82}\text{Pb} + ??? \)
39.6 Natural Transmutation of Elements

think!

Complete the following nuclear reactions.

\[
a. \quad ^{228}_{88}\text{Ra} \rightarrow ?? + ^0_{-1}\text{e} \\
b. \quad ^{209}_{84}\text{Po} \rightarrow ^{205}_{82}\text{Pb} + ??
\]

Answer:

\[
a. \quad ^{228}_{88}\text{Ra} \rightarrow ^{228}_{89}\text{Ac} + ^0_{-1}\text{e} \\
b. \quad ^{209}_{84}\text{Po} \rightarrow ^{205}_{82}\text{Pb} + ^4_2\text{He}
\]
39.6 Natural Transmutation of Elements

think!

What finally becomes of all the uranium-238 that undergoes radioactive decay?
39.6 Natural Transmutation of Elements

**think!**
What finally becomes of all the uranium-238 that undergoes radioactive decay?

**Answer:**
All the uranium-238 will ultimately become lead. On the way to becoming lead, it will exist as a series of other elements.
39.6 Natural Transmutation of Elements

How is the chemical identity of a radioactive isotope affected by alpha or beta decay?
39.7 Artificial Transmutation of Elements

The elements beyond uranium in the periodic table—the *transuranic* elements—have been produced through artificial transmutation.
New Zealander Ernest Rutherford, in 1919, was the first physicist to succeed in artificially transmuting a chemical element. He bombarded nitrogen nuclei with alpha particles and found traces of oxygen and hydrogen that were not there before. Rutherford accounted for the presence of the oxygen and hydrogen with the nuclear equation

\[ ^{14}_7\text{N} + ^{4}_2\text{He} \rightarrow ^{17}_8\text{O} + ^{1}_1\text{H} \]
39.7 Artificial Transmutation of Elements

a. When nitrogen gas is exposed to alpha particles, some of the nitrogen becomes oxygen and hydrogen.
39.7 Artificial Transmutation of Elements

a. When nitrogen gas is exposed to alpha particles, some of the nitrogen becomes oxygen and hydrogen.

b. A particle accelerator’s high energies easily transmute elements.
39.7 Artificial Transmutation of Elements

Many such nuclear reactions followed—first with natural bombarding particles from radioactive elements. Later, scientists used more energetic particles hurled by giant atom-smashing particle accelerators. The elements beyond uranium in the periodic table have been produced through artificial transmutation. These elements have half-lives much less than the age of Earth.
39.7 Artificial Transmutation of Elements

Which elements have been produced through artificial transmutation?
39.8 Carbon Dating

Scientists can figure out how long ago a plant or animal died by measuring the ratio of carbon-14 to carbon-12 in the remains.
39.8 Carbon Dating

Earth’s atmosphere is continuously bombarded by cosmic rays—mainly high-energy protons—from beyond Earth.

This results in the transmutation of atoms in the upper atmosphere.

Protons quickly capture stray electrons and become hydrogen atoms in the upper atmosphere.
39.8 Carbon Dating

Neutrons keep going for long distances because they have no charge and do not interact electrically with matter. Many of them collide with the nuclei of atoms in the lower atmosphere.

When nitrogen-14 is hit by a neutron ($^0_n$), carbon-14 and hydrogen are produced.

$$^{14}_7N + ^1_0n \rightarrow ^{14}_6C + ^1_1H$$
39.8 Carbon Dating

Most of the carbon that exists on Earth is stable carbon-12. In the air, it appears mainly in the compound carbon dioxide. Because of the cosmic bombardment, less than one-millionth of 1% of the carbon in the atmosphere is carbon-14. Like carbon-12, it joins with oxygen to form carbon dioxide, which is taken in by plants.
39.8 Carbon Dating

All plants have a tiny bit of radioactive carbon-14 in them. All living things contain some carbon-14. The ratio of carbon-14 to carbon-12 in living things is the same as the ratio of carbon-14 to carbon-12 in the atmosphere. Carbon-14 is a beta emitter and decays back into nitrogen.

\[ ^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + ^0_{-1}\text{e} \]
39.8 Carbon Dating

In a living plant, a radioactive equilibrium is reached where there is a fixed ratio of carbon-14 to carbon-12. When a plant or animal dies, it stops taking in carbon-14 from the environment. Then the percentage of carbon-14 decreases—at a known rate. The longer an organism has been dead, the less carbon-14 that remains.
39.8 **Carbon Dating**

Scientists can find how long ago a plant or animal died by measuring the ratio of carbon-14 to carbon-12 in the remains.

The half-life of carbon-14 is 5730 years.

Half of the carbon-14 atoms that are now present in the remains of a body, plant, or tree will decay in the next 5730 years.

The radioactivity of once-living things gradually decreases at a predictable rate.
39.8 **Carbon Dating**

The radioactive carbon isotopes in the skeleton diminish by one half every 5730 years. The red arrows symbolize relative amounts of carbon-14.
39.8 Carbon Dating

Archeologists use the carbon-14 dating technique to establish the dates of wooden artifacts and skeletons. Because of fluctuations in the production of carbon-14 through the centuries, this technique gives an uncertainty of about 15%.

For many purposes, this is an acceptable level of uncertainty. If greater accuracy is desired, then other techniques must be employed.
39.8 Carbon Dating

think!

