SECTION 5

Wave-Particle Model of Light: Two Models Are Better Than One!

Section Overview

Students begin with an investigation of how waves behave and how light models these behaviors. They do this by considering examples that distinguish between particle motion and wave motion. The features of wave motion are explored by analyzing water waves and waves produced by musical instruments like the guitar. Students stretch a coiled spring and sketch standing wave patterns and identify the nodes in these standing waves, concluding that coiled spring waves are waves because they can interfere with one another. Students also observe how sound produced by a tuning fork exhibits the wave phenomenon of interference. The behavior of light is then investigated by projecting a coherent beam of light from a laser beam though a slit onto a piece of paper and measuring the slit's thickness. A wave's ability to bend and squeeze through narrow spaces and then spread out through the process of diffraction is one of the defining characteristics of waves. Light's ability to duplicate this phenomenon leads to the conclusion that light has wave-like properties.

Students investigate Einstein's theory of photoelectric effect using an analogy with vending machines and use the photoelectric equation to solve problems that further confirm the concept of photons and the particle-like nature of light. The Davisson-Germer experiment on electron diffraction is discussed as a basis for de Broglie's electron-wave hypothesis. Students sketch the predicted electron positions based upon experimental results of de Broglie's hypothesis shown in a diagram illustrating the interference phenomenon of electrons. Students compare the electron waves of de Broglie to the standing waves formed by a guitar and a coiled spring and are led to conclusion that electrons too have wave-like as well as particle-like properties.

Background Information

This section brings together physics principles that have been discussed earlier in the course. To continue developing your model of the atom, you must ask some basic questions, such as: What is light? Early in the history of the study of light, the question became that of deciding between a binary choice: Is light a beam of particles, *or* is light a wave? Newton argued for particles, Hooke and Huygens for waves. What does the evidence say? Waves will exhibit diffraction and interference, so when Thomas Young first carried out the double-slit experiment in 1800 (and interference was observed) convincing evidence existed that "light is a wave."

The question of "what is light?" was considered closed, especially after Maxwell showed in the 1860s that waves in the electromagnetic field move at the speed of light (the basis of radio and radar). But in other phenomena, such as the photoelectric effect that was discovered late in the nineteenth century, "light as waves" was not an interpretation that fit the facts. In 1905, Albert Einstein suggested that in some circumstances it is more accurate to think of light as a beam of particles. Where one would say the light wave has frequency f, the particles of light have energy hf, where h is Planck's constant. Which model—wave or particle—works best for light depends on the question you put to nature in your experiment! If you send light through the double slit, then it is "wave-like," but if you shine light on a sample of cesium metal, it is as though you compel light to become "particle-like."

While still a graduate student in 1923, Louis de Broglie realized that the argument could be turned around: There might exist situations where objects modeled exclusively as particles, such as electrons, might require a wave model for certain phenomena in which they participate to be interpreted consistently. This prediction was confirmed by Thompson and Davisson and Germer in the late 1920s. They bounced electrons off a thin foil and a nickel crystal; the planes of atoms provided a set of "slits" through which the "electron waves" could diffract and interfere (analogous to bouncing light through a set of slits or off a CD and seeing the interference between light beams that reflect off different sets of etch marks on the disc). The pattern of where the reflected electrons landed exhibited the same kind of interference that one would expect of waves. Wave-particle duality really occurs.

"Waves" and "particles" are models, which is to say conceptual representations, of objects and processes. Particle and wave models are based on everyday experiences with baseballs and surf, and extrapolating those mental pictures down to the microscopic world of the atom. Because light or electrons cannot be completely described by a single model shows here at least the limits of what either model can do by itself. Whatever light "really" is, whatever electrons "really" are, a single model in terms of which all about light or electrons can be understood has not been found.

One is reminded of the parable of the blind men and the elephant: One man grabs the tail and says the elephant is like a rope; another grasps the leg and says the elephant is like a tree, etc. These diverse conceptions of the creature show that the blind men have only a partial "view," and they cannot form the single concept of "elephant" in terms of which all their observations make sense. None of the blind men are wrong because their interpretation of the elephant is consistent with their limited data. Their separate mental pictures of the elephant are not wrong, but incomplete. You are in a similar situation with light and electrons (and other microscopic systems in general) and the wave and particle models of them.

Perhaps one of your students will be the first person with enough insight, cleverness, and independence of mind to "think outside the box" and create a single conceptual framework in terms of which the behavior of light and electrons will become simple!

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Crucial Physics

- The duality of light says that light may behave as either a wave or a particle, but never both at the same time.
- Interference and diffraction are properties of light that indicate its wave nature.
- The photoelectric effect is a property of light that indicates its particle nature.
- The energy of a photon (E) is directly proportional to its frequency (f), and expressed in the equation $E = hf$ where h is Planck's constant, $6.63 \times 10^{-34}\ \text{J} \cdot \text{s}$.
- In the photoelectric effect, when a photon strikes an atom, the photon may eject an electron from the atom if it has sufficient energy. The kinetic energy (KE) of the ejected electron depends upon the frequency (f) of the photon and the ionization energy of the electron from the atom (w_o). This is expressed by the equation $KE = hf - w_o$.
- Experiments have shown that matter also exhibits both wave and particle properties, but never both at the same time. The wavelength associated with matter is so small that it is only visible on the atomic or subatomic level.
- Electron wavelengths determine the energy levels of the atom.

NOTES

Learning Outcomes	Location in the Section	Evidence of Understanding
Observe the diffraction of light waves.	***Investigate*** Part A, Step 4	Students project a laser beam onto a piece of paper and measure its thickness. Then they project the beam through slits of varying width and observe what happens to the thickness of the beam.
Observe the interference of sound waves.	***Investigate*** Part A, Step 5 ***Physics Talk***	Students hear the sounds produced by a tuning fork. When the tuning fork is rotated, they note how the volume changes from high to low and conclude that sound waves from the tuning fork are interfering. Students read about constructive and destructive interference of sound waves produced by a tuning fork.
Observe the interference of light waves.	***Investigate*** Step 7	Students observe patterns of laser light projected through slits of a diffraction grating onto a screen. By observing the light and dark areas on the screen, they infer the places where light interferes constructively and destructively.
Construct a model of wave interference.	***Investigate*** Part C, Steps 1–3	From the effects generated by laser light passing through a diffraction grating and the interference of sound waves from a tuning fork, the students investigate how only waves are capable of producing these effects.
Solve simple problems related to the photoelectric effect.	***Investigate*** Part B, Steps 1–3	Students calculate if the energy of a photon is sufficient to provide the kinetic energy needed by an electron to be released from a metal with a given work function. By putting in the values for the energy of light and the work function of the metal in the equation for the photoelectric effect, students determine if the electron is freed from an atom, and the kinetic energy if it is ejected.
Describe the wave-particle duality of light.	***Investigate*** Part A, Step 5 Part B, Steps 1–3 ***Physics Talk***	Students investigate and describe the duality of light by relating their investigations of diffraction and the photoelectric effect to the particle and wave models of light. They read about the photoelectric effect that demonstrates the particle nature of light and diffraction patterns on a screen that demonstrates wave behavior.
Describe the wave-particle duality of electrons.	***Investigate*** Part B, Steps 1–2 Part C, Steps 1–2 ***Physics Talk***	Students model the wave-particle duality of electrons by investigating the Davisson-Germer experiment on electron diffraction, and then sketching diagrams of standing waves in a box and determine the nodes and antinodes of an electron wave.

NOTES

Section 5 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Ruler, metric, in./cm	1 per group	
Coil, helical	1 per group	
Laser pointer, class 2	1 per group	
Tuning fork, single, 512 Hz	1 per group	
Transparency, diffraction grating, double slit, single	1 per group	
Diffraction grating, square, 5 cm x 5 cm	1 per group	
Paper, single sheet	1 per group	
Access to a large area (to make waves with spring)*	1 per group	
Access to a wall (to shine laser pointer)*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and one-half class periods, or 60 minutes for the students to complete the *Investigate* portion of this section.

Teacher Preparation

- Darken the room to make the outlines of the laser beam more visible.
- The tuning forks used for *Part A* need not be of all the same frequency, but interference is easier to discern for higher frequencies the than lower ones.
- The opening width required to observe diffraction with a laser beam is quite small. Commercially prepared openings are available, and are best to use to obtain a series of slits of different widths.
- Open space is needed for the students to *Part A, Step 3*.
- For *Part A, Step 6*, with a typical pen laser and diffraction grating, a distance between the grating and the screen of one meter is sufficient to see the interference pattern.
- Search the Internet to find an animation of models of the hydrogen atom or the Bohr model of the atom such as the Photoelectric effect to show the students.

Safety Requirements

- Students must wear safety goggles during this *Investigate.*
- If you are using a helical spring for *Part A, Step 3*, warn the students that once they stretch the helical spring they must be very careful not to suddenly release the end of the spring when it is under tension. The spring will recoil rapidly and can cause injury to an unprepared holder of the other end.
- If the students are generating a standing wave with the helical spring when holding the spring in the air, be aware that a large amplitude standing wave may build quickly. Ensure that no students are standing alongside the spring, and that both students have a firm grip on the spring ends.
- Caution the students not to strike the tuning forks on hard surfaces such as student desks. A rubber striker is best, but hitting the tuning fork on the sole of a shoe is an acceptable substitute.
- Students should be careful when holding the tuning fork up near their ears to avoid hitting their ear with it.
- Observe all laser safety precautions. Caution students to never shine a laser into a person’s eyes.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Ruler, metric, in./cm		1 per class
Coil, helical		1 per class
Laser pointer, class 2		1 per class
Tuning fork, single, 512 Hz	1 per group	
Transparency, diffraction grating, double slit, single		1 per class
Diffraction grating, square, 5 cm x 5 cm		1 per class
Paper, single sheet	1 per group	
Access to a large area (to make waves with spring)*		1 per class
Access to a wall (to shine laser pointer)*		1 per class

*Additional items needed not supplied

Time Requirement

- Allow 45 minutes or one class period to do the *Investigate* portion of this section as a teacher-led demonstration and to discuss the *Physics Talk*.

Teacher Preparation

- Darken the room to make the outlines of the laser beam more visible.
- A red light pen laser may not be sufficiently bright for the students to observe the increased beam width during *Step A, Parts 5* and 6. A helium-neon laser or a green pen laser may be required.
- The tuning forks used for *Part A* need not be of all the same frequency, but the interference is easier to discern for higher frequencies than lower ones.
- The opening width required to observe diffraction with a laser beam is quite small. Commercially prepared openings are available, and are best to use to obtain a series of slits of different widths.
- Open space is needed for the students to complete *Part A, Step 3*.
- Ask for volunteer students to help with the measurements of the beam width when doing *Part A, Step 5*, and to help with the standing waves for *Part A, Step 3*.
- Search the Internet to find a Web site that has an animation of models of the hydrogen atom or the Bohr model of the atom such as the Photoelectric effect to show the students.

Safety Requirements

- Student helpers must wear safety goggles during this Investigate.
- If you are using a helical spring for *Part A, Step 3*, warn the student volunteer holding the other end of the spring that once the helical spring is stretched, they must be very careful not to suddenly release the end of the spring when it is under tension. The spring will recoil rapidly and can cause injury to an unprepared holder of the other end.
- When generating a standing wave with the helical spring in the air, be aware that a large amplitude standing wave may build quickly. Ensure that no students are near the sides of the spring, and that those generating the waves have a firm grip on the spring ends.
- Do not to strike the tuning forks on hard surfaces such as a desk. A rubber striker is best, but hitting the tuning fork on the sole of a shoe is an acceptable substitute.
- Be careful when holding the tuning fork up near an ear to avoid hitting the ear with it.
- Observe all laser safety precautions. Never shine a laser into a person's eyes. This is particularly important if you are using a green laser, which is more powerful.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Predicting wave behavior	***Investigate*** Steps 2 and 4	**Augmentation** • Some students may have trouble visualizing how water waves plus water waves could equal still water. Show students a video from the Internet to give them a visual image of a very common example of wave interference.
Using coiled springs	***Investigate*** Step 3	**Augmentation** • Students who struggle with attention and following directions often struggle to use a coiled spring correctly because one second of bad judgment could lead to a very tangled coiled spring. Model for students how to properly hold the coiled spring with two hands, and remind students that they must walk toward each other and gently release the coiled spring. Set clear consequences for misusing the coiled spring before the activity begins.
Reading comprehension	***Investigate*** Part B, Step 2	**Augmentation** • Students who struggle to decode and/or comprehend text will struggle with this part of the *Investigate* because it relies primarily on reading to introduce a new concept. Students could work in small groups to introduce one of each of the bullet points and following paragraph to the class. Then students are only responsible for reading and comprehending a few sentences, but every student will hear all of the information from their classmates. • Provide direct instruction to teach the basic principles of the photoelectric effect. **Accommodation** • Provide a photocopy of the text for students to highlight. Then students should be instructed to highlight one sentence in each point that is not related to the vending machine but instead explains a principle of the photoelectric effect.
Understanding essential concepts (wave-particle duality)	***Physics Talk*** ***Physics Essential Questions*** ***Physics to Go*** Questions 1, 6, and 11	**Augmentation** • Students are required to describe the wave-particle duality of light and electrons. Have students create two T-charts—one for light and one for electrons. Ask them to list the particle properties on the left side of the page and the wave properties on the right side of the page. Allow students 10 minutes to work on this independently. Next ask students to collaborate with a partner to expand their list. Finally, create a class list for both light and electrons. • During this activity, provide students with sticky notes or note cards to write down questions that may arise as they are making their charts. **Accommodation** • Provide a list of wave and particle properties that are not in any particular order, and ask students to cut them apart, sort them, and tape them onto the T-chart or just copy the properties onto the T-chart.

