تغطية اختبار نهاية الفصل انسباير





تم تحميل هذا الملف من موقع المناهج الإماراتية	
موقع المناهج ⇦ المناهج الإماراتية ⇦ الصف الثاني عشر المتقدم ⇦ فيزياء ⇦ الفصل الأول ⇦ ملفات متنوعة ⇦ الملف	
تاريخ إضافة الملف على موقع المناهج: 2026-11-10 09:31:30	
ملفات ا كتب للمعلم ا كتب للطالب ا اختبارات الكترونية ا اختبارات ا حلول ا عروض بوربوينت ا أوراق عمل منهج انجليزي ا ملخصات وتقارير ا مذكرات وبنوك ا الامتحان النهائي ا للمدرس	المزيد من مادة فيزياء:
إعداد: Hoda	

التواصل الاجتماعي بحسب الصف الثاني عشر المتقدم					
صفحة المناهج الإماراتية على فيسبوك					
المواد على تلغرام	التربية الاسلامية	اللغة العربية	اللغة الانجليزية	الرياضيات	

المزيد من الملفات بحسب الصف الثاني عشر المتقدم والمادة فيزياء في الفصل الأول	
هيكل اختبار نهاية الفصل انسباير	1
هيكل اختبار نهاية الفصل في بريدج	2
قوانين كامل الفصل الأول	3
أسئلة تدريبية على قانون جاوس للتماثل الكروي	4
الهيكل 2027 بريدج	5

تحميل تطبيق المناهج للهواتف الذكية	
تطبيق المناهج على Store App (آبل)	تطبيق المناهج على Play Google (أندرويد)

EOT – Term 1 – Exam Coverage Problems

Grade 12 Advanced

Inspire

SIMPLE PHYSICS
With Ms. Heda

1	-Define potential energy and gravitational potential energy. -Relate gravitational potential energy to mass and height (GPE = mgh). -Show that work done by gravity is opposite to the change in gravitational potential energy. -Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Student Textbook · p. 14

LESSON 2

THE MANY FORMS OF ENERGY

FOCUS QUESTION

What are some forms of energy?

Changing Forms of Energy

Recall that the work-energy theorem states that doing work on a system causes a change in the energy of that system. That is, work is the process that transfers energy between a system and the external world. When an agent performs work on a system, the system's energy increases. When the system does work on its surroundings, the system's energy decreases.

In some ways, energy is like ice cream—it comes in different varieties. You can have vanilla, chocolate, or peach ice cream. These are different varieties, but they are all ice cream. However, unlike ice cream, energy can be changed from one form to another. A system of objects can possess energy in a variety of forms.



Figure 12 Energy can manifest itself in a variety of ways, such as light and sound in a July 4 fireworks display.

At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. For example, when you experience a fireworks display, such as the one shown in **Figure 12**, you hear and see the results of the energy released in the chemical reactions in the fireworks in the form of moving, colorful lights and loud pops. You may even feel the warmth given off during the explosion if you are close enough (but not too close).

In this lesson, you will learn how energy is transformed from one variety (or form) to another and how to keep track of the changes.

Get It?

Describe an example of an event in which more than one form of energy is evident.

LHB Photo/Alamy Stock Photo

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Review the News

Obtain information from a current news story about energy or energy resources. Evaluate your source and communicate your findings to your class.

Revisit the Encounter the Phenomenon Question

What information from this lesson can help you answer the Unit and Module questions?

1	-Define potential energy and gravitational potential energy. -Relate gravitational potential energy to mass and height (GPE = mgh). -Show that work done by gravity is opposite to the change in gravitational potential energy. -Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Student Textbook · p. 15

Translational and Rotational Kinetic Energy

In the examples we have considered so far, moving objects that were changing position had kinetic energy $\left(\frac{1}{2}mv^2\right)$ due to their motion. What about energy due to an object's changing position?

Translational kinetic energy Energy due to changing position is called **translational kinetic energy** and can be represented by the following equation.

Translational Kinetic Energy

A system's translational kinetic energy is equal to one-half times the system's mass multiplied by the system's speed squared.

$$KE_{trans} = \frac{1}{2}mv^2$$

Translational kinetic energy is proportional to the object's mass. For example, a 7.26-kg bowling ball thrown through the air has more translational kinetic energy than a 0.148-kg baseball, like the one shown in **Figure 13,** moving with the same speed.

An object's translational kinetic energy is also proportional to the square of the object's speed. A car moving at 20 m/s has four times the translational kinetic energy of the same car moving at 10 m/s.



Figure 13 A baseball has less translational kinetic energy than a bowling ball moving with the same speed.

Get It?

Explain Using the equation for translational kinetic energy, show why a car moving at 20 m/s has four times the translational kinetic energy of the same car moving at 10 m/s.

SCIENCE USAGE v. COMMON USAGE

Energy

Science usage: the ability of a system to produce a change in itself or the world around it

The kinetic energy of the soccer ball decreased as it slowed down.

Common usage: the capacity of acting or being active

The young students had a lot of energy during recess.

aron W. Henderson/Getty Images

1	-Define potential energy and gravitational potential energy. -Relate gravitational potential energy to mass and height (GPE = mgh). -Show that work done by gravity is opposite to the change in gravitational potential energy. -Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Student Textbook · p. 16

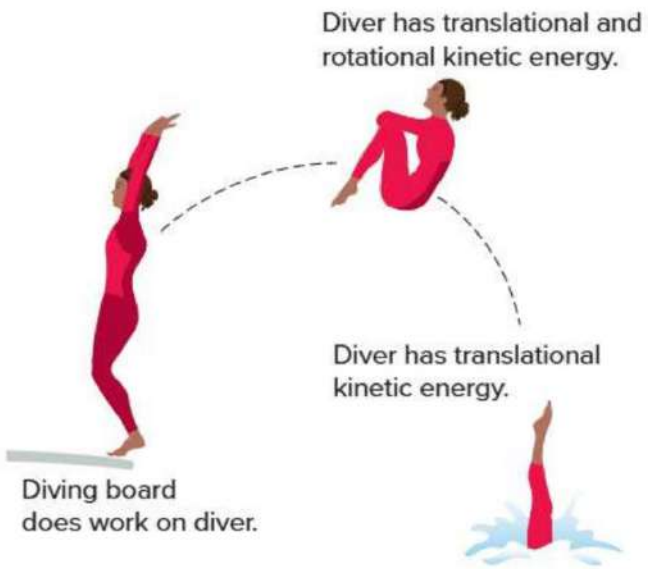


Figure 14 The diving board does work on the diver. This work increases the diver's kinetic energy.

In **Figure 14,** the diving board does work on a diver, transferring translational and rotational kinetic energy to the diver. Her center of mass moves as she leaps, so she has translational kinetic energy. She rotates about her center of mass, so she has rotational kinetic energy. When she slices into the water, she has mostly translational kinetic energy.

Potential Energy

Let's return to the money and energy model from Lesson 1. Money and energy can be in different forms. You can have one five-dollar bill, 500 pennies, or 20 quarters—in all forms, you still have five dollars. In the same way, energy can be kinetic energy, stored energy, or another form.

Consider some boulders on a mountain. They have been moved from Earth's center by geological processes against gravity. Thus, the Earth-boulders system has stored energy. Energy that is stored due to interactions between objects in a system is called **potential energy.** But not all potential energy is due to gravity. A spring-loaded toy is a system that has potential energy, but the energy is stored due to a compressed spring, not gravity.

CCC CROSSCUTTING CONCEPTS

Systems and System Models Mathematical models can be used to predict the behavior of a system, but models can be limited. Choose an example of a mathematical model used to make an energy calculation based on a realistic situation, such as ice-skating or pushing different materials across different surfaces. What evidence do you have that the model is limited? Explain your model as well as its limitations to a peer.

Rotational kinetic energy If you spin a toy top in one spot, you might say that it does not have kinetic energy because the top does not change its position. However, to make the top rotate, you had to do work on it. The top has **rotational kinetic energy,** which is energy due to rotational motion. Rotational kinetic energy can be calculated using $KE_{rot} = \frac{1}{2} I\omega^2$, where I is the object's moment of inertia and ω is the object's angular velocity.

1	-Define potential energy and gravitational potential energy. -Relate gravitational potential energy to mass and height (GPE = mgh). -Show that work done by gravity is opposite to the change in gravitational potential energy. -Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Student Textbook · p. 17



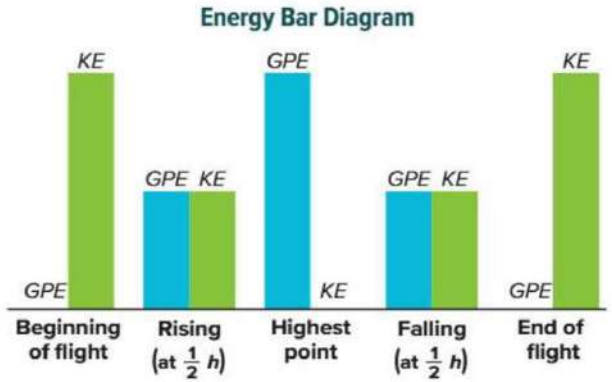


Figure 15 As the ball rises, its kinetic energy transforms into potential energy in the ball-Earth system. As it falls, the potential energy is transformed into kinetic energy. In this process, Earth also gains and loses very small amounts of kinetic energy. The energy bar diagrams show how the ball's energy changes.

Gravitational Potential Energy

Look at the balls being juggled in **Figure 15**. If you consider the system to be only one ball, then it has several external forces acting on it. The force of the juggler's hand does work, giving the ball its initial kinetic energy. After the ball leaves the juggler's hand, only the gravitational force acts on it, assuming that air resistance is negligible. How much work does gravity do on the ball as its height changes?

Work done by gravity Let h represent the ball's height measured from the juggler's hand. On the way up, its displacement is upward but the gravitational force on the ball (F_g) is downward, so the work done by gravity is negative: $W_g = -mgh$. On the way back down, the force and displacement are in the same direction, so the work done by gravity is positive: $W_g = mgh$. Thus, while the ball is moving upward, gravity does negative work, slowing the ball to a stop. On the way back down, gravity does positive work, increasing the ball's speed and thereby increasing its kinetic energy. The ball recovers all of its original kinetic energy when it returns to the same height as the juggler's hand, as shown in the energy bar diagrams in **Figure 15.** Notice in the diagrams that the ball has equal amounts of gravitational potential energy and kinetic energy at $\frac{1}{2}h$.

Get It?

Describe the energy transformations in the dam at the beginning of the module.

According to Newton's law of universal gravitation, there is a gravitational attraction between any pair of objects. This gravitational attraction between the objects is a force that performs work when one of the objects moves. Usually, we are most concerned with the gravitational potential energy between an object and Earth. For this particular example, we choose to discuss the object and Earth together as a system. If the object moves away from Earth, the system stores energy due to the gravitational force between the object and Earth. The stored energy due to gravity is called **gravitational potential energy,** or *GPE*. The height to which the object has risen is determined by using a **reference level,** the position where *GPE* is defined to be zero. In the example of the juggler, the reference level is the juggler's hand.

hmtonphoto/123RF

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Student Textbook · p. 18

Calculating gravitational potential energy

For an object with mass m at height h above the reference level, the *GPE* of the object-Earth system is represented by the following equation.

Gravitational Potential Energy

The *GPE* of an object-Earth system is equal to the product of the object's mass, the gravitational field strength, and the object's distance above the reference level.

$$GPE = mgh$$

In this equation, g is the gravitational field strength. *GPE*, like kinetic energy, is measured in joules.

Energy transformations Consider the energy of a system consisting of Earth and a ball being juggled. The energy of the system is in two forms: kinetic energy and gravitational potential energy. At the beginning of the ball's flight, all the energy is in the form of kinetic energy, as shown on the left in **Figure 16.** As the ball rises, it slows down and the system's energy changes from kinetic energy to gravitational potential energy. At the highest point of the ball's flight, the velocity is zero and all the energy is in the form of gravitational potential energy.

Changes of energy in a system can be described in terms of energy flowing into, out of, and within that system.

As the ball falls, gravitational potential energy changes back into kinetic energy, or flows within that system as it transforms back into kinetic energy. The sum of kinetic energy and gravitational potential energy is constant at all times because no work is done on the system by forces outside of the system.

Reference levels So far, we have set the reference level to be the juggler's hand. That is, the height of the ball is measured from where it left contact with the juggler's hand. Thus, at the juggler's hand, $h = 0$ m and $GPE = 0$ J. However, you can set the reference level at any height that is convenient for solving a given problem.

Suppose the reference level is set at the highest point of the ball's flight. Then, $h = 0$ m and the system's $GPE = 0$ J at that point, as illustrated on the right side of **Figure 16.** The system's potential energy is negative at the beginning of the ball's flight, zero at the highest point, and negative at the end of the ball's flight. If you were to calculate the total energy of the system represented on the left in **Figure 16,** it would be different from the total energy of the system represented on the right in **Figure 16.** This is because the reference levels are different in each case. However, the total energy of the system in each situation is constant at all times during the flight of the ball.

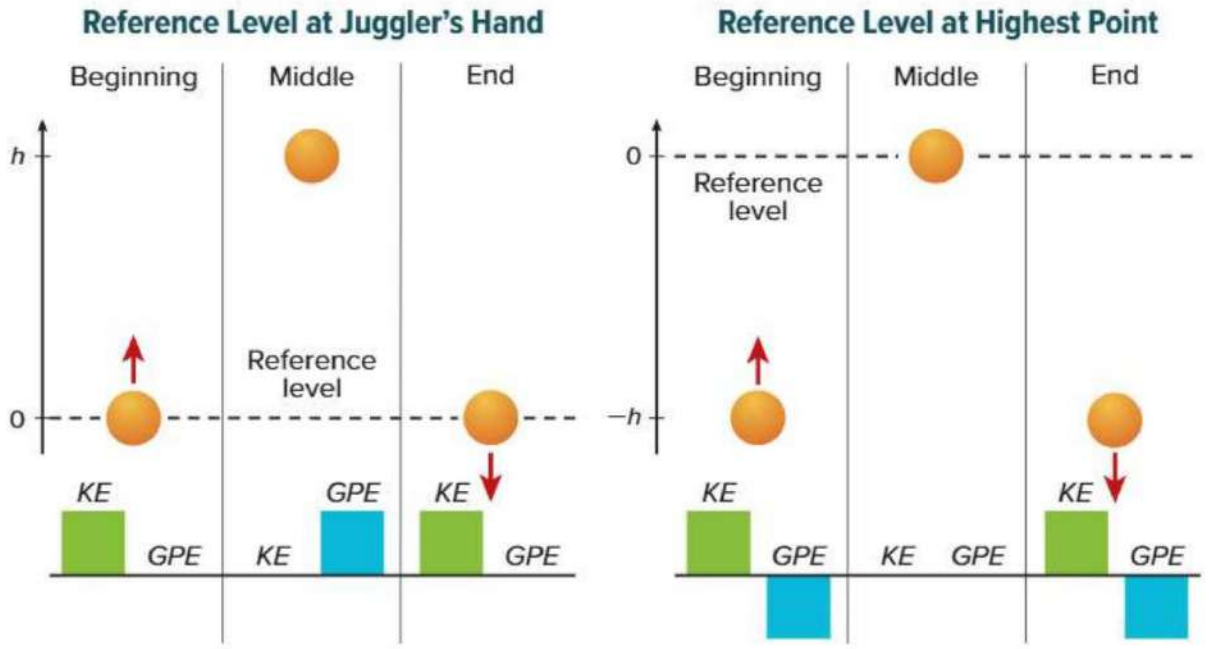


Figure 16 Where you put the reference level affects the system's *GPE*. Where you put the reference level does not affect how the system's *GPE* changes over time, however.

Analyze *Where else might you place the reference level?*

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Example Problem 4 · p. 19

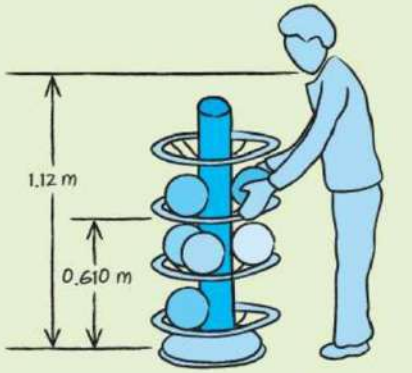
EXAMPLE Problem 4

GRAVITATIONAL POTENTIAL ENERGY You lift a 7.30-kg bowling ball from the storage rack and hold it up to your shoulder. The storage rack is 0.610 m above the floor and your shoulder is 1.12 m above the floor.

a. When the bowling ball is at your shoulder, what is the ball-Earth system's gravitational potential energy relative to the floor?

b. When the bowling ball is at your shoulder, what is the ball-Earth system's gravitational potential energy relative to the rack?

c. How much work was done by gravity as you lifted the ball from the rack to shoulder level?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Choose a reference level.
- Draw an energy bar diagram showing the gravitational potential energy with the floor as the reference level.

Known

$m = 7.30$ kg $\quad g = 9.8$ N/kg

$h_r = 0.610$ m (rack relative to the floor)

$h_s = 1.12$ m (shoulder relative to the floor)

Unknown

$GPE_{s\,rel\,f} = ?$

$GPE_{s\,rel\,r} = ?$

$W = ?$



2 SOLVE FOR THE UNKNOWN

a. Set the reference level to be at the floor.

Determine the gravitational potential energy of the system when the ball is at shoulder level.

$GPE_{s\,rel\,f} = mgh_s = (7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m

$= 8.0\times10^{1}$ J

b. Set the reference level to be at the rack height.

Determine the height of your shoulder relative to the rack.

$h = h_s - h_r$

Determine the gravitational potential energy of the system when the ball is at shoulder level.

$GPE_{s\,rel\,r} = mgh = mg(h_s - h_r)$ Substitute $h = h_s - h_r$

$= (7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m} - 0.610\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m, $h_r = 0.610$ m

$= 36$ J This also is equal to the work done by you as you lifted the ball.

c. The work done by gravity is the weight of the ball times the distance the ball was lifted.

$W = Fd = -(mg)h = -(mg)(h_s - h_r)$ The weight opposes the motion of lifting, so the work is negative.

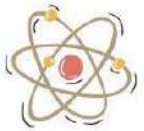
$= -(7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m} - 0.610\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m, $h_r = 0.610$ m

$= -36$ J

3 EVALUATE THE ANSWER

- **Are the units correct?** Both potential energy and work are measured in joules.
- **Does the answer make sense?** The system should have a greater *GPE* measured relative to the floor than relative to the rack because the ball's distance above the floor level is greater than the ball's distance above the rack.

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Check Your Progress 35 · p. 22

35. **Elastic Potential Energy** You compress the spring in a jumping toy, then release it. The toy then flies straight up. Draw bar graphs that show the forms of energy present in the following instances. Assume the system includes the spring toy and Earth.

a. The toy is pushed down thereby compressing the spring.

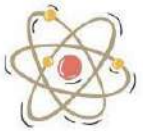
b. The spring expands and the toy jumps.

c. The toy reaches the top of its flight.

d. Describe how energy manifests itself in different ways in this system.

c. What motions and interactions does this system depend on?

1	-Define potential energy and gravitational potential energy. -Relate gravitational potential energy to mass and height (GPE = mgh). -Show that work done by gravity is opposite to the change in gravitational potential energy. -Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Check Your Progress 36 · p. 22

36. **Potential Energy** A 25.0-kg shell is shot from a cannon at Earth's surface. The reference level is Earth's surface.

a. What is the shell-Earth system's gravitational potential energy when the shell's height is 425 m?

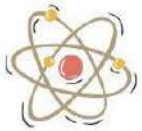
b. What is the change in the system's potential energy when the shell falls to a height of 225 m?

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

Check Your Progress 37 · p. 22

37. **Rotational Kinetic Energy** On a playground, some children push a merry-go-round so that it turns twice as fast as it did before they pushed it. What are the relative changes in angular momentum and rotational kinetic energy of the merry-go-round?

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Check Your Progress 38 · p. 22

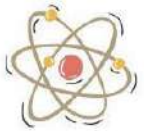
38. **Critical Thinking** In the school lab, Karl uses an air hose to exert a constant horizontal force to move a puck a fixed distance on a friction-less air table.

a. Explain what happens in terms of work and energy. Draw bar graphs.

b. Karl uses a different puck with half the first one's mass. All other conditions remain the same. How do the kinetic energy and work done differ from the kinetic energy and work done in part a?

c. Describe what happened in parts a and b in terms of impulse and momentum.

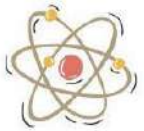
1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Practice Problem 31 · p. 20

31. If you slowly lower a 20.0-kg bag of sand 1.20 m from the trunk of a car to the driveway, how much work do you do?

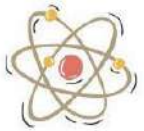
1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Practice Problem 32 · p. 20

32. A boy lifts a 2.2-kg book from his desk, which is 0.80 m high, to a bookshelf that is 2.10 m high. What is the potential energy of the book-Earth system relative to the desk when the book is on the shelf?

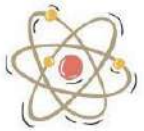
1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Practice Problem 33 · p. 20

33. You are walking around an old building and notice that it is falling apart. If a 1.8-kg brick falls to the ground from the building's chimney, which is 6.7 m high, what is the change in the potential energy of the brick-Earth system?

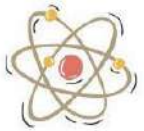
1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Practice Problem 34 · p. 20

34. CHALLENGE A worker picks up a 10.1-kg box from the floor and sets it on a table that is 1.1 m high. He slides the box 5.0 m along the table and then lowers it back to the floor. What were the changes in the box-Earth system's energy, and how did the system's total energy change? (Ignore friction.)

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25

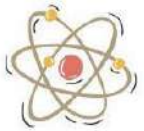


Get It? · p. 25

Get It?

Analyze how the ball's final kinetic energy in **Figure 23** would be different if friction transformed some of the system's energy.

1	•-Define potential energy and gravitational potential energy. •-Relate gravitational potential energy to mass and height (GPE = mgh). •-Show that work done by gravity is opposite to the change in gravitational potential energy. •-Discuss energy transformations when an object moves vertically upward or downward.	Student Textbook Example Problem 4 Check Your Progress Practice problems 31,32,33,34 Get it	14-18 19 22 20 25



Get It? · p. 25



Get It?

Analyze If most of the kinetic energy of a bouncing ball transforms into elastic potential energy, what happens to the rest of the kinetic energy?

2	•-Define elastic potential energy and give examples. •-Interpret mass as rest energy ($E = mc^2$) and identify other forms of energy.	Student Textbook Check Your Progress 35	20-22 22

Student Textbook · p. 20

PRACTICE Problems **ADDITIONAL PRACTICE**

30. In Example Problem 4, what is the potential energy of the ball-Earth system when the bowling ball is on the floor? Use the rack as your reference level.
31. If you slowly lower a 20.0-kg bag of sand 1.20 m from the trunk of a car to the driveway, how much work do you do?
32. A boy lifts a 2.2-kg book from his desk, which is 0.80 m high, to a bookshelf that is 2.10 m high. What is the potential energy of the book-Earth system relative to the desk when the book is on the shelf?
33. You are walking around an old building and notice that it is falling apart. If a 1.8-kg brick falls to the ground from the building's chimney, which is 6.7 m high, what is the change in the potential energy of the brick-Earth system?
34. **CHALLENGE** A worker picks up a 10.1-kg box from the floor and sets it on a table that is 1.1 m high. He slides the box 5.0 m along the table and then lowers it back to the floor. What were the changes in the box-Earth system's energy, and how did the system's total energy change? (Ignore friction.)

Elastic Potential Energy

When the bow string shown in **Figure 17** is pulled, work is done on the bow string and energy is transferred to the bow. If you identify the system as the bow, the arrow, and Earth, the energy of the system increases. When the string and the arrow are released, the stored energy is changed into kinetic energy.

The stored energy due to the pulled string and bent bow is **elastic potential energy,** which is stored energy due to an object's change in shape. Systems that include springs, rubber bands, and trampolines have elastic potential energy.

Get It?

Define the term *elastic potential energy.*

You can also store elastic potential energy in a system when you bend an elastic object in that system. For example, when stiff metal or bamboo poles were used in pole-vaulting, the poles did not bend easily. Little work was done on the poles, and the poles did not store much potential energy. Since flexible fiberglass poles were introduced, however, record pole-vaulting heights have soared.

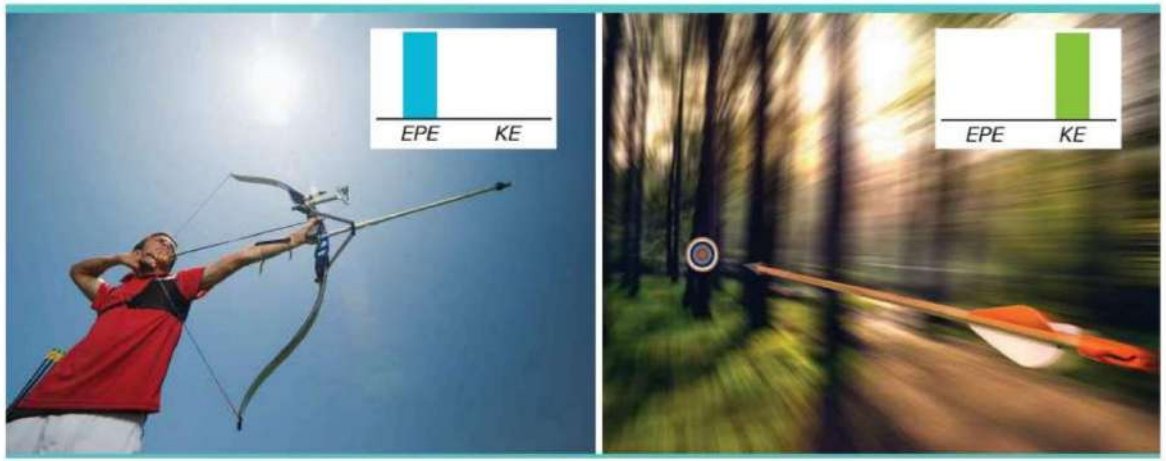


Figure 17 The archer-bow-arrow system has maximum elastic potential energy before the string is released, as shown on the left. When the arrow and string disengage, the elastic potential energy is completely transformed into kinetic energy, as shown on the right.

Tetra Images - Erik Isakson/Brand X Pictures/Getty Images; (br)Steve Allen/Brand X Pictures

2	•-Define elastic potential energy and give examples. •-Interpret mass as rest energy ($E = mc^2$) and identify other forms of energy.	Student Textbook Check Your Progress 35	20-22 22

Student Textbook · p. 21

A pole-vaulter runs with a flexible pole and plants its end into a socket in the ground. When the pole-vaulter bends the pole, as shown in **Figure 18**, some of the pole-vaulter's kinetic energy is transformed to elastic potential energy. When the pole straightens, the elastic potential energy is transformed to gravitational potential energy and kinetic energy as the pole-vaulter is lifted as high as 6 m above the ground.



Figure 18 The pole-vaulter stores elastic potential energy in the pole-vaulter-track system. The elastic potential energy of this system then changes into kinetic energy and gravitational potential energy.

Other Forms of Energy

Think about all the forms and sources of energy you encounter every day. Gasoline provides energy to run your car. You eat food to obtain energy. Power plants harness the energy of wind, water, fossil fuels (**Figure 19**), and atoms and transform it into electrical energy.

Some of these forms of energy are best understood if we think of energy as a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. (Radiation, including light, is the transfer of energy by electromagnetic waves, which you will encounter in a later module.) For example, nuclear energy is the energy stored in the bonds inside the nucleus of an atom. Without understanding the structure and chemical subprocesses within an atom, we would not be able to develop mathematical models to predict the amount of energy that could be released.

Get It?

Explain In your own words, explain why we need to understand the interactions in a process or subprocess in order to understand a system.

Chemical and nuclear energy When you eat, your body uses the energy from the chemical bonds in your food as an energy source. The bonds inside an atom's nucleus also store energy. This energy is called nuclear energy and is released when the structure of an atom's nucleus changes.



