Atomic Theory (Lec-02)

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Reference Book:
Garcia Narciso, Damask Arthur, Physics for Computer Science Students, Springer-Verlag

Franck-Hertz Experiment

The existence of discrete energy levels in atoms was demonstrated directly by James Franck and Gustav Hertz in 1914.

A schematic of the experimental set-up is shown in Figure. The essential part of the apparatus consists of a tube containing vapor of the element under study. The tube contains three electrodes: a filament **(F)** that provides electrons when heated, a plate **(P)**, and a grid **(G)**. A grid is a charged screen that can attract or repel electrons but, because most of it is open space, the majority of the electrons pass through it. A variable accelerating voltage V_0 is applied between the filament and the grid. As a consequence of this potential difference, the electrons will reach the grid (in the absence of collisions) with a kinetic energy $E_k = eV_0$. After reaching the grid the majority of these electrons will go through the holes in the grid, be collected by the plate **P**, and contribute to the plate current i, which can be measured by the ammeter A. A small, constant retarding voltage $V_r (\approx 1V)$ is applied between the plate and the grid. If $V_r > V_0$, the electrons will be turned back before they can reach the plate and they will not contribute to the current measured by A. But even if $V_r < V_0$, the electrons will not be able to reach the plate if they lose enough kinetic energy through collisions with the atoms in the tube as they travel between the filament and the grid.

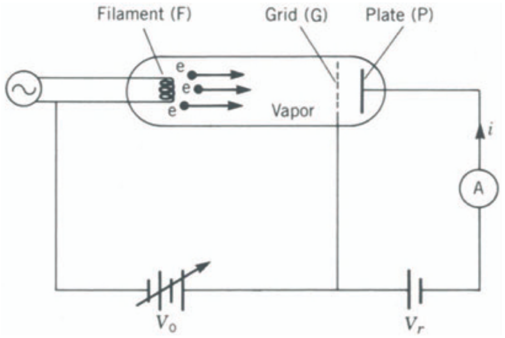


Figure 1: Schematic of the apparatus used in the Franck-Hertz experiment to show the quantization of the internal energy of atoms.

In the absence of any vapor, that is, a vacuum, the $i - V_0$ characteristics are those of a typical vacuum tube. This dependence is shown by the dashed line of Figure 2. If vapor of some element is present in the tube, one observes a series of fairly sudden dips superimposed on the monotonic vacuum curve. The solid curve in Figure 2 shows this effect for the case where mercury vapor is present in the tube.

The fact that there is no drop in the current until certain voltage is reached ($V_0 = 4.9V$ in this case) indicates that the electrons do not lose energy through collisions until they have a particular value of kinetic energy ($4.9eV$ in this case).

If the gas atoms in the tube can have a continuous distribution of internal energy states, the transfer of kinetic energy from the bombarding electrons to the atoms could and should occur regardless of the energy of the electrons, that is, the drop in the current should occur for any value of V_0. The fact that the drop occurs only when $V_0 = 4.9V$ (and therefore the E_k of the electrons is $4.9eV$) indicates that the first excited state of the gas atom used in the tube is $4.9eV$ above the ground state. As V_0 increases beyond the $4.9V$, the current begins to increase again because, although the electrons can and do collide inelastically and lose $4.9eV$ of energy, they still have enough energy remaining to overcome the small retarding voltage V_r. When $V_0 = 2{\times}4.9V$ or $3{\times}4.9V$, or so on, dips in the current occur again because now the electrons can undergo two, three, or more inelastic collisions with the gas atom; in each collision they lose $4.9eV$.

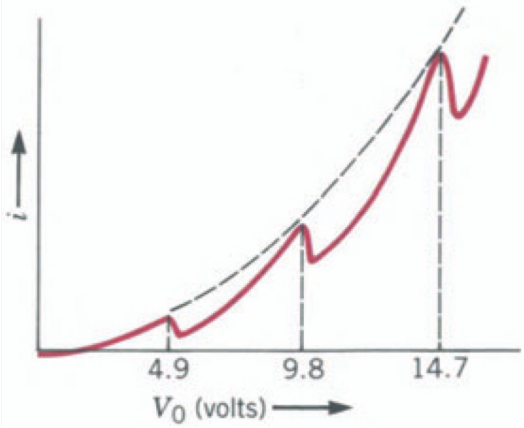


Figure 2: Dependence of the plate current i (measured by the ammeter A in the apparatus of Figure 1) on the accelerating voltage V_0.

