TOPIC 1 Quantum Theory of Radiation

SQ 18.1.1 What did Max Planck suggest in 1901?

Answer

Max Planck suggested that energy is radiated or absorbed in discrete packets of energy called quanta, rather than as a continuous wave.

SQ 18.1.2 Define a quantum.

Definition

A quantum is a discrete packet of energy. Each quantum is associated with radiation of a single frequency.

SQ 18.1.3 Write Planck's relation and the value of Planck's constant.

Formula

$E = hf$

Value

$h = 6.63 \times 10^{-34}\,\mathrm{J\,s}$

SQ 18.1.4 For what was Max Planck awarded the Nobel Prize?

Answer

Max Planck received the Nobel Prize in physics in 1918 for his discovery of energy quanta.

SQ 18.1.5 What are photons?

Definition

Einstein postulated that packets or tiny bundles of energy are an integral part of all electromagnetic radiations and that they could not be sub-divided. These indivisible tiny bundles of energy he called photons.

SQ 18.1.6 What does a monochromatic beam of light consist of?

Answer

A monochromatic beam of light of wavelength λ consists of a stream of photons travelling at speed c and carrying energy $E = hf$

SQ 18.1.7 Derive the momentum of a photon.

Derivation

From relativity

$E = mc^2$

and the relativistic momentum is

$p = mc$

so

$E = pc$

Since

$E = hf$

and

$c = f\lambda$

Result

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

SQ 18.1.8 Why is the particle nature of a mass on a spring invisible?

Reason

The quantum theory may be extended to any system, but the energy steps are far <u>too small</u> to be detected, so any particle nature is invisible.

SQ 18.1.9 When are quantum effects important?

Answer

Quantum effects are only important when observing atom-sized objects, where h is a significant factor in any detectable energy change.

TOPIC 2 Photoelectric Effect

SQ 18.2.1 Define the photoelectric effect.

Definition

The process of emission of electrons from a metal surface when exposed to light of suitable frequency is called the photoelectric effect. The emitted electrons are known as photoelectrons.

SQ 18.2.2 Describe the apparatus used to demonstrate the photoelectric effect.

Apparatus

An evacuated glass tube contains two electrodes. The electrode connected to the positive terminal of the battery acts as the anode, and the metal electrode connected to the negative terminal acts as the cathode.

SQ 18.2.3 What proves that the photoelectric current flows because of incident light?

Answer

The current stops when the light is <u>cut off</u>, which proves that the current flows because of the incident light. This current is therefore called the photoelectric current.

SQ 18.2.4 Define stopping potential.

Definition

When the connections of the battery are reversed, the photoelectrons are repelled by the anode. At a certain negative value of this potential, called the stopping potential, the current becomes zero.

SQ 18.2.5 Write the maximum kinetic energy of photoelectrons in terms of stopping potential.

Formula

$(KE)_{max} = \frac{1}{2}mv_{max}^2 = V_0e$

SQ 18.2.6 What is the effect of increasing the intensity of light?

Answer

If the experiment is repeated with a beam of higher intensity, the amount of current increases, but the current stops for the <u>same value</u> of stopping potential.

SQ 18.2.7 **What is observed when the frequency of incident light is changed?**

Answer
If the intensity is kept constant and the frequency is changed, the current is the same but the stopping potential is different for each frequency. This indicates the proportionality of maximum kinetic energy with the frequency of light.

SQ 18.2.8 **On what does the maximum energy of photoelectrons depend?**

Answer
The electrons are emitted with different energies. The maximum energy of photoelectrons depends on the particular metal surface and on the frequency of the incident light.

SQ 18.2.9 **Define threshold frequency.**

Definition
There is a minimum frequency called the threshold frequency, below which no electrons are emitted, however intense the light may be. This threshold frequency varies from metal to metal.

SQ 18.2.10 **Give an example illustrating threshold frequency.**

Example
Blue light produces photoelectric emission in sodium metal, but red light does not, however intense the red light may be.

