

### 1.3 The Photoelectric Effect

The Nobel Prize in Physics, 1921: awarded to Albert Einstein (figure 3),

*for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect.*

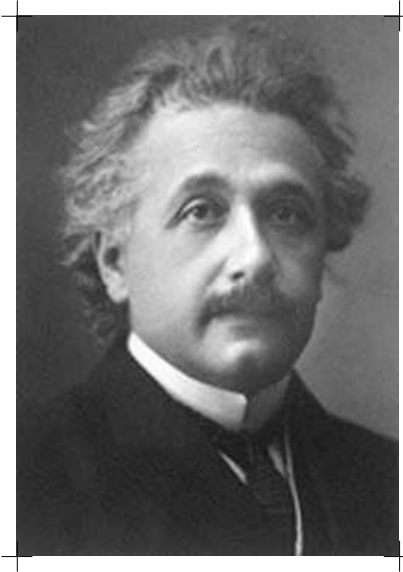


Figure 3: Albert Einstein (1879–1955): winner of Nobel Prize for Physics in 1921.

1887: Heinrich Hertz observed experimentally that electrons were emitted when light was shone upon a clean metal plate in a vacuum.

Such an emission of electrons from a metal surface is referred to as the **photoelectric effect**.

Let us create a similar experiment to that of Hertz. Consider figure 4:

- Monochromatic light illuminates a plate P in an evacuated enclosure.
- A battery maintains a potential difference (i.e. voltage) between the plate and a metal cylinder C which collects the emitted photoelectrons.
- When the collector is positively charged with respect to the plate, the photoelectrons are attracted to it, and the ammeter registers a **current** of these photoelectrons.

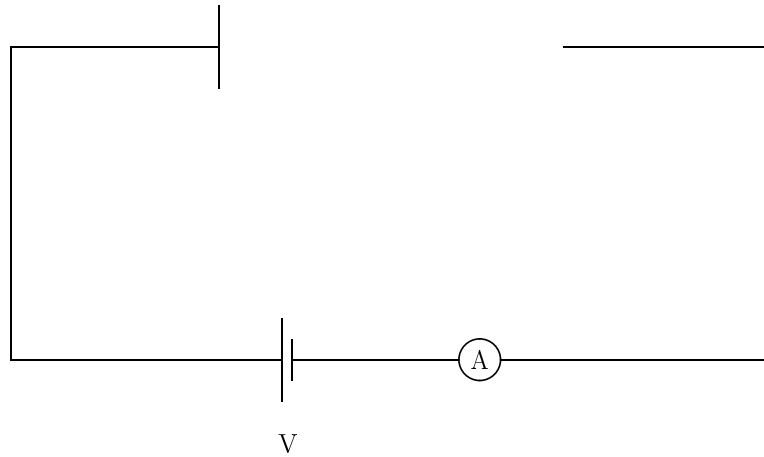


Figure 4: Experimental schematic of the photoelectric effect.

Suppose that we increase the potential difference. What happens to the photoelectron current? Consider figure 5: we find that

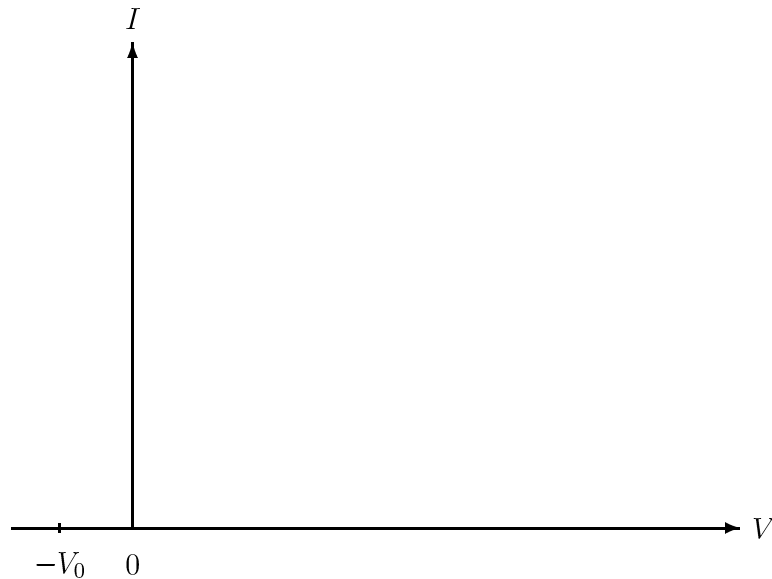


Figure 5: I-V graph for the photoelectric effect.

