13.2 The photoelectric effect

Specification reference: 4.5.2

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ the photoelectric effect and its demonstration

→ the interaction between one photon and one surface electron

→ work function and threshold frequency

→ the effects of the intensity of the incident radiation on the emission of photoelectrons.

Surface charging

Surface charging is a phenomenon experienced by all spacecraft. Outside the Earth's protective atmosphere, high-energy electromagnetic radiation causes electrons to be emitted from the metal parts of the spacecraft facing the Sun. This is called the **photoelectric effect**.

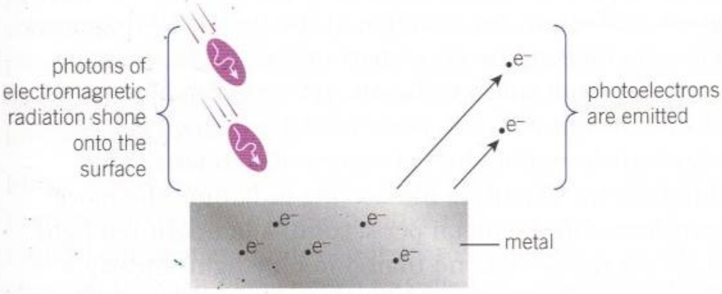
Surface charging results in some parts of the spacecraft carrying a positive charge, potentially leading to a damaging flow of charge through key electronic components inside the spacecraft. Engineers have to design solutions to this problem to ensure that charges cannot build up to potentially damaging levels.

▲ **Figure 1** *The European Space Agency and its Japanese equivalent plan to launch the BepiColumbo probe, designed to minimise the hazards caused by surface charging, to Mercury in 2016*

The photoelectric effect

In 1887 Heinrich Hertz reported that when he shone UV radiation onto zinc, electrons were emitted from the surface of the metal.

This is the photoelectric effect. The emitted electrons are sometimes called **photoelectrons**. They are normal electrons, but their name describes their origin – emitted through the photoelectric effect (Figure 2).

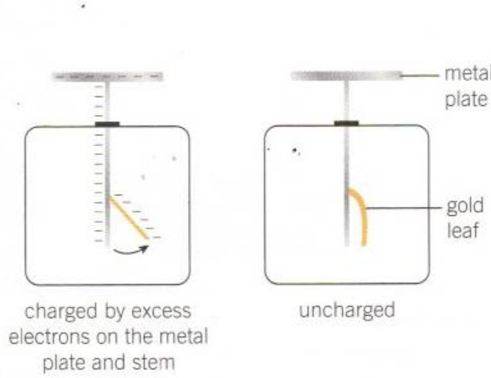


▲ **Figure 2** *The photoelectric effect occurs when electromagnetic radiation incident on the surface of a metal causes electrons to be emitted*

The gold-leaf electroscope

A simple demonstration of the effect can be seen with a **gold-leaf electroscope**. These were originally designed to measure p.d. (an early voltmeter). However, we can use them to demonstrate how like electrical charges repel each other.

Briefly touching the top plate with the negative electrode from a high-voltage power supply will charge the electroscope. Excess electrons are deposited onto the plate and stem of the electroscope. Any charge developed on the plate at the top of the electroscope spreads to the stem and the gold leaf. As both the stem and gold leaf have the same charge, they repel each other, and the leaf lifts away from the stem (Figure 3). If a clean piece of zinc is placed on top of a negatively charged



▲ **Figure 3** *Charged and uncharged electroscopes* electroscope and UV radiation shines onto the zinc surface, then the gold leaf slowly falls back towards the stem. This shows that the electroscope has gradually lost its negative charge, because the incident radiation (in this case UV) has caused the free electrons to be emitted from the zinc. These electrons are known as photoelectrons.

Three key observations from the photoelectric effect

The electroscope experiment is simple, but it was revolutionary. When different frequencies of incident radiation were investigated in more detail, scientists at the time made three key observations.

1 Photoelectrons were emitted only if the incident radiation was above a certain frequency (called the **threshold frequency** f_0) for each metal. No matter how intense the incident radiation (how bright the light), not a single electron would be emitted if the frequency was less than the threshold frequency.

2 If the incident radiation was above the threshold frequency, emission of photoelectrons was instantaneous.

3 If the incident radiation was above the threshold frequency, increasing the intensity of the radiation did not increase the maximum kinetic energy of the photoelectrons. Instead more electrons were emitted. The only way to increase the maximum kinetic energy was to increase the frequency of the incident radiation.

