

### The Photoelectric Effect

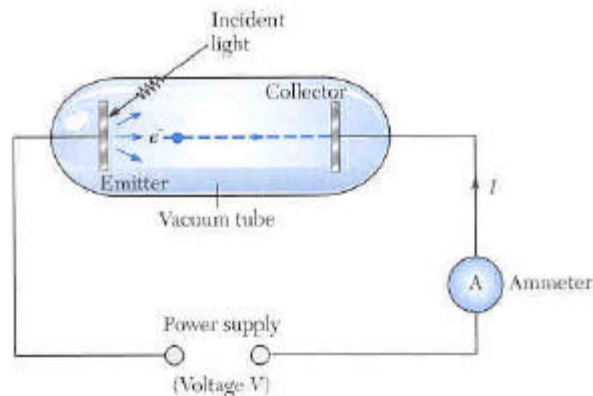
Hertz observed the photoelectric effect (spark assisted by light) while conducting experiments on the transmission and detection of electromagnetic waves.

Thomson established that the emitted particles induced by light are the same particles found in cathode rays. His method was to enclose the metallic surface to be exposed to radiation in a vacuum tube, in other words to make it the cathode in a cathode ray tube. The new feature was that electrons were to be ejected from the cathode by the radiation, rather than by the strong electric field used previously.

By this time, there was a plausible picture of what was going on. Atoms in the cathode contained electrons, which were shaken and caused to vibrate by the oscillating electric field of the incident radiation. Eventually some of them would be shaken loose, and would be ejected from the cathode. It is worthwhile considering carefully how the number and speed of electrons emitted would be expected to vary with the intensity and color of the incident radiation.

- (1) Increasing the intensity of radiation would shake the electrons more violently, so one would expect more to be emitted, and they would shoot out at greater speed, on average.
- (2) Increasing the frequency of the radiation would shake the electrons faster, so might cause the electrons to come out faster.
- (3) For very dim light, it would take some time for an electron to work up to a sufficient amplitude of vibration to shake loose.

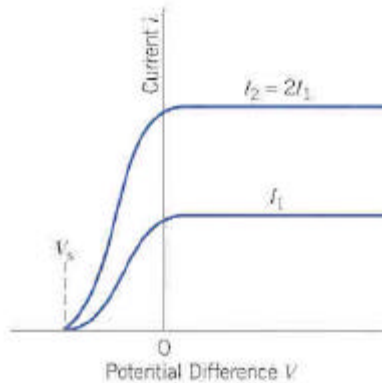
In 1902, Lenard studied how the energy of the emitted photoelectrons varied with the intensity of the light. The ejected electrons hit another metal plate, the collector, which was connected to the cathode by a wire with a sensitive ammeter, to measure the current produced by the illumination. To measure the energy of the ejected electrons, Lenard charged the collector plate negatively, to repel the electrons coming towards it. Thus, only electrons ejected with enough kinetic energy to get up this potential hill would



contribute to the current. Lenard discovered that there was a well-defined minimum voltage that stopped any electrons getting through, we'll call it the stopping potential  $V_s$ . This corresponds to

$$K_{\max} = eV_s$$

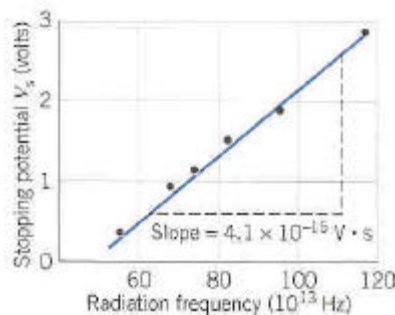
(1) To his surprise, he found that  $V_s$  did not depend at all on the intensity of the light! Doubling the light intensity doubled the number of electrons emitted, but did not affect the energies of the emitted electrons. The more powerful oscillating field ejected more electrons, but the maximum individual energy of the ejected electrons was the same as for the weaker field.



(2) Lenard also found that the maximum energy of the ejected electrons did depend on the color, higher frequency light caused electrons to be ejected with more energy. This was, however, a fairly qualitative conclusion --- the energy measurements were not very reproducible, because they were extremely sensitive to the condition of the surface, in particular its state of partial oxidation. Later (after Einstein's original paper), accurate experiments were conducted by Millikan and he found that

$$K_{\max} = h\nu - \phi$$

where  $h$  is the Planck constant (as suggested by Einstein) and  $\phi$  is the work function of the cathode material. The photoelectric effect does not occur at all if the frequency of the light source is below a certain value no matter how intense the light source is. This minimum frequency is called the cutoff frequency  $\nu_c$  and depends on the material of the cathode.



(3) It was found later that the first photoelectrons are emitted virtually instantaneously (within  $10^{-9}$  s) after the light source is turned on. The wave theory predicts a measurable time delay, so this result also disagrees with the wave theory.

### *Einstein's theory*

In 1905 Einstein gave a very simple interpretation of Lenard's results. He just assumed that: The incoming radiation should be thought of as energy quanta of  $e = h\nu$ , with  $\nu$  the frequency. In photoemission, one such quantum is absorbed by one electron.

Some of this energy is used to overcome the work function of the metal  $\phi$ . The rest is in the form of kinetic energy. However, electrons some distance into the material could also lose energy as they move towards the surface due to collisions inside the cathode. Thus, the most energetic electrons emitted will be those very close to the surface without undergoing collisions, and they will leave the cathode with kinetic energy

$$K_{\max} = h\nu - \phi$$

On cranking up the negative voltage on the collector plate until the current just stops, the highest kinetic energy electrons must have had energy  $eV_s$  on leaving the cathode. Thus,

$$K_{\max} = h\nu - \phi = eV_s$$

Thus Einstein's theory makes a very definite quantitative prediction: if the frequency of the incident light is varied, and  $V_s$  plotted as a function of frequency, the slope of the line should be  $h/e$ . It is also clear that there is a minimum light frequency for a given metal. There, the quantum of energy is equal to the work function. Light below that frequency, no matter how bright, will not cause photoemission. Millikan attempts to disprove Einstein's Theory and worked for ten years, until 1916, on the photoelectric effect. For all his efforts he found the results: Einstein is right and the Planck's constant can be measured by this method to within 0.5%.

### *Photon*

The energy packet of the electromagnetic radiation with  $e = h\nu$  is called a photon. It is massless and travels at speed of light  $c$ . It has a momentum  $p = e/c = h\nu/c = h/\lambda$ . A photon can be created or destroyed when radiation is emitted or absorbed. A photon can undergo collisions just like other particles.