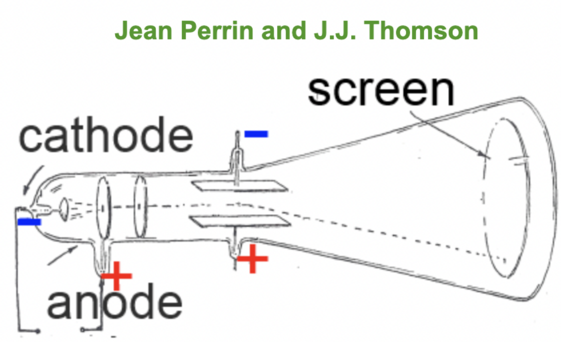
The Electron

1 The Discovery of the Electron

1.1 Cathode Rays

We are now approaching the dicoveries made around the turn of the 20th century. At this time, electronics were known of, observed and used (the likes of Tesla, Faraday and Maxwell were well known by now), but the actual physical phenomena were not well understood. Physicists had observed charge, but had yet to answer the question, what is a charge, physically?

In 1857, some scientists were investigating the conductivity of gas. Gases are not usually conductive, but at very high pressures they can ionise, and the ions can conduct electricity. They set up the following apparatus:



It was noticed that of the gas pressure inside a glass tube was reduced to a near vaccuum, the glass walls of the tube fluoresced. They called this fluorescence **cathode rays**.

Jean Perrin (France) was the first to use this apparatus to prove that cathode rays are charge. If you connect an electroscope to the right end of the cathode ray tube, and deflect the cathode ray beam toward the electroscope, you will see that the electroscope leaves diverge. This proves that the cathode ray consists of beams of charge.

J.J. Thompson continued this work by showing that electrons have a negative charge. He showed that you can deflect a cathode ray using a magnetic field. The direction in which it moves shows that the charge is negative.

He also showed that the beam was deflected by a fixed amount each time. This proves that all electrons have the same mass and charge.

The idea that there was a natural unit of electricity in each atom was suggested by an Irishman, George Stoney. He was the first person to coin the term 'electron'.

1.2 The Electron-Volt

If you place an electron in an electric field, it will move; it gains kinetic energy. The stronger the electric field, the more energy it gains. If you accelerate an electron across a potetial of 1V, you will find that it gains $1.6x10^{-19}J$. For convenience, we define $1.6x10^{-19}J$ as one **electron-volt**, or 1eV. By extension, when the voltage is 1kV, the energy gained by the electron is 1keV. When the voltage is 1MV, the energy gained is 1MeV, and so on.

1.3 Millikan's Oil Drop

In 1909, American experimental physicist Robert Millikan invented a way to measure the exact charge on an electron, and simultaneously showed that the electron is the fundamental unit of charge. He set up a capacitor oriented horizontally. He sprayed a mist of oil drops into the space between the capacitors. You expect some oil drops to fall down due to gravity, but some will become ionised when sprayed (Millikan, in practice, ensured all of them were ionised using an x-ray). First, he measured the rate at which the droplets fell due to gravity, then passed a voltage between the plates such that the electromagnetic force pushing the ionised droplets up cancelled out gravity, so they were suspended between the capacitor plates. He knew the voltage, and the gravitational force (which must be equal to the electromagnetic force resulting from the charge). From this, he could calculate the charge on the electron.

By repeating this several times, he found that all of his answers were integer multiples of $1.6x10^{-19}J$. He concluded that this is the charge of one electron.

1.4 Thermionic Emission

If you heat a metal plate enough, it will emit electrons. This can be seen by setting up an anode and cathode in a vacuum tube in series with a voltmeter, with a hot filament near the cathode. In heating up the cathode, electrons will be emitted and cause a current to flow.

What's happening here is that once electrons gain enough thermal energy, they are able to break free of the bonds tying them to the metal. The higher the temperature of the metal, the more electrons will be emitted. The minimum amount of energy needed to break these bonds is called the **work function**. The work function will depend on the type of metal used.