This interpretation is corroborated by the electromagnetic radiation emitted by Hg atoms. There should be a spectral line whose frequency is given by $h\nu = 4.9eV$ or $\lambda = 2530\text{Å}$. Such a wavelength is found in the spectrum of Hg. An energy diagram for Hg is shown in Figure 3. The energy difference ΔE between the first excited state and the ground state is $\Delta E = 10.4eV - 5.5eV = 4.9eV$.

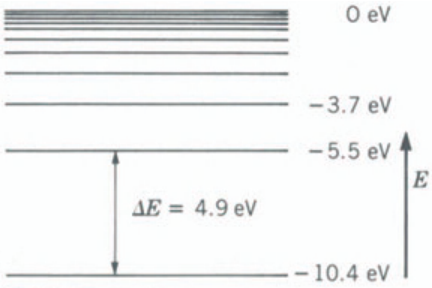


Figure 3: Atomic energy levels of a mercury atom

Fundamental Principles of Quantum Mechanics

Photoelectric effect

Photoelectric effect is the phenomenon of emission of electron from a metallic surface when radiation of suitable frequency falls on it. The electrons thus emitted are called photoelectrons.

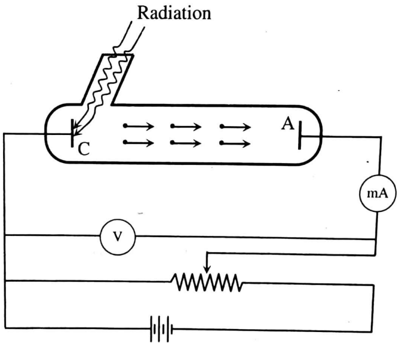


Figure 4: Experimental arrangement for photoelectric effect

Experimental Arrangement to Study Photoelectric Effect A systematic study of photoelectric effect can be made in the lab with the apparatus as shown in figure. Two metal plates C and A are sealed in a vacuum chamber. Light of reasonably high frequency pases through the transparent window and falls on the plate C which is called the cathode or the emitter. The electrons are emitted by C and collected by the plate A called anode or the collector. The potential difference between the cathode and anode can be varied externally. The anode potential can be made positive or negative with respect to the cathode. The electrons collected by the anode A flow through the ammeter, batteries etc. and are back to cathode and hence the electric current is established in the circuit. Such a current is called a **photocurrent**.

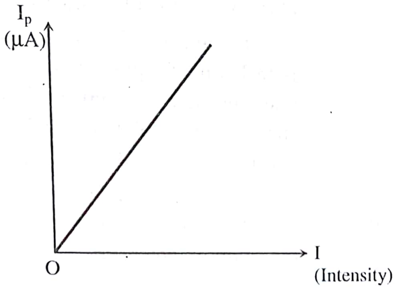
When intensity and frequency of the incident light are kept fixed while the potential of the anode is varied, it is increased in positive potential on the anode A till it reaches a value when photoelectric current reaches a saturation value. Here *all the emitted electrons reach the anode A and there is no further increase in photocurrent with the increase in the positive potential of electrode A.*

On the other hand, if the negative potential is applied to the plate A with respect to the cathode and is increased gradually, we find that photocurrent decreases rapidly and finally becomes zero at a certain negative potential on plate A. *The minimum value of negative potential to plate A at which photoelectric current becomes zero is called stopping potential or cut off potential (V_0).* In such a case, the work done by stopping potential is equal to the maximum kinetic energy of the photoelectrons emitted. *i.e.*,

$$eV_0 = \frac{1}{2}mv_{max}^2$$

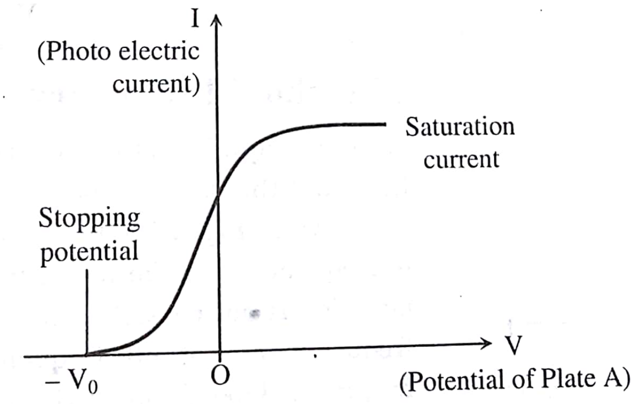
Effect of Intensity of Incident Light on the Photo Electric Current

As the intensity of the incident light increases keeping frequency constant more photoelectrons are emitted by the electrode C and hence photoelectric current increases linearly as shown in figure. SInce more intensity means more number of photons per second, the number of electrons emitted from the metal surface increases with increase in intensity of radiation.



