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CUET · PHYSICS · CLASS XII · CODE 322

Dual Nature of Radiation and Matter

CUET unit: Dual Nature of Radiation and Matter

By **UniDrill** · NCERT-grounded study material

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📌 Snapshot

- Establishes that light, classically a wave, also behaves as a stream of discrete energy packets (photons) when interacting with matter — the photoelectric effect is the key evidence.
- Introduces the work function ϕ_0 as the minimum energy required to eject an electron from a metal surface, and the three modes of electron emission (thermionic, field, photoelectric).
- Gives Einstein's photoelectric equation $K_{max} = h\nu - \phi_0 = eV_0$, which links stopping potential, threshold frequency, and Planck's constant.
- Extends the wave-particle duality to matter via de Broglie's relation $\lambda = h/p$, with the special accelerated-electron form $\lambda = 12.27/\sqrt{V}$ Å.
- CUET tests this chapter for definitions (work function, threshold frequency, stopping potential), graph interpretation (I–V, V_0–ν), photon energy/momentum calculations, and de Broglie wavelength numericals.

📖 Detailed Notes

2.1 Core concepts

By the end of the nineteenth century, electrons had been identified as constituents of all matter, with a universal charge-to-mass ratio independent of the parent material (NCERT §11.1, p. 274). The next question is: how do these electrons get out of a metal? Inside the metal the free electrons drift around freely, but at the surface they are pulled back by the residual positive-ion attraction; an electron trying to escape has to do work against this attraction. The minimum energy needed to do so is the **work function** ϕ_0, measured in electron-volts (1 eV = 1.602×10^{-19} J). The work function depends both on the metal and on the state of its surface — even small contamination changes ϕ_0 (NCERT §11.2, p. 275). Typical values: caesium 2.14 eV, sodium 2.75 eV, copper 4.7 eV, platinum 5.65 eV.

There are three principal ways the required energy can be supplied to free an electron from a metal surface (NCERT §11.2, p. 275–276): **thermionic emission**, where the metal is heated so that some electrons acquire enough thermal energy (used in vacuum tubes); **field emission**, where a very strong external electric field of the order of 10^8 V m^{-1} is applied to literally pull electrons out of the surface (this is what happens at the tip of a spark plug); and **photoelectric emission**, where electromagnetic radiation of suitable frequency is absorbed and the energy is delivered to an electron, which then escapes. The third is the focus here because it shaped quantum theory.

Discovery (NCERT §11.3, p. 276). Heinrich Hertz, while studying his spark-gap apparatus in 1887, noticed that the high-voltage sparks at the detector loop were enhanced when the emitter plate was illuminated with ultraviolet light — the first observation of photoelectric emission. In 1888 Wilhelm **Hallwachs** showed that a freshly polished zinc plate, negatively charged, lost its charge under UV; an uncharged plate became positively charged; and a positively charged plate gained more positive charge — proving the ejected particles were negatively charged (electrons). Philipp **Lenard** (1862–1947) then built the modern photoelectric experimental cell: an evacuated glass/quartz tube containing two metal plates, with monochromatic UV falling on the emitter. Current flowed instantly when the light was switched on and stopped instantly when it was switched off; current was observed only above a certain **threshold frequency** ν_0 characteristic of the emitter material.

Experimental study (NCERT §11.4, p. 277). The standard cell uses an evacuated glass/quartz tube with photosensitive emitter C and collector A; an external battery and commutator set the C-to-A potential difference V (either accelerating or retarding), a voltmeter reads V, and a sensitive microammeter measures the photocurrent. Monochromatic light enters through a quartz window W (quartz transmits UV; ordinary glass does not). The experiment maps out three dependencies.

(a) Effect of intensity (§11.4.1, p. 278). Keep frequency ν above threshold and the accelerating potential fixed, vary only the intensity I of incident light. The photocurrent rises linearly with I — the photoelectric current is directly proportional to intensity. Physically, more intense light delivers more energy per second to the surface, ejecting more photoelectrons per second.

(b) Effect of collector potential (§11.4.2, p. 278–279). At fixed frequency and intensity, increase the positive collector potential. The current rises and then **saturates** at a maximum value — the saturation current, reached when every photoelectron is collected. If instead the collector is made negative (retarding), the current falls because the field now decelerates electrons. At a sharply defined value of the negative potential — the **stopping potential V_0** — the current drops to zero: only those electrons with kinetic energy $\geqslant eV_0$ can reach the collector, so the maximum kinetic energy of photoelectrons is eV_0. Repeating with brighter light gives a higher saturation current but the same stopping potential — V_0 is independent of intensity.

