Dual nature of matter and radiation

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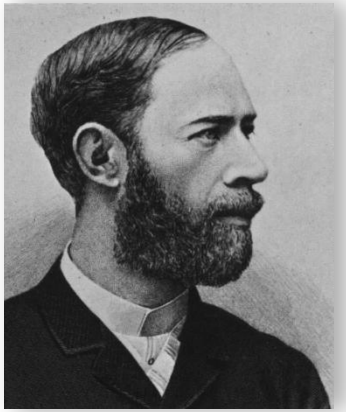
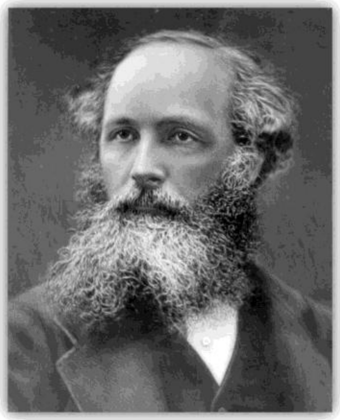


Gustav Ludwig Hertz



James Clerk Maxwell

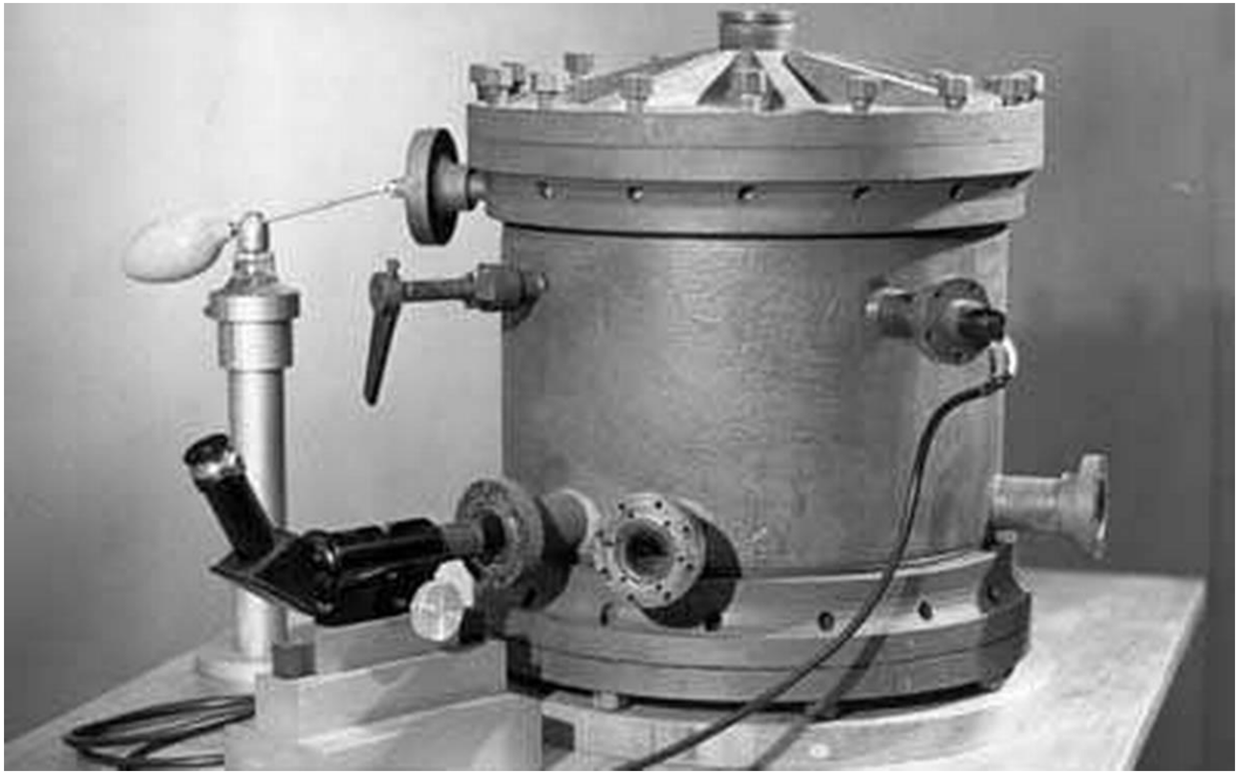
Maxwell's equations of electromagnetism and Hertz experiments on the generation and detection of electromagnetic waves in **1887**

