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Class 12 Physics - Chapter 11

⚛️ DUAL NATURE OF RADIATION AND MATTER

📌 Chapter Overview

This chapter explores one of the most revolutionary discoveries in physics - the dual nature of electromagnetic radiation and matter. Light exhibits both wave-like properties (interference, diffraction) and particle-like properties (photoelectric effect). Similarly, matter particles like electrons also show wave behavior. This chapter covers:

- Electron emission mechanisms
- Photoelectric effect - experimental observations
- Einstein's photon theory and photoelectric equation
- Particle nature of light - The Photon
- de Broglie's hypothesis - Wave nature of matter

🔬 1. INTRODUCTION

📜 Historical Background

Late 19th Century Discoveries:

- **1887:** Heinrich Hertz established wave nature of light through electromagnetic wave experiments
- **1895:** Wilhelm Roentgen discovered X-rays
- **1897:** J.J. Thomson discovered the electron through cathode ray experiments
- **1870:** William Crookes discovered cathode rays

Cathode Rays - Key Properties:

- Travel at speeds of 0.1-0.2 times the speed of light
- Charge to mass ratio: $e/m = 1.76 \times 10^{11}$ C/kg
- Universal nature - independent of cathode material or gas used
- Named "electrons" by J.J. Thomson in 1897

🏆 R.A. Millikan's Oil Drop Experiment (1913)

Millikan's groundbreaking experiment established that:

- Electric charge is **quantized**
- Elementary charge: $e = 1.602 \times 10^{-19}$ C
- All charges are integral multiples of this elementary charge
- Electron mass can be determined: $m = e/(e/m) = 9.1 \times 10^{-31}$ kg

2. ELECTRON EMISSION

Work Function (φ_0)

Definition: The minimum energy required by an electron to escape from a metal surface is called the **work function** of the metal.

$$\varphi_0 = \text{Minimum energy for electron emission (in eV)}$$

Key Points:

- Measured in electron volts (eV)
- 1 eV = 1.602×10^{-19} J
- Work function depends on the metal and its surface nature
- Different metals have different work functions

🔋 Three Methods of Electron Emission

Method	Description	Application
1. Thermionic Emission	Electrons are emitted when metal is heated to high temperature, providing sufficient thermal energy to overcome work function	Vacuum tubes, electron guns, cathode ray tubes
2. Field Emission	Application of very strong electric field (~10^8 V/m) pulls electrons out of metal surface	Spark plugs, field emission microscopy
3. Photoelectric Emission	Electrons are emitted when light of suitable frequency illuminates the metal surface	Photoelectric cells, solar panels, light sensors

💡 Why Can't Electrons Normally Escape?

Free electrons in metals are held inside by attractive forces from positive ions in the metal lattice. When an electron tries to escape, the surface becomes positively charged and pulls the electron back. Only when sufficient energy is supplied (greater than work function) can the electron overcome this attractive pull and escape.

🌟 3. PHOTOELECTRIC EFFECT

PHOTOELECTRIC EFFECT = Emission of electrons from metal surface when illuminated by light of suitable frequency

🔬 3.1 Historical Observations

Heinrich Hertz's Discovery (1887)

While studying electromagnetic waves, Hertz observed:

- High voltage sparks across detector loop were enhanced when emitter plate was illuminated by ultraviolet light
- Light facilitated the escape of charged particles (later identified as electrons)
- This was the first observation of photoelectric effect

Hallwachs and Lenard's Investigations (1886-1902)

Wilhelm Hallwachs (1888):

- Negatively charged zinc plate lost its charge when illuminated by UV light
- Uncharged zinc plate became positively charged under UV light
- Positive charge on zinc plate increased when illuminated by UV light
- Concluded: Negatively charged particles are emitted under UV light

Philipp Lenard (1862-1947):

- Studied photoelectric current in evacuated glass tubes
- Current flowed when UV light fell on emitter plate
- Current stopped when UV light was stopped
- Discovered the concept of **threshold frequency**

🔑 Key Discovery - Threshold Frequency (v_0)

No electrons are emitted when the frequency of incident light is below a certain minimum value called the **threshold frequency**, regardless of the intensity of light.

$$v_0 = \varphi_0/h \text{ (Threshold Frequency)}$$

Metal Sensitivity:

- Zinc, cadmium, magnesium → Respond only to UV light (short wavelength)
- Alkali metals (Li, Na, K, Cs, Rb) → Sensitive even to visible light

🧪 3.2 Experimental Study of Photoelectric Effect

⚙️ Experimental Setup

Components:

