Dual Nature of Light
Warm-Up

LESSON Question

How does light behave as both a particle and a wave?

Goals

Explore the dual nature of light.

Describe and give evidence for the dual nature of light.

Examine the photoelectric effect.

Calculate the energy of a photon.

Dual Nature of Light
Warm-Up

Words to Know

Fill in this table as you work through the lesson. You may also use the glossary to help you.

Planck's constant	a constant that relates the energy and frequency of a photon
quantum	the smallest packet of electromagnetic energy that can be absorbed or emitted
photoelectric effect	the emission of electrons from a metal when light of certain frequencies strikes the metal
frequency threshold	the minimum frequency required to eject electrons from a metal
luminous	emitting light
photon	a particle of electromagnetic energy that has zero mass

The Behavior of Light

Light interacts with matter.

- Reflection
- Refraction
- Diffraction

Dual Nature of Light
Instruction

Light in Ancient Greece

- Ancient Greeks had differing thoughts on the __nature__ and behavior of light. Some thought that light is:
    - a __wave__ or disturbance that travels through spaces in the air.
    - a substance carrying particles that flow with a measurable velocity from a light source.
    - a stream of __rays__ that comes with great velocity from the eyes of an observer.
    - the result of rays that leave the eyes, reflect off an object, and __interact__ with sunlight to become visible.

Newton's Prism Experiment

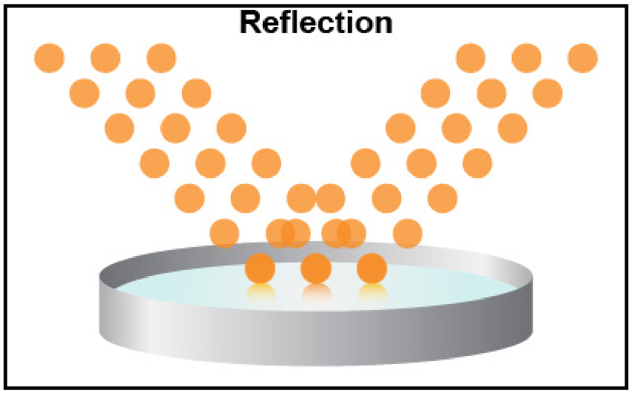
- In the 1600s, Sir Isaac Newton performed an experiment that separated __white__ light into colors.
    - He thought of light as a stream of tiny particles discharged by luminous objects that travel in __straight__ paths.

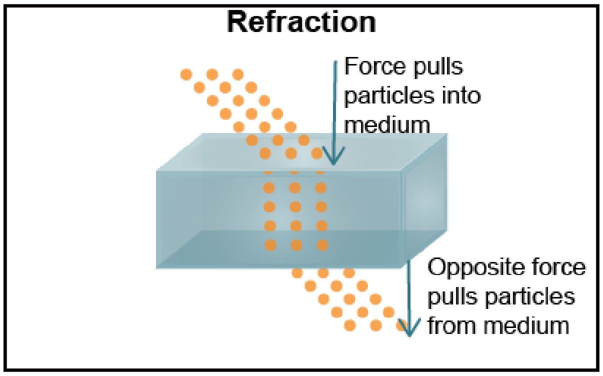
Dual Nature of Light

Instruction

Reflection and Refraction with Light Particles

Reflection and refraction can be explained by the particle theory of light.



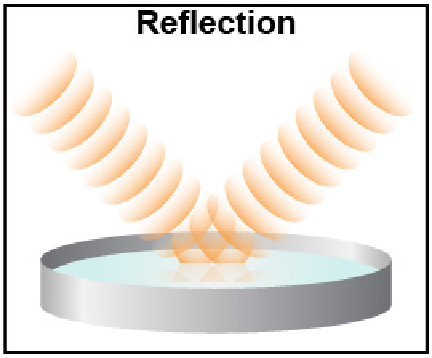


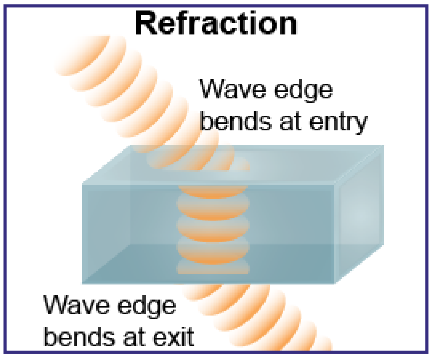
Particles bounce off a surface, much like an elastic ball bounces off a wall.

