9.4.2 Photoelectric Effect

The reconceptualisation of the model of light led to an understanding of the photoelectric effect and black body radiation

2.1 Describe **Hertz's observation of the effect of a radio wave on a receiver** and the **photoelectric effect** he produced but failed to investigate

- Hertz (1888) **conducted experiments to produce EMR** after existence propounded by **Maxwell**
  - Maxwell identified that an **oscillating charge will generate a changing electric field**, which generates a **changing magnetic field** and etc., **propagates through space** as a wave at speed of light

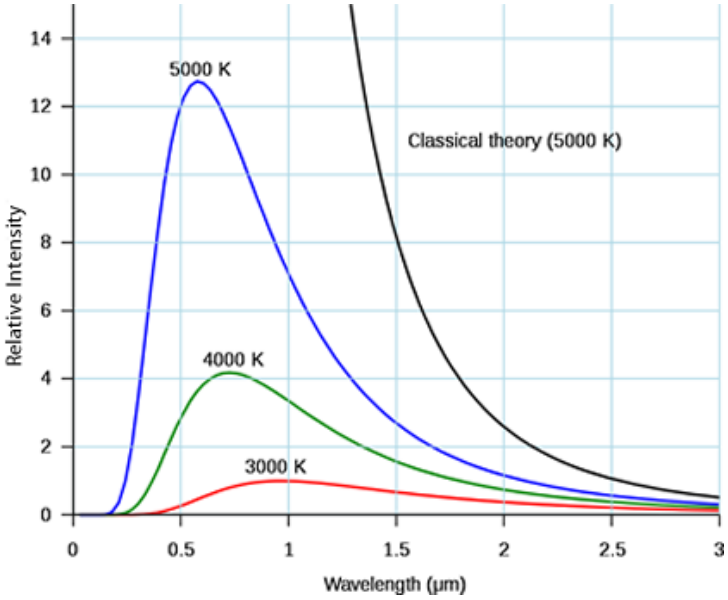
- Current fed into **primary loop** from induction coil, spark produced between which caused **EMR wave**
- EMR wave (radio wave) focussed by parabolic plates, travelled to receiving coil
- EMR focused into receiving coil, causing electrons to oscillate **regenerating electric signal in primary loop**
  - Much weaker (spark fainter) – energy lost in transmission
- Hertz observed **light/UV** made the receiver sparks to be more vigorous
  - Did not **investigate this – was the photoelectric effect**

2.2 Outline qualitatively **Hertz's experiments** in measuring the **speed of radio waves and how they relate to light waves**

- Hertz determined the **speed of the EMR** by applying $v = f\lambda$
  - **Frequency**: frequency of oscillation of oscillation of current
    - Used an electric circuit with a capacitor and inductor, measured close to 100 MHz
  - **Wavelength**: measurements from interference pattern generated
    - Used principle of superposition to build interference patterns of sparks
    - Depending on **path difference** (reflected path – direct path) of EMR, wavelength determined
- **Therefore measured** velocity of the produced wave **– not the same as light**
- Also determined they had **the same properties of light** – reflection, refraction, interference and polarisation
  - Reflected by a metal mirror
  - Refracted when passed through a prism of pitch
  - Polarised by connecting 2 loops with wire, varying orientation of detecting loop
    - Produced different spark intensities: no spark (destructive) to large spark (constructive)
  - Showed similarities to light waves

2.3 Identify **Planck's hypothesis** that **radiation emitted** and absorbed by the walls of **a black body cavity is quantised**

- **Black body**: an object that **can absorb and/or emit energy perfectly**, e.g. tungsten
  - When a **black body is heated in a vacuum**, it starts emitting radiation perfectly
  - Emits all types of radiation (light, IR, UV, etc.)
- Intensity of this radiation varies with the wavelength, can be **plotted**
  - For a given temperature, black body radiation has a **peak** – wavelength with highest intensity
  - When temperature increased, height of curve is increased, shifts to smaller wavelengths



UV CATASTROPHE

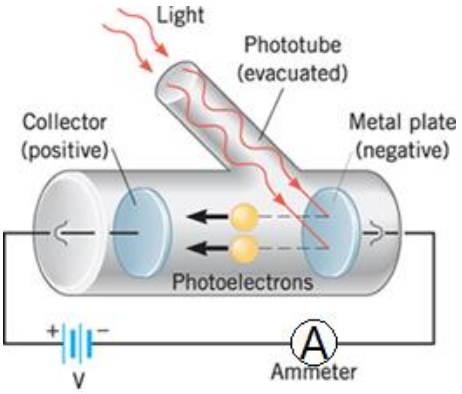
- The curve was only obtained **empirically by plotting experimental measurements** – not a formula
- Classical theory suggested **the hotter the object, the more energy it releases**
  - **Worked well** to explain larger wavelengths, but broke down for short UV wavelengths
  - **Called the UV catastrophe**
- **Problems** with classical theory:
  - Infinite energy at low wavelengths – impossible due to conservation of energy
  - Shift in peak intensities, and peak in wavelength were not explained
- Quantum theory (Max **Planck's Hypothesis)** suggested a new theory that matched with results
  - Energy not continuous but **occurring in discrete levels/packets of energy called quanta**
    - Energy only existing in discrete levels based on **constant h,** $\mathbf{6.626 \times 10^{-3}\ Js}$

$$E = hf$$

Where E = energy carried by photon (J), f = frequency (Hz), Planck's constant (Js)