(c) Effect of frequency (§11.4.3, p. 279–280). Keep intensity fixed, vary frequency above threshold. The saturation current is essentially unchanged for the same intensity, but the stopping potential V_0 becomes more and more negative as ν is increased — i.e., Kmax = eV_0 grows linearly with ν. Plotting V_0 versus ν gives a straight line of slope h/e with a positive x-intercept at $\nu = \nu_0$, the **threshold frequency**. Below ν_0 no photoemission occurs, no matter how intense or how prolonged the illumination.

This experimental package yields the four laws of photoelectric emission (NCERT §11.4.3, p. 280): (i) photocurrent is proportional to intensity (above threshold); (ii) saturation current is proportional to intensity, but stopping potential is independent of intensity; (iii) a threshold frequency ν_0 exists for each metal, below which no emission occurs, and above ν_0 the maximum kinetic energy of photoelectrons varies linearly with ν; (iv) photoemission is essentially instantaneous — within ~10^{-9} s of switching the light on, even at intensities so low that classical theory predicts hours-long energy build-up.

Why classical wave theory fails (NCERT §11.5, p. 280–281). In the wave picture, light delivers energy continuously over the entire wavefront. Intensity → energy per second per unit area, so a brighter beam should give photoelectrons of greater Kmax; with very dim light the time needed to accumulate enough energy at a single electron should be measurable in minutes or hours; and any frequency, given enough time, should eventually liberate electrons — there should be no threshold frequency. Every one of these predictions is contradicted by experiment.

Einstein's photon hypothesis (NCERT §11.6, p. 281–283). In 1905 Einstein proposed that light of frequency ν is exchanged with matter in discrete energy packets — **photons** or light quanta — each of energy $h\nu$. Photoelectric emission is then a one-to-one process: a single photon is absorbed by a single electron, gives up all its energy $h\nu$, of which ϕ_0 is spent in liberating the electron from the surface and the remainder appears as kinetic energy:

$K_{max} = h\nu - \phi_0 = eV_0$ (Einstein's photoelectric equation, Eq. 11.2, p. 281).

This single equation accounts for every experimental fact. The linear Kmax–ν relation is built in; the threshold frequency is $\nu_0 = \phi_0/h$ (below which Kmax would be negative, i.e., no emission); the saturation current is proportional to intensity because intensity now means number of photons per second; and emission is instantaneous because each absorption event is itself an instantaneous process. Combining $K_{max} = eV_0$ with the photoelectric equation gives $V_0 = (h/e)\nu - \phi_0/e$, a straight line of slope h/e independent of the metal (NCERT Eq. 11.4, p. 282). Millikan (1906–1916), who initially disbelieved the photon picture, painstakingly verified this prediction for several alkali metals and used the slope to measure Planck's constant as $h \approx 6.63 \times 10^{-34}$ J s — bringing him a Nobel Prize and Einstein the 1921 Physics Nobel for the photoelectric law.

The photon (NCERT §11.7, p. 283). Photons have energy $E = h\nu$, momentum $p = h\nu/c = h/\lambda$, speed c, are electrically neutral and are not deflected by electric or magnetic fields. Their rest mass is zero (they exist only at speed c). In a photon–particle collision, total energy and total momentum are conserved, but the number of photons need not be — a photon may be absorbed, emitted or created. An intense light beam consists of many photons travelling together; "intensity" is energy per second per unit area = (number of photons per second per unit area) × $h\nu$.

de Broglie hypothesis (NCERT §11.8, p. 285). In 1924 Louis de Broglie argued for the converse of Einstein's idea: if light (wave) has particle aspects, then matter (particle) should have wave aspects. He proposed that to every particle of momentum p is associated a wave of wavelength **$\lambda = h/p = h/(mv)$** — the de Broglie wavelength. The relation reduces correctly to a photon's $\lambda = c/\nu$, so it is consistent with what is already known about light. For macroscopic objects the wavelength is unimaginably tiny — a 0.12-kg cricket ball at 20 m/s has $\lambda \approx 2.76 \times 10^{-34}$ m, far below any conceivable experimental resolution. But for an electron the same momentum gives λ comparable to the spacings between atomic planes in a crystal, which is what made Davisson–Germer's 1927 electron-diffraction experiment possible.

