CHAPTER

17

Key Concepts

In this chapter, you will learn about:

- charge-to-mass ratio
- quantum mechanical model
- standard model of matter

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- explain the discovery and identification of subatomic particles
- explain why high-energy particle accelerators are required
- describe the modern model of the proton and neutron
- compare and contrast elementary particles and their antiparticles
- describe beta decays

Science, Technology, and Society

- explain the use of concepts, models, and theories
- explain the link between scientific knowledge and new technologies

Skills

- observe relationships and plan investigations
- analyze data and apply models
- work as members of a team
- apply the skills and conventions of science

The development of models of the structure of matter is ongoing.

Antimatter, quarks, particles appearing out of nowhere! Although these concepts may seem like science fiction, they are crucial for understanding the nature of matter.

You are about to enter the world of undetectable particles that blink in and out of existence. You will see that a calculation by a theoretical physicist in the 1920s led to sophisticated new medical technology that uses a previously unknown form of matter (Figure 17.1). You will learn about the peculiar properties of quarks, the elusive building blocks for protons, neutrons, and many other subatomic particles.

Quantum effects can make the subatomic world seem very strange indeed. This chapter introduces some of the most unusual and challenging ideas in all of physics. You will learn that experiments are showing that in some profound ways the universe is stranger than anyone could have imagined a century ago. The theories that you will explore next are exhilarating, difficult, weird, and yet elegant. They are a key to the next century of atomic physics.

▲ **Figure 17.1** Recent findings in atomic physics may seem strange, but they have led to amazing advances in technology, as well as better models of the structure of matter.

17-1 QuickLab

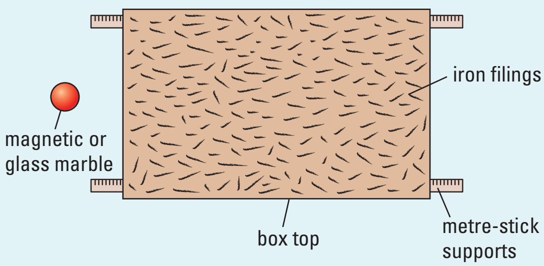
Particle Tracking Simulation

Problem

What can magnetic tracking reveal about the properties and collisions of objects?

Materials

lid from shirt box or shoe box
magnetic metal marbles
glass marbles
iron filings
metre-sticks or wood slats



▲ **Figure 17.2**

Procedure

1. Turn the lid upside down and use metre-sticks or wood slats to support it above a smooth surface such as a tabletop. The gap should allow the marbles to roll freely under the lid.
2. Spread iron filings evenly over the lid (Figure 17.2).
3. Roll a glass marble and a magnetic marble under the lid and observe how they affect the filings.
4. Set the lid aside and place a line of five magnetic marbles spaced about 3 cm apart across the middle of the space between the supports. Estimate what percentage of glass marbles rolled between the supports will hit one of the five magnetic marbles.
5. Shake the lid to spread the filings evenly again and put it back on the supports. Then, roll glass marbles under the lid at least 10 times. After each collision, put the magnetic marbles back in line and spread the filings evenly. Note the number and shape of any tracks resulting from collisions between the glass marbles and the magnetic ones. Watch for any pattern in the formation of the tracks.

Questions

1. What can you conclude about the magnetic field from the glass marbles?
2. Calculate the percentage of glass marbles that appeared to collide with the magnetic marbles in step 5. How close was your estimate? Account for any difference between your estimate and your observations.
3. Did any factor appear to affect the length of the collision tracks?
4. How would you expect the tracks to change if you repeated step 5 using round plastic beads instead of glass marbles?
5. How could you use the electric field from charged particles to detect these particles? How could you detect uncharged particles?

Think About It

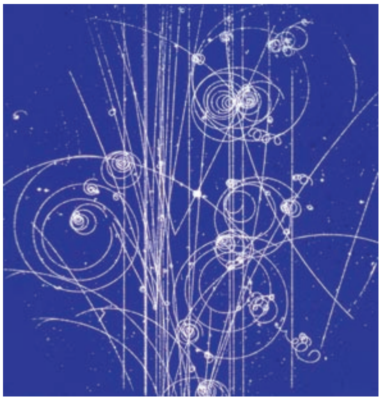
1. How can you tell if a particle is fundamental?
2. What did the measurement of beta decays reveal about the structure of matter?
3. How many fundamental particles are there?

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes in your ideas.

17.1 Detecting and Measuring Subatomic Particles

A skilled wilderness guide can tell a great deal about an animal from its tracks, not just identifying the animal but also estimating its age and how fast it was moving (Figure 17.3). In a similar way, physicists use tracks left by subatomic particles to identify the particles, study their interactions, and deduce the structure of matter (Figure 17.4).

▲ **Figure 17.3** Tracks of an adult snowshoe hare. What do these tracks tell you about the hare's speed?



▲ **Figure 17.4** Tracks of subatomic particles. The heavier particles have straighter tracks.

Cloud Chambers and Bubble Chambers

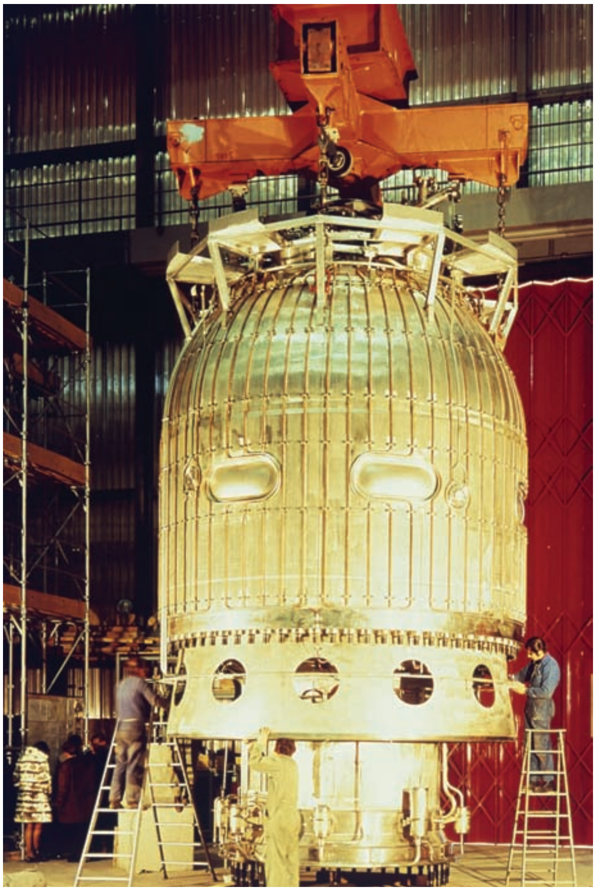
cloud chamber: a device that uses trails of droplets of condensed vapour to show the paths of charged particles

A **cloud chamber** contains dust-free air supersaturated with vapour from a liquid such as water or ethanol. The amount of vapour air can hold depends on temperature and pressure. Air is supersaturated when it contains more vapour than it would normally hold at a given temperature and pressure. So, the liquid and vapour in a cloud chamber are not in equilibrium, and a tiny disturbance can trigger condensation of vapour into droplets of liquid. A charged particle speeding through the supersaturated air will ionize some molecules along its path. The ions trigger condensation, forming a miniature cloud along the trajectory of the speeding particle. This cloud track shows the path of the particle the way a vapour trail formed by condensing exhaust gases shows the path of a jetliner through the sky.

◀ **Figure 17.5** One of Charles Wilson's cloud chambers. The glass sphere is an expansion chamber used to lower the pressure in the cylindrical cloud chamber.

Charles Thomson Rees Wilson (1869–1969) made the first observations of particle tracks in a cloud chamber in 1910 (Figure 17.5). For the next 50 years, cloud chambers were the principal tools of atomic physics. They are to atomic physics what telescopes are to astronomy.

The **bubble chamber** (Figure 17.6) was developed in 1952 by the physicist Donald Glaser (b. 1926). It contains a liquefied gas, such as hydrogen, helium, propane, or xenon. Lowering the pressure in the chamber lowers the boiling point of this liquid. When the pressure is reduced so that the boiling point is just below the actual temperature of the liquid, ions formed by a charged particle zipping through the liquid cause it to boil. Thus, the particle forms a trail of tiny bubbles along its path. Bubble chambers reverse the process used in cloud chambers: particle tracks are formed by a liquid turning into vapour instead of a vapour turning into liquid.



◀ **Figure 17.6** One of the large bubble chambers at the CERN laboratory near Geneva, Switzerland

Neutral particles will not create tracks in a cloud or bubble chamber. However, it is possible to calculate some of the properties of neutral particles from the tracks of charged particles that interact with them.

Concept Check

Outline possible reasons why neutral particles will not show up in a bubble chamber. How could you tell if a neutron were involved in a particle collision in a bubble chamber?

info BIT

Charles Wilson built the first cloud chamber in 1894 to study how clouds form. He shared a Nobel Prize for his contribution to particle physics. Wilson was a renowned meteorologist and an avid mountaineer.

bubble chamber: a device that uses trails of bubbles in a superheated liquid to show the paths of charged particles

info BIT

CERN stands for *C*onseil *E*uropéen pour la *R*echerche *N*ucléaire. It is the world's largest particle physics laboratory.

e SIM

To see an animation of particle tracks, follow the links at www.pearsoned.ca/school/physicssource.

17-2 Inquiry Lab

Building a Cloud Chamber

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question

Can types of radiation be identified by the characteristics of their tracks?

Hypothesis

Since alpha, beta, and gamma radiations have different properties, the tracks they produce in a cloud chamber will be different.

Materials and Equipment

- clear glass container
- flat glass or plastic cover
- black blotting paper to fit the bottom of the container
- dry ice (frozen carbon dioxide)
- reagent grade ethanol (ethyl alcohol)
- foam plastic insulation
- tape
- silicone grease
- lamp with reflector
- radiation sources

CAUTION: The temperature of dry ice is −78 °C. Handle it only with tongs or thick gloves.

Be careful not to damage the casing on the radioactive samples.

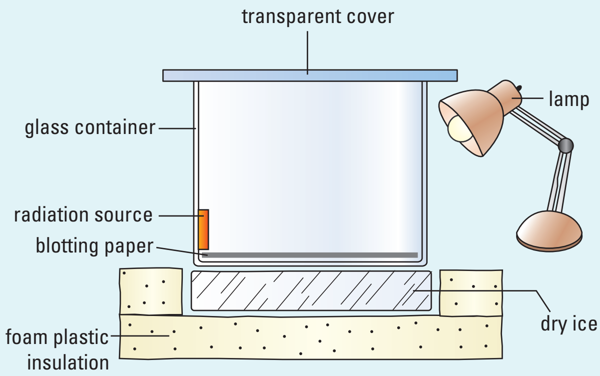
Variables

Identify the manipulated, responding, and controlled variables in this experiment.

Procedure

Work with a partner or a small group of classmates.