SQ 18.2.11 **Define threshold wavelength.**

Definition
The wavelength of incident light corresponding to the threshold frequency is called the threshold wavelength, related by
$c = f_0\lambda_0$

SQ 18.2.12 **What determines the number of emitted photoelectrons?**

Answer
Electrons are emitted instantaneously, and the intensity of light determines only their number.

SQ 18.2.13 **Why could classical wave theory not explain the photoelectric effect?**

Reason
According to wave theory, increasing the intensity of incident light should increase the kinetic energy of the emitted electrons, which contradicts the experimental result.

Also
The classical theory cannot explain the threshold frequency, since even light of lesser energy should eventually transfer enough energy to liberate electrons.

SQ 18.2.14 **Define work function.**

Definition
The electron needs a certain minimum energy, called the work function, to be knocked out from the metal surface.

SQ 18.2.15 **Write Einstein's photoelectric equation.**

Formula
$hf = \phi + \frac{1}{2}mv^2_{max}$
Here ϕ is the work function of the metal.

SQ 18.2.16 **Why do not all emitted electrons possess the maximum kinetic energy?**

Reason
Some electrons come straight out of the metal surface, while others lose energy in atomic collisions before coming out. The equation holds good only for those electrons which come out with full surplus energy.

SQ 18.2.17 **For what was Einstein awarded the Nobel Prize?**

Answer
Albert Einstein was awarded the Nobel Prize in physics in 1921 for his explanation of the photoelectric effect.

SQ 18.2.18 **What does the photoelectric effect prove about light?**

Answer
The photoelectric effect cannot be explained by assuming light consists of waves with energy uniformly distributed over its wavefront. It can only be explained by assuming light consists of photons, thus showing the particle nature of light.

SQ 18.2.19 **Find the energy of a photon of blue light of wavelength 450 nm.**

Solution
$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{450 \times 10^{-9}}$

Result
$E = 4.42 \times 10^{-19}\,\text{J} = 2.76\,\text{eV}$

SQ 18.2.20 **Yellow light on cesium gives a stopping voltage of 0.25 V. Find the maximum K.E.**

Solution
$(KE)_{max} = V_0e = 0.25 \times 1.6 \times 10^{-19}$

Result
$(KE)_{max} = 4 \times 10^{-20}\,\text{J} = 0.25\,\text{eV}$

SQ 18.2.21 **For 577 nm light on cesium with (K.E.)max = 4×10^{-20} J, find the work function.**

Solution
$\phi = \frac{hc}{\lambda} - (KE)_{max} = 3.45 \times 10^{-19} - 4 \times 10^{-20}$

Result
$\phi = 3.05 \times 10^{-19}\,\text{J} = 1.9\,\text{eV}$

TOPIC 3 Compton Effect

SQ 18.3.1 **Who discovered the Compton effect and how?**

Answer
Arthur Holly Compton at Washington University in 1923 studied the scattering of X-rays by loosely bound electrons from a graphite target.

SQ 18.3.2 **Define the Compton effect.**

Definition

Compton found that the wavelength of the scattered X-rays is greater than the wavelength of the incident X-rays. This is known as the Compton effect.

SQ 18.3.3 **Why could the Compton effect not be explained classically?**

Reason

The increase in wavelength of the scattered X-rays could not be explained on the basis of classical wave theory.

SQ 18.3.4 **What did Compton suggest to explain his effect?**

Answer

In order to explain this effect, Compton suggested that X-rays consist of photons with energy $\frac{hc}{\lambda}$ and momentum $\frac{h}{\lambda}$.

SQ 18.3.5 **Define Compton shift.**

Definition

The change in wavelength $\Delta\lambda$ between the incident and scattered X-rays is known as the Compton shift in wavelength.

SQ 18.3.6 **How is the photon-electron collision treated in the Compton effect?**

Answer

The photon suffers collision with the electron like a billiard ball, and the laws of conservation of energy and momentum are applied to the collision.

SQ 18.3.7 **Which process dominates the interaction of radiation with matter at low energies?**

Answer

At low energies, less than 0.51 MeV, the dominant process is the photoelectric effect.