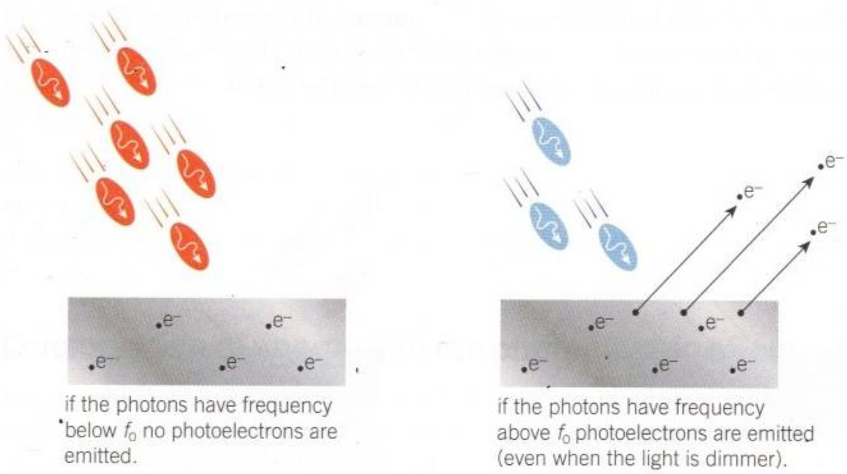
These observations could not be explained using wave model of electromagnetic radiation. For example, if the threshold frequency for a particular metal is in the green part of the visible spectrum, bright red light does not cause emission, yet very dim blue light would. This does not fit with the wave model, in which the rate of energy transferred by the radiation is dependent on its intensity (brightness). The more intense the radiation, the more energy is transferred to the metal per second, and bright red light transfers more energy per second than dim blue light. Clearly a new model for electromagnetic radiation was needed to explain the observations.

Using photons to illuminate the photoelectric effect

The observations in the photoelectric effect can be explained if the wave model of light is replaced with the photon model. In 1905 Einstein published an explanation of the effect. Building on Planck's work, he proposed the idea of electromagnetic radiation as a stream of photons, rather than continuous waves.

He suggested that each electron in the surface of the metal must require a certain amount of energy in order to escape from the metal, and that each photon could transfer its exact energy to one surface electron in a one-to-one interaction.

As the energy of the photon is dependent on its frequency ($E = hf$), if the frequency of the photon is too low, the intensity of the light – that is, the number of photons per second – does not matter, as a single photon delivers its energy to a single surface electron in a one-to-one interaction. If a photon does not carry enough energy on its own to free an electron, the number of photons makes no difference. However, when the frequency of the light is above the threshold frequency f_0 for the metal, then each individual photon has enough energy to free a single surface electron and so photoelectrons are emitted (Figure 4).



▲ **Figure 4** *Replacing the wave model with the photon model allowed Einstein to explain the photoelectric effect*

This also explained why there was no time delay. As long as the incident radiation has frequency greater than, or equal to, the threshold frequency, as soon as photons hit the surface of the metal, photoelectrons are emitted. Electrons cannot accumulate energy from multiple photons. Only one-to-one interactions are possible between photons and electrons.

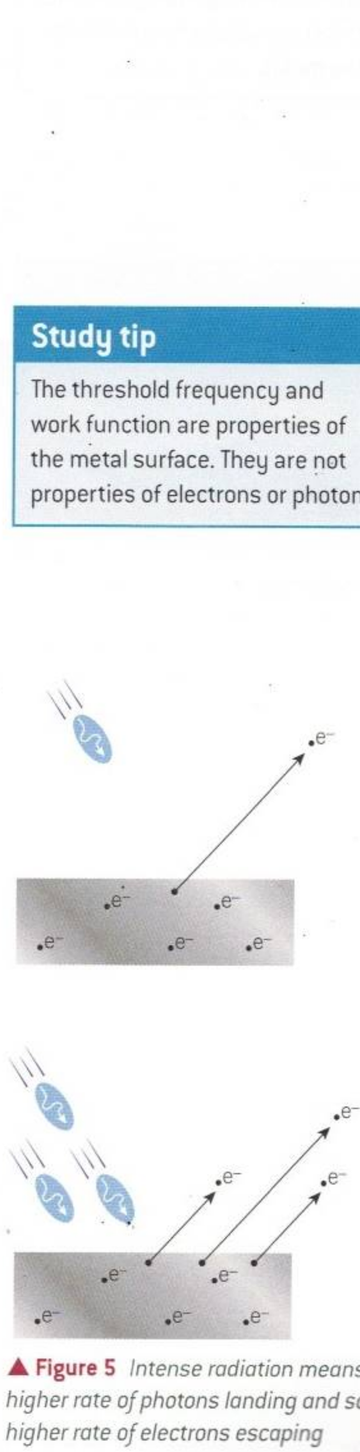
Einstein was also able to explain the third observation. Depending on their position relative to the positive ions in the metal, electrons would require different amounts of energy to free them. Einstein defined a constant for each metal which he called the **work function** ϕ. This is the *minimum* energy required to free an electron from the surface of the metal.