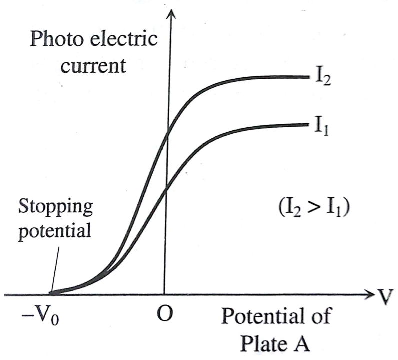
Effect of Potential on the Photo Electric Current

For fixed frequency and intensity of light, photoelectric current increases with increase in applied positive potential of plate A. When all the photoelectrons emitted by electrode C reach the plate A, the photoelectric current attains maximum value known as saturation current. If the potential of plate A is decreased such that it attains negative potential with respect to electrode C, no photoelectrons reach the plate A at certain value of such negative potential. The potential is defined as stopping potential of cut-off potential. The I-V curve of photocurrent due to a radiation of fixed frequency and intensity is shown in the Figure.



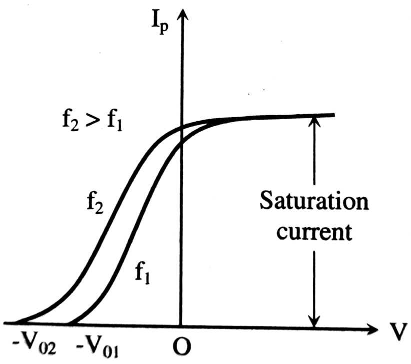
Effect of Intensity of Light on the Photo Electric Current

If the intensity of the incident light is increased and frequency is kept same then the value of photoelectric current and saturated current increase but there is no change on stopping potential.

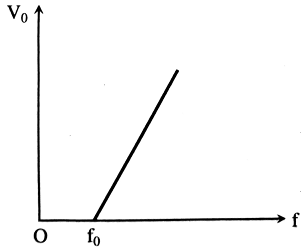


Effect of Frequency of Light on the Photo Electric Current

The intensity of incident light is kept constant, but the frequency is changed so that in each case the saturation current is exactly the same. Now for a given frequency f1 of the incident light, the positive potential at plate A is decreased to zero. Now, the plate A is given negative potential be V01. The experiment is repeated with the incident light of frequency f2¿f1. It is found that stopping potential also increases. Thus, we found that the value of stopping potential depends on upon the frequency of the incident light.

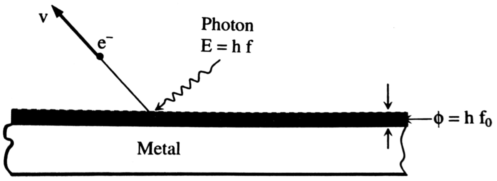


Threshold Frequency: When a graph is plotted between the frequency of the incident light and the stopping potential, it is found to be a straight line as shown in the figure. It shows that there is a minimum value of frequency f0 of the incident light below which photoelectrons emission is not possible. This frequency is known as threshold frequency or cut-off frequency f0. The value of threshold frequency depends on the nature of the substance emitting the photo-electrons.



Laws of Photoelectric Emission

1. The minimum frequency, which can cause photoelectric emission, is called the threshold frequency.
2. The rate of emission is directly proportional to the intensity of the incident light, provided the frequency is greater than the threshold frequency.
3. The velocity and hence the energy of the emitted photoelectrons is independent of the intensity of the light and depends only in the frequency of the incident of light and the nature of the metal.
4. There is an instantaneous emission of photo-electrons within the limits of experimental accuracy.
5. The maximum velocity and hence the stopping potential are independent of the intensity of the incident light but are directly proportional to the frequency of the incident radiation for a given metal