SQ 18.3.8 **Which processes dominate at intermediate and higher energies?**

Answer

At intermediate energies the dominant process is the Compton effect.

At higher energies, more than 1.02 MeV, the dominant process is pair production.

TOPIC 4 Wave Nature of Particles

SQ 18.4.1 **What did de Broglie propose?**

Answer

Assuming symmetry in nature, the French physicist Louis de Broglie proposed in 1924 that particles should also possess wave-like properties.

SQ 18.4.2 **Write the de Broglie relation.**

Formula

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

Here λ is the wavelength associated with particle waves.

SQ 18.4.3 **Why are wave effects negligible for large objects?**

Reason

An object of large mass and ordinary speed has such a small wavelength that its wave effects, such as interference and diffraction, are negligible.

SQ 18.4.4 **Find the de Broglie wavelength of a 20 g bullet moving at 330 m s^{-1}.**

Solution

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{2 \times 10^{-2} \times 330}$$

Result

$$\lambda = 1 \times 10^{-34}\,\text{m}$$

This wavelength is so small that it is not measurable.

SQ 18.4.5 **Find the de Broglie wavelength of an electron moving at 1 × 10^{6} m s^{-1}.**

Solution

$$\lambda = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1 \times 10^{6}}$$

Result

$$\lambda = 7 \times 10^{-10}\,\text{m}$$

This wavelength is in the X-ray range, so diffraction effects for electrons are measurable.

SQ 18.4.6 **Find the wavelength of the photons produced when a positron-electron pair annihilates.**

Data

The rest mass energy of each photon is

$$0.51\,\text{MeV} = 8.16 \times 10^{-14}\,\text{J}$$

Solution

$$\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{8.16 \times 10^{-14}}$$

Result

$$\lambda = 2.43 \times 10^{-12}\,\text{m}$$

SQ 18.4.7 **What did Davisson and Germer show?**

Answer

They provided convincing evidence of the wave nature of electrons, showing that electrons are diffracted from metal crystals in exactly the same manner as X-rays or any other wave.

SQ 18.4.8 **Describe the Davisson and Germer apparatus.**

Apparatus

Electrons from a heated filament are accelerated by an adjustable applied voltage. The electron beam is then made incident on a nickel crystal, and the scattered electrons are detected.

SQ 18.4.9 **How did Davisson and Germer interpret their results?**

Answer

The scattered electrons came off in regular peaks. They interpreted this peak pattern as a result of diffraction, just like X-ray diffraction by an NaCl crystal.

SQ 18.4.10 Write the de Broglie wavelength in terms of accelerating voltage.

Derivation

The gain in kinetic energy of an electron accelerated through potential V is

$$\frac{1}{2}mv^2 = Ve$$

Result

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

SQ 18.4.11 What wavelength was found in the Davisson-Germer experiment?

Answer

For an accelerating voltage of 54 volts, and using Bragg's equation with

$$d = 0.91 \times 10^{-10}\ \text{m}$$

and a glancing angle of 65°, the wavelength was found to be 1.65×10^{-10} m.

Conclusion

The experimentally observed wavelength is in excellent agreement with the theoretically predicted wavelength.

SQ 18.4.12 With which other particles have diffraction patterns been observed?

Answer

Diffraction patterns have also been observed with protons, neutrons, hydrogen atoms and helium atoms, giving substantial evidence for the wave nature of particles.

SQ 18.4.13 Who received Nobel Prizes for the wave nature of particles?

Answer

Prince Louis Victor de Broglie received the 1929 Nobel Prize for his work on the dual nature of particles.
Clinton Joseph Davisson and George Paget Thomson shared the Nobel Prize in 1937 for their experimental confirmation.

TOPIC 5 Wave-Particle Duality

SQ 18.5.1 Which phenomena provide evidence for the wave nature of light?

Answer

Interference and diffraction of light provide evidence for its wave nature.

SQ 18.5.2 Which phenomena prove the particle nature of light?