Using content vocabulary	***Physics Words***	**Augmentation** • Students with language-based learning disabilities or short-term memory issues often struggle to learn new vocabulary. Take this opportunity to teach students a couple of ways to study vocabulary. • Students can write sentences or a story and try to use at least eight of the words correctly. • Students can make note cards with the word on one side and the definition on the other. • Students can make vocabulary cards that include the word, a definition, a sentence, and a picture. A variation to this approach is asking students to also include a non-example of the word on their vocabulary card. • Encourage students to say the words and definitions aloud as they are studying. People remember more when they see and hear the information at the same time. **Accommodation** • Provide blank graphic organizers for the above options to help students organize their thoughts. Some students may need examples to get started.

Strategies for Students with Limited English-Language Proficiency

Point out new vocabulary words in context and practice using the words as much as possible throughout the section. As you work through the section, have students write the terms in their *Active Physics* log and add the definitions in their own words. Encourage students to accompany the sentences with labeled diagrams and illustrations.

constructive interference
destructive interference
diffraction
frequency
model
node
particles
Photoelectric effect
photon
threshold frequency
wavelength
wave-particle duality
waves

There are many new vocabulary words in this section. A solid grasp of the vocabulary is essential for students to fully understand waves. One way to practice using the vocabulary is for students to work in teams to write meaningful sentences about the content in this section. Students should strive to write simple sentences using the vocabulary words. The goal is to use as many words as possible correctly. The sentences should be in proper English. Encourage students to include some compound sentences to demonstrate their understanding of bits of related information or opposite information. For example:

"Constructive interference happens when waves combine crest-to-crest, while destructive interference happens when waves combine crest-to-trough."

The rubric for grading these sentences should include four elements: correct science, correct usage of vocabulary, correct sentence structure and grammar, and quality of work.

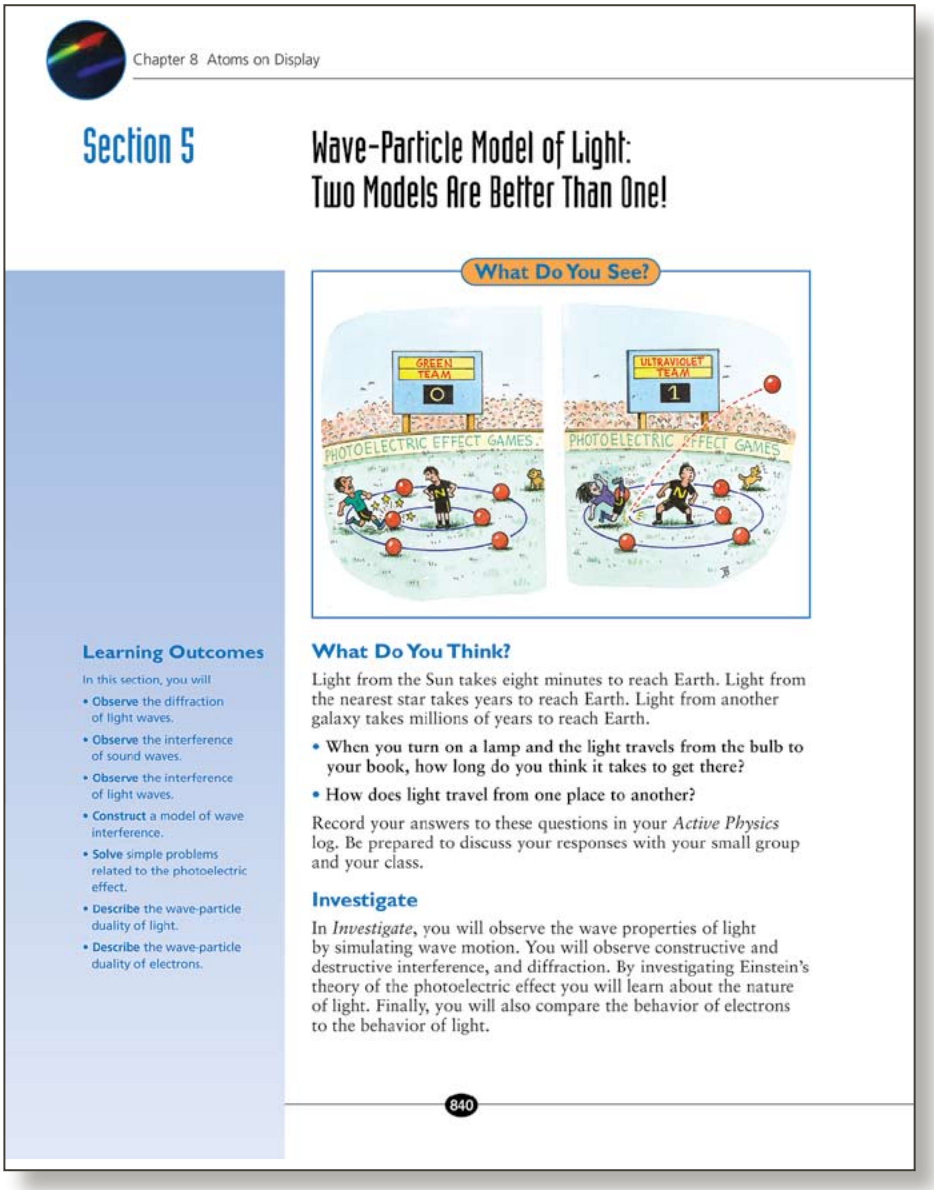
Rapid feedback about students' sentences is essential because the sentences and errors will be fresh in the students' minds. A quick and powerful method for providing this feedback is to prepare a list of examples of incorrect sentences from the work collected. Divide examples into the following categories: incorrect science, incorrect usage of vocabulary, incorrect sentence structure, and incorrect grammar. Choose several examples from the collected work to use in each category and edit the sentences until they contain only one or two obvious errors, or limit the choices to these kinds of sentences. At the beginning of class on the day following the sentence-writing activity, provide each student with a page containing a double-spaced, typed list of the incorrect sentences, with headings for the categories. Allow students 10 minutes to silently make corrections to the sentences. Then, place a copy of the list on the overhead projector and collect students' ideas on how to repair the sentences, guiding them toward correct science and English usage.

SECTION 5

Teaching Suggestions and Sample Answers

What Do You See?

The signs indicating the teams (green and ultraviolet) and the facial expressions of the soccer players provide useful points of discussion that you can build on as students spend some time trying to figure what is happening in the illustration. You might want to ask students why the player in one visual appears to be ineffectual while the player in the other one seems to be so happy. Ask students why the person wearing the shirt with the letter "N" also has a change of expression in both the visuals. Point out to students that this illustration is full of hints that connect to the physics concepts they will be studying in this section.



Chapter 8 Atoms on Display

Section 5

Wave-Particle Model of Light: Two Models Are Better Than One!

What Do You See?

Learning Outcomes

In this section, you will

- **Observe** the diffraction of light waves.
- **Observe** the interference of sound waves.
- **Observe** the interference of light waves.
- **Construct** a model of wave interference.
- **Solve** simple problems related to the photoelectric effect.
- **Describe** the wave-particle duality of light.
- **Describe** the wave-particle duality of electrons.

What Do You Think?

Light from the Sun takes eight minutes to reach Earth. Light from the nearest star takes years to reach Earth. Light from another galaxy takes millions of years to reach Earth.

- **When you turn on a lamp and the light travels from the bulb to your book, how long do you think it takes to get there?**
- **How does light travel from one place to another?**

Record your answers to these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

In *Investigate*, you will observe the wave properties of light by simulating wave motion. You will observe constructive and destructive interference, and diffraction. By investigating Einstein's theory of the photoelectric effect you will learn about the nature of light. Finally, you will also compare the behavior of electrons to the behavior of light.

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Students' Prior Conceptions

In this section, it is vital for students to embrace the duality of light by accepting that light may sometimes act like a particle and sometimes like a wave. Only waves produce interference patterns. The process of shining light upon a metallic surface to emit electrons is the photoelectric effect, and is a signature behavior of a particle. Students should learn that the photoelectric effect is the foundation for solar-powered devices such as digital cameras, solar collectors, and photogates.

1. **The primary misconception students may hold is that any light may free any electron from a metal surface.** Recall misconception 3 from *Section 4*— Electrons can be in any orbit they wish and reemphasize that specific quanta of energy must be absorbed in order for an electron to move from one orbit to another and a specific amount of energy known as the first ionization energy must be absorbed by an outermost electron in order for it to be released from the surface of a metal. A simplistic view is that the photoelectric effect is "proof" of the quantum nature of matter and of the electromagnetic field.

Additional misconceptions identified by research about how students learn may be addressed by the teacher when discussing the dual nature of light. These misconceptions are as follows:

2. **Light is one or the other—a particle or a wave—only.**
3. **Light can be a particle at one point in time and a wave at another point in time.**

Encourage them to make connections and share their responses with you and others in their class. Have students write what they see so that they can return to this illustration at a later point and recognize different aspects of the images that the artist has skillfully captured.

What Do You Think?

The introductory passage to *What Do You Think?* is meant to guide students toward thinking about the nature of light. Engage students' curiosity by asking what their experience suggests about how long it takes light to reach them according to their distance from its source. As students discuss their answers, remind them to record their answers in their *Active Physics* logs. You might want to point to the connection between the questions asked and the title of this section. Let students know that their answers will not be evaluated for correctness, but it is imperative for them to write down their responses so that they can refer to their previous conceptions and realize how their knowledge of physics concepts involving light has grown.

What Do You Think?

A Physicist's Response

The speed of light in air is approximately 2.997×10^8 m/s and in a vacuum is approximately 3×10^8 m/s. The speed of light also depends on the medium in which it travels. It decreases with the increasing optical density (index of refraction) of the substance in which it travels. In a vacuum, the speed of light is the fastest because it doesn't come across any resistance. The time it would take light to travel from your lamp to your book can be calculated by dividing the distance between the book and the lamp with the speed of light. Light travels in packets of energy called quanta that have both a particle and wave-like nature.

4. Particles can't have wave properties.

5. Waves can't have particle properties.

6. All photons have the same energy.

You may evaluate these prior conceptions as they spring up in student explanations, student logs, and the *Engineering Design Process.* You may also consider student explanations of interference to ascertain if they continue to hold the belief that

7. Light exits in the crest of a wave and darkness in the trough.
An interference pattern is one of cancellation between a crest and a trough of light and reinforcement between a crest and a crest of light or a trough and a trough of light.

