The Dual Nature of Light

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Concept 1 The Dual Nature of Light

Lesson Objectives

The student will:

- name the model that replaced the Bohr model of the atom.
- explain the concept of wave-particle duality.
- solve problems involving the relationship between the frequency and the energy of a photon.

Vocabulary

- black body radiation
- diffraction
- interference
- photoelectric effect
- photon
- quantum
- quantum mechanics
- quantum theory
- wave-particle duality

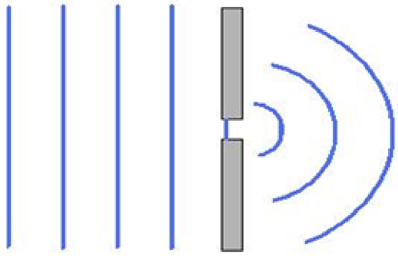
Introduction

Further development in our understanding of the behavior of electrons in an atom's electron cloud required some major changes in our ideas about both matter and energy.

The branch of physics that deals with the motions of objects under the influence of forces is called mechanics. Classical mechanics refers to the laws of motion developed by Isaac Newton in the 1600s. When the Bohr model of the atom could not predict the energy levels of electrons in atoms with more than one electron, it seemed a new approach to explaining the behavior of electrons was necessary. Developed in the early 1900s, this new approach was based on the work of many scientists. The new approach came to be known as quantum mechanics (also called wave mechanics). **Quantum mechanics** is the branch of physics that deals with the behavior of matter at the atomic and subatomic level.

Properties of Waves

The controversy over the nature of light in the 1600s was partially due to the fact that different experiments with light gave different indications about the nature of light. Energy waveforms, such as water waves or sound waves, were found to exhibit certain characteristics, including **diffraction** (the bending of waves around corners) and **interference** (the adding or subtracting of energies when waves overlap).



In the image above, the sketch on the left shows a series of ocean wave crests (the long straight blue lines) striking a sea wall. The sea wall has a gap between the cement barriers, which allows the water waves to pass through. The energy of the water waves passes through the gap and essentially bends around the corners so that the continuing waves are now circular and spread out on either side of the gap. The photograph on the right shows a real example of water waves diffracting through a gap between small rocks. This type of behavior is characteristic of energy waveforms.

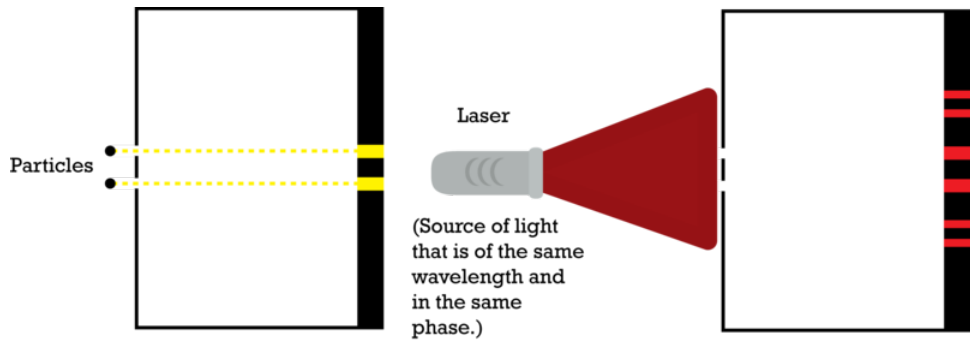
When a body of water has more than one wave, like in the image above, the different waves will overlap and create a new wave pattern. For simplicity, we will consider a case of two water waves with the same amplitude. If the crests of both waves line up, then the new wave will have an amplitude that is twice that of the original waves. The superposition of two crests is represented in the image above as a light area. Similarly, if a trough superimposes over another trough, the new trough will be twice as deep (the darker areas in the image above). In both cases, the amplitude of the new wave is greater than the amplitudes of the individual waves.

Now imagine what would happen if the crest from one water wave is superimposed on a trough from another wave. If both waves are of equal amplitude, the upward pull of the crest and the downward pull of the trough will cancel out. In this case, the water in that area will be flat. The amplitude of this new wave is smaller than the amplitudes of the individual waves.

This process of superimposing waves that occupy the same space is called interference. When the amplitude of the new wave pattern is greater than the amplitudes of the individual waves, it is called constructive interference. When the amplitude of the new wave pattern is smaller than the amplitudes of the individual waves, it is called destructive interference. Interference behavior occurs with all energy waveforms.

Light as a Wave

Light also undergoes diffraction and interference. These characteristics of light can be demonstrated with what is called a double-slit experiment. A box is sealed on all sides so that no light can enter. On one side of the box, two very thin slits are cut. A light source placed in front of the slits will allow light to enter the two slits and shine on the back wall of the box.



If light behaved like particles, the light would go straight from the slits to the back of the box and appear on the back wall as two bright spots (see the left side of the image above). If light behaved like waves, the waves would enter the slits and diffract. On the back wall, an interference pattern would appear with bright spots showing areas of constructive interference and dark spots showing areas of destructive interference (see the right side of the image above). When this double-slit experiment was conducted, researchers saw an interference pattern instead of two bright spots, providing reasonably conclusive evidence that light behaves like a wave.