- **Evacuated glass/quartz tube:** Contains two metal plates
- **Plate C (Emitter):** Photosensitive plate on which light falls
- **Plate A (Collector):** Collects emitted electrons
- **Quartz window (W):** Permits UV radiation to pass through
- **Variable battery:** Maintains potential difference, polarity can be reversed by commutator
- **Voltmeter (V):** Measures potential difference
- **Microammeter (μA):** Measures photoelectric current

📊 Experimental Observations

Observation 1: Effect of Intensity on Photocurrent

Procedure:

- Keep frequency of incident light constant
- Keep potential difference constant (A positive w.r.t. C)
- Vary intensity of light by changing distance of source

Result:

Photocurrent ∝ Intensity of incident light

Interpretation:

- Number of photoelectrons emitted per second is directly proportional to intensity
- Higher intensity → More photons → More electrons emitted

Observation 2: Effect of Potential on Photocurrent

When A is Positive (Accelerating Potential):

- Photocurrent increases with increase in positive potential
- At certain positive potential, current reaches maximum value called **saturation current**
- Further increase in potential doesn't increase current
- Saturation occurs when ALL emitted electrons reach collector

When A is Negative (Retarding Potential):

- Electrons are repelled, only energetic electrons reach collector
- Photocurrent decreases rapidly
- At certain negative potential V_0, photocurrent becomes zero

V_0 = Stopping Potential (Cut-off Potential)

Physical Meaning of Stopping Potential:

$$K_{max} = eV_0$$

(Maximum KE of photoelectrons = Work done against stopping potential)

Observation 3: Effect of Frequency on Stopping Potential

Procedure:

- Keep intensity constant
- Vary frequency of incident light
- Measure stopping potential for each frequency

Results:

1. **Stopping potential varies linearly with frequency:** $V_0 \propto \nu$
2. **Saturation current remains same** for different frequencies (at same intensity)
3. **Threshold frequency exists:** Below ν_0, no photoelectric emission occurs
4. **Higher frequency → Higher stopping potential** ($V_{03} > V_{02} > V_{01}$ if $\nu_3 > \nu_2 > \nu_1$)

$K_{max} = eV_0 \propto \nu$ (Maximum KE increases linearly with frequency)

⏱️ Observation 4: Time Lag

Instantaneous Process: Photoelectric emission is instantaneous (time lag ~ 10^{-9} s or less), even when incident radiation is very dim.

This means emission starts immediately when light of appropriate frequency falls on the surface, without any noticeable delay.

📝 Summary of Experimental Features

Observation	Result
1. Intensity Effect	For given frequency ($\nu > \nu_0$), photocurrent $\propto$ intensity
2. Saturation Current	Proportional to intensity; Stopping potential independent of intensity
3. Threshold Frequency	Below ν_0, no emission (regardless of intensity); Above ν_0, $K_{max} \propto (\nu - \nu_0)$
4. Time Lag	Emission is instantaneous ($\sim 10^{-9}$ s), even for dim light

❌ 4. WAVE THEORY vs PHOTOELECTRIC EFFECT

🚫 Failure of Classical Wave Theory

Classical Wave Theory Predictions:

- Electrons absorb energy continuously from radiation
- Greater intensity → Greater amplitude → More energy absorbed per electron
- K_{max} should increase with intensity (WRONG!)
- No threshold frequency should exist - sufficient time should allow any frequency to emit electrons (WRONG!)
- Time lag should exist - electrons need time to absorb sufficient energy (WRONG!)

Why Wave Theory Failed:

Wave Theory CONTRADICTS:
✗ Independence of K_{max} on intensity
✗ Existence of threshold frequency
✗ Instantaneous emission

Specific Problem with Time Lag:

According to wave theory, energy is absorbed continuously across entire wavefront by large number of electrons. Energy absorbed per electron per unit time is very small. Calculations show it would take **hours or more** for a single electron to accumulate enough energy to overcome work function. This completely contradicts the observation of instantaneous emission!

💡 5. EINSTEIN'S PHOTOELECTRIC EQUATION

🏆 Albert Einstein (1879-1955)

Revolutionary Contribution (1905):

Einstein proposed a radically new picture of electromagnetic radiation to explain photoelectric effect. His photon theory earned him the Nobel Prize in Physics in 1921.