- Varying the potential difference has **no** effect on the current.
- The maximum current is determined by the intensity of the incident radiation.

Suppose that we reverse the polarity of the battery (corresponds to  $V < 0$  in figure 5):

- The photoelectrons are repelled, and only the most energetic ones reach C, creating a current.

- When the retarding potential difference reaches a critical value, the current drops to zero – at this so-called **stopping potential**, or **cut-off voltage**,  $V_0$ , only those photoelectrons with the maximum kinetic energy reach C.

Let us summarise the important experimental results:

- A current of photoelectrons is seen as soon as the light is switched on.
- The maximum current is proportional to the intensity of the light.
- The voltage/potential difference corresponding to the stopping potential is the same for a particular metal at **any** light intensity.
- The stopping potential varies with the frequency of the radiation. For example, for three different metals A, B and C, figure 6 shows the  $V_0$  against  $\nu$  graph.
  - For any metal, there is a **cut-off** frequency for which  $V_0 = 0$ .
  - This cut-off frequency is the same for a particular metal at any intensity.

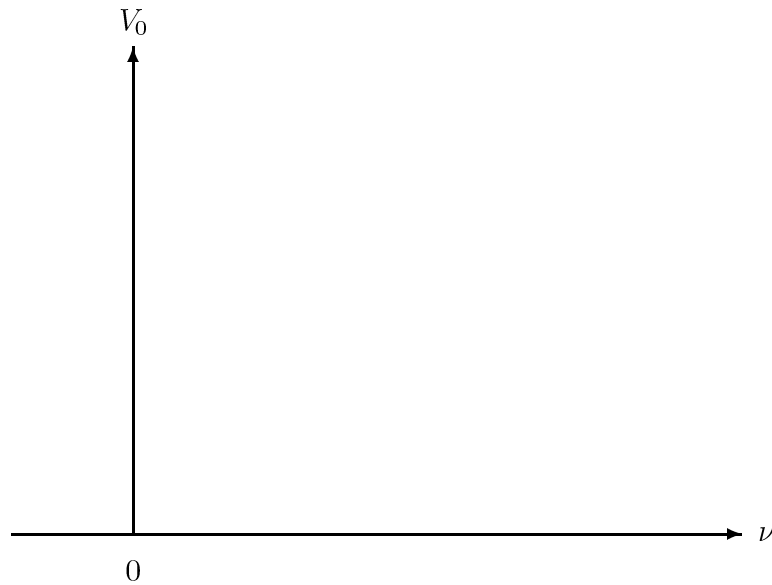


Figure 6: Stopping voltage–frequency curves for different metal surfaces.

So can the above results be explained classically?

### Time Delay

From wave theory, the energy of the incident light wave must be "soaked up" by the electrons in the surface of the metal. The effective area from which the electrons soak up this energy cannot be much larger than the cross section of the atom.

- Suppose there are  $10^{19}$  atoms on the surface of the metal plate.
- Suppose the intensity of the light is  $10^{-6} \text{ W m}^{-2}$ .
- So  $10^{19}$  atoms get  $10^{-6} \text{ W m}^{-2}$  of light.
- So 1 atom gets  $10^{-25} \text{ W m}^{-2}$  of light.
- The sort of energy the electron must absorb to escape from the surface of the metal is typically of magnitude  $10^{-19} \text{ J}$ .
- Hence, for our electron to absorb  $10^{-19} \text{ J}$  of energy takes a time

$$\frac{10^{-19}}{10^{-25}} = 10^6 \text{ s} \approx 11.6 \text{ days} .$$

- A time delay of 11.6 days is most definitely observable!

## Intensity

In wave theory, if the intensity of a beam of light is increased, then the magnitude of the oscillating electric field vector  $\underline{E}$  increases.

- The force that the incident beam exerts on an electron is  $e\underline{E}$  (where  $e$  is the electronic charge  $e = 1.6 \times 10^{-19} \text{ C}$ ).
- As the intensity of the light is increased, we expect that the energy of the ejected photoelectrons increases.
- Hence, since the photoelectrons are more energetic, the greater the stopping potential needs to be to stop them.
- Therefore, we expect that the stopping potential  $V_0$  should vary with the light intensity.
- However, as seen in the current–potential difference graph (figure 5), this is not the case.