Figure 19 Coal-burning plants harness energy and transform it into something more useful, such as electrical energy.

oodboard/Alamy Stock Photo; (b) Bildagentur Zoonar GmbH/Shutterstock.com

CCC CROSSCUTTING CONCEPTS

Energy and Matter Changes of energy and matter in a system can be described in terms of energy and matter flow within that system. In a labeled poster, show the changes in energy flow in a pole-vaulter-track system from the moment the vaulter places the pole in the socket in the ground to the moment the vaulter lands. What evidence is there of a change in energy?

2	•-Define elastic potential energy and give examples. •-Interpret mass as rest energy ($E = mc^2$) and identify other forms of energy.	Student Textbook Check Your Progress 35	20-22 22

Student Textbook · p. 22

Thermal energy Thermal energy, which is associated with temperature, is the sum of the kinetic energy and potential energy of the particles in a system. When you rub your hands together, you transform kinetic energy into thermal energy. Thermal energy can also be transferred, such as a stove like the one in **Figure 20** transferring thermal energy to a pan.

Electrical and radiant energy Power plants transform various types of energy into electrical energy, which is energy associated with charged particles. Electrical energy can be transmitted through wires like those in **Figure 21** to your home, where appliances transform it into other forms of energy, such as radiant energy in lightbulbs.

Mass Albert Einstein demonstrated that mass represents a form of energy, called rest energy (E_0): $E_0 = mc^2$. Mass is a form of energy that can be transformed into other forms of energy. Mass-energy equivalence is only apparent when large amounts of energy are involved, such as during nuclear explosions and particle physics experiments.



Figure 20 In your daily activities, you encounter many types of energy, such as thermal energy when cooking your food.



Figure 21 Transmitting electrical energy is critical for our day-to-day needs.

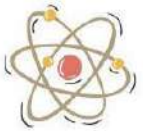
Check Your Progress

35. **Elastic Potential Energy** You compress the spring in a jumping toy, then release it. The toy then flies straight up. Draw bar graphs that show the forms of energy present in the following instances. Assume the system includes the spring toy and Earth.
    a. The toy is pushed down thereby compressing the spring.
    b. The spring expands and the toy jumps.
    c. The toy reaches the top of its flight.
    d. Describe how energy manifests itself in different ways in this system.
36. **Potential Energy** A 25.0-kg shell is shot from a cannon at Earth's surface. The reference level is Earth's surface.
    a. What is the shell-Earth system's gravitational potential energy when the shell's height is 425 m?
    b. What is the change in the system's potential energy when the shell falls to a height of 225 m?
    c. What motions and interactions does this system depend on?
37. **Rotational Kinetic Energy** On a playground, some children push a merry-go-round so that it turns twice as fast as it did before they pushed it. What are the relative changes in angular momentum and rotational kinetic energy of the merry-go-round?
38. **Critical Thinking** In the school lab, Karl uses an air hose to exert a constant horizontal force to move a puck a fixed distance on a frictionless air table.
    a. Explain what happens in terms of work and energy. Draw bar graphs.
    b. Karl uses a different puck with half the first one's mass. All other conditions remain the same. How do the kinetic energy and work done differ from the kinetic energy and work done in part a?
    c. Describe what happened in parts a and b in terms of impulse and momentum.

LEARNSMART Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

PHOTOS.com/Getty Images; Bojan Jan peng/Shutterstock.com

2	•-Define elastic potential energy and give examples. •-Interpret mass as rest energy ($E = mc^2$) and identify other forms of energy.	Student Textbook Check Your Progress 35	20-22 22



Check Your Progress 35 · p. 22

35. **Elastic Potential Energy** You compress the spring in a jumping toy, then release it. The toy then flies straight up. Draw bar graphs that show the forms of energy present in the following instances. Assume the system includes the spring toy and Earth.
    a. The toy is pushed down thereby compressing the spring.
    b. The spring expands and the toy jumps.
    c. The toy reaches the top of its flight.
    d. Describe how energy manifests itself in different ways in this system.

c. What motions and interactions does this system depend on?

3	•-Compare elastic and inelastic collisions. •-Explain the loss of kinetic energy in inelastic collisions. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Student Textbook Example Problem 6 Practice problems 44	29-31 31 32

Student Textbook · p. 29



Figure 25 In a car crash, the *KE* decreases.
Explain *What happened to the energy?*

Analyzing Collisions

A collision between any two objects, whether the objects include automobiles such as the ones shown in **Figure 25**, hockey players, or subatomic particles, is one of the most common situations analyzed in physics. The details of a collision can be complex during the collision itself, so the strategy is to find the motion of the objects just before and just after the collision. What conservation laws can be used to analyze such a system? If the system is closed and isolated, then momentum and energy are conserved. However, the potential or thermal energy in the system might decrease, remain the same, or increase. Therefore, you cannot predict whether kinetic energy is conserved. **Figure 26** on the next page shows four different kinds of collisions. Look at the calculations for kinetic energy for each of the cases. In all the cases except case 1, there is a change in the amount of kinetic energy.

Get It?
Calculate the initial and final momenta for the remaining cases in **Figure 26.** Verify that momentum is conserved for each case.

Elastic and inelastic collisions Next, consider the kinetic energy of the system in each case. In case 1, the kinetic energy of the system before and after the collision was the same. A collision in which the kinetic energy does not change is called an **elastic collision.** Collisions between hard objects, such as those made of steel or hard plastic, often are called nearly elastic collisions.

Kinetic energy decreased in cases 2 and 3. Some of it may have been transformed to thermal energy. A collision in which kinetic energy decreases is called an **inelastic collision.** Objects made of soft, sticky materials, such as clay, act in this way. In case 2, the objects stuck together after colliding. A collision in which colliding objects stick together is called a perfectly inelastic collision.

In case 1, the momentum of the system before and after the collision is represented as

$$p_i = p_{Ai} + p_{Bi}$$
$$= (1.00\ \text{kg})(1.00\ \text{m/s}) + (1.00\ \text{kg})(0.00\ \text{m/s})$$
$$= 1.00\ \text{kg·m/s}$$
$$p_f = p_{Af} + p_{Bf} = (1.00\ \text{kg})(0.00\ \text{m/s}) +$$
$$(1.00\ \text{kg})(1.00\ \text{m/s})$$
$$= 1.00\ \text{kg·m/s}$$

Thus, in case 1, the momentum is conserved.

In case 4, the kinetic energy of the system increased. If energy in the system is conserved, then one or more other forms of energy must have decreased. Perhaps potential energy from a compressed spring was released during the collision, adding kinetic energy to the system. This kind of collision is called a superelastic or explosive collision.

The four kinds of collisions can be represented using energy bar diagrams, also shown in **Figure 26.** The kinetic energies before and after the collisions can be calculated, but we do not always have detailed information about the other forms of energy involved.

In automobile collisions, kinetic energy can be transformed into thermal energy and sound, but they are difficult to measure. We infer their amounts from the amount of kinetic energy that is transformed.

Get It?
Compare and contrast elastic collisions and inelastic collisions.

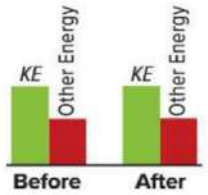
ert Crum/iStock/Getty Images

3	•-Compare elastic and inelastic collisions. •-Explain the loss of kinetic energy in inelastic collisions. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Student Textbook Example Problem 6 Practice problems 44	29-31 31 32

Student Textbook · p. 30

Figure 26 In a closed, isolated system, momentum is conserved when objects collide. Whether kinetic energy is conserved depends on whether the collision is elastic, inelastic, or superelastic.

Case 1: Elastic Collision $KE_f = KE_i$



Before collision



$v_{Ai} = 1.00$ m/s $\quad v_{Bi} = 0.00$ m/s

$KE_i = KE_{Ai} + KE_{Bi}$

$= \frac{1}{2}(1.00\text{ kg})(1.00\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.00\text{ m/s})^2$

$= 0.50$ J

After collision



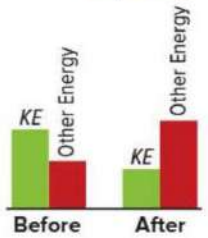
$v_{Af} = 0.00$ m/s $\quad v_{Bf} = 1.00$ m/s

$KE_f = KE_{Af} + KE_{Bf}$

$= \frac{1}{2}(1.00\text{ kg})(0.00\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(1.00\text{ m/s})^2$

$= 0.50$ J

Case 2: Perfectly Inelastic Collision $KE_f < KE_i$



Before collision



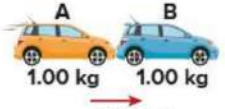
$v_{Ai} = 1.00$ m/s $\quad v_{Bi} = 0.00$ m/s

$KE_i = KE_{Ai} + KE_{Bi}$

$= \frac{1}{2}(1.00\text{ kg})(1.00\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.00\text{ m/s})^2$

$= 0.50$ J

After collision



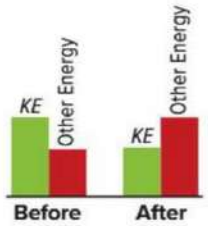
$v_{Af} = v_{Bf} = 0.50$ m/s

$KE_f = KE_{Af} + KE_{Bf}$

$= \frac{1}{2}(1.00\text{ kg})(0.50\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.50\text{ m/s})^2$

$= 0.25$ J

Case 3: Inelastic Collision $KE_f < KE_i$



Before collision



$v_{Ai} = 1.00$ m/s $\quad v_{Bi} = 0.00$ m/s

$KE_i = KE_{Ai} + KE_{Bi}$

$= \frac{1}{2}(1.00\text{ kg})(1.00\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.00\text{ m/s})^2$

$= 0.50$ J

After collision



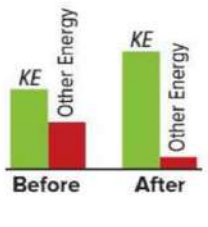
$v_{Af} = 0.25$ m/s $\quad v_{Bf} = 0.75$ m/s

$KE_f = KE_{Af} + KE_{Bf}$

$= \frac{1}{2}(1.00\text{ kg})(0.25\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.75\text{ m/s})^2$

$= 0.31$ J

Case 4: Superelastic Collision $KE_f > KE_i$



Before collision



$v_{Ai} = 1.00$ m/s $\quad v_{Bi} = 0.00$ m/s

$KE_i = KE_{Ai} + KE_{Bi}$

$= \frac{1}{2}(1.00\text{ kg})(1.00\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(0.00\text{ m/s})^2$

$= 0.50$ J

After collision



$v_{Af} = 0.20$ m/s $\quad v_{Bf} = 1.20$ m/s

$KE_f = KE_{Af} + KE_{Bf}$

$= \frac{1}{2}(1.00\text{ kg})(-0.20\text{ m/s})^2 + \frac{1}{2}(1.00\text{ kg})(1.20\text{ m/s})^2$

$= 0.74$ J

3	•-Compare elastic and inelastic collisions. •-Explain the loss of kinetic energy in inelastic collisions. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Student Textbook Example Problem 6 Practice problems 44	29-31 31 32

Student Textbook · p. 31

EXAMPLE Problem 6

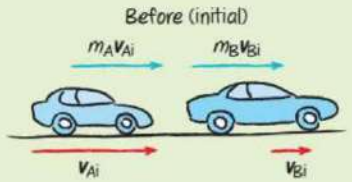
INELASTIC COLLISION In an accident on a slippery road, a compact car with a mass of 1150 kg moving at 15.0 m/s smashes into the rear end of a car with a mass of 1575 kg moving at 5.0 m/s in the same direction.

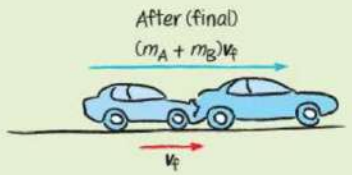
a. What is the final velocity if the wrecked cars lock together?

b. How much is the kinetic energy decreased in the collision?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the initial and final conditions.
- Sketch the momentum diagram.





Known

$m_A = 1150$ kg

$m_B = 1575$ kg

$v_{Ai} = 15.0$ m/s

$v_{Bi} = 5.0$ m/s

$v_{Af} = v_{Bf} = v_f$

Unknown

$v_f = ?$

$\Delta KE = KE_f - KE_i = ?$

2 SOLVE FOR THE UNKNOWN

a. Use conservation of momentum to find the final velocity.

$$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$$

$$m_A v_{Ai} + m_B v_{Bi} = (m_A + m_B)v_f$$

$$v_f = \frac{m_A v_{Ai} + m_B v_{Bi}}{m_A + m_B}$$

$$= \frac{(1150\text{ kg})(15.0\text{ m/s}) + (1575\text{ kg})(5.0\text{ m/s})}{(1150\text{ kg} + 1575\text{ kg})}$$

Substitute $m_A = 1150$ kg, $v_{Ai} = 15.0$ m/s, $m_B = 1575$ kg, $v_{Bi} = 5.0$ m/s

$= 9.2$ m/s, in the direction of the motion before the collision

b. To determine the change in kinetic energy of the system, KE_f and KE_i are needed.

$$KE_f = \frac{1}{2}mv_f^2 = \frac{1}{2}(m_A + m_B)v_f^2$$

Substitute $m = m_A + m_B$

$$= \frac{1}{2}(1150\text{ kg} + 1575\text{ kg})(9.2\text{ m/s})^2$$

Substitute $m_A = 1150$ kg, $m_B = 1575$ kg, $v_f = 9.2$ m/s

$$= 1.2\times10^5\text{ J}$$

$$KE_i = KE_{Ai} + KE_{Bi}$$

$$= \frac{1}{2}(m_A v_{Ai}^2) + \frac{1}{2}(m_B v_{Bi}^2)$$

Substitute $KE_{Ai} = \frac{1}{2}(m_A v_{Ai}^2)$, $KE_{Bi} = \frac{1}{2}(m_B v_{Bi}^2)$

$$= \frac{1}{2}(1150\text{ kg})(15.0\text{ m/s})^2 + \frac{1}{2}(1575\text{ kg})(5.0\text{ m/s})^2$$

Substitute $m_A = 1150$ kg, $m_B = 1575$ kg, $v_{Ai} = 15.0$ m/s, $v_{Bi} = 5.0$ m/s

$$= 1.5\times10^5\text{ J}$$

Solve for the change in kinetic energy of the system.

$$\Delta KE = KE_f - KE_i$$

$$= 1.2\times10^5\text{ J} - 1.5\times10^5\text{ J} = -3\times10^4\text{ J}$$

Substitute $KE_f = 1.2\times10^5$ J, $KE_i = 1.5\times10^5$ J

3 EVALUATE THE ANSWER

- **Are the units correct?** Velocity is measured in meters per second; energy is measured in joules.
- **Does the sign make sense?** The change in kinetic energy is negative, meaning that kinetic energy decreased as expected in an inelastic collision.

3	•-Compare elastic and inelastic collisions. •-Explain the loss of kinetic energy in inelastic collisions. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Student Textbook Example Problem 6 Practice problems 44	29-31 31 32

Example Problem 6 · p. 31

EXAMPLE Problem 6

INELASTIC COLLISION In an accident on a slippery road, a compact car with a mass of 1150 kg moving at 15.0 m/s smashes into the rear end of a car with a mass of 1575 kg moving at 5.0 m/s in the same direction.

a. What is the final velocity if the wrecked cars lock together?

b. How much is the kinetic energy decreased in the collision?

1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the initial and final conditions.
- Sketch the momentum diagram.

Known

$m_A = 1150\ \text{kg}$

$m_B = 1575\ \text{kg}$

$v_{Ai} = 15.0\ \text{m/s}$

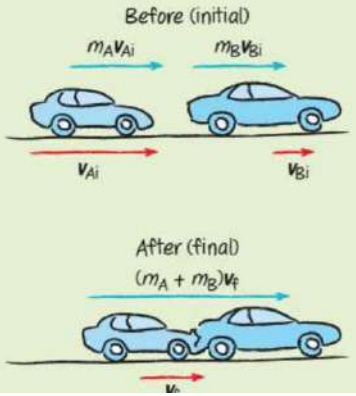
$v_{Bi} = 5.0\ \text{m/s}$

$v_{Af} = v_{Bf} = v_f$

Unknown

$v_f = ?$

$\Delta KE = KE_f - KE_i = ?$



2 SOLVE FOR THE UNKNOWN

a. Use conservation of momentum to find the final velocity.

$$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$$

$$m_A v_{Ai} + m_B v_{Bi} = (m_A + m_B)v_f$$

$$v_f = \frac{m_A v_{Ai} + m_B v_{Bi}}{m_A + m_B}$$

$$= \frac{(1150\ \text{kg})(15.0\ \text{m/s}) + (1575\ \text{kg})(5.0\ \text{m/s})}{(1150\ \text{kg} + 1575\ \text{kg})}$$

Substitute $m_A = 1150\ \text{kg}$, $v_{Ai} = 15.0\ \text{m/s}$, $m_B = 1575\ \text{kg}$, $v_{Bi} = 5.0\ \text{m/s}$

$= 9.2\ \text{m/s}$, in the direction of the motion before the collision

b. To determine the change in kinetic energy of the system, KE_f and KE_i are needed.

$$KE_f = \frac{1}{2}mv_f^2 = \frac{1}{2}(m_A + m_B)v_f^2$$

Substitute $m = m_A + m_B$

$$= \frac{1}{2}(1150\ \text{kg} + 1575\ \text{kg})(9.2\ \text{m/s})^2$$

Substitute $m_A = 1150\ \text{kg}$, $m_B = 1575\ \text{kg}$, $v_f = 9.2\ \text{m/s}$

$$= 1.2\times10^5\ \text{J}$$

$$KE_i = KE_{Ai} + KE_{Bi}$$

$$= \frac{1}{2}(m_A v_{Ai}^2) + \frac{1}{2}(m_B v_{Bi}^2)$$

Substitute $KE_{Ai} = \frac{1}{2}(m_A v_{Ai}^2)$, $KE_{Bi} = \frac{1}{2}(m_B v_{Bi}^2)$

$$= \frac{1}{2}(1150\ \text{kg})(15.0\ \text{m/s})^2 + \frac{1}{2}(1575\ \text{kg})(5.0\ \text{m/s})^2$$

Substitute $m_A = 1150\ \text{kg}$, $m_B = 1575\ \text{kg}$, $v_{Ai} = 15.0\ \text{m/s}$, $v_{Bi} = 5.0\ \text{m/s}$

$$= 1.5\times10^5\ \text{J}$$

Solve for the change in kinetic energy of the system.

$$\Delta KE = KE_f - KE_i$$

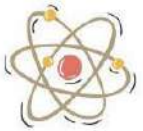
$$= 1.2\times10^5\ \text{J} - 1.5\times10^5\ \text{J} = -3\times10^4\ \text{J}$$

Substitute $KE_f = 1.2\times10^5\ \text{J}$, $KE_i = 1.5\times10^5\ \text{J}$

3 EVALUATE THE ANSWER

- **Are the units correct?** Velocity is measured in meters per second; energy is measured in joules.
- **Does the sign make sense?** The change in kinetic energy is negative, meaning that kinetic energy decreased as expected in an inelastic collision.

3	•-Compare elastic and inelastic collisions. •-Explain the loss of kinetic energy in inelastic collisions. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Student Textbook Example Problem 6 Practice problems 44	29-31 31 32



Practice Problem 44 · p. 32

44. An 8.00-g bullet is fired horizontally into a 9.00-kg block of wood on an air table and is embedded in it. After the collision, the block and bullet slide along the frictionless surface together with a speed of 10.0 cm/s. Find the initial speed of the bullet.

4	•-Describe thermal radiation and the emission spectrum of an object. •-Relate the frequency at which the emission spectrum peaks to the object's temperature. •-Describe where classical electromagnetic wave theory agrees with and fails to explain thermal-radiation data.	Student Textbook	46-48

Student Textbook · p. 46

LESSON 1

A PARTICLE MODEL OF WAVES

FOCUS QUESTION

Can light behave like a particle?

A New Model Based on Packets of Energy

James Maxwell's electromagnetic wave theory, that electromagnetic radiation can be modeled as a wave of changing electric and magnetic fields, is useful for explaining many features of electromagnetic radiation, including interference, diffraction, and polarization. But it could not explain others, including the spectrum of electromagnetic waves emitted by all objects and the emission of electrons from metals exposed to ultraviolet radiation.

Electromagnetic radiation from objects The lightbulb shown in **Figure 1** is connected to a dimmer control that varies the potential difference to the bulb. As the potential difference increases, the temperature of the bulb's glowing filament increases. As a result, the color changes from deep red to orange to yellow and finally to white as the hotter filament emits higher-frequency colors blue and violet.



Figure 1 The color of the glow of the lightbulb depends on the temperature of the filament.

Richard Hutchings/Digital Light Source

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Is light a wave or a particle?

HS-PS4-3. Evaluate the claims evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.

4	•-Describe thermal radiation and the emission spectrum of an object. •-Relate the frequency at which the emission spectrum peaks to the object's temperature. •-Describe where classical electromagnetic wave theory agrees with and fails to explain thermal-radiation data.	Student Textbook	46-48

Student Textbook · p. 47

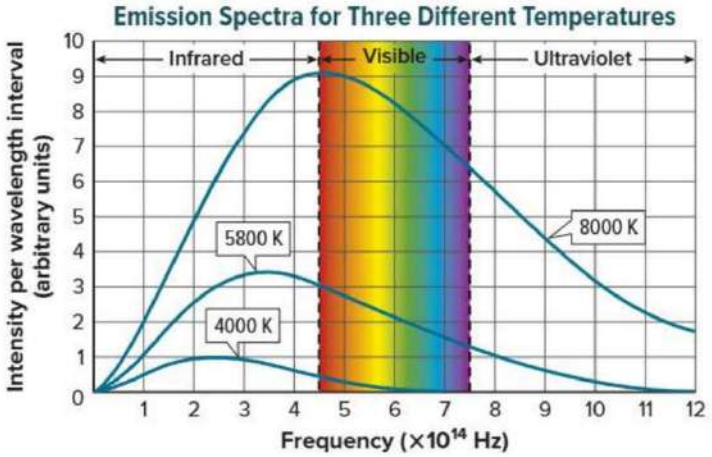


Figure 2 The frequency at which an object's emission spectrum peaks depends on that object's temperature. As the temperature of the object increases, the peak frequency also increases.

As predicted by electromagnetic wave theory, the vibrating charged particles within each bulb filament emit light and infrared radiation. While all objects, from very cold to extremely hot objects, emit a range of electromagnetic waves, the filament glows brightly in the visible light range because it is hot. (This is called incandescence; hence, the name incandescent lightbulb.) The colors you see depend on the relative intensities of the emitted electromagnetic waves of various frequencies and the sensitivity of your eyes to those waves.

Emission spectra What would you expect to see if you viewed the glowing filament through a diffraction grating? When viewed in this way, all the colors of the rainbow would be visible. **Figure 2** shows the visible colors that correspond to the frequencies around 6×10^{14} Hz. The bulb also emits other radiation that you would not see. A graph of the intensity of the radiation emitted from an object over a range of frequencies is known as an **emission spectrum.** Emission spectra of objects at temperatures of 4000 K, 5800 K, and 8000 K are shown in **Figure 2.** Note that at each temperature there is a frequency at which the maximum amount of energy is emitted. If you compare the curves, you will see that as the temperature increases, the frequency at which the maximum amount of energy is emitted also increases.

Get It?

Explain the changes observed in the spectrum of the glowing lightbulb at the beginning of this module as the dimmer control was turned up.

ASTRONOMY Connection The total power emitted by an object also increases with temperature. The power (energy emitted per second) of an electromagnetic wave is proportional to the hot object's kelvin temperature raised to the fourth power (T^4). Thus, hotter objects radiate considerably more energy per second than do cooler objects. Probably the most common example of a hot object radiating a great amount of power is the Sun. The Sun's surface temperature is about 5800 K, and it radiates 4×10^{26} W of power—an enormous quantity. On average, each square meter of Earth's surface receives about 1000 J of energy per second (1000 W) from the Sun. This is enough energy to power ten 100-W lightbulbs.

Get It?

Explain how the power emitted by an object changes if the object's kelvin temperature is doubled.

4	•-Describe thermal radiation and the emission spectrum of an object. •-Relate the frequency at which the emission spectrum peaks to the object's temperature. •-Describe where classical electromagnetic wave theory agrees with and fails to explain thermal-radiation data.	Student Textbook	46-48

Student Textbook · p. 48

Explaining emission spectra

Between 1887 and 1900, many physicists used electromagnetic wave theory to try to predict emission spectra, but they all failed. **Figure 3** shows the difference between the predicted spectrum and the observed spectrum. In 1900, German physicist Max Planck found that he could calculate the correct spectrum if an atom could only emit or absorb particular amounts of energy. Planck hypothesized an atom's energy changes in a solid were proportional to a frequency of vibration times an integer.

Energy of Vibration

The energy emitted or absorbed by a vibrating atom is equal to the product of an integer, Planck's constant, and the frequency of vibration.

$$E = nhf$$

In the equation, f is the frequency of vibration of the atom, h is a constant called Planck's constant, which has a value of 6.626×10^{-34} J/Hz, and n is an integer such as 0, 1, 2, 3 . . .

$$n = 0\text{: } E = (0)hf = 0$$

$$n = 1\text{: } E = (1)hf = hf$$

$$n = 2\text{: } E = (2)hf = 2hf$$

The energy of the radiation (E) can have values of hf, 2hf, 3hf, and so on, but it can never have fractional values such as $\frac{2}{3}$ hf or $\frac{3}{4}$ hf. In other words, energy is **quantized**—it exists only in bundles of specific amounts. For calculations, the constant h is usually rounded to 6.63×10^{-34} J/Hz.

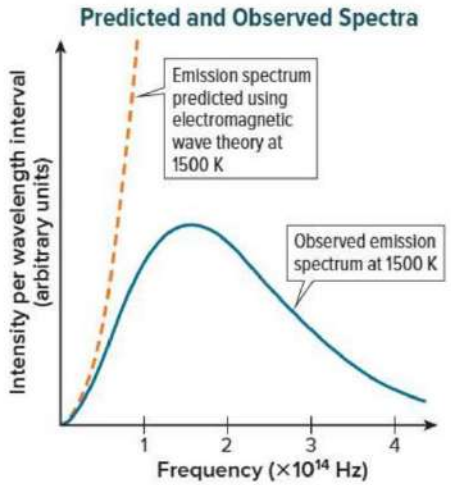


Figure 3 The red, dashed line shows the emission spectrum predicted using the electromagnetic wave theory. The theory predicts any object will radiate an infinite amount of energy. This does not match the observed emission spectrum, shown in blue.

Identify *the region of the graph where electromagnetic wave theory is a good model for the observed emission spectrum.*

Changes in vibrations

Electromagnetic wave theory would allow atoms to continuously emit radiation at all times. Instead, Planck proposed that atoms emit radiation only at the particular moments when their vibrational energy changes. For example, if the energy of an atom changes from 3hf to 2hf, according to wave theory, the atom emits radiation only while the energy changes. The energy radiated is equal to the change in energy of the atom, in this case hf. Similarly if the atom absorbed energy hf, its energy could change from 2hf to 3hf.

Planck found that because the constant h has an extremely small value, the energy-changing steps are very small. You would not notice them in the motions of objects in everyday life. Still, the idea of quantized energy troubled physicists, even Planck himself. It hinted that the classical physics of Newton and Maxwell might apply only under certain conditions. Planck's troubling idea was the first step on the way to the development of solar power cells, modern electronics, and computers.

CCC CROSSCUTTING CONCEPTS

Systems and System Models The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. Create a two-sided poster. On one side identify and explain one feature using the wave model. On the other side identify and explain one feature using the particle model.

5	•-Explain Planck's concept of quantization of energy. •-Describe that emitted or absorbed radiation corresponds to a change in vibrational energy. •-Calculate quantized energy using E = nhf.	Student Textbook Practice Problems 1,2,3,4	48 52

Student Textbook · p. 48

Explaining emission spectra Between 1887 and 1900, many physicists used electromagnetic wave theory to try to predict emission spectra, but they all failed. **Figure 3** shows the difference between the predicted spectrum and the observed spectrum. In 1900, German physicist Max Planck found that he could calculate the correct spectrum if an atom could only emit or absorb particular amounts of energy. Planck hypothesized an atom's energy changes in a solid were proportional to a frequency of vibration times an integer.

