Collegedunia NCERT Notes

The Ultimate NCERT Revision Guide for Class 12 Physics

Chapter 11: Dual Nature of Radiation and Matter

What This Chapter Is About

By the end of Class 11, light was settled as a wave (interference, diffraction, polarisation all confirmed it). This chapter shatters that simple picture. Light, when it hits a metal surface, behaves like a stream of particles called **photons**. And in a stunning twist, electrons — which had been particles since Thomson — are shown to diffract like waves. Both radiation and matter carry a **dual nature**. The two cornerstone experiments here are the **Photoelectric Effect** (radiation as particles) and the **Davisson–Germer Experiment** (matter as waves).

1 Electron Emission and Work Function

Free electrons in a metal are not actually free to leave it. They float around inside the metal lattice but are held back at the surface by the attractive pull of positive ions. To eject an electron, we must supply energy strong enough to break this surface barrier. The minimum energy required is called the **work function** of the metal.

1.1 Work Function (ϕ_0)

The work function ϕ_0 is the minimum energy needed by an electron to just escape the metal surface. It is a property of the metal surface, not of the bulk metal alone — a freshly polished alkali metal has a very different work function from the same metal with an oxide layer on top.

Work Function

$$\phi_0 = h\nu_0 = \frac{hc}{\lambda_0}$$

- ϕ_0 = work function (Joule or eV)

- ν_0 = threshold frequency (Hz)
- λ_0 = threshold wavelength (m)
- Energy unit: 1 eV $= 1.602 \times 10^{-19}$ J

Work functions are usually expressed in electron-volts because the numbers come out tidy: caesium 2.14 eV, sodium 2.75 eV, copper 4.65 eV, platinum 5.65 eV. Alkali metals (Cs, Na, K, Rb) have low work functions, which is why they are used in photoelectric cells.

Why Alkali Metals Are Photo-Sensitive

Their loosely held single valence electron is far from the nucleus and weakly bound. Even visible light has enough energy per photon to knock it out. Heavier metals like platinum need ultraviolet.

1.2 Methods of Electron Emission

There are four standard ways to give electrons enough energy to escape:

1. **Thermionic emission** — heating the metal so that thermal energy of electrons exceeds ϕ_0. Used in old vacuum tubes and CRTs.
2. **Field emission** — applying a very strong external electric field ($\sim 10^8$ V/m) that yanks electrons out. Used in scanning electron microscopes.
3. **Photoelectric emission** — shining light of frequency $\nu \geq \nu_0$ on the surface so each photon delivers enough energy to one electron. The subject of this chapter.
4. **Secondary emission** — bombarding the surface with high-energy electrons or other particles, which dislodge surface electrons.

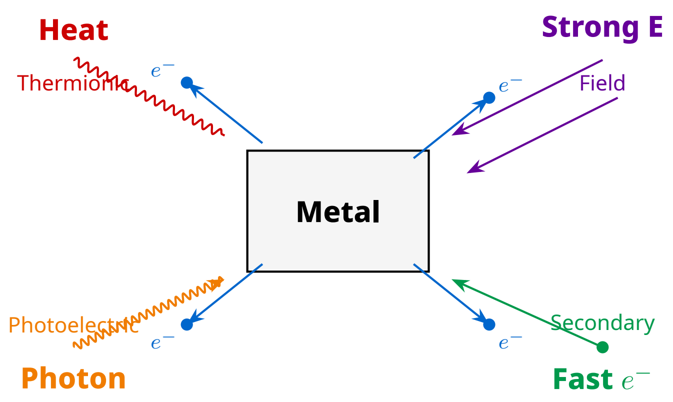

Figure 1.1: Four ways to liberate electrons from a metal surface.

Quick Tip

For board questions, examiners often ask "Name the four methods of electron emission". Memorise the order: **Thermionic, Field, Photoelectric, Secondary**. Even one missed method costs a mark.

1.3 Electron Volt — A Useful Energy Unit

When dealing with electrons, the joule is far too large. We use the electron-volt (eV) instead.

Electron Volt Definition

The energy gained by an electron when accelerated through a potential difference of 1 V.

$$1 \text{ eV} = e \times 1 \text{ V} = 1.602 \times 10^{-19} \text{ J}$$

So a 4 eV photon carries 6.4×10^{-19} J. Visible light photons range from about 1.65 eV (red) to 3.1 eV (violet). Ultraviolet photons start above 3.1 eV.

2 Photoelectric Effect — Discovery and Setup

The photoelectric effect is the emission of electrons from a metal surface when light of suitable frequency is incident on it. The emitted electrons are called **photoelectrons**, and the resulting current in the circuit is the **photoelectric current** (or photocurrent).

2.1 Hertz's Observation (1887)

While performing experiments to demonstrate electromagnetic waves, Hertz noticed that the spark in his receiver gap leapt across more easily when ultraviolet light was shone on the negative electrode. He had unknowingly produced the first photoelectric effect, but he did not pursue it.