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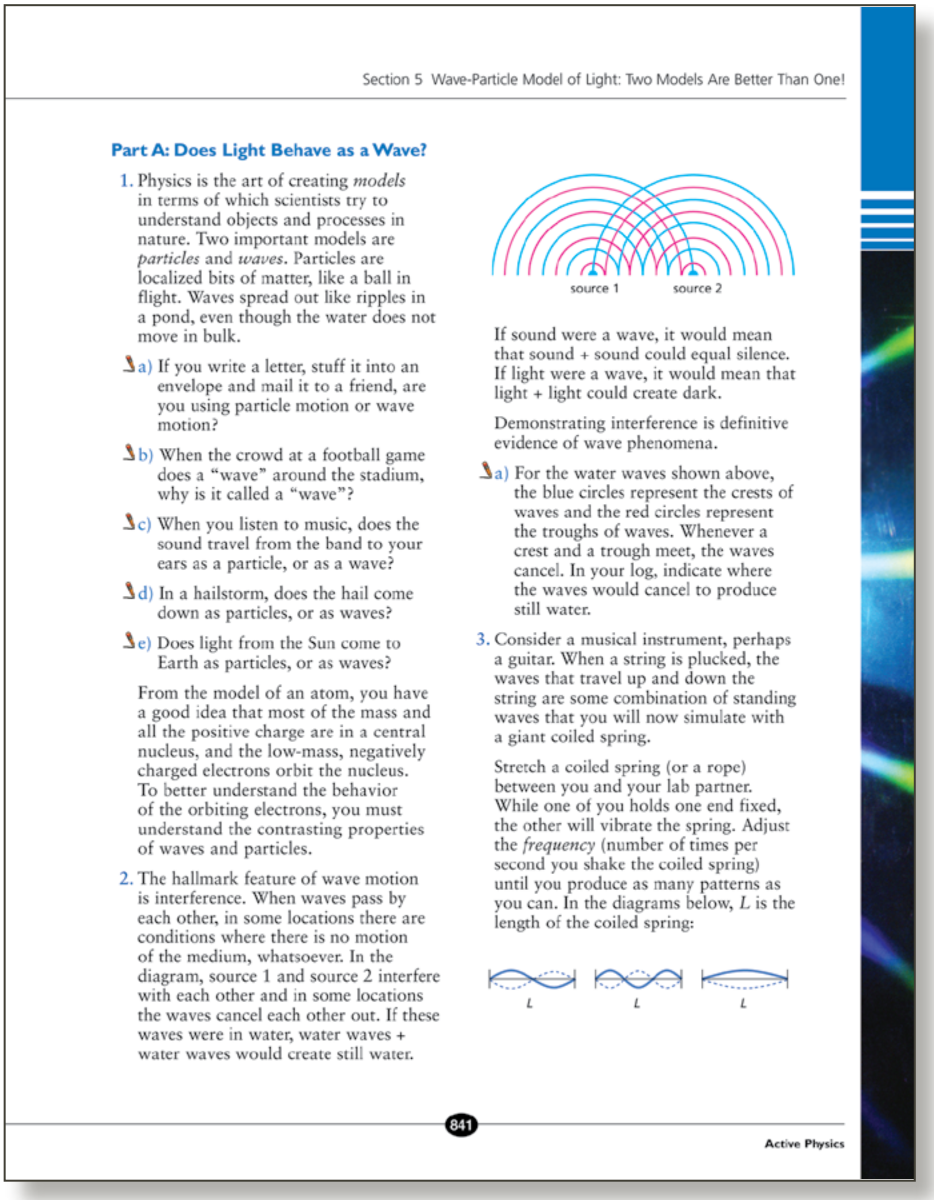

Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

Part A: Does Light Behave as a Wave?

1. Physics is the art of creating *models* in terms of which scientists try to understand objects and processes in nature. Two important models are *particles* and *waves*. Particles are localized bits of matter, like a ball in flight. Waves spread out like ripples in a pond, even though the water does not move in bulk.

a) If you write a letter, stuff it into an envelope and mail it to a friend, are you using particle motion or wave motion?

b) When the crowd at a football game does a "wave" around the stadium, why is it called a "wave"?

c) When you listen to music, does the sound travel from the band to your ears as a particle, or as a wave?

d) In a hailstorm, does the hail come down as particles, or as waves?

e) Does light from the Sun come to Earth as particles, or as waves?

From the model of an atom, you have a good idea that most of the mass and all the positive charge are in a central nucleus, and the low-mass, negatively charged electrons orbit the nucleus. To better understand the behavior of the orbiting electrons, you must understand the contrasting properties of waves and particles.

2. The hallmark feature of wave motion is interference. When waves pass by each other, in some locations there are conditions where there is no motion of the medium, whatsoever. In the diagram, source 1 and source 2 interfere with each other and in some locations the waves cancel each other out. If these waves were in water, water waves + water waves would create still water.

If sound were a wave, it would mean that sound + sound could equal silence. If light were a wave, it would mean that light + light could create dark.

Demonstrating interference is definitive evidence of wave phenomena.

a) For the water waves shown above, the blue circles represent the crests of waves and the red circles represent the troughs of waves. Whenever a crest and a trough meet, the waves cancel. In your log, indicate where the waves would cancel to produce still water.

3. Consider a musical instrument, perhaps a guitar. When a string is plucked, the waves that travel up and down the string are some combination of standing waves that you will now simulate with a giant coiled spring.

Stretch a coiled spring (or a rope) between you and your lab partner. While one of you holds one end fixed, the other will vibrate the spring. Adjust the *frequency* (number of times per second you shake the coiled spring) until you produce as many patterns as you can. In the diagrams below, L is the length of the coiled spring:

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Investigate

Part A

1.a)

Sending a letter would be particle motion.

1.b)

It's called a "wave" because the disturbance travels around the stadium without any person moving from one location to another.

1.c)

Sound travels as a wave. (No breeze carries the sound from the band to you!)

1.d)

The hailstones come down like particles.

1.e)

Trick question! Yes (both). The sunlight acts like a wave (for example, it can show diffraction when passing through a slit) but when the light interacts with, say, the photosynthesis antenna in a plant, the energy exchange between the light and the plant is more like a collision between a particle of light (photon) and an electron.

8-5a **Blackline Master**

2.a)

Anywhere a blue line crosses a red line, the waves cancel and still water is the result.

3.a)

Sketches should look like those found in the *Student Edition* for *Step* 3.

3.b)

The points that do not move (the nodes) are where the dotted line and solid line cross in the diagram.

4.a)

As the tuning fork is rotated, students should hear the sound become louder and softer.

Teaching Tip

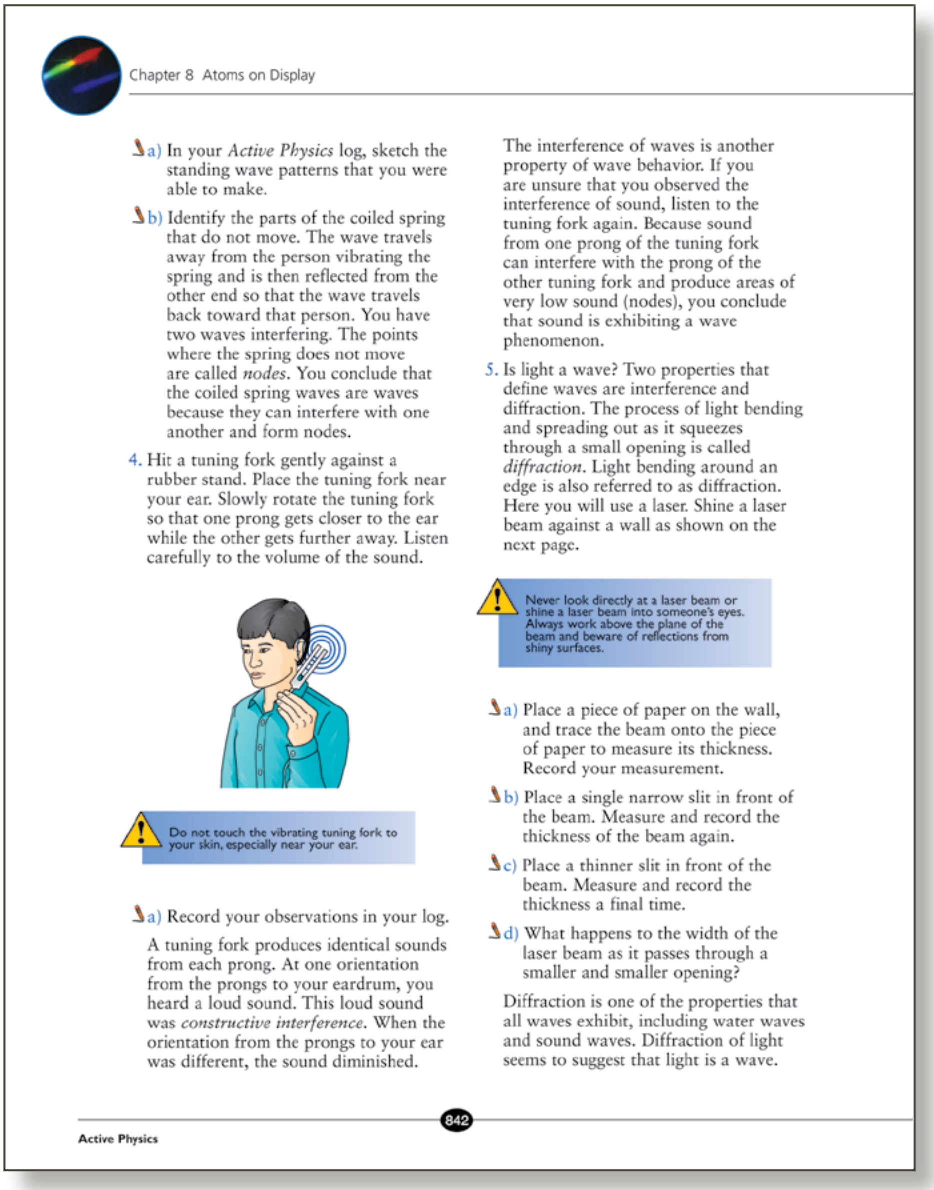
When using the tuning forks to sound interference, higher frequency forks work somewhat better than lower frequency forks. Do not allow the students to strike the tuning forks on a hard surface because it tends to damage the forks.

5.a)

Students mark off the thickness of the laser beam and record its size. The size of the beam will vary with the type of laser used and distance from the wall.

Teaching Tip

Diffraction of light requires a coherent light source, such as a laser, and will not be observable with a normal light source. The opening size for light to show appreciable diffraction is of the order of a 10 to 100 times the wavelength of light. Openings of millimeter size and larger will not demonstrate any appreciable diffraction. Be sure to keep the measuring surface the same distance from the light source so that any spreading of the light beam is because of diffraction and not because of increased distance from the source.



Chapter 8 Atoms on Display

a) In your *Active Physics* log, sketch the standing wave patterns that you were able to make.

b) Identify the parts of the coiled spring that do not move. The wave travels away from the person vibrating the spring and is then reflected from the other end so that the wave travels back toward that person. You have two waves interfering. The points where the spring does not move are called *nodes*. You conclude that the coiled spring waves are waves because they can interfere with one another and form nodes.

4. Hit a tuning fork gently against a rubber stand. Place the tuning fork near your ear. Slowly rotate the tuning fork so that one prong gets closer to the ear while the other gets further away. Listen carefully to the volume of the sound.

Do not touch the vibrating tuning fork to your skin, especially near your ear.

a) Record your observations in your log.

A tuning fork produces identical sounds from each prong. At one orientation from the prongs to your eardrum, you heard a loud sound. This loud sound was *constructive interference*. When the orientation from the prongs to your ear was different, the sound diminished.

The interference of waves is another property of wave behavior. If you are unsure that you observed the interference of sound, listen to the tuning fork again. Because sound from one prong of the tuning fork can interfere with the prong of the other tuning fork and produce areas of very low sound (nodes), you conclude that sound is exhibiting a wave phenomenon.

5. Is light a wave? Two properties that define waves are interference and diffraction. The process of light bending and spreading out as it squeezes through a small opening is called *diffraction*. Light bending around an edge is also referred to as diffraction. Here you will use a laser. Shine a laser beam against a wall as shown on the next page.

Never look directly at a laser beam or shine a laser beam into someone's eyes. Always work above the plane of the beam and beware of reflections from shiny surfaces.

a) Place a piece of paper on the wall, and trace the beam onto the piece of paper to measure its thickness. Record your measurement.

b) Place a single narrow slit in front of the beam. Measure and record the thickness of the beam again.

c) Place a thinner slit in front of the beam. Measure and record the thickness a final time.

d) What happens to the width of the laser beam as it passes through a smaller and smaller opening?

Diffraction is one of the properties that all waves exhibit, including water waves and sound waves. Diffraction of light seems to suggest that light is a wave.

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Active Physics

5.b)

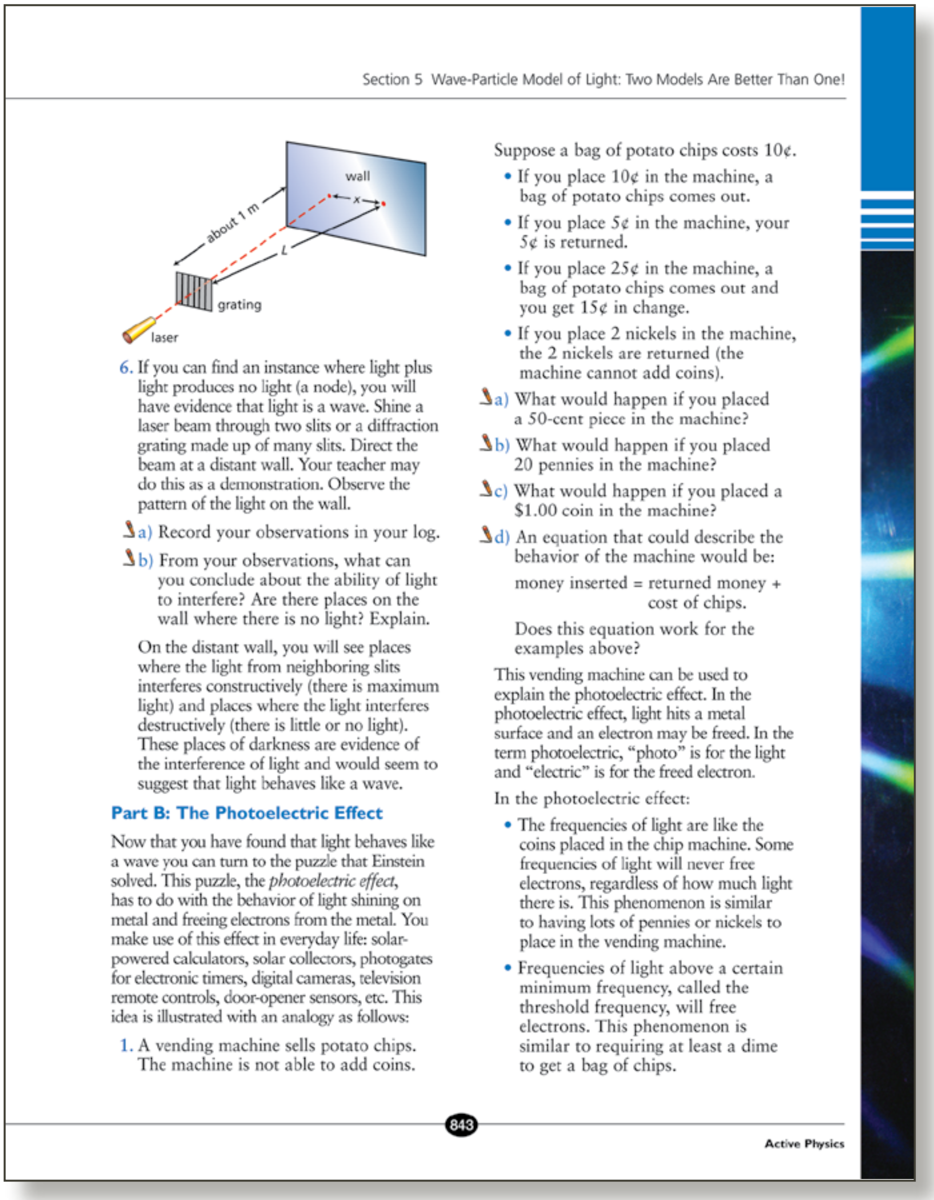
Placing a narrow slit in front of the beam will cause the beam to spread out. If the distance is kept constant the thickness of the beam will depend upon the width of the slit.