1. Cut a piece of black blotting paper to fit the bottom of the glass container.
2. Saturate this blotting paper with alcohol, but avoid having a pool of alcohol in the container.
3. Cover the container using silicone grease to ensure a good seal between the cover and the container.
4. Use a piece of foam plastic insulation as the base for your cloud chamber. Place a piece of dry ice at least 2.5 cm thick in the centre of this base, then put the glass container on top of the dry ice. Placing more insulation around the sides of the dry ice will make it last longer.
5. Position the lamp so it shines down from the side of the chamber (Figure 17.7). Darken the room and wait several minutes. Note any changes that you observe in the cloud chamber.
6. Now tape an alpha-radiation source onto the inside of the container near the bottom. Write a description of any tracks that appear. If the tracks have a consistent shape or pattern, sketch a typical track.
7. Repeat step 6 with beta- and gamma-radiation sources.



▲ **Figure 17.7** A simple cloud chamber

Analyzing and Interpreting

1. Were all of the tracks you observed produced by the three radiation sources? What else could produce tracks in your cloud chamber? Explain your reasoning.

2. Describe any relationship you see between the appearance of the tracks and the type of radiation that produced them.

3. Suggest improvements to the design of this experiment.

Forming Conclusions

4. Do your observations support the hypothesis? If so, which properties of the radiation might be responsible for any differences in the tracks?

5. Under what conditions will subatomic particles travelling through the ethanol cloud not produce observable tracks?

Extending

6. Hold a strong magnet against the side of the cloud chamber and observe the magnetic field's effect on tracks from the three radiation sources. Explain whether you could use the magnet to help distinguish between different types of radiation.

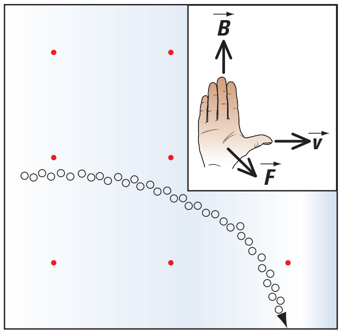
7. Make a hypothesis about how taping the radiation sources to the outside of the glass container would affect the tracks produced by each source. Test your hypothesis. Could your results help you distinguish between different types of radiation? What other methods could you use?

Analyzing Particle Tracks

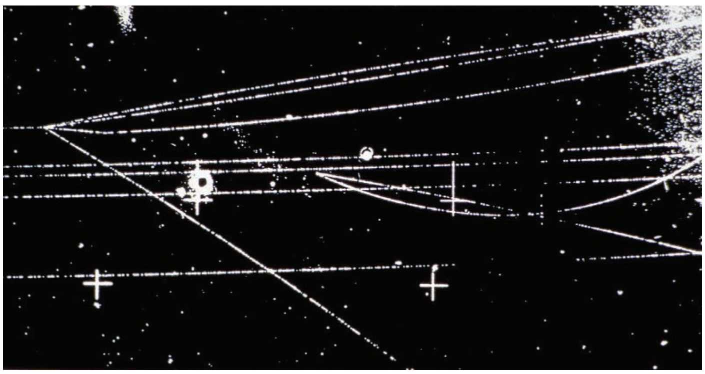
Physicists use cloud and bubble chambers as a key part of a controlled environment for studying subatomic particles. Applying a magnetic field across the chamber causes charged particles to follow curved or spiral paths. Measurements of the resulting tracks can be used to determine the mass and charge of the particles.

For example, Figure 17.8 shows the path of a particle moving in a cloud chamber in which a magnetic field is coming out of the page. The particle entered the chamber from the left. Applying the right-hand rule to this track shows that the particle must have a positive charge.

Often, a photograph of a cloud or bubble chamber will show tracks from a number of particles entering the chamber. Once in a while, a single track will suddenly branch into several diverging tracks, as shown in Figure 17.9. Such tracks suggest that the original particle has transformed into two or more different particles.



▲ **Figure 17.8** The right-hand rule shows that the particle must have a positive charge. Orient your right hand as shown and then rotate your hand so that your fingers point out of the page. Your palm points in the same direction as the force on a positively charged particle.



◀ **Figure 17.9** These tracks suggest that a particle interaction can form two or more different particles.

The following example demonstrates how a particle's track can reveal its charge-to-mass ratio.

▲ **Figure 17.10** Why are these particle tracks spiral rather than circular?

Example 17.1

Assume that the tracks shown in Figure 17.10 were made by particles moving at a speed of $0.10c$ through a uniform magnetic field of 30 mT [out of the page]. The initial radius of each track is 5.7 mm. Determine the charge-to-mass ratio for the particles. Then, make a hypothesis about what the particles are. What is unusual about this pair of particles?

Given

$v = 0.10c = 3.0 \times 10^7$ m/s $r = 5.7$ mm $= 0.0057$ m

$|\vec{B}| = 30$ mT $= 0.030$ T

Required

$\frac{q}{m}$ identification of each particle

Analysis and Solution

- Applying the right-hand rule shows that the particle spiralling clockwise has a positive charge. Similarly, the left-hand rule shows that the particle spiralling counterclockwise has a negative charge.
- Since there was no track before the two particles appeared, they must have originated from a photon or a neutral particle. For charge to be conserved, the net charge on the two new particles must be zero. Therefore, these particles must have equal but opposite charges.
- The charge-to-mass ratio for a particle moving perpendicular to a magnetic field can be derived from

$$|\vec{F}_{\mathrm{m}}| = |\vec{F}_{\mathrm{c}}|$$

$$|\vec{B}|qv = \frac{mv^2}{r}$$

$$|\vec{B}|q = \frac{mv}{r}$$

$$\frac{q}{m} = \frac{v}{|\vec{B}|r}$$

- Since the values of q, v, r, and B are the same for both particles, their masses must also be equal.

Substituting the known values gives

$$\frac{q}{m} = \frac{3.0 \times 10^7 \text{ m/s}}{0.030 \text{ T} \times 0.0057 \text{ m}}$$

$$= \frac{3.0 \times 10^7 \text{ m/s}}{0.030 \dfrac{\text{kg}}{\text{A•s}^2} \times 0.0057 \text{ m}}$$

$$= 1.8 \times 10^{11} \text{ A•s/kg}$$

$$= 1.8 \times 10^{11} \text{ C/kg}$$

The charge-to-mass ratio for an electron is

$$\frac{1.60 \times 10^{-19} \text{ C}}{9.11 \times 10^{-31} \text{ kg}} = 1.76 \times 10^{11} \text{ C/kg.}$$

The ratios for protons or small ions are about four orders of magnitude smaller.

Paraphrase

The charge-to-mass ratio of the negative particle is 1.8×10^{11} C/kg. Since this ratio matches the ratio for an electron, this particle very likely is an electron. However, the other particle has a charge-to-mass ratio of 1.8×10^{11} C/kg. This particle appears to be a positron, an antimatter particle.

PHYSICS INSIGHT

The tesla is a derived unit that can be expressed in terms of SI base units:

$$1 \text{ T} = 1 \frac{\text{kg}}{\text{A•s}^2}$$

Practice Problems

1. Measurement of a particle track shows a radius of deflection of 8.66×10^{-4} m for a proton travelling at a speed of 4.23×10^5 m/s perpendicular to a 5.10-T magnetic field. Calculate the charge-to-mass ratio for a proton.
2. Determine the radius of the path of an electron moving at a speed of 3.2×10^5 m/s perpendicular to a 1.2-mT magnetic field.

Answers

1. 9.58×10^7 C/kg
2. 1.5 mm

Concept Check

Can you tell whether momentum was conserved in the subatomic process in Example 17.1? Explain your reasoning.

Example 17.1 illustrates how a conservation law can be a powerful tool for understanding the interactions of subatomic particles. Physicists often apply the conservation laws for charge, momentum, and mass-energy in this way. Experiments and theoretical calculations have shown that several other quantities are also conserved when particles interact.

17.1 Check and Reflect

Knowledge

1. Compare the process for forming tracks in a cloud chamber with the process in a bubble chamber.

2. (a) List two subatomic particles that will leave tracks in a bubble chamber.

(b) List two subatomic particles that will not leave tracks in a bubble chamber.

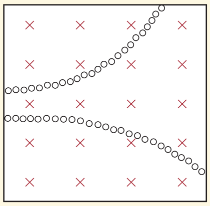
3. (a) Why does applying a magnetic field cause the particle tracks in a cloud or bubble chamber to curve?

(b) What can the curvature of a particle's track in a magnetic field reveal about the particle?

Applications

4. Will X-ray photons produce tracks in a bubble chamber? Justify your answer.

5. (a) Determine the type of charge on each particle moving through the magnetic field in this diagram.



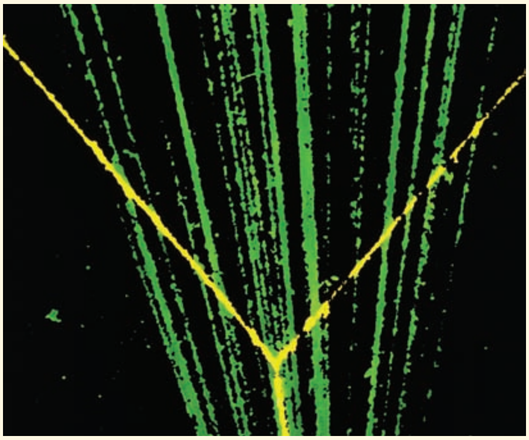
(b) What information would you need to determine which particle is moving faster?

6. Describe and explain the differences in the tracks made in a bubble chamber by the particles in each pair:

(a) protons and alpha particles

(b) protons and electrons

7. In this bubble-chamber photograph, a particle enters from the bottom and collides with a helium nucleus.



(a) Use conservation of momentum to show that the incoming particle was an alpha particle rather than a proton.

(b) Describe how you could show that the particles have a positive charge.

Extension

8. Bubble chambers have replaced cloud chambers in many research laboratories. What advantages do bubble chambers have over cloud chambers?

e TEST

To check your understanding of methods for detecting and measuring subatomic particles, follow the eTest links at www.pearsoned.ca/school/physicssource.

17.2 Quantum Theory and the Discovery of New Particles

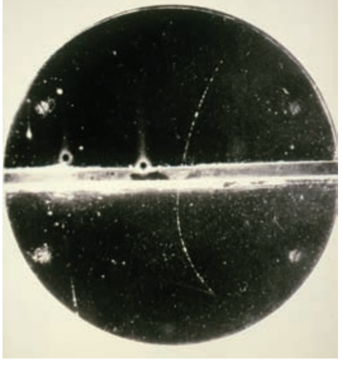
fundamental particle: a particle that cannot be divided into smaller particles; an elementary particle

Early in the 20th century, many scientists thought that there were just three **fundamental particles**: the electron, the proton, and the neutron. However, developments in quantum theory in the 1920s and 1930s suggested the possibility of other subatomic particles, some with peculiar properties.

The Discovery of Antimatter

In 1928, British physicist Paul Adrien Maurice Dirac (1902–1984) predicted the existence of peculiar particles such as the positive electron in Example 17.1 (pages 833–834). Dirac combined Einstein's theory of relativity with Schrödinger's wave equation (described in section 15.5). Dirac's calculations, with the resulting relativistic wave equation, predicted that antimatter could exist. As mentioned in section 16.2, a particle of antimatter has a key property, such as charge, that is opposite to that of the corresponding particle of ordinary matter.