2.2 Hallwachs and Lenard (1886–1902)

Wilhelm Hallwachs and Philipp Lenard then studied the effect systematically and noted these key facts:

- A negatively charged zinc plate **loses its charge** when exposed to ultraviolet light.
- A neutral plate **becomes positively charged** on UV exposure — showing that negatively charged particles (electrons) were leaving.
- Below a certain frequency (the threshold), **no emission** happens, no matter how bright the light.
- Emission, when it happens, is **instantaneous** (within 10^{-9} s).

Hallwachs-Lenard Headlines

The photoelectric effect needs a minimum frequency. Once that is met, the number of electrons emitted depends on the intensity, but the energy of each electron does not. These two observations broke classical wave theory.

2.3 Experimental Setup for Studying the Photoelectric Effect

A standard photocell consists of an evacuated glass tube containing a photo-sensitive metal cathode (emitter C) and a small metal anode (collector A). Monochromatic light of variable frequency and intensity is shone on C through a quartz window. A potential difference V between A and C can be varied (and reversed in polarity) by a sliding contact, and the resulting photocurrent is read by a microammeter.

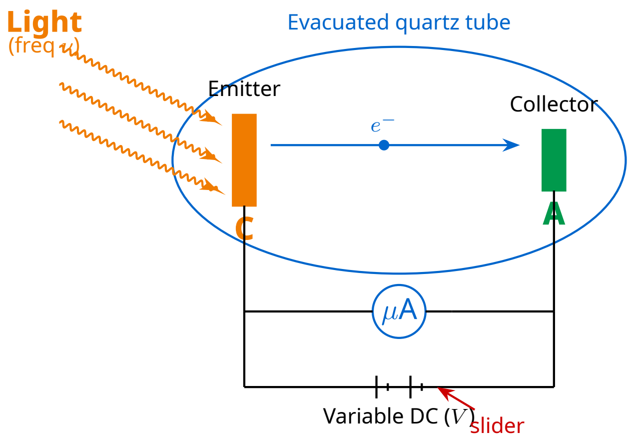

Figure 2.1: Schematic of the photoelectric effect apparatus. Light frees electrons at C; they cross the gap and are collected at A, registering as photocurrent on the microammeter.

The three things that can be varied independently in this setup are: the **intensity** of incident light, the **frequency** of incident light, and the **accelerating potential** between A and C. The next three subsections study what each one does to the photocurrent.

2.4 Effect of Intensity on Photocurrent

Hold frequency fixed at $\nu \geq \nu_0$ and the accelerating voltage V at some positive value. Now slowly increase the intensity of incident light.

- Photocurrent increases **linearly with intensity**.
- This means the **number of photoelectrons emitted per second** is proportional to intensity.
- Stopping potential is unaffected (so the maximum kinetic energy of each electron does not change).

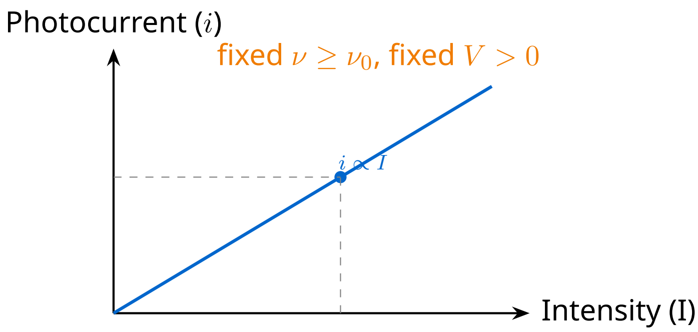

Figure 2.2: Photocurrent rises linearly with light intensity.

Intensity $\rightarrow$ Number of Electrons

A brighter light frees more electrons, but each individual electron does not get any more energetic. This is impossible to explain on a wave picture, where a stronger wave should impart more energy per electron.

2.5 Effect of Potential on Photocurrent

Hold light frequency and intensity fixed. Vary the accelerating voltage V from large positive (anode positive, attracting electrons) through zero to negative (anode negative, repelling them).

- For positive V, photocurrent rises and reaches a flat **saturation current** — every emitted electron is now collected.
- As V becomes negative, the slowest electrons are turned back; photocurrent drops.
- At a particular negative voltage $-V_0$, even the fastest electrons are stopped and the photocurrent becomes zero. This V_0 is called the **stopping potential**.

Stopping Potential and Maximum KE

The maximum kinetic energy of a photoelectron equals the work done against the stopping potential:

$$K_{\text{max}} = eV_0 = \tfrac{1}{2}mv_{\text{max}}^2$$

If the intensity is now *doubled* (frequency same), the saturation current doubles — but the stopping potential stays exactly the same.