5.c)

A thinner slit will lead to greater spreading of the laser beam.

5.d)

The narrower the slit, the wider the laser beam spreads.



Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

6. If you can find an instance where light plus light produces no light (a node), you will have evidence that light is a wave. Shine a laser beam through two slits or a diffraction grating made up of many slits. Direct the beam at a distant wall. Your teacher may do this as a demonstration. Observe the pattern of the light on the wall.

a) Record your observations in your log.

b) From your observations, what can you conclude about the ability of light to interfere? Are there places on the wall where there is no light? Explain.

On the distant wall, you will see places where the light from neighboring slits interferes constructively (there is maximum light) and places where the light interferes destructively (there is little or no light). These places of darkness are evidence of the interference of light and would seem to suggest that light behaves like a wave.

Part B: The Photoelectric Effect

Now that you have found that light behaves like a wave you can turn to the puzzle that Einstein solved. This puzzle, the *photoelectric effect*, has to do with the behavior of light shining on metal and freeing electrons from the metal. You make use of this effect in everyday life: solar-powered calculators, solar collectors, photogates for electronic timers, digital cameras, television remote controls, door-opener sensors, etc. This idea is illustrated with an analogy as follows:

1. A vending machine sells potato chips. The machine is not able to add coins.

Suppose a bag of potato chips costs 10¢.

- If you place 10¢ in the machine, a bag of potato chips comes out.
- If you place 5¢ in the machine, your 5¢ is returned.
- If you place 25¢ in the machine, a bag of potato chips comes out and you get 15¢ in change.
- If you place 2 nickels in the machine, the 2 nickels are returned (the machine cannot add coins).

a) What would happen if you placed a 50-cent piece in the machine?

b) What would happen if you placed 20 pennies in the machine?

c) What would happen if you placed a $1.00 coin in the machine?

d) An equation that could describe the behavior of the machine would be:

money inserted = returned money + cost of chips.

Does this equation work for the examples above?

This vending machine can be used to explain the photoelectric effect. In the photoelectric effect, light hits a metal surface and an electron may be freed. In the term photoelectric, "photo" is for the light and "electric" is for the freed electron.

In the photoelectric effect:

- The frequencies of light are like the coins placed in the chip machine. Some frequencies of light will never free electrons, regardless of how much light there is. This phenomenon is similar to having lots of pennies or nickels to place in the vending machine.
- Frequencies of light above a certain minimum frequency, called the threshold frequency, will free electrons. This phenomenon is similar to requiring at least a dime to get a bag of chips.

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Active Physics

8-5b **Blackline Master**

6.a)

Students should see a series of spots radiating from the slits with areas of no light (dark areas) between the spots.

Teaching Tip

When shining a laser through a diffraction grating, the interference pattern is in the form of dots. These dots will appear at angles of 15 degrees or larger from the centerline of the laser beam, so it may be necessary to bring the screen to 1 m or less from the grating to see the side maxima. An interesting alternative to diffraction gratings is the "fireworks glasses" that show rainbow colors when looking at white light. They are also diffraction gratings of a different type, and will show the typical diffraction pattern when illuminated by a laser.

6.b)

Students should recognize that the bright areas are regions of constructive interference and the dark areas are destructive interference, indicating that light interferes like a wave.

Part B

1.a)

You would get 1 bag of potato chips and 40 cents in change.

1.b)

20 pennies would come out of the machine and no bag of chips.

1.c)

You would get one bag of potato chips and 90 cents in change.

1.d)

Yes, the example works.

2.a)

$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$ gives $12\text{ eV} = KE_{\text{electron}} + 7\text{ eV}$ or $KE_{\text{electron}} = 5\text{ eV}$. The electron is ejected with a kinetic energy of 5 eV.

2.b)

$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$ gives $12\text{ eV} = KE_{\text{electron}} + 12\text{ eV}$ or $KE_{\text{electron}} = 0\text{ eV}$. The electron just drifts off the atom without any kinetic energy.

2.c)

$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$ gives $18\text{ eV} = KE_{\text{electron}} + 7\text{ eV}$ or $KE_{\text{electron}} = 11\text{ eV}$. The electron is ejected with a kinetic energy of 11 eV.

2.d)

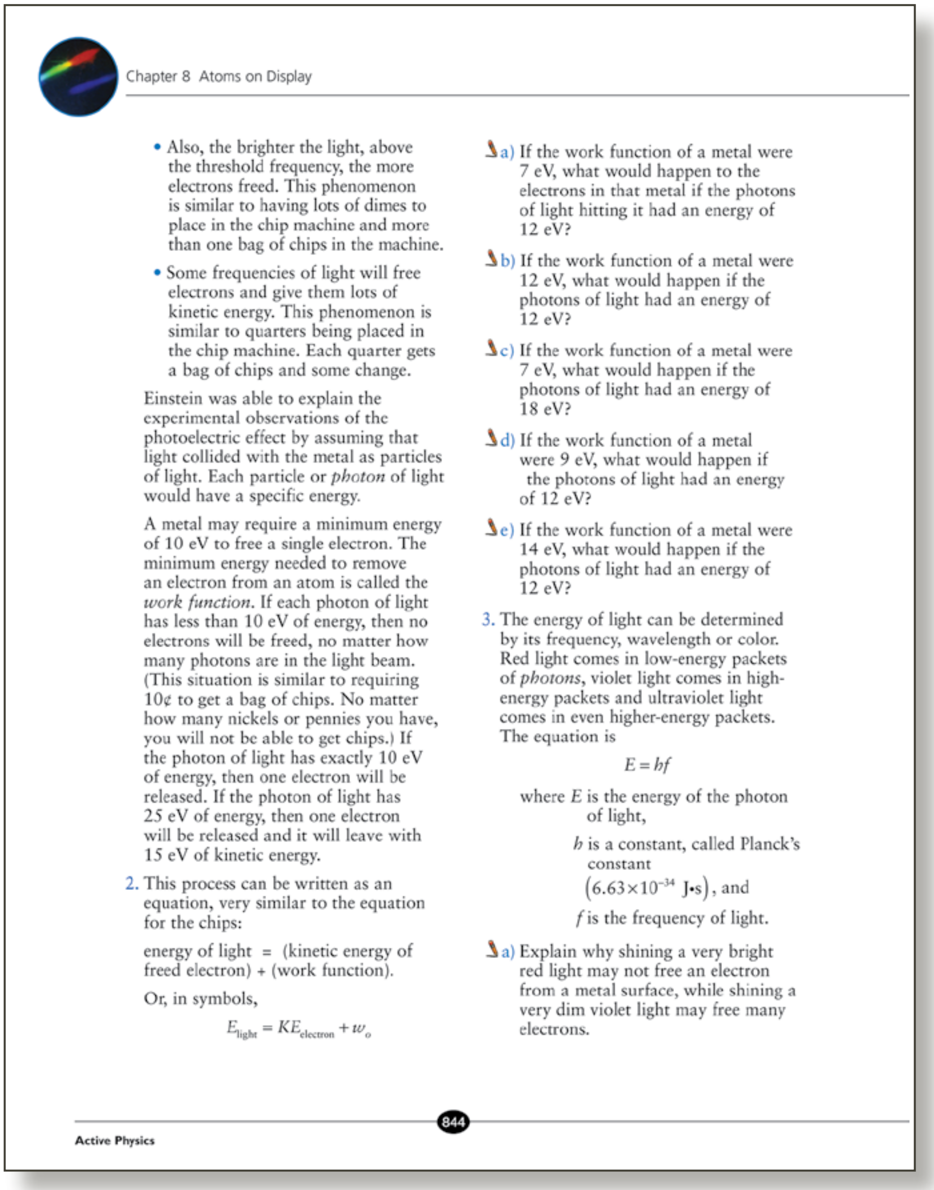
$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$ gives $12\text{ eV} = KE_{\text{electron}} + 9\text{ eV}$ or $KE_{\text{electron}} = 3\text{ eV}$. The electron is ejected with a kinetic energy of 3 eV.

2.e)

$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$ gives $12\text{ eV} = KE_{\text{electron}} + 14\text{ eV}$ or $KE_{\text{electron}} = -2\text{ eV}$. This photon would be rejected, and no electron would be ejected from the atom.

3.a)

A very bright red light consists of many photons of red light, but each photon has a relatively low energy, which may be less than the work function of the atom. Therefore, no electrons will be ejected. Although a very dim violet light only consists of a few photons, each photon would have energy greater than the work function of the atom, so any photon that strikes an atom would eject an electron with some kinetic energy.



- Also, the brighter the light, above the threshold frequency, the more electrons freed. This phenomenon is similar to having lots of dimes to place in the chip machine and more than one bag of chips in the machine.
- Some frequencies of light will free electrons and give them lots of kinetic energy. This phenomenon is similar to quarters being placed in the chip machine. Each quarter gets a bag of chips and some change.

Einstein was able to explain the experimental observations of the photoelectric effect by assuming that light collided with the metal as particles of light. Each particle or *photon* of light would have a specific energy.

A metal may require a minimum energy of 10 eV to free a single electron. The minimum energy needed to remove an electron from an atom is called the *work function*. If each photon of light has less than 10 eV of energy, then no electrons will be freed, no matter how many photons are in the light beam. (This situation is similar to requiring 10¢ to get a bag of chips. No matter how many nickels or pennies you have, you will not be able to get chips.) If the photon of light has exactly 10 eV of energy, then one electron will be released. If the photon of light has 25 eV of energy, then one electron will be released and it will leave with 15 eV of kinetic energy.

2. This process can be written as an equation, very similar to the equation for the chips:

energy of light = (kinetic energy of freed electron) + (work function).

Or, in symbols,

$$E_{\text{light}} = KE_{\text{electron}} + w_{\text{o}}$$

a) If the work function of a metal were 7 eV, what would happen to the electrons in that metal if the photons of light hitting it had an energy of 12 eV?

b) If the work function of a metal were 12 eV, what would happen if the photons of light had an energy of 12 eV?

c) If the work function of a metal were 7 eV, what would happen if the photons of light had an energy of 18 eV?

d) If the work function of a metal were 9 eV, what would happen if the photons of light had an energy of 12 eV?

e) If the work function of a metal were 14 eV, what would happen if the photons of light had an energy of 12 eV?