William Crookes

J J Thomson

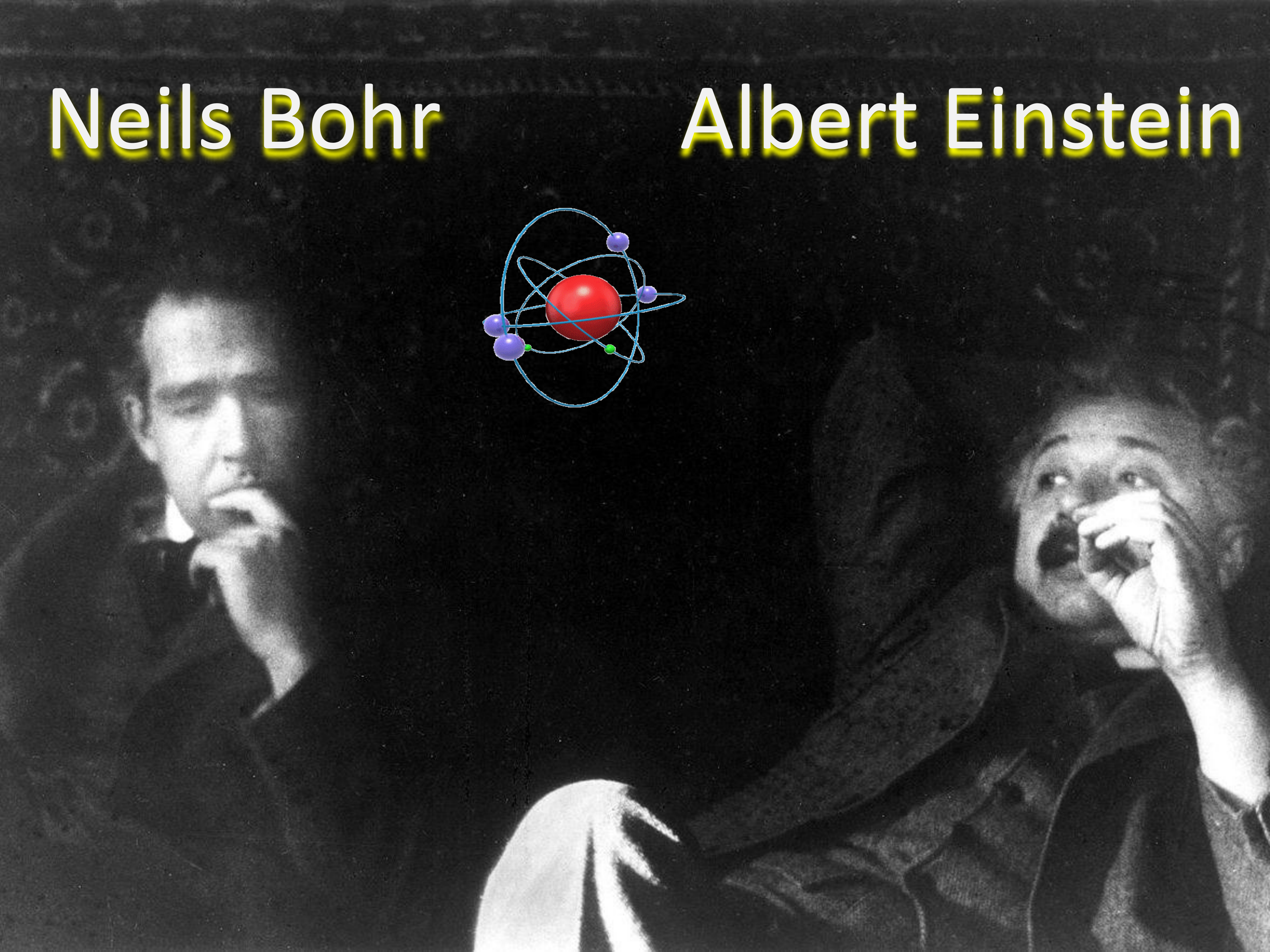
Observation of cathode rays by William Crookes in **1870**, and discovery of electron by J. J. Thomson in **1897**, were important milestones in understanding of atomic structure.

Cathode rays are a beam of fast moving electrons observed when gas between two electrodes is maintained at a very low pressure (of about 0.001 mm of Hg)



Robert Andrews Millikan oil drop experiment setup

American physicist R. A. Millikan performed the pioneering oil-drop experiment **1913** for the precise measurement of the charge on an electron.