A gram of carbon from an ancient bone measures between 7 and 8 beta emissions per minute. A gram of carbon extracted from a fresh piece of bone gives off 15 betas per minute. Estimate the age of the ancient bone. Now suppose the carbon sample from the ancient bone were only one fourth as radioactive as a gram of carbon from new bone. Estimate the age of the ancient bone.
39.8 Carbon Dating

**think!**

A gram of carbon from an ancient bone measures between 7 and 8 beta emissions per minute. A gram of carbon extracted from a fresh piece of bone gives off 15 betas per minute. Estimate the age of the ancient bone. Now suppose the carbon sample from the ancient bone were only one fourth as radioactive as a gram of carbon from new bone. Estimate the age of the ancient bone.

**Answer:**

Since beta emission for the first old sample is one half that of the fresh sample, about one half-life has passed, 5730 years. In the second case, the ancient bone is two half-lives of carbon-14 or about 11,460 years old.
How can scientists determine the age of carbon-containing artifacts?
39.9 Uranium Dating

The dating of very old, nonliving things is accomplished with radioactive minerals, such as uranium.
39.9 Uranium Dating

The naturally occurring isotopes U-238 and U-235 decay very slowly and ultimately become isotopes of lead.

- U-238 decays through several stages to become Pb-206.
- U-235 finally becomes the isotope Pb-207.
- Most of the lead isotopes 206 and 207 that exist were at one time uranium.
- The older the uranium-bearing rock, the higher the percentage of these lead isotopes.

One ton of ordinary granite contains about 9 grams of uranium and 20 grams of thorium. Basalt rocks contain 3.5 and 7.7 grams of the same.
39.9 Uranium Dating

You can calculate the age of a rock from the half-lives of the uranium isotopes and the percentage of lead isotopes in the rock.

Rocks dated in this way have been found to be as much as 3.7 billion years old.

Samples from the moon, where there has been less obliteration of early rocks than on Earth, have been dated at 4.2 billion years.
39.9 Uranium Dating

How do scientists date very old, nonliving things?
39.10 Radioactive Tracers

Scientists can analyze biological or mechanical processes using small amounts of radioactive isotopes as tracers.
39.10 Radioactive Tracers

Radioactive isotopes of the elements have been produced by bombarding the elements with neutrons and other particles. These isotopes are inexpensive, quite available, and very useful in scientific research and industry. Scientists can analyze biological or mechanical processes using small amounts of radioactive isotopes as tracers.
For example, researchers mix a small amount of radioactive isotopes with fertilizer before applying it to growing plants. Once the plants are growing, the amount of fertilizer taken up by the plant can be easily measured with radiation detectors. From such measurements, researchers can tell farmers the proper amount of fertilizer to use.
39.10 Radioactive Tracers

Tracers are used in medicine to study the process of digestion and the way in which chemicals move about in the body. Food containing a tiny amount of a radioactive isotope is fed to a patient. The paths of the tracers in the food are then followed through the body with a radiation detector.
There are hundreds more examples of the use of radioactive isotopes.

- Radioactive isotopes can prevent food from spoiling quickly by killing the microorganisms that normally lead to spoilage.
There are hundreds more examples of the use of radioactive isotopes.

- Radioactive isotopes can prevent food from spoiling quickly by killing the microorganisms that normally lead to spoilage.
- Radioactive isotopes can also be used to trace leaks in pipes.
39.10 Radioactive Tracers

There are hundreds more examples of the use of radioactive isotopes.

- Radioactive isotopes can prevent food from spoiling quickly by killing the microorganisms that normally lead to spoilage.
- Radioactive isotopes can also be used to trace leaks in pipes.
- Engineers study automobile engine wear by making the cylinder walls in the engine radioactive and measuring particles that wear away with a radiation detector.
39.10 Radioactive Tracers

The shelf life of fresh strawberries and other perishables is markedly increased when the food is subjected to gamma rays from a radioactive source.
How can scientists use radioactive isotopes to analyze biological or mechanical processes?
Sources of natural radiation include cosmic rays, Earth minerals, and radon in the air.
Radioactivity has been around longer than humans have.

- It is as much a part of our environment as the sun and the rain.
- It is what warms the interior of Earth and makes it molten.
- Radioactive decay inside Earth heats the water that spurts from a geyser or that wells up from a natural hot spring.
- Even the helium in a child’s balloon is the result of radioactivity. Its nuclei are nothing more than alpha particles that were once shot out of radioactive nuclei.
Sources of natural radiation include cosmic rays, Earth minerals, and radon in the air. Radiation is in the ground you stand on, and in the bricks and stones of surrounding buildings. Even the cleanest air we breathe is slightly radioactive. If our bodies could not tolerate this natural background radiation, we wouldn’t be here.
39.11 Radiation and You

The pie chart shows origins of radiation exposure for an average individual in the United States.
39.11 Radiation and You

Cosmic Rays

Much of the radiation we are exposed to is cosmic radiation streaming down through the atmosphere.

Most of the protons and other atomic nuclei that fly toward Earth from outer space are deflected away.

The atmosphere, acting as a protective shield, stops most of the rest.
39.11 Radiation and You

Some cosmic rays penetrate the atmosphere, mostly in the form of secondary particles such as muons.
Two round-trip flights between New York and San Francisco expose you to as much radiation as in a chest X-ray.
The air time of airline personnel is limited because of this extra radiation.
Neutrinos

We are bombarded most by what harms us least—neutrinos.