3. The energy of light can be determined by its frequency, wavelength or color. Red light comes in low-energy packets of *photons*, violet light comes in high-energy packets and ultraviolet light comes in even higher-energy packets. The equation is

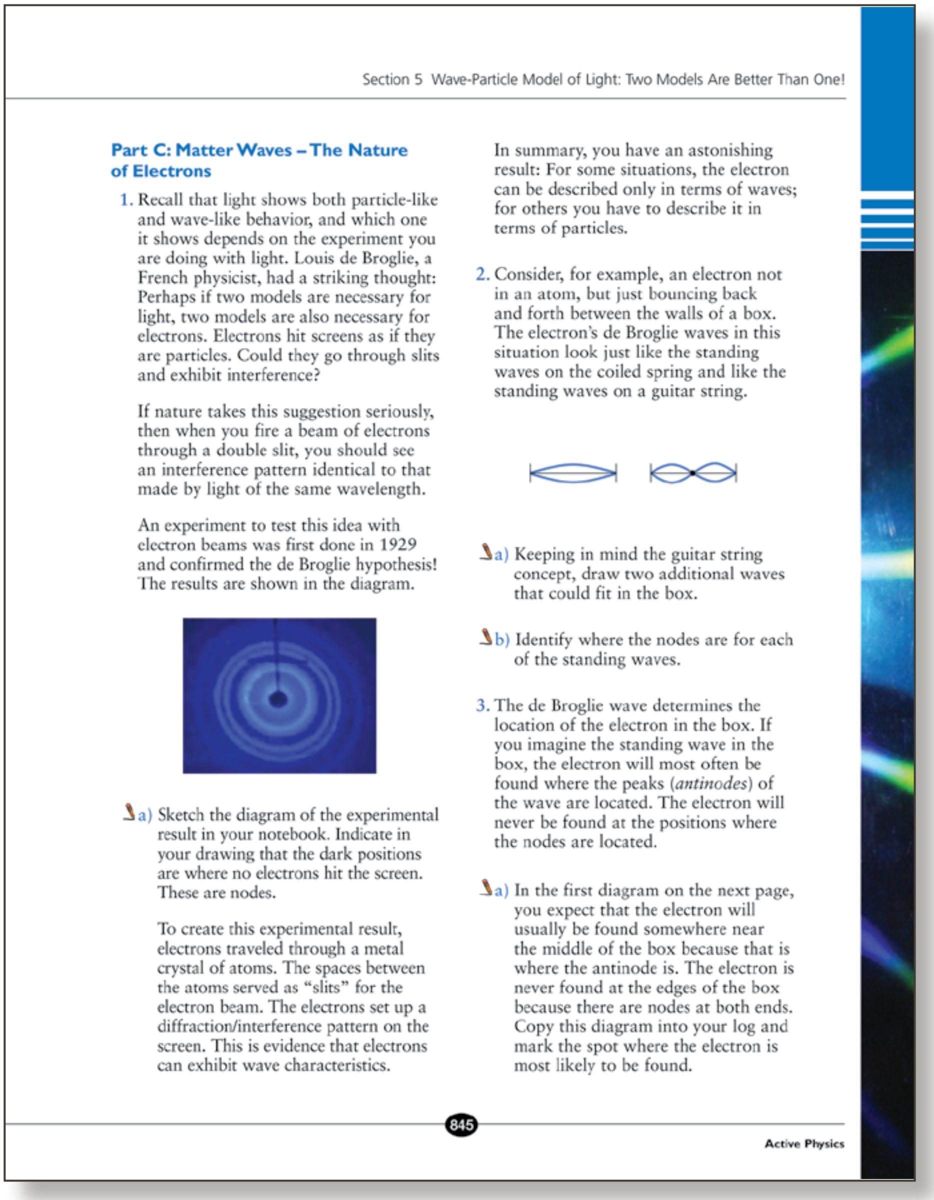
$$E = hf$$

where E is the energy of the photon of light,

h is a constant, called Planck's constant $(6.63\times10^{-34}\text{ J}\cdot\text{s})$, and

f is the frequency of light.

a) Explain why shining a very bright red light may not free an electron from a metal surface, while shining a very dim violet light may free many electrons.



Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

Part C: Matter Waves – The Nature of Electrons

1. Recall that light shows both particle-like and wave-like behavior, and which one it shows depends on the experiment you are doing with light. Louis de Broglie, a French physicist, had a striking thought: Perhaps if two models are necessary for light, two models are also necessary for electrons. Electrons hit screens as if they are particles. Could they go through slits and exhibit interference?

   If nature takes this suggestion seriously, then when you fire a beam of electrons through a double slit, you should see an interference pattern identical to that made by light of the same wavelength.

   An experiment to test this idea with electron beams was first done in 1929 and confirmed the de Broglie hypothesis! The results are shown in the diagram.

   a) Sketch the diagram of the experimental result in your notebook. Indicate in your drawing that the dark positions are where no electrons hit the screen. These are nodes.

   To create this experimental result, electrons traveled through a metal crystal of atoms. The spaces between the atoms served as "slits" for the electron beam. The electrons set up a diffraction/interference pattern on the screen. This is evidence that electrons can exhibit wave characteristics.

   In summary, you have an astonishing result: For some situations, the electron can be described only in terms of waves; for others you have to describe it in terms of particles.

2. Consider, for example, an electron not in an atom, but just bouncing back and forth between the walls of a box. The electron's de Broglie waves in this situation look just like the standing waves on the coiled spring and like the standing waves on a guitar string.

   a) Keeping in mind the guitar string concept, draw two additional waves that could fit in the box.

   b) Identify where the nodes are for each of the standing waves.

3. The de Broglie wave determines the location of the electron in the box. If you imagine the standing wave in the box, the electron will most often be found where the peaks (*antinodes*) of the wave are located. The electron will never be found at the positions where the nodes are located.

   a) In the first diagram on the next page, you expect that the electron will usually be found somewhere near the middle of the box because that is where the antinode is. The electron is never found at the edges of the box because there are nodes at both ends. Copy this diagram into your log and mark the spot where the electron is most likely to be found.

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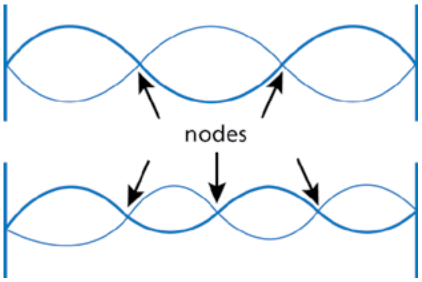
Part C

1.a)

Students copy the diagram in the left column of the *Student Edition* page into their notebooks and mark the dark areas between the bright rings as nodes.

2.a)

Two additional waves that fit in the box would have the same distance between the ends but would have three and four loops.



2.b)

The nodes in the left diagram would be at either end. For the diagram on the right, the nodes would be at each end plus the center. For the diagram with three and four loops, the nodes are in the positions shown plus the ends.

3.a)

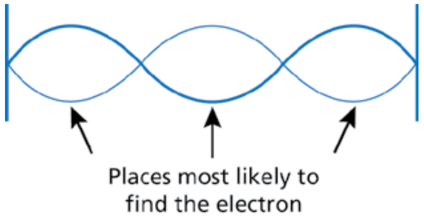
Students copy the diagram into their logs.

3.b)

Students copy the diagram into their logs.

3.c)

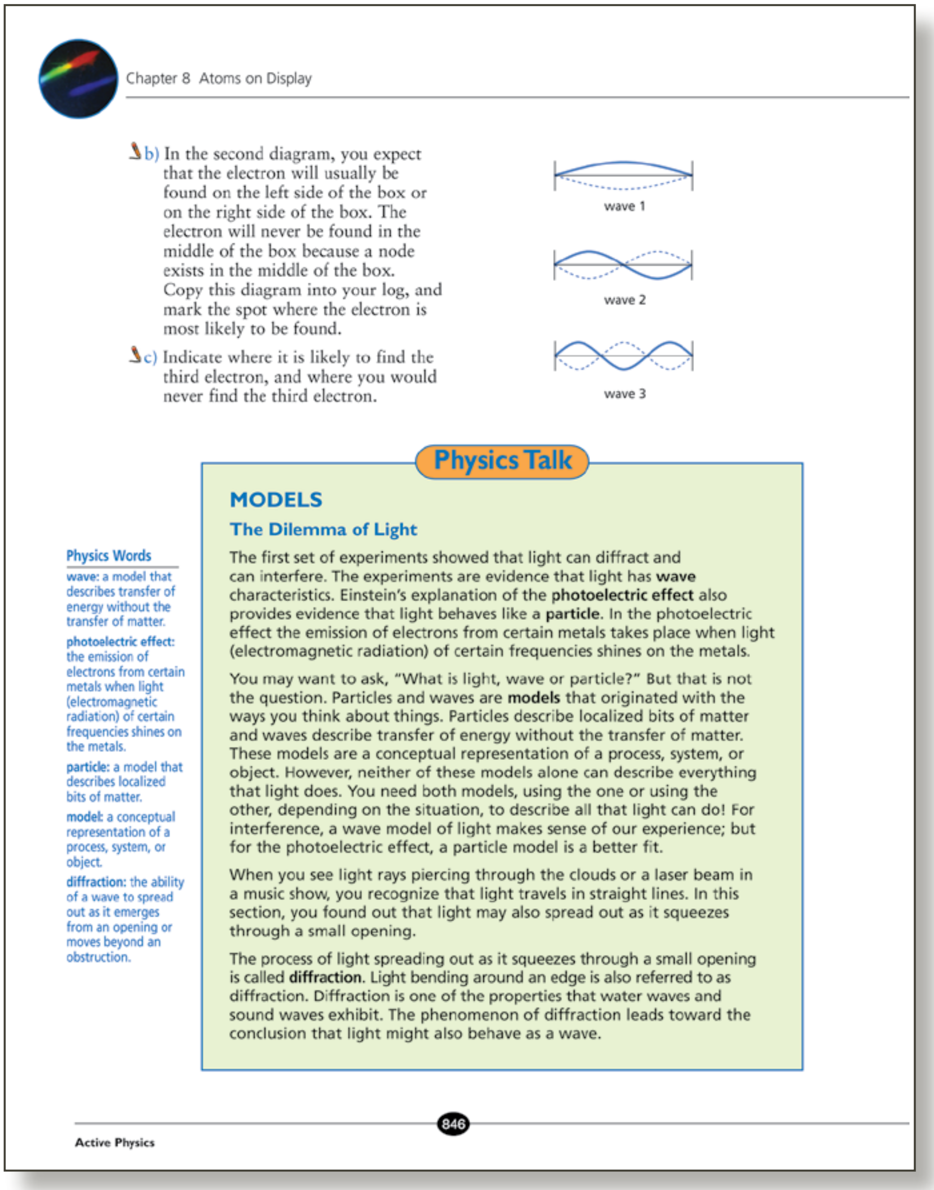
The electron is most likely to be found at the center, and in the left and right sides of the box as shown in the diagram below:



8-5c Blackline Master

Physics Talk

Students are introduced to the dilemma of light. They read about Einstein's explanation of the photoelectric effect and the phenomenon of diffraction. An analysis of the particle and wave nature of light explains why each of these models alone do not account for the behavior of light. Students then compare the dual nature of light to the dual nature of electrons and learn about Schrödinger's theory of probability and the equation that describes the most probable location for an electron of a specific energy. They discover why the subatomic world lies beyond everyday world experiences and contradicts common sense, but the models that have been developed of the subatomic world give accurate predictions.



Chapter 8 Atoms on Display

b) In the second diagram, you expect that the electron will usually be found on the left side of the box or on the right side of the box. The electron will never be found in the middle of the box because a node exists in the middle of the box. Copy this diagram into your log, and mark the spot where the electron is most likely to be found.

c) Indicate where it is likely to find the third electron, and where you would never find the third electron.

Physics Talk

MODELS

The Dilemma of Light

The first set of experiments showed that light can diffract and can interfere. The experiments are evidence that light has **wave** characteristics. Einstein's explanation of the **photoelectric effect** also provides evidence that light behaves like a **particle**. In the photoelectric effect the emission of electrons from certain metals takes place when light (electromagnetic radiation) of certain frequencies shines on the metals.

You may want to ask, "What is light, wave or particle?" But that is not the question. Particles and waves are **models** that originated with the ways you think about things. Particles describe localized bits of matter and waves describe transfer of energy without the transfer of matter. These models are a conceptual representation of a process, system, or object. However, neither of these models alone can describe everything that light does. You need both models, using the one or using the other, depending on the situation, to describe all that light can do! For interference, a wave model of light makes sense of our experience; but for the photoelectric effect, a particle model is a better fit.

When you see light rays piercing through the clouds or a laser beam in a music show, you recognize that light travels in straight lines. In this section, you found out that light may also spread out as it squeezes through a small opening.

The process of light spreading out as it squeezes through a small opening is called **diffraction**. Light bending around an edge is also referred to as diffraction. Diffraction is one of the properties that water waves and sound waves exhibit. The phenomenon of diffraction leads toward the conclusion that light might also behave as a wave.

Physics Words

wave: a model that describes transfer of energy without the transfer of matter.

photoelectric effect: the emission of electrons from certain metals when light (electromagnetic radiation) of certain frequencies shines on the metals.

particle: a model that describes localized bits of matter.

model: a conceptual representation of a process, system, or object.

diffraction: the ability of a wave to spread out as it emerges from an opening or moves beyond an obstruction.

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Active Physics

Ask students to relate the experiments in the *Investigate* to the characteristics of waves and the models that describe particles and waves. Review why a wave model of light makes sense of wave interference, but a particle model describes the photoelectric effect. To reinforce the phenomenon of diffraction, have students draw diagrams of standing waves showing where constructive and destructive interference occurs. Ask them why the evidence of interference of light demonstrates that light has wave-like properties.