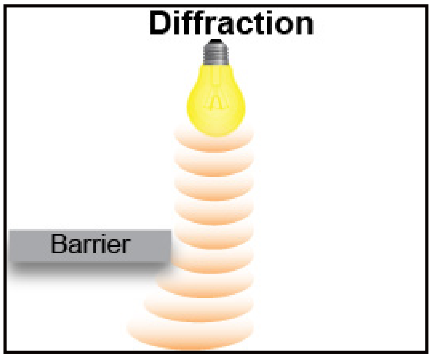
Particles refract as forces cause light to pass through one medium to another.

Light as a Wave

In 1678, Christiaan Huygens theorized that light is made of bend that can bend and spread out.





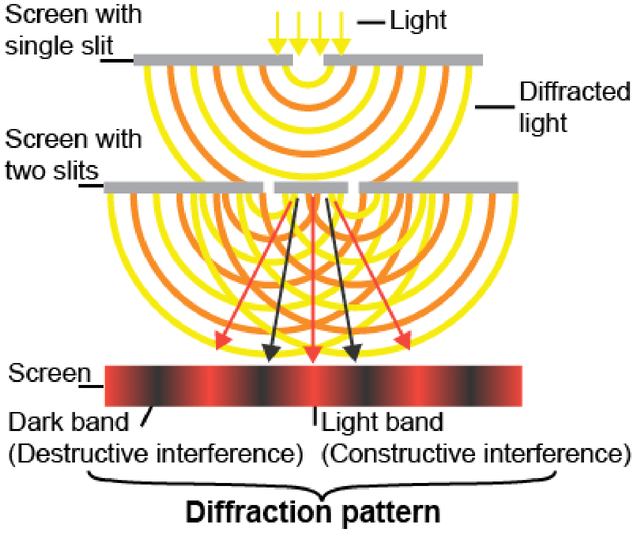


Dual Nature of Light

Instruction

Young's Double Slit Experiment

- In 1803, Thomas Young performed the double slit experiment.
- Experimental results supported the ____wave____ theory of light.
  - Waves spread through slits, in accordance with ____Huygens's principle____.
- Waves interfered, resulting in a pattern called the diffraction pattern.



Maxwell's Electromagnetic Theory

- In 1873, James Clerk Maxwell built on the work of other scientists to mathematically explain how electric and ____magnetic____ fields can induce each other.
- He concluded that ____light____ is produced by the interaction between electric and magnetic fields

Hertz's Experiment

- In 1880, Heinrich Hertz observed that radio waves have the ____same____ properties as light, so he concluded that light is made of waves.

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The Photoelectric Effect

- In 1887, Heinrich Hertz discovered the photoelectric effect, the emission of electrons from a metal when it is struck by light of certain frequencies.
- Each metal has its own frequency threshold, which is the minimum frequency required to eject electrons.

The Wave Theory of Light and the Photoelectric Effect

- The results of experiments with the photoelectric effect were different from scientists' predictions, which were based on the classical physics explanation of wave behavior.
- These results weakened the wave theory and strengthened the particle theory.

Expected results	Experimental results
Light of any frequency (color) will cause the ejection of electrons.	Frequencies of light lower than the frequency threshold of the metal did not eject electrons.
There will be a time gap between when the light strikes the metal and when electrons are ejected.	As soon as light struck the metal, electrons were ejected.
Increasing the intensity of the light will cause the kinetic energy of the ejected electrons to increase.	The kinetic energy of the ejected electrons depended only on the frequency of light.

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Einstein's Photons

- In 1905, Albert Einstein explained the results of the photoelectric experiments by suggesting that a __quantum__ of electromagnetic energy with zero mass causes the ejection of an electron.
- A quantum is the smallest packet of __electromagnetic energy__ that can be absorbed or emitted.
- A photon is a quantum particle of electromagnetic energy with zero __mass__.

Photons Used in the Explanation of Results

- The observed results of photoelectric effect experiments can be explained by __photons__.