Increasing the intensity of the radiation means more photons per second hit the metal surface. As each photon interacts one-to-one with a single surface electron, as long as the radiation has frequency above the threshold frequency for the metal, more photons per second means a greater rate of photoelectrons emitted from the metal. The rate of emission of photoelectrons is directly proportional to the intensity of the incident radiation. Double the intensity and you double the number of photons per second, leading to a doubling in the number of electrons emitted from the metal per second.

Using the principle of conservation of energy, Einstein deduced that the kinetic energy of each photoelectron depends on how much energy was *left over* after the electron was freed from the metal (more

Study tip

The threshold frequency and work function are properties of the metal surface. They are not properties of electrons or photons.



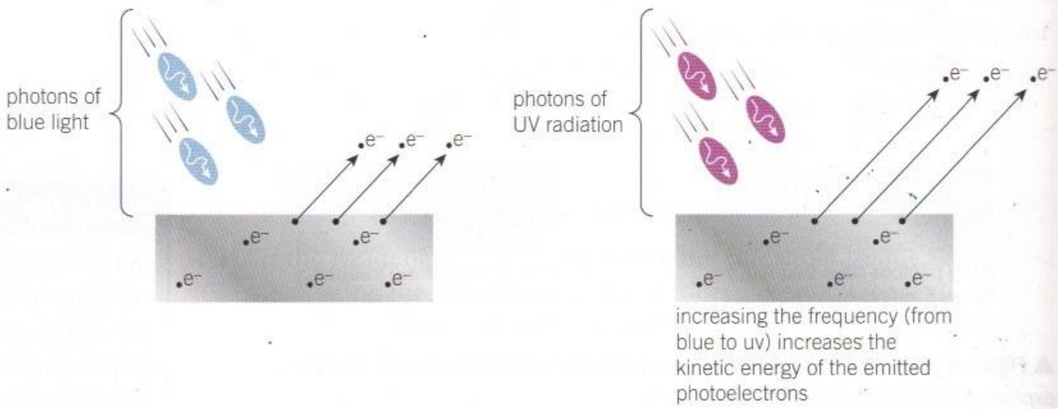
▲ **Figure 5** *Intense radiation means a higher rate of photons landing and so a higher rate of electrons escaping*

Study tip

Remember the three key ideas about the photoelectric effect: $E \propto f$ for photons, it is a one-to-one interaction (one photon causes the emission of one surface electron), and brighter light means a greater rate of photons incident on the metal.

on this in Topic 13.3, Einstein's photoelectric effect equation). At a given frequency all photons have the same amount of energy, and the metal a specific work function, so there is a maximum value of kinetic energy that any emitted photoelectrons can have. Increasing the intensity results in a greater rate of emission, but none of the emitted photoelectrons will move any faster.

The only way to increase the maximum kinetic energy of the emitted photoelectrons is to increase the frequency of the radiation. In this case each photon has more energy and so each electron has more kinetic energy after it has been freed from the metal.



▲ **Figure 6** *Increasing the frequency results in the emission of photoelectrons with a higher kinetic energy (as there is more energy to spare after the electrons have been freed from the metal)*

Summary questions

1 Describe what would happen to an uncharged gold-leaf electroscope if its top surface were to come into contact with a positive electrode. *(2 marks)*

2 If a particular metal had a threshold frequency in the red part of the visible spectrum, explain what would happen to the metal if radiation was incident on its surface from:
   - **a** the infrared part of the spectrum; *(2 marks)*
   - **b** the blue part of the visible spectrum. *(1 mark)*

3 Explain why the maximum kinetic energy of photoelectrons emitted during the photoelectric effect depends on the frequency of the incident radiation. *(3 marks)*

4 The threshold wavelength λ_0 is the *longest* wavelength that will give rise to the photoelectric effect. Derive an expression for λ_0 in terms of the threshold frequency f_0. *(2 marks)*

5 State and explain the effect of quadrupling the intensity of incident radiation (keeping the frequency constant) on a metal surface emitting photoelectrons. *(3 marks)*