Discuss the photoelectric effect and how Einstein developed a model for the process, which described the behavior of light as a photon colliding with an electron. Determine if students understand the concept of a photon and the idea that light behaves sometimes like a wave and sometimes like a particle.

Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

You also explored another property of water and sound waves. When water waves meet, they interfere with one another. **Constructive interference** occurs when the crests of a wave meet the crests of the second wave, and there is lots of movement of the water. **Destructive interference** occurs when the troughs of one wave meet the crests of the other wave and the water remains still.

You used a tuning fork to investigate if sound waves also interfere. A tuning fork produces identical sounds from each prong. At one orientation from the prongs to your eardrum, you heard a loud sound. This loud sound was constructive interference. When the orientation from the prongs to your ear was different, the sound diminished. The sound from one source can meet with the sound from another source and produce silence! The interference of waves is another property of wave behavior.

If light behaves like a wave, then it, too, must show interference. When you shone a laser beam through two slits onto a distant wall, you saw an interference pattern. There were places where the light from neighboring slits interfered constructively (there was maximum light) and places where the light interfered destructively (there was little or no light). Evidence of the interference of light would seem to prove that light behaves like a wave. The colors you see when light reflects off a CD or soap bubble are interference effects.

After you found that light behaves like a wave, you turned to the puzzle of the twentieth century that Einstein solved. The puzzle had to do with the behavior of light when it freed an electron from a metal. In the photoelectric effect, when beams of light shine on metals, some **wavelengths** (and **frequencies**) of light will always free electrons, while other wavelengths (and frequencies) will never free electrons. For some materials, light of high frequency (ultraviolet light) frees electrons and gives them kinetic energy. Light of low frequency (red light) is not able to free any electrons. Einstein developed a model of the process

→

Physics Words

constructive interference: the result of adding waves crest-to-crest to produce a wave with a greater amplitude.

destructive interference: the result of adding waves crest-to-trough to produce a wave with a decreased amplitude.

wavelength: crest-to-crest distance in a wave.

frequency: number of cycles per second in the wave's vibration.

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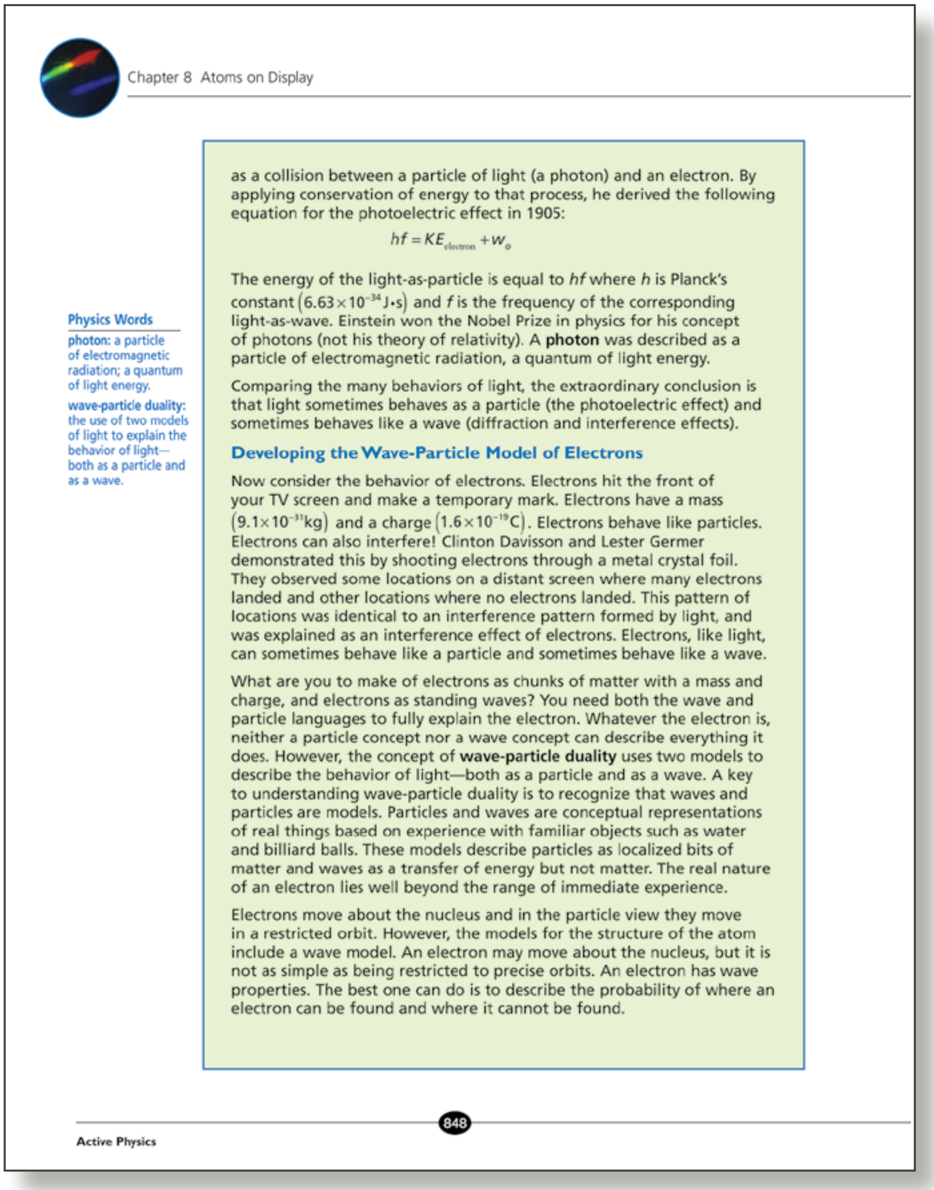
Active Physics

As students consider the behavior of electrons, discuss Davisson's and Germer's experiment that explored the interference effect of electrons and helped scientists to conclude that electrons, too, have a wave-like and particle-like nature. Encourage them to draw diagrams that illustrate the photoelectric effect and the structure of an atom that shows the position of electrons indicating a wave-like orbit. Emphasize how the theories that explained the behavior of electrons developed gradually and more accurately explained their wave-like nature. Ask students to trace the timeline of this development from Neils Bohr to Erwin Schrödinger.



Physics Words

photon: a particle of electromagnetic radiation; a quantum of light energy.

wave-particle duality: the use of two models of light to explain the behavior of light—both as a particle and as a wave.

as a collision between a particle of light (a photon) and an electron. By applying conservation of energy to that process, he derived the following equation for the photoelectric effect in 1905:

$$hf = KE_{\text{electron}} + w_o$$

The energy of the light-as-particle is equal to hf where h is Planck's constant $(6.63 \times 10^{-34}\,\text{J}\cdot\text{s})$ and f is the frequency of the corresponding light-as-wave. Einstein won the Nobel Prize in physics for his concept of photons (not his theory of relativity). A **photon** was described as a particle of electromagnetic radiation, a quantum of light energy.

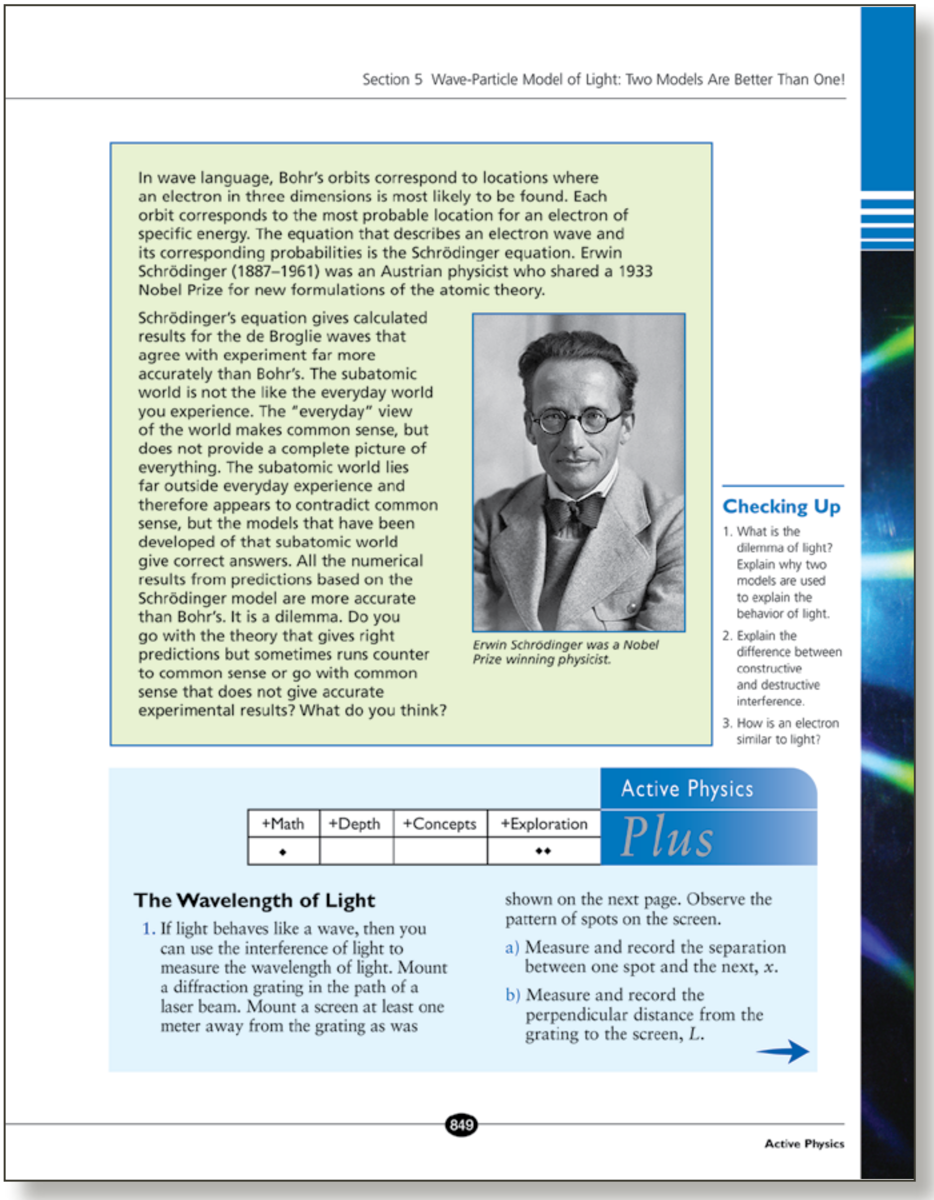
Comparing the many behaviors of light, the extraordinary conclusion is that light sometimes behaves as a particle (the photoelectric effect) and sometimes behaves like a wave (diffraction and interference effects).

Developing the Wave-Particle Model of Electrons

Now consider the behavior of electrons. Electrons hit the front of your TV screen and make a temporary mark. Electrons have a mass $(9.1 \times 10^{-31}\,\text{kg})$ and a charge $(1.6 \times 10^{-19}\,\text{C})$. Electrons behave like particles. Electrons can also interfere! Clinton Davisson and Lester Germer demonstrated this by shooting electrons through a metal crystal foil. They observed some locations on a distant screen where many electrons landed and other locations where no electrons landed. This pattern of locations was identical to an interference pattern formed by light, and was explained as an interference effect of electrons. Electrons, like light, can sometimes behave like a particle and sometimes behave like a wave.

What are you to make of electrons as chunks of matter with a mass and charge, and electrons as standing waves? You need both the wave and particle languages to fully explain the electron. Whatever the electron is, neither a particle concept nor a wave concept can describe everything it does. However, the concept of **wave-particle duality** uses two models to describe the behavior of light—both as a particle and as a wave. A key to understanding wave-particle duality is to recognize that waves and particles are models. Particles and waves are conceptual representations of real things based on experience with familiar objects such as water and billiard balls. These models describe particles as localized bits of matter and waves as a transfer of energy but not matter. The real nature of an electron lies well beyond the range of immediate experience.

Electrons move about the nucleus and in the particle view they move in a restricted orbit. However, the models for the structure of the atom include a wave model. An electron may move about the nucleus, but it is not as simple as being restricted to precise orbits. An electron has wave properties. The best one can do is to describe the probability of where an electron can be found and where it cannot be found.



Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

In wave language, Bohr's orbits correspond to locations where an electron in three dimensions is most likely to be found. Each orbit corresponds to the most probable location for an electron of specific energy. The equation that describes an electron wave and its corresponding probabilities is the Schrödinger equation. Erwin Schrödinger (1887–1961) was an Austrian physicist who shared a 1933 Nobel Prize for new formulations of the atomic theory.

Schrödinger's equation gives calculated results for the de Broglie waves that agree with experiment far more accurately than Bohr's. The subatomic world is not the like the everyday world you experience. The "everyday" view of the world makes common sense, but does not provide a complete picture of everything. The subatomic world lies far outside everyday experience and therefore appears to contradict common sense, but the models that have been developed of that subatomic world give correct answers. All the numerical results from predictions based on the Schrödinger model are more accurate than Bohr's. It is a dilemma. Do you go with the theory that gives right predictions but sometimes runs counter to common sense or go with common sense that does not give accurate experimental results? What do you think?