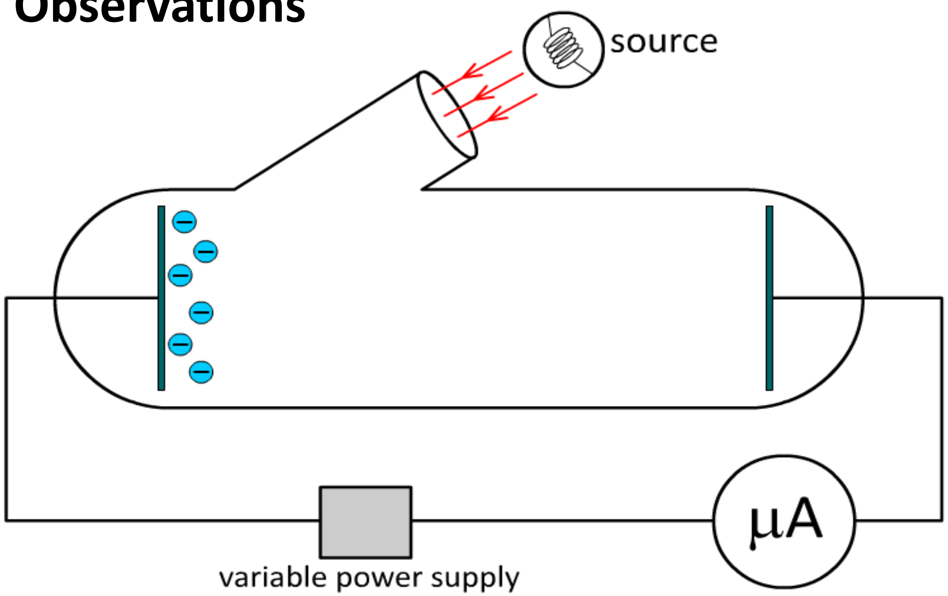

Neils Bohr
Albert Einstein

Photoelectric effect

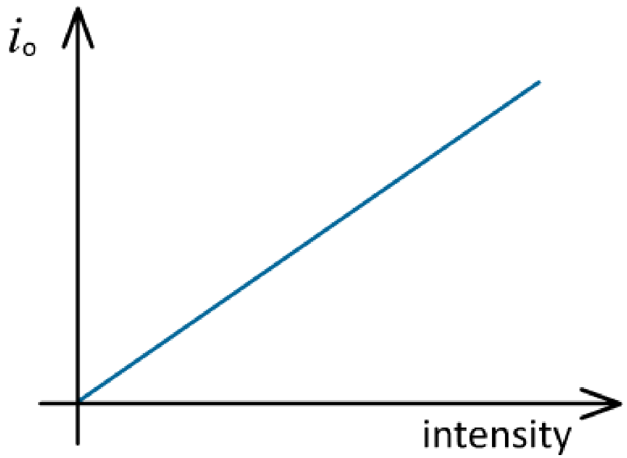
It is a phenomenon of emission of electrons from certain metallic surfaces when light of suitable frequency is incident on it.

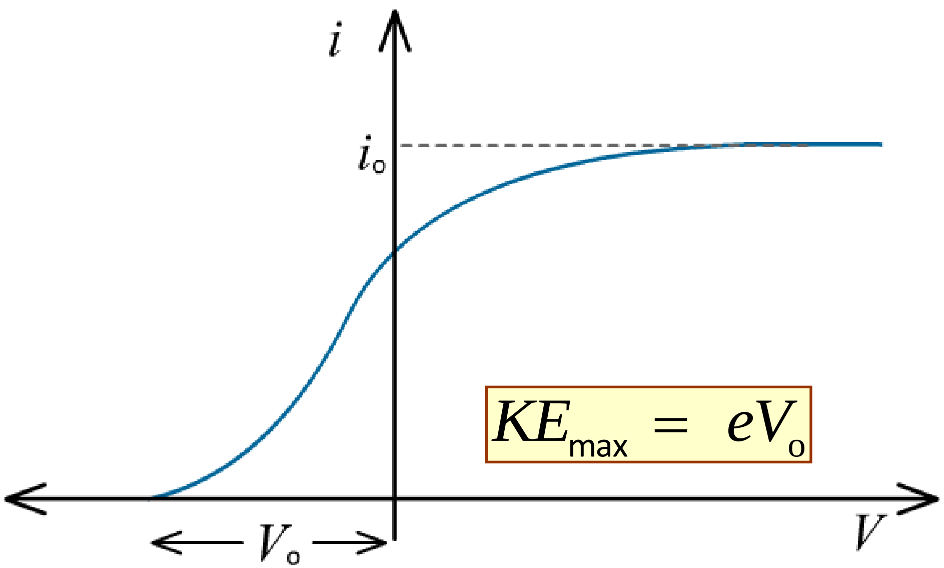
Observations	Inferences
Photoelectric current increases linearly with intensity of radiation incident on the photometal.	Number of photoelectrons emitted per second is directly proportional to intensity of incident radiation.
Stopping potential (required to make photo current zero) is dependent on frequency and not on intensity of light	Energy of photo-electrons depends on frequency and not on intensity of radiation
Changing temperature resulted in no notable change	This effect is not induced by heat energy (i.e. it is not thermal emission)
Increasing the electric field (P.D. applied across the plates) did not initiate photo current for low frequencies	This effect is not induced due to electric field (i.e. it is not field emission)