In 1932, the American physicist Carl Anderson (1905–1991) provided the first evidence that antimatter really does exist. He photographed a cloud chamber track of a positron, as shown in Figure 17.11. For this achievement, Anderson won the Nobel Prize for physics in 1936.



▲ **Figure 17.11** A picture worth a Nobel Prize: Anderson's photograph provided evidence for the existence of the positron. Anderson used this path (the white streak in the photo) to show that the particle that made it had a positive charge but a mass equal to that of the electron.

Concept Check

How could Anderson tell that the particle track in Figure 17.11 showed a positively charged particle going down rather than a negative particle going up? His ingenious solution was to pass the particle through a thin lead plate. This plate slowed the particle a bit. Explain how Anderson could use this change in speed to confirm that the particle had positive charge. (Hint: The magnetic field for the cloud chamber in the photograph was directed into the page.)

annihilate: convert entirely into energy

Quantum theory predicts that each kind of ordinary particle has a corresponding antiparticle. One of the startling properties of antimatter is that a collision between a particle and its antiparticle can **annihilate** both particles and create a pair of high-energy gamma-ray photons travelling in opposite directions. For example, an electron-positron collision can be written as

$$e^+ + e^- \rightarrow 2\gamma$$

Such electron-positron annihilations are part of the nuclear processes in stars. Note that e^+ is the symbol for a positron. In general, charged antiparticles are represented by simply reversing the sign of the charge on the symbol for the corresponding ordinary particles. Antiparticles for neutral particles are indicated by adding a bar over the symbol for the corresponding ordinary matter. Thus, the symbol for an antineutron is $\bar{n}$.

Concept Check

Consider the example of a head-on collision between a positron and an electron travelling at equal speeds. Explain why momentum would not be conserved if all the energy of the two particles transformed into a single photon.

Scientific Knowledge Can Lead to New Technologies

The discovery of the positron made it possible to develop a powerful new medical diagnostic instrument. Positron emission tomography (PET) is an imaging technique that uses gamma rays from electron-positron annihilations to produce images of cross sections through a patient's body. A computer can then generate a three-dimensional image by combining successive plane images (Figure 17.12).

The patient receives an injection of a radioactive tracer containing an isotope, usually fluorine-18, that gives off positrons as it decays. As these positrons meet electrons within the patient's body, they create pairs of gamma-ray photons. Several rings of gamma-ray detectors rotate around the patient. As the photon pairs register on diametrically opposite detectors, a computer builds up an image of the location and concentration of the radioactive tracer. These images can show a wide variety of vital information, such as blood flow, brain function, and the location of tumours.

▲ **Figure 17.12** A PET scanner

e WEB

To learn more about PET scanners, follow the links at www.pearsoned.ca/school/physicssource.

Quantum Field Theory

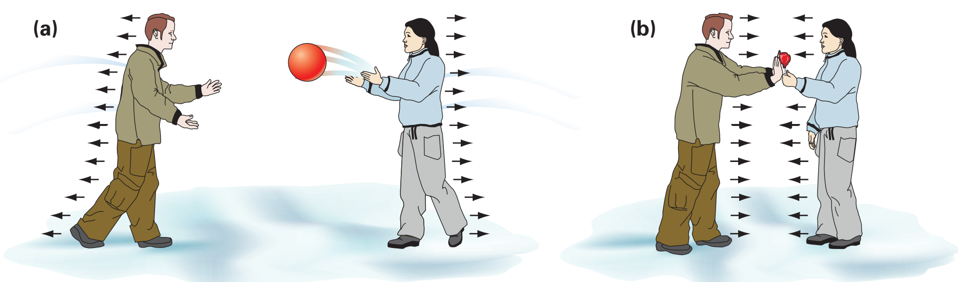
By 1930, Dirac, Heisenberg, Born, and others had established the foundations of **quantum field theory**. In this theory, **mediating particles** are the mechanism by which the fundamental forces act over the distance between particles. Particles that mediate a force exist for such a brief time that they cannot be observed. For these **virtual particles**, energy, momentum, and mass are not related as they are for real particles.

quantum field theory: a field theory developed using both quantum mechanics and relativity theory

mediating particle: a virtual particle that carries one of the fundamental forces

virtual particle: a particle that exists for such a short time that it is not detectable

To help understand this concept, imagine two people tossing a ball back and forth while standing on a very slippery surface, such as a smooth, wet sheet of ice. Throwing and catching the ball pushes the two people farther and farther apart (Figure 17.13(a)). In this analogy, the people correspond to ordinary particles and the ball corresponds to a mediating particle. For an attractive force, picture the same two people handing a somewhat sticky candy apple back and forth. The force that each person exerts to free the candy apple from the other person's hand pulls the two people toward each other (Figure 17.13(b)). Note, however, that quantum field theory is a complex mathematical model with aspects that cannot be explained by such analogies.



◀ **Figure 17.13** (a) Throwing a ball back and forth while on a slippery surface pushes these people apart. (b) Handing a sticky object back and forth pulls them together.

quantum electrodynamics: quantum field theory dealing with the interactions of electromagnetic fields, charged particles, and photons

The concept of mediating particles was first applied to the electromagnetic force, in a theory called **quantum electrodynamics**. This theory states that virtual photons exchanged between charged particles are the carriers of the attractive or repulsive force between the particles. For example, consider the electromagnetic repulsion between two electrons. One electron emits a virtual photon in the direction of the other electron. According to Newton's third law, the first electron will recoil and its momentum will change by an amount opposite to the momentum of the photon. Similarly, when the second electron absorbs the photon, this electron will gain momentum directed away from the first electron. You can think of the photon for an attractive force as acting a bit like the shared electron holding two atoms together in a covalent chemical bond.

In the latter part of the 20th century, calculations using a refined version of quantum electrodynamics gave results that matched observed values with amazing accuracy — sometimes to 10 significant digits.

Mediating Particles

gluon: the mediating particle for the strong nuclear force

By 1970, research with high-energy particle accelerators led physicists to suggest that the strong nuclear force is mediated by zero-mass particles called **gluons**. So far, there is only indirect evidence for the existence of gluons.

Advances in quantum theory also led to the conjecture that the weak nuclear force is mediated by three particles, designated W^+, W^-, and Z^0. Experiments using extremely powerful accelerators detected these three particles in 1983. Some physicists think that the gravitational force also has a mediating particle, which they call the **graviton**. As yet, there is no experimental evidence that gravitons exist.

graviton: the hypothetical mediating particle for the gravitational force

Table 17.1 summarizes the current thinking about mediating particles.

Project **LINK**

For your unit project, you may want to describe the search for gluons and gravitons.

▼ **Table 17.1** The Fundamental Forces and Their Mediating Particles

Force	Range	Relative Strength for Protons in Nucleus	Mediating Particles	Particle Observed?
Electromagnetic	infinite	10^{-2}	photons	yes
Weak nuclear	<0.003 fm	10^{-6}	W^+, W^-, Z^0	yes
Strong nuclear	<1 fm	1	gluons	indirectly
Gravitational	infinite	10^{-38}	gravitons	no

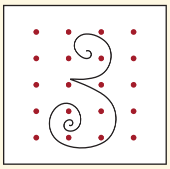
17.2 Check and Reflect

Knowledge

1. Describe the difference between ordinary matter and antimatter.
2. Outline how Anderson provided evidence for the existence of the positron.
3. (a) Which fundamental force is the strongest over large distances?
   (b) Which fundamental force is the weakest at nuclear distances?
4. (a) List the mediating particle for each of the fundamental forces.
   (b) Which of these mediating particles has not been detected at all?
5. Explain why a PET scan is like being X-rayed from the inside out.

Applications

6. (a) What event is represented by the equation $e^- + e^+ \rightarrow 2\gamma$?
   (b) Why is the event $e^- + e^+ \rightarrow \gamma$ not possible?
7. (a) Under what conditions will two protons attract each other?
   (b) Under what conditions will they repel each other?
8. The tracks in this diagram show the creation of two particles in a bubble chamber. Initially, the two particles have the same speed.



   (a) What evidence suggests that a photon created the two particles?
   (b) Describe the path of this photon.
   (c) Which of the tracks shows the path of a positively charged particle?
   (d) Give two reasons why the other track must show the path of a negatively charged particle.
   (e) How are the mass and charge of the two particles related?
   (f) Why is it likely that the interaction involves an antiparticle?
9. Explain how the stability of helium nuclei demonstrates that the electromagnetic force is weaker than the nuclear forces.

Extension

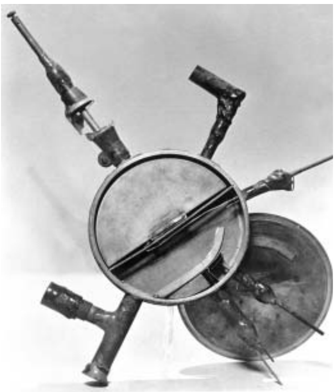
10. Research the Lamb shift and the Casimir effect at a library or on the Internet. Explain how these phenomena support the quantum field theory.

e TEST

To check your understanding of quantum theory and antimatter, follow the eTest links at www.pearsoned.ca/school/physicssource.

17.3 Probing the Structure of Matter

Our understanding of the structure of matter comes from a series of remarkable technological advances over the past century. For example, the first circular particle accelerator (Figure 17.14(a)) was about 12 cm in diameter and generated particles with energies up to 13 keV. Now, the most powerful accelerators are up to 8.5 km in diameter and can reach energies of a teraelectron volt (10^{12} eV). This huge increase in energy reflects an interesting overall trend: To probe matter at smaller and smaller scales, physicists need bigger and bigger machines! This trend results from the nature of matter: All of the fundamental forces become markedly stronger at distances less than the diameter of a nucleus.



▲ **Figure 17.14** (a) The first circular particle accelerator (b) Fermilab near Chicago, Illinois. Its Tevatron accelerator ring is 2 km in diameter.

Energy Requirements

13.6 eV is sufficient to ionize a hydrogen atom. With energies of a few hundred electron volts, you can study electron shells of atoms and of molecules (using a spectrograph, for example). To determine the size of a nucleus, you need charged particles with enough energy to get close to it despite strong electrostatic repulsion. For his ground-breaking scattering experiment, Rutherford used alpha particles with energies in the order of 10 MeV. To examine the structure of the nucleus, the energy requirements are much greater because the probe particles have to overcome the strong nuclear force. Within the nucleus, this short-range force is about a hundred times stronger than the electromagnetic force. The fundamental forces within individual subatomic particles are stronger still. So, probing the structure of stable particles such as protons and neutrons requires even more energy.

With early, relatively low-energy accelerators, physicists could conduct experiments in which accelerated particles scattered from nuclei or split nuclei into lighter elements (hence the nickname "atom-smasher"). With high-energy particles, physicists can also study interactions that create new types of particles. Producing some of the heavier particles requires a minimum of several gigaelectron volts.