Accelerated electron (NCERT §11.8 and Summary point 9, p. 285–287). A common laboratory situation is an electron starting from rest and accelerated through potential difference V volts. Its kinetic energy is $eV = p^2/(2m)$, so $p = \sqrt{(2meV)}$. Substituting into $\lambda = h/p$ gives $\lambda = h/\sqrt{(2meV)}$. Plugging in numerical values ($h = 6.63 \times 10^{-34}$ J s, $m = 9.11 \times 10^{-31}$ kg, $e = 1.6 \times 10^{-19}$ C) yields the workhorse formula **$\lambda = 12.27/\sqrt{V}$ Å** when V is in volts and λ in ångströms. A 100-V electron has $\lambda \approx 1.23$ Å — comparable to inter-atomic distances, hence its diffraction by crystals.

2.2 Definitions to memorise

Term	Definition	Page
Work function (ϕ_0)	Minimum energy required by an electron to escape from the metal surface; depends on the metal and its surface; measured in eV	275
Electron volt (eV)	Energy gained by an electron accelerated through a potential difference of 1 V; $1\ \text{eV} = 1.602 \times 10^{-19}$ J	275
Thermionic emission	Electron emission by heating the metal to supply thermal energy	275
Field emission	Electron emission by applying a very strong electric field ($\sim 10^8\ \text{V m}^{-1}$) to the metal	276
Photoelectric emission	Emission of electrons from a metal surface when light of suitable frequency illuminates it	276
Photoelectron	Electron emitted from a metal surface in the photoelectric effect	276
Photoelectric current	Current due to photoelectrons in the external circuit	277
Threshold frequency (ν_0)	Minimum frequency of incident radiation below which no photoelectric emission occurs, no matter how intense the light; $\nu_0 = \phi_0/h$	277, 280
Threshold wavelength (λ_0)	Maximum wavelength of incident radiation that can produce photoelectric emission; $\lambda_0 = c/\nu_0 = hc/\phi_0$	280
Stopping potential (V_0)	Minimum negative (retarding) potential on the collector at which the photocurrent becomes zero; $eV_0 = K_{max}$	278
Saturation current		278

Term	Definition	Page
	Maximum photocurrent when all emitted photoelectrons reach the collector; proportional to intensity	
Intensity of light	Energy per second per unit area; equivalently, number of photons per second per unit area times $h\nu$	278
Einstein's photoelectric equation	$Kmax = h\nu - \phi_0$; energy conservation for the one-photon-one-electron event	281
Photon	Light quantum, a particle of light with energy $h\nu$, momentum $h\nu/c$, speed c, zero charge	283
Photon energy	$E = h\nu = hc/\lambda$	283
Photon momentum	$p = h\nu/c = h/\lambda$	283
Planck's constant	$h = 6.626 \times 10^{-34}$ J s; sets the scale of all quantum effects	282
de Broglie hypothesis	Every moving particle has an associated matter wave	285
de Broglie wavelength (λ)	Wavelength of matter wave associated with a particle of momentum p; $\lambda = h/p = h/mv$	285
de Broglie wavelength of accelerated electron	$\lambda = 12.27/\sqrt{V}$ Å, V in volts	287
Matter wave	Wave associated with a moving particle, exhibiting interference and diffraction	285
Davisson–Germer experiment	Demonstrated diffraction of electrons by a nickel crystal, confirming de Broglie's hypothesis	287

2.3 Diagrams / processes to remember

- **Fig. 11.1 (p. 277):** Experimental arrangement for photoelectric effect — evacuated tube, monochromatic source S, quartz window W (UV-transparent), emitter C, collector A, commutator to reverse polarity, voltmeter V, microammeter mA. The whole cell is in series with a variable battery.
- **Fig. 11.2 (p. 278):** Photoelectric current vs intensity of incident light — straight line through the origin, illustrating $I_{photo} \propto I_{light}$.
- **Fig. 11.3 (p. 278):** Photocurrent vs collector plate potential for three intensities $I_1 < I_2 < I_3$ at fixed frequency — three curves saturate at progressively higher levels but all hit zero current at the same stopping potential V_0 on the negative-V side.
- **Fig. 11.4 (p. 279):** Photocurrent vs collector potential for three frequencies $\nu_1 < \nu_2 < \nu_3$ at fixed intensity — same saturation current but the stopping potentials shift V_{01}, V_{02}, V_{03} further into the negative-V region with increasing ν.
- **Fig. 11.5 (p. 279):** Stopping potential V_0 vs frequency ν — straight line of slope h/e with x-intercept ν_0 (threshold). Two metals A and B give parallel lines (same slope) but different x-intercepts (different ϕ_0).