Energy of Vibration

The energy emitted or absorbed by a vibrating atom is equal to the product of an integer, Planck's constant, and the frequency of vibration.

$$E = nhf$$

In the equation, f is the frequency of vibration of the atom, h is a constant called Planck's constant, which has a value of 6.626×10^{-34} J/Hz, and n is an integer such as 0, 1, 2, 3 . . .

$$n = 0\text{: } E = (0)hf = 0$$

$$n = 1\text{: } E = (1)hf = hf$$

$$n = 2\text{: } E = (2)hf = 2hf$$

The energy of the radiation (E) can have values of hf, 2hf, 3hf, and so on, but it can never have fractional values such as $\frac{2}{3}$ hf or $\frac{3}{4}$ hf. In other words, energy is **quantized**—it exists only in bundles of specific amounts. For calculations, the constant h is usually rounded to 6.63×10^{-34} J/Hz.

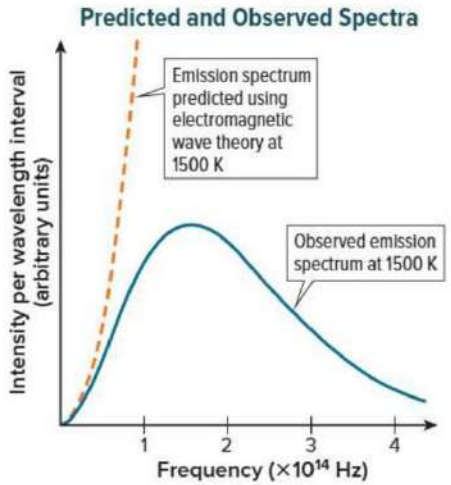


Figure 3 The red, dashed line shows the emission spectrum predicted using the electromagnetic wave theory. The theory predicts any object will radiate an infinite amount of energy. This does not match the observed emission spectrum, shown in blue.

Identify *the region of the graph where electromagnetic wave theory is a good model for the observed emission spectrum.*

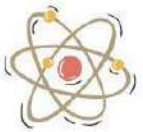
Changes in vibrations Electromagnetic wave theory would allow atoms to continuously emit radiation at all times. Instead, Planck proposed that atoms emit radiation only at the particular moments when their vibrational energy changes. For example, if the energy of an atom changes from 3hf to 2hf, according to wave theory, the atom emits radiation only while the energy changes. The energy radiated is equal to the change in energy of the atom, in this case hf. Similarly if the atom absorbed energy hf, its energy could change from 2hf to 3hf.

Planck found that because the constant h has an extremely small value, the energy-changing steps are very small. You would not notice them in the motions of objects in everyday life. Still, the idea of quantized energy troubled physicists, even Planck himself. It hinted that the classical physics of Newton and Maxwell might apply only under certain conditions. Planck's troubling idea was the first step on the way to the development of solar power cells, modern electronics, and computers.

CCC CROSSCUTTING CONCEPTS

Systems and System Models The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. Create a two-sided poster. On one side identify and explain one feature using the wave model. On the other side identify and explain one feature using the particle model.

5	•-Explain Planck's concept of quantization of energy. •-Describe that emitted or absorbed radiation corresponds to a change in vibrational energy. •-Calculate quantized energy using E = nhf.	Student Textbook Practice Problems 1,2,3,4	48 52

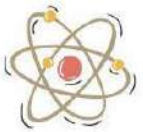


Practice Problem 1 · p. 52

Use E = 1240 eV•nm/λ to solve the following problems.

1. What is a photon's energy if the photon's wavelength is 515 nm?

5	•-Explain Planck's concept of quantization of energy. •-Describe that emitted or absorbed radiation corresponds to a change in vibrational energy. •-Calculate quantized energy using E = nhf.	Student Textbook Practice Problems 1,2,3,4	48 52

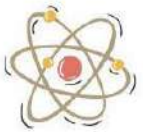


Practice Problem 2 · p. 52

Use E = 1240 eV•nm/λ to solve the following problems.

2. A photon's energy is 2.03 eV. What is the photon's wavelength?

5	•-Explain Planck's concept of quantization of energy. •-Describe that emitted or absorbed radiation corresponds to a change in vibrational energy. •-Calculate quantized energy using E = nhf.	Student Textbook Practice Problems 1,2,3,4	48 52



Practice Problem 3 · p. 52

Use E = 1240 eV•nm/λ to solve the following problems.

3. Rank the following photons from least to greatest energy.

a. 4.0 eV
b. 320 nm
c. 811 nm
d. 2.1 eV

5	•-Explain Planck's concept of quantization of energy. •-Describe that emitted or absorbed radiation corresponds to a change in vibrational energy. •-Calculate quantized energy using E = nhf.	Student Textbook Practice Problems 1,2,3,4	48 52

Practice Problem 4 · p. 52

4. CHALLENGE The diagram in **Figure 6** shows the visible light spectrum. What is the range of energies associated with photons in the visible light spectrum?



Figure 6

6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58

Student Textbook · p. 49

The Photoelectric Effect

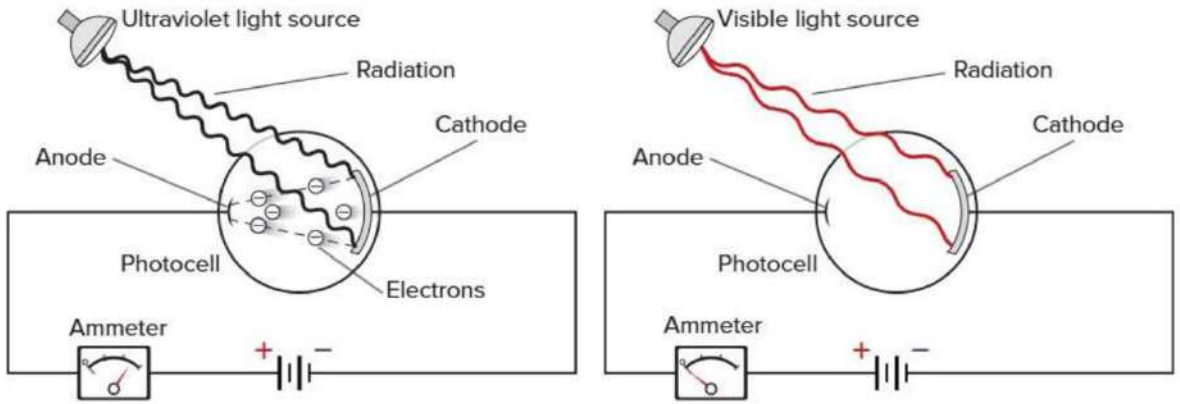
Physicists of the early 1900s were also challenged by another experimental result that could not be explained by electromagnetic wave theory. When ultraviolet light shines on a negatively charged zinc plate, the plate can produce an electrical discharge—a stream of electrons jumping from the plate. Even a low-intensity ultraviolet light can produce this effect. When visible light shines on the same charged plate, the plate does not discharge. This is true even when the visible light has a high intensity. This result is contrary to electromagnetic wave theory, which predicts the plate would emit electrons when any frequency of electromagnetic radiation shines on the plate. Higher-frequency ultraviolet radiation and lower frequency visible light are forms of electromagnetic radiation, so why would one cause the zinc plate to discharge but not the other? The emission of electrons when electromagnetic radiation falls on an object is called the **photoelectric effect.**

The photocell The photoelectric effect can be studied in a photocell, shown in **Figure 4.** The cell contains two metal electrodes sealed in a tube from which the air has been removed. The evacuated tube prevents the metal surfaces from oxidizing and keeps emitted electrons from being slowed or stopped by gas particles. The larger electrode, called the cathode, usually is coated with cesium or another alkali metal. The smaller electrode, called the anode, is made of a thin wire so that it blocks only a very small amount of radiation. The tube allows ultraviolet light to pass through it. A potential difference placed across the electrodes attracts electrons ejected from the cathode to the anode.

Photovoltaic materials emit electrons when they absorb light of a high-enough frequency. When no light falls on the cathode, which is the negative electrode, there is no current in the circuit. However, when light with certain frequencies falls on the cathode, a current is produced, which is measured by the ammeter, as shown in **Figure 4.** Electrons in the cathode absorb the energy from the light. The electrons escape the potential energy holding them in the cathode and travel to the anode, which is the positive electrode. This flow of photoelectrons forms the current.

Figure 4 Charges flow in a photocell only if the radiation striking the cathode has enough energy.

Compare *the ultraviolet radiation's wavelength to visible light's wavelength. What does the comparison tell you about the relative energies of the two types of radiation?*



The photoelectric effect is demonstrated by the photocell illuminated by ultraviolet light.

The same photocell, illuminated by visible light, does not display the photoelectric effect.

6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58

Student Textbook · p. 50

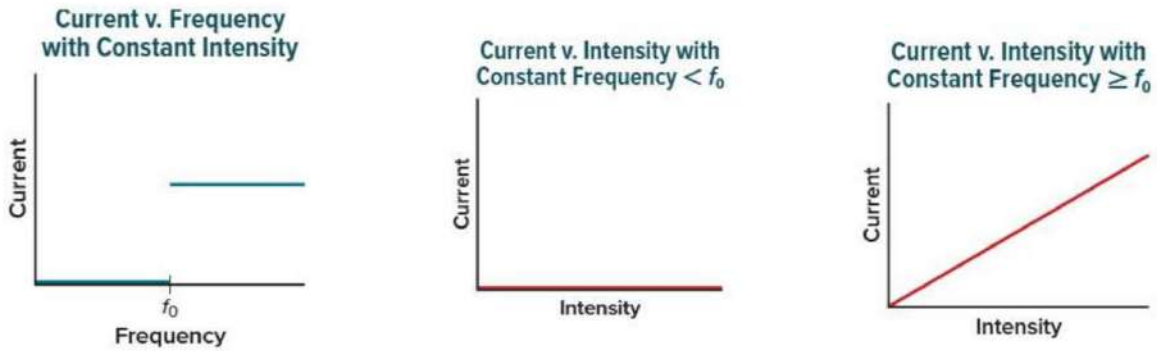


Figure 5 The emission of photoelectrons depends on the incident light's frequency. The threshold frequency must be exceeded in order to produce photoelectrons.

Threshold frequency Not all radiation falling on a photocell causes a current. Electrons eject from the cathode only if the frequency of the incident radiation is greater than a certain minimum value, called the **threshold frequency** (f_0). The graph on the left in **Figure 5** shows there is a current only when the threshold frequency is reached. The value of the threshold frequency varies widely and depends on the type of metal used for the cathode. For example, all frequencies of visible light except low-frequency red eject electrons from cesium. No frequency of visible light ejects electrons from zinc. Higher-frequency ultraviolet radiation ejects electrons from zinc.

The center graph in **Figure 5** shows that even intense radiation with a frequency below f_0 will not cause the emission of electrons. Conversely, the graph on the right shows that even very low-intensity radiation with a frequency at or above f_0 causes the immediate emission of electrons from the cathode. When the incoming radiation, also called the incident radiation, has a frequency equal to or greater than the threshold frequency, increasing the intensity of the radiation increases the current through the photocell.

The electromagnetic wave theory would say that the electric field in the light wave accelerates and ejects the electrons from the metal. The strength and energy of the electric field are related to the intensity of the light (not to its frequency). Thus, it follows that electrons in the metal could absorb energy from a low-intensity, low-frequency light source for a long time and eventually gain enough energy to be ejected. As you just read, however, this is not the case. Observations show that electrons are ejected immediately when even low-intensity radiation at or above the threshold frequency shines on the metal.

Photons and quantized energy In 1905 Albert Einstein published a revolutionary theory that explained the photoelectric effect. According to Einstein, visible light and other forms of electromagnetic radiation consist of discrete, quantized bundles of energy, each of which was later called a **photon.** The energy of a photon depends on its frequency.

Energy of a Photon

The energy of a photon is equal to the product of Planck's constant and the frequency of the photon.

$$E = hf$$

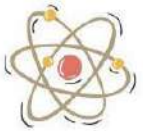
Real-World Physics



SOLAR PANELS A solar panel consists of a grid of solar cells made of semiconducting material. Solar cells are human-made devices that capture the sun's energy and produce electrical energy. Photons from the Sun that have a certain threshold frequency can cause electrons to break free from atoms of the semiconducting material, resulting in an electric current within the solar panel.

snoyarsk/123RF

6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58



Student Textbook · p. 51

Electron volts In the equation for the energy of a photon, f is frequency, which has units of hertz (Hz), and h is Planck's constant, which has units of joules per hertz (J/Hz). Recall that the unit Hz is defined as $\frac{1}{s}$ or s^{-1}. Therefore, the $\frac{J}{Hz}$ unit of Planck's constant is also equivalent to J•s.

Get It?

Demonstrate how the unit $\frac{J}{Hz}$ is equivalent to J•s.

Because the joule is too large a unit of energy to use with atomic-sized systems, the more convenient energy unit of the electron volt (eV) is often used. One electron volt is the energy of an electron accelerated across a potential difference of 1 V.

$$1\text{ eV} = (1.602\times10^{-19}\text{ C})(1\text{ V})$$
$$= 1.602\times10^{-19}\text{ C•V}$$
$$= 1.602\times10^{-19}\text{ J}$$

Using the definition of an electron volt allows the photon energy equation to be rewritten in a simplified form, as shown below.

Energy of a Photon

The energy of a photon is equal to the constant 1240 eV•nm divided by the wavelength of the photon.

$$E = \frac{hc}{\lambda} = \frac{1240\text{ eV•nm}}{\lambda}$$

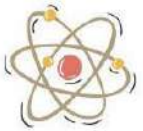
PROBLEM-SOLVING STRATEGIES

Units of hc and Photon Energy

Converting the quantity hc to the unit eV•nm results in a simplified equation that you can use to solve problems involving photon wavelength.

1. The energy of a photon of frequency f is given by this equation:
$$E = hf$$
2. Recall that $f = \frac{c}{\lambda}$, where c is the speed of light in a vacuum. The equation above can therefore be written
$$E = \frac{hc}{\lambda}$$
3. When using the equation $E = \frac{hc}{\lambda}$, if the value of hc in eV•nm is divided by λ in nm, you will obtain the energy in eV. Thus, it is useful to know the value of hc in eV•nm. Because h and c are constants, the value of hc is also a constant.
4. The conversion of hc to the unit eV•nm is as follows:
$$hc = (6.626\times10^{-34}\text{ J/Hz})(2.998\times10^{8}\text{ m/s})\left(\frac{1\text{ eV}}{1.602\times10^{-19}\text{ J}}\right)\left(\frac{10^{9}\text{ nm}}{1\text{ m}}\right)$$
$$= 1240\text{ eV•nm}$$
5. Substituting hc = 1240 eV•nm into the equation for the energy of a photon yields the following, where λ is in nm and E is in eV:
$$E = \frac{hc}{\lambda} = \frac{1240\text{ eV•nm}}{\lambda}$$
6. Use the above equation to solve photon energy problems when energy in eV is desired.

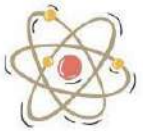
6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58



Check Your Progress 16 · p. 58

16. **Photovoltaic Materials** Why is high-intensity, low-frequency light unable to eject electrons from a metal, whereas low-intensity, high-frequency light can?

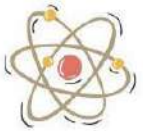
6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58



Check Your Progress 17 · p. 58

17. **Frequency and Energy of Hot-Object Radiation** As the temperature of an object is increased, how does the frequency of peak intensity change? How does the total amount of radiated energy from the object change?

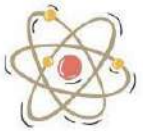
6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58



Check Your Progress 20 · p. 58

20. **Photoelectric Effect** Green light ($\lambda = 532$ nm) strikes an unknown metal, causing electrons to be ejected. The ejected electrons can be stopped by a potential of 1.44 V. What is the work function, in eV, of the metal?

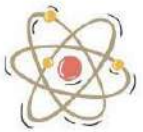
6	•-Define the photoelectric effect, photoelectrons, photons, and threshold frequency. •-Explain how the photoelectric effect occurs when light shines on a metal surface. •-Define the electron volt (eV).	Student Textbook Check Your Progress 16,17,20,21	49-51 58



Check Your Progress 21 · p. 58

21. **Energy of a Photon** What is the energy, in eV, of the photons of a 650-nm laser pointer?

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Student Textbook · p. 51

Electron volts In the equation for the energy of a photon, f is frequency, which has units of hertz (Hz), and h is Planck's constant, which has units of joules per hertz (J/Hz). Recall that the unit Hz is defined as $\frac{1}{s}$ or s^{-1}. Therefore, the $\frac{J}{Hz}$ unit of Planck's constant is also equivalent to J•s.

Get It?

Demonstrate how the unit $\frac{J}{Hz}$ is equivalent to J•s.

Because the joule is too large a unit of energy to use with atomic-sized systems, the more convenient energy unit of the electron volt (eV) is often used. One electron volt is the energy of an electron accelerated across a potential difference of 1 V.

$$1\text{ eV} = (1.602\times10^{-19}\text{ C})(1\text{ V})$$
$$= 1.602\times10^{-19}\text{ C•V}$$
$$= 1.602\times10^{-19}\text{ J}$$

Using the definition of an electron volt allows the photon energy equation to be rewritten in a simplified form, as shown below.

Energy of a Photon

The energy of a photon is equal to the constant 1240 eV•nm divided by the wavelength of the photon.

$$E = \frac{hc}{\lambda} = \frac{1240\text{ eV•nm}}{\lambda}$$

PROBLEM-SOLVING STRATEGIES

Units of hc and Photon Energy

Converting the quantity hc to the unit eV•nm results in a simplified equation that you can use to solve problems involving photon wavelength.

1. The energy of a photon of frequency f is given by this equation:
$$E = hf$$
2. Recall that $f = \frac{c}{\lambda}$, where c is the speed of light in a vacuum. The equation above can therefore be written
$$E = \frac{hc}{\lambda}$$
3. When using the equation $E = \frac{hc}{\lambda}$, if the value of hc in eV•nm is divided by λ in nm, you will obtain the energy in eV. Thus, it is useful to know the value of hc in eV•nm. Because h and c are constants, the value of hc is also a constant.
4. The conversion of hc to the unit eV•nm is as follows:
$$hc = (6.626\times10^{-34}\text{ J/Hz})(2.998\times10^{8}\text{ m/s})\left(\frac{1\text{ eV}}{1.602\times10^{-19}\text{ J}}\right)\left(\frac{10^{9}\text{ nm}}{1\text{ m}}\right)$$
$$= 1240\text{ eV•nm}$$
5. Substituting hc = 1240 eV•nm into the equation for the energy of a photon yields the following, where λ is in nm and E is in eV:
$$E = \frac{hc}{\lambda} = \frac{1240\text{ eV•nm}}{\lambda}$$
6. Use the above equation to solve photon energy problems when energy in eV is desired.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

Student Textbook · p. 52

PRACTICE Problems — ADDITIONAL PRACTICE

Use E = 1240 eV•nm/λ to solve the following problems.

1. What is a photon's energy if the photon's wavelength is 515 nm?
2. A photon's energy is 2.03 eV. What is the photon's wavelength?
3. Rank the following photons from least to greatest energy.
   a. 4.0 eV
   b. 320 nm
   c. 811 nm
   d. 2.1 eV
4. **CHALLENGE** The diagram in **Figure 6** shows the visible light spectrum. What is the range of energies associated with photons in the visible light spectrum?



Figure 6

Planck and Einstein

It is important to note that Einstein's photon theory goes further than Planck's hypothesis of radiation from hot objects. While Planck proposed that atoms vibrating at frequency f emit electromagnetic radiation with energy equal to nhf, he did not suggest that light and other forms of electromagnetic radiation act like particles. Einstein's photon theory reinterpreted and extended Planck's hypothesis of radiation emitted by objects.

Einstein's photon theory explains the existence of a threshold frequency and the prompt emission of electrons during the photoelectric effect. A photon with a minimum frequency and energy (hf_0) can eject an electron from metal. If the photon frequency is less than f_0, the photon will not have the energy needed to pry the electron from the metal. Because one photon interacts with one electron, an electron cannot simply store energy from low frequency photons until it collects enough energy to break free. On the other hand, radiation with a frequency greater than f_0 provides more than enough energy to eject an electron. In fact, the excess energy, $hf - hf_0$, becomes the ejected electron's kinetic energy.

Kinetic Energy of an Electron Ejected Due to the Photoelectric Effect

The kinetic emergy of an ejected electron is equal to the difference between the incident photon energy (hf) and the energy of a photon with the threshold frequency (hf_0).

$$KE = hf - hf_0$$

Note that hf_0 is the minimum energy needed to free the most loosely held electron in an atom. Not all electrons in a metal have the same energy; some will require more than this minimum energy in order to escape. As a result, the ejected electrons have differing kinetic energies. Thus, it is important to realize that the phrase "kinetic energy of the ejected electrons" refers to the maximum kinetic energy that an ejected electron could have. Some of the ejected electrons will have less.

Get It?

Explain how an electron emitted by the photoelectric effect can have kinetic energy less than the threshold energy.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

Student Textbook · p. 53

Testing the photon theory One way to test the photon theory is to measure the electrons' kinetic energy and compare the results to the value predicted by the theory. The device in **Figure 7** can indirectly measure the electrons' kinetic energy. In the device, the potential difference across the tube is adjustable. When the potential difference is adjusted to make the anode negative, the ejected electrons experience a force opposing their motion due to the electric field between the cathode and anode. As a result, the electrons' kinetic energy decreases as they approach the anode. Only electrons ejected with enough kinetic energy reach the anode.

Increasing the opposing potential difference makes the anode more negative, which means the electron's initial kinetic energy must be greater to reach the anode. At a certain potential difference, called the stopping potential, the current stops because no electrons ejected from the cathode have enough kinetic energy to reach the anode.

At the stopping potential, the electrons' kinetic energy at the cathode equals the work done by the electric field to stop them. In equation form this is

$$KE = -e\Delta V_0$$

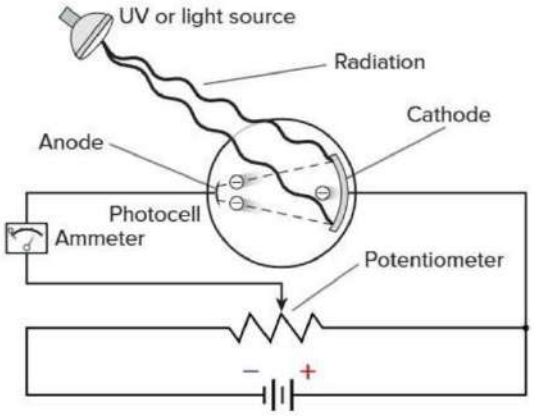
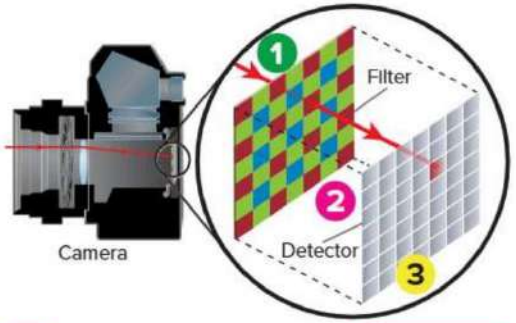


Figure 7 The potentiometer controls the potential difference inside the photocell. By carefully adjusting the potentiometer, you can determine the potential that results in zero current. At the zero current threshold, all electrons fail to reach the anode. Instead, they fall back on the cathode due to the force caused by the electric field between the cathode and the anode.

In this equation, ΔV_0 is the magnitude of the stopping potential difference in volts (J/C), and e is the charge of the electron (-1.602×10^{-19} C). Note that the negative sign in the equation along with the negative value of e yield a positive value for *KE*. Calculations of electrons' kinetic energy based on this experiment support Einstein's photon theory.

Application of the photoelectric effect If you have ever used a digital camera, you have used a device that takes advantage of the photoelectric effect. The digital camera shown in **Figure 8** uses a grid of tiny photoelectric detectors—several million of them packed in a few square centimeters.

In a typical design, light enters the camera through the lens and passes through a grid of filters placed over the photoelectric detectors. The filters allow only certain wavelengths of light, corresponding to specific colors of light, to pass through to an individual detector. Photons that strike a detector result in photoelectrons being stored in the detector. The amount of charge stored at the detector's location indicates the brightness of light. The information from the entire grid of detectors is then compiled to recreate the image. Because the photoelectrons generate a voltage within the detectors, the process is a variation of the photoelectric effect known as the photovoltaic effect.



1. The filter grid limits the wavelengths of light reaching a detector. There are more green filters in the grid because the human eye is more sensitive to these wavelengths.
2. Photons that pass through the filter strike the photoelectric detector. This results in a charge being stored in the detector.
3. Information from all the detectors is compiled by the camera's built-in circuitry. Data from adjacent detectors helps the computer determine the best color for each pixel in the picture.

Figure 8 A digital camera's image detector relies on the photoelectric effect to generate a voltage. The picture is digitized and stored as the values of an array of pixels.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

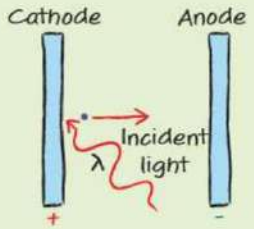
Student Textbook · p. 54

EXAMPLE Problem 1

PHOTOELECTRON KINETIC ENERGY The stopping potential difference of a certain photocell is 4.0 V. How much kinetic energy does the incident light give the electrons? Give your answer in both joules and electron volts.

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and the anode, the incident radiation, and the direction of the ejected electron. Note that the stopping potential prevents electrons from flowing across the photocell.



Known
$\Delta V = 4.0\ \text{V}$

$e = -1.602\times10^{-19}\ \text{C}$

Unknown
KE (in J and eV) = ?

2 SOLVE FOR THE UNKNOWN

The electric field does work on the electrons, so the final kinetic energy of an electron equals the initial kinetic energy plus the work done on the electron.

$KE_{initial} + W_{electric\ field\ on\ electron} = KE_{final}$

$KE_{initial} + W_{electric\ field\ on\ electron} = 0\ \text{J}$ The applied potential difference is the stopping potential, so $KE_{final} = 0$ J.

Solve for $KE_{initial}$.

$KE_{initial} = -W_{electric\ field\ on\ electron}$

$= -e\Delta V_0$ Use the definition of electric potential difference $\left(\Delta V = \frac{W_{on\ e}}{e}\right)$ to find $W_{on\ e} = e\Delta V$.

$= -(-1.602\times10^{-19}\ \text{C})(4.0\ \text{V})$ Substitute $e = -1.602\times10^{-19}$ C, $\Delta V_0 = 4.0$ V.

$= +6.4\times10^{-19}\ \text{J}$

Convert KE from joules to electron volts.

$KE = (6.4\times10^{-19}\ \text{J})\frac{1\text{eV}}{1.602\times10^{-19}\ \text{J}}$

$= 4.0\ \text{eV}$

3 EVALUATE THE ANSWER

- **Are the units correct?** Joules and electron volts are both units of energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Is the magnitude realistic?** One electron volt is the energy of an electron accelerated across a potential difference of 1 V. The electron is accelerated by a potential difference of 4 V, so 4 eV is reasonable.

PRACTICE Problems

ADDITIONAL PRACTICE

5. An electron has an energy of 2.3 eV. What is the kinetic energy of the electron in joules?
6. What is the velocity of the electron in the previous problem?
7. What is the kinetic energy in eV of an electron with a velocity of 6.2×10^{6} m/s?
8. The stopping potential for a photoelectric cell is 5.7 V. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.
9. The stopping potential for a photoelectric cell is 5.1 V. How much kinetic energy does the incident light give the electrons in joules?
10. The maximum kinetic energy of emitted photoelectrons in a photoelectric cell is 7.5×10^{-19} J. What is the stopping potential?
11. **CHALLENGE** The stopping potential required to prevent current through a photocell is 3.2 V. Calculate the maximum kinetic energy in joules of the photoelectrons as they are emitted.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

Student Textbook · p. 55

Table 1 Threshold Frequency, Threshold Wavelength, and Work Function for Selected Metals

Metal	Threshold Frequency ($\times 10^{14}$ Hz)	Threshold Wavelength (nm)	Work Function (eV)
Cesium	4.70	637	1.95
Magnesium	8.84	339	3.66
Silver	11.1	270	4.6
Sodium	5.70	526	2.36

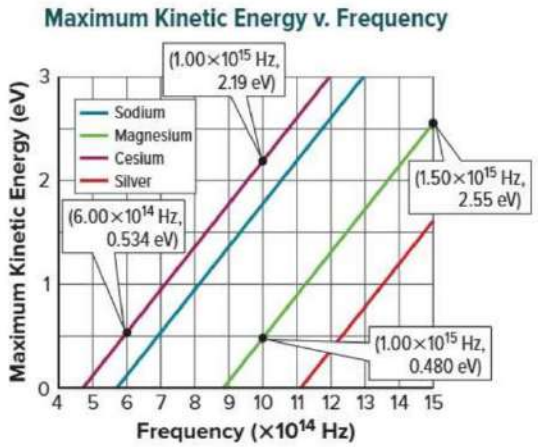


Figure 9 The metal's threshold frequency equals the line's *x*-intercept. Each line's slope equals Planck's constant.