- Neutrinos are the most weakly interacting of all particles.
- They have near-zero mass, no charge, and are produced frequently in radioactive decays.
- They are the most common high-speed particles known.
- About once per year on the average, a neutrino triggers a nuclear reaction in your body.
- We don’t hear much about neutrinos because they ignore us.
39.11 Radiation and You

Gamma Rays

Of the types of radiation we have focused upon in this chapter, gamma radiation is by far the most dangerous. It emanates from radioactive materials and makes up a substantial part of the normal background radiation.
39.11 Radiation and You

When gamma radiation encounters molecules in the body, it produces damage on the atomic scale. These altered molecules are often harmful. Altered DNA molecules, for example, can produce harmful genetic mutations.
39.11 Radiation and You

Radiation Safety

Cells can repair most kinds of molecular damage if the radiation they are exposed to is not too intense. On the other hand, people who work around high concentrations of radioactive materials must be protected to avoid an increased risk of cancer. Whenever possible, exposure to radiation should be avoided.
This is the internationally used symbol to indicate an area where radioactive material is being handled or produced.
What are sources of natural radiation?
Assessment Questions

1. In the nucleus of an atom, the strong force is a relatively
   a. short-range force.
   b. long-range force.
   c. unstable force.
   d. neutralizing force.
1. In the nucleus of an atom, the strong force is a relatively
   a. short-range force.
   b. long-range force.
   c. unstable force.
   d. neutralizing force.

Answer: A
Assessment Questions

2. Which of the following do electric or magnetic fields not deflect?
   a. alpha particles
   b. beta particles
   c. gamma rays
   d. Magnetic and electric fields deflect alpha particles, beta particles, and gamma rays.
2. Which of the following do electric or magnetic fields not deflect?
   a. alpha particles
   b. beta particles
   c. gamma rays
   d. Magnetic and electric fields deflect alpha particles, beta particles, and gamma rays.

Answer: C
Assessment Questions

3. Which of these is the most penetrating in common materials?
   a. alpha particles
   b. beta particles
   c. gamma rays
   d. all are equally penetrating
Assessment Questions

3. Which of these is the most penetrating in common materials?
   a. alpha particles
   b. beta particles
   c. gamma rays
   d. all are equally penetrating

Answer: C
Assessment Questions

4. Uranium-235, uranium-238, and uranium-239 are different
   a. elements.
   b. ions.
   c. isotopes.
   d. nucleons.
Assessment Questions

4. Uranium-235, uranium-238, and uranium-239 are different
   a. elements.
   b. ions.
   c. isotopes.
   d. nucleons.

Answer: C
Assessment Questions

5. The half-life of carbon-14 is about 5730 years. Which of the following statements about the amount of carbon present in your bones is accurate?

   a. The present amount of carbon in your bones will reduce to zero when you die.
   b. The present amount of carbon in your bones will reduce to zero in about 5730 years.
   c. The present amount of carbon in your bones will reduce to zero in 11,460 years.
   d. The present amount of carbon in your bones will never reach zero, as the amount of carbon will continue to decrease by half of the amount remaining.
Assessment Questions

5. The half-life of carbon-14 is about 5730 years. Which of the following statements about the amount of carbon present in your bones is accurate?
   a. The present amount of carbon in your bones will reduce to zero when you die.
   b. The present amount of carbon in your bones will reduce to zero in about 5730 years.
   c. The present amount of carbon in your bones will reduce to zero in 11,460 years.
   d. The present amount of carbon in your bones will never reach zero, as the amount of carbon will continue to decrease by half of the amount remaining.

Answer: D
6. A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by
   a. zero.
   b. minus 1.
   c. minus 2.
   d. minus 3.
Assessment Questions

6. A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by
   a. zero.
   b. minus 1.
   c. minus 2.
   d. minus 3.

Answer: A
Assessment Questions

7. Atoms can
   a. only transmute into completely different atoms in nature.
   b. only transmute into completely different atoms in laboratories.
   c. transmute into completely different atoms in both nature and laboratories.
   d. never transmute into completely different atoms.
Assessment Questions

7. Atoms can
   a. only transmute into completely different atoms in nature.
   b. only transmute into completely different atoms in laboratories.
   c. transmute into completely different atoms in both nature and laboratories.
   d. never transmute into completely different different atoms.

Answer: C
Assessment Questions

8. Carbon-14 is a radioactive isotope of carbon that is primarily produced by cosmic radiation in the
   a. atmosphere.
   b. food we eat.
   c. interior of Earth.
   d. fallout of nuclear bomb tests.
8. Carbon-14 is a radioactive isotope of carbon that is primarily produced by cosmic radiation in the

a. atmosphere.

b. food we eat.

c. interior of Earth.

d. fallout of nuclear bomb tests.

Answer: A
To date the age of the oldest materials, scientists turn to the radioactivity of

a. carbon.
b. uranium.
c. lead.
d. nitrogen.
Assessment Questions

9. To date the age of the oldest materials, scientists turn to the radioactivity of
   a. carbon.
   b. uranium.
   c. lead.
   d. nitrogen.

Answer: B
Assessment Questions

10. Radioactive tracers
   a. are beneficial only in agriculture.
   b. are harmful when used to extend the shelf life of perishables.
   c. have broad and beneficial applications in many fields.
   d. are always harmful.
Assessment Questions

10. Radioactive tracers
   a. are beneficial only in agriculture.
   b. are harmful when used to extend the shelf life of perishables.
   c. have broad and beneficial applications in many fields.
   d. are always harmful.