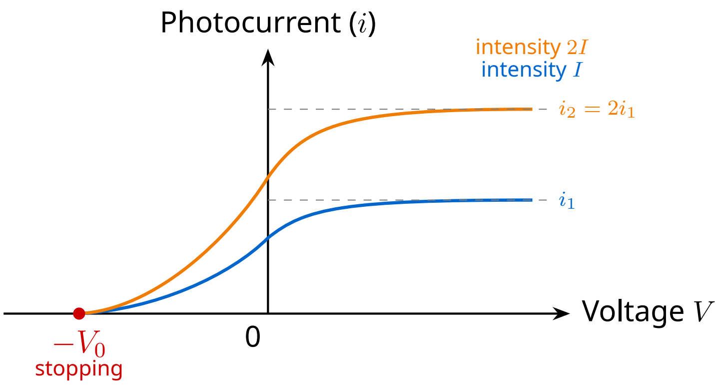

Figure 2.3: Photocurrent vs voltage at two intensities (same frequency). Stopping potential V_0 is identical for both — intensity affects how many electrons leave, not their maximum energy.

2.6 Effect of Frequency on Stopping Potential

Now keep the intensity fixed and change the frequency of incident light. Saturation current still depends on the intensity, but the stopping potential changes:

- Higher frequency gives a larger stopping potential.
- Plotting V_0 against ν gives a **straight line** that intersects the ν-axis at the threshold frequency ν_0.
- The slope of the line is the **same for all metals** — and equals h/e.

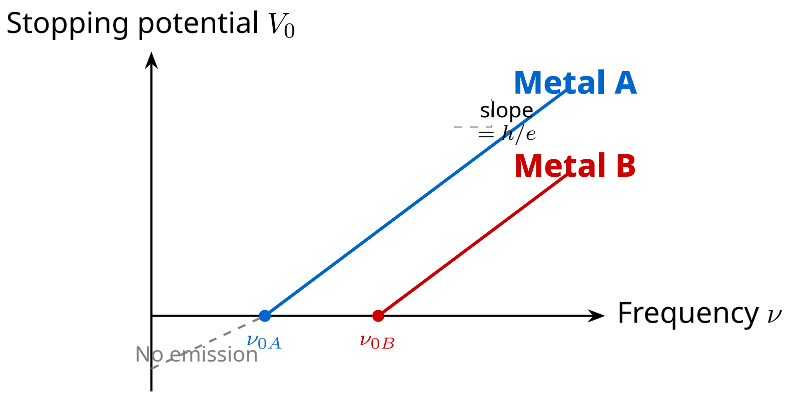

Figure 2.4: Stopping potential vs frequency for two metals. Same slope (h/e), different intercepts (work functions). Below ν_0, no photocurrent flows at all.

Three Photoelectric Headlines from Experiment

(i) Intensity decides how many electrons. **(ii)** Frequency decides how energetic each electron is. **(iii)** Below ν_0, nothing happens, no matter how intense the light.

2.7 Laws of Photoelectric Emission

The four experimental laws emerging from the above observations:

1. For a given metal and a given frequency ($\nu \geq \nu_0$), the photocurrent is directly proportional to the intensity of incident light.
2. For a given metal, there exists a threshold frequency ν_0 below which no emission takes place, however intense the light.
3. Above ν_0, the maximum kinetic energy of photoelectrons depends only on the frequency of light, not on its intensity.
4. Photoelectric emission is essentially instantaneous — there is no observable lag between light striking the surface and electron emission ($< 10^{-9}$ s).

Quick Tip

Examiners love asking ”State the laws of photoelectric emission”. Write all four with one line each. Skip ”instantaneous emission” at your peril — it is the single observation that wave theory cannot fix even with mathematical gymnastics.

Common Mistake

Students often confuse ”intensity affects photocurrent” with ”intensity affects energy of each electron”. The first is true; the second is false. Increasing intensity of monochromatic light just means more photons per second, hence more electrons emitted per second.

3 Failure of Wave Theory and Einstein’s Equation

The photoelectric facts above were a serious problem for the classical wave picture of light. Light, on a wave model, should deliver energy continuously to the metal. The energy carried by a wave depends on its amplitude (intensity), not its frequency. Three predictions of wave theory clash directly with experiment.

3.1 Where Wave Theory Breaks

- **Wave theory says:** Bright light of any frequency should eventually pump enough energy into an electron to liberate it.
  Experiment says: Below ν_0, no emission — ever.
- **Wave theory says:** The maximum kinetic energy of emitted electrons should depend on intensity.
  Experiment says: It depends only on frequency.
- **Wave theory says:** For dim light, electrons should take many seconds (sometimes hours) to soak up enough energy before they can escape.
  Experiment says: Emission begins instantly — no detectable lag.

Why Classical Light Fails

A wave delivers energy spread out over the whole wavefront. To kick out one electron, it must somehow concentrate. Wave theory has no mechanism for this. It also has no place for a frequency threshold — a wave is a wave at any frequency.