Measuring h A graph of the maximum kinetic energies of the electrons ejected from a metal versus the frequencies of the incident photons is a straight line, as shown in **Figure 9**. All metals have similar graphs with the same slope. This slope equals the rise/run ratio of the line, which is equal to Planck's constant (h).

The graphs of various metals differ only in the threshold frequency needed to free the electrons. In **Figure 9**, the threshold frequency (f_0) is the point at which $KE = 0$. Looking at the graph, we see that f_0 is located at the intersection of the line with the *x*-axis. For example, the *x*-intercept, and therefore the threshold frequency, for cesium is 4.70×10^{14} Hz. A photon with that frequency has just enough energy to eject an electron from the metal. This minimum energy, called the **work function** of a metal, is the energy needed to free the most weakly bound electron from the metal. The magnitude of the work function is equal to hf_0. When a photon of frequency f_0 is incident on a metal, the energy of the photon is sufficient to release an electron but not sufficient to provide the electron with any kinetic energy.

CONNECTING MATH to Physics

Slope of a Line The lines in **Figure 9** are parallel. That means they all have the same slope. Below are the calculations for cesium and magnesium.

Math	Physics	
	Cesium	Magnesium
(x_1, y_1), (x_2, y_2)	$(6.00\times10^{14}$ Hz, 0.534 eV), $(1.00\times10^{15}$ Hz, 2.19 eV)	$(1.00\times10^{15}$ Hz, 0.480 eV), $(1.50\times10^{15}$ Hz, 2.55 eV)
$m = \frac{y_2 - y_1}{x_2 - x_1}$	$m = \frac{2.19\text{ eV} - 0.534\text{ eV}}{1.00\times10^{15}\text{ Hz} - 6.00\times10^{14}\text{ Hz}}$	$m = \frac{2.55\text{ eV} - 0.480\text{ eV}}{1.50\times10^{15}\text{ Hz} - 1.00\times10^{15}\text{ Hz}}$
	$m = 4.14\times10^{-15}$ eV/Hz	$m = 4.14\times10^{-15}$ eV/Hz

All lines in **Figure 9** have a slope of 4.14×10^{-15} eV/Hz. When converted to J/Hz, this value becomes the familiar value of Planck's constant:

$$4.14\times10^{-15}\ \frac{\text{eV}}{\text{Hz}}\left(\frac{1.602\times10^{-19}\text{ J}}{1\text{ eV}}\right) = 6.63\times10^{-34}\text{ J/Hz}$$

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

Student Textbook · p. 56

EXAMPLE Problem 2

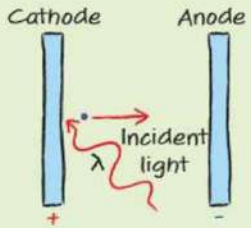
WORK FUNCTION AND ENERGY A particular photocell uses a sodium cathode. Sodium has a threshold wavelength of 526 nm.

a. Find the work function of sodium in eV.

b. If ultraviolet radiation with a wavelength of 348 nm falls on sodium, will the cathode discharge electrons? If so, what is the maximum energy of the ejected electrons in eV?

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and anode, the incident radiation, and the direction of the ejected electron.



Known

$\lambda_0 = 526$ nm $\quad \lambda = 348$ nm

$hc = 1240$ eV·nm

Unknown

$W = ?$ $\quad KE = ?$

2 SOLVE FOR THE UNKNOWN

a. Find the work function using Planck's constant and the threshold wavelength.

$$W = hf_0 = \frac{hc}{\lambda_0}$$
$$= \frac{1240 \text{ eV·nm}}{526 \text{ nm}} \qquad \text{Substitute } hc = 1240 \text{ eV·nm}, \lambda_0 = 526 \text{ nm}.$$
$$= 2.36 \text{ eV}$$

b. Use the relationship between a photon's energy and wavelength to find the photon's energy.

$$E = \frac{1240 \text{ eV·nm}}{\lambda}$$
$$= \frac{1240 \text{ eV·nm}}{348 \text{ nm}} \qquad \text{Substitute } \lambda = 348 \text{ nm}.$$
$$= 3.56 \text{ eV}$$

To calculate the kinetic energy of the ejected electron, subtract the work function from the energy of the incident radiation.

$$KE = hf - hf_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$
$$= E - W \qquad \text{Substitute } \frac{hc}{\lambda} = E, \frac{hc}{\lambda_0} = W.$$
$$= 3.56 \text{ eV} - 2.36 \text{ eV} \qquad \text{Substitute } E = 3.56 \text{ eV}, W = 2.36 \text{ eV}.$$
$$= 1.20 \text{ eV}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Performing dimensional analysis on the units verifies that electron volts is the proper unit for kinetic energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Are the magnitudes realistic?** Work functions given in Table 1 are a few electron volts, so the magnitude is realistic.

PRACTICE Problems

ADDITIONAL PRACTICE

12. The threshold wavelength of zinc is 310 nm. Find the threshold frequency, in Hz, and the work function, in eV, of zinc.

13. The work function for cesium is 1.95 eV. What is the maximum kinetic energy, in eV, of photoelectrons ejected when 425-nm violet light falls on the cesium?

14. When a metal is illuminated with 193-nm ultraviolet radiation, electrons with kinetic energies of 3.5 eV are emitted. What is the work function of the metal?

15. CHALLENGE A researcher illuminates a sample of metal and finds the longest wavelength to eject electrons is 273 nm. Find the work function. Use **Table 1** to identify the most likely metal.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

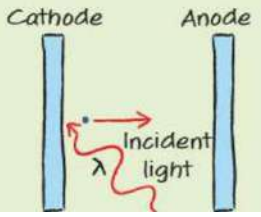
Example Problem 1 · p. 54

EXAMPLE Problem 1

PHOTOELECTRON KINETIC ENERGY The stopping potential difference of a certain photocell is 4.0 V. How much kinetic energy does the incident light give the electrons? Give your answer in both joules and electron volts.

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and the anode, the incident radiation, and the direction of the ejected electron. Note that the stopping potential prevents electrons from flowing across the photocell.



Known

$\Delta V = 4.0\ \text{V}$

$e = -1.602\times10^{-19}\ \text{C}$

Unknown

KE (in J and eV) = ?

2 SOLVE FOR THE UNKNOWN

The electric field does work on the electrons, so the final kinetic energy of an electron equals the initial kinetic energy plus the work done on the electron.

$KE_{initial} + W_{electric\ field\ on\ electron} = KE_{final}$

$KE_{initial} + W_{electric\ field\ on\ electron} = 0\ \text{J}$ The applied potential difference is the stopping potential, so $KE_{final} = 0$ J.

Solve for $KE_{initial}$.

$KE_{initial} = -W_{electric\ field\ on\ electron}$

$= -e\Delta V_0$ Use the definition of electric potential difference $\left(\Delta V = \frac{W_{on\ e}}{e}\right)$ to find $W_{on\ e} = e\Delta V$.

$= -(-1.602\times10^{-19}\ \text{C})(4.0\ \text{V})$ Substitute $e = -1.602\times10^{-19}$ C, $\Delta V_0 = 4.0$ V.

$= +6.4\times10^{-19}\ \text{J}$

Convert KE from joules to electron volts.

$KE = (6.4\times10^{-19}\ \text{J})\frac{1\text{eV}}{1.602\times10^{-19}\ \text{J}}$

$= 4.0\ \text{eV}$

3 EVALUATE THE ANSWER

- **Are the units correct?** Joules and electron volts are both units of energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Is the magnitude realistic?** One electron volt is the energy of an electron accelerated across a potential difference of 1 V. The electron is accelerated by a potential difference of 4 V, so 4 eV is reasonable.

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56

Example Problem 2 · p. 56

EXAMPLE Problem 2

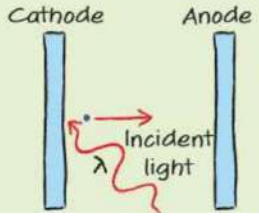
WORK FUNCTION AND ENERGY A particular photocell uses a sodium cathode. Sodium has a threshold wavelength of 526 nm.

a. Find the work function of sodium in eV.

b. If ultraviolet radiation with a wavelength of 348 nm falls on sodium, will the cathode discharge electrons? If so, what is the maximum energy of the ejected electrons in eV?

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and anode, the incident radiation, and the direction of the ejected electron.



Known

$\lambda_0 = 526$ nm $\quad \lambda = 348$ nm

$hc = 1240$ eV·nm

Unknown

$W = ? \quad KE = ?$

2 SOLVE FOR THE UNKNOWN

a. Find the work function using Planck's constant and the threshold wavelength.

$$W = hf_0 = \frac{hc}{\lambda_0}$$

$$= \frac{1240 \text{ eV·nm}}{526 \text{ nm}} \qquad \text{Substitute } hc = 1240 \text{ eV·nm}, \lambda_0 = 526 \text{ nm}.$$

$$= 2.36 \text{ eV}$$

b. Use the relationship between a photon's energy and wavelength to find the photon's energy.

$$E = \frac{1240 \text{ eV·nm}}{\lambda}$$

$$= \frac{1240 \text{ eV·nm}}{348 \text{ nm}} \qquad \text{Substitute } \lambda = 348 \text{ nm}.$$

$$= 3.56 \text{ eV}$$

To calculate the kinetic energy of the ejected electron, subtract the work function from the energy of the incident radiation.

$$KE = hf - hf_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

$$= E - W \qquad \text{Substitute } \frac{hc}{\lambda} = E, \frac{hc}{\lambda_0} = W.$$

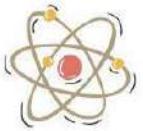
$$= 3.56 \text{ eV} - 2.36 \text{ eV} \qquad \text{Substitute } E = 3.56 \text{ eV}, W = 2.36 \text{ eV}.$$

$$= 1.20 \text{ eV}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Performing dimensional analysis on the units verifies that electron volts is the proper unit for kinetic energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Are the magnitudes realistic?** Work functions given in Table 1 are a few electron volts, so the magnitude is realistic.

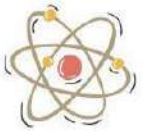
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 5 · p. 54

5. An electron has an energy of 2.3 eV. What is the kinetic energy of the electron in joules?

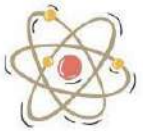
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 6 · p. 54

5. An electron has an energy of 2.3 eV. What is the kinetic energy of the electron in joules?
6. What is the velocity of the electron in the previous problem?

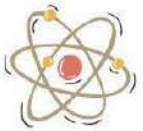
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 7 · p. 54

7. What is the kinetic energy in eV of an electron with a velocity of 6.2×10^{6} m/s?

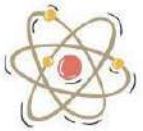
7	• -Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 8 · p. 54

8. The stopping potential for a photoelectric cell is 5.7 V. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.

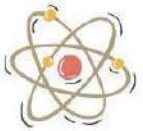
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 9 · p. 54

9. The stopping potential for a photoelectric cell is 5.1 V. How much kinetic energy does the incident light give the electrons in joules?

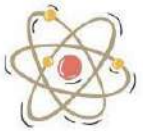
7	• -Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 10 · p. 54

10. The maximum kinetic energy of emitted photoelectrons in a photoelectric cell is 7.5×10^{-19} J. What is the stopping potential?

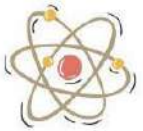
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 11 · p. 54

11. CHALLENGE The stopping potential required to prevent current through a photocell is 3.2 V. Calculate the maximum kinetic energy in joules of the photoelectrons as they are emitted.

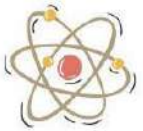
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 12 · p. 56

12. The threshold wavelength of zinc is 310 nm. Find the threshold frequency, in Hz, and the work function, in eV, of zinc.

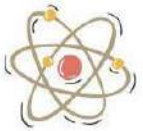
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 13 · p. 56

13. The work function for cesium is 1.95 eV. What is the maximum kinetic energy, in eV, of photoelectrons ejected when 425-nm violet light falls on the cesium?

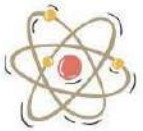
7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 14 · p. 56

14. When a metal is illuminated with 193-nm ultraviolet radiation, electrons with kinetic energies of 3.5 eV are emitted. What is the work function of the metal?

7	•-Calculate photon energy from wavelength or frequency. • -Explain that maximum photoelectron kinetic energy is independent of incident-light intensity, while photoelectric current is proportional to intensity.	Student Textbook Example Problems 1,2 Practice Problems	51-56 54,56,56



Practice Problem 15 · p. 56

15. CHALLENGE A researcher illuminates a sample of metal and finds the longest wavelength to eject electrons is 273 nm. Find the work function. Use **Table 1** to identify the most likely metal.

8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54

Student Textbook · p. 50

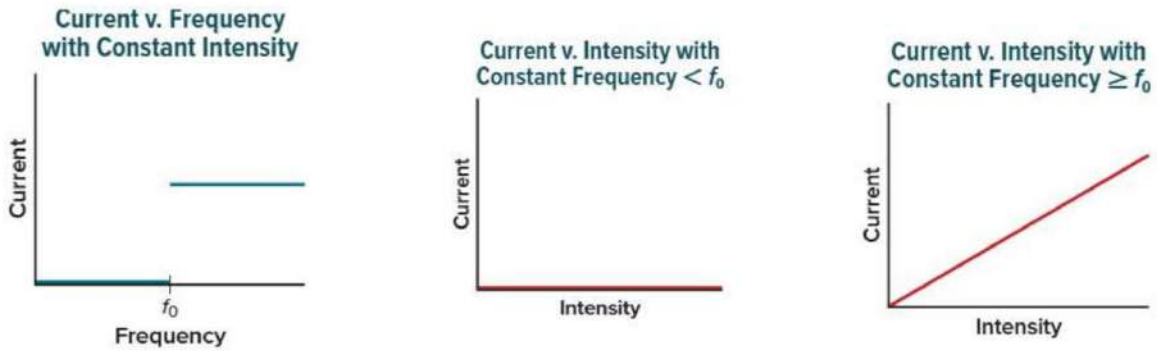


Figure 5 The emission of photoelectrons depends on the incident light's frequency. The threshold frequency must be exceeded in order to produce photoelectrons.

Threshold frequency Not all radiation falling on a photocell causes a current. Electrons eject from the cathode only if the frequency of the incident radiation is greater than a certain minimum value, called the **threshold frequency** (f_0). The graph on the left in **Figure 5** shows there is a current only when the threshold frequency is reached. The value of the threshold frequency varies widely and depends on the type of metal used for the cathode. For example, all frequencies of visible light except low-frequency red eject electrons from cesium. No frequency of visible light ejects electrons from zinc. Higher-frequency ultraviolet radiation ejects electrons from zinc.

The center graph in **Figure 5** shows that even intense radiation with a frequency below f_0 will not cause the emission of electrons. Conversely, the graph on the right shows that even very low-intensity radiation with a frequency at or above f_0 causes the immediate emission of electrons from the cathode. When the incoming radiation, also called the incident radiation, has a frequency equal to or greater than the threshold frequency, increasing the intensity of the radiation increases the current through the photocell.

The electromagnetic wave theory would say that the electric field in the light wave accelerates and ejects the electrons from the metal. The strength and energy of the electric field are related to the intensity of the light (not to its frequency). Thus, it follows that electrons in the metal could absorb energy from a low-intensity, low-frequency light source for a long time and eventually gain enough energy to be ejected. As you just read, however, this is not the case. Observations show that electrons are ejected immediately when even low-intensity radiation at or above the threshold frequency shines on the metal.

Photons and quantized energy In 1905 Albert Einstein published a revolutionary theory that explained the photoelectric effect. According to Einstein, visible light and other forms of electromagnetic radiation consist of discrete, quantized bundles of energy, each of which was later called a **photon.** The energy of a photon depends on its frequency.

Energy of a Photon

The energy of a photon is equal to the product of Planck's constant and the frequency of the photon.

$$E = hf$$

Real-World Physics



SOLAR PANELS A solar panel consists of a grid of solar cells made of semiconducting material. Solar cells are human-made devices that capture the sun's energy and produce electrical energy. Photons from the Sun that have a certain threshold frequency can cause electrons to break free from atoms of the semiconducting material, resulting in an electric current within the solar panel.

snoyarsk/123RF

8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54

Student Textbook · p. 53

Testing the photon theory One way to test the photon theory is to measure the electrons' kinetic energy and compare the results to the value predicted by the theory. The device in **Figure 7** can indirectly measure the electrons' kinetic energy. In the device, the potential difference across the tube is adjustable. When the potential difference is adjusted to make the anode negative, the ejected electrons experience a force opposing their motion due to the electric field between the cathode and anode. As a result, the electrons' kinetic energy decreases as they approach the anode. Only electrons ejected with enough kinetic energy reach the anode.

Increasing the opposing potential difference makes the anode more negative, which means the electron's initial kinetic energy must be greater to reach the anode. At a certain potential difference, called the stopping potential, the current stops because no electrons ejected from the cathode have enough kinetic energy to reach the anode.

At the stopping potential, the electrons' kinetic energy at the cathode equals the work done by the electric field to stop them. In equation form this is

$$KE = -e\Delta V_0$$

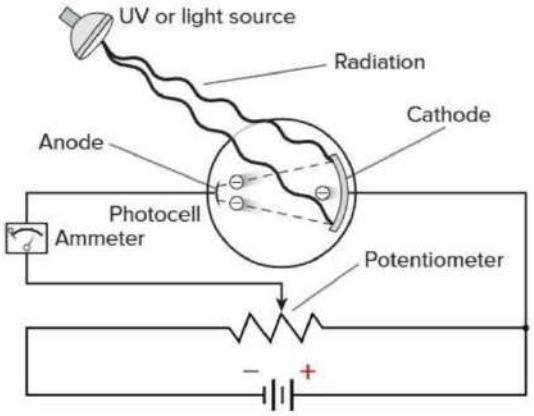


Figure 7 The potentiometer controls the potential difference inside the photocell. By carefully adjusting the potentiometer, you can determine the potential that results in zero current. At the zero current threshold, all electrons fail to reach the anode. Instead, they fall back on the cathode due to the force caused by the electric field between the cathode and the anode.

In this equation, ΔV_0 is the magnitude of the stopping potential difference in volts (J/C), and e is the charge of the electron (-1.602×10^{-19} C). Note that the negative sign in the equation along with the negative value of e yield a positive value for *KE*. Calculations of electrons' kinetic energy based on this experiment support Einstein's photon theory.

Application of the photoelectric effect If you have ever used a digital camera, you have used a device that takes advantage of the photoelectric effect. The digital camera shown in **Figure 8** uses a grid of tiny photoelectric detectors—several million of them packed in a few square centimeters.

In a typical design, light enters the camera through the lens and passes through a grid of filters placed over the photoelectric detectors. The filters allow only certain wavelengths of light, corresponding to specific colors of light, to pass through to an individual detector. Photons that strike a detector result in photoelectrons being stored in the detector. The amount of charge stored at the detector's location indicates the brightness of light. The information from the entire grid of detectors is then compiled to recreate the image. Because the photoelectrons generate a voltage within the detectors, the process is a variation of the photoelectric effect known as the photovoltaic effect.

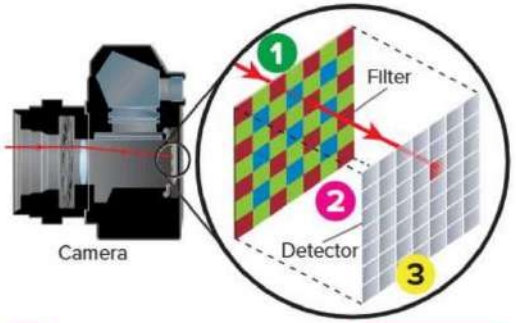
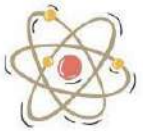


Figure 8 A digital camera's image detector relies on the photoelectric effect to generate a voltage. The picture is digitized and stored as the values of an array of pixels.

1. The filter grid limits the wavelengths of light reaching a detector. There are more green filters in the grid because the human eye is more sensitive to these wavelengths.
2. Photons that pass through the filter strike the photoelectric detector. This results in a charge being stored in the detector.
3. Information from all the detectors is compiled by the camera's built-in circuitry. Data from adjacent detectors helps the computer determine the best color for each pixel in the picture.

8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Check Your Progress 20 · p. 58

20. **Photoelectric Effect** Green light ($\lambda = 532$ nm) strikes an unknown metal, causing electrons to be ejected. The ejected electrons can be stopped by a potential of 1.44 V. What is the work function, in eV, of the metal?

8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54

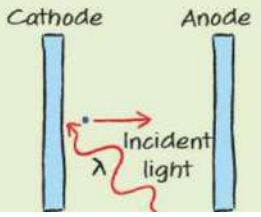
Example Problem 1 · p. 54

EXAMPLE Problem 1

PHOTOELECTRON KINETIC ENERGY The stopping potential difference of a certain photocell is 4.0 V. How much kinetic energy does the incident light give the electrons? Give your answer in both joules and electron volts.

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and the anode, the incident radiation, and the direction of the ejected electron. Note that the stopping potential prevents electrons from flowing across the photocell.



Known
$\Delta V = 4.0\ \text{V}$
$e = -1.602\times10^{-19}\ \text{C}$

Unknown
KE (in J and eV) = ?

2 SOLVE FOR THE UNKNOWN

The electric field does work on the electrons, so the final kinetic energy of an electron equals the initial kinetic energy plus the work done on the electron.

$$KE_{initial} + W_{electric\ field\ on\ electron} = KE_{final}$$

$$KE_{initial} + W_{electric\ field\ on\ electron} = 0\ \text{J}$$

The applied potential difference is the stopping potential, so $KE_{final} = 0$ J.

Solve for $KE_{initial}$.

$$KE_{initial} = -W_{electric\ field\ on\ electron}$$

$$= -e\Delta V_0$$

Use the definition of electric potential difference $\left(\Delta V = \frac{W_{on\ e}}{e}\right)$ to find $W_{on\ e} = e\Delta V$.

$$= -(-1.602\times10^{-19}\ \text{C})(4.0\ \text{V})$$

Substitute $e = -1.602\times10^{-19}$ C, $\Delta V_0 = 4.0$ V.

$$= +6.4\times10^{-19}\ \text{J}$$

Convert KE from joules to electron volts.

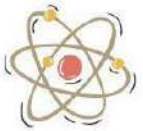
$$KE = (6.4\times10^{-19}\ \text{J})\frac{1\text{eV}}{1.602\times10^{-19}\ \text{J}}$$

$$= 4.0\ \text{eV}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Joules and electron volts are both units of energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Is the magnitude realistic?** One electron volt is the energy of an electron accelerated across a potential difference of 1 V. The electron is accelerated by a potential difference of 4 V, so 4 eV is reasonable.

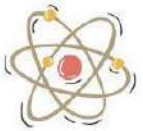
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 5 · p. 54

5. An electron has an energy of 2.3 eV. What is the kinetic energy of the electron in joules?

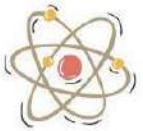
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 6 · p. 54

5. An electron has an energy of 2.3 eV. What is the kinetic energy of the electron in joules?
6. What is the velocity of the electron in the previous problem?

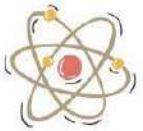
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 7 · p. 54

7. What is the kinetic energy in eV of an electron with a velocity of 6.2×10^{6} m/s?

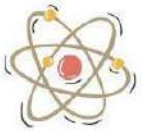
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 8 · p. 54

8. The stopping potential for a photoelectric cell is 5.7 V. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.

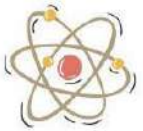
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 9 · p. 54

9. The stopping potential for a photoelectric cell is 5.1 V. How much kinetic energy does the incident light give the electrons in joules?

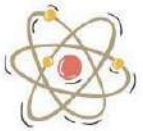
8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 10 · p. 54

10. The maximum kinetic energy of emitted photoelectrons in a photoelectric cell is 7.5×10^{-19} J. What is the stopping potential?

8	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret the graph of maximum kinetic energy versus photon frequency and identify threshold frequency and Planck's constant.	Student Textbook Check Your Progress 20 Example problem 1 Practice problem 5-11	50,53 55 54 54



Practice Problem 11 · p. 54

11. CHALLENGE The stopping potential required to prevent current through a photocell is 3.2 V. Calculate the maximum kinetic energy in joules of the photoelectrons as they are emitted.

9	•-Calculate the momentum of a photon. •-Explain the Compton effect and how it supports the particle theory of light. •-Describe that photon-particle collisions obey conservation of energy and momentum.	Student Textbook Check Your Progress 18,24	57,58 58

Student Textbook · p. 57

The Compton Effect

The photoelectric effect demonstrates that a photon has kinetic energy even though it has no mass. In 1916, Einstein predicted that the photon should also have another particle property—momentum. He argued that the momentum of a photon should be equal to $\frac{E}{c}$. Because $E = hf$ and $\frac{f}{c} = \frac{1}{\lambda}$, the photon's momentum is given by the following equation.

Photon Momentum

The momentum of a photon is equal to Planck's constant divided by the photon's wavelength.

$$p = \frac{hf}{c} = \frac{h}{\lambda}$$

Experiments done in 1922 by American physicist Arthur Holly Compton tested Einstein's hypothesis. Compton's results further supported the particle model of light. Compton directed X-rays of a known wavelength at a graphite target, as shown on the left in **Figure 10**, and measured the wavelengths of the X-rays scattered by the target. He observed that some of the X-rays were scattered without change in wavelength, whereas others had a longer wavelength than that of the original radiation. These results are shown on the right panel in **Figure 10.** Note that the peak wavelength for the unscattered X-rays corresponds to the wavelength of the original incident X-rays, whereas the peak wavelength for the scattered X-rays is greater than that of the original incident X-rays.

Recall that the equation for the energy of a photon, $E = hf$, also can be written as $E = \frac{hc}{\lambda}$. This second equation shows that the energy of a photon is inversely proportional to its wavelength. The increase in wavelength that Compton observed meant that the X-ray photons had lost both energy and momentum. The shift in the energy of scattered photons is called the **Compton effect.** This shift in energy, indicated by a shift in wavelength, is very small—only about 10^{-3} nm. It is a measurable effect only when electromagnetic waves have wavelengths less than 10^{-2} nm.

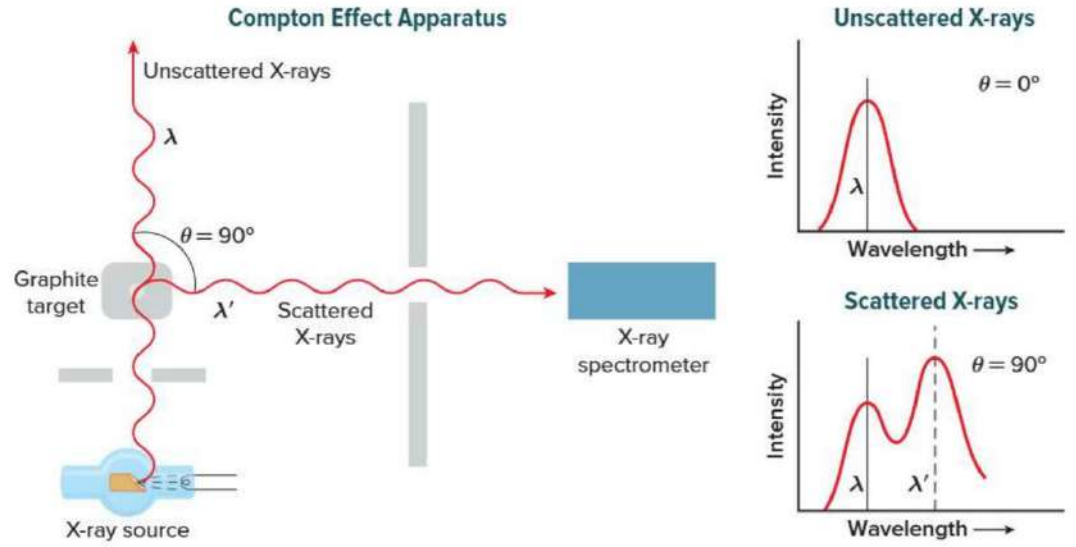


Figure 10 The shift in the peak wavelength of scattered X-rays indicates that the scattered photons lost energy and momentum.