Natural Sources of Energetic Particles

Some naturally radioactive isotopes emit particles that are useful for probing the structure of the atom. For example, Rutherford used polonium and radium as particle sources for his experiments. However, the maximum energy of particles from natural radioactive decay is roughly 30 MeV, which is not enough to probe the structure of nuclei.

The other major natural particle source is cosmic radiation. Cosmic rays are high-energy particles that stream into Earth's atmosphere from outer space. Astronomers are not certain about the origin of these particles. Some of them may come from solar flares and from distant supernovae. About 90% of cosmic rays are protons and most of the rest are alpha particles with a few electrons, positrons, antiprotons, and other particles. The energies of these particles range from roughly 10^2 to 10^{14} MeV. The particles from space (**primary cosmic rays**) rarely reach the ground because they interact with atoms in the atmosphere, producing less energetic **secondary cosmic rays**.

primary cosmic rays: high-energy particles that flow from space into Earth's atmosphere

secondary cosmic rays: the shower of particles created by collisions between primary cosmic rays and atoms in the atmosphere

Particle Accelerators

The first particle accelerators were built around 1930. These accelerators, and the much more powerful ones developed since then, use electric and magnetic fields to accelerate and direct charged particles, usually in a vacuum chamber. Here is a brief description of some of the major types of particle accelerators.

- **Van de Graaff:** A moving belt transfers charge to a hollow, conductive sphere, building up a large potential difference. This potential difference then propels ions through an accelerator chamber.
- **Drift Tube:** An alternating voltage accelerates charged particles through a series of electrodes shaped like open tubes. The applied voltage reverses as the particles pass through each tube, so the particles are always attracted to the next tube in the line.
- **Cyclotron:** A magnetic field perpendicular to the paths of the charged particles makes them follow circular paths within two hollow semicircular electrodes. An alternating voltage accelerates the charged particles each time they cross the gap between the two electrodes. The radius of each particle's path increases with its speed, so the accelerated particles spiral toward the outer wall of the cyclotron.
- **Synchrotron:** This advanced type of cyclotron increases the strength of the magnetic field as the particles' energy increases, so that the particles travel in a circle rather than spiralling outward. Some of the largest and most powerful particle accelerators are synchrotron rings.

Concept Check

Explain the advantages and disadvantages of studying nuclei with protons from a large accelerator as opposed to alpha particles produced by radioactive decay.

e WEB

To learn more about particle accelerators, follow the links at www.pearsoned.ca/school/physicssource.

info BIT

Marietta Blau published a number of papers on cosmic rays in the 1920s and 1930s. She was nominated for the Nobel Prize several times.

muon: an unstable subatomic particle having many of the properties of an electron but a mass 207 times greater

pion: an unstable subatomic particle with a mass roughly 270 times that of an electron

lepton: a subatomic particle that does not interact via the strong nuclear force

hadron: a subatomic particle that does interact via the strong nuclear force

meson: a hadron with integer spin

baryon: a hadron with half-integer spin

spin: quantum property resembling rotational angular momentum

fermion: particle with half-integer spin

boson: particle with integer spin

PHYSICS INSIGHT

How Small Are Electrons?

Experiments have shown that electrons are less than 10^{-18} m across, while protons are roughly 1.6×10^{-15} m in diameter. Leptons might be mathematical points with no physical size at all!

Although particle accelerators were originally developed for pure research, they now have medical and industrial uses as well. Many hospitals use accelerated particles for generating intense beams of X rays that can destroy cancerous tumours. Bombarding elements with particles from cyclotrons produces radioactive isotopes for diagnostic techniques, radiation therapy, testing structural materials, and numerous other applications. Particle accelerators can make a variety of specialized industrial materials by, for example, modifying polymers and implanting ions in semiconductors and ceramics. Accelerators are also powerful tools for analyzing the structure and composition of materials. Particle accelerators have even been used to verify the authenticity of works of art.

The Subatomic Zoo

In 1937, Carl Anderson and Seth Neddermeyer used a cloud chamber to discover **muons** in cosmic rays. These particles behave much like electrons, but have a mass 207 times greater and decay rapidly. Ten years later, Cecil Frank Powell discovered π-mesons, or **pions**, by using a photographic technology that Marietta Blau had developed. This method records tracks of particles on a photographic plate coated with a thick emulsion containing grains of silver bromide. Pions are much less stable than muons, and have some properties unlike those of electrons, protons, or neutrons.

Improved particle accelerators and detectors led to the discovery of many more subatomic particles. Over 300 have now been identified. Most of these particles are highly unstable and have lifetimes of less than a microsecond.

Studies of the interactions and decays of these particles show that there are two separate families of particles: **leptons**, which do not interact by means of the strong nuclear force, and **hadrons**, which do. The term *lepton* comes from *leptos*, a Greek word for “thin” or “small,” and *hadron* comes from *hadros*, a Greek word for “thick.” The diameters of leptons are much smaller than those of hadrons. The hadrons are divided into two subgroups, **mesons** (from *meso*, Greek for “middle”) and **baryons** (from *barus*, Greek for “heavy”).

One of the key quantum properties for classifying particles is their **spin**. This property is like angular momentum from rotation of the particle. The spin of a particle can be either an integer or half-integer multiple of Planck’s constant divided by 2π. Particles that have half-integer spin (such as $\frac{1}{2}$ or $\frac{3}{2}$) are called **fermions**, while those that have integer spin (such as 0, 1, or 2) are called **bosons**. Leptons and baryons are fermions. Mesons and mediating particles are bosons. Spin can affect the interactions and energy levels of particles.

▼ **Table 17.2** Classification of Subatomic Particles

	Leptons	Hadrons	Meditating Particles
Fermions	all leptons	baryons	
Bosons		mesons	all mediating particles

There are far more types of hadrons than types of leptons. In fact, physicists have found only six leptons plus their corresponding antiparticles. Table 17.3 compares the mass and stability of the leptons and some of the more significant hadrons. You are not required to memorize this table. Its purpose is to show a tiny set of the dozens of particles that physicists had discovered by the 1960s. What they were desperately seeking, and what you will learn about in the next section, was an underlying theory that could help make sense of this "subatomic zoo."

▼ **Table 17.3** An Introduction to the Subatomic Zoo

	Particle	Symbol	Mass (MeV/c^2)	Lifetime (s)
Leptons	electron electron neutrino	e^- ν_e	0.511 $< 7 \times 10^{-6}$	stable stable?
	muon muon neutrino	μ^- ν_μ	106 < 0.17	2.2×10^{-6} stable?
	tauon tauon neutrino	τ^- ν_τ	1777 < 24	2.9×10^{-13} stable?
Mesons	pions	π^+	140	2.6×10^{-8}
		π^0	135	8.4×10^{-17}
	kaons	K^+	494	1.2×10^{-8}
		K^0	498	9×10^{-20}
	psi	ψ	3097	8×10^{-21}
	upsilon	Υ	9460	1.3×10^{-20}
Baryons	proton	p^+	938.3	10^{31}?
	neutron	n	939.6	885*
	lambda	Λ^0	1116	2.6×10^{-10}
	sigma	Σ^+ Σ^0	1189 1192	8×10^{-11} 7.4×10^{-20}
	xi	Ξ^0 Ξ^-	1315 1321	2.9×10^{-10} 1.6×10^{-10}
	omega	Ω^-	1672	8.2×10^{-11}

*lifetime for a free neutron; neutrons in nuclei are stable

info **BIT**

A pion will decay in the time it takes light to travel across a classroom.

Units for Subatomic Masses

Note that Table 17.3 lists masses in units of MeV/c^2. The kilogram is not always the most convenient unit for expressing the mass of subatomic particles. Physicists often deal with transformations between mass and energy using Einstein's famous equation $E = mc^2$. Rearranging this equation gives $m = \frac{E}{c^2}$. It follows that mass can be expressed in terms of units of $\frac{\text{energy}}{\text{speed of light squared}}$.

Particle physicists find it convenient to use a factor of c^2 to relate mass to electron volts, the traditional energy unit for particle physics. Conversion factors for such units are

$1\ \text{eV}/c^2 = 1.7827 \times 10^{-36}\ \text{kg}$

$1\ \text{MeV}/c^2 = 1.7827 \times 10^{-30}\ \text{kg}$
$1\ \text{GeV}/c^2 = 1.7827 \times 10^{-27}\ \text{kg}$

e **MATH**

To better understand the relative sizes of subatomic particles, visit www.pearsoned.ca/school/physicssource.

For example, the mass of a proton expressed in these units is

$$m_p = 1.6726 \times 10^{-27}\ \text{kg} \times \frac{1\ \text{MeV}/c^2}{1.7827 \times 10^{-30}\ \text{kg}}$$
$$= 938.23\ \text{MeV}/c^2$$

The masses of the known subatomic particles range from 0.5 MeV/c^2 to 10 GeV/c^2, so exponent notation is usually not necessary with these units. Table 17.4 compares subatomic masses expressed in several common units.

▼ **Table 17.4** Comparison of Mass Units for Subatomic Particles (to Five Significant Digits)

Particle	Mass (kg)	Mass (u)	Mass (MeV/c^2)
Electron	9.1094×10^{-31}	5.4858×10^{-4}	0.511 00
Proton	1.6726×10^{-27}	1.0073	938.23
Neutron	1.6749×10^{-27}	1.0087	939.52

17.3 Check and Reflect

Knowledge

1. Why do physicists require extremely high-energy particles for studying the structure of nucleons?

2. List two natural sources of energetic particles.

3. What is the advantage of high-altitude locations for performing experiments with cosmic rays?

4. List two uses of particle accelerators in
(a) medicine
(b) industry

5. Identify a major difference that distinguishes
(a) leptons from hadrons
(b) mesons from baryons

Applications

6. Can alpha particles from the radioactive decay of polonium be used to probe the nucleus? Explain your answer.

7. Calculate the momentum and kinetic energy of a proton that is accelerated to a speed of
(a) $0.01c$
(b) 5.0×10^5 m/s

8. (a) Find the energy equivalent of the mass of an electron.
(b) The mass of a psi particle is 3.097 GeV/c^2. Express this mass in kilograms.

9. Calculate the conversion factor between atomic mass units and MeV/c^2. Give your answer to four significant digits.

Extensions

10. How has the development of superconducting electromagnets aided research into the structure of matter?

11. (a) What relativistic effect limits the energy of particles accelerated in an ordinary cyclotron?
(b) Describe three different ways this limit can be overcome.

eTEST

To check your understanding of particle accelerators and subatomic particles, follow the eTest links at www.pearsoned.ca/school/physicssource.

17.4 Quarks and the Standard Model

By 1960, physicists faced a large and growing menagerie of subatomic particles. Since the leptons are small and there are only a few types of them, it seemed likely that they were fundamental particles. However, the number of hadrons was a puzzle: Could there really be a hundred or more fundamental particles?

info BIT

Gell-Mann coined the term "quark" from an obscure line in a novel by the Irish writer James Joyce. Zweig had called the new fundamental particles "aces."