3.2 Einstein's Photoelectric Equation (1905)

Einstein resolved the puzzle in one bold step. He proposed that light is not a continuous wave when it interacts with matter — it travels in discrete packets called **photons**. Each photon carries energy $E = h\nu$. When a photon strikes an electron in the metal, it gives up *all* its energy to that one electron in a single instantaneous transaction. The electron uses part of this energy to overcome the work function ϕ_0 and keeps the rest as kinetic energy.

Einstein's Photoelectric Equation

$$K_{\text{max}} = h\nu - \phi_0$$
$$\frac{1}{2}mv^2_{\text{max}} = h\nu - h\nu_0$$
$$eV_0 = h\nu - h\nu_0$$

- K_{max} = maximum kinetic energy of photoelectron
- $h\nu$ = energy of incident photon
- $\phi_0 = h\nu_0$ = work function of metal
- V_0 = stopping potential, ν_0 = threshold frequency

3.3 How Einstein's Equation Explains Every Observation

- **Threshold frequency:** If $h\nu < \phi_0$, the photon does not have enough energy to free an electron. Below ν_0, no emission — explained.
- K_{max} **depends only on frequency:** The energy each electron gets is $h\nu - \phi_0$, which depends on ν alone.
- **Intensity decides number:** Higher intensity means more photons per second, hence more electrons emitted per second — but each absorbs the same $h\nu$, so each individual electron's energy is unchanged.
- **Instantaneous emission:** The interaction is a single one-photon-one-electron event. There is no waiting for energy to accumulate.

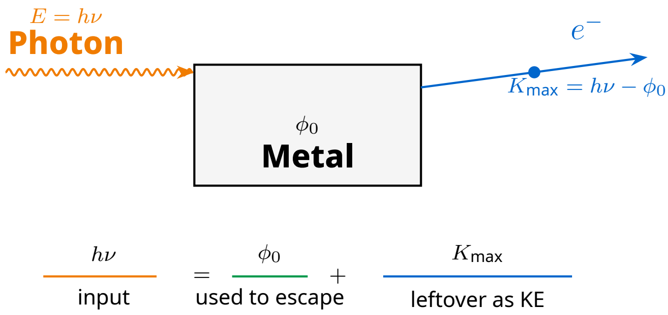

Figure 3.1: Energy bookkeeping in a photoelectric event. The photon's full energy goes into one electron; part pays the work function, the rest is kinetic energy.

Real-World Application

Solar cells use the photoelectric effect in reverse logic — photons knock electrons out of a semiconductor, and these electrons then flow as current through an external circuit. Better solar cells work hard to push their effective threshold frequency *below* visible red light so that they can absorb as much of the solar spectrum as possible.

3.4 Stopping Potential vs Frequency Graph (Slope Method)

Rearranging Einstein's equation:

$$V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$$

This is the equation of a straight line in (ν, V_0) coordinates. The slope is h/e and the ν-intercept is $\nu_0 = \phi_0/h$.

- Slope is universal: $h/e \approx 4.14 \times 10^{-15}$ V s — same for every metal.
- Each metal has its own ν_0 (different intercept on ν-axis).
- This experiment is the standard textbook way to determine Planck's constant h.

Quick Tip

A typical numerical: "Stopping potential is V_1 at frequency ν_1 and V_2 at ν_2. Find h." Use $h = e(V_2 - V_1)/(\nu_2 - \nu_1)$. Two unknowns ($h$ and ϕ_0) need two equations, which is why two frequencies are given.

Memory Aid

F-N-I for the photoelectric trio: **F**requency decides whether emission happens, **N**umber of electrons depends on intensity, **I**nstantaneous emission rules out wave delays.

3.5 NCERT-Style Comparison Table

Wave Theory Prediction	Experimental Observation
Emission possible at any frequency given enough intensity	No emission below threshold ν_0
K_{max} should depend on intensity	K_{max} depends only on frequency
Time lag for low-intensity light expected	Emission instantaneous ($< 10^{-9}$ s)
Photocurrent should depend on frequency continuously	Photocurrent depends on intensity, independent of frequency above threshold

Table 3.1: Wave theory's predictions vs photoelectric reality.

3.6 Worked Numerical Walkthroughs

The same templates appear again and again in board, JEE and NEET papers. Three patterns are worth practising explicitly.

Pattern 1 — Find K_{max} given λ and ϕ_0. Light of wavelength 300 nm falls on a metal of work function 2.13 eV. Find K_{max}.

Photon energy: $E = 1240/300 = 4.13$ eV. Then $K_{\text{max}} = 4.13 - 2.13 = 2.00$ eV.

Pattern 2 — Find threshold ν_0 given two readings. Stopping potential is 0.6 V at $\nu_1 = 5.5 \times 10^{14}$ Hz and 1.1 V at $\nu_2 = 6.7 \times 10^{14}$ Hz. Find h and ϕ_0.

