

The Photoelectric Effect

When light strikes a metal surface, it can liberate electrons from the metal surface. This is known as the photoelectric effect.

Many people are aware that Einstein was awarded the Nobel Prize in Physics in 1921 for his work on the photoelectric effect in 1905, but fewer people are aware of the work that preceded his explanation.

In 1887, Heinrich Hertz first observed the photoelectric effect when investigating “spark gap” radio receivers. The gap is formed between two metal electrodes. He noticed that, for the same voltage, a spark could jump across a larger gap if the apparatus was exposed to light, as opposed to being placed in a darkened box. Furthermore, he noticed that when illuminated through glass, the spark length was shorter than if through quartz (which does not block as much UV light as glass). We now know that this behaviour was due to electrons being photo-excited from the electrode surfaces, which then aid in spark formation when a voltage is applied. In the absence of light, the spark required a higher electric field to form.

In 1899, J.J. Thompson discovered the electron through observations of electric current emitted from the surface of a metal by the photoelectric effect.

In 1902, Philipp von Lenard made the observations of the photoelectric effect that challenged the conventional wisdom of the day, and prompted Einstein’s famous explanation of the effect. He noticed the kinetic energy of the emitted electrons was *independent of the intensity of the light*. This did not make sense. In classical wave theories of light, more intense sources contained more energy that would be transferred to the outgoing electrons, much as a higher amplitude wave at the beach contains more energy and can do more damage to the shoreline.

Enter Einstein. Max Planck had already proposed the quantum nature of light in 1901 to explain the blackbody spectrum emitted by an object at a given temperature. He did this as a matter of mathematical necessity, and not because he believed that light consisted of discrete quanta. Einstein, on the other hand, took this mathematical “trick”, and interpreted it literally: if light could only possess energies which were integer multiples of the Planck discrete energy, $E=hf$, perhaps light was actually *composed* of discrete packets (photons), each possessing an energy hf .

If this conjecture were true, it would have the following consequences in the photoelectric effect:

- 1) When a single photon interacts with a single electron, it can only transfer an energy, hf , to that electron. Therefore, if the light intensity is increased, the *number* of electrons emitted should increase, but the *kinetic energy* of an individual electron will be unchanged.
- 2) If the energy of an incident photon is less than the binding energy holding an electron in the surface of the metal, no electrons can be emitted, even if the intensity (number) of the incident photons is increased. In practice, we call this binding energy in a metal surface the *work function* (often noted as ϕ). Different metals have different work functions.
- 3) If a photon has an energy greater than the metal’s work function, an electron may be emitted, but the maximum kinetic energy the electron can possess after escaping the surface of the metal is equal to the photon energy, hf , minus the metal work function.

These predictions were in complete agreement with experiment, and Einstein’s interpretation of the photoelectric effect paved the way for modern quantum mechanics.

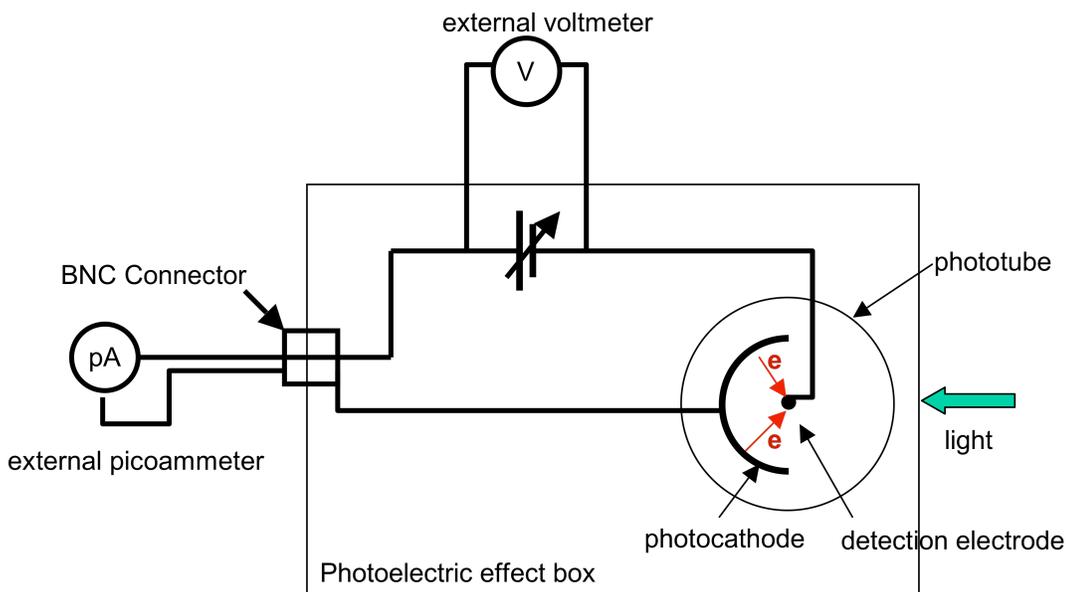
The photoelectric effect is widely used as an experimental tool today. There is an entire field of study, known as photoelectron spectroscopy, where monochromatic light sources, ranging from the visible to X-rays, are used to photoexcite electrons from a sample (metal, semiconductor or insulator). Energy distribution of the emitted electrons is measured. Because of the Einstein’s explanation of the photoelectric effect, the researcher can then work backwards, since the photon energy is known, and determine the binding energy that a detected electron originated from within the sample. This technique has been used to study the conduction electrons of high temperature superconductors, to understand the interactions at