The Quark Model

In the 19th century, chemists studied the properties and reactions of the elements. The patterns observed in these properties led to the development of the periodic table and an understanding of the electron structure in atoms. Physicists searched for similar patterns in the properties and interactions of subatomic particles.

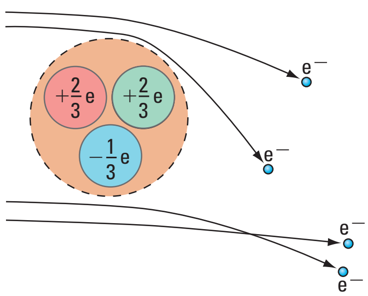
quark: any of the group of fundamental particles in hadrons

In 1963, Americans Murray Gell-Mann (b. 1929) and George Zweig (b. 1937) independently proposed that *all* hadrons are composed of simpler particles, which Gell-Mann called **quarks**. By grouping the subatomic particles into distinct classes and families, Gell-Mann and Zweig showed that all the hadrons then known could be made from just three smaller particles and their antiparticles. These three particles are now called the up quark, the down quark, and the strange quark. This theory required that the quarks have fractional charges that are either one-third of the charge on an electron or two-thirds of the charge on a proton. Understandably, many physicists had trouble accepting this radical concept.

info BIT

Richard Taylor was born in Medicine Hat and became interested in experimental physics while studying at the University of Alberta. In 1990, he shared the Nobel Prize in physics with Friedman and Kendall.

Using the quark model, Gell-Mann accurately predicted not only the existence of the omega (Ω^-) particle, but also the exact method for producing it. The quark model also accurately predicted key aspects of electron-positron interactions. Stronger evidence for the quark theory came in 1967 when Jerome Friedman, Henry Kendall, and Richard Taylor used the powerful Stanford Linear Accelerator to beam extremely high-energy electrons at protons. The electrons scattered off the protons, somewhat like the alpha particles that scattered off the gold nuclei in Rutherford's scattering experiment (Figure 17.15). The pattern of the scattered electrons suggested that the mass and charge of a proton are concentrated in three centres within the proton. Later experiments confirmed these results and showed a similar pattern for scattering from neutrons.



▲ **Figure 17.15** Scattering of high-energy electrons from a proton

In the quark model, protons and neutrons contain only up and down quarks. The strange quark accounts for the properties of **strange particles**, hadrons that decay via the weak nuclear force even though they originate from and decay into particles that can interact via the strong nuclear force.

strange particle: a particle that interacts primarily via the strong nuclear force yet decays only via the weak nuclear force

In 1974, the discovery of the psi meson confirmed the existence of a fourth quark, the charm quark. Then, in 1977, the heavy upsilon meson was detected and found to involve a fifth quark, the bottom quark. Since there are six leptons, physicists wondered if there might be an equal number of quarks. In 1995, a large team of researchers at Fermilab found evidence for the top quark. This discovery required a huge accelerator because the top quark is about 40 000 times heavier than the up quark.

e WEB

To learn more about the strange particles, follow the links at www.pearsoned.ca/school/physicssource.

THEN, NOW, AND FUTURE — Small Particles and Big Science

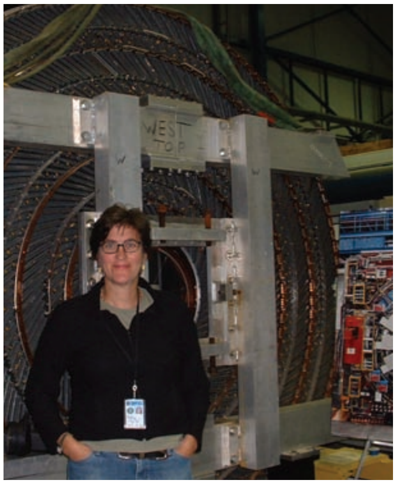
In the summer of 1936, Carl Anderson and his first graduate student, Seth Neddermeyer, lugged a cloud chamber and photographic equipment to the summit of Pikes Peak in Colorado, about 4300 m above sea level. They chose this location because the cosmic rays at that altitude were then the only source of the high-energy particles needed for their research. The work was lonely, uncomfortable, and poorly funded. It was also highly successful. Anderson and Neddermeyer discovered the muon with the cloud chamber photographs they took during their summer on Pikes Peak.

Flash forward 60 years. How particle physics has changed! In 1995, the Fermi National Accelerator Laboratory (Fermilab) near Chicago, Illinois, announced that a team of researchers there had discovered the elusive top quark. In all, 450 people worked on this project.

A key member of the team was Melissa Franklin (Figure 17.16), who has worked for over 18 years on the collider detector at Fermilab, a machine for studying the interactions resulting from colliding high-energy protons and antiprotons. A graduate of the University of Toronto and Stanford University, she is now a professor of physics at Harvard. Franklin is seeking to understand the structure of matter at the smallest scale, as Anderson did. However, Franklin collaborates with physicists from around the world and uses particle accelerators and detectors costing hundreds of millions of dollars. Although her work centres on tiny particles, she practises science on a big scale!

Questions

1. What other fields of scientific research require huge budgets and international cooperation?
2. What are some advantages and drawbacks of "big science"?
3. Teamwork skills are becoming increasingly important in many areas of research. What other skills would be useful for a career in science?



▲ **Figure 17.16** Melissa Franklin

Table 17.5 compares some properties of the six quarks. The mass of an individual quark cannot be measured directly. The masses given here were derived mainly by taking the total mass of various particles and subtracting estimates of the mass-energy the quarks gain from motion and interactions via the strong nuclear force within the particles. For each quark there is a corresponding antiquark with the opposite charge.

info **BIT**

To name quarks, physicists chose words that would not be mistaken for visible physical properties. In Europe, physicists commonly call the top quark "truth" and the bottom quark "beauty."

▼ **Table 17.5** Some Properties of Quarks

Generation	Name	Symbol	Mass (MeV/c^2)	Charge
First	up	u	1.5–4*	$+\frac{2}{3}e$
	down	d	4–8	$-\frac{1}{3}e$
Second	strange	s	80–130	$-\frac{1}{3}e$
	charm	c	$1.15–1.35 \times 10^3$	$+\frac{2}{3}e$
Third	bottom (or beauty)	b	$4.1–4.9 \times 10^3$	$-\frac{1}{3}e$
	top (or truth)	t	$1.7–1.9 \times 10^4$	$+\frac{2}{3}e$

*Some physicists think the up quark may be essentially massless.

Individual quarks probably cannot be observed. The strong nuclear force binds the quarks in a particle very tightly. The energy required to separate quarks is large enough to create new quarks or antiquarks that bind to the quark being separated before it can be observed on its own.

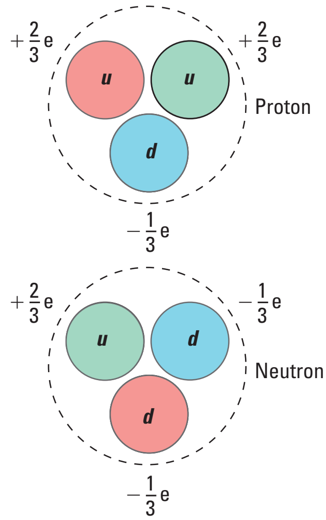
eWEB

To learn more about the difficulties in measuring quarks, follow the links at www.pearsoned.ca/school/physicssource.

Composition of Protons and Neutrons

The proton and the neutron contain only first-generation quarks. As shown in Figure 17.17, the proton consists of a down quark and two up quarks. The net charge of these three quarks is $\left(+\frac{2}{3}e\right) + \left(+\frac{2}{3}e\right) + \left(-\frac{1}{3}e\right) = +e$. The other quantum properties of the quarks also sum to those of a proton.

Similarly, a neutron consists of two down quarks and an up quark. In this combination, the positive charge on the up quark exactly balances the negative charge on the two down quarks.



▲ **Figure 17.17** The quarks making up protons and neutrons

Composition of Other Hadrons

All of the hadrons discovered in the 20th century can be accounted for with a combination of either two or three quarks:

- All the mesons consist of a quark and an antiquark.
- All the baryons consist of three quarks.
- All the antibaryons consist of three antiquarks.

However, experiments in 2003 produced strong evidence that the recently discovered theta particle (θ^+) consists of five quarks: two up quarks, two down quarks, and an antistrange quark.

Table 17.6 gives some examples of quark combinations.

▼ **Table 17.6** Some Quark Combinations

Meson	Composition	Baryon	Composition	Antibaryon	Composition
pion (π^+)	$u\bar{d}$	proton (p)	uud	antiproton (p^-)	$\bar{u}\bar{u}\bar{d}$
pion (π^0)	$u\bar{u}$	neutron (n)	udd	antineutron ($\bar{n}$)	$\bar{u}\bar{d}\bar{d}$
pion (π^-)	$\bar{u}d$	sigma-plus (Σ^+)	uus		
kaon (K^+)	$u\bar{s}$	sigma-minus (Σ^-)	dds		

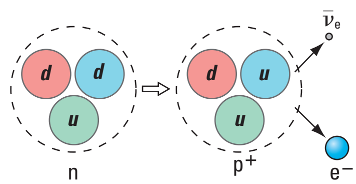
Describing Beta Decay Using Quarks and Leptons

Recall from section 16.2 that during beta decays of elements, the nuclei emit either an electron or a positron. Since both these particles are leptons, beta decay must proceed via the weak nuclear force.

In β^- decay of nuclei, a neutron transforms into a proton, an electron, and an antineutrino. Figure 17.18 shows that a neutron consists of an up quark and two down quarks while a proton consists of two up quarks and a down quark. So, the decay can be written as:

$$udd \rightarrow uud + e^- + \bar{\nu}_e$$

Charge is conserved since the difference between the $-\frac{1}{3}e$ charge on the down quark and the $+\frac{2}{3}e$ charge on the new up quark equals the charge on the electron emitted by the neutron. Physicists think that the down



▲ **Figure 17.18** During β^- decay, a down quark changes into an up quark.

quark emits a virtual W^- particle (a mediator for the weak nuclear force) that then decays into an electron and an antineutrino:

$$d \rightarrow u + [W^-] \quad \llcorner\!\!\longrightarrow e^- + \bar{\nu}_e$$

The idea of mediating particles is essential to understanding beta decay and is a central idea in the standard model.

Similarly, in β^+ decay of nuclei, an up quark in a proton turns into a down quark by emitting a virtual W^+ particle that then decays into a positron and a neutrino:

$$uud \rightarrow udd + [W^+] \quad \llcorner\!\!\longrightarrow e^+ + \nu_e$$

e **WEB**

To learn more about the decay of subatomic particles, follow the links at www.pearsoned.ca/school/physicssource.

