Homework 24

Photoelectric effect. Particle nature of radiation

The experiments which indicated the particle nature of radiation were performed by Heinrich Hertz in 1886 and 1887. In these experiments energy of light was used to “rip” the electrons out of a metal electrode. This effect is called photoelectric effect. Hertz discovered that not only the intensity, but also the frequency of light is important for the photoelectric effect.

The apparatus used to study the photoelectric effect is shown in Figure 1.

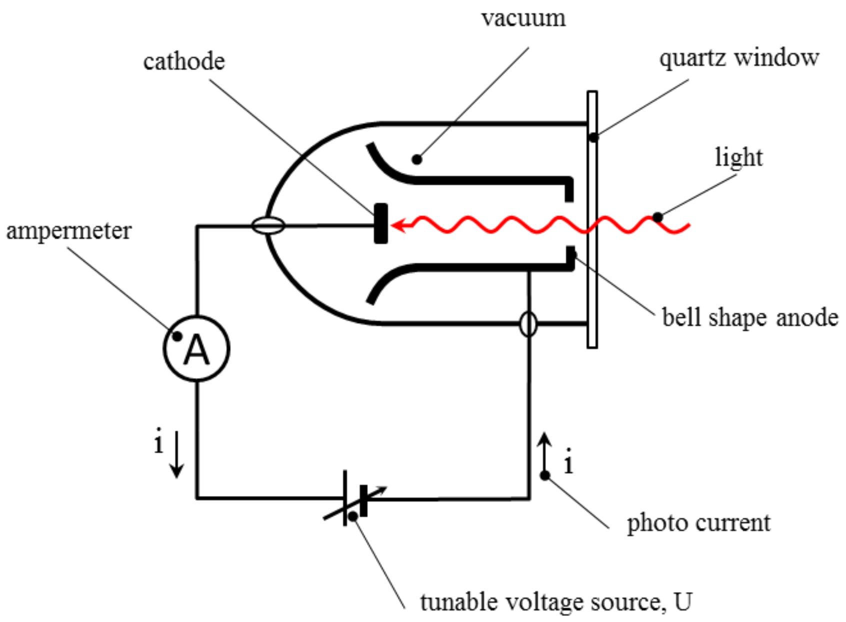

Figure 1. Heinrich Hertz apparatus for studying the photoelectric effect.

Two electrodes – a cathode and a bell shape anode were placed in an evacuated glass vessel with a quartz window. The device was connected in series with an ampermeter and a tunable voltage source.

When the cathode was exposed to light, the electrons were ripped off the cathode surface and electrical current was flowing through the circuit. Two plots of the electrical current as a function of the voltage U corresponding to different light intensities are shown in Figure 2.

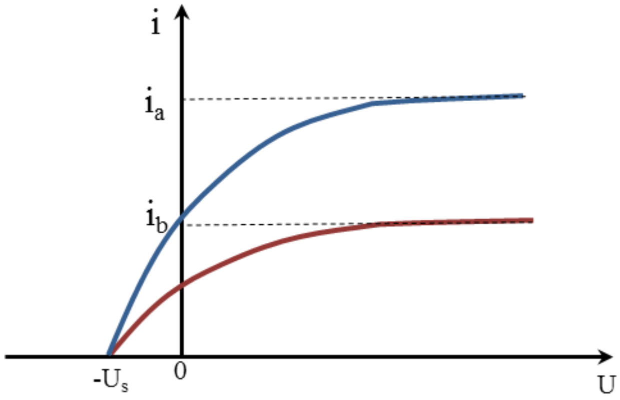

Figure 2. Electrical current i (photocurrent) as a function of the voltage U at different light intensities. i_a corresponds to higher light intensity.