Answer: C
Assessment Questions

11. Most of the radiation in Earth’s biosphere
   a. is the result of military activities.
   b. originates from nuclear power plants.
   c. occurs as natural background radiation.
   d. is in the form of cosmic rays.
Assessment Questions

11. Most of the radiation in Earth’s biosphere
   a. is the result of military activities.
   b. originates from nuclear power plants.
   c. occurs as natural background radiation.
   d. is in the form of cosmic rays.

Answer: C
Nuclear fission and nuclear fusion reactions release huge amounts of energy.
In 1939, just at the beginning of World War II, a nuclear reaction was discovered that released much more energy per atom than radioactivity, and had the potential to be used for both explosions and power production. This was the splitting of the atom, or nuclear fission.
Nuclear fission occurs when the repelling electrical forces within a nucleus overpower the attracting nuclear strong forces.
40.1 Nuclear Fission

The splitting of atomic nuclei is called nuclear fission. Nuclear fission involves the balance between the nuclear strong forces and the electrical forces within the nucleus. In all known nuclei, the nuclear strong forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape, electrical forces may push it into an even more elongated shape.
40.1 Nuclear Fission

Nuclear deformation leads to fission when repelling electrical forces dominate over attracting nuclear forces.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

The absorption of a neutron by a uranium nucleus supplies enough energy to cause such an elongation. The resulting fission process may produce many different combinations of smaller nuclei. The fission of one U-235 atom releases about seven million times the energy released by the explosion of one TNT molecule. This energy is mainly in the form of kinetic energy of the fission fragments.
40.1 Nuclear Fission

In a typical example of nuclear fission, one neutron starts the fission of the uranium atom and three more neutrons are produced when the uranium fissions.

\[ _{0}^{1}n + _{92}^{235}U \rightarrow _{36}^{91}Kr + _{56}^{142}Ba + 3(_{0}^{1}n) \]
40.1 Nuclear Fission

Chain Reaction

Note that one neutron starts the fission of the uranium atom, and, in the example shown, three more neutrons are produced.

- Most nuclear fission reactions produce two or three neutrons.
- These neutrons can, in turn, cause the fissioning of two or three other nuclei, releasing from four to nine more neutrons.
- If each of these succeeds in splitting an atom, the next step will produce between 8 and 27 neutrons, and so on.
A chain reaction is a self-sustaining reaction. A reaction event stimulates additional reaction events to keep the process going.
40.1 Nuclear Fission

Chain reactions do not occur in uranium ore deposits. Fission occurs mainly for the rare isotope U-235. Only 0.7% or 1 part in 140 of uranium is U-235. The prevalent isotope, U-238, absorbs neutrons but does not undergo fission. A chain reaction stops as the U-238 absorbs neutrons.
40.1 Nuclear Fission

If a chain reaction occurred in a chunk of pure U-235 the size of a baseball, an enormous explosion would likely result. In a smaller chunk of pure U-235, however, no explosion would occur.

- A neutron ejected by a fission event travels a certain average distance before encountering another uranium nucleus.
- If the piece of uranium is too small, a neutron is likely to escape through the surface before it “finds” another nucleus.
- Fewer than one neutron per fission will be available to trigger more fission, and the chain reaction will die out.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

An exaggerated view of a chain reaction is shown here.

a. In a small piece of pure U-235, the chain reaction dies out.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

An exaggerated view of a chain reaction is shown here.

a. In a small piece of pure U-235, the chain reaction dies out.

b. In a larger piece, a chain reaction builds up.
40.1 Nuclear Fission

Critical Mass

The **critical mass** is the amount of mass for which each fission event produces, on the average, one additional fission event.

A *subcritical* mass is one in which the chain reaction dies out. A *supercritical* mass is one in which the chain reaction builds up explosively.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

Two pieces of pure U-235 are stable if each of them is subcritical.

If the pieces are joined together and the combined mass is supercritical, we have a nuclear fission bomb.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

Each piece is subcritical because a neutron is likely to escape. When the pieces are combined, there is less chance that a neutron will escape. The combination may be supercritical.
40.1 Nuclear Fission

A simplified diagram of a uranium fission bomb is shown here.
40.1 Nuclear Fission

Building a uranium fission bomb is not a formidable task. The difficulty is separating enough U-235 from the more abundant U-238.

It took more than two years to extract enough U-235 from uranium ore to make the bomb that was detonated over Hiroshima in 1945.

Uranium isotope separation is still a difficult, expensive process today.
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

think!

Five kilograms of U-235 broken up into small separated chunks is subcritical, but if the chunks are put together in a ball shape, it is supercritical. Why?
40 Nuclear Fission and Fusion

40.1 Nuclear Fission

think!

Five kilograms of U-235 broken up into small separated chunks is subcritical, but if the chunks are put together in a ball shape, it is supercritical. Why?

Answer:

Five kilograms of U-235 in small chunks will not support a sustained reaction because the path for a neutron in each chunk is so short that the neutron is likely to escape through the surface without causing fission. When the chunks are brought together there is sufficient material that the neutron is likely to hit a nucleus and to cause fission rather than escape.
40.1 Nuclear Fission

What causes nuclear fission?
In order to sustain a chain reaction in uranium, the sample used must contain a higher percentage of U-235 than occurs naturally.
40.2 Uranium Enrichment

Uranium-235 undergoes fission when it absorbs a neutron, but uranium-238 normally doesn’t.

