Index

The big picture (HL)

Higher level (HL)

? Guiding question(s)

- How can light be used to create an electric current?
- What is meant by wave-particle duality?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

What is the nature of light? Light is an electromagnetic wave (see subtopic C.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43778/)), and can be reflected, refracted and diffracted (see subtopic C.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44900/)), just as mechanical waves can be.

But how did we develop this understanding of the nature of light, and what else do we know about light?

Video 1 looks at whether light can be considered as a particle or a wave.

How has the theory of light changed over time? What are the names and nationalities of the scientists involved in each of the theories about the nature of light?

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Video 1. The nature of light.

International Mindedness

What do you think are the advantages of international collaboration? How do you think international collaboration is different now to how it was in the time of the Ancient Greeks or Isaac Newton?

The nature of light has long been the focus of scientific debate.

Theory of Knowledge

Isaac Newton believed that light was a particle, while Christian Huygens believed that it was a wave. ‘Does competition between scientists help or hinder the production of knowledge?’ *(IB TOK Guide, 2020)*

There is evidence that light is a wave and a particle. How can light be used to create an electric current? Why do some colours of light create an electric current while others do not?

Prior learning

Before you study this subtopic make sure that you understand the following:

- Momentum (see subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/)).

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- Wave behaviour (see subtopic C.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44900/)).
- Photons and discrete energy levels (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

The particle nature of light (HL)

E.2.1: The photoelectric effect (HL) E.2.2: Threshold frequency (HL) E.2.3: The work function of a metal (HL)
E.2.7: Compton scattering (HL) E.2.8: Photon scattering and increased wavelength (HL)
E.2.9: Shift in photon wavelength after scattering (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe how the photoelectric effect is evidence for the particle nature of light and understand the concept of threshold frequency.
- Understand the concept of work function and use the equation for maximum kinetic energy of photoelectrons:

$$E_{\text{max}} = hf - \phi$$

- Describe how Compton scattering of light is evidence for the particle nature of light and use the equation for the shift in photon wavelength:

$$\begin{aligned}\lambda_{\text{f}} - \lambda_{\text{i}} &= \Delta\lambda \\ &= \frac{h}{m_e c}\left(1 - \cos\theta\right)\end{aligned}$$

Imagine heating water on a stove. You supply energy in the form of heat and the water evaporates – the particles leave the surface. In a metal, there are electrons which can gain energy. What happens to the electrons in a metal when energy is supplied? Are

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there any similarities between electrons and evaporating hot water? What are the differences?

Figure 1. A pan of steaming water.

Credit: saturar, Getty Images

The photoelectric effect

Video 1 in The big picture (/study/app/physics/sid-423-cid-762593/book/the-big-picture-hl-id-46454/) introduces the concept of wave-particle duality. This is the idea that light sometimes behaves as a wave, and sometimes behaves as a particle. You have met the concept of light as a wave (see subtopic C.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43778/)), but what is the evidence for light as a particle?

The primary evidence for light as a particle is the photoelectric effect. This is the emission of photoelectrons from a metal when electromagnetic radiation is incident on it.

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/the-big-picture-hl-id-46454/print/) Assign

The electromagnetic spectrum is a continuous spectrum of electromagnetic waves.

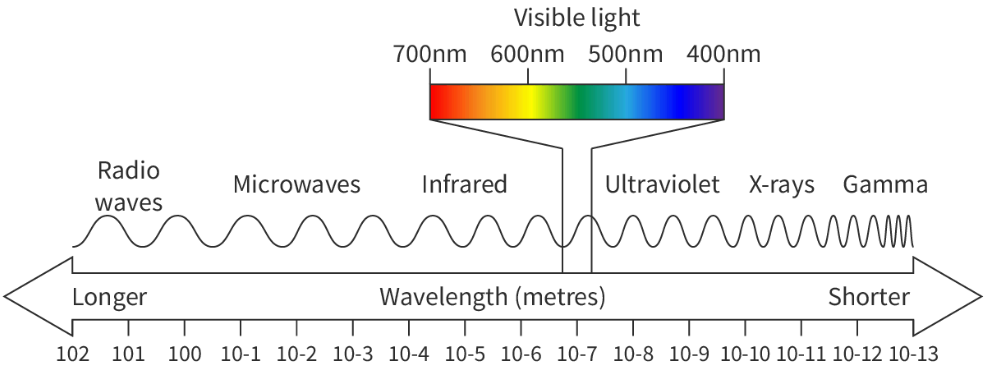

Figure 2. The electromagnetic spectrum.

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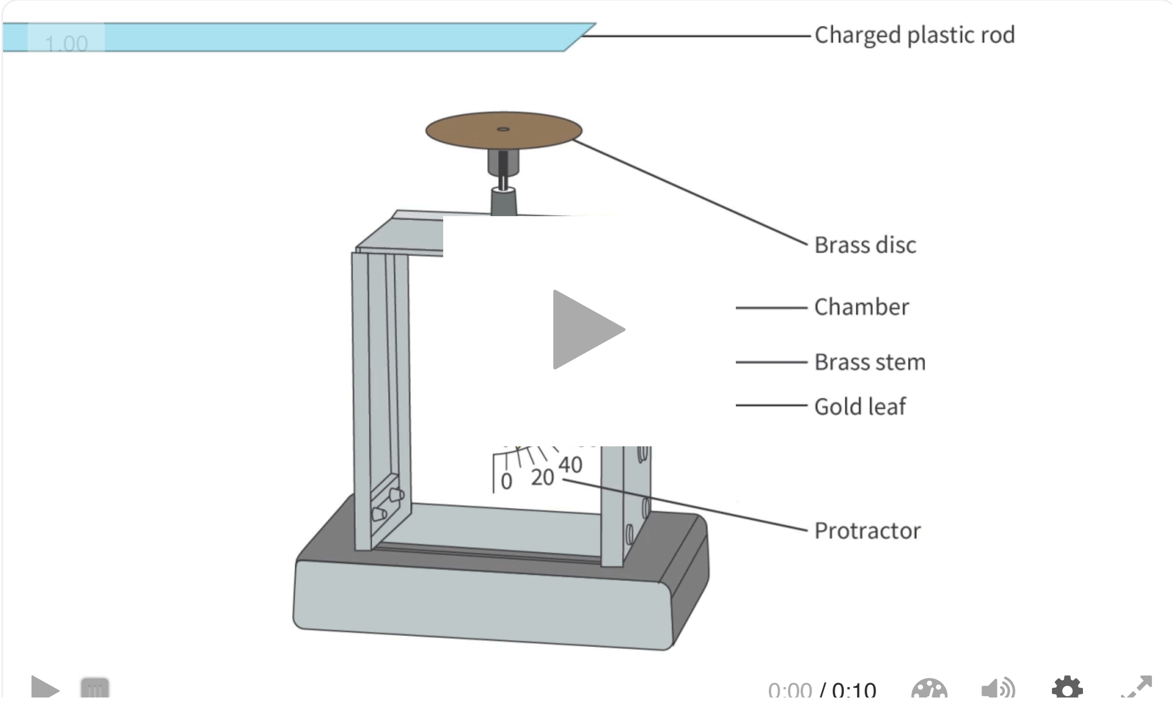
More information for figure 2

The image is a diagram that illustrates the electromagnetic spectrum, displaying various categories of electromagnetic waves with their respective wavelengths. At the top, there is a color bar labeled 'Visible light' ranging from 700nm to 400nm, showing colors from red to violet. Below the color bar, the types of electromagnetic waves are labeled with oscillating lines: 'Radio waves,' 'Microwaves,' 'Infrared,' 'Ultraviolet,' 'X-rays,' and 'Gamma rays.' Beneath these labels, an arrow extends horizontally to show wavelength in metres, marked from 102 to 10-13, indicating longer wavelengths on the left and shorter on the right.

[Generated by AI]

The electromagnetic spectrum ranges from radio waves of long wavelength and low frequency to gamma rays of short wavelength and high frequency.

The photoelectric effect can be demonstrated using a gold leaf electroscope, which consists of a very thin piece of gold foil (the gold leaf) in a chamber, connected to a brass disc outside the chamber, via a brass stem (**Interactive 1**).



Interactive 1. A Gold Leaf Electroscope.

More information for interactive 1

This interactive features a video demonstrating the photoelectric effect using a gold leaf electroscope. The setup consists of a gold leaf electroscope housed within a chamber, with a charged plastic rod positioned above it. The key components shown in the visual include:
A brass disc is placed at the top of an electroscope, which is connected to a brass stem that leads to a gold leaf at the bottom inside a chamber. A charged plastic rod is brought closer to the brass disc, and as it gets nearer, the gold leaf deflects, indicating the redistribution of charges. A protractor next to the gold leaf is used to measure the degree of its movement. Initially, the gold leaf is set at an angle of 10°. As the charged plastic rod approaches, the angle increases to 30°.

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In the video, the charged plastic rod is moved downward toward the brass disc. As the rod gets closer, the thumb touches the rod while the index finger makes contact with the brass disc. After this, the rod slowly moves back to its original position, and the gold leaf returns to its resting state. Even after the charged rod is moved back to its initial position, the angle remains at 30°, demonstrating how the charge redistribution causes a permanent shift in the gold leaf's position. The protractor measures this change, reflecting the impact of the charged rod on the electroscope.

This visual effectively demonstrates how charges on a charged object, in this case, the plastic rod, can induce a redistribution of charges in the electroscope. The movement of the gold leaf provides a clear indication of how the system reacts to the charge.

In **Interactive 1** the electroscope is charged by electrostatic induction (see section D.2.1 (/study/app/physics/sid-423-cid-762593/book/electric-charge-id-46475/)). As the positively charged plastic rod is brought close to the brass disc, the charges on the disc, stem and gold leaf are redistributed. If the disc is then grounded, negative charges flow from the Earth. When the grounding is removed the electroscope has an excess of negative charges. This causes the gold leaf to move away from the brass stem as they both have the same charge. We can measure the angle between the brass stem and the gold leaf using the protractor inside the chamber.

Work through this activity to find out what happens to the gold leaf when light is incident on the metal disc of the gold leaf electroscope.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 15 minutes
- **Activity type:** Pair activity

Watch the two short video clips.

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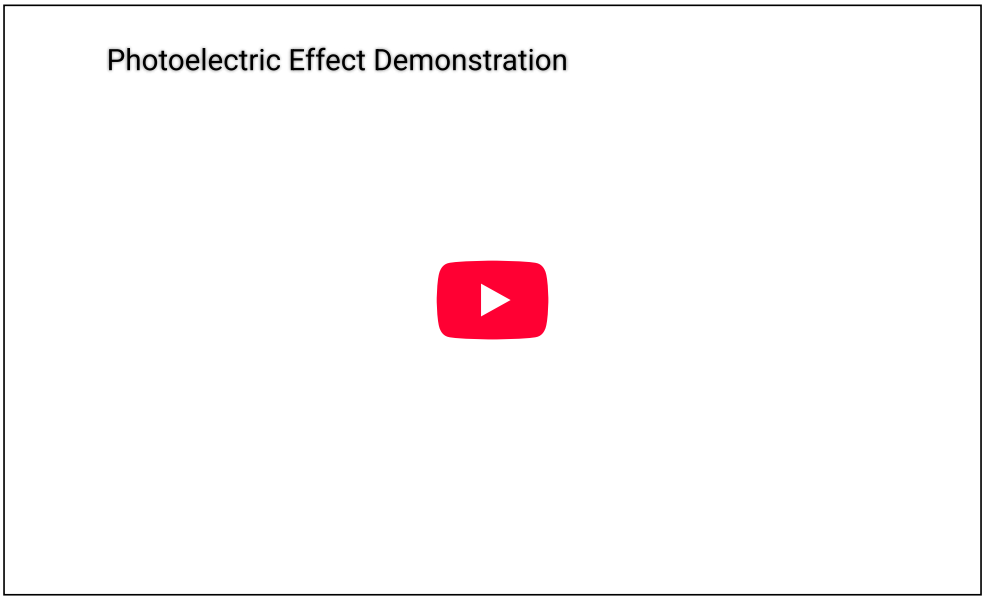
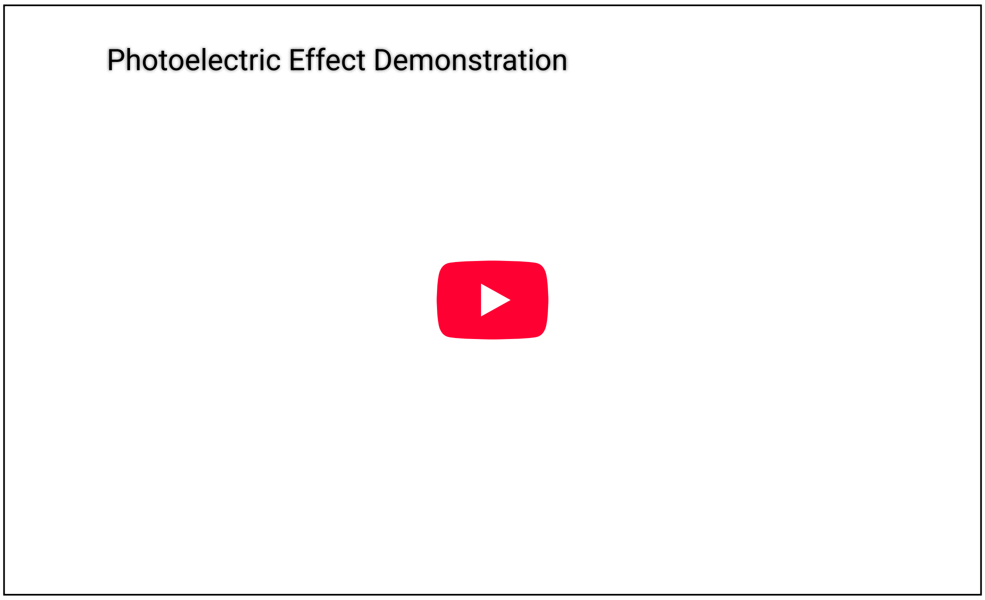


Video 1. The effect of visible light on gold leaf.