- The qualitative picture of one-photon-one-electron absorption inside the metal: incoming photon $h\nu$ → liberates one electron at cost ϕ_0 → leftover energy $h\nu - \phi_0$ appears as Kmax.

2.4 Common confusions / NTA trap points

- **Stopping potential vs work function:** V_0 depends on frequency and metal but is independent of intensity; ϕ_0 depends only on the metal. Students often write $V_0 \propto$ intensity — wrong.
- **Saturation current vs Kmax:** saturation current depends on intensity (number of photoelectrons per second) but NOT on frequency; Kmax depends on frequency but NOT on intensity. NTA likes to swap these.
- **Threshold condition:** below ν_0, no emission whatsoever; "very intense" or "long exposure" does not help — a direct contradiction of wave theory that examiners exploit.
- **Photon momentum:** $p = h\nu/c = h/\lambda$. Beware the wrong "p = mv" form — photons have zero rest mass. Photon energy $E = h\nu$ and $E = pc$ are the correct relations.
- **de Broglie for accelerated electron:** the working formula is $\lambda = 12.27/\sqrt{V}$ Å only when V is in volts and λ is in ångströms; if V is in kilovolts or λ asked in nm, do not blindly apply the constant.
- **Slope of V_0–ν line:** the slope is h/e and is the **same for all metals**; only the x-intercept ν_0 changes from metal to metal.
- **Photon number conservation:** in collisions, energy and momentum are conserved but **photon number is not**.
- **Quartz vs glass:** the photoelectric cell uses a quartz window because ordinary glass blocks UV. A common conceptual trap.
- **Instantaneous emission:** the wave theory's predicted "build-up time" is contradicted; emission occurs within ~10^{-9} s.
- **Field-emission threshold:** 10^8 V m^{-1} is the textbook signature; lower fields do not eject electrons by this mechanism.
- **Negative Kmax is unphysical:** if $h\nu < \phi_0$, the photoelectric equation would give Kmax < 0 — instead, no emission occurs.
- **Wavelength of a macroscopic object:** for cricket balls etc. λ is so tiny it cannot be measured; matter-wave effects matter only for subatomic particles.

2.5 Key formulas table

Symbol	Formula	Meaning	NCERT page
ϕ_0	$\phi_0 = h\nu_0$	Work function in terms of threshold frequency	280

Symbol	Formula	Meaning	NCERT page
ν_0	$\nu_0 = \phi_0/h$	Threshold frequency	280
λ_0	$\lambda_0 = c/\nu_0 = hc/\phi_0$	Threshold wavelength	280
Einstein eqn.	$K_{max} = h\nu - \phi_0$	Max KE of photoelectron	281, Eq. 11.2
Stopping potential	$eV_0 = K_{max}$	Relates V_0 to Kmax	278
V_0 vs ν	$V_0 = (h/e)\nu - \phi_0/e$	Slope h/e, universal	282, Eq. 11.4
Photon energy	$E = h\nu = hc/\lambda$	Energy of one photon	283
Photon momentum	$p = h\nu/c = h/\lambda$	Momentum of one photon	283
Intensity	$I = N h\nu$ (per unit area per s)	Light intensity in photon terms	283
de Broglie wavelength	$\lambda = h/p = h/(mv)$	Matter wave of moving particle	285, Eq. 11.5
Accelerated electron λ	$\lambda = h/\sqrt{(2meV)}$	Electron after pd V	287
Numerical (electron)	$\lambda = 12.27/\sqrt{V}$ Å	V in volts, λ in ångström	287
Compton-form photon	$E = pc$	For zero-rest-mass photon	283
Planck constant	$h = 6.626 \times 10^{-34}$ J s	Quantum-scale constant	282
1 eV	1 eV = 1.602×10^{-19} J	Energy unit	275
Photoemission rate	$n_e \propto I$	Photoelectron rate ∝ intensity	278
Saturation current	$I_{sat} \propto I_{light}$	Independent of ν, depends on intensity	280
Threshold check	$h\nu \geq \phi_0$ required for emission	Onset condition	281
Photon momentum unit	$p = h\nu/c$ (kg m s^{-1})	Always non-zero for $\nu > 0$	283
KE of accelerated electron	$KE = eV$	In joules when V in volts	287