Key Achievements:

- Introduced concept of light quanta (photons)
- Explained all features of photoelectric effect
- Unified particle and wave nature of radiation
- Provided foundation for quantum mechanics

🔑 Einstein's Photon Theory - Key Concepts

Fundamental Postulates:

1. **Energy Quantization:** Radiation energy is built up of discrete units called **quanta or photons**
2. **Energy of Photon:**

$$E = h\nu$$

$$(h = \text{Planck's constant} = 6.626 \times 10^{-34}\ \text{J·s})$$

3. **Single Photon Absorption:** In photoelectric effect, an electron absorbs **one complete photon** (not continuous energy)
4. **Energy Conservation:** If photon energy exceeds work function, electron is emitted with kinetic energy

📐 Einstein's Photoelectric Equation - Derivation

Energy Conservation Principle:

When a photon of energy hv is absorbed by an electron:

Energy of photon = Work function + Kinetic energy of electron

$$h\nu = \varphi_0 + K$$

For maximum kinetic energy (least bound electrons):

$$K_{max} = h\nu - \varphi_0$$

⭐ **EINSTEIN'S PHOTOELECTRIC EQUATION** ⭐

Alternative Forms:

Since $K_{max} = eV_0$ and $\varphi_0 = h\nu_0$:

$$eV_0 = h\nu - h\nu_0 = h(\nu - \nu_0)$$

$$V_0 = (h/e)\nu - (\varphi_0/e)$$

$$V_0 = (h/e)\nu - (h/e)\nu_0$$

✅ How Einstein's Equation Explains All Observations

Observation	Einstein's Explanation
1. K_{max} independent of intensity	$K_{max} = h\nu - \varphi_0$ depends only on frequency ν, not on number of photons (intensity). Each photon-electron interaction is independent.
2. Threshold frequency exists	For emission: $h\nu > \varphi_0$, so $\nu > \nu_0 = \varphi_0/h$. Below this frequency, individual photon energy is insufficient to overcome work function.
3. Current ∝ intensity	Intensity ∝ number of photons per unit time. More photons → more electrons emitted → higher current (for $\nu > \nu_0$).
4. Instantaneous emission	Single photon-electron interaction is instantaneous. No accumulation time needed.
5. Linear V_0 vs ν graph	$V_0 = (h/e)\nu - \varphi_0/e$ is linear equation with slope h/e, independent of metal.

🔬 Millikan's Verification (1916)

The Great Irony: Millikan performed experiments (1906-1916) trying to **disprove** Einstein's photoelectric equation!

What He Did:

- Measured slope of V_0 vs v graph for various metals (especially sodium)
- Used known value of e to calculate h from slope (h/e)
- Found $h = 6.626 \times 10^{-34}$ J·s
- This matched Planck's constant from entirely different (blackbody radiation) context!

Result: Instead of disproving Einstein, Millikan's precise measurements **confirmed** the photoelectric equation! This led to acceptance of the photon picture of light.

🏆 Nobel Prizes:

- **1921:** Einstein - For photoelectric effect theory
- **1923:** Millikan - For elementary charge and photoelectric effect verification

📝 NCERT Example 11.1 - Laser Photon Emission

Problem: Monochromatic light of frequency 6.0×10^{14} Hz is produced by a laser. The power emitted is 2.0×10^{-3} W.

(a) What is the energy of a photon in the light beam?

(b) How many photons per second are emitted by the source?

Solution:

(a) Energy of one photon:

$E = h\nu = (6.63 \times 10^{-34}\ J \cdot s)(6.0 \times 10^{14}\ Hz)$

$\mathbf{E = 3.98 \times 10^{-19}\ J}$

(b) Number of photons per second:

Power P = N × E (where N = number of photons per second)

$N = P/E = (2.0 \times 10^{-3}\ W)/(3.98 \times 10^{-19}\ J)$

$\mathbf{N = 5.0 \times 10^{15}}$ **photons/second**

📝 NCERT Example 11.2 - Caesium Photoelectric Effect

Problem: The work function of caesium is 2.14 eV. Find:

(a) The threshold frequency for caesium

(b) The wavelength of incident light if photocurrent is brought to zero by stopping potential of 0.60 V

Solution:

(a) Threshold frequency:

At threshold: $h\nu_0 = \varphi_0$

$\nu_0 = \varphi_0/h = (2.14 \text{ eV})/(6.63 \times 10^{-34} \text{ J·s})$

$\nu_0 = (2.14 \times 1.6 \times 10^{-19} \text{ J})/(6.63 \times 10^{-34} \text{ J·s})$

$\nu_0 = 5.16 \times 10^{14}$ **Hz**

Below this frequency, no photoelectrons are emitted from caesium.