Video 2. The effect of UV light on gold leaf.

What happens when:

- visible light is incident on the metal disc?
- ultraviolet light is incident on the metal disc?

Record your observations and think about some possible scientific explanations for your observations. Discuss your ideas and develop them further.

In the activity you saw that:

- The gold leaf in the electroscope is deflected from the brass stem because the gold leaf and the brass stem are both negatively charged and repel each other.

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- When visible light is incident on the zinc plate, the gold leaf remains in the deflected position.
- When UV light is incident on the zinc plate, the gold leaf returns to its undeflected position.

Explore this phenomenon in more detail by working through **Activity A** in the next section (section E.2.1b (/study/app/physics/sid-423-cid-762593/book/activity-photoelectric-simulation-hl-id-46473/)). Then return here and continue reading.

The photoelectric effect experiment

In the experiment that is simulated in section E.2.1b (/study/app/physics/sid-423-cid-762593/book/activity-photoelectric-simulation-hl-id-46473/), two metal plates inside an evacuated tube are connected to the terminals of a variable voltage power source. Light of one wavelength is incident on one of the metal plates, which is called the emitter plate. **Figure 3** shows this arrangement.

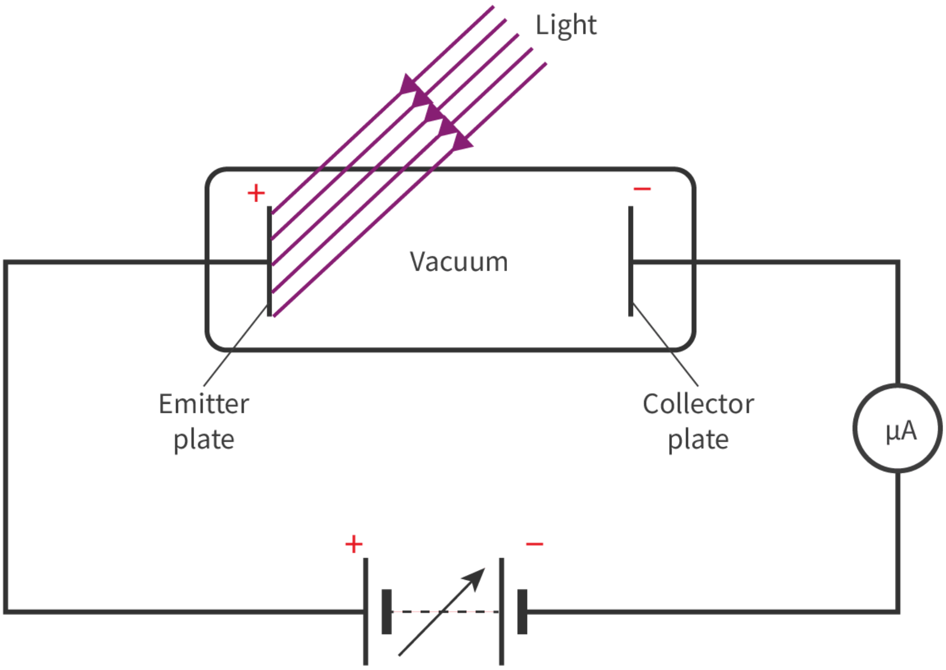

Figure 3. The setup for the photoelectric effect experiment.

More information for figure 3

The diagram shows the setup for a photoelectric effect experiment. It consists of two metal plates inside a vacuum tube. On the left is the emitter plate, denoted with a positive sign, and on the right is the collector plate with a negative sign. Light is depicted as entering the tube and striking the emitter plate. This light is represented by parallel purple lines with arrowheads pointing towards the emitter plate. These lines are labeled "Light." An external circuit connects the plates and includes a variable voltage source indicated by a symbol with a positive and negative terminal with an arrow through it, and an ammeter labeled with the symbol μA, which appears after the collector plate in the circuit path. The overall layout shows the flow of electrons between the two plates and the measurement of current as the primary activity in this experiment.

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The light may cause the emitter plate to emit electrons. These are called photoelectrons (since their emission is caused by light, and ‘photo’ means light). When electrons are crossing the gap between the emitter plate and the collector plate, the ammeter measures a current.

Threshold frequency and work function

Consider the three key observations from the photoelectric effect experiment:

- Observation 1: Below a particular frequency, no electrons are emitted at all, no matter how long the light shines on the metal. This frequency is known as the threshold frequency.
- Observation 2: At frequencies above the threshold frequency, increasing the frequency increases the maximum velocity of the photoelectrons, but not the rate at which they are emitted.
- Observation 3: At frequencies above the threshold frequency, increasing the intensity of the light does not affect the maximum velocity of the photoelectrons, but it does increase the rate at which they are emitted.

These observations are not consistent with the wave model of light. Why not?

Energy is needed to release an electron from a metal. The exact amount of energy depends on how far the electron is below the surface. An electron that is at the surface requires the least energy to escape. This minimum energy is called the work function, and it differs for different metals.

Imagine a tall tube with a table tennis ball at the bottom, as shown in **Interactive 2**. The ball represents an electron at the surface of the metal and the height of the tube represents the work function.

The tap represents a light source and the water represents a light wave. When water enters the tube, the ball rises. Eventually, the ball reaches the top of the tube and ‘escapes’. Using this model, we would expect any light wave to release electrons from a metal. If the power of the light wave is low, it might take some time for electrons to gain enough energy to escape, but it should happen eventually.

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Interactive 2. Why Can't the Wave Model Explain the Photoelectric Effect?

More information for interactive 2

This interactive video shows a transparent tall tube with a ball at the bottom of the tube. The tube has a water tap at the top, and as water flows in, the ball starts to rise. The ball moves slowly upwards as more water fills the tube.

Once the water fills the entire tube, the tap closes. Eventually, the ball reaches the top of the tube and topples onto the floor. After bouncing a few times, it continues to roll on the floor toward the left side. The height of the ball corresponds to how far it moves inside the tube,

This visual is meant to represent the concept of the photoelectric effect, where light energy causes electrons to escape from a metal surface. Just like the water raises the ball in the tube, light needs to provide enough energy to release electrons from the metal.

Imagine that, instead of a tap at the top of the tube in **Interactive 2**, there is a spring at the bottom of the tube that can be compressed. Compressing the spring a short distance and then releasing it will not be enough to shoot the ball out of the tube. The ball will rise part-way up the tube and then fall back down. No matter how many times the spring is compressed, the ball will not escape.

But if enough energy is given to the spring, the ball will escape on the first attempt.

Each compression of the spring represents one particle of light – called a photon – being absorbed by the electron. If the energy of the photon is too low, the electron does not escape. If the energy of the photon is high enough, each photon can release an electron. The energy of each photon depends only on the frequency f of the light, according to the equation $E = hf$ where h is the Planck constant (see section E.1.1 (/study/app/physics/sid-423-cid-762593/book/atoms-and-photons-id-46593/)).

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In the photoelectric effect experiment, increasing the intensity of the light increases the rate of emission of electrons because increasing the intensity means increasing the number of photons per second (but it does not affect the energy of each photon).

Drag and drop each explanation in **Interactive 3** into the table beside the observation that it best explains.

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Interactive 3. Photoelectric effect observations and explanations.

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More information for interactive 3

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This drag-and-drop activity presents a table with two columns labeled "Observation" and "Explanation." The left column contains four distinct observations related to the photoelectric effect, and the right column provides four empty spaces to match with corresponding explanations. Users are meant to drag explanation boxes provided at the bottom of the screen and drop them into the appropriate blank spaces next to the relevant observations.

The four observations listed in the left column are as follows:

First row, first column
"For low frequencies, no photoelectrons are emitted. Increasing the intensity does not change this."

Second row, first column
"For a particular metal, there is a minimum frequency at which photoelectrons start to be emitted from its surface."

Third row, first column
"There is no delay between the incidence of light on the metal and the emission of photoelectrons."

Fourth row, first column
"When the frequency is at or above the minimum the rate of emission of photoelectrons increases as the intensity increases. The rate of emission of photoelectrons (and the current) is directly proportional to the intensity."

There are four draggable explanation tiles at the bottom of the interface.

The first tile says, "Above the threshold frequency the incident photons have enough energy to release electrons from the metal. Increasing the intensity increases the rate of photon incidence and the rate of photoelectron emission."

The second tile states, "The energy from the photons does not 'build up' as it would in the wave model of light. An electron only absorbs the energy from a photon, and is released from the metal, if the photon's frequency is greater than or equal to the threshold frequency."

The third tile reads, "Light is a particle with energy given by $E = hf$, rather than a wave. Electrons need a minimum amount of energy to leave the atom. There is a minimum frequency, $f = E/h$, needed in order for photoelectrons to be emitted. This is the threshold frequency. Below this frequency, increasing the intensity increases the rate at which the light source emits photons, but each photon does not have enough energy to release an electron from its atom."

The fourth tile says, "The wavelength corresponds to the threshold which can be calculated using $f = E/h$."

The goal is for users to carefully match each observation with the correct scientific explanation that supports it. The "Check" button at the bottom left allows users to verify if their selections are correct.

Solution:

First row, first column: Third tile.

Second row, first column: Fourth tile.

Third row, first column: Second tile.

Fourth row, first column: First tile.

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This drag-and-drop interactivity effectively reinforces key concepts of the photoelectric effect by encouraging users to connect real-world observations with theoretical explanations.

Maximum kinetic energy of the photoelectrons

Scientists had been studying the quantum nature of energy and the photoelectric effect for several years when, in 1905, Albert Einstein theorised that one could be used to explain the other. He proposed that the electrons in different metals required a different minimum amount of energy in order to escape the atom. This minimum amount of energy is the work function, ϕ, of the metal.

- If the energy of a photon incident on the metal is less than the work function of the metal, no photoelectron is emitted.
- If the energy of a photon incident on the metal is equal to the work function of the metal, it can give an electron the exact amount of energy required to escape the metal.
- If the energy of a photon incident on the metal is greater than the work function of the metal, a photoelectron is emitted and any remaining energy from the photon is transferred to the kinetic energy of the emitted photoelectron.

The maximum kinetic energy of the photoelectron is the difference between the energy carried by the incident photon and the work function of the metal (**Table 1**).

Table 1. Equations for maximum kinetic energy.

Equation	Symbols	Units
$E_{\text{max}} = hf - \phi$	E_{max} = maximum kinetic energy of emitted photoelectron	joules (J)
	h = Planck constant (6.63×10^{-34} J s)	joules seconds (J s)
	f= frequency of incident radiation	hertz (Hz)
	ϕ = work function of the metal	joules (J)

Study skills

In quantum physics, electronvolts (eV) are typically used instead of joules (J) because the quantities of energy are very small. The electronvolt is equivalent to the energy required to move one electron across an electric potential difference of one volt (see subtopic D.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44743/)).

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To convert from joules to electronvolts, divide by the elementary charge, e $(1.60\times10^{-19}\ \text{C})$.

For example, to convert 2.3×10^{-19} J to eV:

$$\frac{2.3 \times 10^{-19}}{1.60 \times 10^{-19}} = 1.4\ \text{eV}$$

Worked example 1

Ultraviolet light is incident on a copper plate and photoelectrons are emitted with a speed of $2.2 \times 10^5\ \text{m s}^{-1}$.

Determine the wavelength of the incident light.

The work function of copper is 4.7 eV.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$v = 2.2\times10^5\ \text{m s}^{-1}$ $\phi = 4.7\ \text{eV}$ $1\ \text{eV} = 1.6\times10^{-19}\ \text{J}$
Step 2: Convert the work function to joules.	$\phi = 4.7\times1.6\times10^{-19}$ $= 7.52\times10^{-19}\ \text{J}$
Step 3: Determine the maximum kinetic energy of the photoelectrons.	$E_\text{k} = \frac{1}{2}mv^2$ $= \frac{1}{2}\left(9.110 \times 10^{-31}\right)\left(2.2 \times 1\text{(}\right.$ $= 2.205\times10^{-20}\ \text{J}$
Step 4: Write out and rearrange the equations.	$E_\text{max} = hf - \phi$ and $f = \frac{c}{\lambda}$ $E_\text{max} = \frac{hc}{\lambda} - \phi$ $\lambda = \frac{hc}{E_\text{max} + \phi}$
Step 5: Substitute the values given.	$= \frac{\left(6.63 \times 10^{-34}\right)\left(3.00 \times 10^8\right)}{2.205 \times 10^{-20} + 7.52 \times 10^{-19}}$

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Solution steps	Calculations
Step 6: State the answer with appropriate units and the number of significant figures used in rounding	$= 2.57\times10^{-7}\ \text{m} = 257\ \text{nm} = 260$ ı

Consider again the setup for the photoelectric effect experiment (**Figure 4**).