To sustain a chain reaction in uranium, the sample must contain a higher percentage of U-235 than occurs naturally. Since atoms U-235 and U-238 are virtually identical chemically, they cannot be separated by a chemical reaction. They must be separated by physical means.
40 Nuclear Fission and Fusion

40.2 Uranium Enrichment

*Gaseous diffusion* takes advantage of the difference in their masses.

- For a given temperature, heavier molecules move more slowly on average than lighter ones.
- Gaseous diffusion uses uranium hexafluoride (UF$_6$) gas.
- Molecules of the gas with U-235 move faster than molecules with U-238.
- Lighter molecules containing U-235 hit a diffusion membrane on average 0.4% more often than a molecule with U-238.
40.2 Uranium Enrichment

Gas leaving the chamber is slightly enriched in the U-235 isotope.

The gas is passed through thousands of interconnected stages to enrich uranium sufficiently in the U-235 isotope for it to be used in a power reactor (3% U-235) or a bomb (U-235 > 90%).

A newer method of isotope separation involves gas centrifuges. The uranium hexafluoride gas is spun at high speed. The lighter molecules with U-235 tend toward the center of the centrifuge.
40.2 Uranium Enrichment

What is necessary to sustain a chain reaction?
A nuclear fission reactor generates energy through a controlled nuclear fission reaction.
A liter of gasoline can be used to make a violent explosion. Or it can be burned slowly to power an automobile. Similarly, uranium can be used for bombs or in the controlled environment of a power reactor.

About 19% of electrical energy in the United States is generated by nuclear fission reactors.
40.3 The Nuclear Fission Reactor

A nuclear fission reactor generates energy through a controlled nuclear fission reaction. These reactors are nuclear furnaces, which boil water to produce steam for a turbine. One kilogram of uranium fuel, less than the size of a baseball, yields more energy than 30 freight-car loads of coal.
40.3 The Nuclear Fission Reactor

A nuclear fission power plant converts nuclear energy to electrical energy.
Components of a Fission Reactor

A reactor contains three main components:

• the nuclear fuel combined with a moderator,
• the control rods, and
• water.
40.3 The Nuclear Fission Reactor

The nuclear fuel is uranium, with its fissionable isotope U-235 enriched to about 3%. Because the U-235 is so highly diluted with U-238, an explosion like that of a nuclear bomb is not possible.

The moderator may be graphite or it may be water.
40.3 The Nuclear Fission Reactor

Control rods that can be moved in and out of the reactor control how many neutrons are available to trigger additional fission events.

The control rods are made of a material (usually cadmium or boron) that readily absorbs neutrons. Heated water around the nuclear fuel is kept under high pressure and is thus brought to a high temperature without boiling.

It transfers heat to a second, lower-pressure water system, which operates the electric generator in a conventional fashion.
A major drawback to fission power is the generation of radioactive waste products of fission. When uranium fissions into two smaller elements, the ratio of neutrons to protons in the product is too great to be stable. These fission products are radioactive. Safely disposing of these waste products requires special storage casks and procedures, and is subject to a developing technology.
40.3 The Nuclear Fission Reactor

American policy has been to look for ways to deeply bury radioactive wastes.

Many scientists argue that “spent” nuclear fuel should first be treated in ways to derive value from it or make it less hazardous.

If these wastes are kept where they are accessible, it may turn out that they can be modified to be less of a danger to future generations than is thought at present.
40.3 The Nuclear Fission Reactor

think!

What would happen if a nuclear reactor had no control rods?
Think!
What would happen if a nuclear reactor had no control rods?

Answer:
Control rods control the number of neutrons that participate in a chain reaction. They thereby keep the reactor in its critical state. Without the control rods, the reactor could become subcritical or supercritical.
40.3 The Nuclear Fission Reactor

How does a nuclear fission reactor generate energy?
40.4 Plutonium

Pu-239, like U-235, will undergo fission when it captures a neutron.
40.4 Plutonium

When a neutron is absorbed by a U-238 nucleus, no fission results. The nucleus that is created, U-239, emits a beta particle instead and becomes an isotope of the element neptunium. This isotope, Np-239, soon emits a beta particle and becomes an isotope of plutonium. This isotope, Pu-239, like U-235, will undergo fission when it captures a neutron.

As part of its normal operation, any nuclear power plant converts some of its U-238 to Pu-239.
40.4 Plutonium

The half-life of neptunium-239 is only 2.3 days, while the half-life of plutonium-239 is about 24,000 years. Plutonium can be separated from uranium by ordinary chemical methods. It is relatively easy to separate plutonium from uranium.
40.4 Plutonium

The element plutonium is chemically a poison in the same sense as are lead and arsenic. It attacks the nervous system and can cause paralysis. Death can follow if the dose is sufficiently large. Fortunately, plutonium rapidly combines with oxygen to form three compounds, PuO, PuO$_2$, and Pu$_2$O$_3$. These plutonium compounds do not attack the nervous system and have been found to be biologically harmless.
40.4 Plutonium

Plutonium in any form, however, is radioactively toxic. It is more toxic than uranium, although less toxic than radium.

Pu-239 emits high-energy alpha particles, which kill cells rather than simply disrupting them and leading to mutations.

The greatest danger that plutonium presents is its potential for use in nuclear fission bombs. Its usefulness is in breeder reactors.
40.4 Plutonium

What happens when Pu-239 captures a neutron?
A breeder reactor converts a non-fissionable uranium isotope into a fissionable plutonium isotope.
40.5 The Breeder Reactor

When small amounts of Pu-239 are mixed with U-238 in a reactor, the plutonium liberates neutrons that convert non-fissionable U-238 into more of the fissionable Pu-239.