(b) Wavelength of incident light:

Einstein's equation: $eV_0 = h\nu - \varphi_0 = hc/\lambda - \varphi_0$

$\lambda = hc/(eV_0 + \varphi_0)$

$\lambda = (6.63 \times 10^{-34} \times 3 \times 10^{8})/[(0.60 + 2.14) \text{ eV}]$

$\lambda = (19.89 \times 10^{-26} \text{ J·m})/(2.74 \times 1.6 \times 10^{-19} \text{ J})$

λ = 454 nm (Blue light)

6. PARTICLE NATURE OF LIGHT - THE PHOTON

💫 The Photon - Properties and Characteristics

Definition: A photon is a quantum (discrete packet) of electromagnetic radiation carrying energy and momentum.

Photon Energy: $E = h\nu = hc/\lambda$

Photon Momentum: $p = h\nu/c = h/\lambda$

Key Properties of Photons:

Property	Description
1. Energy	$E = h\nu$ (proportional to frequency, not intensity)
2. Momentum	$p = h/\lambda$ (inversely proportional to wavelength)
3. Speed	Always travels at speed of light $c = 3 \times 10^8$ m/s
4. Rest Mass	Zero ($m_0 = 0$) - photons cannot be at rest
5. Electric Charge	Zero (electrically neutral)
6. Intensity	Determined by NUMBER of photons, not individual photon energy
7. In Collisions	Energy and momentum conserved; number of photons may change
8. Magnetic/Electric Fields	Not deflected (due to zero charge)

🔬 Compton Effect (1924)

A.H. Compton's Experiment: Further confirmed particle-like behavior of light through X-ray scattering from electrons.

Observation: When X-rays collide with electrons:

- X-ray wavelength increases (frequency decreases)
- Electrons recoil with kinetic energy
- Both energy and momentum are conserved in collision
- Behaves exactly like collision between two particles!

Significance: Compton effect provided conclusive evidence for particle nature of electromagnetic radiation.

🎯 Important Photon Concepts

1. Intensity and Number of Photons:

For light of frequency ν:

- Each photon has same energy E = hν
- Increasing intensity → Increasing number of photons/second
- Energy of individual photon remains constant

2. Why Higher Frequency Gives More Energy:

E = hν shows energy is directly proportional to frequency:

- UV photon (high ν) has more energy than visible light photon
- Visible photon has more energy than infrared photon
- This explains why UV can cause photoelectric effect but red light cannot

3. Photon-Particle Collisions:

In photon-electron collision:

- Total energy before = Total energy after
- Total momentum before = Total momentum after
- Photon may be absorbed (disappear) or scattered (change direction/energy)
- New photons may be created (emission)

🌊 7. WAVE NATURE OF MATTER - DE BROGLIE'S HYPOTHESIS

👤 Louis de Broglie (1892-1987)

Revolutionary Hypothesis (1924):

French physicist Louis de Broglie proposed a bold hypothesis that if electromagnetic radiation (thought to be waves) can behave as particles (photons), then **matter particles should also exhibit wave-like properties**.

Reasoning:

- Nature is symmetrical
- Two basic physical entities: Matter and Energy
- If radiation shows dual nature → So should matter!

🏆 **Nobel Prize 1929:** Awarded to de Broglie for discovery of wave nature of electrons.

⭐ DE BROGLIE RELATION ⭐

$$\lambda = h/p = h/(mv)$$

λ = de Broglie wavelength

p = momentum of particle

m = mass, v = velocity

h = Planck's constant

🔑 Understanding de Broglie's Relation

Dual Aspect:

- **Left side (λ):** Wave property - wavelength
- **Right side ($p = mv$):** Particle property - momentum
- **Planck's constant h:** Bridges the two aspects

Verification for Photons:

For a photon: $p = h\nu/c$

Therefore: $\lambda = h/p = h/(h\nu/c) = c/\nu$

This matches the electromagnetic wave relation: $\lambda = c/\nu$ ✓

Conclusion: de Broglie's relation is consistent with photon properties!

📏 When is de Broglie Wavelength Significant?