Subtract: $e(V_2 - V_1) = h(\nu_2 - \nu_1) \Rightarrow h = e \cdot \dfrac{0.5}{1.2 \times 10^{14}} \approx 6.67 \times 10^{-34}$ J s. Then $\phi_0 = h\nu_1 - eV_1 \approx 1.67$ eV.

Pattern 3 — Photons per second from a laser. A 9.42 mW He-Ne laser emits at 632.8 nm. How many photons per second?

$E_{\text{photon}} = 1240/632.8 = 1.96$ eV $= 3.14 \times 10^{-19}$ J.
$N = P/E = 9.42 \times 10^{-3}/3.14 \times 10^{-19} \approx 3.0 \times 10^{16}$ photons/s.

> **Quick Tip**
>
> The trick across all three is the same: spot whether the question gives you energy directly, frequency, or wavelength, then convert once and stay in those units. Mixing eV and J midway is the most common source of arithmetic errors.

4 Particle Nature of Light — The Photon

The photoelectric effect forces us to accept that light, in its interaction with matter, behaves as a stream of particles called photons. Each photon is a discrete packet of electromagnetic energy.

4.1 Properties of a Photon

- Travels with the speed of light c in vacuum.
- Has zero rest mass — a stationary photon does not exist.
- Energy $E = h\nu = hc/\lambda$.
- Momentum $p = E/c = h\nu/c = h/\lambda$.
- Electrically neutral — not deflected by electric or magnetic fields.
- In a photon-electron collision, total energy and total momentum are both conserved.
- All photons of a given frequency have the **same** energy and momentum, regardless of the source's intensity.
- Increasing intensity of monochromatic light means **more photons per second**, not more energetic photons.

Photon Energy and Momentum

$$E = h\nu = \frac{hc}{\lambda}, \qquad p = \frac{h\nu}{c} = \frac{h}{\lambda}$$

Useful shortcut: $E\ [\text{eV}] = \dfrac{1240}{\lambda\ [\text{nm}]}$

Quick Tip

The shortcut E [eV] $= 1240/\lambda$ [nm] is gold for objective questions. For a 620 nm photon, $E = 1240/620 = 2$ eV — in your head, no calculator.

4.2 Number of Photons per Second

If a source emits power P at wavelength λ, the number of photons emitted per second is:

$$N = \frac{P}{E_{\text{photon}}} = \frac{P\lambda}{hc}$$

A modest 1 mW red laser at 632.8 nm pumps out roughly 3.18×10^{15} photons every second — the granularity is invisible to the eye.

Real-World Application

Night-vision goggles and astronomical CCDs deal with situations where photons arrive one at a time. They count individual photon hits on their detectors, which is why you sometimes see "photon-counting" specifications on high-end cameras.

Common Mistake

Photon momentum is $p = h/\lambda$, not $p = mv$. Don't try to plug in a mass for the photon — its rest mass is zero. The momentum comes from its energy via $E = pc$ for a massless particle.

5 Wave Nature of Matter — de Broglie Hypothesis

If radiation has both wave and particle aspects, why should matter be different? In 1924, Louis de Broglie proposed that every moving particle has an associated wave, with a wavelength fixed by its momentum.

5.1 de Broglie Hypothesis

de Broglie Wavelength

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

For a particle with kinetic energy K:

$$\lambda = \frac{h}{\sqrt{2mK}}$$

- λ = de Broglie wavelength (m)
- p = momentum of the particle (kg m/s)
- m = mass, v = velocity, K = kinetic energy
- For a charged particle accelerated through potential V: $\lambda = h/\sqrt{2mqV}$

5.2 Why de Broglie Waves Are Hidden in Daily Life

The wavelength is significant only when h is comparable to the momentum. For everyday objects, p is enormous compared to h, so λ is absurdly small.

- Cricket ball (150 g, 30 m/s): $\lambda \approx 1.5 \times 10^{-34}$ m — 10^{19} times smaller than an atomic nucleus. Undetectable.
- Electron (9.11×10^{-31} kg, 10^6 m/s): $\lambda \approx 0.73$ nm — comparable to atomic spacings, well within range of crystal-diffraction experiments.

Why Macroscopic Waves Are Invisible

Because h is tiny, only particles whose momentum is also tiny show measurable wavelengths. This is why we never bumped into matter waves before electrons were studied — macroscopic objects always have momenta many orders of magnitude too large.

5.3 de Broglie Wavelength of an Electron Accelerated Through Potential V

[*JEE/NEET extension — the algebraic derivation has been removed from the rationalised NCERT, but the formula and its applications are still asked.*]

A charged particle of charge q accelerated from rest through potential V acquires kinetic energy qV. Substituting:

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

For an electron:

$$\lambda_e = \frac{12.27}{\sqrt{V}}\ \text{Å} = \frac{1.227}{\sqrt{V}}\ \text{nm} \quad (V \text{ in volts})$$

This is the formula every student should remember. It gives λ directly in angstroms for an electron accelerated through V volts.