This process not only produces useful energy, it also “breeds” more fission fuel. A reactor with this fuel is a breeder reactor.

A breeder reactor is a nuclear fission reactor that produces more nuclear fuel than it consumes.
40.5 The Breeder Reactor

After the initial high costs of building such a device, this is an economical method of producing vast amounts of energy.

After a few years of operation, breeder-reactor power utilities breed twice as much fuel as they start with.
40.5 The Breeder Reactor

Pu-239, like U-235, undergoes fission when it captures a neutron.
40 Nuclear Fission and Fusion

40.5 The Breeder Reactor

Fission power has several benefits.

• It supplies plentiful electricity.
• It conserves the many billions of tons of coal, oil, and natural gas every year.
• It eliminates the megatons of sulfur oxides and other poisons that are put into the air each year by the burning of these fuels.
• It produces no carbon dioxide or other greenhouse gases.
40.5 The Breeder Reactor

The drawbacks of fission power include:

- the problems of storing radioactive wastes,
- the production of plutonium,
- the danger of nuclear weapons proliferation, and
- low-level release of radioactive materials into the air and groundwater, and the risk of an accidental (or terrorist-caused) release of large amounts of radioactivity.
40.5 The Breeder Reactor

Reasoned judgment is not made by considering only the benefits or the drawbacks of fission power. You must also compare nuclear fission to alternate power sources. Fission power is a subject of much debate.
40.5 The Breeder Reactor

What is the function of a breeder reactor?
During fission, the total mass of the fission fragments (including the ejected neutrons) is less than the mass of the fissioning nucleus.
40.6 Mass-Energy Equivalence

The key to understanding why a great deal of energy is released in nuclear reactions is the equivalence of mass and energy. Mass and energy are essentially the same—they are two sides of the same coin. Mass is like a super storage battery. It stores energy that can be released if and when the mass decreases.

\[ E = mc^2 \] says that mass and energy are two sides of the same coin.
40.6 Mass-Energy Equivalence

Mass Energy

If you stacked up 238 bricks, the mass of the stack would be equal to the sum of the masses of the bricks. Is the mass of a U-238 nucleus equal to the sum of the masses of the 238 nucleons that make it up? Consider the work that would be required to separate all the nucleons from a nucleus.
40 Nuclear Fission and Fusion

40.6 Mass-Energy Equivalence

Recall that work, which transfers energy, is equal to the product of force and distance.

Imagine that you can reach into a U-238 nucleus and, pulling with a force, remove one nucleon.

That would require considerable work.

Then keep repeating the process until you end up with 238 nucleons, stationary and well separated.
You started with one stationary nucleus containing 238 particles and ended with 238 separate stationary particles. Work is required to pull a nucleon from an atomic nucleus. This work goes into mass energy. The separated nucleons have a total mass greater than the mass of the original nucleus. The extra mass, multiplied by the square of the speed of light, is exactly equal to your energy input: $\Delta E = \Delta mc^2$.  

40.6 Mass-Energy Equivalence
40.6 Mass-Energy Equivalence

Binding Energy

One way to interpret this mass change is that a nucleon inside a nucleus has less mass than its rest mass outside the nucleus.

How much less depends on which nucleus.

The mass difference is related to the “binding energy” of the nucleus.

Mass is congealed energy.
40.6 Mass-Energy Equivalence

For uranium, the mass difference is about 0.7%, or 7 parts in a thousand.

The 0.7% reduced nucleon mass in uranium indicates the binding energy of the nucleus.
40.6 Mass-Energy Equivalence

The masses of the pieces that make up the carbon atom—6 protons, 6 neutrons, and 6 electrons—add up to about 0.8% more than the mass of a C-12 atom. That difference indicates the binding energy of the C-12 nucleus.

We will see shortly that binding energy per nucleon is greatest in the nucleus of iron.
40.6 Mass-Energy Equivalence

Measuring Nuclear Mass

The masses of ions of isotopes of various elements can be accurately measured with a mass spectrometer. This device uses a magnetic field to deflect ions into circular arcs.

The ions entering the device all have the same speed. The greater the inertia (mass) of the ion, the more it resists deflection, and the greater the radius of its curved path.
In a mass spectrometer, ions of a fixed speed are directed into the semicircular “drum,” where they are swept into semicircular paths by a strong magnetic field. Heavier ions are swept into curves of larger radii than lighter ions.
40.6 Mass-Energy Equivalence

A graph of the nuclear masses for the elements from hydrogen through uranium shows how nuclear mass increases with increasing atomic number.

The slope curves slightly because there are proportionally more neutrons in the more massive atoms.
40.6 Mass-Energy Equivalence

Nuclear Mass per Nucleon

A more important graph plots nuclear mass per nucleon from hydrogen through uranium. This graph indicates the different average effective masses of nucleons in atomic nuclei.
40.6 **Mass-Energy Equivalence**

**Nuclear Mass per Nucleon**

A proton has the greatest mass when it is the nucleus of a hydrogen atom. None of the proton’s mass is binding energy.
40.6 Mass-Energy Equivalence

Nuclear Mass per Nucleon

The low point of the graph occurs at the element iron. This means that pulling apart an iron nucleus would take more work per nucleon than pulling apart any other nucleus. Iron holds its nucleons more tightly than any other nucleus does. Beyond iron, the average effective mass of nucleons increases.
For elements lighter than iron and heavier than iron, the binding energy per nucleon is less than it is in iron.
40 Nuclear Fission and Fusion

40.6 Mass-Energy Equivalence

If a uranium nucleus splits in two, the masses of the fission fragments lie about halfway between uranium and hydrogen. The mass per nucleon in the fission fragments is less than the mass per nucleon in the uranium nucleus.

