The Photoelectric Effect

Hertz and Hallwachs in 1887, and Lenard in 1900, performed experiments to show that **surfaces will emit negatively charged particles when illuminated by electromagnetic radiation *above* a particular frequency.** Since J.J. Thompson's discovery in 1897, these particles are known as **electrons**, possibly the most fundamental unit of readily movable electric charge. The interaction of light and electricity in this way is called the **Photoelectric Effect.** The *classical* wave model of radiation suggests that more intense radiation would always result in greater numbers of electrons, since the amount of energy absorbed by a surface is increased in proportion to the square of the amplitude of the radiation, and also frequency. However, careful experiments (the most famous being by Millikan in 1914) showed that *no electrons are emitted*, regardless of radiation intensity, *if the radiation frequency is below a particular threshold.* Albert Einstein explained this effect by proposing that light moves in discrete 'energy quanta' i.e. *particles* called **photons**. He applied 'quantum' ideas first developed by Max Planck to describe the spectrum of radiation emitted from hot bodies, such as the Sun.

Albert Einstein
1879 – 1955
Nobel Prize 1921

$$E = hf$$

E is the energy of a photon, which has an associated wave representation of frequency f.
h is **Planck's constant** $h = 6.62607004 \times 10^{-34}\ \mathrm{m^2\ kgs^{-1}}$

In Einstein's model, **only the frequency of the radiation effects the energy of a photon**. A greater radiation intensity just means 'more photons.' Einstein proposed that electrons can be liberated from a surface if the photon energy exceeds a certain amount of work associated with the electromagnetic binding of the electrons within the atoms which comprise the surface. Once the photon energy is above this limit, the excess energy is converted into the kinetic energy of the electron. Experimental verification of this model not only galvanized the *quantum revolution* (i.e. there really are such discrete things as photons, and these came in discrete packets of energy) but also helped consolidate the **atomic theory of matter**, since the photoelectric effect is only really understandable if treated as an atomic scale phenomenon.

Material	Work function /eV
Silver (Ag)	4.3
Aluminium (Al)	4.3
Gold (Au)	5.1
Copper (Cu)	4.7
Tin (Sn)	4.4
Lead (Pb)	4.3
Tungsten (W)	4.5
Nickel (Ni)	4.6
Sodium (Na)	2.4

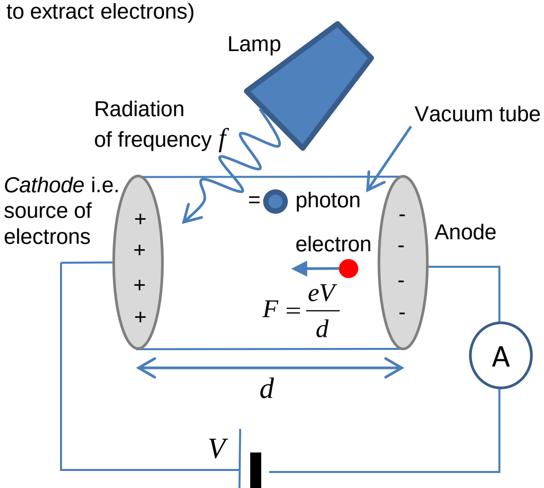
Robert Millikan
1868-1953
Nobel Prize 1923

$$E = hf - W$$

Maximum kinetic energy of emitted electrons (W is the *minimum* energy to extract electrons)

Photon energy

'Work function' or 'binding energy' of electron in the surface.



Applied voltage (which can be varied and reversed)

The photoelectric effect can be used to calculate *both* Planck's constant and the work function of the material, assuming the charge on the electron (e) is known.

Radiation from a lamp is increased in frequency until electrons are emitted from a metal plate in an evacuated tube. This plate is part of a pair in a circuit, and both are charged (in opposite senses) by an electrical power supply of variable voltage.

A voltage is applied such that **the electric field between the plates is sufficient to zero the current caused by the migration of electrons from one plate to another.** This occurs when

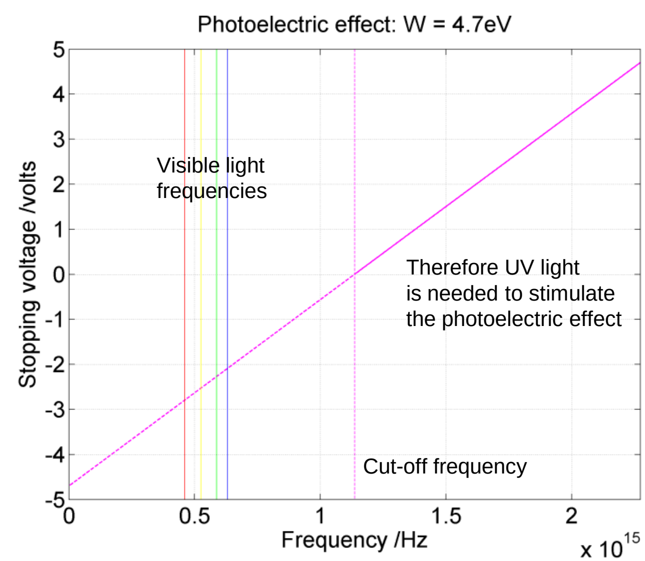
$$eV = E = hf - W \quad \therefore V = \frac{h}{e} f - \frac{W}{e}$$

i.e. the work done by the electric field on the electron equates to its *maximum* kinetic energy at the point of emission. A graph of 'stopping voltage' vs radiation frequency should therefore be *linear*, with gradient h/e and V intercept $-W/e$

Note the V intercept will need to be *extrapolated*, as no current will flow when the frequency is less than the cut-off frequency

$$f_{cutoff} = \frac{W}{h}$$

Above the cut-off frequency, one should experience a **rise in current** in proportion to the intensity of light from the lamp. However, the **stopping voltage should be *independent* of the intensity of the light**, as this only depends on the frequency of the light and the work function of the surface.



$e = 1.6021766208(98) \times 10^{-19}\,\mathrm{C}$ electron charge