Quick Tip

For an electron through 100 V: $\lambda = 12.27/\sqrt{100} = 1.227$ Å. Through 54 V (the Davisson–Germer value): $\lambda = 12.27/\sqrt{54} \approx 1.67$ Å. Memorise these; they are favourite numericals.

Common Mistake

For massless particles like photons, do **not** use $\lambda = h/\sqrt{2mK}$. The correct relation for a photon is $\lambda = hc/E = h/p$. Always check whether the particle has rest mass before picking the formula.

5.4 Comparison of de Broglie Wavelengths

For particles with the *same kinetic energy*, since $\lambda \propto 1/\sqrt{m}$, the lighter particle has the longer wavelength. So:

$$\lambda_{\text{electron}} > \lambda_{\text{proton}} = \lambda_{\text{neutron}} > \lambda_{\alpha}$$

For particles with the *same accelerating potential*, $\lambda \propto 1/\sqrt{mq}$, so the same hierarchy holds (electrons have the longest wavelength).

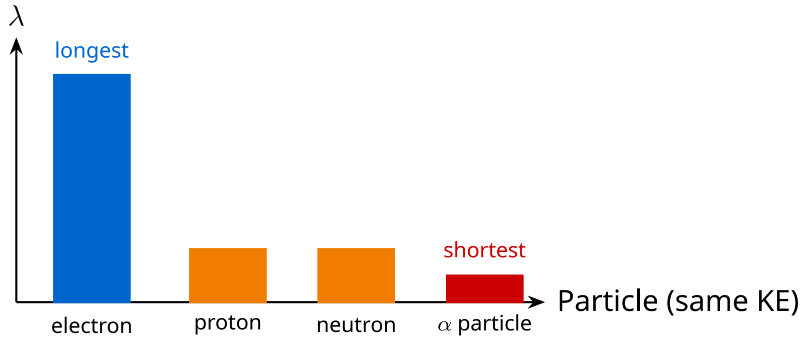

Figure 5.1: For the same kinetic energy, the lightest particle has the longest de Broglie wavelength. Proton and neutron almost overlap.

Real-World Application

Electron microscopes exploit the small de Broglie wavelength of accelerated electrons. With λ around 0.05 nm, they resolve features hundreds of times finer than the best optical microscope, which is limited by visible light's 400–700 nm wavelength.

Memory Aid

Light particles have long waves. The lighter the particle, the longer its de Broglie wavelength. Same KE? Electron wins. Same momentum? They tie. Same accelerating potential? Lightest one wins again.

5.5 Worked Numericals — de Broglie Style

Pattern 1 — Electron through known voltage. Find λ for an electron accelerated through 100 V.

Direct shortcut: $\lambda = 12.27/\sqrt{100} = 1.227$ Å $= 0.123$ nm. Comparable to atomic spacings — which is exactly why electron diffraction works.

Pattern 2 — Particles with same KE. A proton and an alpha particle have the same kinetic energy. Find the ratio λ_p/λ_α.

$\lambda \propto 1/\sqrt{m}$ for fixed KE. Mass of α is $4m_p$. So $\lambda_p/\lambda_\alpha = \sqrt{4} = 2$. The proton's wavelength is twice the alpha's.

Pattern 3 — Particles through same potential. An electron and a proton are accelerated through the same potential V. Compare λ_e and λ_p.

$\lambda \propto 1/\sqrt{mq}$. Charges are equal in magnitude, so $\lambda_e/\lambda_p = \sqrt{m_p/m_e} \approx \sqrt{1836} \approx 42.85$. Electrons have a ~ 43-fold longer wavelength.

5.6 Photon vs Matter Wave — Side by Side

A common question type asks students to compare the photon and the matter wave. Memorise this side-by-side table.

Property	Photon	Matter wave
Rest mass	Zero	Non-zero (for particle)
Speed in vacuum	c	$< c$ (depends on KE)
Energy	$E = h\nu = hc/\lambda$	$E = K + mc^2$ (rel.) or $K = p^2/2m$
Momentum	$p = h/\lambda$	$p = h/\lambda = mv$
Charge	Neutral	May be charged
Wavelength relation	$\lambda = c/\nu$	$\lambda = h/(mv)$
Field deflection	No	If charged, yes

Table 5.1: Comparison of photon and matter wave properties.

6 Davisson–Germer Experiment

The de Broglie hypothesis remained an idea on paper until Davisson and Germer accidentally produced its experimental confirmation in 1927. They observed the diffraction of an electron beam by a nickel crystal — exactly what waves do, never what classical particles do.

6.1 Experimental Setup

A heated tungsten filament emits electrons by thermionic emission. They are accelerated through a variable potential V in an electron gun, producing a fine beam of monoenergetic electrons. This beam strikes a single-crystal nickel target. Electrons scatter from the crystal in all directions; a movable detector measures the intensity of scattered electrons as a function of the scattering angle ϕ (measured from the incident beam direction).