For energy release, Lose Mass is the name of the game—any game.
40.6 Mass-Energy Equivalence

When this decrease in mass is multiplied by the speed of light squared, it is equal to the energy yielded by each uranium nucleus that undergoes fission. The missing mass is equivalent to the energy released.
40.6 Mass-Energy Equivalence

The mass-per-nucleon graph is an energy valley that starts at hydrogen, drops to the lowest point (iron), and then rises gradually to uranium.

Iron is at the bottom of the energy valley, which is the place with the greatest binding energy per nucleon.
40.6 Mass-Energy Equivalence

Any nuclear transformation that moves nuclei toward iron releases energy.

Heavier nuclei move toward iron by dividing—nuclear fission. A drawback is that the fission fragments are radioactive because of their greater-than-normal number of neutrons.

A more promising source of energy is to be found when lighter-than-iron nuclei move toward iron by combining.
40.6 Mass-Energy Equivalence

think!

If you know the mass of a particular nucleus, how do you calculate the mass per nucleon?
think!

If you know the mass of a particular nucleus, how do you calculate the mass per nucleon?

Answer:
You divide the mass of the nucleus by the number of nucleons in it.
40.6 Mass-Energy Equivalence

How does the total mass of the fission fragments compare to the mass of the fissioning nucleus?
40.7 Nuclear Fusion

After fusion, the total mass of the light nuclei formed in the fusion process is less than the total mass of the nuclei that fused.
40.7 Nuclear Fusion

The steepest part of the energy hill is from hydrogen to iron.

Energy is released as light nuclei fuse, or combine, rather than split apart. This process is nuclear fusion.

Energy is released when heavy nuclei split apart in the fission process.

In nuclear fusion, energy is released when light nuclei fuse together.

A proton has more mass by itself than it does inside a helium nucleus.
40.7 Nuclear Fusion

a. The mass of a single proton is more than the mass per nucleon in a helium-4 nucleus.
40.7 Nuclear Fusion

a. The mass of a single proton is more than the mass per nucleon in a helium-4 nucleus.

b. Two protons and two neutrons have more total mass when they are free than when they are combined in a helium nucleus.
40.7 Nuclear Fusion

Atomic nuclei are positively charged. For fusion to occur, they must collide at very high speeds to overcome electrical repulsion.

Fusion brought about by high temperatures is called **thermonuclear fusion**.
40.7 Nuclear Fusion

In the central part of the sun, about 657 million tons of hydrogen are converted into 653 million tons of helium each second.

The missing 4 million tons of mass is discharged as radiant energy.
In both chemical and nuclear burning, a high temperature starts the reaction.

- The release of energy by the reaction maintains a high enough temperature to spread the reaction.
- The result of the chemical reaction is a combination of atoms into more tightly bound molecules.
- In nuclear reactions, the result is more tightly bound nuclei.
- The difference between chemical and nuclear burning is essentially one of scale.
40.7 Nuclear Fusion

think!

First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction?
First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction?

**Answer:**
This is contradictory only if the same element is said to release energy by both the processes of fission and fusion. Only the fusion of light elements and the fission of heavy elements result in a decrease in nucleon mass and a release of energy.
40.7 Nuclear Fusion

How does the total mass of the products of fusion compare to the mass of the nuclei that fused?
40.8 Controlling Nuclear Fusion

Producing thermonuclear fusion reactions under controlled conditions requires temperatures of hundreds of millions of degrees.
### 40.8 Controlling Nuclear Fusion

Producing and sustaining such high temperatures along with reasonable densities is the goal of much current research.

No matter how the temperature is produced, a problem is that all materials melt and vaporize at the temperatures required for fusion.

One solution to this problem is to confine the reaction in a nonmaterial container, such as a magnetic field.
A magnetic bottle is used for containing plasmas for fusion research.
A magnetic field is nonmaterial, can exist at any temperature, and can exert powerful forces on charged particles in motion. “Magnetic walls” of sufficient strength can hold hot ionized gases called plasmas. Magnetic compression heats the plasma to fusion temperatures.

Fusing hydrogen releases less energy per nucleus than fissioning uranium. But since there are more atoms in a gram of hydrogen than in a gram of uranium, gram for gram, fusion releases more energy.
40 Nuclear Fission and Fusion

40.8 Controlling Nuclear Fusion

At about a million degrees, some nuclei are moving fast enough to overcome electrical repulsion and slam together, but the energy output is much smaller than the energy used to heat the plasma.

At about 350 million degrees, the fusion reactions will produce enough energy to be self-sustaining.

At this *ignition temperature*, nuclear burning yields a sustained power output without further input of energy.
40.8 Controlling Nuclear Fusion

The State of Fusion Research

Fusion has already been achieved in several devices, but instabilities in the plasma have prevented a sustained reaction.

A big problem is devising a field system that will hold the plasma in a stable and sustained position while a number of nuclei fuse.
Another promising approach uses high-energy lasers. One technique is to aim laser beams at a common point and drop solid pellets of frozen hydrogen isotopes through the crossfire. The resulting heat will be carried off by molten lithium to produce steam.
40.8 Controlling Nuclear Fusion

In the pellet chamber at Lawrence Livermore Laboratory, the laser source is Nova, the most powerful laser in the world, which directs 10 beams into the target region.
Fusion power is nearly ideal.