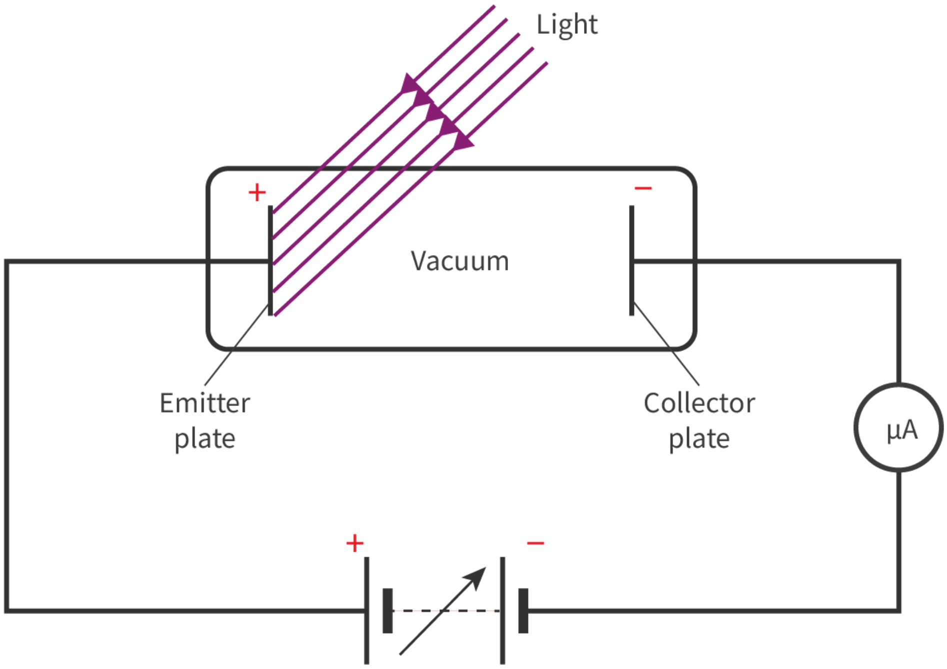

Figure 4. The setup for the photoelectric effect experiment.

More information for figure 4

The image depicts a diagram representing the setup for a photoelectric effect experiment. It includes a circuit with an emitter plate and a collector plate inside a vacuum tube. Light rays, represented by lines with arrows, are directed towards the emitter plate, which is marked with a plus symbol indicating a positive charge. The collector plate is marked with a minus symbol indicating a negative charge. The vacuum is labeled in the center of the tube. The circuit also includes a microammeter (μA) on the right to measure current, and a voltage source at the bottom of the circuit, with positive and negative terminals indicated. The electron flow is marked between the plates across the vacuum.

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The energy change when an electron crosses the gap between the plates is given by the equation for work done in moving a charge q in an electric field (see subtopic D.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44743/)):

$$W = q\Delta V_e$$

This is a transfer of energy from kinetic to electrical potential: the negatively charged electron slows down and its electrical potential energy increases as it approaches the negatively charged plate.

If the electric potential difference across the plates is increased until even the photoelectrons with the most initial kinetic energy cannot quite reach the negative plate, the electric current in the circuit becomes zero because no charge flows across the gap.

The electric potential difference of the battery at this point is known as the stopping potential, V_s.

The work done on the photoelectrons by the battery is:

$$W = qV_s$$

As the charge, q, being moved is an electron:

$$W = eV_s$$

As the work done is slowing the charge, the work done is equal to the kinetic energy gained by the electron at the instant it leaves the positive plate (left-hand side), so:

$$E_k = eV_s$$

Concept

If a photoelectron only just fails to reach the negative plate, the electric potential energy the electron gains in crossing the gap must equal its initial kinetic energy:

$$eV_s = \frac{1}{2}mv^2{}_{\text{max}}$$

where m is the mass of an electron and v_{max} is the initial velocity of the electron.

The only unknown in this equation is v_{max}; all of the other quantities are either known (e, m) or can be measured (V). Therefore it is possible to deduce v_{max}, the maximum velocity of a photoelectron, from the results of the experiment.

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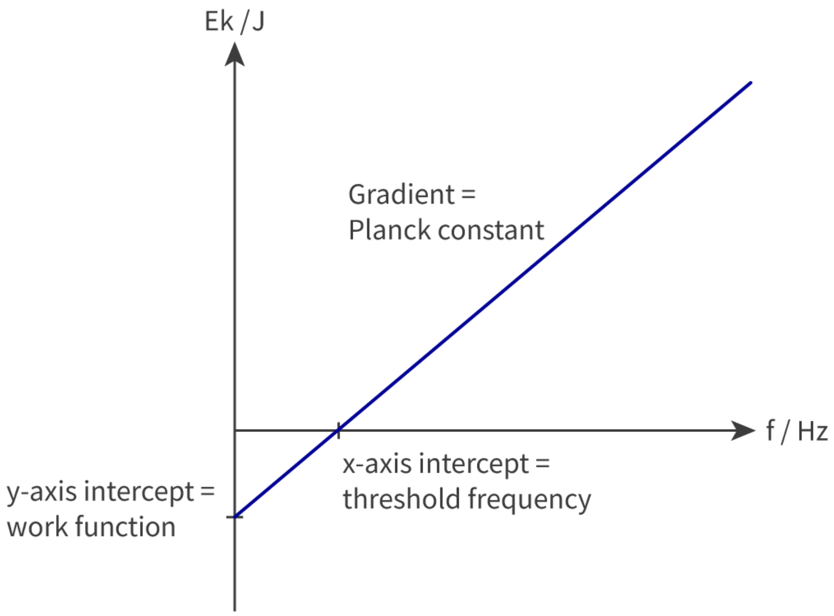
Work through **Activity B** in the next section (section E.2.1b (/study/app/physics/sid-423-cid-762593/book/activity-photoelectric-simulation-hl-id-46473/)) to determine the relationship between the frequency of the light and the maximum initial kinetic energy of the photoelectrons.

How can your graph of maximum kinetic energy against frequency be used to find the threshold frequency of the metal and its work function?



Graph of kinetic energy against frequency.

Exercise 1

Click a question to answer

Higher level (HL)

Worked example 2

The graph shows the kinetic energy of photoelectrons emitted from a sample of sodium against the frequency of incident photons.

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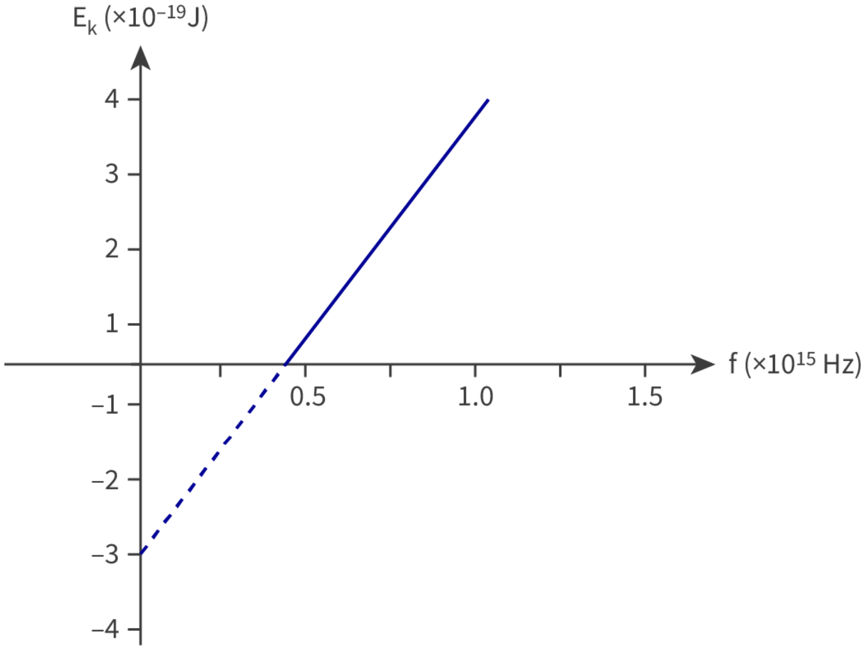

Figure 5. Kinetic energy v. frequency of sodium.

More information for figure 5

The graph illustrates the relationship between kinetic energy (E_k) in units of 10^(-19) Joules and frequency (f) in units of 10^15 Hertz for emitted photoelectrons from sodium. The X-axis represents frequency, ranging from 0 to 1.5 x 10^15 Hz. The Y-axis depicts kinetic energy starting from -4 x 10^(-19) J and going up to 4 x 10^(-19) J.

The graph features a dashed line extending from the origin where frequency is 0 and kinetic energy is -3 x 10^(-19) J, rising linearly to intersect the kinetic energy axis above 4 x 10^(-19) J when the frequency is approximately 1.6 x 10^15 Hz. This indicates a positive trend between frequency and kinetic energy, in line with the photoelectric effect. The linear section of the graph highlights that as the frequency of incident photons increases, so does the kinetic energy of the ejected electrons from the sodium sample.

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Determine the maximum kinetic energy of an emitted photoelectron, due to an incident photon with a frequency of 2.0 PHz.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$f = 2.0\ \text{PHz}$ $= 2.0\ \times 10^{15}\,\text{Hz}$ Work function, ϕ, is equal to y-intercept on g $\phi = 3.0 \times 10^{-19}\,\text{J}$
Step 2: Write out the equation.	$E_{\text{max}} = hf - \phi$
Step 3: Substitute the values given.	$E_{\text{max}} = \left(6.63\ \times\ 10^{-34} \times 2.0 \times 10^{15}\right) - 3.($
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 1.026{\times}10^{-18}\,\text{J} = 1.0{\times}10^{-18}\,\text{J}\ (2\ \text{s.f.})$

Graphs of kinetic energy against frequency can be compared to see the difference between metals.

AB

Exercise 2

Click a question to answer

Higher level (HL)

In graphs of kinetic energy against frequency the equation for the line can be used to identify errors by considering what the properties of the line should be.

AB

Exercise 3

Click a question to answer

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Higher level (HL)

Compton scattering

In 1922, Arthur Compton discovered further evidence that supported the theory that light could behave as particles. When Compton fired X-rays at a carbon target, he observed that the **scattered** wave had a longer wavelength (and a lower frequency) than the **incident** wave.

Interactive 4 shows the Compton scattering of light by an electron.

Interactive 4. The Compton Scattering of Light by Electrons.

More information for interactive 4

A slideshow viewer with three images, each accompanied by a descriptive text panel on the right side. The slideshow navigation bar is located at the bottom, displaying the current slide number (1/3 or 2/3) and providing buttons to move between slides. A blue progress indicator shows the position within the slideshow. In the bottom right corner, there is an expand button to view the images in full screen

In the first slide, we see a single particle labeled "Target electron at rest," depicted as a grey circular symbol with a negative sign inside it, signifying a stationary electron. There is no other particle shown yet, and this slide serves to establish the initial condition: an electron at rest before any interaction takes place. The text above the electron clearly states its label, helping learners orient themselves before the action begins.

The second slide introduces an approaching wave labeled "Incident photon." This wave, drawn in blue and moving from left to right, is shown heading straight toward the mentioned "Target electron at rest". It is accompanied by the symbol "λ_i" (lambda sub i), which represents the wavelength of the incoming photon before interaction. This scene captures the critical setup of Compton scattering—where a photon with energy and momentum approaches an electron initially at rest. The caption reinforces the scientific terminology while visually mapping the concept for the learner.

The third slide illustrates the aftermath of the photon-electron interaction. The photon, now shown in red and labeled "Scattered photon," has been deflected at an angle represented by "θ." The electron, no longer stationary, is labeled "Recoil electron" and is shown moving away from the point of interaction at a different angle, marked "φ." The scattered photon has a longer wavelength, now represented as "λf" (lambda sub f),

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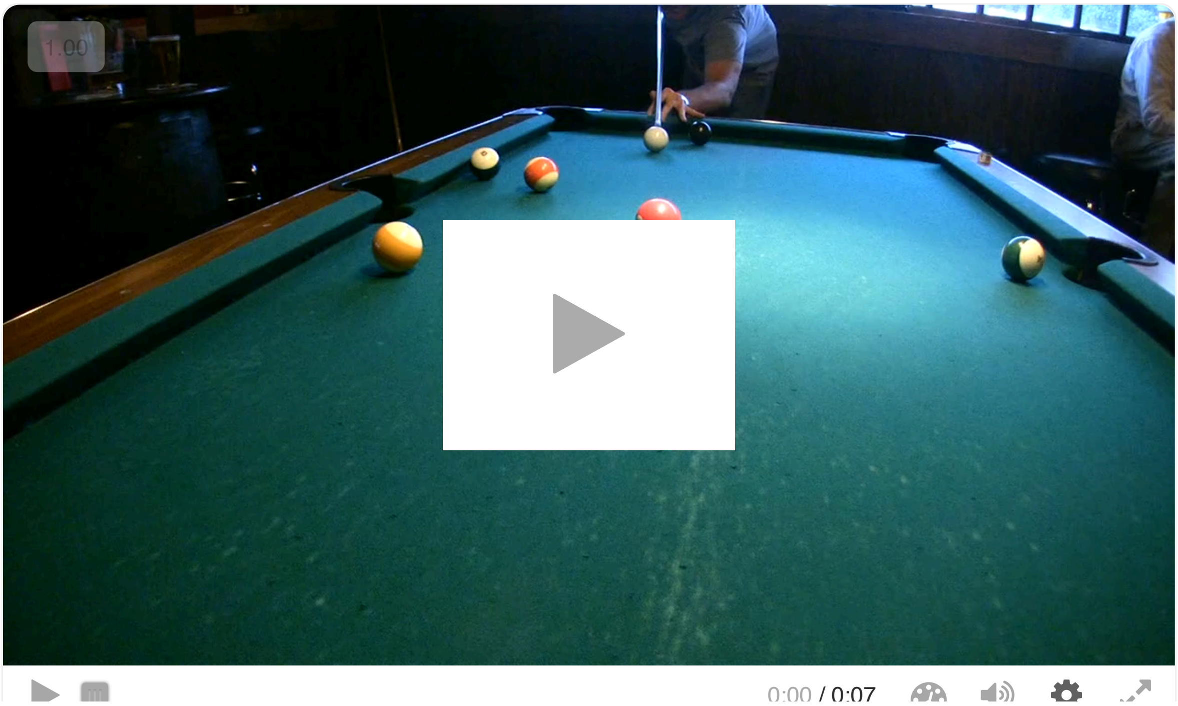
indicating that it has lost energy in the collision. The entire visual reinforces the conservation of energy and momentum principles in Compton scattering, showing both angular deviation and energy loss. The angles and directional arrows help clarify the movement and relative positioning after the interaction.