Erwin Schrödinger was a Nobel Prize winning physicist.

Checking Up

1. What is the dilemma of light? Explain why two models are used to explain the behavior of light.
2. Explain the difference between constructive and destructive interference.
3. How is an electron similar to light?

Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
◆			◆◆

The Wavelength of Light

1. If light behaves like a wave, then you can use the interference of light to measure the wavelength of light. Mount a diffraction grating in the path of a laser beam. Mount a screen at least one meter away from the grating as was shown on the next page. Observe the pattern of spots on the screen.
   a) Measure and record the separation between one spot and the next, x.
   b) Measure and record the perpendicular distance from the grating to the screen, L.

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Active Physics

Checking Up

1.

The dilemma of light is that it appears to behave as both a particle and a wave, depending upon the way it interacts with our observations. Light behaves as a wave in experiments that measure interference, and as a particle in experiments that verify the photoelectric effect. Because these two conflicting behaviors cannot reconcile, two models to explain the behavior of light are chosen.

2.

Constructive interference occurs when waves arrive at a point in phase (crest on crest and trough on trough), and two waves combine to produce a wave with an amplitude that is the sum of the two individual wave amplitudes. Destructive interference occurs when waves arrive at a point that is out of phase (crest on trough) and two waves combine to produce a wave that has an amplitude equal to the difference between the amplitudes of the two individual waves.

3.

An electron is similar to light because it sometimes behaves as a wave and sometimes as a particle. The electron behaves as a particle in collision experiments, but also has a wave nature, allowing it to exhibit interference.

Active Physics Plus

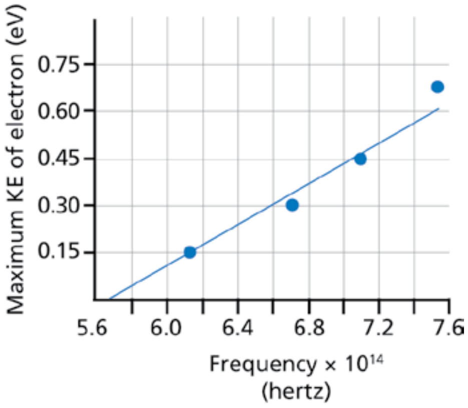
Students use diffraction patterns on a screen to calculate the wavelength of light by measuring the distance between two adjacent areas of constructive interference (bright spots) and using the equation $\lambda = dx/L$. They study the photoelectric effect by graphing the kinetic energy of the ejected electron against the frequency of the incident light to determine the threshold frequency of the material.

1.a)–c)

Student activity. If using a red diode (pen) laser, the students should expect a wavelength of 670 nm. If using a helium-neon laser, the wavelength should be 633 nm. The spacing of the lines will depend upon the diffraction grating used. To get the spacing between the diffraction grating lines if only the lines/mm is listed take the inverse of the lines/mm to get the mm/line. This distance is essentially the same as the distance between the lines.

2.a)

The students graph should be similar to the one shown below.



2.b)

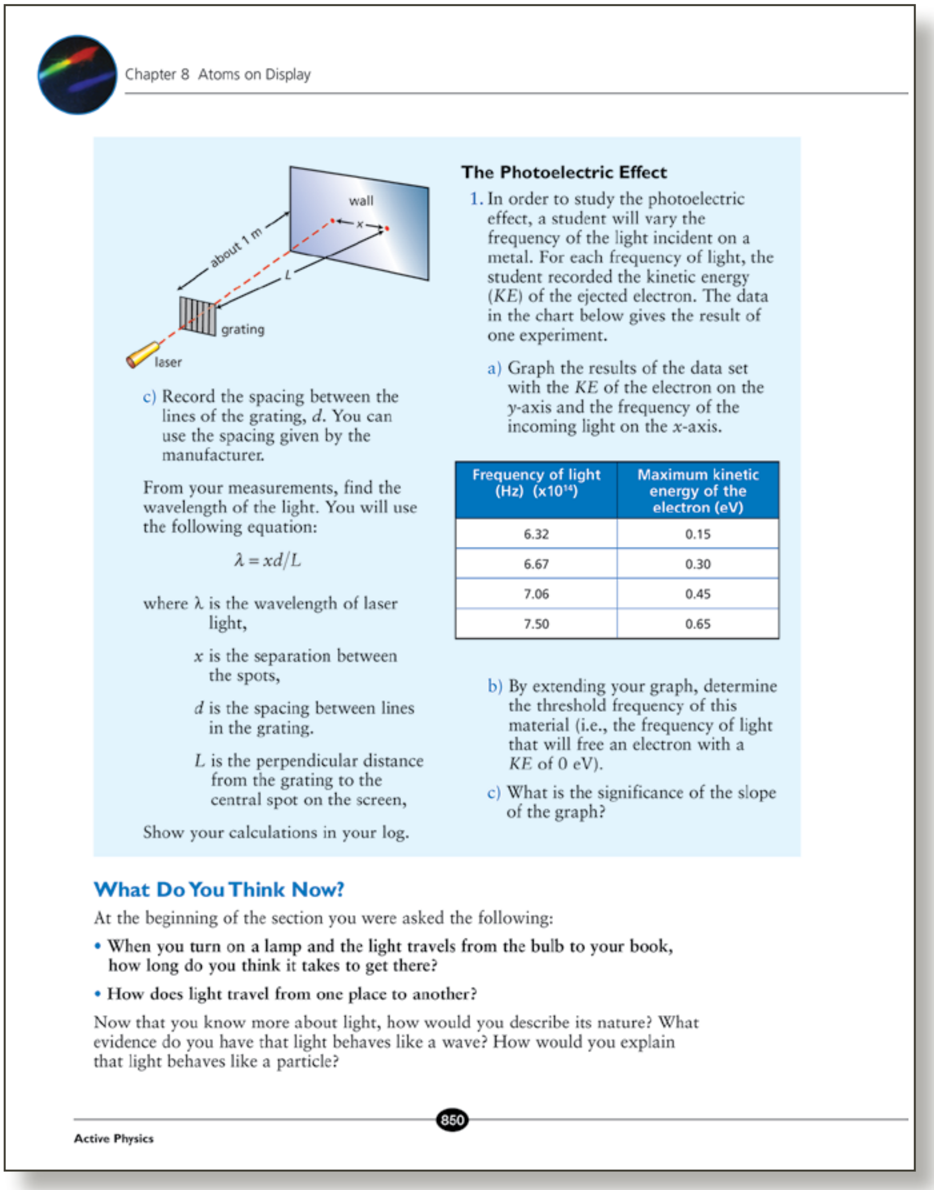
According to the graph, the threshold frequency is approximately 5.7×10^{14} Hz.

2.c)

The slope of the graph is Planck's Constant.

What Do You Think Now?

Students should be able to describe the nature of light traveling from the lamp to the book as electromagnetic radiation that cannot be explained by either the particle or wave model alone. Their answers should include an explanation that light travels as photons that have both wave and particle properties. Share *A Physicist's Response* and encourage students to update and revise their answers. Invite them to discuss any questions they might have and refer to prior conceptions, pointing out how their investigations have helped them in modifying commonly held beliefs.



Chapter 8 Atoms on Display

c) Record the spacing between the lines of the grating, *d*. You can use the spacing given by the manufacturer.

From your measurements, find the wavelength of the light. You will use the following equation:

$$\lambda = xd/L$$

where λ is the wavelength of laser light,

x is the separation between the spots,

d is the spacing between lines in the grating.

L is the perpendicular distance from the grating to the central spot on the screen,

Show your calculations in your log.

The Photoelectric Effect

1. In order to study the photoelectric effect, a student will vary the frequency of the light incident on a metal. For each frequency of light, the student recorded the kinetic energy (*KE*) of the ejected electron. The data in the chart below gives the result of one experiment.

a) Graph the results of the data set with the *KE* of the electron on the *y*-axis and the frequency of the incoming light on the *x*-axis.

Frequency of light (Hz) ($\times 10^{14}$)	Maximum kinetic energy of the electron (eV)
6.32	0.15
6.67	0.30
7.06	0.45
7.50	0.65

b) By extending your graph, determine the threshold frequency of this material (i.e., the frequency of light that will free an electron with a *KE* of 0 eV).

c) What is the significance of the slope of the graph?

What Do You Think Now?

At the beginning of the section you were asked the following:

- When you turn on a lamp and the light travels from the bulb to your book, how long do you think it takes to get there?
- How does light travel from one place to another?

Now that you know more about light, how would you describe its nature? What evidence do you have that light behaves like a wave? How would you explain that light behaves like a particle?

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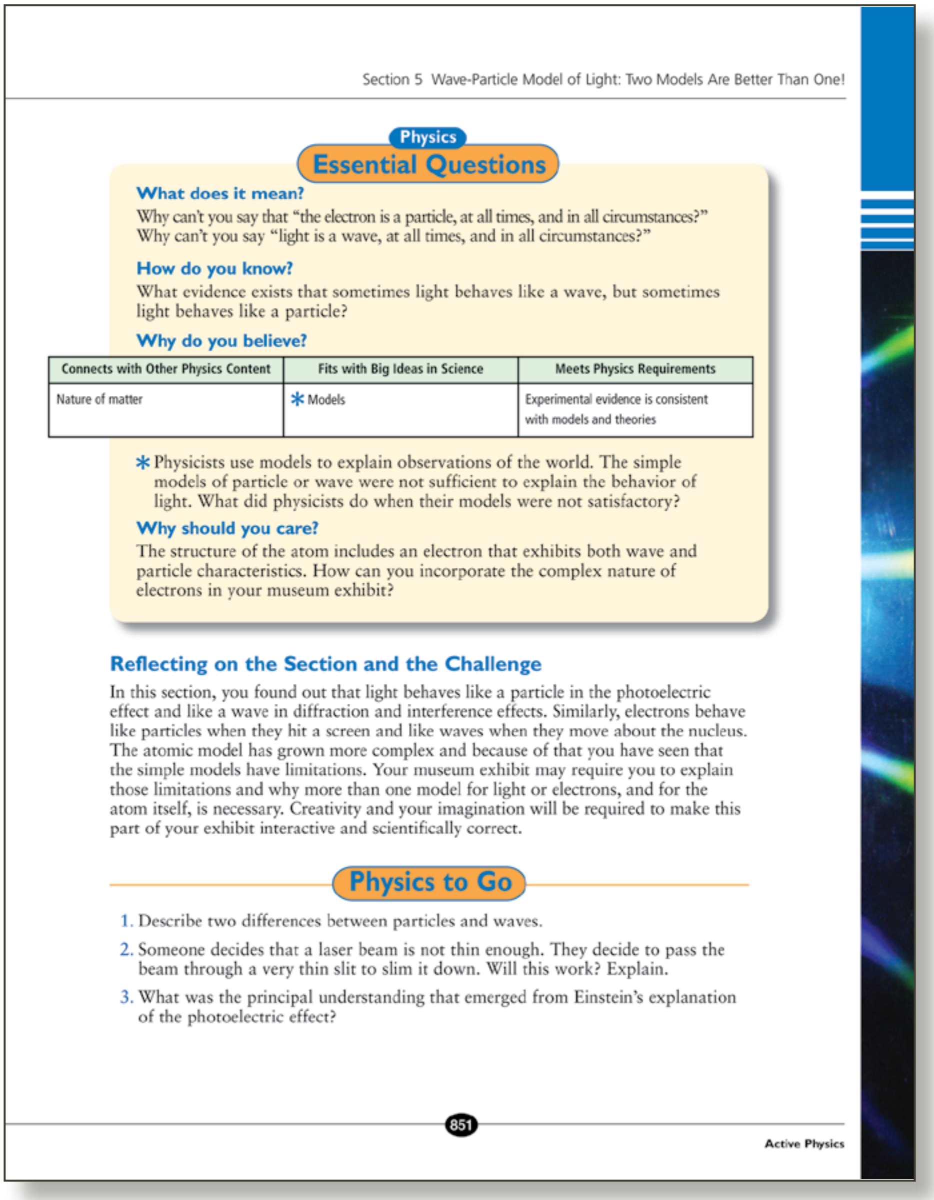
Active Physics

Reflecting on the Section and the Challenge

As you allow time for students to reflect on what they have learned about the nature of light, consider asking them to review how the photoelectric effect supports the particle model of light and interference and diffraction support the wave model. De Broglie's hypothesis extends the duality of light to the duality of matter and demonstrates the symmetry of nature in the quantum region. Emphasize that students should include the limitations of each model when they present the structure of an atom for their *Chapter Challenge*.



Section 5 Wave-Particle Model of Light: Two Models Are Better Than One!

Physics Essential Questions

What does it mean?

Why can't you say that "the electron is a particle, at all times, and in all circumstances?" Why can't you say "light is a wave, at all times, and in all circumstances?"

How do you know?