As the voltage increases the photocurrent increases as well – this is understandable. But as the voltage is zero, there is still current in the circuit. We can explain that as well. The energy of the absorbed light is higher than it is needed just to rip off the electrons, so electrons, ejected from the cathode have certain kinetic energy (and, hence, the nonzero velocity) and are able to reach the anode without pulling force provided by the applied voltage. To stop the photo current we have to apply negative voltage, so the ejected electrons are accelerated back to the cathode and do not go to the anode. The negative voltage U_s at which the photocurrent is equal to zero is called stopping potential. The voltage U_s multiplied by the electron charge gives the kinetic energy K_{max} of the fastest electron, ejected from the cathode.

$$K_{max} = e \cdot U_s$$

It turns out that K_{max} does not depend on the intensity of light as we can see from Figure 2**. *This was totally surprising. As we remember the intensity of light is related to the light energy (the more intensity, the brighter light) and to the amplitude of the light wave. It seems that the more intense is the light the higher is the energy K_{max} of the ejected electrons. So at higher intensity we have to see the increase the absolute value of U_s.***

Another surprising result was obtained as the frequency (or wavelength) of the light was varied. The plot of the stopping potential as a function of the light frequency is shown in Figure 3.

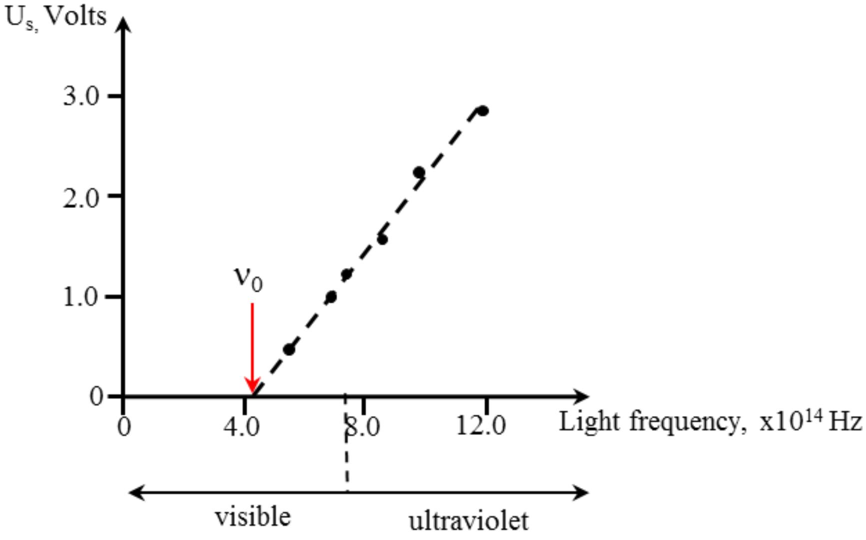

Figure 3. Stopping potential U_s as a function of the light frequency for a sodium cathode. The cutoff frequency is $4.39x10^{14}$Hz.

These data were reported in 1916 by an American physicist R.A. Millikan. R.A Millikan was the first native-born American awarded with Nobel Prize (He received it in 1923 for his fundamental work on determining the electron charge and the photo effect).

R. A. Millikan (1868-1953).

As we can see from Figure 3 the stopping potential and, hence K_{max} depends linearly on the light frequency and becomes zero at a certain light frequency which we call cutoff frequency.

These results did not agree with the classical theory. There were three major interpretation problems: the intensity problem, the frequency problem and the time delay problem.

<u>The intensity problem.</u>

We have already discussed it. The stopping potential does not depend on the intensity of light.

<u>The frequency problem.</u>

According to the classical wave theory, the photo effect should take place at any frequency, provided that the light have enough intensity to provide energy necessary to eject electrons from the cathode. However, the experiment demonstrates that for any cathode material there is a characteristic cutoff frequency below which no photo effect is observed.

The time delay problem.

Since the size of the atom is very small, each atom of the cathode absorbs a very small fraction of the light energy which is supposed to be distributed uniformly over the wave front (according to the wave theory). So, to get enough energy to leave the cathode, the electron has to accumulate it for a long time. This fact would lead to a time delay between the start moment of illumination and the onset of the photo current. In contrast to this conclusion, no detectable time delay was measured.

Problem:

A foil of potassium is placed at a distance of 3m from a point light source with a power of 1W. Assume that an ejected photoelectron is collecting the light energy from a circular area of the foil whose radius is one atomic radius ($\sim 5 \times 10^{-11}$m). If the energy required to remove an electron through the potassium surface is ~1.8eV, how long would it take for such a target to absorb this much energy from such a light source?