Answer

The photoelectric effect and the Compton effect prove the particle nature of light.

SQ 18.5.3 Define wave-particle duality.

Definition

Matter and radiation have a dual wave-particle nature. All micro-particles propagate as if they were waves and exchange energies as if they were particles.

SQ 18.5.4 State Bohr's principle of complementarity.

Statement

Niels Bohr pointed out that both wave and particle aspects are required for the complete description of both radiation and matter.

SQ 18.5.5 Can both aspects be revealed in a single experiment?

Answer

Both aspects are always present and either may be revealed by an experiment. However, both aspects cannot be revealed simultaneously in a single experiment.

SQ 18.5.6 What determines which aspect of light is revealed?

Answer

A particular aspect is determined by the nature of the experiment being done.

Examples

A diffraction grating in the path of a light beam reveals it as a wave, while allowing the beam to hit a metal surface requires us to regard it as a stream of particles.

SQ 18.5.7 When does light behave as a wave and when as a stream of photons?

Answer

Light behaves as a stream of photons when it interacts with matter, and behaves as a wave in travelling from a source to the place where it is detected.

TOPIC 6 Electron Microscope

SQ 18.6.1 On what principle does an electron microscope work?

Principle

The electron microscope uses the wave nature of electrons, whose de Broglie wavelength is a thousand times shorter than the wavelength of visible light.

SQ 18.6.2 What advantage does the shorter wavelength give?

Answer

It enables the electron microscope to see fine details not visible to the optical microscope.

SQ 18.6.3 Describe the working of an electron microscope.

Working

Electrons from a source are passed through an electromagnetic lens called the condenser, which focuses the beam on the specimen. The beam is accelerated by voltages of several megavolts.

Imaging

An electromagnetic objective lens forms the image, which is further magnified by an electromagnetic projector lens.

SQ 18.6.4 **Why does a higher speed of electrons give higher resolution?**

Reason
The higher the speed of the electrons, the shorter is the wavelength, and hence the higher is the resolution.

SQ 18.6.5 **What is a micrograph?**

Definition
The image photographed on a film by the electromagnetic projector lens of an electron microscope is called a micrograph.

SQ 18.6.6 **What is a scanning electron microscope?**

Answer
A three dimensional image of remarkable quality can be achieved by modern versions of the electron microscope called scanning electron microscopes.

SQ 18.6.7 **Give the uses of the electron microscope.**

Uses
The electron microscope can see details down to the nanometre, that is about the atomic level.
Uses include the study of cell structure, viruses and bacteria in microbiology, and the investigation of metal fractures, materials and crystal structure.

TOPIC 7 Atomic Spectra

SQ 18.7.1 **What is the basis of atomic spectra?**

Answer
The evidence of the particle nature of quantized photons using a spectrometer is the basis of atomic spectra.

SQ 18.7.2 **Describe the experimental arrangement for observing atomic spectra.**

Arrangement
The arrangement consists of a discharge tube, a spectrometer and a diffraction grating. A series of lines are viewed in a dark background through the eyepiece of the spectrometer.

SQ 18.7.3 **What are spectral series and what is their use?**

Definition
The vapours of different elements exhibit different patterns of lines called spectral series.

Use
These can be used to identify different elements.

SQ 18.7.4 **Who identified the Balmer series and where does it lie?**

Answer
One such series was identified by J. J. Balmer in 1885 in the spectrum of atomic hydrogen. It is in the visible region of the electromagnetic spectrum and consists of four spectral lines.

SQ 18.7.5 **Write the Rydberg formula for the Balmer series.**

Formula
$$\frac{1}{\lambda} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$
Here
$n = 3, 4, 5, \ldots$
and
$R_H = 1.0974 \times 10^7\,\mathrm{m}^{-1}$

SQ 18.7.6 **Write the formula for the Lyman series.**

Formula
$$\frac{1}{\lambda} = R_H\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$$
Here
$n = 2, 3, 4, \ldots$
and the series lies in the ultraviolet region.