interfaces between metals and semiconductors used in electronic devices, and to investigate chemical reactions that take place on the surfaces of metals (of great interest in the field of catalysis), to name a few.

Experiment

You have been provided with the apparatus necessary to investigate all of the above effects:

- 1) The following light sources will be used:
 - a. Light emitting diodes (LEDs) – provide relatively narrow-band emission (spectra available), and their intensity is easy to vary over a wide range. A variety of LEDs are available, covering the optical spectrum from red to violet. Use these to investigate the retarding (stopping) potential as a function of wavelength.
 - b. A mercury discharge lamp and power supply. This lamp produces light in the visible and UV parts of the spectrum. An optical filter is installed which isolates one narrow emission line at 436nm. Fixed intensity.
- 2) Photoelectric effect tube. This tube contains a metal surface, from which electrons are photoexcited, a detection electrode, from which the emitted electron current can be measured, and a retarding electrode, which is used to study the kinetic energy of the emitted electrons. The retarding electrode is a wire mesh placed between the metal surface and the detection electrode. If a positive voltage is placed on the retarding electrode, relative to the emitting metal surface, it will accelerate electrons toward the detection electrode, resulting in efficient electron collection. If, however, a negative voltage is placed on the retarding electrode, it will slow down the emitted electrons. If the negative voltage is large enough, such that the electronic charge times the retarding voltage is greater than or equal to the electrons' kinetic energy, the retarding voltage will prevent the electrons from reaching the detection electrode. Therefore, by analysing the detected current as a function of the retarding voltage, the electrons' kinetic energy can be determined.



Method

When performing the experiment, do not exceed 10mA drive current to the LEDs. Adjust the LED drive current so that the photocurrent is less than or equal to 30nA when the retarding potential is zero (without exceeding 10mA driver current!). Measure the detected photocurrent as a function of retarding voltage for each available light emitting diode. Note that when the retarding voltage is zero, the detected current is negative (electrons flowing from the detection electron, through the picoammeter, but when the retarding voltage is large (above the stopping potential), the current is *positive* and not zero, as expected. This occurs for the following reason: photoelectrons are also emitted from the detection electrode, as well as the photocathode! This results in a photo current in the opposite direction to that which we are trying to measure. Note that the retarding potential is actually an accelerating potential for electrons emitted from the detection electrode. To minimize this error, the manufacturer of the tube makes the cross sectional area of the detection electrode much smaller than the photocathode, so that less light strikes it. Make sure that you take enough data points above the retarding voltage to characterize this reverse current, so that it can be subtracted from the data!

When measuring the photocurrent as a function of retarding voltage, you are interested in two things: The stopping potential (the minimum retarding voltage which blocks all of the photocurrent), and the shape of the photocurrent vs retarding voltage curve, particularly in the near the stopping potential.

We know that the maximum kinetic energy of an emitted electron is equal to the photon energy minus the photocathode's "work function", and that the stopping potential is equal the maximum kinetic energy...

$$KE_{\max} = eV_{\text{stop}} = E_{\text{photon}} - \phi = \frac{hc}{\lambda} - \phi$$

Therefore, we can determine the value of Planck's constant (in eV·s) if we plot V_{stop} as a function of c/λ , and determine the slope. We can also determine the workfunction of the photocathode from the intercept.

Repeat the measurements of photocurrent vs retarding voltage using the Hg lamp. Do the values of V_{stop} agree with the predictions from the fitted line above? If not, why?