Compton theorised that if light was a photon, as suggested by the photoelectric experiment, then when the photon collided with an electron in the carbon, the linear momentum and the total energy of the system must be conserved (see subtopics A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/) and A.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43083/)).

In other words, some of the energy and momentum of the photon must be transferred to the electron, and the energy and momentum of the photon would decrease. A decrease in the energy of the photon would result in a decrease in frequency and an increase in wavelength.

We can think of this as two balls in a game of billiards, snooker or pool. The white ball (representing a photon) travels at a given velocity across the table and collides with the red stationary ball (representing an electron). Some of the energy and momentum of the white ball is transferred to the red ball. The white ball moves in a different direction at a lower speed, while the red ball has a velocity (and energy and momentum) as shown in **Video 3**. (See section A.2.7 (/study/app/physics/sid-423-cid-762593/book/collisions-and-explosions-id-44738/) for a quantitative approach to the conservation of momentum in two-dimensional collisions and explosions.)



Video 3. When They Collide, Some of the Energy and Momentum of the White Ball Is Transferred to the Red Ball.

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More information for video 3

The video of a game of pool where a player is taking a shot. The camera is focused on the pool table, capturing the action from a perspective that shows both the cue ball (white ball) and several colored balls. The cue ball is initially positioned near the bottom left corner of the table.
The player, visible in the background, aims and strikes the cue ball with the cue stick. The cue ball travels across the table and collides with the orange solid ball. Upon impact, the orange solid ball begins to move, rolling across the table while the cue ball slows down. The orange ball hits the opposite edge, bounces back, and reaches the pocket. The camera captures this moment as the action on the table concludes, with the player stepping out of frame.

Concept

The law of **conservation of momentum** states that linear momentum remains constant unless the system is acted on by an external force (see subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/)).

The principle of **conservation of energy** states that energy cannot be created or destroyed, only transferred from one form to another (see subtopic A.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43083/)).

The linear momentum, p, of a body is the product of the mass of the body and its velocity: $p = mv$ (see subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/)). This can lead to the misconception that because a photon has momentum, it must also have mass.

However, photons are massless particles. How can photons have momentum but not mass? Watch **Video 4** to see an explanation of how a massless photon can have momentum. (You do not need to know this as part of IB Physics.)

How can a photon have momentum?

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Video 4. How can a photon have momentum?

Theory of Knowledge

The law of conservation of momentum and the principle of conservation of energy have always been obeyed at a microlevel and a macrolevel. Is there ever sufficient evidence to prove with certainty that these laws are true?

Research the four truth tests and apply them to the physics laws of conservation.

Evaluate whether the laws of conservation meet these conditions.

Work through **Activity C** in the section (section E.2.1c (/study/app/physics/sid-423-cid-762593/book/activity-compton-scattering-simulation-hl-id-47370/)) to investigate the factors that affect the change in wavelength of the scattered photon.

The shift in the wavelength of the scattered photon can be calculated using the equation in **Table 2**. **Figure 6** shows the meaning of θ, the photon scattering angle.

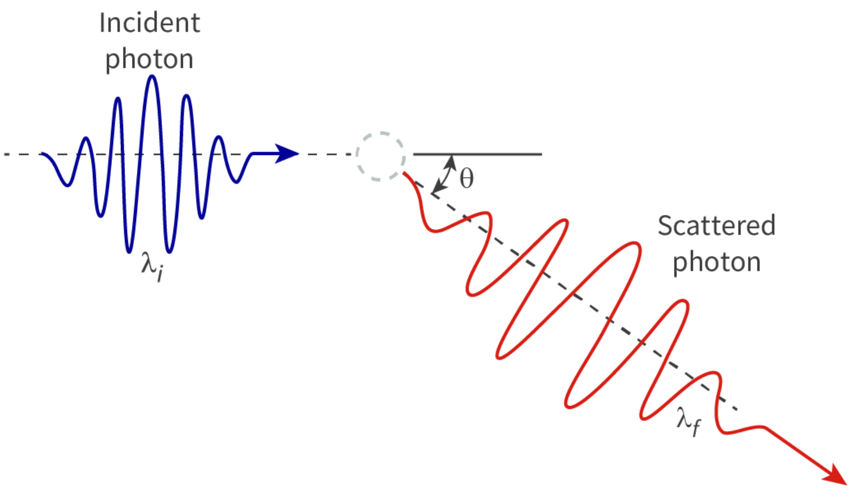

Figure 6. Compton scattering, showing scattering angle θ.

More information for figure 6

The image depicts a diagram of Compton scattering. It shows an incident photon, represented by a wave-like line with a label (\lambda_i), approaching from the left with an arrow indicating its direction. At the center is a dotted circle denoting the scattering interaction, marked with an angle (\theta). The scattered photon is shown emerging from the circle, depicted with a dashed wave-like line in a different direction, labeled (\lambda_f). The diagram conveys the change in direction and wavelength associated with the scattering process.

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Table 2. Change in wavelength equation.

Equation	Symbols	Units
$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$	λ_f = wavelength of scattered photon	metres (m)
	λ_i = wavelength of incident photon	metres (m)
	$\Delta\lambda$ = change in wavelength	metres (m)
	h = Planck constant (6.63×10^{-34} J s)	joule seconds (J s)
	m_e = electron rest mass (9.110×10^{-31} kg)	kilograms (kg)
	c = speed of light (3.00×10^{8} m s^{-1})	metres per second (m s^{-1})
	θ = photon scattering angle	degrees (°)

The change in the wavelength of the incident and scattered photon is known as the Compton shift.

Nature of Science

Aspect: Theories

The photoelectric effect is supported by the principle of conservation of energy.

The principle of conservation of energy and the law of conservation of momentum applies to Compton scattering.

Since we can directly measure the incoming and outgoing photon energies, and that of the scattered electron, we can apply the conservation laws more rigorously, and predict and explain the behaviour of the system accurately. Can you think of any other areas of physics where several laws of conservation are applied?

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Worked example 3

X-rays are fired at a carbon target and undergo Compton scattering. The scattered photons are detected at an angle of 42° to the incident X-rays. Determine the change in wavelength of the scattered photon.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$\theta = 42^{\circ}$
Step 2: Write out the equation.	$\Delta\lambda = \frac{h}{m_{e}c}(1 - \cos\theta)$
Step 3: Substitute the values given.	$= \frac{6.63 \times 10^{-34}}{(9.11 \times 10^{-31})(3.00 \times 10^{8})}$ (1
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 6.23 \times 10^{-13}\text{ m} = 6.2 \times 10^{-13}$ ı

Aspect: Evidence

Why is Compton scattering more convincing evidence for the particle nature of light than that from the photoelectric effect?

Work through the activity to check your understanding of the particle nature of light.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts.
- **Time required to complete activity:** 5 minutes

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- **Activity type:** Individual activity

Drag and drop the observations into the correct places in the table in **Interactive 5** to show whether they are evidence for the photoelectric effect or Compton scattering.

Photoelectric effect	Compton scattering
The frequency of the incident radiation needed to observe the effect depends on the metal	There is no photon remaining after the process occurs.
The incident radiation must be very high frequency X-rays or gamma waves	When the frequency of the incident radiation is greater than the threshold frequency, increasing its intensity increases the current

Check

Interactive 5. Photoelectric Effect Or Compton Scattering.

5 section questions

Question 1

HL Difficulty:

Red light is incident on a sodium plate connected in a circuit.

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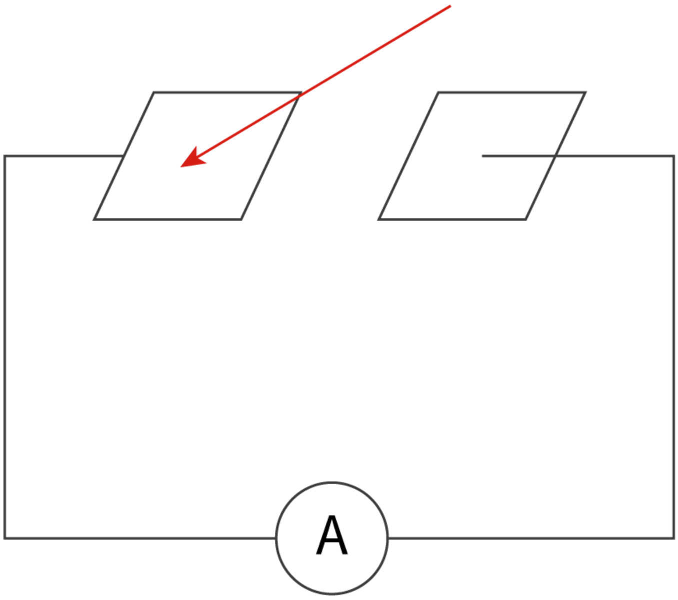

More information

The reading on the ammeter is 0 A.

What change would cause an increase in the current?

1 Decreasing the wavelength of the light ✓

2 Increasing the intensity of the light

3 Leaving the light on for longer

4 None of the above

Explanation

Initially the current is zero because the frequency of the red light is lower than the threshold frequency. A sufficient decrease in the wavelength of the light would increase the frequency above the threshold frequency, thus releasing electrons from the metal and producing a current.

Increasing the intensity of the red light would increase the rate of emission of photons, but their energies would remain below the threshold frequency, so no photoelectrons would be emitted and the current would remain at zero.

Leaving the red light on for longer would not increase the frequency of the photons emitted, so no photoelectrons would be released from the metal.

Question 2

HL Difficulty:

Light with a frequency of 8.2×10^{14} Hz is incident on a sample of calcium with a work function of 2.9 eV.

Determine the maximum kinetic energy of the photoelectrons released.

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view

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Give your answer to an appropriate number of significant figures.

The maximum kinetic energy is 1 0.50 ✓ eV.

Accepted answers and explanation

#1 0.50

0,50

0.50 eV

0,50 eV

0.50eV

0,50eV

General explanation

$$f = 8.2\times10^{14}\text{ Hz}$$

$$\phi = 2.9\text{ eV}$$

$$1\text{ eV} = 1.6\times10^{-19}\text{ J}$$

$$\begin{aligned}\phi &= 2.9\times1.6\times10^{-19}\\ &= 4.64\times10^{-19}\text{ J}\end{aligned}$$

$$\begin{aligned}E_{\text{max}} &= hf - \phi\\ &= \left(6.63\times10^{-34}\right)\left(8.2\times10^{14}\right) - \left(4.64\times10^{-19}\right)\\ &= 7.966\times10^{-20}\text{ J}\end{aligned}$$

Conversion to eV:

$$\begin{aligned}E_{\text{max}} &= \frac{7.966\times10^{-20}}{1.6\times10^{-19}}\\ &= 0.498\text{ eV}\\ &= 0.50\text{ eV (2 s.f.)}\end{aligned}$$

Question 3

HL Difficulty:

A photoelectric experiment is carried out using a metal with work function ϕ.

The graph shows the relationship between kinetic energy of emitted photoelectrons and frequency of incident light.

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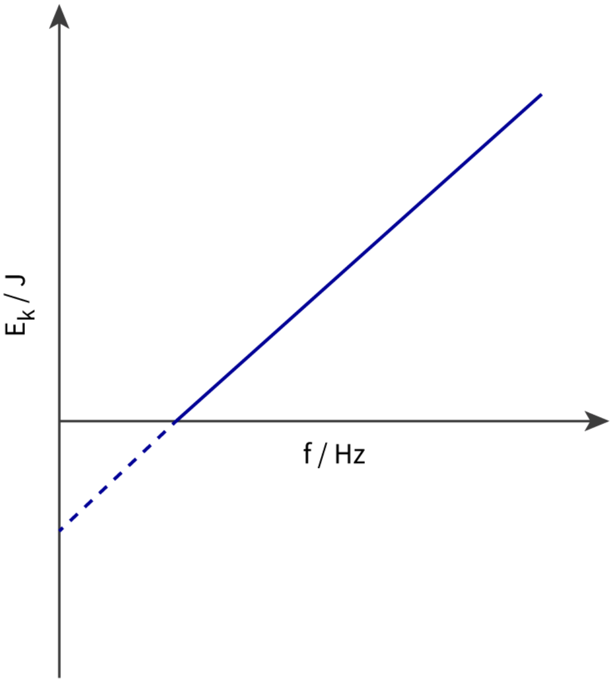
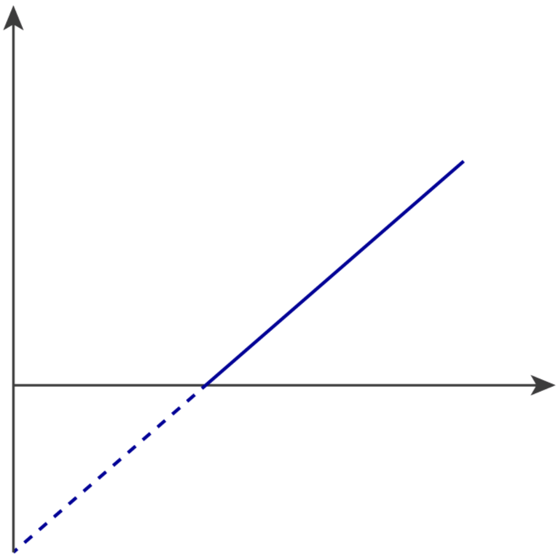


More information

The experiment is repeated using a metal with a greater work function.

