Photons

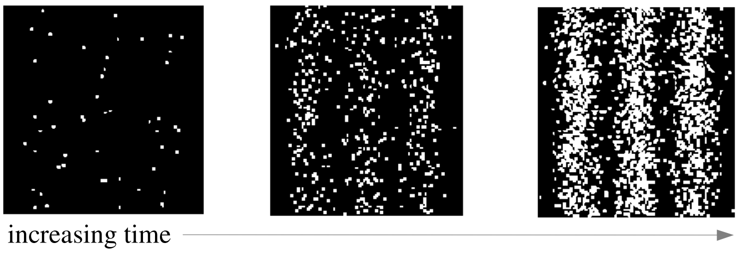
Photons

There are some situations in which light's behaviour cannot be explained by the wave theory of light. For example, a photographic film exposed to an extremely low intensity light source will show an increasing number of dots over time. These dots are not seen in everyday life because the pattern is changing too fast for human eyes to detect.

Light is bundled in discrete packets called photons, which act like particles when light interacts with matter. These are also referred to as *quanta* of light (a single photon is one quantum of light). Each dot on an image corresponds to one photon which hit the film.
The energy of the photons is given by $E = hf$ where E is the energy, f is the frequency and h is Planck's constant.

Photons also have momentum, even though they have no mass. The momentum of a photon is $p = \frac{h}{\lambda}$

This effect can even be observed during two-slit interference, as shown below.



The Photoelectric Effect

When a photon of light with a high enough frequency (and therefore energy) strikes matter (usually a metal), it may be absorbed and cause an electron to be emitted. This is called the ‘photoelectric effect’. The minimum frequency f_o at which electrons are emitted varies with the type of material, and is called the ‘threshold frequency’.

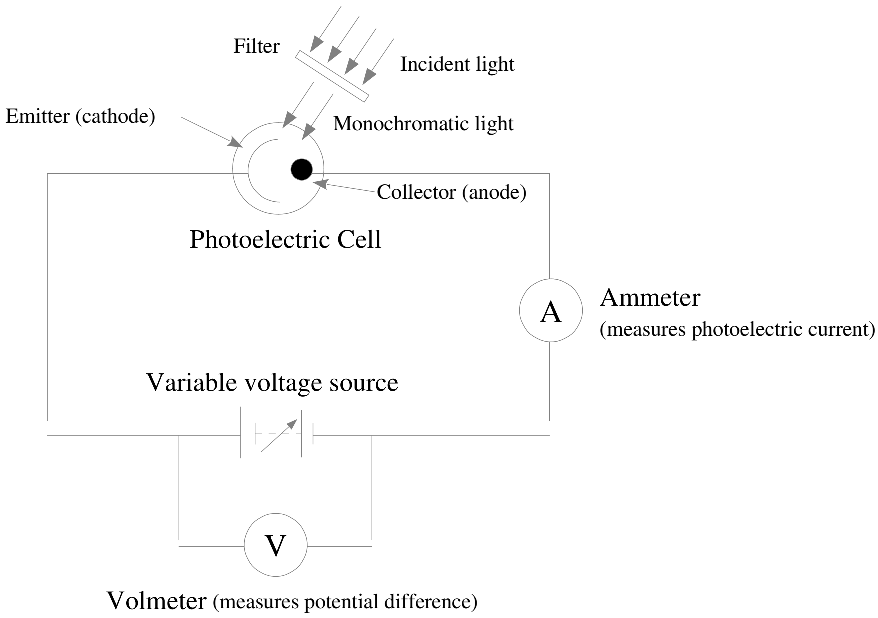
Note that the energy of the emitted electron is not dependent on the number of photons (intensity of light) hitting the surface. The intensity of the light determines the *number* of electrons emitted.
Every surface has a minimum energy required to remove an electron from it. This is called the 'work function' W of the surface, and is related to the threshold frequency by $W = hf_o$.

A photoelectric cell (or photoelectric tube) produces current by the photoelectric effect. It is usually an evacuated transparent container containing a hollow cathode (which receives the light and emits electrons if the frequency of light is high enough) and a collecting anode.