Einstein's Photoelectric Equation According to quantum theory of radiation, light of frequency f consists of a photons each of energy hf. When a photon of light of frequency f is incident on a metal, the energy is completely transferred to a free electron in the metal. A part of the energy acquired by the electron is used to pull out the electron from the surface of the metal and the rest of its utilized in imparting K.E. to the emitted electron. Let ϕ be the energy used up in liberating the electrons from the surface of metal (work function) and $\frac{1}{2}mv^2$ is K.E. of the photoelectron, then,

$$h\nu = \phi + \frac{1}{2}mv^2$$

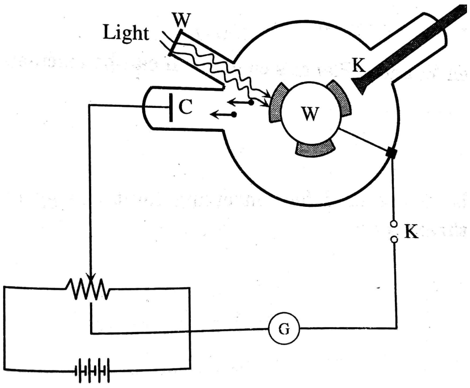
This relation is known as the Einsteins photoelectric equation. If f_0i s the threshold frequency which just ejects an electron from the metal surface without any velocity, then,

$$hf_0 = \phi + \frac{1}{2}m(0)^2 \quad \Rightarrow \phi = hf_0$$

Important Terms

1. Threshold frequency (f_0)
   The minimum frequency of incident radiation which is just sufficient to eject an electron (i.e. with zero velocity) from the surface of the metal is known as threshold frequency (f_0) for that metal.
2. Threshold wavelength (λ_0)
   The wavelength corresponding to threshold frequency is known as threshold wavelength λ_0, The incident radiation with threshold wavelength is just capable of ejecting photoelectrons. If the wavelength is more than λ_0, no photoelectrons are emitted.
3. Work function(ϕ)
   The minimum energy of photon required to just liberate an electron from the metal surface with zero velocity is known as work function (ϕ) of that metal.

Millikan's Photoelectric Experiment



In this experiment, alkali metal is used as emitters. Cylindrical blocks made by sodium, potassium or lithium are placed around a wheel W at the centre of the glass flask. To avoid tarnishing and the formation of oxide films on the metal surface, the metals are housed in a vacuum. Their surface was kept clean by a cutting knife K which could be moved and turned by the means of a magnet outside. When a beam of monochromatic light falls on the alkali metal, photoelectrons are emitted. The photoelectrons emitted reach the electrode C. the electrode C is usually kept negative with respect to the cylindrical blocks. Therefore, photo electrons will be repelled and only fast moving electrons will be able to reach the electrode C. Since the negative potential of electrode C is increased until the fastest moving photoelectrons are repelled back and thus the current falls to zero.

Therefore,

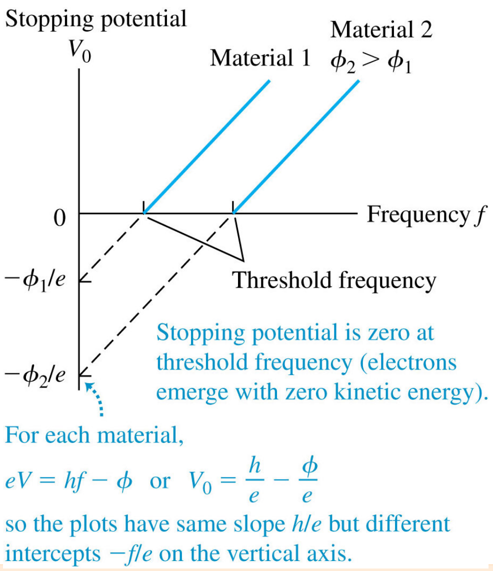
$$\frac{1}{2}mv_{max}^2 = eV_0$$

From Einstein's photoelectric equation, $hf = \phi + \frac{1}{2}mv_{max}^2 = \phi + eV_0$

$$hf = \phi + \frac{1}{2}mv_{max}^2 \Rightarrow hf = \phi + eV_0$$

$$V_0 = \frac{h}{e}f - \frac{\phi}{e}$$

This equation can be compared with equation of straight line $y = mx + c$ with $y = V_0$, $m = h/e$, $x = f$, and $c = -(\phi/e)$, as shown in figure. Therefore, once the slope of the straight line is obtained from observation, Planck's constant (h) can be estimated.



Stopping potential is zero at threshold frequency (electrons emerge with zero kinetic energy).

For each material,

$$eV = hf - \phi \quad \text{or} \quad V_0 = \frac{h}{e} - \frac{\phi}{e}$$

so the plots have same slope h/e but different intercepts $-f/e$ on the vertical axis.