SQ 18.7.7 **Define ground state and excited states.**

Ground State
The state for
$n = 1$
is said to be the ground state.

Excited States
The states
$n = 2, 3, 4, \ldots$
are called excited states.

SQ 18.7.8 **What happens when an atom absorbs energy?**

Answer
An atom absorbs energy in discrete amounts only and is raised to one of its excited states. The excited states have a very short life.

SQ 18.7.9 **How is an emission spectrum produced?**

Answer
The electron soon returns to a lower energy level by emitting photons, observed as an emission spectrum consisting of several spectral lines.

SQ 18.7.10 **What is the relation between absorption and emission line spectra?**

Answer
The wavelengths missing from an absorption line spectrum are those present in the emission line spectrum.

TOPIC 8 Uncertainty Principle

SQ 18.8.1 **State Heisenberg's uncertainty principle.**

Statement
The product of the uncertainty Δx in the position of a particle at some instant, and the uncertainty Δp in the x-component of its momentum at the same instant, approximately equals Planck's constant.

Formula
$\Delta x\,\Delta p \approx h$

SQ 18.8.2 Is the uncertainty due to the measuring instrument?

Answer

No. This uncertainty is not associated with the measuring instrument. It is a consequence of the wave-particle duality of matter and radiation.

SQ 18.8.3 Who proposed the uncertainty principle and when?

Answer

It was first proposed by Werner Heisenberg in 1927, and hence is known as Heisenberg's uncertainty principle. He was awarded the Nobel Prize in 1932.

SQ 18.8.4 For which objects is the uncertainty negligible?

Answer

This fundamental uncertainty is completely negligible for measurements of position and momentum of macroscopic objects in daily life, but is a predominant fact of life in the atomic domain.

SQ 18.8.5 Give an example showing why uncertainty matters at atomic scale.

Example

A stream of light photons striking a flying tennis ball hardly affects its path, but one photon striking an electron drastically alters its motion.

SQ 18.8.6 Why does using short wavelength light make momentum less precise?

Reason

To observe the position of an electron with less uncertainty we must use light of short wavelength. But such light carries larger momentum $\frac{h}{\lambda}$, which alters the motion drastically, making the momentum measurement less precise.

SQ 18.8.7 Prove that electrons do not exist inside the nucleus.

Proof

The diameter of a nucleus is of the order of 10^{-15} m, so the uncertainty in position would be 10^{-15} m.
The uncertainty in momentum is

$$\Delta p \approx \frac{h}{\Delta x} = 6.63 \times 10^{-19}\,\mathrm{N\,s}$$

Result

The corresponding energy uncertainty is of the order of GeV. No such electron has been found in the atom, so electrons do not exist inside the nucleus.

SQ 18.8.8 Write the energy-time form of the uncertainty principle.

Formula

$$\Delta E\,\Delta t \approx h$$

Meaning

The more accurately we determine the energy of a particle, the more uncertain we will be of the time during which it has that energy.

SQ 18.8.9 Write Heisenberg's more careful forms of the uncertainty relations.

Formulas

$$\Delta x\,\Delta p \geq \frac{h}{2\pi}$$

$$\Delta E\,\Delta t \geq \frac{h}{2\pi}$$

SQ 18.8.10 Find the velocity of an electron confined in a box of size 1.0×10^{-10} m.

Solution

Using

$$m\Delta v\,\Delta x = h$$

therefore

$$\Delta v = \frac{h}{m\Delta x}$$

Calculation

$$\Delta v = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1.0 \times 10^{-10}}$$

Result

$$\Delta v = 7.3 \times 10^{6}\,\mathrm{m\,s^{-1}}$$

SQ 18.8.11 Find the uncertainty in energy of a photon emitted from an atom radiating for 10^{-8} s.

Solution

Using

$$\Delta E = \frac{h}{\Delta t}$$

Calculation

$$\Delta E = \frac{6.63 \times 10^{-34}}{10^{-8}}$$

Result

$$\Delta E = 6.63 \times 10^{-26}\,\mathrm{J}$$