Observations

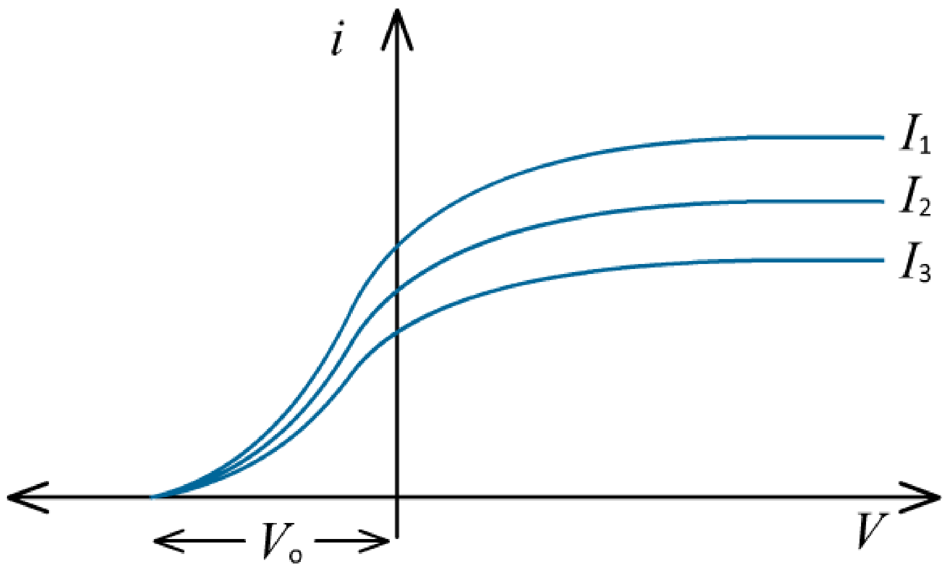


- Saturation current is the maximum possible current as all photoelectrons are collected by the collector
- Stopping potential (V_o): The minimum P.D. required to make photo current zero.
  It depends on frequency (and not on intensity) of incident radiation.