## Frequency

According to the wave theory of light, the photoelectric effect should occur at any frequency of the incident light, provided that the light is intense enough.

- However, as the stopping potential–frequency figure 6 shows, there is a characteristic "cut-off", below which the photoelectric effect does not occur, no matter how intense the light.

So each of the experimental observations totally contradicts classical physics. What is going on?

1905: Einstein, using Planck's idea of energy quanta, was able to explain the photoelectric effect theoretically. He postulated that the energy associated with a beam of light of frequency  $\nu$  is itself quantised as

$$E = h\nu , \tag{1.33}$$

i.e. we think of the light falling upon the metal plate as being composed of a collection of discrete energy packets or quanta.

The name **photons** was given to these light quanta.

Let us explain the experimental observations of the photoelectric effect in terms of the **photon model**:

### **Time Delay**

In the photon model, it is postulated that a photon of light, on colliding with an electron on the metal surface, gives up **all** of its energy to the electron, causing it to undergo photoemission **instantaneously**.

- Hence, there is no time delay.

### **Intensity**

In the photon model, doubling the intensity of light simply **doubles** the number of photons.

- The energy of the individual photons is **not** affected.
- Therefore, the maximum energy that a photoelectron can obtain from a photon is **unchanged** – the stopping potential will remain the same.
- Increasing the intensity increases the number of photoelectrons (i.e. the photocurrent).

### **Frequency**

In the photon model, the conduction electrons are held within the metal target by an electric field (force  $e\mathbf{E}$ ).

- To be ejected, an electron must obtain a minimum amount of energy from the photon to be able to overcome the forces binding it to the metal surface.
- This minimum energy is called the **work function**,  $\phi$  – i.e. it is the minimum energy required to eject an electron from the surface of a material.
- Therefore, for a photon of energy  $E = h\nu$ ,

If  $h\nu > \phi$  – the photoelectric effect occurs.

If  $h\nu < \phi$  – the photoelectric effect does not occur.

- Hence, we have a **cut-off** or **threshold frequency**,  $\nu_0$ , which determines whether or not the photoelectric effect can occur.
- So the work function can be expressed as

$$\phi = h\nu_0 . \tag{1.34}$$

So we see that the experimental observations of the photoelectric effect can be explained within the photon model of light.

If the photoelectric effect occurs, the energy of the photon must be greater than, or equal to, the work function. Any remaining energy is used as kinetic energy  $K$  by the photoelectron; i.e. we have

$$h\nu = \phi + K , \tag{1.35}$$

or, if  $v$  is the speed of the photoelectron, and its mass is  $m$ ,

$$h\nu = \phi + \frac{1}{2}mv^2 . \tag{1.36}$$

At the stopping potential  $V_0$ , only electrons with the maximum kinetic energy can reach the detector, and we have

$$\frac{1}{2}mv_{\max}^2 = eV_0 . \tag{1.37}$$

So using (1.37) in (1.36) gives

$$h\nu = \phi + eV_0 , \tag{1.38}$$

or

$$V_0 = \frac{h}{e} \nu - \frac{\phi}{e}. \quad (1.39)$$

This is an equation of the form  $y = mx + c$ , and so plotting  $V_0$  against  $\nu$ , we get the straight-line graph shown in figure 7.