Light as a Particle

Although the results of the double-slit experiment strongly suggested that light is a wave, a German physicist named Max Planck found experimental results that suggested light behaved more like a particle when he was studying black body radiation. A black body is a theoretical object that absorbs all light that falls on it. It reflects no radiation and appears perfectly black. **Black body radiation** is the energy that would be emitted from an ideal black body. In the year 1900, Planck published a paper on the electromagnetic radiation emitted from a black object that had been heated. In trying to explain the black body radiation, Planck determined that the experimental results could not be explained with the wave form of light. Instead, Planck described the radiation emission as discrete bundles of energy, which he called quanta. A **quantum** (singular form of quanta) is a small unit into which certain forms of energy are divided. These "discrete bundles of energy" once again raised the question of whether light was a wave or a particle – a question once thought settled by Maxwell's work. Planck's work also pointed out that the energy of a quantum of light was related only to its frequency. Planck's equation for calculating the energy of a bundle of light is $E = hf$, where E is the energy of the photon in joules (J), f is the frequency in hertz (s^{-1}), and h is Planck's constant, 6.63×10^{-34} J $\cdot$ s. (A **photon** is a particle of light. The word quantum is used for energy in any form; when the type of energy under discussion is light, the words quantum and photon become interchangeable.)

Example:

What is the frequency of a photon of light whose energy is 3.00×10^{-19} joules?

$$f = \frac{E}{h} = \frac{3.00\times10^{-19}\text{ J}}{6.63\times10^{-34}\text{ J}\cdot\text{s}} = 4.52 \times 10^{14}\text{ Hz}$$

Example:

What is the energy of a photon whose frequency is 2.00×10^{15} s^{-1}?

$$E = hf = (6.63 \times 10^{-34}\ \text{J} \cdot \text{s}) \cdot (2.00 \times 10^{15}\ \text{s}^{-1}) = 1.33 \times 10^{-18}\ \text{J}$$

Planck's work became the basis for quantum theory. **Quantum theory** is the theory that energy can only exist in discrete amounts (quanta). For example, we assume that we can cause an automobile to travel any speed we choose. Quantum theory says this is not true. The problem involved in demonstrating this theory is that the scale of a quantum of energy is much smaller than the objects we normally deal with. Imagine having a large delivery truck sitting on a scale. If we throw one more molecule onto the truck, can we expect to see the weight change on the scale? We cannot, because we lack instruments that can detect such a small change. Even if we added a thousand molecules to the truck, we still would not see a difference in the truck's weight.

For the same reason, we cannot tell that an automobile's speed is quantized (in discrete amounts). The addition of one quantum of kinetic energy to an automobile might change its velocity from 30.1111111111 miles per hour to 30.1111111122 miles per hour. Therefore, according to quantum theory, a speed of 30.1111111117 mph is *not* possible. (Note that these numbers are used for illustrative purposes only.) We are not able to detect this change because we can't measure speeds that finely. To test this theory, we must look at objects that are very tiny in order to detect a change in one quantum.

One place where we can measure quantum-sized energy changes is in the internal vibration of molecules, or the stretching and contracting of bond lengths. When the internal vibration of molecules is measured in the laboratory, it is found that the vibration motion is stair-stepped. A particular molecule may be found vibrating at 3 cycles per second 6 cycles per second or 9 cycles per second, but those molecules are *never* found vibrating at 1, 2, 4, 5, 7, or 8 cycles per second. (Again, these numbers are used for illustrative purposes only.) The fact that only certain vibration levels are available to molecules is strong support for the quantum theory.

Quantum theory can also be used to explain the result of this next experiment on light called the photoelectric effect. The **photoelectric effect** is a phenomenon in which electrons are emitted from the surface of a material after the absorption of energy. This experiment involves having light strike a metal surface with enough force to knock electrons off the metal surface. The results of the photoelectric effect indicated that if the experimenter used low frequency light, such as red, no electrons were knocked off the metal. No matter how many light waves were used and no matter how long the light was shined on the metal, red light could not knock off any electrons. If a higher frequency light was used, such as blue light, then many electrons were knocked off the metal. Albert Einstein used Planck's quantum theory to provide the explanation for the photoelectric effect. A certain amount of energy was necessary for electrons to be knocked off a metal surface. If light were quantized, then only particles of higher frequency light (and therefore higher energy) would have enough energy to remove an electron. Light particles of lower frequency (and therefore lower energy) could never remove any electrons, regardless of how many of them were used.

As a historical side note, many people may think that Einstein won the Nobel Prize for his theory of relativity, but in fact Einstein's only Nobel Prize was for his explanation of the photoelectric effect.

Wave-Particle Duality

At this point, scientists had some experimental evidence (diffraction and interference) that indicated light was a wave and other experimental evidence (black body radiation and the photoelectric effect) that indicated light was a particle. The solution to this problem was to develop a concept known as the **wave-particle duality** of light. The point of this concept is that light travels as a wave and interacts with matter like a particle. Thus when light is traveling through space, air, or other media, we speak of its wavelength and frequency, and when the light interacts with matter, we switch to the characteristics of a particle (quantum).

Lesson Summary

- The work of many scientists led to an understanding of the wave-particle duality of light.
- Light has properties of waves and particles.
- Some characteristics of energy waveforms are that they will undergo diffraction and interference.
- The energy and frequency of a light photon are related by the equation $E = hf$.

Further Reading / Supplemental Links

This website describes the double-slit experience and provides a simulation of the double-slit experiment.

- http://www.colorado.edu/physics/2000/schroedinger/two-slit2.html

Review Questions

1. Name a phenomenon that supports the concept that light is a wave.
2. Name a phenomenon that supports the concept that light is a packet of energy.
3. Calculate the energy in joules of a photon whose frequency is 7.55×10^{14} Hz.