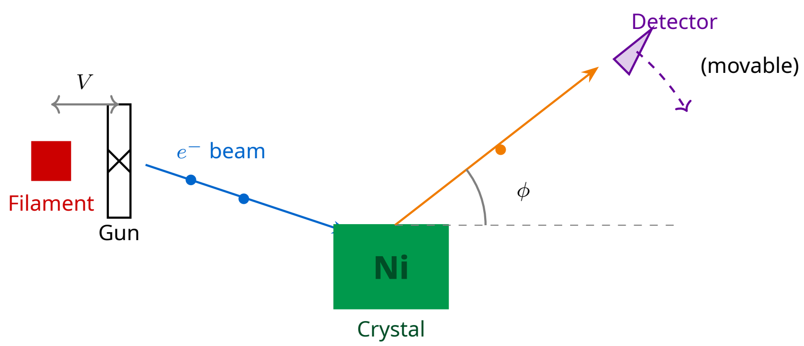

Figure 6.1: Davisson–Germer apparatus. Accelerated electrons strike a nickel crystal; a movable detector measures the angular distribution of scattered electrons.

6.2 Observations

Davisson and Germer plotted scattered electron intensity as a function of ϕ for many accelerating voltages. They found a striking peak in the distribution at $\phi = 50°$ when the accelerating voltage was exactly $V = 54$ V. The intensity peak only made sense as a diffraction maximum — particles do not produce sharply angle-selective peaks, but waves do.

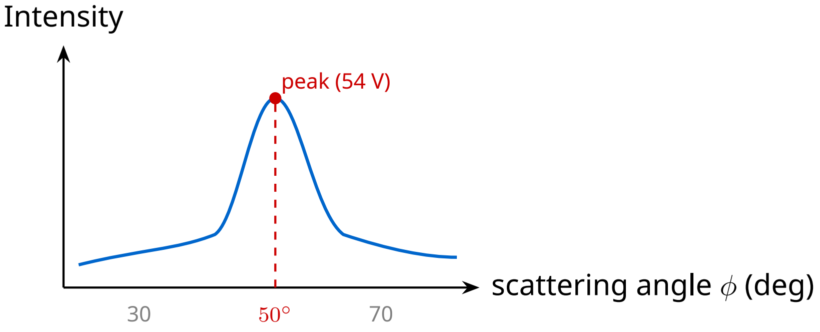

Figure 6.2: Intensity of scattered electrons vs scattering angle, showing the diffraction peak at $\phi = 50°$ for $V = 54$ V.

6.3 Verification of de Broglie's Hypothesis

The wavelength predicted by de Broglie for 54 V electrons:

$$\lambda = \frac{12.27}{\sqrt{54}}\ \text{Å} = 1.67\ \text{Å}$$

The wavelength obtained from the diffraction geometry of the nickel crystal (using the known atomic spacing $d = 0.91$ Å and Bragg's law):

$$\lambda = 2d \sin\theta \approx 1.65\ \text{Å}$$

These two values match within experimental error — confirming that electrons truly do behave as waves with the wavelength de Broglie predicted.

Why This Was a Big Deal

Before this, "wave" and "particle" were two boxes that nature's objects fell into. Davisson and Germer showed that one and the same electron is both. The classical sorting of phenomena into waves vs particles was finished.

Quick Tip

For the board exam, three numbers matter for Davisson–Germer: **accelerating voltage $V = 54$ V, scattering angle $\phi = 50°$, peak wavelength ≈ 1.65 Å.** Quote them in any answer about the experiment.

Real-World Application

The same physics powers electron diffraction crystallography today, used to determine the structure of proteins, viruses, and 2D materials such as graphene. Many of the structures behind modern drugs were first imaged using electron-wave diffraction.

6.4 Confirmation by G.P. Thomson — the Other Half of the Story

In the same year (1927), G.P. Thomson independently observed electron diffraction by passing a beam of fast electrons through thin metal foils and recording diffraction rings on a photographic plate, just as one would expect with X-rays. The result confirmed Davisson and Germer's conclusion — and there is a beautiful historical irony: G.P. Thomson's father, J.J. Thomson, had won the Nobel Prize for showing that the electron was a particle. The son won the Nobel Prize for showing it was also a wave.

Two Independent Confirmations in One Year

Davisson and Germer used a single nickel crystal and a low-energy electron beam (~ 54 V). G.P. Thomson used thin metal foils and high-energy electrons. Two completely different setups; same conclusion. That is what made the case airtight.

7 Applications and Open Questions

The dual nature ideas of this chapter sit underneath much of modern technology and almost all of quantum mechanics. A short tour of where they show up.