🎯 Practice MCQs

📊 PYQ Alignment

This chapter is a CUET Physics staple, contributing roughly 8–10 MCQs across the 2023–25 papers. The most-asked items are: definitions (work function, threshold frequency, stopping potential), graph-reading on the V_0–ν line and I–V curves at different intensities/frequencies, numerical computation of Kmax from $h\nu - \phi_0$, de Broglie wavelength of an electron (both v-given and V-given forms), and statement-based questions distinguishing wave-theory predictions from photon-picture observations.

CUET 2025 — Actual PYQs from this chapter

Q.41 (CUET 2025) Photoelectric current is directly proportional to number of photoelectrons emitted per second. This implies:

- A) Proportional to frequency of radiation B) Inversely proportional to intensity C) Directly proportional to intensity D) Independent of intensity **Tests:** Photoelectric current ∝ intensity of incident radiation **Answer:** Not in extracted key

Q.42 (CUET 2025) The de-Broglie wavelength associated with a ball of mass 150 g moving with speed 30 m/s is:

- A) 1.47×10^{-34} m B) 14.7×10^{-34} m C) 0.147×10^{-34} m D) 7.14×10^{-34} m **Tests:** de Broglie wavelength $\lambda = h/(mv)$ for a macroscopic ball **Answer:** Not in extracted key

Q.50 (CUET 2025) A proton accelerated through potential V has de-Broglie wavelength λ. To obtain the same wavelength for an α-particle, the required accelerating potential is:

- A) V/16 B) V/8 C) 2V D) 4V **Tests:** de Broglie wavelength of accelerated charged particles — proton vs α **Answer:** Not in extracted key

CUET 2024 — Actual PYQs from this chapter

Q.23 (CUET 2024) Radiation frequency $2\nu_0$ incident on metal (threshold ν_0):

- A) No emission B) KE = $h\nu_0$ for all electrons C) Max KE = $h\nu_0$ D) Max KE = $2h\nu_0$ **Tests:** Einstein's photoelectric equation — max KE at $\nu = 2\nu_0$ **Answer:** Not in extracted key

Q.24 (CUET 2024) Photoelectric current vs distance graph when source moved away.

- (options not in extracted source — see official paper) **Tests:** Photoelectric current vs distance from source (intensity $1/r^2$) **Answer:** Not in extracted key

Q.25 (CUET 2024) If accelerating potential doubled, de Broglie wavelength:

- A) Same B) Double C) Four times D) Decreases **Tests:** de Broglie wavelength vs accelerating potential $\lambda \propto 1/\sqrt{V}$ **Answer:** Not in extracted key

CUET 2023 — Actual PYQs from this chapter

Q.33 (CUET 2023) For a proton, electron and alpha particle having same kinetic energy, the de-Broglie wavelength relation is:

- A) (\lambda_\alpha < \lambda_p < \lambda_e) B) (\lambda_e < \lambda_p < \lambda_\alpha) C) (\lambda_p < \lambda_\alpha < \lambda_e) D) (\lambda_\alpha < \lambda_e < \lambda_p) **Tests:** de Broglie wavelength for proton, electron, alpha (same KE) **Answer:** Not in extracted key

Q.34 (CUET 2023) Correct curve between stopping potential (V_0) and intensity of incident radiation is:

- A) Straight decreasing line B) Straight increasing line C) Saturation curve D) Horizontal line **Tests:** Stopping potential vs intensity in photoelectric effect **Answer:** Not in extracted key

Q.35 (CUET 2023) Which statements about photoelectric effect are correct? A. Photocurrent depends on intensity of light B. Maximum kinetic energy depends on frequency C. Photoelectric emission occurs due to absorption of photon D. Emission occurs after some delay Options:

- A) A, B and C only B) B, C and D only C) A, C and D only D) A, B and D only **Tests:** Photoelectric effect — intensity, frequency, instantaneous emission **Answer:** Not in extracted key