Prerequisite Knowledge – **Photoelectric Effect**

- The **photoelectric effect** is that when EMR (above a certain frequency) strikes a metal surface, **it emits electrons**
- Maximum kinetic energy of photoelectrons emitted depends on **frequency** rather than **intensity** (which is classical theory)
- When right frequency is achieved, **emission is instantaneous**
- Increase in intensity will only result in larger **photocurrent** (measured by ammeter)



2.4 Identify **Einstein's contribution to quantum theory** and its **relation to black body radiation**

- Understand 2.5 before reading this.
- (1905) –Einstein combined **Planck's hypothesis** and **particle model of light** to explain **photoelectric effect**

1. Light behaves like **photons**, its energy related to frequency by $E = hf$
    - Collision between photon and electron leads to photoelectric effect
2. Only **photons with energy above work function** of a metal (with enough energy) will free electrons
    - **Threshold frequency**: the **minimum frequency** light must have to cause photoelectric effect
    - Determined by $\frac{W}{h}$ where W is the work function and h is Planck's number
    - Therefore, $\boldsymbol{KE_k = hf - w}$ – energy of photon minus the work function
3. Photon only transfers **all or none of its energy**
4. **Stopping Voltage**: When reversing the direction of voltage in the above diagram (makes collector negative)
    - Stopping voltage is the amount of work to stop the photoelectrons from reaching collector

EINSTEIN ALSO **EXPLAINED PROPERTIES OF THE PHOTOELECTRIC EFFECT**

- $E_k = hf - W$. If energy of EMR is not bigger than the work function, then nothing will happen
    - Therefore there is a **minimum frequency** required (see graph p. 202 PiF)
    - **Intensity of EMR does not affect** kinetic energy of photoelectrons
- **All energy or no energy** – either electrons **travel instantaneously** or **no energy** is transferred
- **Intensity** determines number of electrons – a measure of how many photons are received per unit of time

2.5 Explain the **particle model of light in terms of photons** with **particular energy and frequency**

- Light can be reflected, refracted, deflected, interfered and polarised – **wave properties**
- Light, based on **quantum physics**, is quantised and come as packets – **particle properties**
- Each **photon** has an **amount of energy** related to **frequency**, by $E = hf$

2.6 Identify the relationships between photon energy, frequency, speed of light and wavelength: $E = hf$ and $c = f\lambda$

- See formula box for $E = hf$ in 2.3.
    - **E** measures the energy of a particular 'packet' or photon of EMR of a particular frequency

$$v = c = f\lambda$$

Where c = speed of light/EMR (m/s), f = frequency (Hz), λ = wavelength (m)

2.P1 Perform an investigation to **demonstrate the production and reception of radio waves**

- An induction coil and spark gap created
- An AM radio is tuned off a channel to white noise
- When switching on voltage, **sounds increases, generating a buzzing sound**

2.P2 Identify data sources, gather, process and analyse information and use available evidence to **assess Einstein's contribution to quantum theory** and its **relation to black body radiation**

- **Planck proposed the idea/theory of quantisation of energy**
  - However, thought to be radical, contrasting to classical theory
- **Einstein** used this idea to **explain photoelectric effect**
  - Evidence to back up the theory
  - Realisation of new area of physics
- **Millikan verified Einstein's equation** for photoelectric effect $E_k = hf - W$ and plotted it
  - Value of h only empirically realised through experiments
  - Further strengthened quantum theory

2.P3 Identify data sources gather, process and present information to **summarise the use of the photoelectric effect** in

SOLAR CELLS

- This is discussed in more depth in 9.4.3.

PHOTOCELLS

- **Photocell**: electronic devices with resistances that alter the presence of light
- Phototube – a photocell with a low-pressure glass bulb with anode and large cathode
- When connected to circuit, gap between cathode and anode stop a circuit
  - When light shines, electrons are emitted and complete the circuit
  - E.g. alarm systems, automatic doors

2.P4 Solve problems and analyse information using: $\boldsymbol{E = hf}$ **and** $\boldsymbol{c = f\lambda}$

See Physics in Focus 192,193, 200

2.P5 Process information to discuss **Einstein and Planck's differing views** about whether **science research is removed from social and political forces**

- Planck was **loyal to the German government**
  - Supported scientific research for the war effort in World War I
- Einstein was **not loyal to any government**
  - Strongly believer in pacifism – opposing wars and violence
  - Openly criticised German militarism in WWI
  - However, ironically suggested the implementation of nuclear technology for bombs