The Standard Model

standard model: the current theory describing the nature of matter and the fundamental forces

electroweak force: a fundamental force that combines the electromagnetic force and the weak nuclear force

colour: a quantum property related to the strong nuclear force

quantum chromodynamics: quantum field theory that describes the strong nuclear force in terms of quantum colour

The term **standard model** now refers to a model originally proposed in 1978 to explain the nature of matter and the fundamental forces. Here are some key concepts of this model:

- All matter is composed of 12 fundamental particles — the 6 leptons and the 6 quarks — plus their antiparticles.
- The electromagnetic force and the weak nuclear force are both aspects of a single fundamental force. Sheldon Glashow, Abdus Salaam, and Steven Weinberg developed the theory for this **electroweak force** in the late 1960s. This theory accurately predicted the existence and masses of the W^+, W^-, and Z^0 particles.
- The electromagnetic and nuclear forces are mediated by virtual particles. As discussed in section 17.2, these mediating particles are the photon, the gluon, and the W^+, W^-, and Z^0 particles.
- All quarks have a quantum property, termed **colour**, which determines how the strong nuclear force acts between quarks. (Quantum colour is not related to visible colours at all.) The quantum field theory describing the strong nuclear force in this way is called **quantum chromodynamics**. It is analogous to quantum electrodynamics with colour instead of electric charge and gluons instead of photons.

Table 17.7 summarizes the fundamental particles in the standard model.

▼ **Table 17.7** Fundamental Particles in the Standard Model

Matter						
Generation	First		Second		Third	
Quarks	up	down	strange	charm	bottom	top
Leptons	electron	electron-neutrino	muon	muon-neutrino	tau	tau-neutrino
Fundamental Forces						
Force	Electromagnetic		Weak Nuclear		Strong Nuclear	
Mediating particle(s)	photon		W^+, W^-, and Z^0		gluon	

What's Next in Quantum Theory?

Many theorists are working to combine quantum chromodynamics and the electroweak force theory into a **grand unified theory**. One such theory suggests that the electromagnetic, strong nuclear, and weak nuclear forces would blend into a single force at distances less than 10^{-30} m, and leptons and quarks could transform from one into the other. However, it would take tremendously high energy to push particles so close together. Although of no relevance for everyday life, such theories could have a great effect on calculations about the origin of the universe.

Another challenge is to develop a theory that unifies gravity with the other three forces. One of the most promising approaches is **string theory**, which treats all particles as exceedingly tiny vibrating strings of mass-energy. The vibration of the strings is quantized (like standing waves). The various kinds of particles are just different modes of vibration, with the graviton being the lowest mode.

At present, these theories are highly speculative. The only thing known for sure is that the people who solve these problems will be in line for a Nobel Prize!

grand unified theory: quantum theory unifying the electromagnetic, strong nuclear, and weak nuclear forces

string theory: theory that treats particles as quantized vibrations of extremely small strings of mass-energy

Project **LINK**

For your unit project, you may want to describe theories that unify the fundamental forces.

17.4 Check and Reflect

Knowledge

1. What experimental evidence suggests that the proton contains three smaller particles?
2. Why is it probably impossible to observe an individual quark on its own?
3. Compare the quark composition of a proton to that of a neutron.
4. Describe the difference between mesons and baryons in terms of quarks.
5. State two differences between leptons and hadrons.
6. List the 12 fundamental particles of matter in the standard model.

Applications

7. (a) Using quark theory, write an equation for the beta decay of a neutron.
   (b) Show that charge is conserved in this decay process.
8. Is the beta decay $\mu^{+} \rightarrow e^{-} + \nu_{e} + \bar{\nu}_{\mu}$ possible? Justify your answer.
9. Describe what happens in this decay process:

   $$\text{uud} \rightarrow \text{udd} + [W^{+}]$$
   $$[W^{+}] \rightarrow e^{+} + \nu_{e}$$

Extension

10. Explain why a grand unified theory could have a great effect on speculations about the origin of the universe.

e **TEST**

To check your understanding of fundamental particles and the nature of matter, follow the eTest links at www.pearsoned.ca/school/physicssource.

CHAPTER 17 SUMMARY

Key Terms and Concepts

cloud chamber
bubble chamber
fundamental particle
quantum field theory
mediating particle
virtual particle
quantum electrodynamics
gluon
graviton
primary cosmic rays
secondary cosmic rays
Van de Graaff accelerator
drift tube accelerator
cyclotron
synchrotron
muon
pion
lepton
hadron
meson
baryon
spin
fermion
boson
quark
strange particle
standard model
electroweak force
colour
quantum chromodynamics
grand unified theory
string theory

Key Equations

Electron-positron annihilation: $e^{+} + e^{-} \rightarrow 2\gamma$

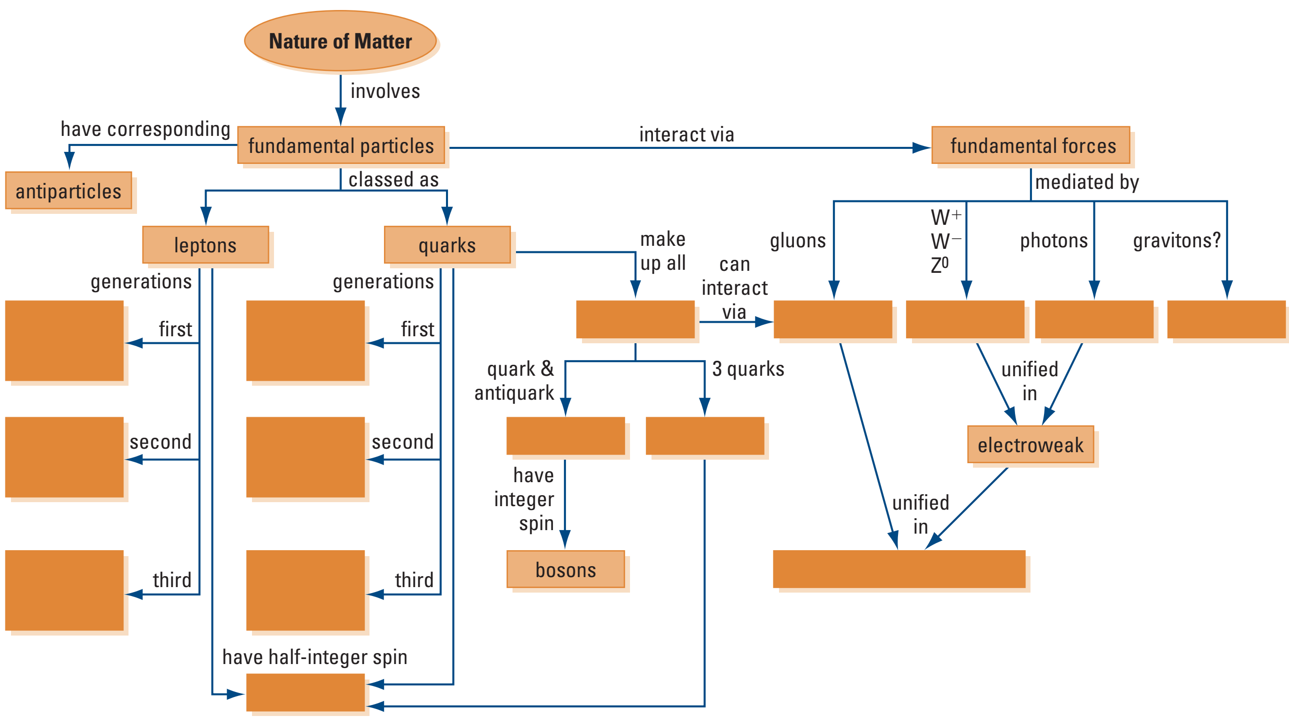
Mass units: $1\ \mathrm{eV}/c^2 = 1.7827 \times 10^{-36}\ \mathrm{kg}$

β^{-} decay: $udd \rightarrow uud + [W^{-}]$, $[W^{-}] \rightarrow e^{-} + \bar{\upsilon}_e$

β^{+} decay: $uud \rightarrow udd + [W^{+}]$, $[W^{+}] \rightarrow e^{+} + \upsilon_e$

Conceptual Overview

Summarize the chapter by copying and completing this concept map.



Knowledge

1. (17.1) How does a bubble chamber detect the path of a charged particle?

2. (17.1) Describe the technological advance in atomic physics made by
(a) Charles Wilson (b) Marietta Blau
(c) Donald Glaser

3. (17.2, 17.4) (a) In the early 1900s, which three subatomic particles were thought to be the fundamental building blocks of matter?
(b) Which of these particles is still thought to be fundamental?

4. (17.2) What theory predicted the existence of antimatter?

5. (17.2) For each of these particles, list the corresponding antimatter particle and explain how it differs from the ordinary matter particle.
(a) electron (b) proton

6. (17.2) How does quantum field theory account for fundamental forces acting over a distance?

7. (17.2, 17.3) Describe a similarity and a difference between a muon and a pion.

8. (17.3) What are two advantages of using units of MeV/c^2 to express the mass of subatomic particles?

9. (17.3) Compare the size of an electron to that of a proton.

10. (17.4) Describe an experiment that provided evidence for the existence of quarks.

11. (17.4) Give two reasons why Millikan did not detect any quarks with his oil-drop experiment.

12. (17.4) (a) Why did physicists suspect that there might be a sixth quark?
(b) What is the name of this sixth quark?
(c) Why was a huge accelerator necessary for the discovery of this quark?

13. (17.4) Compare the quark composition of antiprotons and antineutrons.

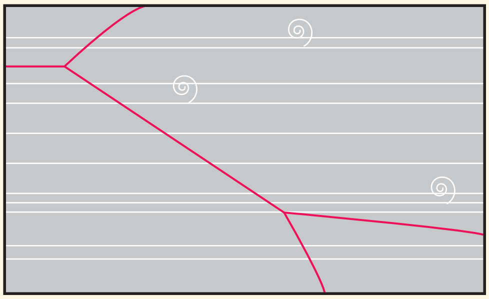
14. (17.4) Which two fundamental forces are united in the standard model?

15. (17.4) How does the string theory explain the various kinds of subatomic particles?

Applications

16. Sketch the paths that alpha, beta, and gamma radiation would follow when travelling perpendicular to a magnetic field directed out of the page.

17. The red tracks in this diagram show a high-speed proton colliding with a hydrogen atom in a bubble chamber, deflecting downward (toward the bottom of the page), and then colliding with another hydrogen atom. These tracks curve clockwise slightly.



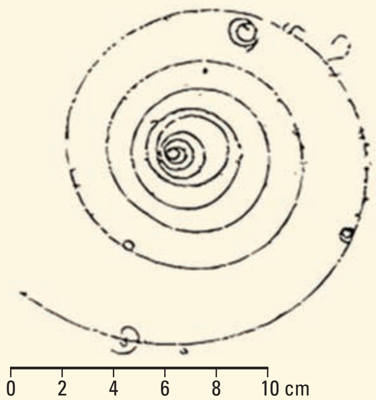
(a) In which direction is the magnetic field oriented?
(b) What conclusions can you make about the mass, speed, and charge of the particles involved in the first collision?
(c) What conclusion can you make about the mass, speed, and charge of the particles that made the small spiral tracks?

18. (a) Write a nuclear decay equation to show how fluorine-18 can produce positrons for use in positron-emission tomography.
(b) Describe the role that quarks play in this decay process.
(c) Write an equation to describe what happens to the positrons within a patient undergoing a PET scan.