1.5 How a cathode ray tube produces a picture

Consider the cathode ray tube apparatus in Section 1.1. A hot cathode will emit electrons by thermionic emission. These can be accelerated inside a vacuum tube towards an anode using a high voltage. At the end of the vacuum tube, there us a phosphorescent screen. When the electron beam hits the screen, it will form a spot of light.

In practice, you'll find that the light spot is fuzzy and out of focus, because the electrons will repel each other as they travel due to them all being negatively charged. You can make a focusing system by placing anodes in the neck of the tube to "push" them back together.

The electron beam can be deflected by an electric field or a magnetic field. If you have two fields at right angles to eachother, and you can control the magnitude of these fields, you can control the exact point at which the electron beam will strike the screen. We can use this to draw pictures.

2 Practical Applications

2.1 Electrocardiograph (ECG)

ECGs monitor the electric signals in the heart using electrodes attached to the body. Using the cathode ray tube we discussed earlier, doctors can print out graphs of the patients heart and use it to diagnose heart disease.

2.2 Oscilloscope

If you want to monitor an electrical signal (in labs, when building electronics ect), you can use a device called an oscilloscope. An oscilloscope contains a cathode ray tube, whose anodes are sensitive to the input voltage. The result is a cathode ray on the screen in teh shape of teh input waveform.

2.3 Television

A TV set is a cathode ray tube. An electron beam sweeps the screen at a rate too fast for the human eye to see. The input signal (the TV signal) varies the strength of the beam and changes the brightness of the screen. The fluorescence lasts for a short time before the electron beam moves down the screen again, allowing for what appears to be a moving image.

2.3.1 Colour TV

To add colour to TV images, the screen is made of lines of three different phosphors, which produce either red, green or blue light when struck by electrons. Now, we use three electron guns (one for each phosphor) exactly as we did with the black and white TV. The combination of the primary colour produces colour TV.

3 The Photoelectric Effect

3.1 The Photoelectric Effect

If you shine light onto a flat, polished metal surface, it will emit electrons. This discovery was made experimentally by Hertz and Hallwachs around the turn of the 20th century. We call the electrons emitted **photoelectrons**. In 1902, an experimental physicist named Lenard showed that:

- Photoelectrons are emitted when light of a suitable frequency falls on a metal surface.
- Below a certain frequency (threshold frequency), no electrons are emitted, regardless of the intensity of the light.
- The number of electrons emitted depends on the intensity of the light.
- The velocity (and therefore energy) of the photoelectrons depends only on the frequency of the light.

These findings caused anarchy in the physics community at the time. The concept that light was a wave had been widely accepted since Young's double slit experiment in 1801. But, if light was a wave, then an intense enough beam of light should emit electrons, regardless of it's frequency. The wave theory of light couldn't account for the fact that there was a clear threshold frequency.

3.2 Planck's Quantum Theory

Enter: Max Planck, one of the Giants of physics. He proposed that light energy was emitted not in waves or particles per se, but in small packets called 'quanta'. Each quantum contains a specific amount of energy which depends only on the frequency of the light. That is to say that the energy of one photon/ quantum of light is:

$E = hf$

where E is energy, f is frequency and h is Planck's constant.

3.3 Einstein's Photoelectric Law

Einstein developed all of these findings in 1905 (known as Einstein's Annus Mirabilis). He proposed that:

- Each photon travels closely concentrated in space.
- In photoelectric emission, a photon gives up all it's energy to one electron.

The minimum amount of energy a photon needs to be 'freed' from the metal is called it's work function. When a photon whose energy hf is greater than the work function strikes metal and 'gives' it's energy to an electron, the electron can escape the surface of the metal.

This is Einstein's Photoelectric Law:

$hf = \Phi + \frac{1}{2}mv^2$

This discovery won Einstein the Nobel Prize for Physics in 1922.