Which graph shows this?

1



✓

More information

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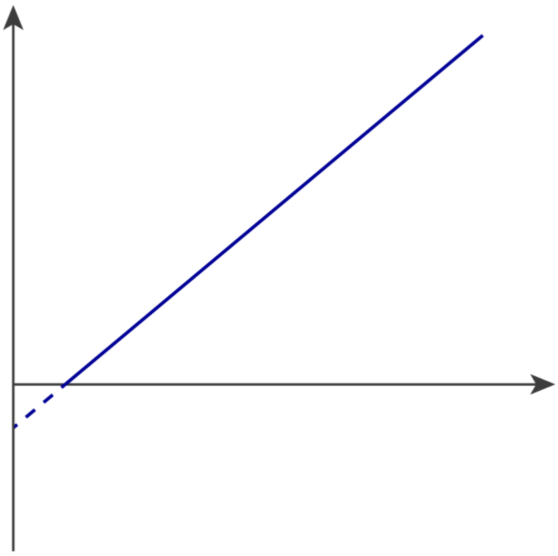
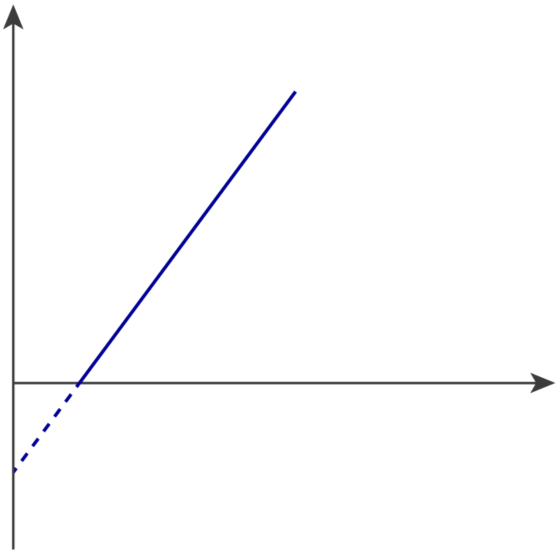


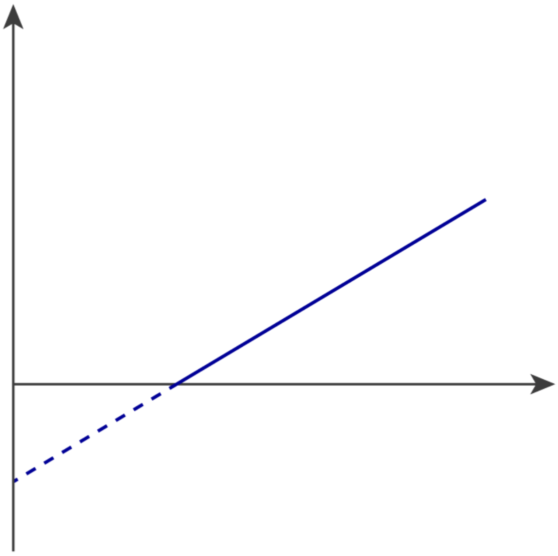
More information

3



More information

4



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More information

Explanation

The y-intercept of the line gives the negative of the work function. A greater work function results in a lower y-intercept, so the line would shift downwards, which would appear as a shift to the right. The gradient would be the same.

Question 4

HL Difficulty:

Light with a wavelength of 120 nm is incident on a metal sample and photoelectrons are released with a velocity of 1.5 × 10^3 km s^{-1}.

Determine the work function of the metal.

Give your answer to an appropriate number of significant figures.

The work function is 1 4.0 ✓ eV.

Accepted answers and explanation

#1 4.0

4,0

4.0 eV

4,0 eV

4.0eV

4,0eV

General explanation

$$\lambda = 120 \text{ nm}$$
$$= 120\times10^{-9} \text{ m}$$

$$v = 1.5\times10^{3} \text{ km s}^{-1}$$
$$= 1.5\times10^{6} \text{ m s}^{-1}$$

$E_{\max} = hf - \phi$ and $E_{\text{k}} = \dfrac{1}{2}mv^2$ hence:

$$\frac{1}{2}mv^2 = hf - \phi$$

Substituting $f = \dfrac{c}{\lambda}$ gives:

$$\frac{1}{2}mv^2 = \frac{hc}{\lambda} - \phi$$

$$\phi = \frac{hc}{\lambda} - \frac{1}{2}mv^2$$

$$\phi = \frac{\left(6.63\times10^{-34}\right)\left(3.00\times10^{8}\right)}{120\times10^{-9}} - \frac{1}{2}\left(9.110\times10^{-31}\right)\left(1.5\times10^{6}\right)^2$$
$$= 6.326\times10^{-19} \text{ J}$$

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$$\phi = \frac{6.326 \times 10^{-19}}{1.6 \times 10^{-19}}$$
$$= 3.95 \text{ eV}$$
$$= 4.0 \text{ eV (2 s.f.)}$$

Question 5

HL Difficulty:

An x-ray experiences a Compton shift of 1.1 pm.

Determine the photon scattering angle.

Give your answer to an appropriate number of significant figures.

The scattering angle is 1 57 ✓ °

Accepted answers and explanation

#1 57

57°

57 degrees

General explanation

$$\Delta\lambda = 1.1 \text{ pm}$$
$$= 1.1 \times 10^{-12} \text{ m}$$

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

$$\theta = \cos^{-1}\left(1 - \frac{\Delta\lambda m_e c}{h}\right)$$
$$= \cos^{-1}\left(1 - \frac{(1.1 \times 10^{-12})(9.110 \times 10^{-31})(3.00 \times 10^{8})}{6.63 \times 10^{-34}}\right)$$
$$= 56.87^\circ$$
$$= 57^\circ \text{ (2 s.f.)}$$

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

Activity: Photoelectric simulation (HL)

E.2.1: The photoelectric effect (HL) E.2.7: Compton scattering (HL) E.2.8: Photon scattering and increased wavelength (HL)

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Interactive 1. Photoelectric effect simulation

Activity

Higher level (HL)

Activity A

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 40 minutes
- **Activity type:** Pair activity

Examine **Interactive 1**. In this interactive, you may need to use scroll bars to see some of the features.

The interactive simulates an experiment in which two metal plates are connected in series with a variable voltage power supply and an ammeter. The plates are inside a glass container which has been evacuated. Since there is a gap between the plates,

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there is not a complete circuit.

For this activity, one learner should perform part A and one person should perform part B. Afterwards, discuss your findings.

Part A: How does the intensity of light affect the size of the electric current?

1. Keep the potential difference across the battery as 0 V. Leave the type of metal as the starting metal (sodium). Shine light on the left-hand plate, setting the intensity slider to about 50% of the maximum.
2. Move the wavelength slider to the far right to choose the highest available wavelength (which is infrared at 850 nm). Gradually move the wavelength slider to the left, decreasing the wavelength. What do you observe? (Look at the electrons and also at the ammeter reading.) Try to be as specific as you can about your observations.
3. Now set the wavelength to about 200 nm, keeping the same type of metal (sodium).
4. Now experiment by varying the intensity. Move the intensity slider to the right to increase the intensity, and to the left to decrease it. What else changes when you change the intensity? What does not change? If you vary the intensity at a wavelength of about 400 nm, do you observe the same effect?
5. For a wavelength of 400 nm, record the current for at least five different light intensities, in a table like **Table 1.**

Table 1. Example results table.

Intensity (%)	Current (A)

6. Plot your results on a graph of current in amperes on the y-axis against intensity percentage on the x-axis.
7. Repeat steps 5 and 6 for a wavelength of 200 nm.
8. Describe the relationship between the current and the intensity of the light.

Part B. How does the type of metal affect the minimum frequency needed to produce an electric current?

1. Move the wavelength slider to 850 nm and move the intensity slider to 100%.
2. Select a metal from the 'Target' drop-down menu.
3. Gradually decrease the wavelength using the slider until the ammeter displays a current of 0.016 A.
4. Repeat for the other metals in the 'Target' list.
5. Record the name of the metal and the wavelength in a table like **Table 2.**

Table 2. Example results table.

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Metal	Wavelength (nm)	Frequency (Hz)

6. Calculate the frequency of each wave using: $c = f\lambda$, where c = 3.00×10^8 m s^{-1}.
7. Plot a bar chart of the frequency required to produce an electric current in hertz on the *y*-axis against type of metal on the *x*-axis.
8. What is the relationship between frequency and type of metal?

Share your conclusions.

Click on 'Show or hide solution' to see the sample answers.

Part A:

When light with a long wavelength is incident on a metal, no electric current is produced. Increasing the light intensity does not affect the electric current. When light with a sufficiently short wavelength is incident on a metal, increasing the intensity increases the electric current. The electric current is directly proportional to the intensity of the light once the maximum wavelength has been reached.

Part B:

For a fixed intensity, the minimum frequency required to produce a current varies depending on the metal. Sodium requires the lowest frequency, while platinum requires the highest frequency.

Activity B

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Examine **Interactive 1**, the photoelectric effect simulation.

1. Set the metal to sodium, the light intensity to about 50%, the wavelength to about 200 nm, and the supply to zero.
2. Experiment with changing the supply voltage. What is the effect on the electrons if you make: the left-hand plate negative and the right-hand plate positive? Compare this to when the left-hand plate positive and the right-hand plate negative. Can you explain why? Can you find a potential difference which prevents any electrons from reaching the right-hand plate?

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3. Select a metal from the 'Target' drop-down menu, move the wavelength slider to 850 nm, and move the 'Intensity' slider to 100%.
4. Decrease the wavelength slider until a current flows.
5. Move the voltage slider on the battery until the current becomes zero.
6. Record the wavelength and stopping potential in a table like **Table 3**.

Table 3. Example results table.

Metal	
Wavelength (nm)	
Stopping potential (V)	
Frequency (Hz)	
Kinetic energy (J)	

7. For the same metal, repeat steps 4 to 6 for seven different wavelengths.
8. For each wavelength, calculate the frequency and the kinetic energy. If you need help, click on 'Show or hide tip'.

To calculate the frequency of the photons use

$f = \frac{c}{\lambda}$ where c is the speed of light in a vacuum.

To calculate the kinetic energy of the photoelectrons use $E_\mathrm{k} = eV_\mathrm{s}$ where e is the elementary charge.

9. Plot a graph of kinetic energy in joules on the *y*-axis against frequency in hertz on the *x*-axis.
10. Research the values for threshold frequency and work function for your chosen metal and compare them to your experimental results.

Can you think of any reasons for differences between the experimental values and the accepted values?

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

Activity: Compton scattering simulation (HL)

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Interactive 1. Investigating the factors that affect change in wavelength.
Credit: Antonio Di Muro

Activity

Higher level (HL)

Activity C

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

Look at **Interactive 1** 'Investigating the factors that affect change in wavelength'. Note: you can set the simulation to full-screen mode for this activity, using the button on the bottom right-hand side.

Tick the 'view the solution' and 'showing directions' boxes.

For this activity, one learner should carry out part A and one person should carry out part B.

Part A:

1. Select a scattering angle, θ, using the slider.
2. Use the slider to change the initial energy of the photon, E_0, to 1.0 MeV (or a value as close as possible).

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3. Record the initial energy, initial wavelength, and final wavelength, of the photon.
4. Using the same scattering angle, repeat steps 2 and 3 for seven different values of initial energy.
5. Record the initial energy, initial wavelength, λ_0, and final wavelength, λ, of the photon in a table like **Table 1**.

Table 1. Example results table.

Initial energy (MeV)	Initial wavelength (pm)	Final wavelength (pm)	Change in waveler (pm)

6. Calculate the change in wavelength for each initial energy in **Table 1**.
7. Plot a graph of change in wavelength in pm on the *y*-axis against initial energy in MeV on the *x*-axis and add a suitable line of best fit.
8. Summarise your observations and conclusions. Share your findings with your partner.

Part B:

1. Use the slider to change the initial energy of the photon, E_0, to 1.0 MeV (or a value as close as possible).
2. Now use the slider to select a scattering angle, θ.
3. Record the scattering angle, initial wavelength, λ_0, and final wavelength, λ, of the photon in a table like **Table 2**.
4. Without changing the initial energy, repeat steps 2 and 3 for seven different values of scattering angle.
5. Calculate the change in wavelength for each scattering angle in **Table 2**.
6. Plot a graph of change in wavelength in pm on the *y*-axis against scattering angle in degrees on the *x*-axis and add a suitable line of best fit.
7. Summarise your observations and conclusions. Share your findings with your partner.

Table 2. Example results table.

Scattering angle (°)	Initial wavelength (pm)	Final wavelength (pm)	Change in wavelength (pm)

For a constant scattering angle, when the initial energy of the photon is increased, the change in wavelength does not change.

For a photon with constant initial energy, as the scattering angle increases, the change in wavelength also increases. The relationship is non-linear.

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This suggests that the only factor that affects the change in wavelength of the photon is the scattering angle.

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

The wave nature of matter (HL)

E.2.4: Particle diffraction (HL) E.2.5: Wave-particle duality (HL) E.2.6: The de Broglie wavelength (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Explain that matter exhibits wave-particle duality.
- Describe how the diffraction of particles is evidence for the wave nature of matter.
- Explain the concept of the de Broglie wavelength of matter and use the equation:

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

Light behaves like a wave. Light waves diffract, refract, interfere and superimpose (see subtopic C.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44900/)) but the photoelectric effect shows that light also behaves like a particle (see section E.2.1 (/study/app/physics/sid-423-cid-762593/book/the-particle-nature-of-light-hl-id-46462/)). How can light behave like a wave and a particle at the same time?