19. The mass of a top quark is about 176 GeV/c^2. Express this mass in kilograms.

20. (a) Determine the charge on a particle having the quark composition uus.
(b) Estimate the mass of this particle.

21. The diagram shows a particle track recorded in a bubble chamber at the CERN particle accelerator. There is good reason to suspect that the particle is either an electron or a positron. The magnetic field in the bubble chamber was 1.2 T directed out of the page.



(a) Does the particle have a positive or negative charge? Explain your reasoning.

(b) Estimate the initial radius of the particle's path.

(c) Determine the initial momentum of the particle. Assume that the particle is an electron or a positron.

(d) Why does the particle's path spiral inward?

(e) What could cause the short tracks that branch off from the large spiral track?

Extension

22. Research Pauli's exclusion principle at the library or on the Internet. Write a paragraph describing this principle and the classes of particles to which it applies.

Consolidate Your Understanding

1. Describe three experiments that discovered new subatomic particles. Explain how these experiments changed physicists' understanding of the nature of matter.

2. Give two examples of theories that accurately predicted the existence of previously unknown subatomic particles.

3. (a) Why was the quark theory first proposed?

(b) Outline the experimental evidence that supports this theory.

(c) Explain to a classmate why the standard model now includes six quarks instead of the three originally suggested by Gell-Mann and Zweig.

Think About It

Review your answers to the Think About It questions on page 829. How would you answer each question now?

e TEST

To check your understanding of the structure of matter, follow the eTest links at www.pearsoned.ca/school/physicssource.

How Atomic Physics Affects Science and Technology

Scenario

Atomic physics has enormously influenced the development of modern science and technology. Advances in atomic physics have profoundly changed scientists' understanding of chemistry, biology, and medicine. A century ago, technology that is taken for granted now would have seemed impossible even in principle. In this project, you will work with two or three classmates to research how the concepts presented in this unit affected an aspect of science or technology.

Planning

Brainstorm with your classmates to make a list of possible topics. Look for branches of science or technology that apply concepts of atomic physics. Here are some starting points:

- medical diagnostic technologies, such as X rays, magnetic resonance imaging (MRI), PET scans, and radioactive tracers
- chemistry applications, such as understanding molecular bonds and using spectroscopy to identify compounds
- biology topics such as quantum effects in photosynthesis and DNA replication
- computer and electronic devices, such as microchips, tunnel diodes, and quantum computers
- nanotechnologies such as nanotubes and atomic force microscopes
- power technologies, such as nuclear reactors, tokamaks, and radioisotope thermoelectric generators (RTGs)

Decide upon a topic to research. Often, you will find it easier to deal with a specific topic rather than a general one. For example, you could focus on nanotubes rather than trying to cover the whole field of nanotechnology. You may want to do some preliminary research on two or three promising ideas to see how much information is available.

Consider the best way to present your findings. You might use a written report, an oral presentation, slides, a poster, a model, a video, or a combination of methods. Consult with your teacher on the format of your presentation.

Assessing Results

Assess the success of your project based on a rubric* designed in class that considers:

- research strategies
- clarity and thoroughness of the written report
- effectiveness of the team's presentation

Materials

- library resources, including books and periodicals
- Web browser and Internet connection

Check with your teacher about any special resources, such as computer software, that you may need for your presentation.

Procedure

1. Assign tasks for each group member. Each member should do part of the research as well as some of the preparation for the presentation, such as writing, preparing graphics, or building a model. Clearly identify who is responsible for each part of your project.
2. Once you have gathered basic information about your topic, consider what further research you need to do. For example, you may be able to interview an expert either in person, or by telephone or e-mail. Many university departments have an outreach program that might suggest an expert you could consult.
3. Check whether the presentation method your group has chosen is suitable for the information you have found during your research. Consult with your teacher if you think you need to change to another type of presentation. If you will be making an oral presentation, practise. Having friends and family critique your presentation can often help you find ways to improve it.

Thinking Further

- Atomic physics often seems to be too abstract or theoretical to have any relevance to the "real world." How has your investigation changed your understanding of the relationship between atomic physics and other disciplines?
- Does the influence of atomic physics extend beyond science? Can you find ways in which atomic physics has influenced the arts or philosophy?
- Science fiction often employs ideas from physics. List several science-fiction books, movies, or television series that use some of the concepts in this unit. How accurate is their treatment of atomic physics?

*Note: Your instructor will assess the project using a similar assessment rubric.

UNIT VIII SUMMARY

Unit Concepts and Skills: Quick Reference

Concepts	Summary	Resources and Skill Building
Chapter 15	**Electric force and energy quantization determine atomic structure.**	
	15.1 The Discovery of the Electron	
cathode rays	Thomson's experiments showed that cathode rays are subatomic particles with a negative charge.	15-1 QuickLab
charge-to-mass ratio	You can use electric and magnetic fields to measure the charge-to-mass ratio of a particle.	Example 15.2
	15.2 Quantization of Charge	
charge quantization	Electric charge exists only in multiples of the fundamental unit of charge, e.	15-2 QuickLab
Millikan's experiment	Millikan's oil-drop experiment measured the charge on an electron and showed that charge is quantized.	Example 15.3 eSIM of Millikan's oil-drop experiment
	15.3 The Discovery of the Nucleus	
classical model of the atom	Rutherford's gold-foil experiment led to the solar-system model with electrons orbiting a tiny positively charged nucleus at the centre of the atom.	15-3 QuickLab Example 15.5
	15.4 The Bohr Model of the Atom	
spectra	Elements and compounds have characteristic emission and absorption line spectra.	15-4 Design a Lab
Bohr model	The Bohr model uses energy levels to account for stability of the atom and to explain line spectra. This model accurately predicts many properties of hydrogen, but has several serious failings.	Example 15.6
energy levels	An electron in an atom can occupy only orbits that give the electron discrete, quantized amounts of energy that are inversely proportional to the square of the principal quantum number.	Example 15.7 15-5 Inquiry Lab
	15.5 The Quantum Model of the Atom	
quantum mechanical model	The wave properties of electrons lead to a powerful new model based on probability distributions.	Figures 15.24–15.25
Chapter 16	**Nuclear reactions are among the most powerful energy sources in nature.**	
	16.1 The Nucleus	
nuclear structure	Nuclei contain protons and neutrons bound together by the strong nuclear force.	Examples 16.1 and 16.2
mass-energy equivalence	Mass and energy are equivalent, and the one can be transformed into the other.	Example 16.3
binding energy, mass defect	The binding energy and mass defect of a nucleus indicate how tightly its nucleons are bound together.	Figure 16.3 Example 16.4
	16.2 Radioactive Decay	
nuclear decay, transmutation	Some nuclei spontaneously transmute into a different element by emitting an alpha or beta particle. Nuclei can also give off gamma rays. All three types of radiation can be harmful.	Examples 16.5–16.10 16-1 Inquiry Lab 16-2 Design a Lab
	16.3 Radioactive Decay Rates	
half-life, activity	You can use the decay constant and the half-life of a radioisotope to predict the activity of a sample.	Examples 16.12 and 16.13
	16.4 Fission and Fusion	
nuclear reactions	Both the fission of a heavy nucleus into smaller nuclei and the fusion of light nuclei into a single heavier nucleus can release tremendous amounts of energy.	Figures 16.17 and 16.18 Examples 16.14–16.16
Chapter 17	**The development of models of the structure of matter is ongoing.**	
	17.1 Detecting and Measuring Subatomic Particles	
particle tracks	The existence and basic properties of subatomic particles can be determined by analyzing the paths of particles in magnetic and electric fields.	Example 17.1 17-1 QuickLab, 17-2 Inquiry Lab
	17.2 Quantum Theory and the Discovery of New Particles	
antimatter	Quantum theory predicted the existence of antimatter, which was confirmed by Anderson's discovery of the positron.	Figure 17.11
quantum field theory	According to this theory, the electromagnetic and nuclear forces are mediated by virtual particles.	Figure 17.13
	17.3 Probing the Structure of Matter	
particle accelerators	Particle accelerators produce high-energy particles, which are used to study the structure of matter.	Figure 17.14
families of particles	Hadrons interact via the strong nuclear force, whereas leptons do not. Bosons have integer spin and fermions have half-integer spin.	Tables 17.2 and 17.3
	17.4 Quarks and the Standard Model	
fundamental particles	The fundamental particles are the six leptons, the six quarks, and their antiparticles. All hadrons consist of a combination of quarks and/or antiquarks.	Tables 17.5,17.6, and 17.7

UNIT VIII REVIEW

Vocabulary

1. Using your own words, define these terms:
   absorption line spectrum
   activity (A) or decay rate
   alpha radiation
   antimatter
   atomic mass number
   atomic mass unit (u)
   atomic number
   baryon
   becquerel (Bq)
   beta (β) particle
   beta radiation
   beta-negative (β^-) decay
   beta-positive (β^+) decay
   binding energy
   Bohr radius
   boson
   bubble chamber
   cathode ray
   cloud chamber
   colour
   cyclotron
   daughter element
   decay constant
   drift tube accelerator
   electroweak force
   elementary unit of charge
   emission line spectrum
   energy level
   excited state
   femto
   fermion
   fission
   Fraunhofer line
   fundamental particle
   fusion
   gamma (γ) decay
   gamma radiation
   gluon
   grand unified theory
   graviton
   gray (Gy)
   ground state
   hadron
   half-life
   ionization energy
   isotopes
   lepton
   mass defect
   mediating particle
   meson
   muon
   neutrino
   neutron
   neutron number
   nucleon
   nucleosynthesis
   orbital
   parent element
   pion
   planetary model
   positron (e^+ or ${}^{0}_{1}\beta$)
   primary cosmic rays
   principal quantum number
   proton
   proton-proton chain
   quantum chromodynamics
   quantum electrodynamics
   quantum field theory
   quark
   radioactive decay series
   radioisotope
   relative biological effectiveness (RBE)
   secondary cosmic rays
   sievert (Sv)
   spectrometer
   spectroscopy
   spin
   standard model
   stationary state
   strange particle
   string theory
   strong nuclear force
   supernova
   synchrotron
   transmute
   Van de Graaff accelerator
   virtual particle
   weak nuclear force

Knowledge

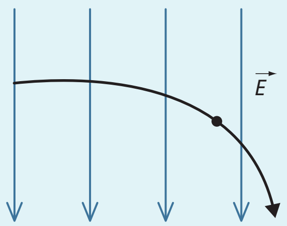
CHAPTER 15

2. Calculate the electrical charge carried by 1 kg of protons. Give your answer to two significant digits.

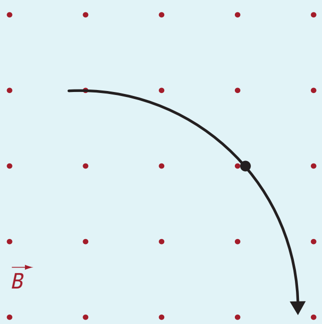
3. How many coulombs of charge are on a dust particle that has gained 10 electrons?

4. Calculate the force exerted by an electric field of strength 100 N/C [S] on a dust particle having a charge of $-10e$.