Explain *why an increase in wavelength indicates a decrease in energy.*

9	•-Calculate the momentum of a photon. •-Explain the Compton effect and how it supports the particle theory of light. •-Describe that photon-particle collisions obey conservation of energy and momentum.	Student Textbook Check Your Progress 18,24	57,58 58

Student Textbook · p. 58

Photons and conservation of energy and momentum

In later experiments, Compton observed that electrons were ejected from the graphite block during the experiment. He suggested that the X-ray photons collided with electrons in the graphite target and transferred energy and momentum to them. Compton thought these photon-electron collisions were similar to the elastic collisions experienced by billiard balls, as shown in **Figure 11.** He tested this idea by measuring the energies of the electrons ejected from the graphite block. Compton found that the energy and momentum gained by the ejected electrons equaled the energy and momentum lost by the photons. Thus, photons obey the laws of conservation of energy and momentum when they collide with other particles.

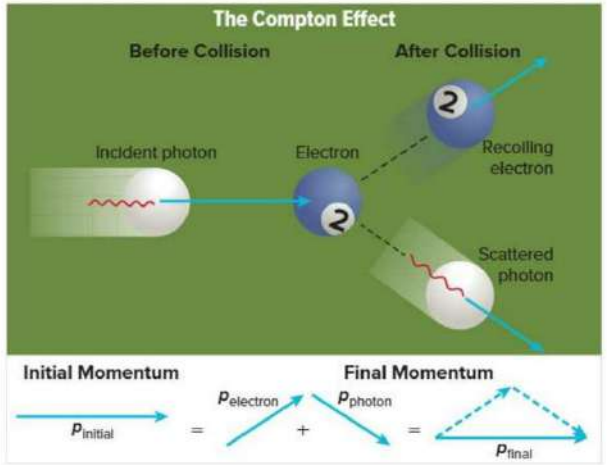


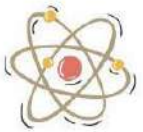
Figure 11 The laws of conservation of energy and momentum apply to collisions between billiard balls and between photons and particles.

Check Your Progress

16. **Photovoltaic Materials** Why is high-intensity, low-frequency light unable to eject electrons from a metal, whereas low-intensity, high-frequency light can?
17. **Frequency and Energy of Hot-Object Radiation** As the temperature of an object is increased, how does the frequency of peak intensity change? How does the total amount of radiated energy from the object change?
18. **Photoelectric and Compton Effects** Distinguish the photoelectric effect from the Compton effect.
19. **Solar Cells** What are solar cells? Describe how they function.
20. **Photoelectric Effect** Green light ($\lambda = 532$ nm) strikes an unknown metal, causing electrons to be ejected. The ejected electrons can be stopped by a potential of 1.44 V. What is the work function, in eV, of the metal?
21. **Energy of a Photon** What is the energy, in eV, of the photons of a 650-nm laser pointer?
22. **Compton Effect** An X-ray strikes a bone, collides with an electron, and scatters. How does the wavelength of the scattered X-ray compare to the wavelength of the incident X-ray?
23. **Photoelectric Effect** An X-ray is absorbed in a bone and releases an electron. The X-ray has a wavelength of about 0.02 nm. Find the electrons' energy, in eV. Assume the work function of bone is negligible compared to the X-ray's energy.
24. **Critical Thinking** Imagine that the collision of two billiard balls models the interaction of a photon and an electron during the Compton effect. Suppose the electron is replaced by a much more massive proton. Would this proton gain as much energy from the collision as the electron does? Would the photon lose as much energy as it does when it collides with the electron?

LEARNSMART Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

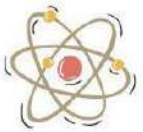
9	•-Calculate the momentum of a photon. •-Explain the Compton effect and how it supports the particle theory of light. •-Describe that photon-particle collisions obey conservation of energy and momentum.	Student Textbook Check Your Progress 18,24	57,58 58



Check Your Progress 18 · p. 58

18. **Photoelectric and Compton Effects** Distinguish the photoelectric effect from the Compton effect.

9	•-Calculate the momentum of a photon. •-Explain the Compton effect and how it supports the particle theory of light. •-Describe that photon-particle collisions obey conservation of energy and momentum.	Student Textbook Check Your Progress 18,24	57,58 58



Check Your Progress 24 · p. 58

24. **Critical Thinking** Imagine that the collision of two billiard balls models the interaction of a photon and an electron during the Compton effect. Suppose the electron is replaced by a much more massive proton. Would this proton gain as much energy from the collision as the electron does? Would the photon lose as much energy as it does when it collides with the electron?

10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61

Student Textbook · p. 59

LESSON 2

MATTER WAVES

FOCUS QUESTION

How can particles be described as waves?

de Broglie Waves

If an electromagnetic wave can behave like a collection of particles, could a particle exhibit interference and diffraction as a wave does? In 1923 French physicist Louis de Broglie proposed that a material particle could be described by a wavelength. This proposal was a brave extension of Einstein's photon theory, and Einstein was an early supporter of de Broglie's waves. Recall that the momentum of an object is equal to its mass times its velocity, $p = mv$. If the massive object is also a wave, then its momentum should be like that of a photon, $p = \frac{h}{\lambda}$. De Broglie proposed that these two expressions for momentum could be equated:

$$p = mv = \frac{h}{\lambda}$$

The wavelength λ calculated from the above relationship represents that of the moving particle and is known as the **de Broglie wavelength.** The following equation solves directly for the de Broglie wavelength.

De Broglie Wavelength

The de Broglie wavelength of a moving particle is equal to Planck's constant divided by the particle's momentum.

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

According to de Broglie, any small particle such as an electron or a proton should show wavelike properties. In 1927, independent experiments confirmed electron diffraction, which is evidence of electrons' wavelike properties. Objects you use every day do not exhibit wavelike properties because their wavelengths are too small to observe. For example, the wavelength of a 0.145-kg baseball hit at 38 m/s is:

$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}\ \text{J·s}}{(0.145\ \text{kg})(38\ \text{m/s})} = 1.2\times10^{-34}\ \text{m}$$

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Identify Crosscutting Concepts

Create a table of the crosscutting concepts and fill in examples you find as you read.

Review the News

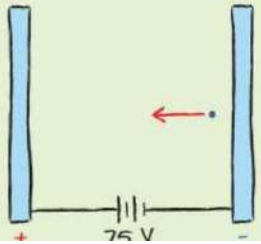
Obtain information from a current news story about technology that makes use of quantum or atomic physics. Evaluate your source and communicate your findings to your class.

10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61

Example Problem 3 · p. 60

EXAMPLE Problem 3

DE BROGLIE WAVELENGTH An electron is accelerated by a potential difference of 75 V. What is its de Broglie wavelength?



1 ANALYZE AND SKETCH THE PROBLEM

Include the positive and the negative plates in your drawing.

Known		Unknown
$\Delta V = 75\ \text{V}$	$m_e = 9.11\times10^{-31}\ \text{kg}$	$\lambda = ?$
$e = -1.602\times10^{-19}\ \text{C}$	$h = 6.63\times10^{-34}\ \text{J}\cdot\text{s}$	

2 SOLVE FOR THE UNKNOWN

Write relationships for the kinetic energy of the electron based on potential difference and motion, and use them to calculate the electron's velocity.

$KE = -e\Delta V$, and $KE = \frac{1}{2}mv^2$

$\frac{1}{2}mv^2 = -e\Delta V$ Equate the expressions for *KE*.

Solve for *v*.

$$v = \sqrt{\frac{-2e\Delta V}{m}}$$

$$= \sqrt{\frac{-2(-1.602\times10^{-19}\ \text{C})(75\ \text{V})}{9.11\times10^{-31}\ \text{kg}}}$$ Substitute $e = -1.602\times10^{-19}$ C, $\Delta V = 75$ V, $m_e = 9.11\times10^{-31}$ kg.

$$= 5.1\times10^{6}\ \text{m/s}$$

Use the relationship between mass, velocity, and momentum.

$$p = mv$$

$$= (9.11\times10^{-31}\ \text{kg})(5.1\times10^{6}\ \text{m/s})$$ Substitute $m_e = 9.11\times10^{-31}$ kg, $v = 5.1\times10^{6}$ m/s.

$$= 4.6\times10^{-24}\ \text{kg}\cdot\text{m/s}$$

Use the relationship between momentum and the de Broglie wavelength.

$$\lambda = \frac{h}{p}$$

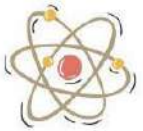
$$= \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{4.6\times10^{-24}\ \text{kg}\cdot\text{m/s}}$$ Substitute $h = 6.63\times10^{-34}$ J·s, $p = 4.6\times10^{-24}$ kg·m/s.

$$= 1.4\times10^{-10}\ \text{m, which equals 0.14 nm}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Dimensional analysis on the units verifies m/s for *v* and nm for λ.
- **Does the sign make sense?** Positive values are expected for both *v* and λ.
- **Are the magnitudes realistic?** The wavelength is close to 0.1 nm, which is in the X-ray region of the electromagnetic spectrum.

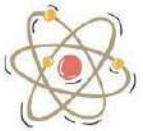
10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



Practice Problem 25 · p. 60

25. What is the de Broglie wavelength and speed of an electron accelerated by a potential difference of 250 V?

10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



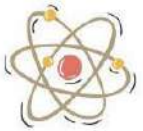
Practice Problem 26 · p. 60

26. A 7.0-kg bowling ball rolls with a velocity of 8.5 m/s.

a. What is the de Broglie wavelength of the bowling ball?

b. Why does the bowling ball exhibit no observable wave behavior?

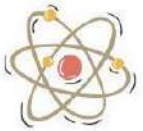
10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



Practice Problem 27 · p. 60

27. What potential difference is needed to accelerate an electron so it has a 0.125-nm wavelength?

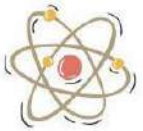
10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



Practice Problem 28 · p. 60

28. CHALLENGE The electron in Example Problem 3 has a de Broglie wavelength of 0.14 nm. What is the kinetic energy, in eV, of a proton with the same wavelength?

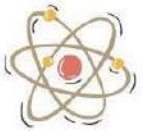
10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



Check Your Progress 29 · p. 61

29. **Waves** Using De Broglie's theory, you can calculate the wavelength of any moving particle. Explain why the wave nature of everyday objects is not obvious.

10	•-Describe de Broglie's hypothesis of the wave nature of matter and its experimental verification by electron diffraction. •-Define and calculate the de Broglie wavelength of a moving particle.	Student Textbook Example Problem 3 Practice Problems 25-28 Check Your Progress 29,31	59 60 60 61



Check Your Progress 31 · p. 61

31. **de Broglie Wavelength** What is the de Broglie wavelength of an electron accelerated through a potential difference of 125 V?

11	•-State Heisenberg's uncertainty principle. •-Describe the limitation on simultaneously measuring a particle's position and momentum.	Student Textbook Check Your Progress 32	61 61

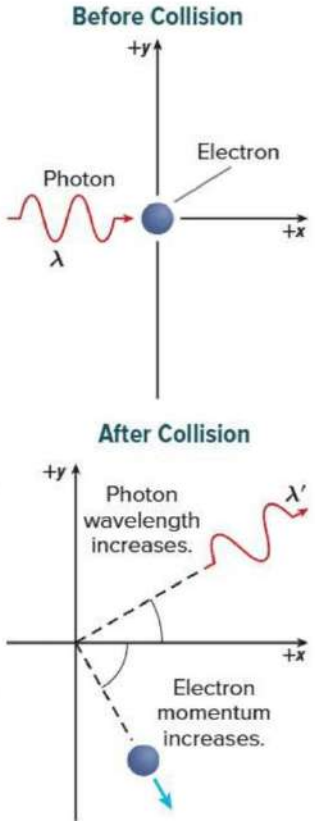
Student Textbook · p. 61

Location and Momentum

De Broglie's theory of particles' wavelike properties led to a fundamental change in our understanding of atomic-sized objects. In everyday experience, it is logical to think that you can measure any property to any desired level of precision. For example, imagine measuring a ball's position during free fall. You might first try using a meterstick and a stopwatch to make the measurements. If you desire more precise measurements, you might use a video camera and a calculator or a computer. You can imagine using more and more sophisticated equipment to achieve ever greater precision. In fact, classical physics sets no limit on a measurement's precision. De Broglie's revolutionary theory of matter waves forced physicists to redefine the limits of measurement.

Heisenberg uncertainty principle Consider measuring the location of an atomic or subatomic scale particle by shining light on it and then collecting the reflected light in a measuring device. Because of diffraction, the reflected light you use to detect the particle spreads out and makes it impossible to locate the particle exactly. If more precise measurements are needed, you can use shorter-wavelength radiation, which decreases diffraction and decreases the uncertainty in the particle's location.

As a result of the Compton effect, however, when short-wavelength, high-energy radiation strikes a particle, the particle's momentum is changed, as shown in **Figure 12.** Therefore, the act of measuring the location of a particle has the effect of changing the particle's momentum. The more precise the determination of a particle's location, the greater the uncertainty is in its momentum. Similarly, if the momentum of the particle is precisely known, the position of the particle becomes less certain.



This situation is summarized by the **Heisenberg uncertainty principle,** which states there is a limit to how precisely a particle's position and momentum can simultaneously be measured. This principle, named for German physicist Werner Heisenberg, is the result of light and matter's dual wavelike and particlelike properties. Even though the effects of the limit are only noticeable when measuring atomic-scale particles, Heisenberg's work led to a fundamental change in our understanding of the world. While the classical theories of Newton and Maxwell are successful models of everyday objects, quantum theory and its models of the dual nature of light and matter are required to accurately describe objects on the atomic scale.

Figure 12 A collision between a photon and the electron is necessary to measure the electron's position. This collision scatters the electron and the photon, changing their momenta.

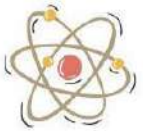
Compare *the photon wavelength before and after the collision. What does this change in wavelength indicate about the photon's energy?*

Check Your Progress

29. **Waves** Using De Broglie's theory, you can calculate the wavelength of any moving particle. Explain why the wave nature of everyday objects is not obvious.
30. **Wavelength** What is the de Broglie wavelength of an alpha particle (helium nucleus) with mass 6.6×10^{-27} kg and speed 120 m/s?
31. **de Broglie Wavelength** What is the de Broglie wavelength of an electron accelerated through a potential difference of 125 V?
32. **Critical Thinking** How does the Heisenberg uncertainty principle explain double-slit interference patterns even if photons or atoms pass through the slits one at a time?

LEARNSMART Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

11	•-State Heisenberg's uncertainty principle. •-Describe the limitation on simultaneously measuring a particle's position and momentum.	Student Textbook Check Your Progress 32	61 61



Check Your Progress 32 · p. 61

32. **Critical Thinking** How does the Heisenberg uncertainty principle explain double-slit interference patterns even if photons or atoms pass through the slits one at a time?

12	•-Describe electron distribution according to Thomson's model and how Rutherford's alpha-particle scattering experiment led to the nuclear model. •-Explain why Rutherford's planetary model cannot explain atomic stability and observed line-emission spectra.	Student Textbook Check Your Progress 41	62-63 74

MINISTRY OF EDUCATION

Student Textbook · p. 62

LESSON 3

BOHR'S MODEL OF THE ATOM

FOCUS QUESTIONS

How were atoms and their structure discovered?

The Nuclear Model

By the end of the 1800s, most scientists agreed that atoms exist. J.J. Thomson's discovery of the electron provided evidence that the atom must be made of even smaller, subatomic particles. But atoms were known to be much more massive than the total mass of the electrons, so scientists wondered where the mass was located. Moreover, atoms were known to be electrically neutral. How were the negatively charged electrons arranged? What made the atoms neutral?

Testing Thomson's model J.J. Thomson proposed that the electrons were distributed throughout a positively charged substance like raisins in a muffin. Ernest Rutherford, along with laboratory collaborators Hans Geiger and Ernest Marsden, however, performed a series of experiments that showed the atom had a very different structure. **Figure 13** shows the equipment Rutherford used to investigate the distribution of mass and charge in the atom.

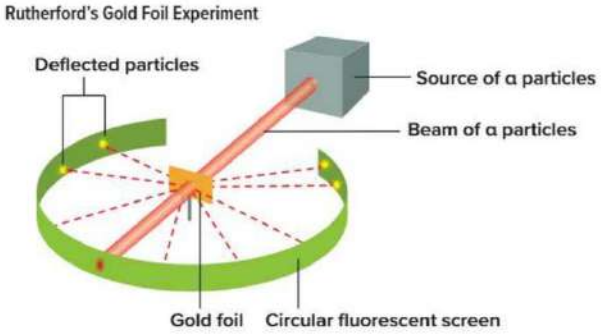


Figure 13 Bombarding metal foil with alpha particles convinced Rutherford's team that most of the atom's mass was concentrated in a small volume in the atom's center.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

PhysicsLAB: Emission Spectra

Analyze data from the emission specta produced by various gases to identify their elemental composition.

PhysicsLAB: Finding the Size of an Atom

Use a large-scale model to determine the size of an atom.

12	•-Describe electron distribution according to Thomson's model and how Rutherford's alpha-particle scattering experiment led to the nuclear model. •-Explain why Rutherford's planetary model cannot explain atomic stability and observed line-emission spectra.	Student Textbook Check Your Progress 41	62-63 74

MINISTRY OF EDUCATION

Student Textbook · p. 63

Rutherford's investigation Rutherford made use of substances that emitted penetrating rays. Some of these emissions, later named **alpha particles,** were known to be massive, positively charged particles that move at high speeds. Alpha particles are represented by the symbol α. The α-particles in Rutherford's experiments could be detected by the small flashes of light produced when the particles collided with a zinc-sulfide-coated screen.

As shown in **Figure 13,** Rutherford directed a beam of α-particles at an extremely thin sheet of gold foil. Rutherford was aware of Thomson's model of the atom, and he expected only minor deflections of the α-particles as they passed through the thin gold foil. He hypothesized that the paths of the massive, high-speed α-particles would be only slightly altered as they passed through the evenly distributed positive charge making up each gold atom. The test results amazed him. While most of the α-particles passed through the gold foil either undeflected or only slightly deflected, a few of the particles were scattered through very large angles. Some even rebounded through angles larger than 90°. **Figure 14** shows a diagram of these results. Rutherford compared his amazement to that of firing a 15-inch cannon shell at tissue paper and then having the shell bounce back and hit him.

Get It?
Explain why Rutherford was so surprised by the results of the gold foil experiment.

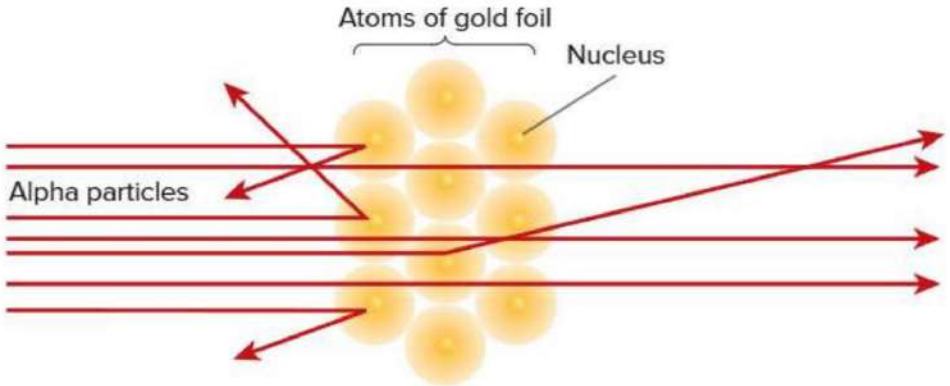


Figure 14 In Rutherford's investigation, most of the alpha particles directed at the thin sheet of gold foil passed through it without deflection. One in 20,000, however, was deflected at a large angle.

Rutherford's revised model of the atom Using Coulomb's law for the force between charged objects and Newton's laws of motion, Rutherford concluded that the results could be explained if all of an atom's positive charge were concentrated in a tiny, massive core, which is now called the **nucleus.** Therefore, Rutherford's model of the atom is called a nuclear model. Researchers have since determined that all the positive charge and more than 99.9 percent of an atom's mass are contained in its nucleus. The electrons do not contribute a significant amount of mass to the atom and are distributed through a large volume that stretches far away from the nucleus. The volume occupied by the electrons defines the overall size, or diameter, of the atom, which is about 50,000 times larger than the diameter of the nucleus. An atom is mostly empty space.

12	•-Describe electron distribution according to Thomson's model and how Rutherford's alpha-particle scattering experiment led to the nuclear model. •-Explain why Rutherford's planetary model cannot explain atomic stability and observed line-emission spectra.	Student Textbook Check Your Progress 41	62-63 74

MINISTRY OF EDUCATION

Check Your Progress 41 · p. 74

41. **Rutherford's Nuclear Model** Summarize the structure of the atom according to Rutherford's nuclear model.

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74

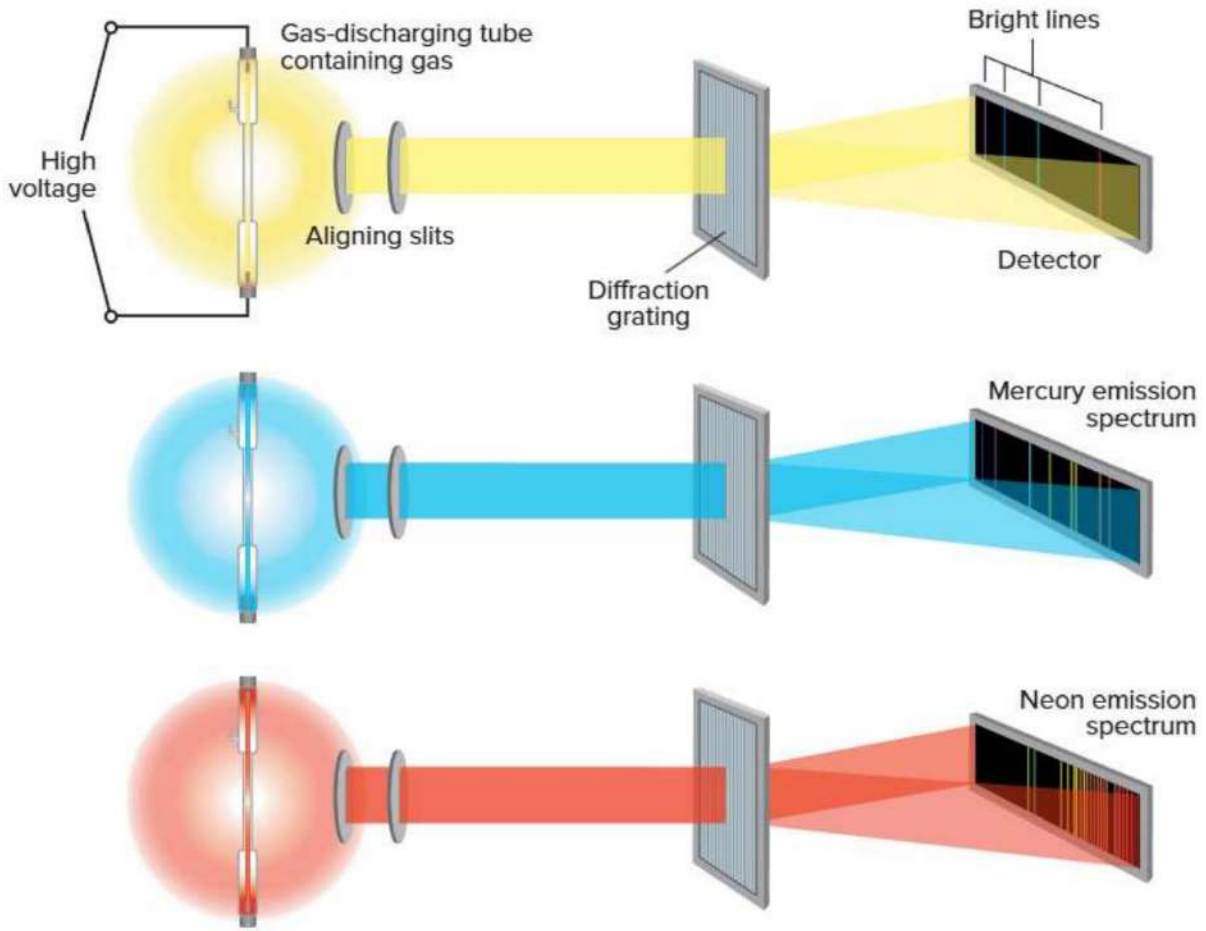
Student Textbook · p. 64

Emission spectra How are the electrons arranged in the atom? One of the clues scientists used to answer this question came from the study of the light emitted by atoms. As shown in **Figure 15,** atoms of a gaseous sample can be made to emit light in a gas-discharge tube. You probably are familiar with the colorful neon signs used by some businesses. These signs work on the same principles as gas-discharge tubes. A gas-discharge tube consists of a low-pressure gas contained within a glass tube that has electrodes attached to each end. The gas glows when a large potential difference is applied across the tube. What interested scientists the most about this phenomenon was the fact that each different gas glowed with a unique color. The characteristic glows emitted by two gases are shown in **Figure 15.**

When the light emitted by the gas is passed through a diffraction grating or a prism, an emission spectrum is obtained that is a fingerprint of each element in the gas. An emission spectrum can be studied in greater detail using an instrument called a spectroscope. As shown in **Figure 15,** light in a diffraction spectroscope passes through a slit and is diffracted through a diffraction grating. The spectroscope forms an image of the slit at a different position for each wavelength.

As you may have read in an earlier lesson, the spectrum of an incandescent solid, such as a lightbulb filament, is a continuous band of colors from red through violet. The spectrum of a gas, however, is a series of distinct lines of different colors. The bright-line emission spectra for mercury and neon are shown in the bottom portion of **Figure 15.** Each colored line corresponds to a particular wavelength of light emitted by the atoms of that gas.

Figure 15 An element's emission spectrum is a unique pattern that can be used to identify an unknown sample.



13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74

Student Textbook · p. 65

Identifying unknown samples An emission spectrum is a useful analytic tool that can be used to identify an unknown sample of gas. When an unknown gas is placed in a gas-discharge tube, it can be made to emit light. The emitted light includes combinations of wavelengths that are uniquely characteristic of the atoms of that gas. Thus, the unknown gas can be identified by comparing its wavelengths with the wavelengths measured in the spectra of known gas samples.

When the emission spectrum of a combination of elements is photographed, an analysis of the lines on the photograph can indicate the identities and the relative concentrations of the elements present. The elements that are present in the greatest concentrations produce emission lines of greater relative intensities. Through a comparison of the line intensities, the percentage composition of the gaseous material can be determined. This type of analysis is used daily to solve problems in chemistry, engineering, medicine, and environmental science.

Get It?

Explain how an emission spectrum can help to identify the composition and concentrations of elements in a sample.

Absorption spectra **Figure 16** illustrates another technique used to identify unknown samples. Passing white light through a gas sample and then through a prism results in the normally continuous spectrum of white light, but with dark lines in it corresponding to wavelengths of light absorbed by the gas. The set of wavelengths absorbed by a gas is the **absorption spectrum** of the gas. For a gas, the bright lines of the emission spectrum and the dark lines of the absorption spectrum occur at the same wavelengths, as shown in the bottom portion of **Figure 16.** Thus, cool, gaseous elements absorb the same wavelengths that they emit when excited. The composition of a gas can be determined from the wavelengths of the dark lines of the gas's absorption spectrum.