When connected to a circuit, the photoelectric cell can be used as a light detector since light shining on the cathode cathode will cause electrons to be collected by the anode and move through the circuit as current.

Investigating the Photoelectric Effect

By setting up equipment as shown below and following the procedure, the relationship between maximum kinetic energy of emitted electrons and the frequency of light incident on a cathode can be experimentally determined. The experiment relies on a variable voltage source being set up to oppose the direction of emitted electron flow.

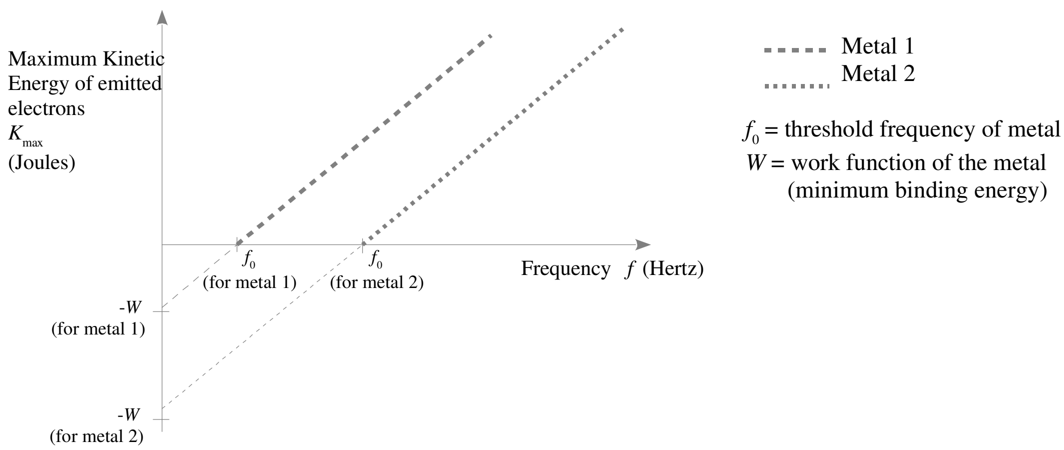


Procedure:

1. Place a filter over the light source so that the light reaching the photoelectric cell is monochromatic.
2. Set the variable voltage source to zero (so the potential difference between cathode and anode is zero to start with)
3. Allow the light to shine on the photoelectric cell. If the frequency of light is high enough, a current will be produced.
4. Increase the voltage. This will increase the potential difference between the cathode and anode, which will do work on the emitted electrons. Since the experiment has been set up so that the voltage opposes the electron direction of motion, this increased voltage therefore should lead to a reduced current.
5. Continue to increase the voltage until the current is reduced to zero; this is called the stopping voltage. The work done stops even the most energetic electrons, so $K_{max} = eV_s$ (V_s is the stopping voltage and e is the charge of an electron. The formula is derived from $W = q\Delta V$ where W is the work done by the stopping voltage).
6. Repeat steps 1-5 for various filters (frequencies of light) and/or different cathode metals.

Steps 1-6 can also be repeated for different intensities of light if desired. Increasing the intensity will increase the current in the circuit (whenever it is flowing) but the stopping voltage (and therefore equation and graph as above) will not change.

Maximum Kinetic Energy against Frequency



The relationship between K_{max} and f:

The slope of the graph is h (Planck's constant) **for every metal** used as the cathode.
The K_{max} intercept is always the negative of the work function (the minimum energy binding an electron to the metal).
Incident photons with energy between zero and the threshold frequency are **not producing electrons** – the frequency must be high enough to impart the work function and then some more energy.

Since the slope is h and the vertical intercept is $-W$, the equation is $K_{max} = hf - W$

Observations:

1. The maximum kinetic energy K_{max} of emitted electrons depends on the **frequency** of light and the **metal used**. Greater frequency leads to greater maximum kinetic energy.
2. There is a minimum 'threshold' frequency f_0 of light required to produce electrons for each particular metal.
3. Increasing the intensity increases the number of electrons emitted but does not alter the maximum kinetic energy of the electrons.
4. Electrons are emitted instantaneously (as soon as the light hits the cathode metal).