$\lambda = h/(mv)$ Analysis:

Particle Type	Mass (m)	de Broglie Wavelength	Significance
Macroscopic Objects (ball, car, human)	Large (kg scale)	Extremely small ($\sim 10^{-34}$ m)	Beyond measurement Wave nature not observable
Microscopic Particles (electrons, protons, neutrons)	Very small (10^{-31} to 10^{-27} kg)	Measurable (comparable to atomic spacing $\sim 10^{-10}$ m)	Wave nature significant Observable in experiments

Why We Don't See Wave Nature in Daily Life:

For macroscopic objects, de Broglie wavelength is:

- Billions of times smaller than atomic size
- Impossible to observe or measure
- This is why classical mechanics works perfectly for everyday objects

📝 NCERT Example 11.3 - de Broglie Wavelength Calculation

Problem: What is the de Broglie wavelength associated with:

(a) An electron moving with speed 5.4×10^6 m/s

(b) A ball of mass 150 g travelling at 30.0 m/s

Solution:

(a) For the electron:

Given:

- Mass: $m = 9.11 \times 10^{-31}$ kg
- Speed: $v = 5.4 \times 10^6$ m/s

Momentum:

$p = mv = (9.11 \times 10^{-31})(5.4 \times 10^6)$

$p = 4.92 \times 10^{-24}$ kg·m/s

de Broglie wavelength:

$\lambda = h/p = (6.63 \times 10^{-34})/(4.92 \times 10^{-24})$

$\lambda = 0.135$ nm = 1.35 Å

💡 **Note:** This wavelength is comparable to X-ray wavelengths and atomic spacing in crystals. Electron waves can be observed through diffraction!

(b) For the ball:

Given:

- Mass: m = 0.150 kg
- Speed: v = 30.0 m/s

Momentum:

$p = mv = (0.150)(30.0) = 4.50$ kg·m/s

de Broglie wavelength:

$\lambda = h/p = (6.63 \times 10^{-34})/(4.50)$

$\lambda = 1.47 \times 10^{-34}$ m

⚠️ **Note:** This wavelength is about 10^{-19} times the size of a proton! Completely beyond measurement. This is why we don't observe wave properties of macroscopic objects.

🌟 Experimental Verification of Matter Waves

🔬 Davisson-Germer Experiment (1927)

First Experimental Proof of Electron Waves:

- Clinton Davisson and Lester Germer performed electron diffraction experiments
- Directed beam of electrons at nickel crystal
- Observed diffraction pattern similar to X-ray diffraction
- Measured wavelength matched de Broglie's prediction: $\lambda = h/(mv)$

Significance:

- First direct evidence of wave nature of matter
- Confirmed de Broglie's hypothesis experimentally
- Opened new field of electron microscopy
- Davisson and G.P. Thomson shared 1937 Nobel Prize for discovery

Interesting Fact: G.P. Thomson (who proved wave nature of electron) was the son of J.J. Thomson (who discovered the electron as a particle)! Father proved particle nature, son proved wave nature!

📊 8. KEY CONCEPTS & IMPORTANT FORMULAE

⚡ FUNDAMENTAL CONSTANTS

Constant	Symbol	Value
Planck's Constant	h	6.626×10^{-34} J·s
Elementary Charge	e	1.602×10^{-19} C
Electron Mass	m_e	9.11×10^{-31} kg
Speed of Light	c	3.0×10^{8} m/s
e/m ratio	e/m	1.76×10^{11} C/kg

📐 PHOTOELECTRIC EFFECT FORMULAE

Formula	Description
$K_{max} = hv - \varphi_0$	Einstein's photoelectric equation
$K_{max} = eV_0$	Maximum KE from stopping potential
$v_0 = \varphi_0/h$	Threshold frequency
$V_0 = (h/e)v - \varphi_0/e$	Stopping potential vs frequency (linear)
$K_{max} = h(v - v_0)$	Alternative form using threshold frequency
$1\ eV = 1.602 \times 10^{-19}\ J$	Electron volt to joule conversion

PHOTON PROPERTIES

Property	Formula
Energy	$E = h\nu = hc/\lambda$
Momentum	$p = h\nu/c = h/\lambda = E/c$
Speed	$c = 3 \times 10^8$ m/s (constant)
Rest Mass	$m_0 = 0$
Charge	$q = 0$ (electrically neutral)
Wave-particle relation	$\lambda = c/\nu$ (electromagnetic wave)

🌊 MATTER WAVES (DE BROGLIE)

Formula	Description
$\lambda = h/p$	**de Broglie wavelength (general)**
$\lambda = h/(mv)$	**de Broglie wavelength (non-relativistic)**
$\lambda = h/\sqrt{(2mE_k)}$	**Wavelength in terms of kinetic energy**
$\lambda = h/\sqrt{(2meV)}$	**For electron accelerated through potential V**

⚠️ 9. COMMON MISTAKES TO AVOID

❌ MISTAKE 1: Confusing Intensity with Frequency

Wrong: "Higher intensity light will eject electrons with higher kinetic energy"

Correct: Higher intensity means more photons, not higher energy per photon. K_{max} depends on frequency, not intensity.