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/activity-photoelectric-simulation-hl-id-46473/print/) Assign

Electrons behave as particles when we perform particle experiments with them. What would happen if, instead of treating an electron as a particle, we treated it as a wave?

Video 1 introduces the concept of the wave behaviour of particles. How has collaboration developed our understanding of quantum physics? How have scientists used their imagination and intuition to create a hypothesis?

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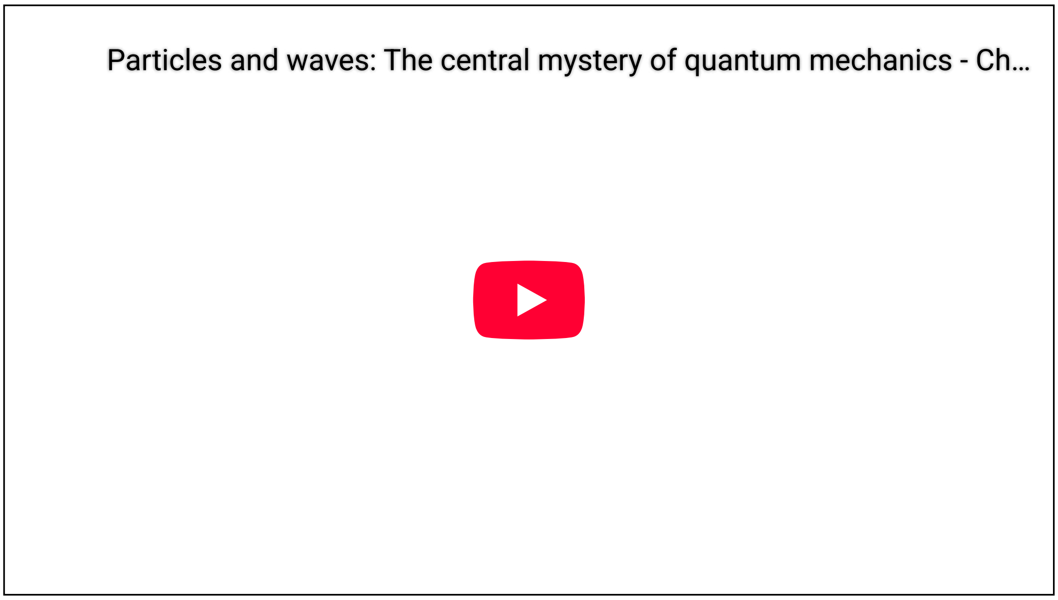
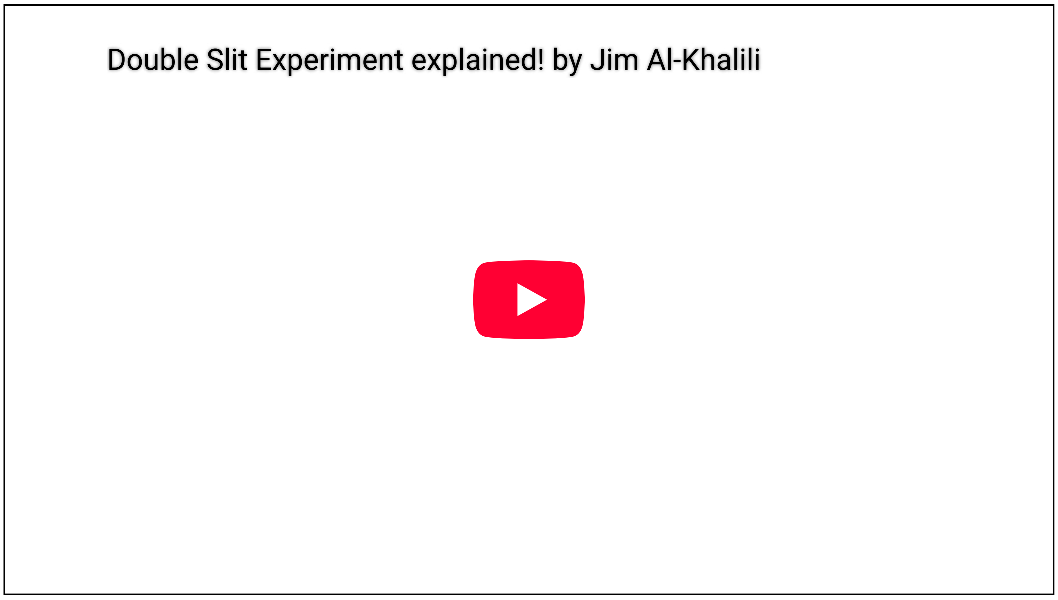


Video 1. The wave behaviour of particles.

The wave nature of matter

Young's double-slit experiment provided definitive evidence for the wave nature of light (see subtopic C.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44900/)). **Video 2** shows what happens when atoms are fired at a double slit.



Video 2. Young's double slit experiment.

Drag and drop the observations in the table in **Interactive 1** to show whether they are evidence for atoms being particles or waves.

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/activity-compton-scattering-simulation-hl-id-47370/print/) Assign

Student view

Interactive 1. Particles or Waves.

The double slit experiment is often carried out using electrons and the diffraction grating can be a thin film of graphite, where the slits are formed by the spaces between the atoms in the lattice structure of the graphite as shown in **Interactive 2**.

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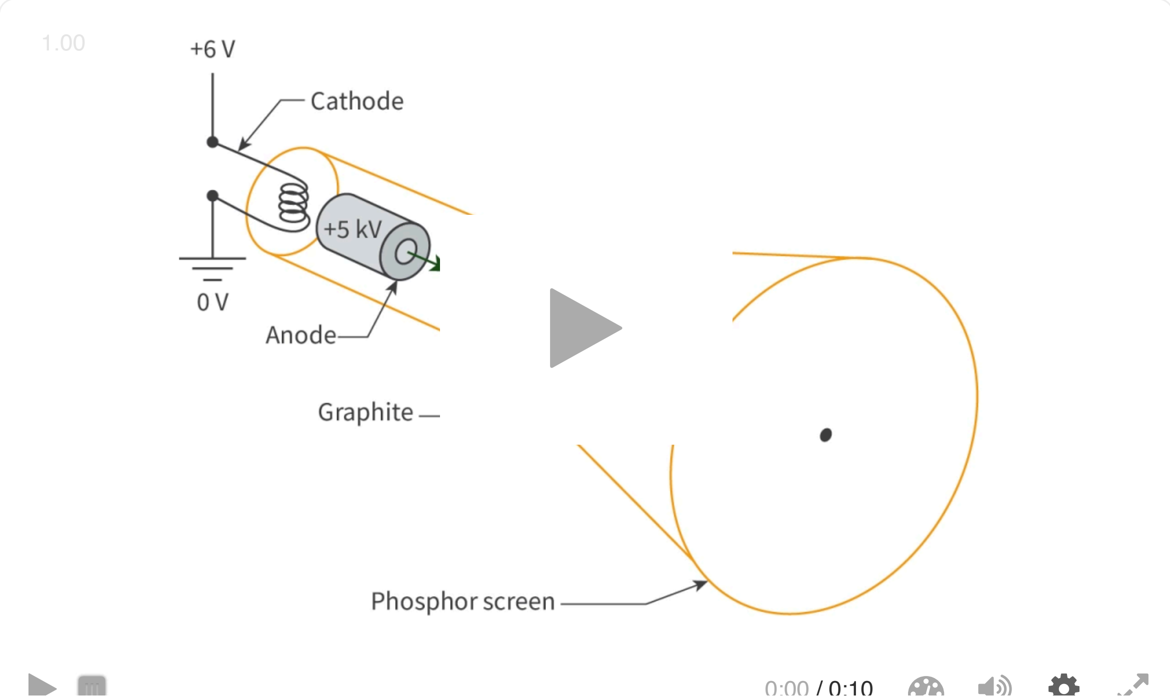

Interactive 2. The Experimental Set up of Electron Diffraction.

More information for interactive 2

The interactive features a video demonstrating the electron diffraction experiment and its dependence on accelerating electric potential difference. Users can control playback using the play/pause button and timeline at the bottom, while the full-screen option in the lower-right corner allows for better viewing of detailed visuals like diffraction rings and equipment labels.

The video opens with an illustration of the experimental setup. Electrons are emitted from a heated cathode and accelerated towards a thin graphite target using an applied electric potential difference. The setup includes an anode with a voltage of +5 kV and a graphite target that diffracts the electron beam. A phosphor screen behind the graphite displays the resulting diffraction pattern in the form of concentric green rings, indicating wave-like behavior of electrons.

In the first case, a low accelerating electric potential difference is applied. As a result, electrons gain relatively low kinetic energy as they move towards the graphite. When these slower electrons interact with the atomic structure of the graphite, they produce wider and more diffuse concentric rings on the phosphor screen. This indicates a longer wavelength due to lower momentum, as predicted by the de Broglie equation. The spread-out pattern clearly demonstrates diffraction at lower energies.

In the second case, a high accelerating electric potential difference is applied to the setup. This causes the electrons to gain higher kinetic energy and approach the graphite with greater velocity. As these faster electrons are diffracted, the resulting pattern on the phosphor screen becomes tighter and more sharply defined. This happens because the electron wavelength is now shorter, leading to closer ring spacing in the diffraction pattern.

Through this sequence, the video visually communicates how varying the potential difference changes the speed—and therefore the wavelength—of the electrons, which in turn alters the diffraction pattern. This provides an effective demonstration of electron wave-particle duality, reinforcing core principles of quantum mechanics.

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You can see from **Interactive 2** that the image produced on the screen is a series of concentric circles, whose diameter depends on the size of the accelerating electric potential difference.

The de Broglie wavelength

In 1923, the French physicist Louis de Broglie reasoned that if light could behave as a particle, then particles must also be able to behave as waves. From this, he devised an equation hypothesising the relationship between the momentum of a particle and its corresponding wavelength. This wavelength is known as the de Broglie wavelength **(Table 1)**.

Table 1. Equation for de Broglie wavelength.

Equation	Symbols	Units
$\lambda = \frac{h}{p}$	λ = wavelength	metres (m)
	h = Planck constant (6.63×10^{-34} J s)	joule seconds (J s)
	p = momentum	kilogram metres per second (kg ms^{-1})

Study skills

Remember that linear momentum is given by:

$p = mv$ (see subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/))

Worked example 1

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/the-particle-nature-of-light-hl-id-46462/print/) Assign

An electron travels at a velocity of 1400 km s^{-1}.

Show that its de Broglie wavelength is approximately 5.2×10^{-10} m.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$v = 1400\,\text{km s}^{-1}$ $= 1400 \times 10^3\,\text{m s}^{-1}$ $= 1.4 \times 10^6\ \text{ms}^{-1}$

Student view

Solution steps	Calculations
Step 2: Write out the equations and equate.	$\lambda = \frac{h}{p}$ and $p = mv$ $\lambda = \frac{h}{mv}$
Step 3: Substitute the values given.	$= \frac{6.63 \times 10^{-34}}{(9.110 \times 10^{-31})\,(1.4 \times 10^{6})}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 5.198 \times 10^{-10}\ = 5.2 \times 10^{-10}\,\text{m}$ In a *show that* question, remember to always quote y calculated value to one or more extra significant figu than the value given in the question.

De Broglie's hypothesis was verified in 1927 by U.S. physicists Clinton Davisson and Lester Germer when they carried out an experiment that involved firing a beam of electrons at a diffraction grating, which was a single crystal of nickel (**Figure 1**).

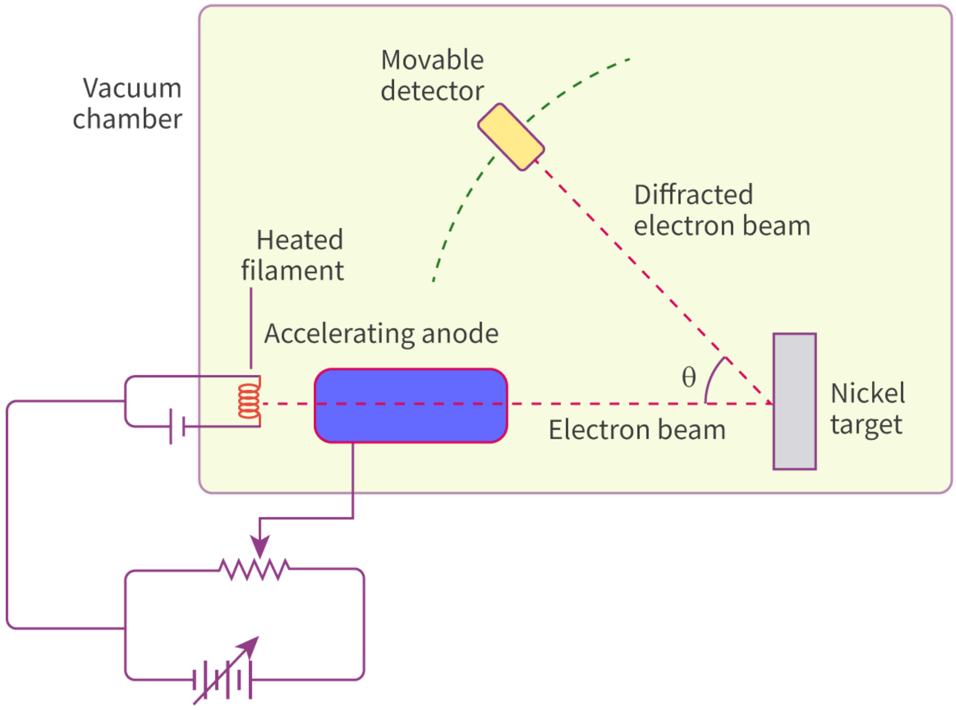

Figure 1. The Davisson-Germer experiment provided experimental evidence that supported de Broglie's hypothesis.