Einstein's Explanation

In order to explain the photoelectric effect, Einstein developed the following concepts:

- A single photon passes its energy to a single electron
  (One photon can't give energy to multiple electrons)
- A photon transfers all **or** none of its energy to an electron
  (A photon can't give a portion of its energy)
- An electron can only absorb the energy of one photon at a time
  (Two photons can't transfer energy to the same electron at once)

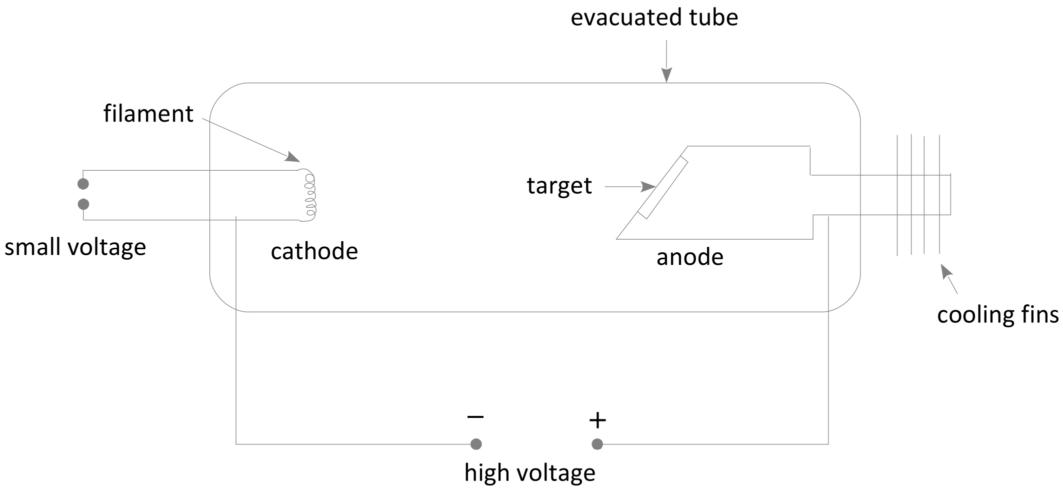
These concepts explain the properties of the photoelectric effect seen on the previous page.

1. Greater frequency leads to greater **maximum** kinetic energy, but the electrons may have any kinetic energy within the range less than this.
   Reason: Electrons within a metal are bound by different amounts of energy (the work function is the **minimum** energy required to release electrons). Since a photon imparts all its energy, electrons with less binding will have more kinetic energy.
2. There is a minimum 'threshold' frequency f_0 for each particular metal
   Reason: A photon transfers all or none of its energy, which is dependent on frequency. Frequencies high enough (above threshold) to overcome the binding energy will transfer all their energy. Photons with energy less than the work function will not cause electrons to be emitted, and impart no energy at all.
3. Increasing the intensity increases **only** the number of electrons emitted
   Reason: Intensity of light is the number of photons. Each photon can only release one electron, and one electron can only be released by one photon at a time.
4. Electrons are emitted instantaneously
   Reason: As soon as a photon collides with the metal, if it has enough energy it will instantly pass on its energy therefore instantly releasing an electron.

X-rays

Light colliding with a target can cause electrons to be emitted, but it works the other way as well. X-rays photons are produced by hitting a metal target with electrons which have been accelerated to high energies. The deceleration of the electrons hitting the surface produces electromagnetic radiation ("braking radiation").

The main components of an X-ray tube are the filament, target, high voltage supply, evacuated tube, and means of cooling the target. An example X-ray device is shown below:



The filament is heated allowing electrons to leave it, and a high potential difference is placed between the cathode and the anode which causes the electrons to be accelerated towards the anode. On striking the anode, the electrons decelerate and some of the kinetic energy is converted into X-ray photons.