Remember:

- Intensity → Number of photoelectrons (photocurrent)
- Frequency → Energy of each photoelectron (K_{max})

❌ MISTAKE 2: Wrong Units in Calculations

Common Error: Using eV directly in formulas meant for Joules

Correct Approach:

- When using E = hν, express energy in Joules
- Convert eV to J: multiply by 1.602×10^{-19}
- OR work entirely in eV by using h in eV·s units

Example: $\varphi_0 = 2.14 \text{ eV} = 2.14 \times 1.602 \times 10^{-19} \text{ J} = 3.43 \times 10^{-19} \text{ J}$

❌ MISTAKE 3: Threshold Confusion

Wrong: "Increasing intensity will eventually cause emission below threshold frequency"

Correct: No matter how intense, if $\nu < \nu_0$, NO emission occurs. Individual photon energy must exceed work function.

❌ MISTAKE 4: Forgetting de Broglie is for MOMENTUM

Wrong: $\lambda = h/mv$ (using v directly for kinetic energy problems)

Correct: When kinetic energy E_k is given:

First find momentum: $E_k = p^2/(2m)$, so $p = \sqrt{(2mE_k)}$

Then: $\lambda = h/p = h/\sqrt{(2mE_k)}$

❌ MISTAKE 5: Sign Errors in Stopping Potential

Remember: Stopping potential V_0 is the magnitude of retarding potential needed to stop electrons.

In equations: $eV_0 = K_{max}$ (both positive)

Don't write: $-eV_0 = K_{max}$ ✗

🎓 10. PRACTICE QUESTIONS

Section A: Multiple Choice Questions (1 mark each)

Q1. The photoelectric work function for a metal surface is 2.3 eV. If light of wavelength 6000 Å is incident on the surface, will photoelectrons be emitted? ($h = 6.63 \times 10^{-34}$ J·s)

(a) Yes
(b) No ✓
(c) Data insufficient
(d) Depends on intensity

Answer: (b) Energy of photon = $hc/\lambda = (6.63\times10^{-34}\times3\times10^{8})/(6000\times10^{-10}) = 3.3\times10^{-19}$ J = 2.06 eV < 2.3 eV. Since photon energy is less than work function, no emission occurs.

Q2. In photoelectric effect, the photocurrent:

(a) Depends on intensity of incident light ✓
(b) Depends on frequency of incident light
(c) Depends on speed of emitted electrons
(d) Is independent of both intensity and frequency

Answer: (a) Photocurrent is proportional to number of photoelectrons emitted per second, which depends on intensity (number of photons) of incident light.

Q3. The de Broglie wavelength associated with a ball of mass 200 g and moving at 5 m/s is:

(a) 6.6×10^{-34} m ✓
(b) 6.6×10^{-32} m
(c) 6.6×10^{-30} m
(d) 6.6×10^{-36} m

Answer: (a) $\lambda = h/(mv) = (6.6\times10^{-34})/[(0.2)(5)] = 6.6\times10^{-34}$ m

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Q4. If the frequency of light in a photoelectric experiment is doubled, the stopping potential will:

(a) Be doubled
(b) Be halved
(c) Become more than double ✓
(d) Become less than double

Answer: (c) $V_0 = (h/e)\nu - \varphi_0/e$. If ν is doubled, V_0 increases by $(h/e)\nu$, making new value more than double (due to $-\varphi_0/e$ term).

Q5. The momentum of a photon of energy 1 MeV in kg·m/s will be:

(a) 5×10^{-22} ✓
(b) 0.33×10^{6}
(c) 7×10^{-24}
(d) 10^{-22}

Answer: (a) $p = E/c = (1\times10^{6}\times1.6\times10^{-19})/(3\times10^{8}) = 5.3\times10^{-22} \approx 5\times10^{-22}$ kg·m/s

Section B: Short Answer Questions (2-3 marks each)

Q6. Define work function. What is threshold frequency? Establish relation between them.

Answer:

Work Function (φ_0): The minimum energy required by an electron to escape from a metal surface. It depends on the nature of metal and its surface.

Threshold Frequency (ν_0): The minimum frequency of incident radiation below which no photoelectric emission occurs, regardless of intensity.

Relation:

At threshold: Photon energy = Work function

$h\nu_0 = \varphi_0$

Therefore: $\nu_0 = \varphi_0/h$

Q7. State the observations that could not be explained by wave theory of light in photoelectric effect.

