3 Quantum Phenomena

3.1 The Photoelectric Effect

Electrons are emitted from the surface of a metal when electromagnetic radiation above a certain frequency was directed at the metal. This is know as the **photoelectric effect**.

Observations could not be explained using the **wave model of light**.

- Photoelectric emission of electrons does not take place if the frequency of the incident EM radiation is below the **threshold frequency**.
- The number of electrons emitted per second is **proportional to the intensity** of the incident radiation.
- Photoelectric emission **occurs without delay**.

According to wave theory, each electron at the surface of a metal should gain some energy from the incoming waves - it cannot explain:

- The existence of a threshold frequency.
- Why photoelectric emission occurs without delay.

The Photon Theory

Light is composed of **wavepackets** or **photons**.

$$\text{Energy of a photon} = hf = \frac{hc}{\lambda}$$

To explain the photoelectric effect

1. An electron at the surface **absorbs a single photon** and therefore gains energy equal to hf.
2. An electron can leave the metal surface if the energy gained from a single photon exceeds the work function ϕ of the metal.
3. Excess energy gained by the photoelectron becomes its **kinetic energy**.

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

Emission can take place from a metal surface provided $E_{\text{Kmax}} > 0$, so the **threshold frequency** of the metal is

$$f_{\text{min}} = \frac{\phi}{h}$$

Electrons that escape from the plate can be attracted back by giving the plate a **sufficient positive charge**. The minimum potential needed to stop photoelectric emission is called the **stopping potential**.

3.2 More about Photoelectricity

The energy of each vibrating atom is **quantised** - only certain energy levels that are multiples of a basic amount are allowed.

- The **work function** is the minimum energy needed for a conduction electron to escape from the metal surface when the metal is at zero potential.
- When an electron absorbs a photon, its kinetic energy increases by an amount equal to the energy of the photon.
- If the energy of the photon exceeds the work function of the metal, the conduction electron can leave the metal.
  - If the electron does not leave the metal, it collides repeatedly with other electrons and ions, quickly loses its extra kinetic energy.

The Vacuum Photocell

A vacuum photocell is a **glass tube** that contains

- A metal plate - the **photocathode**
- A smaller metal electrode - the **anode**

When light of a frequency greater than the threshold frequency for the metal is directed at the photocathode, electrons are emitted from the cathode and are attracted to the anode.

The **photoelectric current** is proportional to the number of electrons per second transferred from the cathode to the anode.

- The photoelcetric current is **proportional to the intensity** of incident light on the cathode.
- The intensity of incident light does not affect the maximum kinetic energy of a photoelectron - the energy gained by a photoelectron is due to the absorption of one photon only.

3.3 Collisions of Electrons with Atoms

An **ion** is a charged atom, the number of electrons in an ion is not equal to the number of protons, it is created by adding or removing electrons from an atom.

Ionisation is any process of creating ions

- α, β and γ radiation create ions when they collide with atoms.
- Electrons passing through a **fluorescent tube** create ions when they collide with atoms of the vapour in the tube.

The **electron volt** (eV) is a unit of energy equal to the work done when an electron is moved through a pd of 1V.

Excitation by Collision

Atoms can absorb energy without being ionised - **excitation** happens at certain energy values known as the atom's **excitation energies**, which are characteristics of the atom.

The excitation energies of atoms in a **gas-filled tube** can be determined by

1. Increasing the potential difference between the filament and anode.
2. Measure the pd when the anode current falls.

Colliding electron makes an electron inside the atom move from an inner shell to an outer shell. The excitation energy is always **less than the ionisation energy** of the atom because the atomic electron is not removed completely.

3.4 Energy Levels in Atoms

Atomic electrons move about the nucleus in **shells** surrounding the nucleus.

- The energy of an electron in a shell is **constant**.
- An electron in a shell near the nucleus has less energy one further away.
- Each shell can only hold a certain number of electrons.

The **ground state** is the lowest energy state of an atom. When an atom absorbs energy, an electron moves to a shell of higher energy, the atom is now in an **excited state**.

The **electron configuration** in an excited atom is unstable because there is a vacancy in an inner shell. The vacancy is filled by an electron from an outer shell transferring to it. The electron emits a photon in the process of **de-excitation**.

$$\text{Energy of emitted photon} = E_1 - E_2$$

An electron in an atom can **absorb a photon** and move to an outer shell only if the energy of the photon <u>exactly equal to the gain of the electron's energy</u>.

Fluorescence

An excited atom can <u>de-excite directly or indirectly</u> to the ground state - an atom absorbs photons of certain energies, and then emit photons of the same or lesser energies.

A **fluorescent tube** is a glass tube with a fluorescent coating in the inner surface, containing mercury vapour.

1. **Ionisation and excitation** of mercury atoms when they collide with electrons in the tube.
2. Mercury atoms emit **ultraviolet photons** when they de-excite.

3. Ultraviolet photons absorbed by atoms of the coating, causing **excitation**.
4. Coating atoms **de-excite in steps** and emit visible photons.

3.5 Energy Levels and Spectra

Glowing gas produce a **spectrum of discrete lines** of different colours.

The wavelengths of the lines on a line spectrum are **characteristics of the atoms** of that element. We can identify the element by measuring the wavelengths of a line spectrum.

3.6 Wave-Particle Duality

The **theory of electromagnetic waves** predicted the existence of electromagnetic waves beyond he visible spectrum. But the **photoelectric effect** can only be explained with the **photon theory** of light - photons are particle-like packets of electromagnetic waves.

Light can behave as a wave or a particle according to circumstances.

- **Wave-like nature** is observed when **diffraction of light** takes place.
- **Particle-like nature** is observed in the **photoelectric effect**.

Matter Waves

de Broglie's hypothesis states

- Matter particles have a dual wave-particle nature.
- The wave-like behaviour of a matter particle is characterised by its **de Broglie's wavelength**.

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

Electron diffraction provides experimental evidence for the hypothesis.

1. A beam of electrons is directed at a thin metal foil consists of positive ions <u>arranged in fixed positions</u> in a regular pattern.
2. Electrons passes through the foil and are **diffracted in certain directions only**.
3. Forming a **concentric ring pattern** at the end of the tube.

Each ring is due to electrons <u>diffracted by the same amount</u> to the incident beam, from grains of <u>different orientations</u>.