What evidence exists that sometimes light behaves like a wave, but sometimes light behaves like a particle?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Nature of matter	* Models	Experimental evidence is consistent with models and theories

* Physicists use models to explain observations of the world. The simple models of particle or wave were not sufficient to explain the behavior of light. What did physicists do when their models were not satisfactory?

Why should you care?

The structure of the atom includes an electron that exhibits both wave and particle characteristics. How can you incorporate the complex nature of electrons in your museum exhibit?

Reflecting on the Section and the Challenge

In this section, you found out that light behaves like a particle in the photoelectric effect and like a wave in diffraction and interference effects. Similarly, electrons behave like particles when they hit a screen and like waves when they move about the nucleus. The atomic model has grown more complex and because of that you have seen that the simple models have limitations. Your museum exhibit may require you to explain those limitations and why more than one model for light or electrons, and for the atom itself, is necessary. Creativity and your imagination will be required to make this part of your exhibit interactive and scientifically correct.

Physics to Go

1. Describe two differences between particles and waves.
2. Someone decides that a laser beam is not thin enough. They decide to pass the beam through a very thin slit to slim it down. Will this work? Explain.
3. What was the principal understanding that emerged from Einstein's explanation of the photoelectric effect?

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Active Physics

Physics to Go

1.

Particles can hit an object at a specific location while waves are spread out. When shot toward two slits, particles go through one slit or the other, while waves go through both slits. Waves can diffract and interfere, while particles do not.

2.

No, this will not work. As the slit gets thinner, there is greater diffraction and the beam will spread out.

3.

Einstein's explanation of the photoelectric effect showed that light can behave as a particle. In particular, the photoelectric makes sense *only* in terms of a *collision* between an electron and a particle of light.

Physics Essential Questions

What does it mean?

Under different circumstances, the electron exhibits wave characteristics or particle characteristics. Neither model explains all characteristics. The same can be said for light.

How do you know?

When light passes through two slits, one observes an interference pattern—evidence that a wave model can describe light. In the photoelectric effect, light hits the metal and releases an electron as if it were a particle.

Why do you believe?

When current models are not able to explain the existing experimental evidence, then new models are created. These models may predict new phenomenon that you can search for.

Why should you care?

Visitors can be asked whether the electron will behave more like a wave or more like a particle. Whichever they choose, experiments that are inconsistent with that model can be displayed.

4.

The baseball has a defined path. It moves left and it moves right. From its past behavior, you have a good chance of knowing where it will be. The electron in a box is restricted in certain ways. This restricts its energy and the probability of where it will be found. The wavelength of the baseball moving at 30 m/s would be given by $\lambda = h/mv$ or

$$\lambda = \frac{(6.6\times10^{-34}\ \text{J}\cdot\text{s})}{(0.145\ \text{kg})(30\ \text{m/s})}$$
$$= 1.5\times10^{-34}\ \text{m}$$

5.

Using $KE_{\text{electron}} = E_{\text{light}} - w_{\text{o}}$ and substituting in the energy of the photon and the work function gives $KE_{\text{electron}} = 10\ \text{eV} - 4.2\ \text{eV} = 5.8\ \text{eV}$

6.

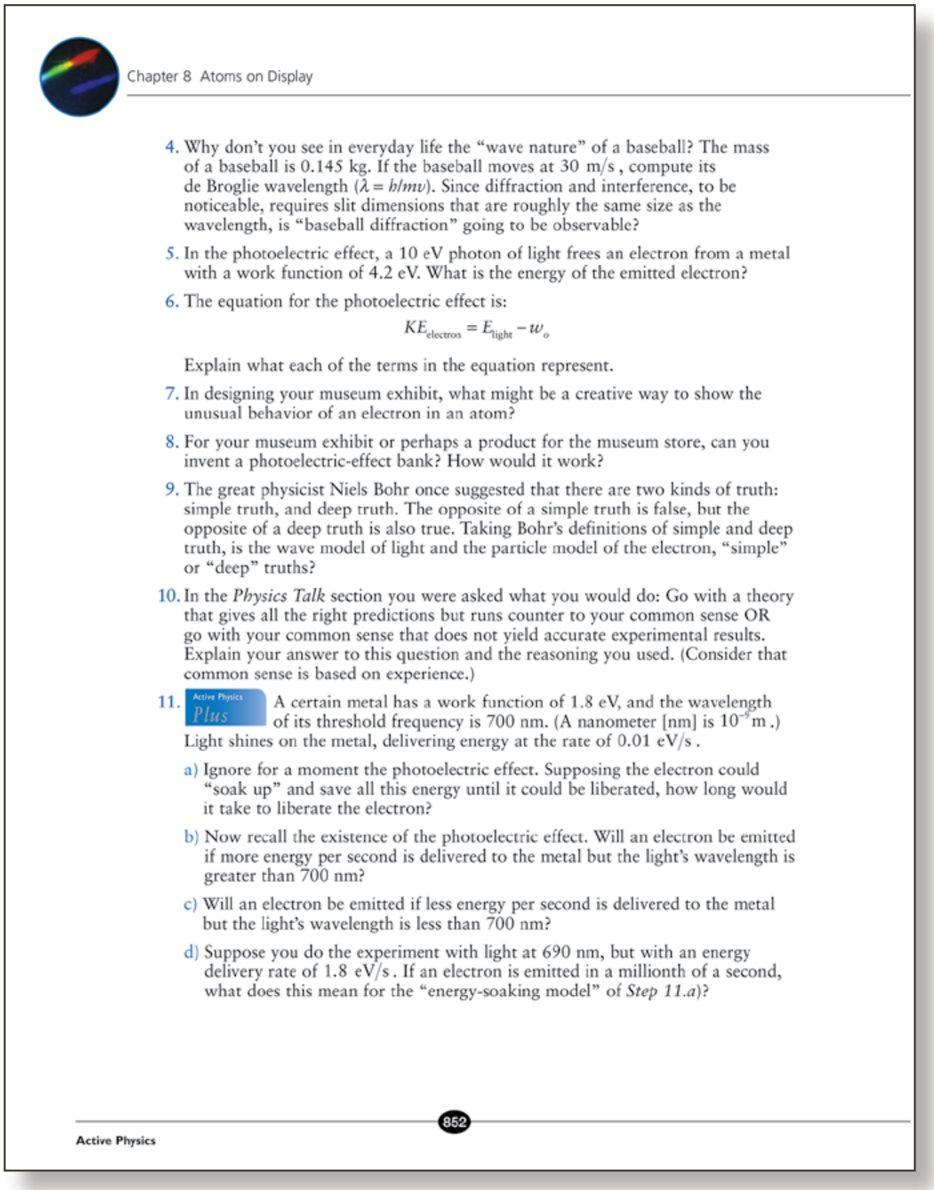
$KE_{\text{electron}} = E_{\text{light}} - w_{\text{o}}$. The KE term represents the kinetic energy of the freed electron. The E_{light} represents the energy of the incoming light The w_{o} represents the work function, the least energy required to free the electron.

7.

Student answers will vary.

8.

Student answers will vary. A photoelectric bank could be made to only accept coins of a certain size or larger. For example, only coins the size of a quarter or larger might fit, while smaller coins would be rejected. A weighing mechanism might be used to determine if the coin was large enough to be accepted.



Chapter 8 Atoms on Display

4. Why don't you see in everyday life the "wave nature" of a baseball? The mass of a baseball is 0.145 kg. If the baseball moves at 30 m/s, compute its de Broglie wavelength ($\lambda = h/mv$). Since diffraction and interference, to be noticeable, requires slit dimensions that are roughly the same size as the wavelength, is "baseball diffraction" going to be observable?

5. In the photoelectric effect, a 10 eV photon of light frees an electron from a metal with a work function of 4.2 eV. What is the energy of the emitted electron?

6. The equation for the photoelectric effect is:

$$KE_{\text{electron}} = E_{\text{light}} - w_{\text{o}}$$

Explain what each of the terms in the equation represent.

7. In designing your museum exhibit, what might be a creative way to show the unusual behavior of an electron in an atom?

8. For your museum exhibit or perhaps a product for the museum store, can you invent a photoelectric-effect bank? How would it work?

9. The great physicist Niels Bohr once suggested that there are two kinds of truth: simple truth, and deep truth. The opposite of a simple truth is false, but the opposite of a deep truth is also true. Taking Bohr's definitions of simple and deep truth, is the wave model of light and the particle model of the electron, "simple" or "deep" truths?

10. In the *Physics Talk* section you were asked what you would do: Go with a theory that gives all the right predictions but runs counter to your common sense OR go with your common sense that does not yield accurate experimental results. Explain your answer to this question and the reasoning you used. (Consider that common sense is based on experience.)

11. Active Physics *Plus* A certain metal has a work function of 1.8 eV, and the wavelength of its threshold frequency is 700 nm. (A nanometer [nm] is 10^{-9} m.) Light shines on the metal, delivering energy at the rate of 0.01 eV/s.

a) Ignore for a moment the photoelectric effect. Supposing the electron could "soak up" and save all this energy until it could be liberated, how long would it take to liberate the electron?

b) Now recall the existence of the photoelectric effect. Will an electron be emitted if more energy per second is delivered to the metal but the light's wavelength is greater than 700 nm?

c) Will an electron be emitted if less energy per second is delivered to the metal but the light's wavelength is less than 700 nm?

d) Suppose you do the experiment with light at 690 nm, but with an energy delivery rate of 1.8 eV/s. If an electron is emitted in a millionth of a second, what does this mean for the "energy-soaking model" of *Step 11.a*)?

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Active Physics

9.

The wave of light and the particle model of the electron would each be simple truths, whereas the true behavior of both is a much more profound truth that combines both concepts in a way we do not truly understand.

10.

Answers will vary and will reflect the students' opinions. Scientists have decided that correct predictions are the way to go.

11.a) Active Physics *Plus*

To liberate an electron, 1.8 eV is needed. At 0.01 eV/s, 180 seconds (3 minutes) would be required to soak up enough energy to free the electron.

11.b) Active Physics *Plus*

No, a wavelength greater than the threshold wavelength would not eject an electron regardless of the length of time the light shines.

11.c) Active Physics *Plus*

Yes, a wavelength shorter than the threshold wavelength of 700 nm will be able to eject an electron since the energy would be concentrated into a single photon with sufficient energy to eject the electron.

11.d) Active Physics *Plus*

An energy of 1.8 eV/s at 1×10^{-6} s gives an average energy delivered 1.8×10^{-6} eV during this time. However, all the energy was delivered in the one millionth of the second, so the electron would be ejected. This disproves the energy-soaking model that would predict taking the full one second to store up enough energy to eject the electron.

NOTES

SECTION 5 QUIZ

8-5d **Blackline Master**

1. Which of the following is evidence for the wave nature of light?

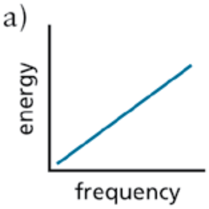
   a) reflection
   b) photoelectric effect
   c) double-slit interference
   d) Rutherford scattering

2. Which of the following is evidence for the particle nature of light?

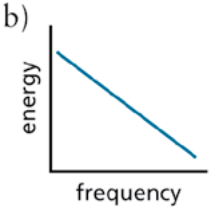
   a) reflection
   b) photoelectric effect
   c) double-slit interference
   d) Millikan experiment

3. Which graph below correctly shows the relationship between the frequency of a photon of light and the energy of the photon?

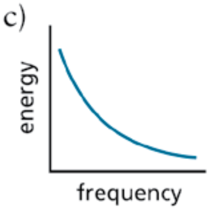
a)



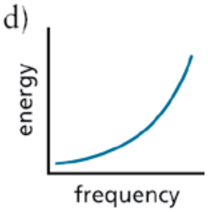
b)



c)



d)



4. A student shines a laser through a series of narrow slits, forming a spot on a screen beyond the slits. As the width of the slits decreases, the spot on the screen

   a) becomes smaller and better focused.
   b) becomes wider and less focused.
   c) remains the same width.
   d) becomes focused down to a single point.

5. Which statement below best compares the behavior of photons of light to electrons?

   a) Electrons always behave as particles and photons always behave as waves.
   b) Electrons always behave as waves and photons always behave as particles.
   c) Both electrons and photons can appear to behave as either particles or waves.
   d) Photons can behave as either particles or waves, but electrons can only behave as particles.

SECTION 5 QUIZ ANSWERS

① c) double-slit interference. The double-slit interference is evidence for the wave nature of light.

② b) photoelectric effect. The photoelectric effect can only be explained by assuming light is a particle. For answer a), although particles will reflect from a surface, waves will as well, not allowing us to choose between the two models for light.

③ a) The energy of a photon is given by the equation $E = hf$. This is a direct relation, which is shown by a graph of a straight line. Answer b is incorrect, since it shows the energy decreasing as the frequency increases.

④ b) becomes wider and less focused. A wave passing through a narrow opening will diffract and spread out, causing the beam to become wider.

⑤ c) Both electrons and photons can appear to behave as either particles or waves. Both electrons and photons exhibit both wave and particle behavior under different circumstances. Neither always acts as a particle or a wave all the time.