- Fusion reactors cannot become “supercritical” and get out of control because fusion requires no critical mass.
- There is no air pollution because the only product of the thermonuclear combustion is helium.
- Disposal of radioactive waste is not a major problem.
The fuel for nuclear fusion is hydrogen—in particular, its heavier isotopes, deuterium (H-2) and tritium (H-3). Hydrogen is the most plentiful element in the universe. Deuterium and tritium are found in ordinary water. Because of the abundance of fusion fuel, the amount of energy that can be released in a controlled manner is virtually unlimited.
40.8 Controlling Nuclear Fusion

In the fusion reactions of hydrogen isotopes, most of the energy released is carried by the lighter-weight particles, protons and neutrons, which fly off at high speeds.

\[
\begin{align*}
\text{2}_1^1H + \text{2}_1^1H & \rightarrow \text{3}_2^2He + \text{1}_0^1n \\
\text{2}_1^1H + \text{3}_1^1H & \rightarrow \text{4}_2^2He + \text{1}_0^1n
\end{align*}
\]
40.8 Controlling Nuclear Fusion

The development of fusion power has been slow and difficult, already extending over 50 years. It is one of the biggest scientific and engineering challenges that we face. Our hope is that it will be achieved and will be a primary energy source for future generations.
Why are thermonuclear fusion reactions so difficult to carry out?
Assessment Questions

1. Which of the following statements is true?
   a. The greater the surface area of a piece of fission material, the less likely an explosion will occur.
   b. The greater the surface area of a piece of fission material, the more likely an explosion will occur.
   c. The greater the mass of a piece of fission material, the more likely an explosion will occur.
   d. The greater the mass of a piece of fission material, the less likely an explosion will occur.
Assessment Questions

1. Which of the following statements is true?
   a. The greater the surface area of a piece of fission material, the less likely an explosion will occur.
   b. The greater the surface area of a piece of fission material, the more likely an explosion will occur.
   c. The greater the mass of a piece of fission material, the more likely an explosion will occur.
   d. The greater the mass of a piece of fission material, the less likely an explosion will occur.

Answer: A
Assessment Questions

2. A major problem in chemically separating uranium-235 from the more abundant uranium-238 stems from the fact that
   a. both are isotopes of the same element.
   b. both have nearly the same mass.
   c. the lighter isotope moves slightly faster than the heavier one.
   d. both are radioactive.
Assessment Questions

2. A major problem in chemically separating uranium-235 from the more abundant uranium-238 stems from the fact that
   a. both are isotopes of the same element.
   b. both have nearly the same mass.
   c. the lighter isotope moves slightly faster than the heavier one.
   d. both are radioactive.

Answer: A
Assessment Questions

3. A nuclear fission reactor
   a. is a major contributor to pollution in the atmosphere.
   b. can be used to produce energy from nothing.
   c. uses coal to heat water and generate energy.
   d. uses uranium to heat water and generate energy.
Assessment Questions

3. A nuclear fission reactor
   a. is a major contributor to pollution in the atmosphere.
   b. can be used to produce energy from nothing.
   c. uses coal to heat water and generate energy.
   d. uses uranium to heat water and generate energy.

Answer: D
Assessment Questions

4. Plutonium is an element that
   a. cannot be used in nuclear power plants.
   b. fissions like uranium.
   c. ranks high as a cancer-producing substance.
   d. poses no danger to humans.
Assessment Questions

4. Plutonium is an element that
   a. cannot be used in nuclear power plants.
   b. fissions like uranium.
   c. ranks high as a cancer-producing substance.
   d. poses no danger to humans.

Answer: B
Assessment Questions

5. A breeder reactor
   a. converts uranium-238 into plutonium.
   b. produces greenhouse gases.
   c. in time produces less fission fuel than it starts with.
   d. produces little electricity.
5. A breeder reactor
   a. converts uranium-238 into plutonium.
   b. produces greenhouse gases.
   c. in time produces less fission fuel than it starts with.
   d. produces little electricity.

Answer: A
Assessment Questions

6. Hydrogen is a lighter element than iron, which is a lighter element than uranium. Which of these three elements has the least mass per nucleon, that is, which has the least massive nucleons in its nucleus?

   a. hydrogen  
   b. iron     
   c. uranium 
   d. The mass per nucleon is equal in each.
Assessment Questions

6. Hydrogen is a lighter element than iron, which is a lighter element than uranium. Which of these three elements has the least mass per nucleon, that is, which has the least massive nucleons in its nucleus?

   a. hydrogen
   b. iron
   c. uranium
   d. The mass per nucleon is equal in each.

Answer: B
Assessment Questions

7. When the process of fission releases energy, the total mass of the material after the event is
   a. less.
   b. the same.
   c. doubled.
   d. tripled.
Assessment Questions

7. When the process of fission releases energy, the total mass of the material after the event is
   a. less.
   b. the same.
   c. doubled.
   d. tripled.

Answer: A
8. What remains unchanged in a fusion event?
   a. energy
   b. the mass of nucleons
   c. the number of nucleons
   d. temperature
Assessment Questions

8. What remains unchanged in a fusion event?
   a. energy
   b. the mass of nucleons
   c. the number of nucleons
   d. temperature

Answer: C