5. Explain how the path of this particle shows whether its charge is positive or negative.



6. Determine whether the charge on this particle is positive or negative.



7. What is an alpha particle?

8. Here are four energy-level transitions for an electron in a hydrogen atom:

   $n_i = 1 \rightarrow n_f = 5$ $\quad n_i = 4 \rightarrow n_f = 1$

   $n_i = 2 \rightarrow n_f = 6$ $\quad n_i = 6 \rightarrow n_f = 2$

   (a) For which transition(s) does the atom lose energy?

   (b) For which transition does the atom gain the most energy?

   (c) Which transition emits the shortest wavelength photon?

9. You are comparing the energy released by two different atomic transitions in a mercury atom. Transition A produces a very bright green line while transition B produces a fainter violet-coloured line. Which of these transitions releases more energy? Explain.

CHAPTER 16

10. How many neutrons are in a nucleus of gallium $^{64}_{31}Ga$? How many protons?

11. Why is the mass of an atom always less than $Zm_{^1_1H} + Nm_{neutron}$?

12. Express the energy equivalent of 0.021 u of mass in electron volts.

13. Express the energy equivalent of 7.0 u in joules.

14. Calculate the binding energy for a nucleus that has a mass defect of 0.0072 u.

15. What is the activity of a sample that contains 1.5×10^{22} nuclei of an element with a decay rate of 1.5×10^{-13} Bq?

16. Write the β^+ decay process for $^{18}_{9}F$, and identify the daughter element.

17. The half-life of sulfur-35 is 87.51 days. How much of a 25-g sample of this isotope will be left after a year?

18. Write the alpha decay process for $^{228}_{90}Th$ and identify the daughter element.

19. Explain the difference between fission and fusion.

CHAPTER 17

20. What is a positron?

21. What is a pion?

22. If an electron and positron collide, they annihilate each other and are converted into energy.

    (a) How much energy does the annihilation of a positron-electron pair produce?

    (b) Explain why the annihilation must produce two gamma rays with the same wavelength.

    (c) Estimate the wavelength of these gamma rays. Assume that the kinetic energy of the electron and positron was negligible.

23. What is a quark?

24. Describe this reaction in words:

    $\bar{\nu}_e + p \rightarrow n + e$

25. Identify the particle formed by each of these combinations of quarks:

    (a) uud $\quad$ (b) $u\bar{s}$

    (c) $u\bar{d}$ $\quad$ (d) dds

26. Use quarks to describe how a neutron decays into a proton and an electron.

Applications

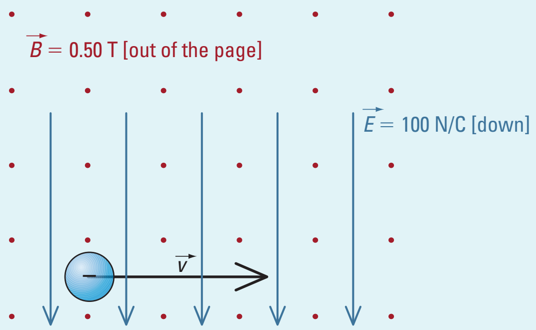
27. A beam of protons enters a vacuum chamber where the electric field strength is 40 kN/C and the magnetic field strength is 0.55 T.

(a) Sketch an orientation of the electric and magnetic fields that could let the protons pass undeflected through the chamber.

(b) What speed must the protons have if they are not deflected by this orientation of the fields?

28. Find the magnetic field strength that will deflect a sodium ion (Na^+) in an arc of radius 0.50 m when the ion has a speed of 1.0×10^6 m/s.

29. This diagram shows an electron moving at 2.5×10^6 m/s through perpendicular electric and magnetic fields.



(a) Calculate the electric and magnetic forces acting on the electron.

(b) Calculate the net force acting on the particle.

30. An oil droplet with a mass of 1.6×10^{-16} kg is suspended motionless in a uniform electric field of strength 981 N/C [down].

(a) Find the charge on this droplet.

(b) How many electrons has the droplet either gained or lost?

31. (a) Find the wavelengths of the first four spectral lines produced by transitions into the $n = 3$ energy level of a hydrogen atom.

(b) What part of the electromagnetic spectrum are these lines in?

32. (a) Use the Bohr model to calculate the radius of the $n = 2$ energy level in a hydrogen atom.

(b) Find the de Broglie wavelength for an electron in this energy level.

(c) Use the formula for the de Broglie wavelength to find the momentum of this electron.

(d) Find the electron's speed and kinetic energy.

33. Calculate the binding energy for ${}^{40}_{20}\text{Ca}$.

34. Identify the nucleus produced in each reaction.

(a) ${}^{12}_{6}\text{C} + \gamma \rightarrow ? + \alpha$

(b) ${}^{14}_{7}\text{N} + \alpha \rightarrow ? + \text{n}$

(c) ${}^{206}_{81}\text{Tl} \rightarrow ? + \beta^- + \bar{v}$

35. Explain why each of these reactions cannot occur.

(a) ${}^{15}_{6}\text{C} \rightarrow {}^{15}_{5}\text{B} + \beta^+ + \bar{v}_e$

(b) ${}^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \beta^+ + v_e$

(c) ${}^{23}_{11}\text{Na} + \text{n} \rightarrow {}^{19}_{9}\text{F} + \alpha$

36. How much energy is released by β^- decay of ${}^{16}_{7}\text{N}$?

37. Some blood-flow tests use iodine-131 as a tracer. This isotope has a half-life of 8.04 days. Estimate the percentage of iodine-131 left after 30 days.

38. How much energy is given off in the alpha decay of neodymium isotope ${}^{144}_{60}\text{Nd}$? What daughter element does this decay produce?

39. A radioactive sample has an activity of 0.50 MBq and a half-life of 6 h. What will the activity of the sample be after 3.0 days?

40. The proportion of carbon-14 in charcoal used in a cave painting is only 12.5% of the proportion in living trees nearby. Estimate the age of this cave painting.

41. Calculate the amount of energy released when a carbon-12 nucleus absorbs an alpha particle and transmutes into oxygen-16.

42. Calculate the energy released by the reaction ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + {}^{1}_{1}\text{H}$.

43. (a) What fundamental particles does a neutron contain, according to the standard model?

(b) Show that this combination of particles has zero net charge.

44. The size of a nucleus is in the order of 1 fm.
   (a) Calculate the electrostatic force of repulsion between two protons separated by 1 fm.
   (b) Determine the potential energy of this pair of protons.
   (c) What keeps a nucleus together despite the electrostatic repulsion between protons?

Extensions

45. Two hydrogen atoms in the ground state collide head on and both ionize. Find the minimum speed at which the atoms could have been moving toward each other.

46. (a) Describe the reaction $\gamma + \mathrm{p} \rightarrow \pi^0 + \mathrm{p}$ in words.
   (b) Calculate the minimum energy the photon must have to produce this reaction.

47. In β^+ decay, a proton becomes a neutron and the nucleus emits a positron and a neutrino. A proton has less mass than a neutron, and the positron and the neutrino carry away some mass and energy. Explain how such decays conserve mass-energy despite this apparent imbalance.

48. A 5.0-GeV photon creates, via pair-production, an electron and a positron. Calculate the total momentum of the two particles and sketch their motion relative to the path of the original photon.

49. Imagine that protons and electrons were not charged but could still form a hydrogen atom through gravitational attraction. Calculate the radius of the ground state. (Hint: Assume that the electron travels in a circular orbit and has a total energy of $-\dfrac{Gm_\mathrm{p}m_\mathrm{e}}{2r}$.)

50. A typical banana contains about 0.40 g of potassium. Naturally occurring potassium is mainly ${}^{39}_{19}\mathrm{K}$, but 0.012% of it is the radioactive isotope ${}^{40}_{19}\mathrm{K}$, which has a decay constant of $1.8 \times 10^{-17}\ \mathrm{s}^{-1}$. The average atomic mass for natural potassium is 39.1 u.
   (a) Calculate the activity of a typical banana.
   (b) Does the radiation exposure from bananas outweigh their health benefit as a source of potassium, fibre, and vitamins A, B6, and C? Explain your reasoning.

51. A spill of radioactive material at an industrial site emits 1.25 mGy per hour, measured at a distance of 1.0 m from the spill. The relative biological effectiveness of this radiation is 2.
   (a) Compare the radiation dose from this spill to exposure from background radiation.
   (b) At what distance from the spill would the annual absorbed dose be less than 0.1 mSv?
   (c) A newspaper headline reads "Dangerous Spill at Local Factory." Is this description fair? Explain why or why not.

52. (a) What is the fundamental difference between a fusion process and one that combines matter and antimatter?
   (b) Compare the energy released by the fusion of ordinary hydrogen into helium-4 with the energy released by combining two protons with two antiprotons.
   (c) Why can antimatter not be used for generating power or propelling a spaceship now?

53. Suppose that an electricity generator powered by the fusion reaction ${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$ has an overall efficiency of 20%. How much deuterium and tritium will this generator need to produce 10 MW•h of electricity, the annual consumption of a typical home?

Skills Practice

54. After two years, 6% remains of the original radioisotope in a sample. Estimate the half-life of this isotope.

55. A nucleus of boron ${}^{10}_{5}\mathrm{B}$ absorbs an alpha particle and emits a proton. Use nuclear notation to write this reaction process, and identify the element that it produces.

56. Does an electron that moves from an energy level of −5.1 eV to an energy level of −6.7 eV emit or absorb a photon? Find the wavelength of the photon.

57. How much energy is produced by the conversion of 0.250 u of matter into energy?

58. Calculate the radius of a hydrogen atom in the $n = 2$ state.

59. An electron jumping from the $n = 3$ to the $n = 2$ state in a hydrogen atom emits a 656-nm photon.
   (a) Which state has the greater energy?
   (b) Find the energy difference between the two states.

60. Calculate the binding energy for ${}^{24}_{12}\mathrm{Mg}$.

61. Find the parent atom for this decay: $? \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} + \bar{v}$

62. Calculate the electrical charge of a particle composed of the quarks uus.

63. Find the activity of a sample containing 1.5×10^{20} radioactive atoms with a decay constant of $3.5 \times 10^{-15}\ \mathrm{s}^{-1}$.

Self-assessment

64. Outline how you would describe Rutherford's gold-foil experiment to a friend. Explain why the results were startling for physicists in 1910.

65. (a) Explain why classical physics predicts that hydrogen will always produce a continuous spectrum rather than discrete spectral lines.
   (b) How does the Bohr model explain spectral lines?

66. Draw a concept map of the atomic physics topics that you find the most difficult. If you have trouble completing this concept map, discuss the concepts with a classmate or your teacher.

67. Explain why pair annihilation, such as $\mathrm{e} + \mathrm{e}^{+} \rightarrow 2\gamma$, does not violate the law of conservation of mass.

68. List the four fundamental forces and explain which ones are involved in nuclear binding energy, decays, fission, and fusion.

eTEST

To check your understanding of atomic physics, follow the eTEST links at www.pearsoned.ca/school/physicssource.