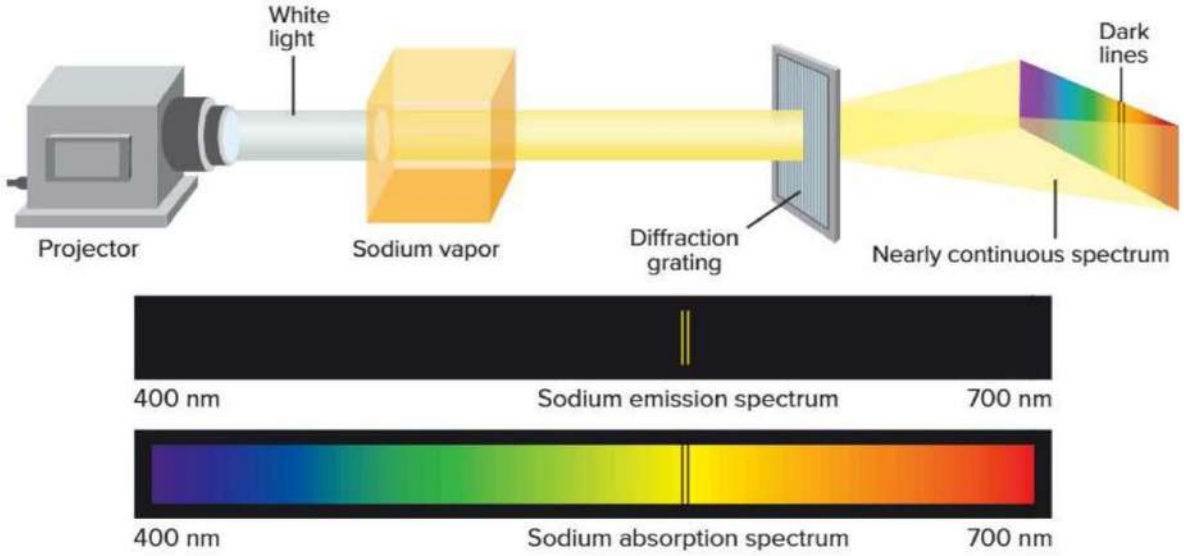


Figure 16 Passing white light through a sample of gas and a prism produces a nearly continuous spectrum. The dark lines missing from the spectrum are the wavelengths absorbed by the gas. Much like emission spectra, absorption spectra can be used to identify unknown samples.

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74

Student Textbook · p. 66

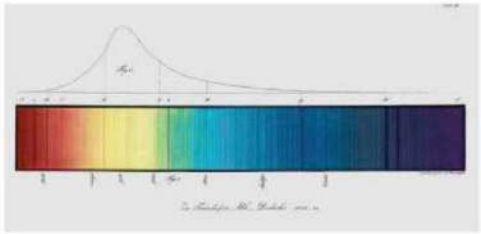


Figure 17 The Sun's absorption spectrum shows characteristic Fraunhofer lines for the elements in the Sun's atmosphere. There are many lines, some of which are faint and others that are very dark, depending on abundance of the elements in the Sun.

ASTRONOMY Connection In 1814 Josef von Fraunhofer observed the presence of several dark lines in the spectrum of sunlight. These dark lines, now called Fraunhofer lines, are seen in **Figure 17.** He reasoned that as sunlight passed through the gaseous atmosphere surrounding the Sun, the gases absorbed certain characteristic wavelengths. These absorbed wavelengths produced the dark lines in the observed spectrum. The composition of the Sun's atmosphere was determined by comparing the missing lines in the observed spectrum with the known emission spectra of various elements. The Sun was found to be mostly hydrogen and helium. The compositions of many other stars have been determined using this technique.

Get It?

Describe how scientists are able to determine the composition of stars.

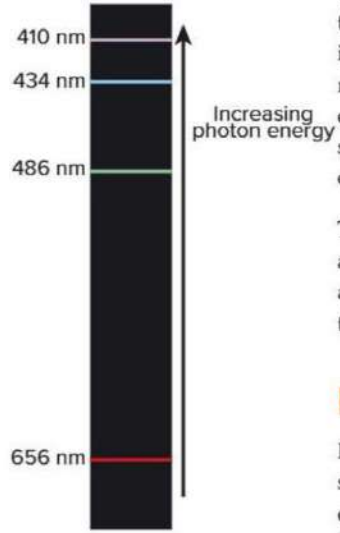


Figure 18 Hydrogen's emission spectrum has four lines in the visible range.

Compare *the difference between adjacent wavelengths of light as the energy increases.*

Spectroscopy As a result of the elements' characteristic spectra, scientists are able to analyze, identify, and quantify unknown materials by observing the spectra that they emit or absorb. The emission and absorption spectra of elements are important in industry as well as in scientific research. For example, steel mills reprocess large quantities of scrap iron of varying compositions. The exact composition of a sample of scrap iron can be determined in minutes by spectrographic analysis. The composition of the steel can then be adjusted to suit commercial specifications.

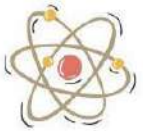
The study of spectra is a branch of science known as spectroscopy. Spectroscopists are employed in research and industrial settings. Spectroscopy is an effective tool for analyzing materials on Earth, and it is the only currently available tool for studying the composition of stars over the vast expanse of space.

Revising Rutherford's Nuclear Model

In the nineteenth century, many physicists studied atomic spectra to determine the structure of the atom. Hydrogen was studied extensively because it is the lightest element and has the simplest spectrum. The visible spectrum of hydrogen consists of four lines: red, green, blue, and violet, as shown in **Figure 18.** Any theory that explained the structure of the atom would have to account for these wavelengths, as well as support the nuclear model of the atom. The nuclear model as proposed by Rutherford was not without its problems, however. Rutherford had suggested that electrons orbit the nucleus much like the planets orbit the Sun. There was, however, a serious flaw in this planetary model.

B Ventures/SuperStock/Alamy Stock Photo

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74



Get It? · p. 65



Get It?

Explain how an emission spectrum can help to identify the composition and concentrations of elements in a sample.

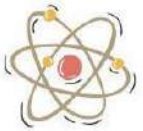
13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74

Get It? · p. 66

Get It?

Describe how scientists are able to determine the composition of stars.

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74



Check Your Progress 40 · p. 74

40. **Photon Absorption** Explain how energy is conserved when an atom absorbs a photon of light.

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74

Check Your Progress 42 · p. 74

42. **Absorption Spectrum** The absorption spectrum for a sample of hydrogen gas is shown in **Figure 24.** Explain how the absorption spectrum of a gas can be determined. Describe the reasons for the spectrum's appearance.

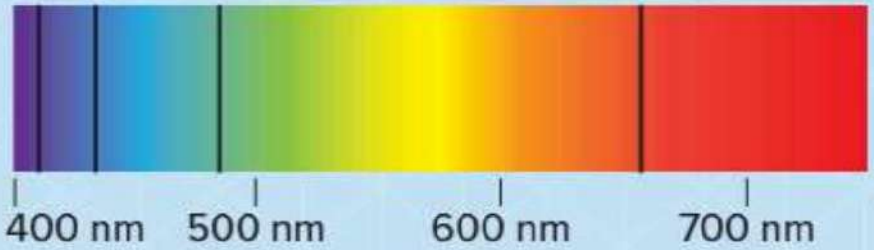
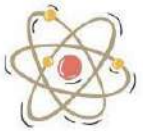


Figure 24

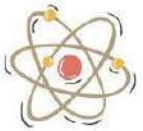
13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74



Check Your Progress 43 · p. 74

43. **Spectra** How do the emission spectra of incandescent solids and atomic gases differ? In what ways are they similar?

13	•-Describe emission from gas-discharge sources and the use of a spectroscope. •-Distinguish continuous emission spectra from discrete line spectra. •-Explain how emission and absorption spectra act as unique fingerprints and can identify unknown samples.	Student Textbook Get it Check Your Progress 40,42,43, 44	64-66 65, 66 74



Check Your Progress 44 · p. 74

44. **Orbit Radius** A helium ion behaves like a hydrogen atom. The radius of the ion's lowest energy level is 0.0265 nm. According to Bohr's model, what is the radius of the second energy level?

14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74

Student Textbook · p. 67

Problems with the planetary model An electron in an orbit constantly accelerates toward the nucleus. From previous study, you know that accelerating electrons radiate energy by emitting electromagnetic waves. At the rate that an orbiting electron would lose energy, it should spiral into the nucleus within a fraction of a second. But we know that atoms are stable, so the planetary model does not agree with the laws of electromagnetism. In addition, the planetary model predicted that the accelerating electrons would radiate energy at all wavelengths. However, as you just read, the light emitted by atoms is radiated only at specific wavelengths.

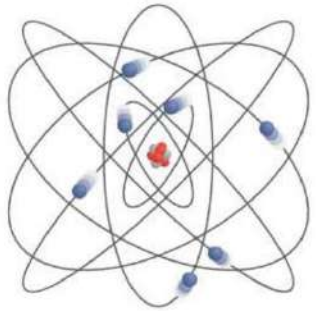


Figure 19 The planetary model of the atom stated electrons move in fixed orbits around the nucleus.

Danish physicist Niels Bohr went to England in 1911 and joined Rutherford's group to work on determining the structure of the atom. He tried to unite the nuclear model of the atom with Planck's quantized energy levels and Einstein's theory of light. This was a courageous idea, because in 1911, neither of these revolutionary ideas was widely understood or accepted.

Quantized Energy

Bohr began with the planetary arrangement of electrons, as diagrammed in **Figure 19**, but then he proposed that the laws of electromagnetism do not apply inside the atom. He postulated that an electron in a stable orbit in an atom does not radiate energy, even though it is accelerating. Bohr referred to this stable condition as a stationary state. He went on to assume that each of the stationary states has its own specific amount of energy. In other words, Bohr considered the energy levels in an atom to be quantized.

As shown in **Figure 20**, the quantization of energies of electrons in atoms can be likened to a flight of stairs with decreasing-height steps. To go up the stairs you must move from one step to the next—it is impossible to stop at a midpoint between steps. Instead of steps, the electrons have quantized amounts of energy, each of which is called an **energy level.** Just as you cannot occupy a position between steps, an electron's energy cannot have a value between allowed energy levels. An atom with the smallest allowable amount of energy is said to be in the **ground state.** When such an atom absorbs energy, one or more of its electrons move to higher energy levels. Any energy level above the ground state is called an **excited state.**

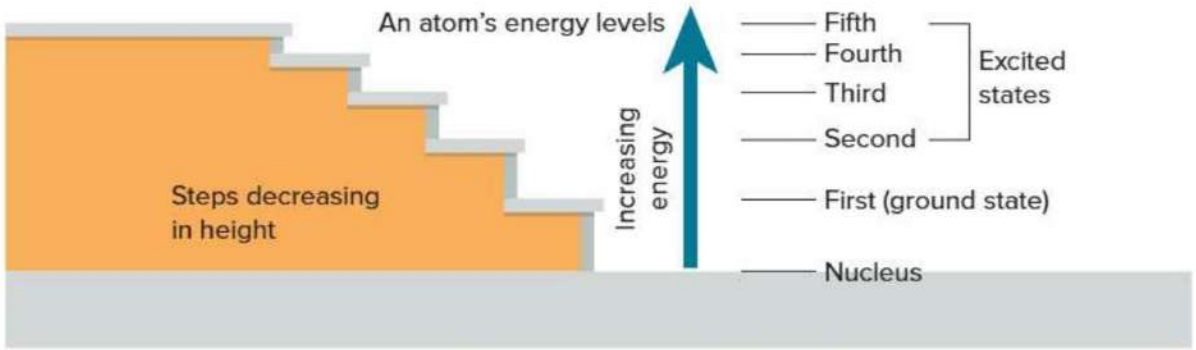


Figure 20 The allowed energy levels in an atom can be compared to a set of stairs. Note how the difference in energy between adjacent energy levels decreases as the energy level increases.

14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74

Student Textbook · p. 68

Energy of an atom What determines the amount of energy an atom has? An atom's energy equals the sum of the kinetic energy of the electrons and the potential energy from the attractive force between the electrons and the nucleus. The energy of an atom with electrons in a nearby orbit is less than that of an atom with electrons in a faraway orbit because work must be done to move the electrons away from the nucleus. Thus, atoms in excited, higher-energy states have electrons in larger, more distant, orbits. Because energy is quantized and energy is related to the size of the orbit, the size of the orbit also is quantized. This model of an atom, that of a central nucleus with orbiting electrons having specific quantized energy levels, is the Bohr model of the atom.

If Bohr was correct in hypothesizing that stable atoms do not radiate energy, then what is responsible for an atom's characteristic emission spectrum? To answer this question, Bohr suggested that electromagnetic energy is emitted when the atom changes from one state to another. Incorporating Einstein's photoelectric theory, Bohr knew that the energy of every photon is given by the equation $E_{photon} = hf$. He then postulated that when an atom absorbs a photon, the atom's energy increases by an amount equal to that of the photon. When this excited atom makes a transition to a lower energy level, it emits a photon.

When the atom makes the transition from its initial energy level (E_i) to its final energy level (E_f) the change in energy (ΔE_{atom}) is given by the following equation:

$$\Delta E_{atom} = E_f - E_i.$$

As shown in **Figure 21**, the amount by which the energy of the atom decreases equals the energy of the emitted photon.

$$E_{photon} = -\Delta E_{atom} = E_i - E_f$$

The following equations summarize the relationships between the change in an atom's energy levels and the emitted photon's energy.

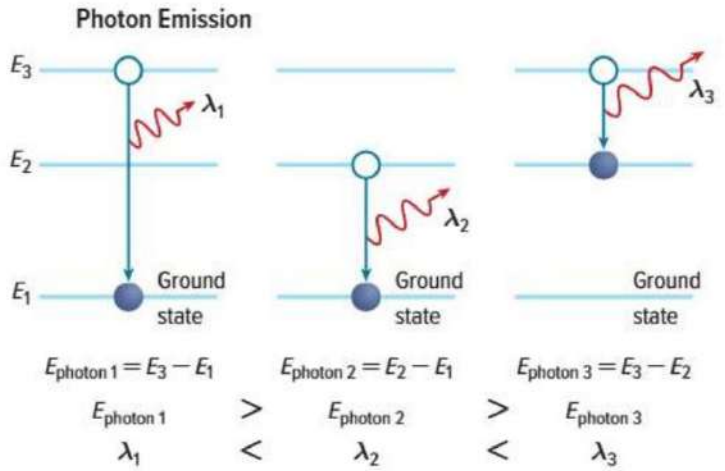
Energy of an Emitted Photon

The energy of an emitted photon equals the product of Planck's constant and the emitted photon's frequency. The energy of an emitted photon also is equal to the decrease in the atom's energy.

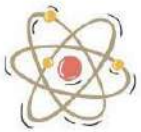
$$E_{photon} = hf = -\Delta E_{atom}$$

Figure 21 An emitted photon's energy is equal to the amount by which the energy of the atom decreases.

Identify *the transition that produces the photon with the greatest energy.*



14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74



Student Textbook · p. 69

Predictions of the Bohr Model

A scientific theory must do more than present postulates; it must allow predictions to be made that can be checked against experimental data. A good theory also can be applied to many different problems, and it ultimately provides a simple, unified explanation of some part of the physical world. Bohr used his theory to calculate the wavelengths of light emitted by a hydrogen atom. The calculations were in excellent agreement with the values measured by other scientists. As a result of this agreement between Bohr's predictions and the measured values, Bohr's model was widely accepted.

Unfortunately, the model only worked for the element hydrogen; it could not predict the spectrum of helium, the next-simplest element. In addition, there was not a good explanation as to why the laws of electromagnetism should work everywhere but inside the atom.

Development of Bohr's model Bohr developed his model by applying Newton's second law of motion ($F_{net} = ma$) to the electron. The net force is described by Coulomb's law for the interaction between an electron of charge −e that is a distance r from a proton of charge +e. That force is given by the following equation:

$$F = \frac{-Ke^2}{r^2}$$

The acceleration of the electron in a circular orbit about a much more massive proton is given by $a = -\frac{v^2}{r}$, where the negative sign shows that the direction is inward. Thus, Bohr obtained the following relationship:

$$\frac{Ke^2}{r^2} = \frac{m_e v^2}{r}$$

Solving this equation for r gives the following relationship:

$$r = \frac{Ke^2}{m_e v^2}$$

In the equation, K, the Coulomb's law constant, is $9.0\times10^9\ N\cdot m^2/C^2$.

Next, Bohr considered the angular momentum of the orbiting electron, which is equal to the product of an electron's momentum and the radius of its circular orbit. The angular momentum of the electron is thus mvr. Bohr postulated that angular momentum also is quantized; that is, an electron's angular momentum can have only certain values. Using n to represent an integer, Bohr proposed that the electron's angular momentum equaled an integer multiple of $\frac{h}{2\pi}$, where h is Planck's constant.

$$m_e v r = \frac{nh}{2\pi}$$

Rearranging the above equation to solve for v yields the following:

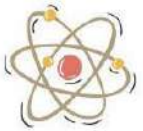
$$v = \frac{nh}{2\pi m_e r}$$

Using this relationship for velocity and the equation for a hydrogen atom's radius given above, Bohr found that the orbital radii of the electrons in a hydrogen atom are given by the following equation.

Electron Orbital Radius in Hydrogen

$$r_n = \frac{h^2 n^2}{4\pi^2 K m_e e^2}$$

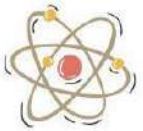
14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74



Practice Problem 33 · p. 72

33. Calculate the energies of the second, third, and fourth energy levels in the hydrogen atom.

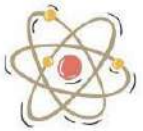
14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74



Practice Problem 35 · p. 72

35. Calculate the energy difference between E_4 and E_2 in the hydrogen atom.

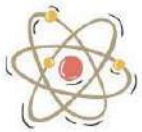
14	•-Describe Bohr's model: stationary states, quantized energy levels, ground state, and excited states. •-Explain absorption or emission of a photon during transitions between energy levels and describe key limitations of the Bohr model.	Student Textbook Practice Problems 33, 35 Check Your Progress 45	67-69 72 74



Check Your Progress 45 · p. 74

45. **Bohr Model** Hydrogen has been detected transitioning from the 101st to the 100th energy levels. What is the radiation's wavelength? Where in the electromagnetic spectrum is this emission?

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74



Student Textbook · p. 69

Predictions of the Bohr Model

A scientific theory must do more than present postulates; it must allow predictions to be made that can be checked against experimental data. A good theory also can be applied to many different problems, and it ultimately provides a simple, unified explanation of some part of the physical world. Bohr used his theory to calculate the wavelengths of light emitted by a hydrogen atom. The calculations were in excellent agreement with the values measured by other scientists. As a result of this agreement between Bohr's predictions and the measured values, Bohr's model was widely accepted.

Unfortunately, the model only worked for the element hydrogen; it could not predict the spectrum of helium, the next-simplest element. In addition, there was not a good explanation as to why the laws of electromagnetism should work everywhere but inside the atom.

Development of Bohr's model Bohr developed his model by applying Newton's second law of motion ($F_{net} = ma$) to the electron. The net force is described by Coulomb's law for the interaction between an electron of charge −e that is a distance r from a proton of charge +e. That force is given by the following equation:

$$F = \frac{-Ke^2}{r^2}$$

The acceleration of the electron in a circular orbit about a much more massive proton is given by $a = -\frac{v^2}{r}$, where the negative sign shows that the direction is inward. Thus, Bohr obtained the following relationship:

$$\frac{Ke^2}{r^2} = \frac{m_e v^2}{r}$$

Solving this equation for r gives the following relationship:

$$r = \frac{Ke^2}{m_e v^2}$$

In the equation, K, the Coulomb's law constant, is $9.0\times10^9\ N\cdot m^2/C^2$.

Next, Bohr considered the angular momentum of the orbiting electron, which is equal to the product of an electron's momentum and the radius of its circular orbit. The angular momentum of the electron is thus mvr. Bohr postulated that angular momentum also is quantized; that is, an electron's angular momentum can have only certain values. Using n to represent an integer, Bohr proposed that the electron's angular momentum equaled an integer multiple of $\frac{h}{2\pi}$, where h is Planck's constant.

$$m_e v r = \frac{nh}{2\pi}$$

Rearranging the above equation to solve for v yields the following:

$$v = \frac{nh}{2\pi m_e r}$$

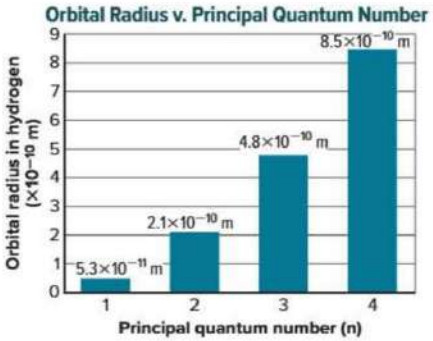
Using this relationship for velocity and the equation for a hydrogen atom's radius given above, Bohr found that the orbital radii of the electrons in a hydrogen atom are given by the following equation.

Electron Orbital Radius in Hydrogen

$$r_n = \frac{h^2 n^2}{4\pi^2 K m_e e^2}$$

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74

Student Textbook · p. 70



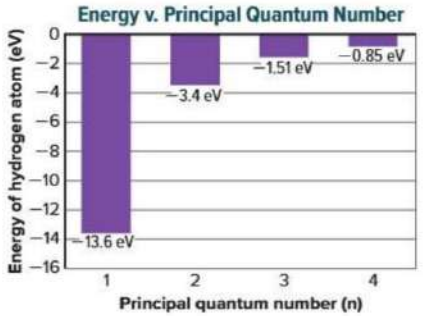


Figure 22 The radius of the hydrogen atom increases as n^2. The energy of the hydrogen atom increases from a minimum of −13.6 eV when $n = 1$ (the ground state) to values closer to 0 eV as n increases.

Calculating orbital radius You can calculate the radius of the innermost orbit of a hydrogen atom, also known as the Bohr radius, by substituting known values and $n = 1$ into the equation for electron orbital radius on the previous page.

$$r_1 = \frac{(6.63\times10^{-34}\ \text{J·s})^2\ (1)^2}{4\pi^2(9.0\times10^9\ \text{N·m}^2/\text{C}^2)(9.11\times10^{-31}\ \text{kg})(1.6\times10^{-19}\ \text{C})^2}$$

$$= 5.3\times10^{-11}\ \text{J}^2\text{·s}^2/(\text{N·m}^2\text{·kg})$$

$$= 5.3\times10^{-11}\ \text{m, or } 0.053\ \text{nm}$$

By performing a little more algebra, you can show that the total energy of the atom, which is the sum of the kinetic energy of the electron and the potential energy, and is given by $\frac{-Ke^2}{2r}$, is represented by the following equation:

$$E_n = \frac{-2\pi^2K^2m_e e^4}{h^2} \times \frac{1}{n^2}$$

By substituting numerical values for the constants, you can calculate the total energy of the atom in joules, which yields the following equation:

$$E_n = -2.17\times10^{-18}\ \text{J} \times \frac{1}{n^2}$$

Converting the relationship to units of electron volts ($1\ \text{eV} = 1.6\times10^{-19}\ \text{J}$) yields the following equation.

Energy of a Hydrogen Atom

The total energy of an atom with principal quantum number n is equal to the product of −13.6 eV and the inverse of n^2.

$$E_n = -13.6\ \text{eV} \times \frac{1}{n^2}$$

You previously read that the electron's orbital radius is quantized. The equation above shows that the energy of the atom is quantized as well. The integer (n) that appears in the equations for hydrogen's energy and electron orbital radius is called the **principal quantum number.** The principal quantum number determines the quantized values of r and E.

Figure 22 summarizes these relationships for the first four values of n. The graph at the top of the figure shows that the electron's orbital radius (r) increases as the square of n. The graph at the bottom of the figure shows that the energy (E) of the hydrogen atom depends on $\frac{1}{n^2}$. As the magnitude of the atom's energy decreases, the electron's orbital radius increases.

Get It?

Describe how the orbital radius and the energy depend on the principal quantum number.

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74

Student Textbook · p. 71

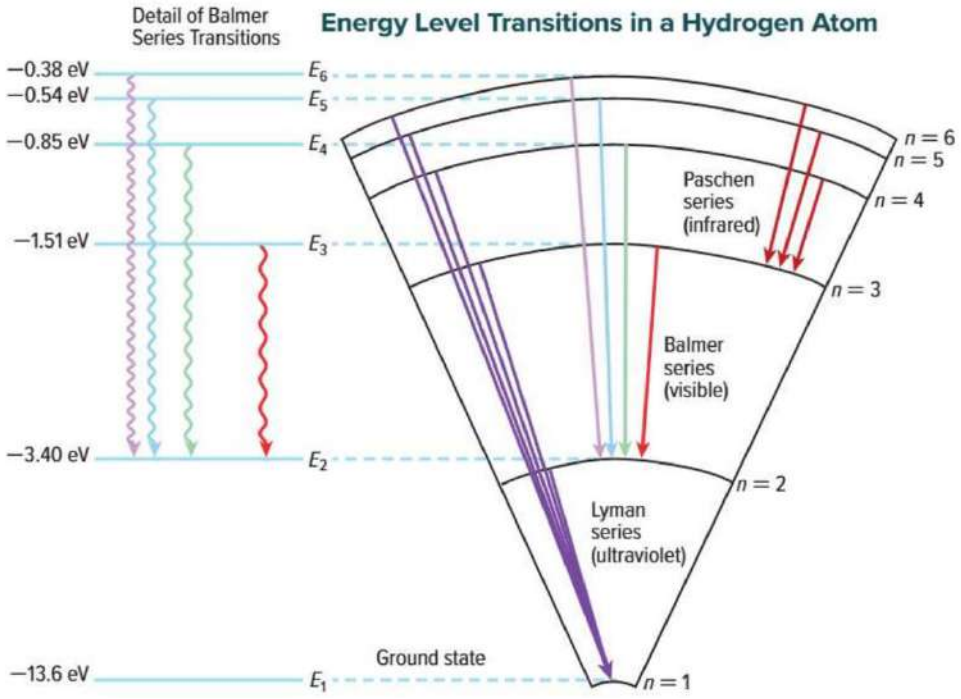


Figure 23 A hydrogen atom emits visible light when electrons transition from higher energy levels to the $n = 2$ energy level. Transitions to other energy levels result in emission of ultraviolet and infrared electromagnetic energy.

Nucleus

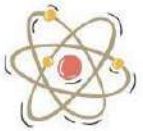
Energy and electron transitions You may be wondering why the energy of an atom in the Bohr model has a negative value. Recall from your study of energy that only energy differences affect the motion of objects. The zero energy level can be chosen at will. In this case, zero energy is defined as the energy of the atom when the electron is infinitely far from the nucleus and has no kinetic energy. This condition exists when the atom has been ionized; that is, when the electron has been removed from the atom. Because work has to be done to ionize an atom, the total energy of an atom that has an orbiting electron is less than zero. When an atom makes a transition from a lower to a higher energy level, the total energy becomes less negative, but the overall energy change is positive.

Some of hydrogen's energy levels and the possible energy level transitions that it can undergo are shown in **Figure 23.** Note that an excited hydrogen atom can emit electromagnetic energy in the infrared, visible, or ultraviolet range, depending on the transition that occurs. Ultraviolet light is emitted when the atom drops into its ground state from any excited state. The four visible lines in the hydrogen spectrum are produced when the atom drops from the $n = 3$ or higher energy state into the $n = 2$ energy state.

Get It?

Describe the electron transitions that result in the visible lines in the hydrogen emission spectrum.

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74



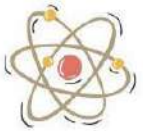
Get It? · p. 70



Get It?

Describe how the orbital radius and the energy depend on the principal quantum number.

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74



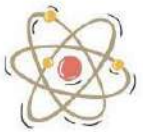
Get It? · p. 71



Get It?

Describe the electron transitions that result in the visible lines in the hydrogen emission spectrum.

15	•Describe quantized orbital radii and total energies in the Hydrogen atom and their dependence on principal quantum number n. •-Explain the zero-energy reference and negative bound-state energy. •-Distinguish the Lyman, Balmer, and Paschen spectral series.	Student Textbook Get it Check Your Progress 46	69-71 70,71 74



Check Your Progress 46 · p. 74

46. **Critical Thinking** The nucleus of a hydrogen atom has a radius of about 1.5×10^{-15} m. If you were to build a model of the hydrogen atom using a softball ($r = 5$ cm) to represent the nucleus, where would you locate an electron in the $n = 1$ Bohr orbit? Would it be in your classroom?