Answer:

Wave theory failed to explain:

1. **Independence of K_{max} on intensity:** According to wave theory, higher intensity should give more energy per electron, but experiments showed K_{max} is independent of intensity
2. **Existence of threshold frequency:** Wave theory predicted that any frequency, given sufficient time, should cause emission. But below ν_0, no emission occurs regardless of intensity or time

3. **Instantaneous emission:** Wave theory predicted time lag (hours) for energy accumulation. Actual emission is instantaneous (~10^{-9} s)
4. **Linear variation of K_{max} with frequency:** Wave theory couldn't explain why K_{max} increases linearly with frequency

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Q8. Light of wavelength 500 nm is incident on a metal of work function 2.28 eV. Find the maximum kinetic energy of photoelectrons.

Answer:

Given: $\lambda = 500$ nm $= 500 \times 10^{-9}$ m, $\varphi_0 = 2.28$ eV

Energy of photon:

$E = hc/\lambda = (6.63\times10^{-34} \times 3\times10^{8})/(500\times10^{-9})$

$E = 3.978 \times 10^{-19}$ J $= 2.49$ eV

Maximum kinetic energy:

$K_{max} = h\nu - \varphi_0 = 2.49 - 2.28$

$K_{max} = 0.21$ eV

Section C: Long Answer Questions (5 marks each)

Q9. State Einstein's photoelectric equation. Using this equation, explain:

(a) Why photoelectric emission is instantaneous

(b) Why threshold frequency exists

(c) Why maximum KE is independent of intensity

Answer:

Einstein's Photoelectric Equation:

$$K_{max} = h\nu - \varphi_0$$

(a) Instantaneous Emission:

According to Einstein's photon theory, photoelectric effect occurs due to one-to-one interaction between a photon and an electron. When a photon of sufficient energy strikes an electron, the entire photon energy is transferred instantaneously to that electron. There is no gradual accumulation of energy over time as predicted by wave theory. Hence, emission is instantaneous ($\sim 10^{-9}$ s).

(b) Existence of Threshold Frequency:

From Einstein's equation: $K_{max} = h\nu - \varphi_0$

For photoelectron to be emitted: $K_{max} \geq 0$

This requires: $h\nu \geq \varphi_0$, or $\nu \geq \varphi_0/h = \nu_0$

Therefore, there exists a minimum frequency ν_0 below which no emission occurs, regardless of intensity. This is because individual photon must have minimum energy φ_0 to overcome work function.

(c) Independence of K_{max} on Intensity:

From equation: $K_{max} = h\nu - \varphi_0$

K_{max} depends only on frequency ν and work function φ_0. Intensity determines the number of photons per unit time, not the energy of each photon. Each photon-electron interaction is independent, and each photon has same energy (hν) for given frequency. Therefore, increasing intensity increases number of photoelectrons but not their maximum kinetic energy.

Q10. Derive de Broglie wavelength expression. Calculate de Broglie wavelength for an electron accelerated through 100 V potential.

Answer:

Derivation of de Broglie Relation:

De Broglie hypothesized that if radiation has particle nature, matter should have wave nature.

For a photon:

Energy: $E = h\nu$

Also: $E = pc$ (energy-momentum relation for photon)

Therefore: $h\nu = pc$

Since $c = \nu\lambda$: $h(c/\lambda) = pc$

This gives: $\lambda = h/p$

De Broglie extended this to material particles:

$$\lambda = h/p = h/(mv)$$

Calculation for electron accelerated through 100 V:

Step 1: Find kinetic energy

When electron is accelerated through potential V:

K.E. = eV = $(1.6 \times 10^{-19})(100) = 1.6 \times 10^{-17}$ J

Step 2: Find momentum

K.E. = $p^2/(2m)$

$p = \sqrt{(2mK.E.)} = \sqrt{(2 \times 9.1\times10^{-31} \times 1.6\times10^{-17})}$

$p = 5.4 \times 10^{-24}$ kg·m/s

Step 3: Calculate wavelength

$\lambda = h/p = (6.63\times10^{-34})/(5.4\times10^{-24})$

$\lambda = 1.23 \times 10^{-10}$ m = 1.23 Å

Alternative Formula: For electron accelerated through V volts:
$\lambda = h/\sqrt{(2meV)} = 12.27/\sqrt{V}$ Å (This is a useful formula to remember!)