More information for figure 1

The diagram illustrates the setup for the Davisson-Germer experiment within a vacuum chamber. It shows a heated filament that emits an electron beam. The beam passes through an accelerating anode before hitting a nickel target at an angle θ, causing diffraction. The diffracted electron beam is detected by a movable detector.

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The diagram also includes a circuit with resistors and a variable capacitor connected to the accelerating anode and heated filament.

[Generated by AI]

The beam of electrons was diffracted and a movable detector measured the intensity of the diffracted beam of electrons at different angles. This data was plotted on a graph like the one in **Figure 2**.

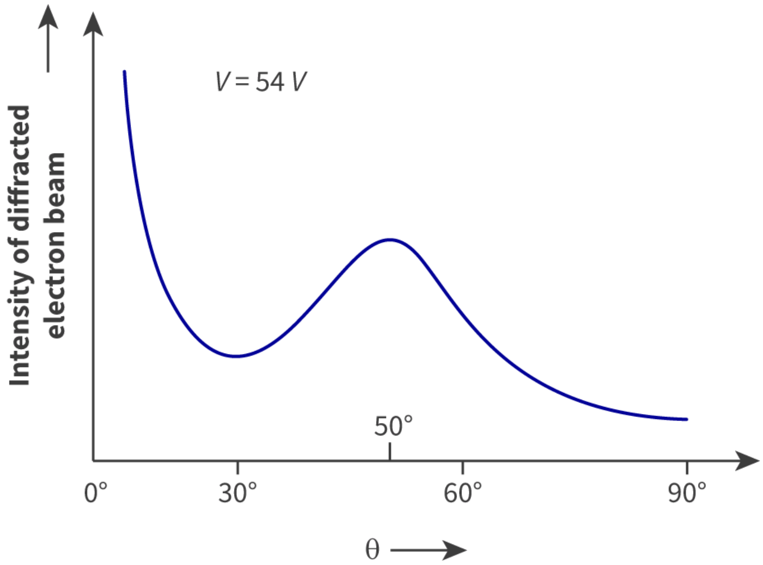

Figure 2. A graph of intensity of diffracted electron beam against scattering angle.

More information for figure 2

The graph illustrates the relationship between the intensity of a diffracted electron beam and the scattering angle. The Y-axis represents the intensity of the diffracted electron beam, with no specific units indicated. The X-axis represents the scattering angle, labeled as θ, ranging from 0° to 90°. A curve on the graph peaks at specific angles, indicating maximum intensities at those points. The graph shows a notable peak in intensity at an angle of about 50°, which aligns with the measurement labeled as "V = 54 V," though the exact significance of this label in terms of intensity is not provided.

[Generated by AI]

In **Figure 2**, you can see that there is a maximum intensity at a specific angle, which was found to agree with that predicted by de Broglie four years previously.

The effect of diffraction is greatest when the size of the gap (or obstacle) is similar to the wavelength (see subtopic C.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44900/)). The diffraction of electrons, which provides evidence of the wave

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behaviour of matter, is best observed when a thin layer of graphite or single crystal of nickel is used as the diffraction grating. This is because the distance between the atoms is similar in size to the range of de Broglie wavelengths of an electron - about 10^{-10} m.

AB Exercise 1

Click a question to answer

Higher level (HL)

If the nickel atoms are chemically bonded in a lattice, they form a diffraction grating, with a slit separation, d, of 0.2 nm. As electrons are diffracted by the lattice, they form a diffraction pattern similar to that seen in **Figure 3** (see section C.3.4 (:sectionlink:141957)).

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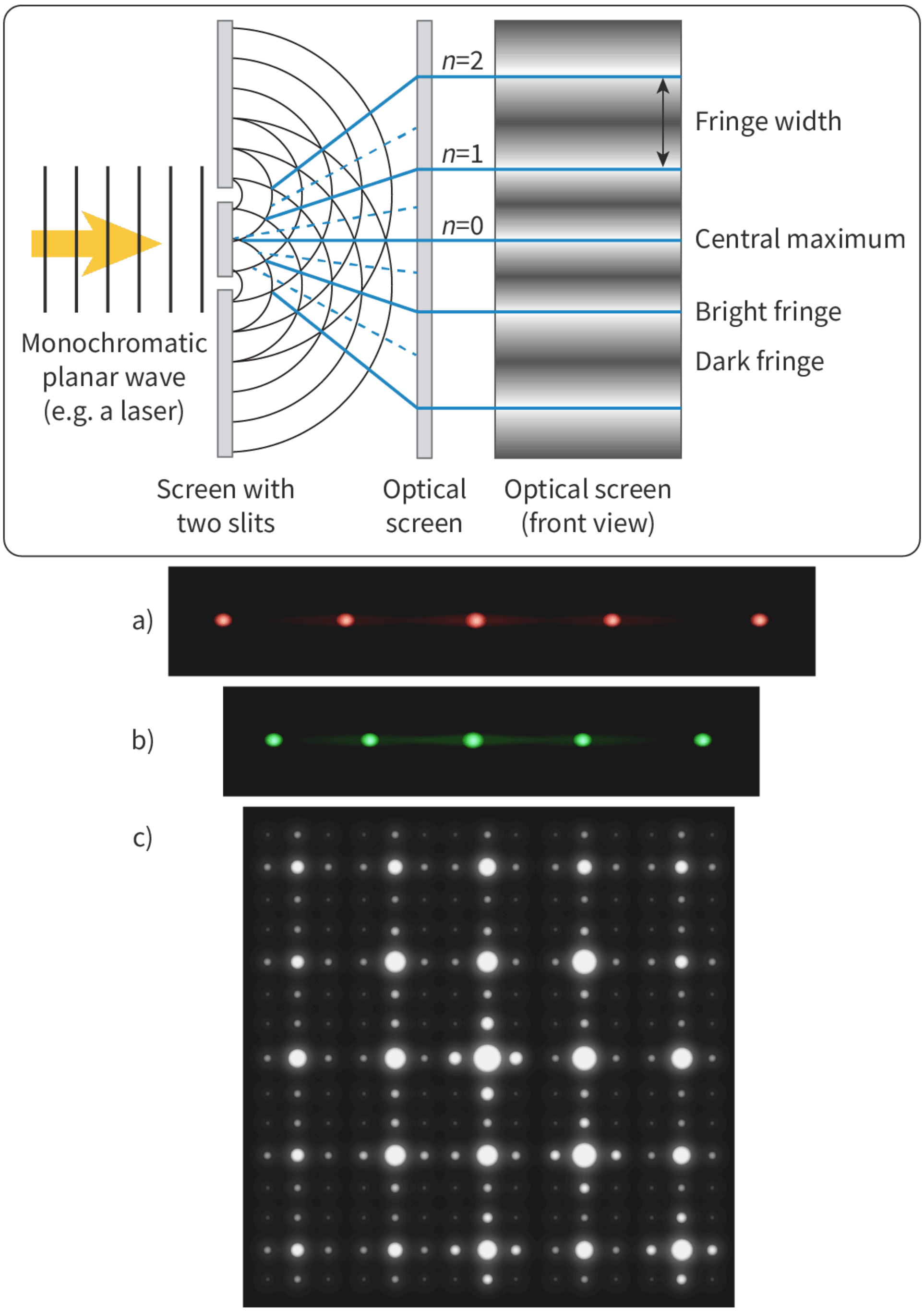

Figure 3. The diffraction pattern formed when a) red light and b) green light pass through a diffraction grating, and when c) electrons pass through a molecular lattice, acting as a diffraction grating.

More information for figure 3

The image is a diagram showing the concept of diffraction patterns formed by waves passing through slits or a lattice structure. On the top, there are three main parts:

1. A schematic with a monochromatic planar wave, such as a laser, entering from the left and passing through a screen with two slits. The optical screen is shown adjacent, where interference results in a diffraction pattern.
2. The diffraction pattern is detailed on the optical screen's front view. Labels indicate 'central maximum' at n=0 position, and 'fringe width' with bright and dark areas indicating bright and dark fringes respectively.

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Below the schematic:

1. Three sections (a, b, and c) show actual diffraction patterns:
2. (a) Diffraction pattern formed by red light passing through a grating, displaying a series of red dots in a line.
3. (b) Diffraction pattern formed by green light, showing green dots in a similar configuration.
4. (c) A more complex diffraction pattern formed by electrons passing through a molecular lattice, resulting in a grid-like pattern of white dots of varying sizes, indicating more complex wave interactions.

[Generated by AI]

Figure 3 shows that there is a central bright maximum with a series of maxima at varying angles to either side. The angular positions of these maxima are given by the diffraction equation:

$$n\lambda = dsin\theta$$

Where n is the 'order' of the maxima. For the maxima nearest the centre, n = 1, and so the equation can be written as:

$$\lambda = dsin\theta$$

where θ is the angle to the first minimum of the diffraction pattern.

Worked example 2

A beam of electrons with energy 2.6 keV is fired at a nickel lattice and diffracted.

Figure 4 shows the effect of the scattering angle on the intensity of the detected electron beam.

Student
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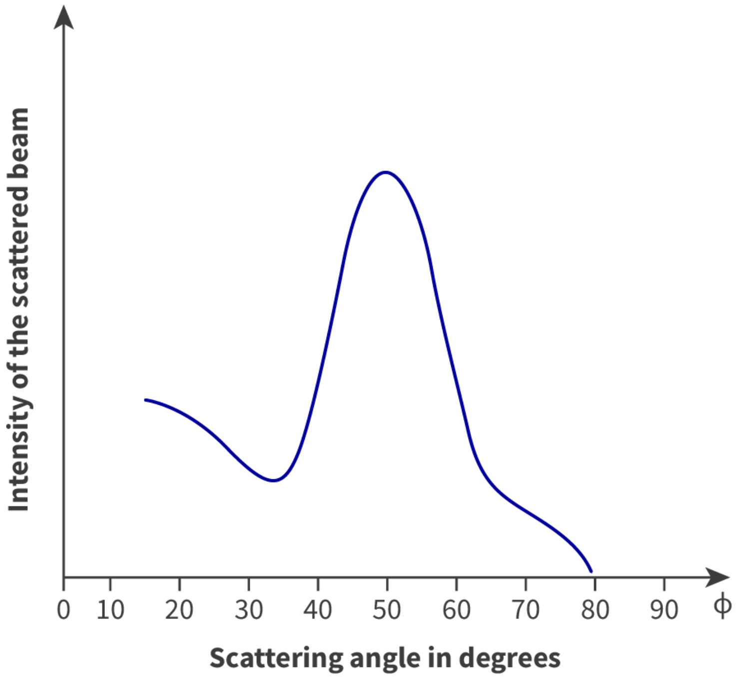

Figure 4. Graph of intensity of detected electron beam against scattering angle.

More information for figure 4

The graph plotted here is a line graph that represents the relationship between the scattering angle, measured in degrees, and the intensity of the scattered electron beam. The X-axis is labeled "Scattering angle in degrees" with a range from 0 to 90 degrees. The Y-axis is labeled "Intensity of the scattered beam." The line graph shows a notable peak around 50 degrees, indicating that the intensity increases significantly as the scattering angle approaches this point and then decreases beyond 60 degrees. This trend suggests that the intensity of the electron beam is highly dependent on the scattering angle, with maximum intensity observed near the peak.

[Generated by AI]

The de Broglie wavelength of an electron can be calculated using:

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2m_e E}}$$

Determine the approximate spacing between neighbouring nickel nuclei where the electron is travelling at 10% the speed of light.

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Solution steps	Calculations
Step 1: Convert to the units required for the equation and write out what we know.	From the graph we find that: $\theta = 35^\circ$ at the first minimum The rest mass of an electron is given in the data booklet as 9.110×10^{-31}kg At 10% the speed of light, we will assume this is relativistic. Converting the energy from eV to Joules: $2.6\ \text{keV} = 4.16 \times 10^{-16}\ \text{J}$
Step 2: Determine the de Broglie wavelength of the electron.	**Equation 1** $\lambda = \frac{h}{mv} = \frac{(6.63 \times 10^{-34})}{(9.110 \times 10^{-31})(0.1 \times 3 \times 10^8)} = 2.426 \times 10^{-11}\ \text{m (3 s.f.)}$ **Equation 2** $\lambda = \frac{h}{\sqrt{2m_eE}} = \frac{(6.63 \times 10^{-34})}{\sqrt{2 \times m_e \times 4.16 \times 10^{-16}}} = 2.424 \times 10^{-11}\ \text{m (3 s.f.)}$ Due to rounding error these dont match exactly are close enough we can be confident in the pr
Step 3: Determine the approximate diameter of the nickel nucleus.	The diffraction spacing, *d*, gives the approximat diameter of the nickel atom (which is the spacin between neighbouring nuclei): $\lambda = d \sin\theta$ $d = \frac{\lambda}{\sin\theta} = \frac{2.426 \times 10^{-11}}{\sin 35^\circ} = 4.2 \times 10^{-11}\ \text{m (2 s.f.)}$

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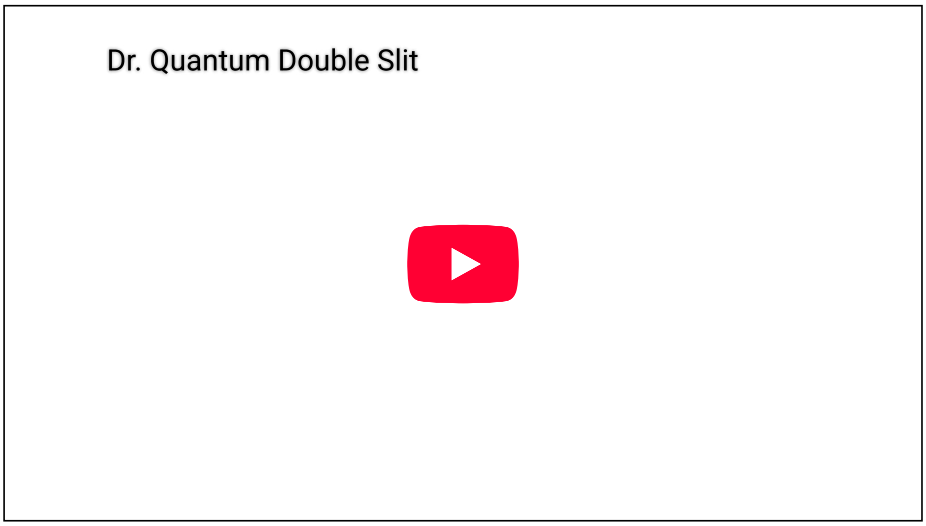
Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 30 minutes
- **Activity type:** Group activity

Quantum physics is one of the most abstract areas of physics and it can be very difficult to communicate in a way that is easy to understand for non-specialists. Your task is to produce a short video (maximum of 2 minutes) to explain one of the concepts in this subtopic.