Expected results	Experimental results
Frequencies of light that were lower than the frequency threshold of the metal did not eject __electrons__.	The energy in each photon is determined by its frequency. Electrons are ejected only if the energy of the photon is at least equal to the __threshold__ frequency.
As soon as light struck the metal, electrons were ejected.	Atoms absorb photons as soon as light strikes the metal.
The kinetic energy of the ejected electrons depends only on the frequency of __light__.	Increasing the intensity increases the number of photons hitting the metal, not the energy of each photon. Increasing the intensity results only in the ejection of more electrons.

The Photoelectric Effect in Everyday Life

REAL-WORLD CONNECTION

- Digital cameras use the photoelectric effect.

Image sensors in cameras absorb __photons__ and release electrons.

Accumulated electrons are responsible for the __pixels__ in an image.

Contemporary Thoughts on the Nature of Light

- Light has a dual nature.
- Light travels and __interacts__ with itself as though it is a wave.
- Light interacts with matter as though it is a __stream__ of photons.

The Uncertainty Principle

In 1927, the German physicist Werner Heisenberg formulated the __uncertainty principle__.

- The principle states that the __speed__ or location of a quantum particle cannot be measured simultaneously.
- This principle applies to:
  - electrons
  - __light__

Dual Nature of Light

Instruction

The Birth of Quantum Mechanics

Dr. Heisenberg's uncertainty principle led to a new field called quantum mechanics.

- Quantum mechanics:
- deals with subatomic particles such as electrons.
- deals with matter such as photons.
- led to a new and exciting field of quantum computing.

Superposition and Quantum Computing

Superposition principle states that a wave or particle can exist in the same position at the same time.

- Quantum computing takes the principles of superposition and the uncertainty principle to create a new way that information or data can be handled by computers.
- Traditional computers input data in 0 and 1.
- In quantum computing, 0 and 1 can exist in superposition, and thus 0 and 1 can exist at the same time.
- This allows a computer to calculate or process multiple data all at once.

Instruction

The Future of Quantum Computing

Quantum computing can be used in cybersecurity.

- Cybersecurity deals with the unauthorized use of information on a computer.
- Quantum computing can:
  - encrypt information quickly
  - thwart hackers effectively.

Energy of a Photon Equation

- Variables
  - E = energy of photon in joules
  - h = Planck's constant, a constant value that is approximately equal to 6.6×10^{-34} J • s and that relates the energy of a photon to the frequency of that photon
  - f = frequency in Hz
- The energy of a photon is directly proportional to frequency.

$$E = hf$$

Calculation of the Energy of a Photon

EXAMPLE

What is the energy of an X-ray photon with a frequency of 3.00×10^{16} Hz? Planck's constant is 6.63×10^{-34} J • s.

Given:

$f = 3.00 \times 10^{16}$ Hz

$h = 6.63 \times 10^{-34}$ J • s

Instruction

Unknown: E

Formula to be used: E = hf

- $E = hf$
- $E = (6.63 \times 10^{-34}\ \text{J} \cdot \text{s})\ (3.00 \times 10^{16}\ \text{Hz})$ where Hz is cycles/s.
- E = 1.99×10^{-17} J

Dual Nature of Light
Summary

LESSON Question

How does light behave as both a particle and a wave?

Answer

Key Concepts

- The current understanding of the nature of light is a result of scientists' experiments, calculations, and observations.

Wave theory of light	Particle theory of light
• Young's double slit experiment • Maxwell's calculations • Hertz's discovery of radio waves	• Newton's prism experiment • Einstein's explanation of the photoelectric effect

- The photoelectric effect is the emission of electrons from a metal when it is struck by light of certain frequencies.
- The energy of a photon can be calculated using the formula E = hf.
- Light has a dual nature.
- Light travels as a wave and interacts with matter as a particle.
- The dual nature of light can be used to explain phenomena that involves light.

Dual Nature of Light

Summary

Phenomenon	Theory of light
Reflection	Wave and particle
Refraction	Wave and particle
Diffraction	Wave
Interference	Wave
Photoelectric effect	Particle

Dual Nature of Light

Summary

Use this space to write any questions or thoughts about this lesson.