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

Student Textbook · p. 75

LESSON 4

THE QUANTUM MODEL OF THE ATOM

FOCUS QUESTION

How do lasers work?

From Orbits to an Electron Cloud

Bohr's model of quantized electron orbits could not correctly predict electron energies for atoms with more than one electron. Recall that de Broglie proposed that particles have wave properties. The de Broglie wavelength of a particle with momentum mv is $\lambda = \frac{h}{mv}$, and the angular momentum is $mvr = \frac{hr}{\lambda}$. Thus, Bohr's required quantized angular-momentum condition, $mvr = \frac{nh}{2\pi}$, can be written $\frac{hr}{\lambda} = \frac{nh}{2\pi}$ or $2\pi r = n\lambda$.

Figure 25 illustrates this relationship that the circumference of the Bohr orbit ($2\pi r$) must be equal to a whole number multiple (n) of de Broglie wavelengths (λ).

de Broglie Waves

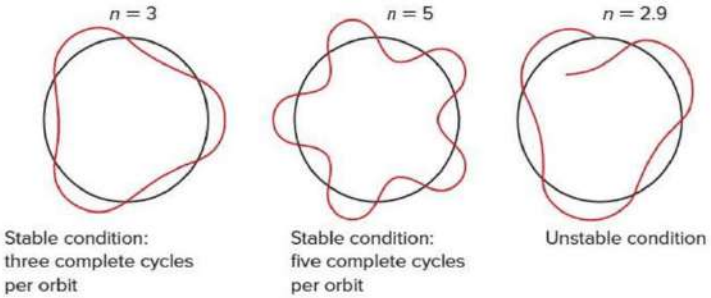


Figure 25 In the Bohr model of the atom, stable electron orbits around the nucleus must have a circumference equal to a whole-number multiple (n) of the de Broglie wavelengths.

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Communicate Information About Multiple Technologies

HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

Student Textbook · p. 76

In 1926, Austrian physicist Erwin Schrödinger extended de Broglie's wave model to create a quantum theory of particles, such as electrons, based on waves. However, the electron itself is not a wave. The wave describes the probability of finding an electron in a particular location or having a particular momentum or energy.

Uncertainty principle applied to atomic theory Heisenberg proposed that it is impossible to measure exactly both the position and momentum of a particle at the same time. You can only know them approximately. Building on Heisenberg's ideas, the modern **quantum model** of the atom predicts only the probability that an electron is in a specific region. The quantum model predicts that the most probable distance between the electron and the nucleus for a hydrogen atom equals the radius predicted by the Bohr model.

The probability of the electron being at any specific radius can be calculated, and a three-dimensional plot will then show regions of equal probability. The region in which there is a high probability of finding the electron is called the **electron cloud.** **Figure 26** shows a slice through the electron cloud for the two lowest energy states of a hydrogen atom.

Get It?
Explain the meaning of the electron cloud.

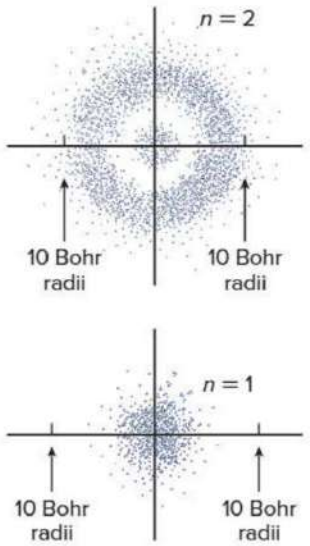


Figure 26 The density of dots in these plots corresponds to the probability of finding the electron in a hydrogen atom in the first and second energy levels.

Even though the quantum model of the atom is difficult to visualize, it was an early success in the development of **quantum mechanics,** the study of the wave properties of matter. Quantum mechanics is a useful tool for physicists, chemists, biologists, and engineers. It has been used to develop new chemicals, new computer chips, new solar power cells, and new medicines. Quantum mechanics also helped analyze the details of atoms' emission and absorption of light, leading to the development of a new type of light source.

Lasers

Most of the light you see is a jumble of uncoordinated waves having many different wavelengths. It is like music from a choir in which every member is singing a different song. As you know, light emitted by an incandescent source such as a filament lightbulb has a continuum of wavelengths, whereas light produced by an atomic gas consists of only a few distinct wavelengths. Light from each of these sources travels in all directions. The waves are not necessarily all at the same point in their cycle at the same time. Such out-of-step light waves are called incoherent light. Waves that are in phase are said to be coherent. Light waves that are coherent are referred to as coherent light. Both types of light waves are shown in **Figure 27.**

Light is emitted by atoms that move from a higher energy state to a lower energy state. So far, you have learned two ways in which atoms can be excited to the higher energy state: thermal excitation and electron collision. In a third process, a photon with exactly the right energy can collide with an atom and excite it. In a laser this process can produce intense, coherent light.

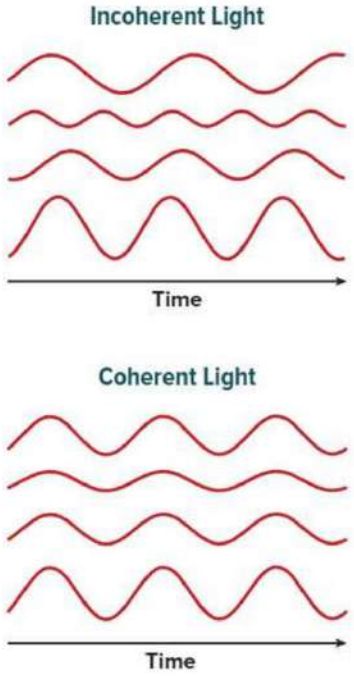


Figure 27 Coherent light is in phase when each wave is at the same point in its cycle at the same time.

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

Student Textbook · p. 77

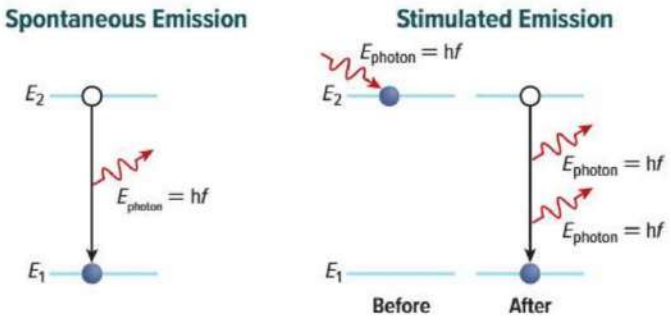


Figure 28 Spontaneous emission occurs when an electron in an atom drops from an excited state to the ground state, emitting a photon. During stimulated emission, an excited atom is struck by a photon with energy $E_2 - E_1$. The atom drops to the ground state and emits two photons. Both of these photons have the same energy: $E_{photon} = E_2 - E_1$.
Compare *the wavelengths of the incident and emitted photons.*

Spontaneous and stimulated emission What happens when an atom is in an excited state? After a very short time, it normally returns to the ground state, giving off a photon of the same energy that it absorbed, as shown in the left panel of **Figure 28.** This process is called spontaneous emission.

In 1917, Einstein considered what happens to an atom already in an excited state that is struck by a photon with an energy equal to the energy difference between the excited state and the ground state. He showed that the atom, by a process known as **stimulated emission,** returns to the ground state and emits a photon with an energy equal to the energy difference between the two states. The photon that caused, or stimulated, the emission is not affected. The two photons leaving the atom not only will have the same frequency, but they will be in step, or coherent, as shown in the right panel of **Figure 28.** Either of the two photons can now strike other excited atoms, thereby producing additional photons that are in step with the original photons. This process can continue and produce an avalanche of photons, all of the same wavelength and all in phase.

Get It?
Compare the two photons emitted by stimulated emission.

For this process to occur, certain conditions must be met. First, there must be other atoms in the excited state. Second, the atoms must remain in the excited state long enough to be struck by a photon. Third, the photons must be contained so that they are able to strike other excited atoms. In 1960, a device called a **laser** was invented that fulfilled all the conditions needed to produce coherent light. The word laser is an acronym that stands for light amplification by stimulated emission of radiation. An atom that emits light when it is stimulated in a laser is said to lase.

Atom excitation The atoms in a laser can be excited, or pumped. An intense flash of light with a wavelength shorter than that of the laser can be used to pump the atoms. The shorter-wavelength, higher-energy photons produced by the flash collide with and excite the lasing atoms. When one of the excited atoms decays to a lower energy state by emitting a photon, the avalanche of photons begins. This results in the emission of a brief flash, or pulse, of laser light. Alternatively, the lasing atoms can be excited by collisions with other atoms. In the helium-neon lasers often seen in science classrooms, an electric discharge excites the helium atoms. These excited helium atoms collide with the neon atoms, pumping them to an excited state and causing them to lase. The laser light resulting from this process is a continuous beam rather than pulsed flashes.

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

Student Textbook · p. 78

Lasing The lasing atoms and their emitted photons are contained within a chamber that has parallel mirrors at each end, one of which allows only about 1 percent of the light hitting it to pass through. Photons emitted toward the mirrors are reflected back into the gas where they strike more atoms that release more photons. Because all the stimulated photons are emitted in step with the photons that struck the atoms, laser light is coherent. The light may also be of one wavelength, or monochromatic. The parallel mirrors produce a highly directional, intense beam with a small diameter. The beam diverges very little and can be focused to a fine point. Finally, stimulated emission can be switched on and off to produce brief, high-power light pulses. These characteristics of laser light make it particularly well-suited to many different applications.

Laser Applications

If you have used a CD, DVD, or Blu-ray player, then you have used a laser. These lasers, as well as the ones used in laser pointers, are made of semiconducting solids. The laser in a CD player is made of layers of gallium arsenide (GaAs) and gallium aluminum arsenide (GaAlAs). The lasing layer is only 200-nm thick, and each side of the crystal is only 1–2 mm long. The atoms in the semiconducting solid are pumped by an electric current, and the resulting photons are amplified as they bounce between the polished ends of the crystal. Shorter wavelength laser beams, such as those used in the DVD player shown in **Figure 29,** can focus on smaller spots. This allows DVDs to store more data than CDs. Blu-ray players use even shorter wavelength lasers than DVD players so that they can store five times more data than DVDs. Because laser beams are narrow and highly directional, surveyors use them in applications such as checking the straightness of long tunnels and pipes. Lasers reflecting off mirrors left on the Moon are used to measure the distance from Earth to the Moon and to measure the movement of Earth's tectonic plates.



Figure 29 The laser used in this DVD player emits light with a wavelength of about 650 nm.

Get It?

Identify the characteristics of laser light that make it well-suited to use in surveying and in measuring large distances.

Because lasers can emit light bursts as brief as 10^{-15} s, they can be used to investigate very fast changes in the structures of atoms or molecules. Other scientists are trying to produce energy from high temperature plasmas using very large lasers that produce petawatt (10^{15} watts) pulses. **Table 2** on the next page summarizes several applications of lasers.

STEM CAREER Connection

Registered Nurse

Do you like helping people? Would you like to work with lasers? The connection between lasers and nursing might not be readily apparent, but lasers have many uses in improving the health and well-being of patients. Under a physician's supervision, registered nurses are able to use lasers to remove spider veins, unwanted hair, or an unwanted tattoo!

and Hutchings/Digital Light Source

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

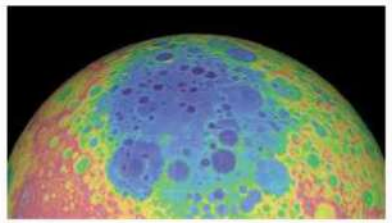
Student Textbook · p. 79

Table 2 Laser Applications



Fiber-Optic Communications

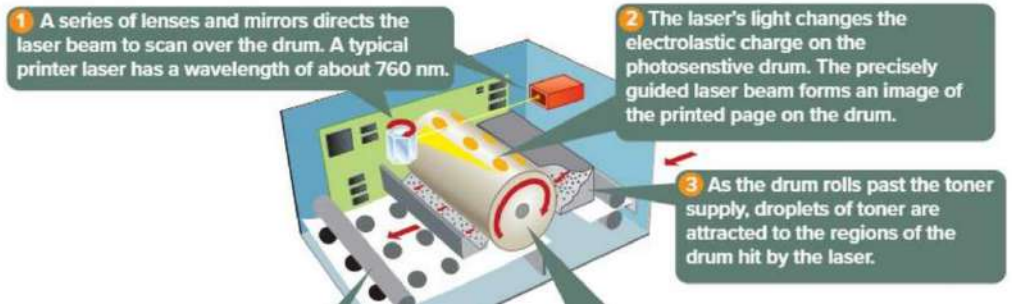
Laser light is commonly used in fiber-optic communications. This technology is based on an understanding of waves and their interactions with matter. A fiber optic cable uses total internal reflection to transmit light over long distances with little loss of signal energy. The laser is rapidly switched on and off, transmitting information as a series of pulses through the fiber. All over the world, optical fibers have replaced copper wires for the transmission of telephone calls, computer data, and television signals.



Lunar Research

The Lunar Reconnaissance Orbiter pointed a laser at the surface of the Moon and recorded the time required for the laser's light to bounce off the Moon's surface and return to the satellite. The data collected during this mission produced topographical maps accurate to within 10 cm. In addition to providing clues about the Moon's history, these maps can be used to select safe landing sites for future robotic and manned missions to the Moon.

Laser Printers



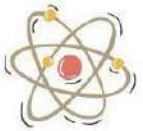
Check Your Progress

47. **Bohr Model Limitations** Although it was able to accurately predict the behavior of hydrogen, in what ways did Bohr's atomic model have serious shortcomings?
48. **Pumping Atoms** Explain whether green light could be used to pump a red laser. Why could red light not be used to pump a green laser?
49. **Laser Light** What are four characteristics of laser light that make it useful?
50. **Critical Thinking** Suppose an electron cloud were reduced to almost the size of the nucleus. Use the Heisenberg uncertainty principle to explain why this process would require adding a tremendous amount of energy.

LEARNSMART Go online to follow your personalized learning path to review, practice, and reinforce your understanding.

Photodisc/Getty Images; ©NASA/Goddard Space Flight Center Scientific Visualization Studio

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



Get It? · p. 76



Get It?

Explain the meaning of the electron cloud.

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79

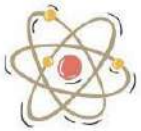
Get It? · p. 77



Get It?

Compare the two photons emitted by stimulated emission.

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



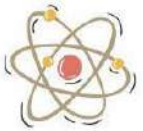
Get It? · p. 78



Get It?

Identify the characteristics of laser light that make it well-suited to use in surveying and in measuring large distances.

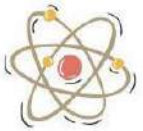
16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



Check Your Progress 47 · p. 79

47. **Bohr Model Limitations** Although it was able to accurately predict the behavior of hydrogen, in what ways did Bohr's atomic model have serious shortcomings?

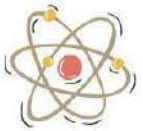
16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



Check Your Progress 48 · p. 79

48. **Pumping Atoms** Explain whether green light could be used to pump a red laser. Why could red light not be used to pump a green laser?

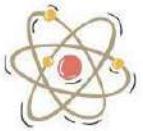
16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



Check Your Progress 49 · p. 79

49. **Laser Light** What are four characteristics of laser light that make it useful?

16	•Describe the quantum model using electron clouds, de Broglie wave-particle duality, and Heisenberg's uncertainty principle. •-Describe spontaneous and stimulated emission, coherent light, and the operation and applications of lasers.	Student Textbook Get it Check Your Progress 47-50	75-79 76-79 79



Check Your Progress 50 · p. 79

50. **Critical Thinking** Suppose an electron cloud were reduced to almost the size of the nucleus. Use the Heisenberg uncertainty principle to explain why this process would require adding a tremendous amount of energy.

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32

Student Textbook · p. 23

LESSON 3

CONSERVATION OF ENERGY

FOCUS QUESTION

Can energy be lost?

The Law of Conservation of Energy

The **law of conservation of energy** states that in a closed, isolated system, energy can neither be created nor destroyed. So, the total change of energy in any system is always equal to the total energy transferred into or out of the system. In other words, energy can be transported from one place to another, transferred between systems, and converted to different forms, such as thermal energy released to the surrounding environment from a running car. However, the system's total energy in all of its forms remains constant.

Within a system, energy is continually transferred from one object to another and between its various possible forms. Therefore, energy is considered a single quantity due to the law of conservation of energy.

Get It?

Explain whether the light from a battery-powered lamp can have more energy than the battery's energy.

Mechanical energy You often focus on the energy that comes from the motions of and interactions between objects. The sum of the *KE* and *PE* of the objects in a system is the system's **mechanical energy** (*ME*). The *KE* includes both the translational and rotational kinetic energies of the objects in the system. Potential energy includes the gravitational and elastic potential energies of the system. In any system, mechanical energy is represented as follows.

Mechanical Energy of a System

The mechanical energy of a system is equal to the sum of the *KE* and *PE* of the system's objects.

$$ME = KE + PE$$

3D THINKING DCI Disciplinary Core Ideas CCC Crosscutting Concepts SEP Science & Engineering Practices

COLLECT EVIDENCE

Use your Science Journal to record the evidence you collect as you complete the readings and activities in this lesson.

INVESTIGATE

GO ONLINE to find these activities and more resources.

Applying Practices: Earth Power

HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

Applying Practices: Modeling Changes in Energy

HS-PS3-1. Create a computational model to calculate the change in the energy of...

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32

Student Textbook · p. 24

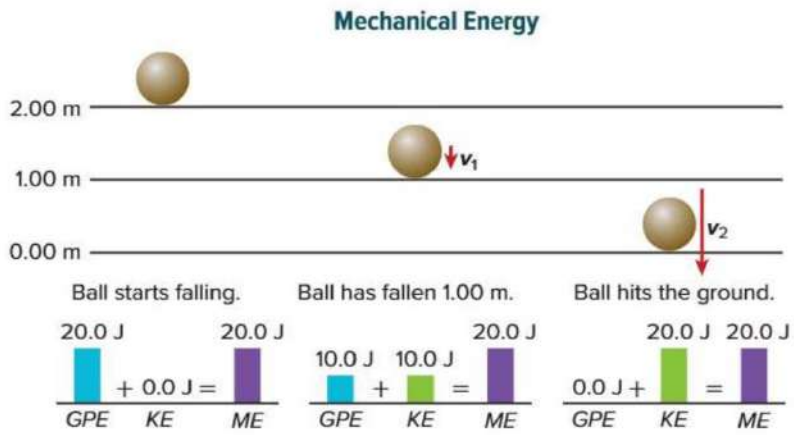


Figure 22 When a bowling ball is dropped, mechanical energy is conserved.

Predict *Suppose the ball started with an upward velocity. What would its energy graph look like?*

Imagine a system consisting of a 10.0-N bowling ball falling to Earth, as shown in **Figure 22.** For this case, the system's mechanical energy is 20.0 J.

Conservation of mechanical energy Suppose that you let go of the bowling ball. As it falls, the *GPE* of the ball-Earth system is transformed into kinetic energy. When the ball is 1.00 m above Earth's surface, $GPE = mgh = F_g h = (10.0\ \text{N})(1.00\ \text{m}) = 10.0\ \text{J}$. What is the system's kinetic energy when the ball is at a height of 1.00 m? The system consisting of the ball and Earth is closed and isolated because no external forces are doing work on it. Therefore, the total mechanical energy of the system remains constant at 20.0 J.

$$ME = KE + PE$$

$$KE = ME - PE$$

$$KE = 20.0\ \text{J} - 10.0\ \text{J} = 10.0\ \text{J}$$

When the ball reaches ground level, the system's potential energy is zero, and the system's kinetic energy is 20.0 J. The availability of energy limits what can occur in this and any system; for example, at a height of 1.00 m, the *GPE* of this 10-N bowling ball cannot exceed 10.0 J.

Conservation of Mechanical Energy

When mechanical energy is conserved, the sum of the system's *KE* and *PE* before an event equals the sum of the system's *KE* and *PE* after the event.

$$KE_i + PE_i = KE_f + PE_f$$

CCC **CROSSCUTTING CONCEPTS**

Systems and System Models Models can be used to predict the behavior of a system, but these predictions have limited precision and liability. Develop an argument that explains why the bowling ball model discussed in the text is limited. What evidence from your life supports your argument? How would you present your case to your peers?

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32

Student Textbook · p. 25

What happens if the ball does not fall straight down but rolls down a ramp, as shown in **Figure 23?** If friction does not affect the system, then the system of the ball and Earth remains closed and isolated. The ball still moves down a vertical distance of 2.00 m, so the decrease in potential energy is 20.0 J. Therefore, the increase in kinetic energy is 20.0 J.

As long as friction doesn't affect the system's energy, the path the ball takes does not matter. However, in the case with the ramp, the kinetic energy is split between translational kinetic energy (it is moving forward) and rotational kinetic energy (it is rolling). Three situations involving conservation of mechanical energy are shown in **Figure 24** on the next page.

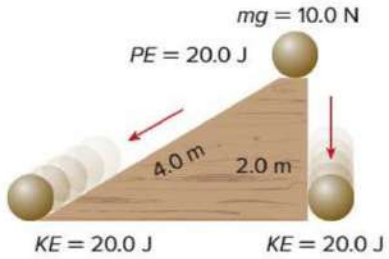


Figure 23 If friction does no work on the ball, the ball's final kinetic energy is equal to its initial gravitational potential energy regardless of which path it follows.

Get It?

Analyze how the ball's final kinetic energy in **Figure 23** would be different if friction transformed some of the system's energy.

Conservation and other forms of energy A swinging pendulum eventually stops, a bouncing ball comes to rest, and the heights of roller-coaster hills get lower and lower as the ride progresses. Where does the mechanical energy in such systems go? Objects moving through the air experience the forces of air resistance. In a roller coaster, there are also frictional forces between the wheels and the tracks. Each force transforms mechanical energy into other forms of energy.

When a ball bounces from a surface, it compresses. Most of the kinetic energy transforms into elastic potential energy. Some, but not all, of this elastic potential energy transforms back into kinetic energy during the bounce. But as in the cases of the pendulum and the roller coaster, some of the original mechanical energy in the system transforms into another form of energy within the system or transmits to energy outside the system, as in air resistance.

Get It?

Analyze If most of the kinetic energy of a bouncing ball transforms into elastic potential energy, what happens to the rest of the kinetic energy?

Mathematical expressions, which quantify how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. The Example Problems in this lesson use the concept of conservation of energy to solve problems, including collisions.

STEM CAREER Connection

Solar Photovoltaic Installer

Alternative energy is an area of global importance today. Solar photovoltaic installers, or PV installers, install and maintain solar panels on homes and for industry. They may also assemble systems. Installers in this rapidly growing field work mostly outside, sometimes work inside as well. They also must travel to their job sites.

CCC CROSSCUTTING CONCEPTS

Energy and Matter Make a simple ramp with a book or a board. Roll a ball down the ramp. Explain how your ramp and ball provide evidence of the law of conservation of energy.

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32

Example Problem 4 · p. 19

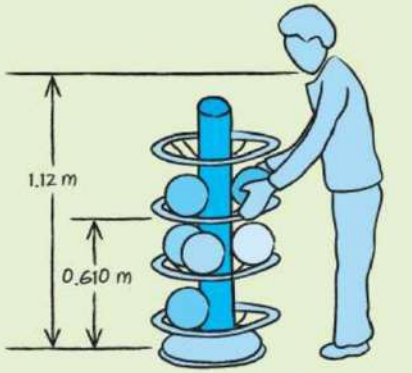
EXAMPLE Problem 4

GRAVITATIONAL POTENTIAL ENERGY You lift a 7.30-kg bowling ball from the storage rack and hold it up to your shoulder. The storage rack is 0.610 m above the floor and your shoulder is 1.12 m above the floor.

a. When the bowling ball is at your shoulder, what is the ball-Earth system's gravitational potential energy relative to the floor?

b. When the bowling ball is at your shoulder, what is the ball-Earth system's gravitational potential energy relative to the rack?

c. How much work was done by gravity as you lifted the ball from the rack to shoulder level?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the situation.
- Choose a reference level.
- Draw an energy bar diagram showing the gravitational potential energy with the floor as the reference level.

Known

$m = 7.30$ kg $\quad g = 9.8$ N/kg

$h_r = 0.610$ m (rack relative to the floor)

$h_s = 1.12$ m (shoulder relative to the floor)

Unknown

$GPE_{s\,rel\,f} = ?$

$GPE_{s\,rel\,r} = ?$

$W = ?$



2 SOLVE FOR THE UNKNOWN

a. Set the reference level to be at the floor.

Determine the gravitational potential energy of the system when the ball is at shoulder level.

$GPE_{s\,rel\,f} = mgh_s = (7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m

$= 8.0\times10^{1}$ J

b. Set the reference level to be at the rack height.

Determine the height of your shoulder relative to the rack.

$h = h_s - h_r$

Determine the gravitational potential energy of the system when the ball is at shoulder level.

$GPE_{s\,rel\,r} = mgh = mg(h_s - h_r)$ Substitute $h = h_s - h_r$

$= (7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m} - 0.610\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m, $h_r = 0.610$ m

$= 36$ J This also is equal to the work done by you as you lifted the ball.

c. The work done by gravity is the weight of the ball times the distance the ball was lifted.

$W = Fd = -(mg)h = -(mg)(h_s - h_r)$ The weight opposes the motion of lifting, so the work is negative.

$= -(7.30\text{ kg})(9.8\text{ N/kg})(1.12\text{ m} - 0.610\text{ m})$ Substitute $m = 7.30$ kg, $g = 9.8$ N/kg, $h_s = 1.12$ m, $h_r = 0.610$ m

$= -36$ J

3 EVALUATE THE ANSWER

- **Are the units correct?** Both potential energy and work are measured in joules.
- **Does the answer make sense?** The system should have a greater *GPE* measured relative to the floor than relative to the rack because the ball's distance above the floor level is greater than the ball's distance above the rack.

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32

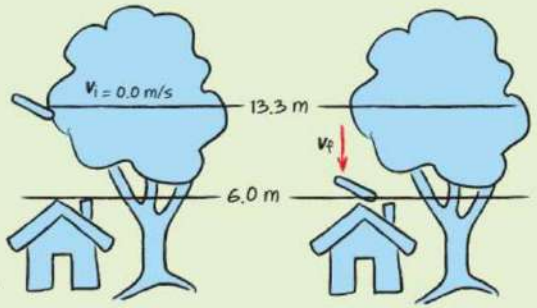
Example Problem 5 · p. 27

EXAMPLE Problem 5

CONSERVATION OF MECHANICAL ENERGY A 22.0-kg tree limb is 13.3 m above the ground. During a tropical storm, it falls on a roof that is 6.0 m above the ground.

a. Find the kinetic energy of the limb when it reaches the roof. Assume that the air does no work on the tree limb.

b. What is the limb's speed when it reaches the roof?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the initial and final conditions.
- Choose a reference level.
- Draw an energy bar diagram.

Known

$m = 22.0$ kg $\quad g = 9.8$ N/kg

$h_{limb} = 13.3$ m $\quad v_i = 0.0$ m/s

$h_{roof} = 6.0$ m $\quad KE_i = 0.0$ J

Unknown

$GPE_i = ?$ $\quad KE_f = ?$

$GPE_f = ?$ $\quad v_f = ?$

2 SOLVE FOR THE UNKNOWN

a. Set the reference level as the height of the roof.

Find the initial height of the limb relative to the roof.

$h = h_{limb} - h_{roof} = 13.3\text{ m} - 6.0\text{ m} = 7.3\text{ m}$ Substitute $h_{limb} = 13.3$ m, $h_{roof} = 6.0$ m

Determine the initial gravitational potential energy of the limb-Earth system.

$GPE_i = mgh = (22.0\text{ kg})(9.8\text{ N/kg})(7.3\text{ m})$ Substitute $m = 22.0$ kg, $g = 9.8$ N/kg, $h = 7.3$ m

$= 1.6\times10^3$ J

Identify the initial kinetic energy of the system.

$KE_i = 0.0$ J The tree limb is initially at rest.

Identify the final potential energy of the system.

$GPE_f = 0.0$ J $h = 0.0$ m at the roof.

Use the law of conservation of energy to find KE_f.