🏆 11. EXAM PREPARATION STRATEGIES

🌟 Master These Concepts:

- ✨ Three types of electron emission and their mechanisms
- ✨ Work function and threshold frequency relationship
- ✨ Complete experimental observations of photoelectric effect
- ✨ Why wave theory failed to explain photoelectric effect
- ✨ Einstein's photoelectric equation: derivation and applications
- ✨ Stopping potential and its physical significance
- ✨ Photon properties: energy, momentum, and characteristics
- ✨ de Broglie hypothesis and matter wave concept
- ✨ Calculation of de Broglie wavelength for different particles
- ✨ Why matter waves are significant only for microscopic particles

💪 KEY TO SUCCESS:

"Understand the DUAL NATURE - Sometimes Particle, Sometimes Wave, Always Fascinating!"

📚 Must Practice:

- ☑ Derive Einstein's photoelectric equation (5 marks question)
- ☑ 15 numerical on photoelectric effect (finding K_{max}, V_0, ν_0, λ)
- ☑ 10 problems on photon energy and momentum
- ☑ 15 de Broglie wavelength calculations
- ☑ Compare wave theory vs photon theory (3 marks)
- ☑ All graph interpretations (V_0 vs ν, I vs V)
- ☑ Unit conversions: eV ↔ J, nm ↔ m, Å ↔ m
- ☑ All NCERT examples and back exercises

💡 EXAM TIPS

For Theory Questions:

- Always define terms before using them (work function, threshold frequency, etc.)
- Draw neat diagrams for experimental setup questions
- Use bullet points for listing observations/properties
- Mention units in all final answers

For Numerical Problems:

- Write "Given" and "To Find" clearly
- Always check units - convert to SI if needed
- For photoelectric effect: Decide if using eV or Joules from start
- Show step-by-step calculations
- Box or underline final answers

Common Question Types:

1. Explain failure of wave theory (3 marks)
2. Derive Einstein's equation (5 marks)
3. Find K_{max}, V_0, or ν_0 (2-3 marks numerical)
4. Calculate de Broglie wavelength (2-3 marks)
5. Graph interpretation (V_0 vs ν) (2-3 marks)

🎯 Important Points for Board Exams

Formulae to Remember:

1. $K_{max} = h\nu - \varphi_0$ (Einstein's photoelectric equation)
2. $K_{max} = eV_0$ (stopping potential relation)
3. $\nu_0 = \varphi_0/h$ (threshold frequency)
4. $E = h\nu$ (photon energy)
5. $p = h/\lambda$ (photon momentum)
6. $\lambda = h/(mv)$ (de Broglie wavelength)

Values to Memorize:

- $h = 6.626 \times 10^{-34}$ J·s
- $e = 1.6 \times 10^{-19}$ C
- $m_e = 9.1 \times 10^{-31}$ kg
- $c = 3 \times 10^{8}$ m/s
- 1 eV = 1.6×10^{-19} J

📚 Study Material Information

This comprehensive study material on **Dual Nature of Radiation and Matter** has been prepared following the latest CBSE curriculum and examination pattern for Class 12 Physics. The content includes detailed explanations of electron emission mechanisms, historical development of photoelectric effect, experimental observations, Einstein's photon theory, photoelectric equation with complete derivation, particle nature of light, de Broglie's matter wave hypothesis, complete worked examples from NCERT, and practice questions aligned with current board exam format.

Key Features of This Material:

- Complete chapter coverage with crystal-clear concepts
- Introduction: Historical background and cathode rays
- Electron emission: Thermionic, field, and photoelectric
- Work function and threshold frequency concepts
- Photoelectric effect: Hertz, Hallwachs, and Lenard's observations
- Detailed experimental setup and observations
- Effect of intensity, potential, and frequency on photocurrent
- Stopping potential and its physical significance
- Failure of classical wave theory
- Einstein's revolutionary photon theory (1905)
- Complete derivation of Einstein's photoelectric equation
- Millikan's experimental verification
- Particle nature of light - The Photon
- Photon properties: energy, momentum, characteristics
- Compton effect as confirmation of particle nature
- de Broglie's wave nature of matter hypothesis (1924)
- Matter waves and de Broglie wavelength
- When matter waves are significant
- Davisson-Germer experimental verification
- All NCERT solved examples (11.1-11.3) with detailed solutions
- Comprehensive formula sheet with all important relations
- Common mistakes to avoid with explanations
- Multiple choice and descriptive practice questions
- Exam-focused tips and strategies

🎯 **Specializing in CBSE Physics, Chemistry, and Mathematics (Classes 6-12)**