EP1108 - Photoelectric effect

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References

- Ref: S.H. Patil . Introduction to Modern Physics.
- https://nptel.ac.in/content/storage2/courses/122101002/downloads/lec-24.pdf NPTEL lecture notes
- https://www.opjsrgh.in/Content/2017/DUAL_NATURE_OF_MATTER_RADIATION.pdf
- http://galileo.phys.virginia.edu/classes/252/home.html For a historical perspective.

Any book on Modern physics should have a nice discussion on photoelectric effect.

Photon

Energy of a photon is given by

$\boxed{E = h\nu = \frac{hc}{\lambda}}$ where h is Planck's constant

c is the speed of light

ν is the frequency of electromagnetic radiation

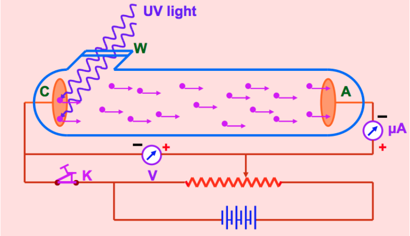
λ is the wavelength of electromagnetic radiation

One can also calculate momentum and "mass" of a photon, which we shall discuss after covering Special Relativity.

Energy of a photon does not change when one travels from one medium to another,

Photoelectric effect setup

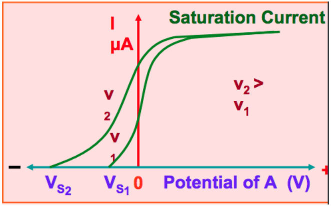
- Hertz found that when a beam of UV radiation from a mercury lamp impinges on the cathode of an alkali metal such as Na, K, Rb, Cs (with small work function) electrons (photo-electrons) are emitted.
- Number of electrons per second and their energies can be studied using an electric field.
- Number of electrons that escape from the cathode per second and are collected by the anode is given by i/e



Photoelectric effect setup

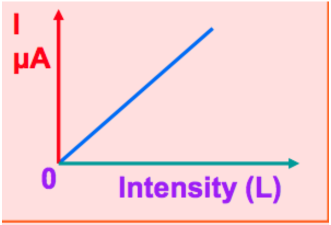
Photoelectric current vs voltage

- By making the anode more positive, with respect to the cathode, more electrons are attracted towards the anode and the photo-current increases.
- When the anode potential is such that all the emitted electrons reach the anode, any further increase in the anode voltage does not increase current any further
- If the voltage is reversed such that even the electrons which are ejected with the maximum kinetic energy cannot overcome the potential, the photo-current becomes zero.
- The reverse voltage which is just enough to stop the most energetic photoelectrons is called the stopping potential (V_s) where $K_{max} = eV_s$.



Photoelectric current vs Intensity

For a fixed frequency, the photoelectric current increases linearly with increase in intensity of incident light.



Photoelectric current vs Intensity

Puzzling Features of Photo-electric effect

- Photoelectrons are not ejected unless the frequency of the incident light is above a certain threshold value ν_{th} (which is dependent on the cathode material
- If $\nu > \nu_{th}$, even a light of very weak intensity will emit photo-e. Photo-current increases with the intensity of light.
- The maximum K.E. of the photoelectrons depend on the frequency of incident radiation and NOT on its intensity.
- The emission of photoelectrons is almost instantaneous. No time lag between switching on the lightsource and the emission of photoelectrons.

Calculation of delay in classical theory

Consider a light source e such as a laser with a power output of 1 mW spread over a narrow beam of cross-section 0.1 cm^2 falling on a surface of a metal. Estimate the time lag of the photo-electron emission as per wave theory.

Solution

$d_A = 10^{-8} cm \implies A \sim 10^{-16} cm^2$

Fraction of light absorbed $= 10^{-16}/0.1 = 10^{-15}$

Energy absorbed by the beam every second $=$

$10^{-15} \times 10^{-3} J = 10^{-18} J \approx 6 eV$

The ionization potential of alkali elements $\sim$ 10 eV

Therefore, it takes about 1.6 secs to absorb the required energy, which is a rough estimate of the time lag.

Einstein solution

- Electromagnetic radiation is quantized into quanta of energy $h\nu$, where h is Planck's constant.
- It is these quanta called *photons* which are absorbed as single units by the electrons. If $h\nu >$ energy required to separate the electron from metal surface, the electron is knocked out. The surplus energy is the energy of the emitted electron.
  $KE = h\nu - W$
  We can define φ as the minimum energy, which must be supplied to the electron to dislodge it from the metal. These electrons are emitted with the maximum possible K.E., or K_{max}.
  $$K_{max} = \frac{1}{2}mv_m^2 = h\nu - \varphi$$
  (Some books denote the work function in terms of $e\phi$)

Einstein solution (contd)

- Since $K.E. > 0 \implies$ there must be a minimum energy for the photoelectric emission to take place $h\nu_{th} = \varphi$ i.e. $\nu_{th} = \frac{\varphi}{h}$. Einstein's equation can be re-written as

  $$K_{max} = h(\nu - \nu_{th})$$

  In terms of stopping potential,

  $$eV_s = h\nu - \varphi$$

  or

  $$eV_s = h(\nu - \nu_{th})$$

  h can be determined from the slope of linear plot of V_s vs ν
- Since photons are absorbed as single units, there is a localization of energy and hence no significant time delay in the emission of electrons.
- Photoelectric effect is one-to-one, i.e. for every photon of a suitable frequency, one electron is emitted.

Practical Applications of Photoelectric Effect

1. Automatic fire alarm
2. Automatic burglar alarm
3. Television transmission scanners
4. Reproduction of sound in cinema film
5. Measure thickness of paper in paper industry
6. locate flaws or holes in finished goods.
7. To determine the opacity of solids and liquids
8. Automatic switching of street lights
9. Control temperature of the furnace
10. Light meters used in cinema industry to check the light
11. Photometry
12. Meterology etc

More on Photoelectric effect

- Only a small fraction (5%) of the incident photons succeed in ejecting photo-electrons, whereas most of them are absorbed by the system as a whole and generate thermal energy.
- Photoelectric effect also possible in terms of gas, e.g. Na, K, vapor and this is process is known as photo-ionization.
- Energy required for heating the electrons may be provided by heating the metal, which results in *thermionic emission* of the electrons
- So far we have assumed that electron receives energy from a single photon, with the process known as *single-photon* process. The development of lasers has provided light beams of very high intensity, which allow us to observe multi-photon process in particular the multi-photon photoelectric effect.

$$K_{max} = Nh\nu - \varphi$$

In this case $\nu_{th} = \varphi/nh$ Corresponding frequency is smaller than that for a single-photon process by a factor of $\frac{1}{N}$