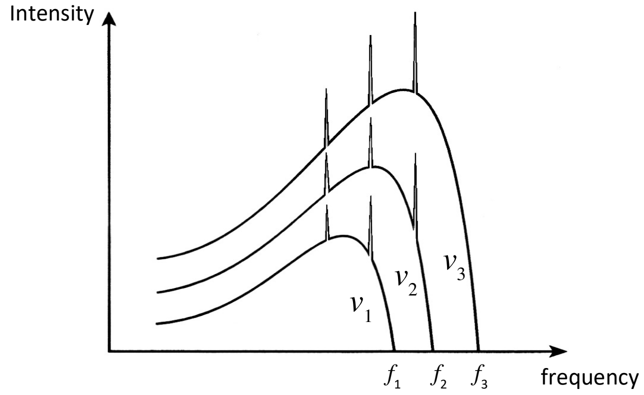
Only about 1% of the kinetic energy becomes photons, the rest is converted into heat. This means that the X-ray device must be designed so that the anode does not melt – often the anode is linked to a cooling fin by copper (a good conductor of heat) to disperse the heat.

The target material needs to be strong enough to withstand the constant bombardment by electrons. A common choice is tungsten, which is hard and has a high melting point.

Each X-ray photon is emitted with a frequency from a continuous range of possible frequencies, since the frequency depends on the amount of energy the electron loses as it decelerates. Electrons that pass into the metal without going close to a nucleus will not brake very much and therefore the photons they emit will have lower frequencies. Electrons that pass fairly close to a nucleus but do not hit it will produce medium frequency photons, and electrons that *directly hit* a nucleus will lose all their energy, producing the maximum frequency photons for that electron velocity and metal.

If the electrons are being accelerated across a sufficient potential difference, particular frequencies of photons will start to appear more often than others. These are 'characteristic' of any given metal, as they depend on the properties of the metal atoms. On a graph of photon intensity for each frequency, these appear as peaks.

Graph of X-Ray *photon intensity* against *frequency* for three different *electron velocities*



Note that the faster electrons are going when they hit the metal, the higher frequency and intensity the photons will be. The equation $f_{max} = \frac{e\Delta V}{h}$ can be derived for the maximum frequency of X-ray photons, where *ΔV* is the potential difference across the X-ray tube used to accelerate the electrons towards the target.

Consider max energy photons:

$E = hf \quad \therefore E_{max} = hf_{max}$

Electrons have energy K, and max energy photons are when all energy from an electron is converted into photon, so when $E_{max} = K$

$\therefore K = hf_{max}$

$\therefore f_{max} = \frac{K}{h}$

K is equal to the work done to accelerate the electrons, so K=$W = q\Delta V$

$K = q\Delta V = e\Delta V \quad \{\text{since charge on an electron is } e = 1.60\times10^{-19}\}$

$\therefore f_{max} = \frac{e\Delta V}{h}$

The Use of X-rays in Medicine

X-rays are often used in medicine to make images of because bones and other details inside a body because they pass through softer tissue but are absorbed and scattered by other materials. The amount X-rays are scattered and absorbed rather than passing through is called *attenuation*. X-rays are attenuated much more by bone and much less by skin and muscle.

The amount of attenuation caused by any given substance depends on the following:

- density (more dense means more attenuation)
- thickness (the more the rays must pass through, the more they are attenuated)
- average atomic number (the bigger the atoms, the more the attenuation)

Any given frequency (and therefore energy) of X-ray will only travel a certain distance through any particular material. This ability to travel is called the *penetrating power* or *hardness* of the X-ray.

- more attenuation means less penetrating power
- greater frequency (higher energy) means greater penetrating power and less attenuation

The maximum frequency (and therefore hardness) of X-rays depends on the potential difference across the X-ray tube, since greater potential difference leads to higher kinetic energy of electrons and therefore greater frequency X-rays.

When X-ray photographs are taken, it is important to minimise the exposure time, so that the image is not blurred. In order to have a short exposure time and still a clear (well constrasted) image, the intensity of X-rays (number of photons) must be increased. This is achieved by increasing the tube current, since the current in the filament influences the number of electrons released.