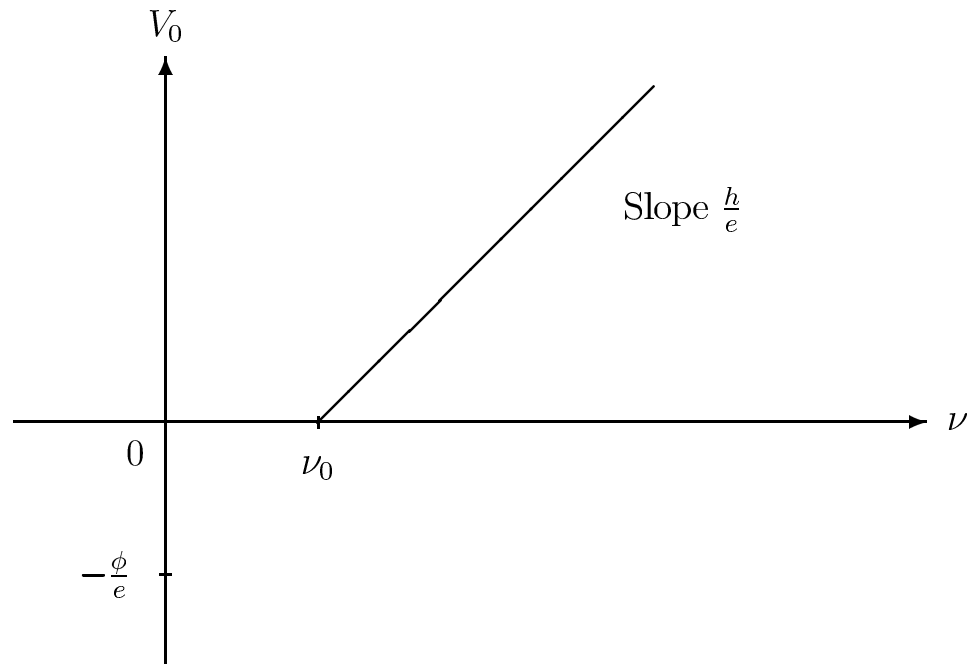


Figure 7: Stopping voltage–frequency curves for a surface.

- Since the gradient of the graph is  $h/e$ , i.e. a ratio of two fundamental physical constants, all metals will have the same **gradient**; only the values of  $\nu_0$  and  $\phi/e$  will vary.

We can summarise the photoelectric effect with figure 8.

**Note:** theoretically, an electron from deeper layers within the metal could be ejected. The energy required to do this would be the energy required to promote the electron to the surface, and then the energy required to eject it from the surface.

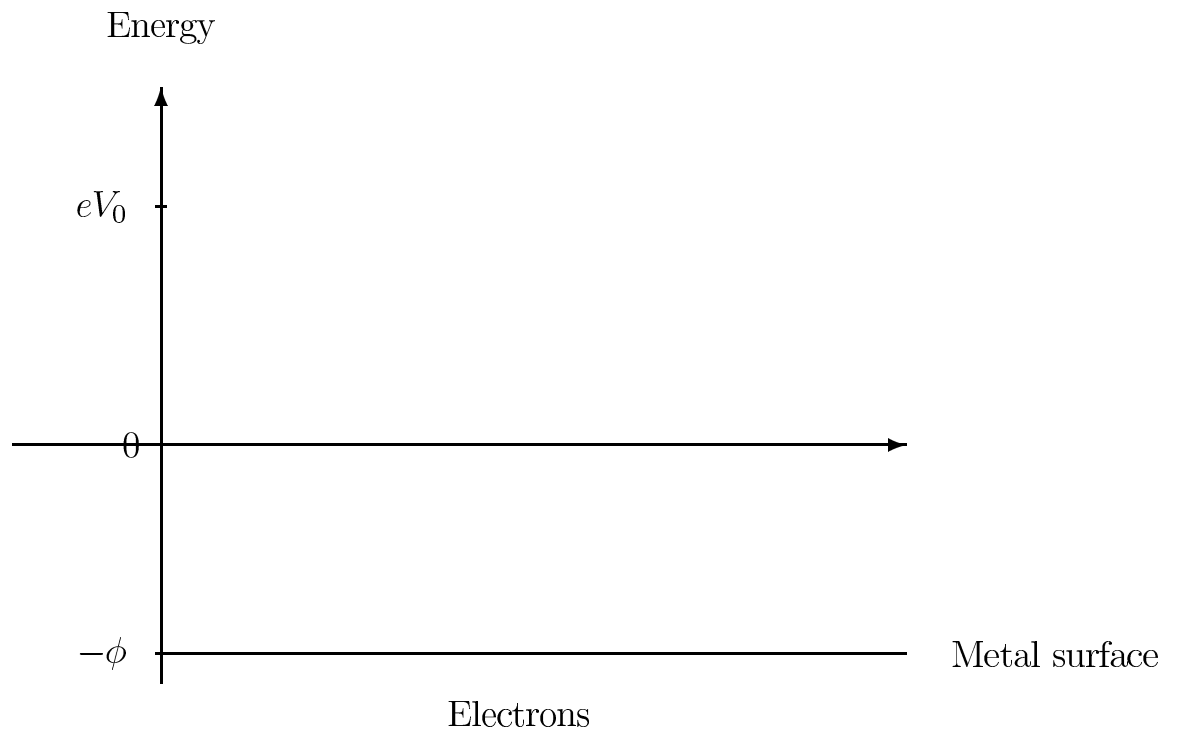


Figure 8: Energy diagram of the photoelectric effect.