7.1 Photoelectric Devices in Daily Life

- **Photodiodes and CCD sensors** — digital cameras and smartphones convert incident photons into electron currents that the sensor reads off pixel by pixel.
- **Solar cells** — semiconductor versions of photoelectric emitters; sunlight knocks electrons across a junction to deliver useful current.
- **Automatic doors and burglar alarms** — a steady light beam strikes a photocell; when the beam is interrupted, the photocurrent drops, triggering the circuit.
- **Photomultiplier tubes** — single-photon detection for medical imaging (PET scanners) and astronomy. The first photoelectron is multiplied through secondary emission stages.

7.2 Matter-Wave Devices

- **Electron microscope (TEM, SEM)** — accelerated electrons act as short-wavelength probes that resolve features below the optical limit.
- **Neutron diffraction** — thermal neutrons have de Broglie wavelengths near 1 Å, making them perfect probes for crystal structures.
- **Atom interferometers** — exploit the wave nature of cold atoms to build extremely precise gravity and rotation sensors.

Real-World Application

A modern transmission electron microscope routinely operates at 200 kV, producing electrons with $\lambda \approx 0.0027$ nm — about $200{,}000$ times finer than the wavelength of green light.

7.3 Bridging to Modern Quantum Mechanics

The dual nature is not a quirk of light or electrons in particular — it is a property of *everything*. Footballs and elephants have de Broglie wavelengths too; they are just so small that no experiment can resolve them. Quantum mechanics — developed by Schrödinger, Heisenberg, Dirac and others through 1925–1932 — generalises the de Broglie picture into a complete framework where every particle is described by a wave function. The chapter you have just finished is the historical doorway into that framework.

Quick Tip

For viva-style or HOTS questions: "Is the dual nature universal?" Answer yes — but its observability scales with the de Broglie wavelength relative to the experimental probe. Nothing about footballs makes them classical; only their size relative to h does.

Common Mistake

The dual nature does **not** mean that a photon is "sometimes a wave and sometimes a particle". It means that one and the same object exhibits wave *or* particle behaviour depending on the experiment we run. There is no flipping or switching — it is a single underlying reality that classical language cannot fully capture.

8 Quick Reference Summary

8.1 Key Formulas at a Glance

Quantity	**Formula**
Photon energy	$E = h\nu = hc/\lambda$
Photon momentum	$p = h/\lambda$
Quick photon energy (eV)	$E = 1240/\lambda$ [nm]
Photons per second from power P	$N = P\lambda/(hc)$
Work function	$\phi_0 = h\nu_0 = hc/\lambda_0$
Maximum KE of photoelectron	$K_{\text{max}} = h\nu - \phi_0$
Stopping potential relation	$eV_0 = h\nu - \phi_0$
Slope of V_0 vs ν	$h/e \approx 4.14 \times 10^{-15}$ V s
de Broglie wavelength	$\lambda = h/p = h/(mv)$
λ in terms of KE	$\lambda = h/\sqrt{2mK}$
λ for charge q through potential V	$\lambda = h/\sqrt{2mqV}$
λ for electron through V volts	$\lambda = 12.27/\sqrt{V}$ Å

8.2 Constants You Must Memorise

- Planck's constant: $h = 6.626 \times 10^{-34}$ J s $= 4.136 \times 10^{-15}$ eV s
- Speed of light: $c = 3 \times 10^8$ m/s
- Mass of electron: $m_e = 9.11 \times 10^{-31}$ kg
- Charge on electron: $e = 1.602 \times 10^{-19}$ C
- $hc = 1240$ eV nm $= 1240$ nm eV
- 1 eV $= 1.602 \times 10^{-19}$ J

8.3 Common Work Functions (eV)

Metal	ϕ_0 **(eV)**	**Metal**	ϕ_0 **(eV)**
Caesium (Cs)	2.14	Calcium (Ca)	3.20
Potassium (K)	2.30	Aluminium (Al)	4.28
Sodium (Na)	2.75	Copper (Cu)	4.65
Lithium (Li)	2.42	Silver (Ag)	4.73
Zinc (Zn)	3.63	Platinum (Pt)	5.65

8.4 Exam Strategy — One-Liners

- Whenever you see "stopping potential", reach for $eV_0 = h\nu - \phi_0$.
- Whenever you see "intensity", remember it changes the **number** of electrons, not their **energy**.
- For "threshold frequency / wavelength", $\nu_0 = \phi_0/h$ and $\lambda_0 = hc/\phi_0$.
- For Planck's constant from a V_0-ν graph, slope $\times e$.
- For the de Broglie wavelength of an accelerated electron, jump straight to

$12.27/\sqrt{V}$ Å.

- Davisson–Germer numbers to remember: $V = 54$ V, $\phi = 50°$, $\lambda \approx 1.65$ Å.

The Big Idea

Light and matter both have a dual nature. Photons (light particles) carry $E = h\nu$ and $p = h/\lambda$. Matter waves have $\lambda = h/p$. Whichever face nature shows depends on the experiment we run — particle in the photoelectric effect, wave in the Davisson–Germer experiment.