You might want to consider analogies or examples of your concept.

You could use **Video 3** for inspiration:



Video 3. Double slit experiment.

5 section questions

Question 1

HL Difficulty:

When a stream of electrons is fired at a thin graphite film, this series of bright bands is observed.

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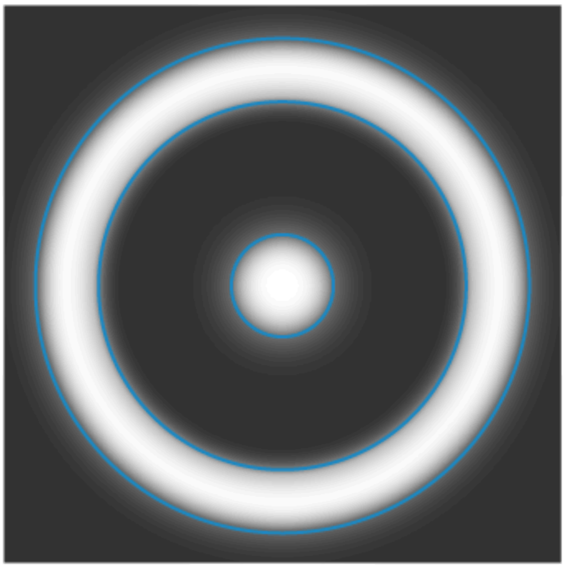

More information

What does this pattern provide evidence for?

1 The wave behaviour of particles ✓

2 The particle behaviour of particles

3 The wave behaviour of light

4 The particle behaviour of light

Explanation

The electrons are diffracted by the spaces between the atoms in the lattice structure of the graphite. If the electrons were particles, they would form only two bright bands.

Question 2

HL Difficulty:

What is the de Broglie wavelength of a proton travelling at 4.5×10^{5} ms^{-1}?

1 8.8×10^{-13} m ✓

2 4.0×10^{-7} m

3 1.5×10^{-38} m

4 7.5×10^{-22} m

Student view

Explanation

$v = 4.5 \times 10^{5}\ \mathrm{m\ s^{-1}}$

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

$$\begin{aligned}\lambda &= \frac{h}{mv} \\ &= \frac{6.63 \times 10^{-34}}{\left(1.673 \times 10^{-27}\right)\left(4.5 \times 10^{5}\right)} \\ &= 8.807 \times 10^{-13} \\ &= 8.8 \times 10^{-13}\ \mathrm{m}\ (2\ \mathrm{s.f.})\end{aligned}$$

Question 3

HL Difficulty:

A beam of electrons is fired through a double slit and a series of bright and dark fringes of equal intensity is observed on a screen.

The double slit is changed to a single slit.

What change, if any, would you expect to see in the pattern on the screen?

1 A bright central maximum with narrower bright and dark maxima of lower intensity ✓

2 No change

3 The same series of bright and dark fringes of equal intensity but with each one half the width of the original pattern

4 The same series of bright and dark fringes of equal intensity but half the intensity of the original pattern

Explanation

A series of light and dark fringes is formed when matter behaves like a wave. When the wave passes through the two slits, it forms two sources of coherent waves that interfere.

Bright fringes are observed when the two waves interfere constructively.

Dark fringes occur when the two waves interfere destructively.

When the double slit is changed to a single slit, the electrons form a single-slit interference pattern.

Question 4

HL Difficulty:

A particle of mass *m* travelling at velocity *v* has de Broglie wavelength, λ. Another particle of mass 0.5*m* travels at a velocity of 2*v*. What is its de Broglie wavelength?

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1 λ

2 $\frac{\lambda}{2}$

3 2λ

4 4λ

Explanation

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

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

From this we can see that:

$$\lambda \, \alpha \, \frac{1}{m}$$

If *m* decreases by a factor of 2, λ will increase by a factor of 2, therefore we have 2λ.

$$\lambda \, \alpha \, \frac{1}{v}$$

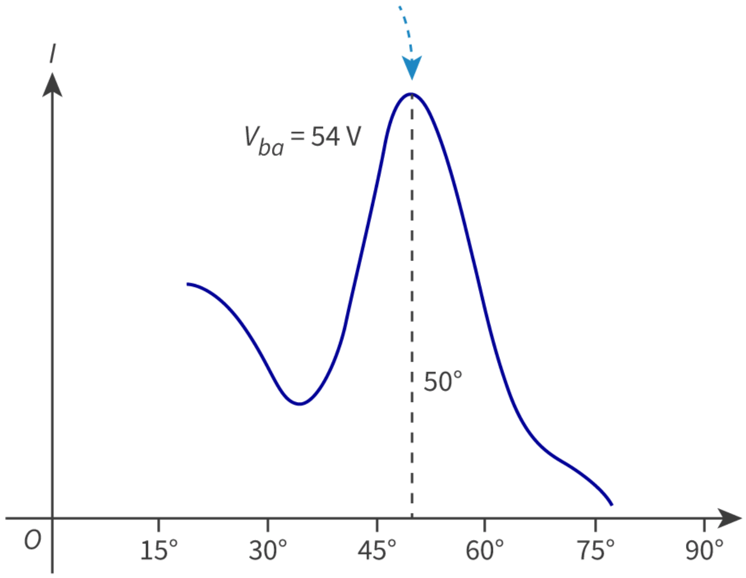
If *v* increases by a factor of 2, λ will decrease by a factor of 2 therefore we are back to λ.

Question 5

HL Difficulty:

A beam of electrons with energy 270 MeV is diffracted by a single crystal of nickel. The graph shows the effect of the scattering angle on the intensity of the electron beam, where the maximum sit on 50^{o}, and the minimum sits on 35^{o}.

Student view



More information

The de Broglie wavelength of an electron can be calculated using:

$$\lambda = \frac{hc}{E}$$

Determine the approximate diameter of the nickel nucleus. Give your answer to an appropriate number of significant figures.

The diameter is 1 8.0 ✓ fm.

Accepted answers and explanation

#1 8.0

8,0

8.0 fm

8,0 fm

8.0fm

8,0fm

General explanation

$$E = 270 \text{ MeV}$$
$$= 270 \times 10^{6} \text{ eV}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

$$E = 270 \times 10^{6} \times 1.6 \times 10^{-19}$$
$$= 4.32 \times 10^{-11} \text{ J}$$

From the graph, the angle, θ, at which the intensity is minimum:

$$\theta = 35°$$

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$$\lambda = \frac{hc}{E}$$
$$= \frac{(6.63 \times 10^{-34}) \times (3.00 \times 10^{8})}{4.32 \times 10^{-11}}$$
$$= 4.60 \times 10^{-15} \text{ m}$$
$$d = \frac{\lambda}{\sin\theta}$$
$$= \frac{4.60 \times 10^{-15}}{\sin 35}$$
$$= 8.03 \times 10^{-15}$$

The diameter is 8.0×10^{-15} m = 8.0 fm (2 s.f.).

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

Summary and key terms (HL)

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/summary-and-key-terms-hl-id-46464/print/) Assign

Higher level (HL)

- Light behaves as both a wave and a particle.
- The photoelectric effect is evidence for the particle nature of light.
- Light incident on a metal needs to have a minimum frequency (the threshold frequency) to release an electron from the metal. Above the threshold frequency, increasing the intensity of the light increases the electric current produced. Below the threshold frequency, no electric current is produced, regardless of the intensity of the light (or the time it is incident on the metal).
- The work function is the minimum amount of energy needed by an electron in order to be released from an atom.
- The maximum kinetic energy of the photoelectron released can be calculated using the equation:

$$E_{\text{max}} = hf - \phi$$

- The Compton scattering of light by electrons is further evidence for the particle nature of light.
- In Compton scattering, the energy of the incident photon does not affect the shift in its wavelength. An increase in the scattering angle of the photon increases the shift in its wavelength.
- The shift in the wavelength of a photon can calculated using the equation:

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$$\begin{aligned} \lambda_f - \lambda_i &= \Delta\lambda \\ &= \frac{h}{m_e c}(1 - \cos\theta) \end{aligned}$$

- Matter behaves as both a wave and a particle.
- When a beam of electrons passes through a diffraction grating, the diffraction pattern formed is evidence for the wave behaviour of particles.
- The de Broglie wavelength of particles can be calculated using the equation:

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

Evidence for wave nature	Evidence for particle nature
Interference	the photoelectric effect
Diffraction	Compton scattering

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/the-wave-nature-of-matter-hl-id-46463/print/) Assign

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Key terms

Review these key terms. Do you know them all? Fill in as many as you can using the terms in this list.

1. A key piece of evidence for the particle nature of light is the .
2. When an electron absorbs a photon and is released from the metal called a .
3. The minimum amount of energy needed by an electron in order to b released from a metal is known as the .
4. The minimum frequency of the photons needed to release an electr from a metal is known as the .
5. Above the threshold frequency, if the intensity of light incident on a is increased, the current .
6. In Compton scattering, a high energy photon collides with an electr and the wavelength of the photon .
7. In Compton scattering, energy and momentum are .

increases | photoelectron | work function | increases | conserved | threshold frequency | photoelectric effect

Check

Interactive 1. Photoelectric Effect and Compton Scattering.

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

Checklist (HL)

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Higher level (HL)

What you should know

After studying this subtopic, you should be able to:

- Describe how the photoelectric effect is evidence for the particle nature of light and understand the concept of threshold frequency.
- Understand the concept of work function and use the equation for maximum kinetic energy of photoelectrons:

$$E_{\max} = hf - \phi$$

- Describe how Compton scattering of light is evidence for the particle nature of light and use the equation for the shift in photon wavelength:

$$\begin{aligned}\lambda_{\mathrm{f}} - \lambda_{\mathrm{i}} &= \Delta\lambda \\ &= \frac{h}{m_e c}(1 - \cos\theta)\end{aligned}$$

- Explain that matter exhibits wave—particle duality.
- Describe how the diffraction of particles is evidence for the wave nature of matter.
- Explain the concept of the de Broglie wavelength of matter and use the equation:

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

E. Nuclear and quantum physics / E.2 Quantum physics (HL)

Investigation (HL)

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/investigation-hl-id-46466/print/) Assign

Higher level (HL)

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Designing procedures and models
- **Time required to complete activity:** 3 hours

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- **Activity type:** Group activity

Over the years, many different scientists have investigated the wave–particle duality of light and matter and made contributions by making observations and developing and testing hypotheses. Creating a hypothesis often requires intuition and imagination, since there are limitations on what we are able to observe directly. For example, we cannot directly see photons – yet it has been possible to develop the idea that light can behave as particles. This gives us the ability to explain and predict various phenomena.

Video 1 shows a 'black box' demonstration: a demonstration of a phenomenon that we can try to explain even though we cannot directly see how it works. It provides an opportunity to practise using the scientific method.

Video 1. A black box experiment.

Your task

1. After watching **Video 1**, make a hypothesis about how the mystery tube works. Explain how your hypothesis predicts your observations from **Video 1.** (You do not have to explain how the tube can be split into two pieces.) If you could experiment with the mystery tube, are there any further experiments you like to carry out to test your hypothesis? (You are not allowed to look inside the tube, or break it!)
2. Watch **Video 2**, which shows how to make a mystery tube. Does the construction of the mystery tube match your hypothesis?

Video 2. How to make a mystery tube.

3. Produce a poster to explain:
    - how the mystery tube works
    - how the mystery tube can be used as a model for the development of our understanding of wave-particle duality.

      The understanding that light also behaves as a particle was the beginning of the development of quantum physics.

      In your poster, include an example of how physicists used the following skills in the development of this field:
        - observations
        - hypotheses
        - experiments
        - theories
        - science as a shared endeavour.
4. Create your own black box demonstration. This could be a version of the mystery tube, or it could be a different demonstration that you have found out about or invented yourself. Show your finished black box demonstration to your peers or some younger students, and ask if they can think of a hypothesis that explains all of the observations. (If their hypothesis explains all of the observations but does not match what is inside the black box, then they have still shown good scientific thinking!)

Creativity, activity, service

Strand: Service
Learning outcome: Demonstrate how to initiate and plan a CAS experience

How could you develop this Investigation into a service opportunity to teach younger students about the scientific method?

Reflection (HL)

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Higher level (HL)

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/physics/sid-423-cid-762593/book/the-big-picture-hl-id-46454/).

- How can light be used to create an electric current?
- What is meant by wave-particle duality?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

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⚠ Once you submit your response, you won't be able to edit it.

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Submit

Rate subtopic E.2 Quantum physics (HL)

Help us improve the content and user experience.

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