$KE_f + GPE_f = KE_i + GPE_i$

$KE_f = KE_i + GPE_i - GPE_f$

$= 0.0\text{ J} + 1.6\times10^3\text{ J} - 0.0\text{ J}$ Substitute $KE_i = 0.0$ J, $GPE_i = 1.6\times10^3$ J, and $GPE_f = 0.0$ J.

$= 1.6\times10^3$ J

b. Determine the speed of the limb.

$KE_f = \frac{1}{2}mv_f^2$

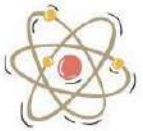
$v_f = \sqrt{\frac{2KE_f}{m}} = \sqrt{\frac{2(1.6\times10^3\text{ J})}{22.0\text{ kg}}}$ Substitute $KE_f = 1.6\times10^3$ J, $m = 22.0$ kg

$= 12$ m/s

3 EVALUATE THE ANSWER

- **Are the units correct?** The magnitude of velocity is measured in m/s, and energy is measured in $kg\cdot m^2/s^2 = J$.
- **Do the signs make sense?** Kinetic energy and speed are both positive in this scenario.

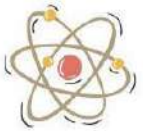
17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Practice Problem 39 · p. 28

39. A bike rider approaches a hill at a speed of 8.5 m/s. The combined mass of the bike and the rider is 85.0 kg. Choose a suitable system. Find the initial kinetic energy of the system. The rider coasts up the hill. Assuming friction is negligible, at what height will the bike come to rest?

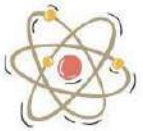
17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Practice Problem 40 · p. 28

40. Suppose that the bike rider in the previous problem pedaled up the hill and never came to a stop. In what system is energy conserved? From what form of energy did the bike gain mechanical energy?

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Practice Problem 41 · p. 28

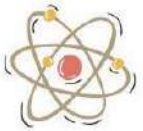
41. A skier starts from rest at the top of a hill that is 45.0 m high, skis down a 30° incline into a valley, and continues up a hill that is 40.0 m high. The heights of both hills are measured from the valley floor. Assume that friction is negligible and ignore the effect of the ski poles.

a. How fast is the skier moving at the bottom of the valley?

b. What is the skier's speed at the top of the second hill?

c. Do the angles of the hills affect your answers?

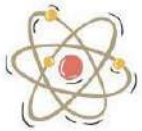
17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Practice Problem 42 · p. 28

42. In a belly-flop diving contest, the winner is the diver who makes the biggest splash upon hitting the water. The size of the splash depends not only on the diver's style, but also on the amount of kinetic energy the diver has. Consider a contest in which each diver jumps from a 3.00-m platform. One diver has a mass of 136 kg and simply steps off the platform. Another diver has a mass of 100 kg and leaps upward from the platform. How high would the second diver have to leap to make a competitive splash?

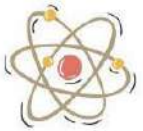
17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Practice Problem 43 · p. 28

43. CHALLENGE The spring in a pinball machine exerts an average force of 2 N on a 0.08-kg pinball over 5 cm. As a result, the ball has both translational and rotational kinetic energy. If the ball is a uniform sphere $\left(I = \frac{5}{2} mr^2\right)$, what is its linear speed after leaving the spring? (Ignore the table's tilt.)

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



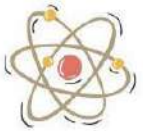
Check Your Progress 47 · p. 32

47. **Energy Diagrams** A child jumps on a trampoline. Draw energy bar diagrams to show the forms of energy in the following situations.

a. The child is at the highest point.

b. The child is at the lowest point.

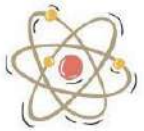
17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Check Your Progress 50 · p. 32

50. **Potential Energy** A rubber ball drops from a height of 8.0 m onto a concrete floor and bounces repeatedly. Each time it hits the floor, the ball-Earth system loses $\frac{1}{5}$ of its *ME*. How many times will the ball bounce before it bounces back up to a height of only 4 m?

17	•-Calculate translational and rotational kinetic energies and solve problems involving rotational kinetic energy. •-Calculate gravitational work and relate it to the change in gravitational potential energy. •-Apply conservation of mechanical energy to solve problems in physical situations.	Student Textbook Example Problem 4,5 Practice Problems 39-43 Check Your Progress 47, 50,51	23-25 19,27 28 32



Check Your Progress 51 · p. 32

51. **Energy** In **Figure 27**, a child slides down a playground slide. At the bottom, she is moving at 3.0 m/s. How much energy was transformed by friction as she slid down the slide?



Figure 27

18	•-Analyze one-dimensional collisions to calculate momenta, velocities, kinetic energies, and other physical quantities before or after the collision. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Example Problem 6 Practice Problems 45, 46 Check Your Progress 49	31 32 32

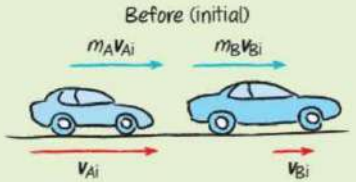
Example Problem 6 · p. 31

EXAMPLE Problem 6

INELASTIC COLLISION In an accident on a slippery road, a compact car with a mass of 1150 kg moving at 15.0 m/s smashes into the rear end of a car with a mass of 1575 kg moving at 5.0 m/s in the same direction.

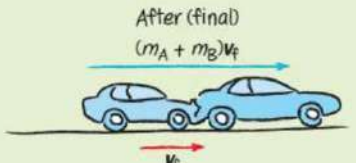
a. What is the final velocity if the wrecked cars lock together?

b. How much is the kinetic energy decreased in the collision?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the initial and final conditions.
- Sketch the momentum diagram.



Known	Unknown
$m_A = 1150$ kg	$v_f = ?$
$m_B = 1575$ kg	$\Delta KE = KE_f - KE_i = ?$
$v_{Ai} = 15.0$ m/s	
$v_{Bi} = 5.0$ m/s	
$v_{Af} = v_{Bf} = v_f$	

2 SOLVE FOR THE UNKNOWN

a. Use conservation of momentum to find the final velocity.

$$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$$

$$m_A v_{Ai} + m_B v_{Bi} = (m_A + m_B)v_f$$

$$v_f = \frac{m_A v_{Ai} + m_B v_{Bi}}{m_A + m_B}$$

$$= \frac{(1150\text{ kg})(15.0\text{ m/s}) + (1575\text{ kg})(5.0\text{ m/s})}{(1150\text{ kg} + 1575\text{ kg})}$$

Substitute $m_A = 1150$ kg, $v_{Ai} = 15.0$ m/s, $m_B = 1575$ kg, $v_{Bi} = 5.0$ m/s

$= 9.2$ m/s, in the direction of the motion before the collision

b. To determine the change in kinetic energy of the system, KE_f and KE_i are needed.

$$KE_f = \frac{1}{2}mv_f^2 = \frac{1}{2}(m_A + m_B)v_f^2$$

Substitute $m = m_A + m_B$

$$= \frac{1}{2}(1150\text{ kg} + 1575\text{ kg})(9.2\text{ m/s})^2$$

Substitute $m_A = 1150$ kg, $m_B = 1575$ kg, $v_f = 9.2$ m/s

$$= 1.2\times10^5\text{ J}$$

$$KE_i = KE_{Ai} + KE_{Bi}$$

$$= \frac{1}{2}(m_A v_{Ai}^2) + \frac{1}{2}(m_B v_{Bi}^2)$$

Substitute $KE_{Ai} = \frac{1}{2}(m_A v_{Ai}^2)$, $KE_{Bi} = \frac{1}{2}(m_B v_{Bi}^2)$

$$= \frac{1}{2}(1150\text{ kg})(15.0\text{ m/s})^2 + \frac{1}{2}(1575\text{ kg})(5.0\text{ m/s})^2$$

Substitute $m_A = 1150$ kg, $m_B = 1575$ kg, $v_{Ai} = 15.0$ m/s, $v_{Bi} = 5.0$ m/s

$$= 1.5\times10^5\text{ J}$$

Solve for the change in kinetic energy of the system.

$$\Delta KE = KE_f - KE_i$$

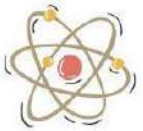
$$= 1.2\times10^5\text{ J} - 1.5\times10^5\text{ J} = -3\times10^4\text{ J}$$

Substitute $KE_f = 1.2\times10^5$ J, $KE_i = 1.5\times10^5$ J

3 EVALUATE THE ANSWER

- **Are the units correct?** Velocity is measured in meters per second; energy is measured in joules.
- **Does the sign make sense?** The change in kinetic energy is negative, meaning that kinetic energy decreased as expected in an inelastic collision.

18	•-Analyze one-dimensional collisions to calculate momenta, velocities, kinetic energies, and other physical quantities before or after the collision. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Example Problem 6 Practice Problems 45, 46 Check Your Progress 49	31 32 32



Practice Problem 45 · p. 32

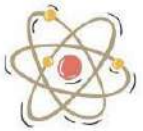
45. A 91.0-kg hockey player is skating on ice at 5.50 m/s. Another hockey player of equal mass, moving at 8.1 m/s in the same direction, hits him from behind. They slide off together.

a. What are the total mechanical energy and momentum of the system before the collision?

b. What is the velocity of the two hockey players after the collision?

c. How much was the system's kinetic energy decreased in the collision?

18	•-Analyze one-dimensional collisions to calculate momenta, velocities, kinetic energies, and other physical quantities before or after the collision. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Example Problem 6 Practice Problems 45, 46 Check Your Progress 49	31 32 32



Practice Problem 46 · p. 32

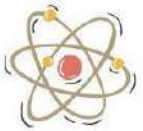
46. CHALLENGE A 0.73-kg magnetic target is suspended on a string. A 0.025-kg magnetic dart, shot horizontally, strikes the target head-on. The dart and the target together act like a pendulum and swing 12.0 cm above the initial level before instantaneously coming to rest.

a. Sketch the situation and choose a system.

b. Decide what is conserved in each step of the process and explain why.

c. What was the initial velocity of the dart?

18	•-Analyze one-dimensional collisions to calculate momenta, velocities, kinetic energies, and other physical quantities before or after the collision. •-Use conservation principles to distinguish and analyze elastic and inelastic collisions.	Example Problem 6 Practice Problems 45, 46 Check Your Progress 49	31 32 32



Check Your Progress 49 · p. 32

49. **Kinetic Energy** Suppose a glob of chewing gum and a small, rubber ball collide head-on in midair and then rebound apart. Would you expect kinetic energy to be conserved? If not, what happens to the energy?

19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58

Student Textbook · p. 55

Table 1 Threshold Frequency, Threshold Wavelength, and Work Function for Selected Metals

Metal	Threshold Frequency ($\times 10^{14}$ Hz)	Threshold Wavelength (nm)	Work Function (eV)
Cesium	4.70	637	1.95
Magnesium	8.84	339	3.66
Silver	11.1	270	4.6
Sodium	5.70	526	2.36

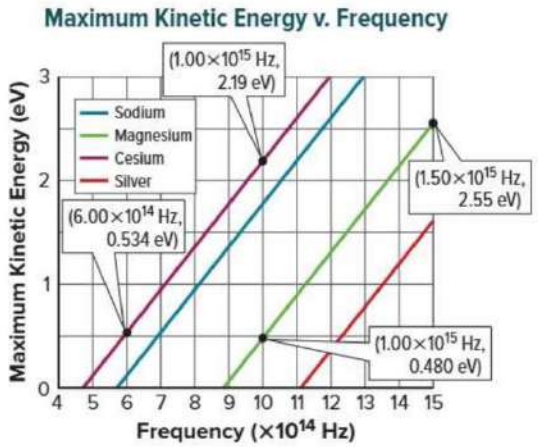


Figure 9 The metal's threshold frequency equals the line's *x*-intercept. Each line's slope equals Planck's constant.

Measuring h A graph of the maximum kinetic energies of the electrons ejected from a metal versus the frequencies of the incident photons is a straight line, as shown in **Figure 9**. All metals have similar graphs with the same slope. This slope equals the rise/run ratio of the line, which is equal to Planck's constant (h).

The graphs of various metals differ only in the threshold frequency needed to free the electrons. In **Figure 9**, the threshold frequency (f_0) is the point at which $KE = 0$. Looking at the graph, we see that f_0 is located at the intersection of the line with the *x*-axis. For example, the *x*-intercept, and therefore the threshold frequency, for cesium is 4.70×10^{14} Hz. A photon with that frequency has just enough energy to eject an electron from the metal. This minimum energy, called the **work function** of a metal, is the energy needed to free the most weakly bound electron from the metal. The magnitude of the work function is equal to hf_0. When a photon of frequency f_0 is incident on a metal, the energy of the photon is sufficient to release an electron but not sufficient to provide the electron with any kinetic energy.

CONNECTING MATH to Physics

Slope of a Line The lines in **Figure 9** are parallel. That means they all have the same slope. Below are the calculations for cesium and magnesium.

Math	Physics	
	Cesium	Magnesium
(x_1, y_1), (x_2, y_2)	$(6.00\times10^{14}$ Hz, 0.534 eV), $(1.00\times10^{15}$ Hz, 2.19 eV)	$(1.00\times10^{15}$ Hz, 0.480 eV), $(1.50\times10^{15}$ Hz, 2.55 eV)
$m = \frac{y_2 - y_1}{x_2 - x_1}$	$m = \frac{2.19\text{ eV} - 0.534\text{ eV}}{1.00\times10^{15}\text{ Hz} - 6.00\times10^{14}\text{ Hz}}$	$m = \frac{2.55\text{ eV} - 0.480\text{ eV}}{1.50\times10^{15}\text{ Hz} - 1.00\times10^{15}\text{ Hz}}$
	$m = 4.14\times10^{-15}$ eV/Hz	$m = 4.14\times10^{-15}$ eV/Hz

All lines in **Figure 9** have a slope of 4.14×10^{-15} eV/Hz. When converted to J/Hz, this value becomes the familiar value of Planck's constant:

$$4.14\times10^{-15}\ \frac{\text{eV}}{\text{Hz}}\left(\frac{1.602\times10^{-19}\text{ J}}{1\text{ eV}}\right) = 6.63\times10^{-34}\text{ J/Hz}$$

19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58

Example Problem 2 · p. 56

EXAMPLE Problem 2

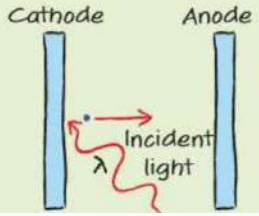
WORK FUNCTION AND ENERGY A particular photocell uses a sodium cathode. Sodium has a threshold wavelength of 526 nm.

a. Find the work function of sodium in eV.

b. If ultraviolet radiation with a wavelength of 348 nm falls on sodium, will the cathode discharge electrons? If so, what is the maximum energy of the ejected electrons in eV?

1 ANALYZE AND SKETCH THE PROBLEM

Draw the cathode and anode, the incident radiation, and the direction of the ejected electron.



Known

$\lambda_0 = 526$ nm $\lambda = 348$ nm

$hc = 1240$ eV·nm

Unknown

$W = ?$ $KE = ?$

2 SOLVE FOR THE UNKNOWN

a. Find the work function using Planck's constant and the threshold wavelength.

$$W = hf_0 = \frac{hc}{\lambda_0}$$
$$= \frac{1240 \text{ eV·nm}}{526 \text{ nm}} \qquad \text{Substitute } hc = 1240 \text{ eV·nm}, \lambda_0 = 526 \text{ nm}.$$
$$= 2.36 \text{ eV}$$

b. Use the relationship between a photon's energy and wavelength to find the photon's energy.

$$E = \frac{1240 \text{ eV·nm}}{\lambda}$$
$$= \frac{1240 \text{ eV·nm}}{348 \text{ nm}} \qquad \text{Substitute } \lambda = 348 \text{ nm}.$$
$$= 3.56 \text{ eV}$$

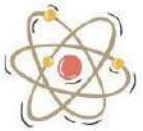
To calculate the kinetic energy of the ejected electron, subtract the work function from the energy of the incident radiation.

$$KE = hf - hf_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$
$$= E - W \qquad \text{Substitute } \frac{hc}{\lambda} = E, \frac{hc}{\lambda_0} = W.$$
$$= 3.56 \text{ eV} - 2.36 \text{ eV} \qquad \text{Substitute } E = 3.56 \text{ eV}, W = 2.36 \text{ eV}.$$
$$= 1.20 \text{ eV}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Performing dimensional analysis on the units verifies that electron volts is the proper unit for kinetic energy.
- **Does the sign make sense?** Kinetic energy is always positive.
- **Are the magnitudes realistic?** Work functions given in Table 1 are a few electron volts, so the magnitude is realistic.

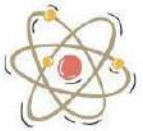
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Practice Problem 12 · p. 56

12. The threshold wavelength of zinc is 310 nm. Find the threshold frequency, in Hz, and the work function, in eV, of zinc.

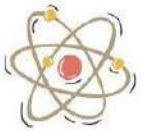
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Practice Problem 13 · p. 56

13. The work function for cesium is 1.95 eV. What is the maximum kinetic energy, in eV, of photoelectrons ejected when 425-nm violet light falls on the cesium?

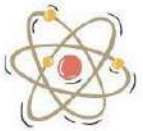
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Practice Problem 14 · p. 56

14. When a metal is illuminated with 193-nm ultraviolet radiation, electrons with kinetic energies of 3.5 eV are emitted. What is the work function of the metal?

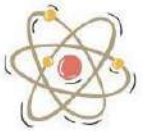
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Practice Problem 15 · p. 56

15. CHALLENGE A researcher illuminates a sample of metal and finds the longest wavelength to eject electrons is 273 nm. Find the work function. Use **Table 1** to identify the most likely metal.

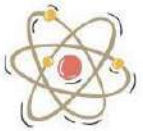
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Check Your Progress 20 · p. 58

20. **Photoelectric Effect** Green light ($\lambda = 532$ nm) strikes an unknown metal, causing electrons to be ejected. The ejected electrons can be stopped by a potential of 1.44 V. What is the work function, in eV, of the metal?

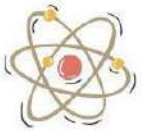
19	•-Calculate photon energy, maximum kinetic energy of emitted electrons, and the work function in photoelectric-effect problems. •-Interpret a graph of maximum kinetic energy versus incident-photon frequency to determine threshold frequency and Planck's constant.	Student Textbook Example Problem 2 Practice problems 12-15 Check Your Progress 20,21	55 56 56 58



Check Your Progress 21 · p. 58

21. **Energy of a Photon** What is the energy, in eV, of the photons of a 650-nm laser pointer?

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74

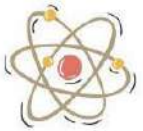


Get It? · p. 63

his amazement to that of firing a 15-inch cannon shell at tissue paper and then having the shell bounce back and hit him.

Get It?

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



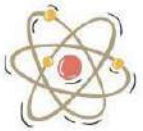
Get It? · p. 65



Get It?

Explain how an emission spectrum can help to identify the composition and concentrations of elements in a sample.

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



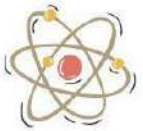
Get It? · p. 66



Get It?

Describe how scientists are able to determine the composition of stars.

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



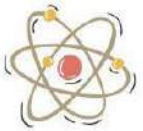
Get It? · p. 70



Get It?

Describe how the orbital radius and the energy depend on the principal quantum number.

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



Get It? · p. 71



Get It?

Describe the electron transitions that result in the visible lines in the hydrogen emission spectrum.

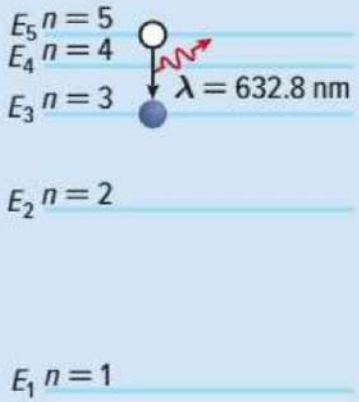
20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74

Physics Challenge · p. 74

PHYSICS Challenge

Although the Bohr atomic model accurately explained the behavior of a hydrogen atom, it was unable to explain the behavior of any other atom. Verify the limitations of the Bohr model by analyzing an electron transition in a neon atom. Unlike a hydrogen atom, a neon atom has ten electrons. One of these electrons makes a transition between the $n = 5$ and the $n = 3$ energy states, emitting a photon in the process.

1. Assuming that the neon atom's electron can be treated as an electron in a hydrogen atom, what photon energy does the Bohr model predict?
2. Assuming that the neon atom's electron can be treated as an electron in a hydrogen atom, what photon wavelength does the Bohr model predict?
3. The actual wavelength of the photon emitted during the transition is 632.8 nm. What is the percent discrepancy of the Bohr model's prediction and the measured photon wavelength?



20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74

Example Problem 4 · p. 72

EXAMPLE Problem 4

ENERGY LEVELS In order for an electron in a hydrogen atom to move from the lowest energy level ($n = 1$) to the second energy level ($n = 2$), the atom must absorb energy. Determine the energy of the first and second energy levels and the energy absorbed by the atom.

1 ANALYZE AND SKETCH THE PROBLEM

- Diagram the energy levels E_1 and E_2.
- Indicate the direction of increasing energy on the diagram.

Known

quantum number of innermost energy level, $n = 1$

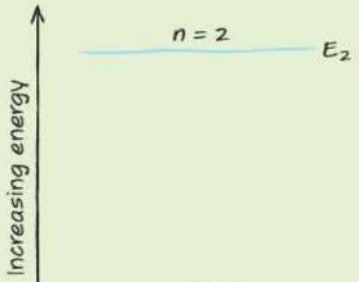
quantum number of second energy level, $n = 2$

Unknown

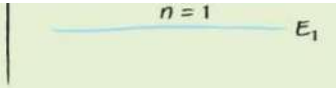
energy of level $E_1 = ?$

energy of level $E_2 = ?$

energy difference, $\Delta E = ?$



2 SOLVE FOR THE UNKNOWN



Use the principal quantum number to calculate the energy of each level.

$$E_n = -13.6 \text{ eV} \times \frac{1}{n^2}$$

$$E_1 = -13.6 \text{ eV} \times \frac{1}{(1)^2} \qquad \text{Substitute } n = 1.$$

$$= -13.6 \text{ eV}$$

$$E_2 = -13.6 \text{ eV} \times \frac{1}{(2)^2} \qquad \text{Substitute } n = 2.$$

$$= -3.40 \text{ eV}$$

The energy absorbed by the atom, ΔE, is equal to the energy difference between the final energy level of the atom, E_f, and the initial energy level of the atom, E_i.

$$\Delta E = E_f - E_i$$

$$= E_2 - E_1 \qquad \text{Substitute } E_f = E_2, E_i = E_1.$$

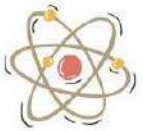
$$= -3.40 \text{ eV} - (-13.6 \text{ eV}) \qquad \text{Substitute } E_2 = -3.40 \text{ eV}, E_1 = -13.6 \text{ eV}.$$

$$= 10.2 \text{ eV} \quad \text{Energy is absorbed.}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Orbital energy values should be measured in electron volts.
- **Is the sign correct?** The energy difference is positive when electrons move from lower energy levels to higher energy levels.
- **Is the magnitude realistic?** The energy needed to move an electron from the first energy level to the second energy level should be approximately 10 eV, which it is.

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



Example Problem 5 · p. 73

EXAMPLE Problem 5

FREQUENCY AND WAVELENGTH OF EMITTED PHOTONS An excited electron in a hydrogen atom drops from the second energy level ($n = 2$) to the first energy level ($n = 1$). Calculate the energy and the wavelength of the emitted photon. Use E_1 and E_2 values from Example Problem 4.

1 ANALYZE AND SKETCH THE PROBLEM

- Diagram the energy levels E_1 and E_2.
- Indicate the direction of increasing energy, and show the emission of a photon on the diagram.

Known

energy of level $E_1 = -13.6$ eV

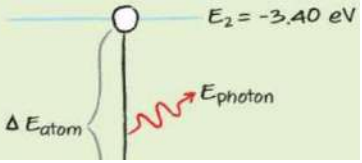
energy of level $E_2 = -3.40$ eV

Unknown

frequency, $f = ?$

wavelength, $\lambda = ?$

energy difference, $\Delta E = ?$



2 SOLVE FOR THE UNKNOWN

The energy of the emitted photon is equal to $-\Delta E$, the energy decrease from the initial energy level (E_i) to the final energy level (E_f).



$$-\Delta E = E_i - E_f$$

$$= E_2 - E_1 \qquad \text{Substitute } E_f = E_1,\ E_i = E_2.$$

$$= -3.40 \text{ eV} - (-13.6 \text{ eV}) \qquad \text{Substitute } E_1 = -13.6 \text{ eV},\ E_2 = -3.40 \text{ eV}.$$

$$= 10.2 \text{ eV} \quad \text{Energy is emitted.}$$

To determine the wavelength of the photon, use the relationships between energy, frequency, and wavelength.

$$\Delta E = hf, \text{ so } f = \frac{\Delta E}{h} \qquad \text{Solve the photon energy equation for frequency.}$$

$$c = \lambda f, \text{ so } \lambda = \frac{c}{f} \qquad \text{Solve the wavelength-frequency equation for wavelength.}$$

$$\lambda = \frac{c}{(\Delta E/h)} \qquad \text{Substitute } f = \frac{\Delta E}{h}.$$

$$= \frac{hc}{\Delta E}$$

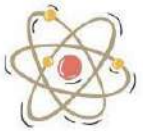
$$= \frac{1240 \text{ eV·nm}}{10.2 \text{ eV}} \qquad \text{Substitute } hc = 1240 \text{ eV·nm},\ \Delta E = 10.2 \text{ eV}.$$

$$= 122 \text{ nm}$$

3 EVALUATE THE ANSWER

- **Are the units correct?** Energy is measured in electron volts. The prefix nano– modifies the base SI unit, the meter, which is the correct unit for the wavelength.
- **Are the signs correct?** Energy is released when the atom emits a photon during the transition from the second energy level to the first; thus, the energy difference is negative.
- **Is the magnitude realistic?** Energy released in this transition produces light in the ultraviolet region below 400 nm.

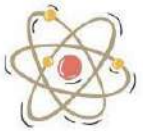
20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



Practice Problem 37 · p. 73

37. Find the wavelength of the light emitted in Practice Problems 34 and 35. Which lines in **Figure 18** correspond to each transition?

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



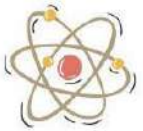
Practice Problem 38 · p. 73

38. For a particular transition, the energy of a mercury atom drops from 8.82 eV to 6.67 eV.

a. What is the energy of the photon emitted by the mercury atom?

b. What is the wavelength of the photon emitted by the mercury atom?

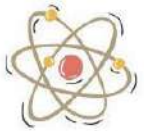
20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



Practice Problem 39 · p. 73

39. CHALLENGE The ground state of a helium ion is −54.4 eV. A transition to the ground state emits a 304-nm photon. What was the energy of the excited state?

20	•-Calculate the change in an atom's energy during transitions between Bohr energy levels. •-Calculate the energy, frequency, and wavelength of emitted or absorbed photons. •-Calculate Hydrogen orbital radius and total energy for a given principal quantum number n.	Get it Example Problem 4 Example Problem 5 Practice Problems 37-39 Check Your Progress 42	74 72 73 73 74



Check Your Progress 42 · p. 74

42. **Absorption Spectrum** The absorption spectrum for a sample of hydrogen gas is shown in **Figure 24.** Explain how the absorption spectrum of a gas can be determined. Describe the reasons for the spectrum's appearance.

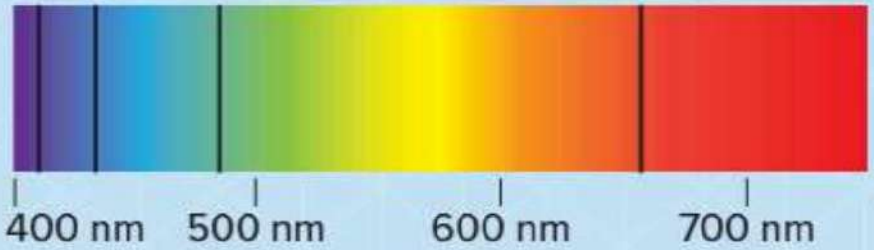


Figure 24