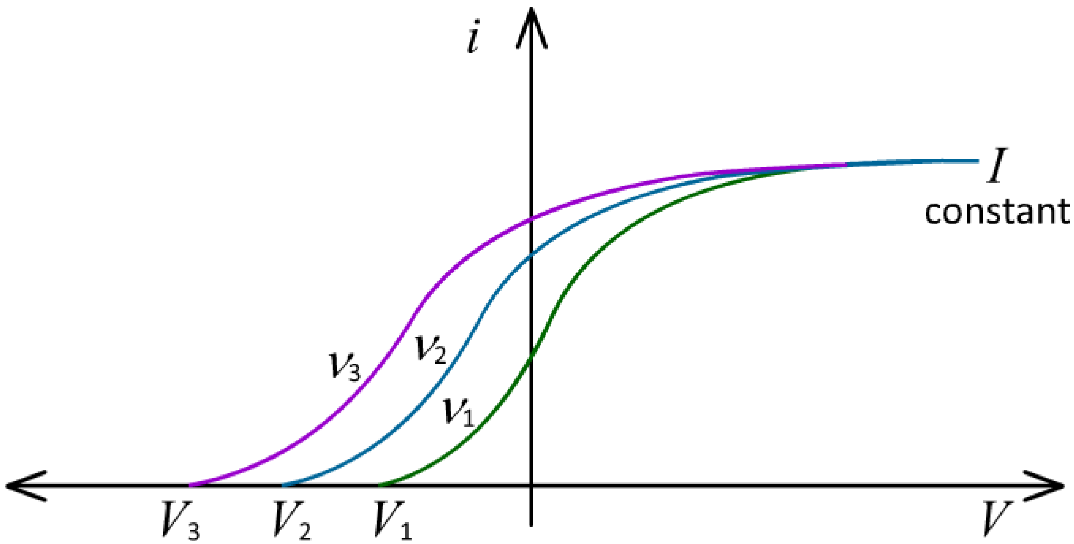


Observations with varying intensity of radiation



- Saturation current increases with the intensity of incident radiation
- Increasing the intensity of incident radiation (while keeping the frequency or colour constant) does not affect the stopping potential

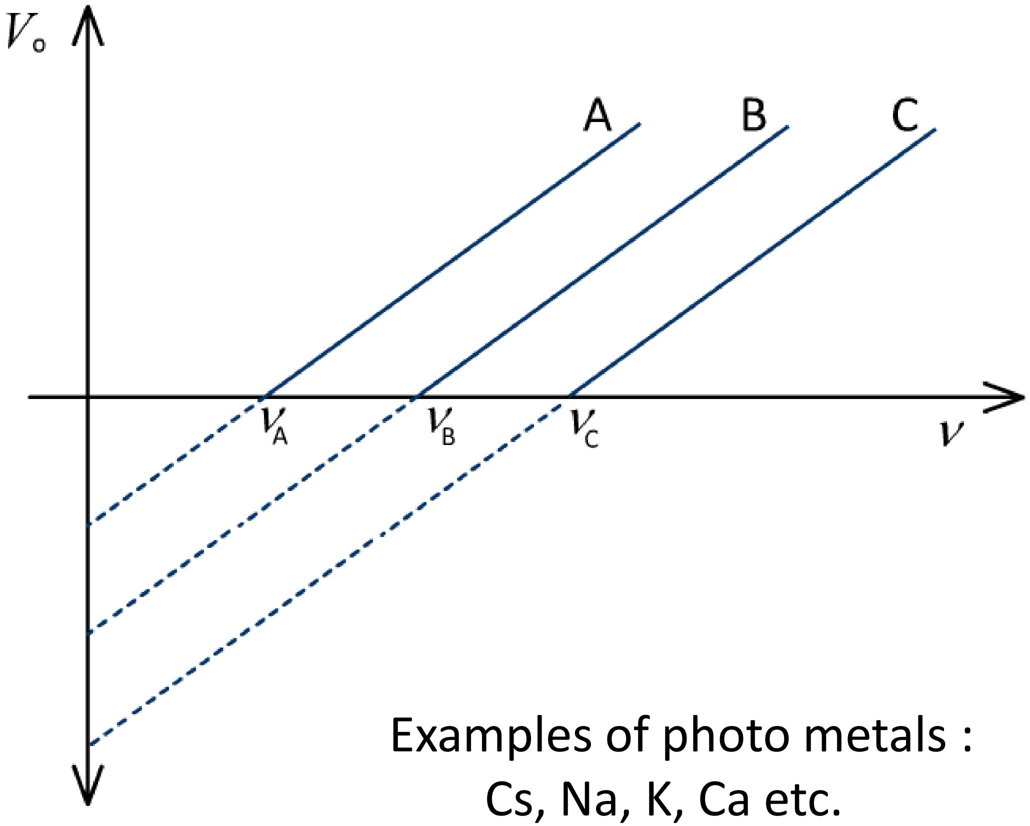
Observations with varying frequency of radiation



- Saturation current remains the same
- Increasing the frequency of incident radiation (while keeping the intensity constant) results in an increase in stopping potential

Observations with different metals and frequencies

- Stopping potential increases linearly with frequency of incident radiation.
- Threshold frequency : It is the minimum frequency required to cause photoelectric effect in a material. It depends on the nature of photo metal.
- Threshold frequency is given by the x-intercept.
- Slope of all plots (i.e. for any photo metal) is the same



Examples of photo metals :
Cs, Na, K, Ca etc.

Summary observations

- For a given photosensitive material, there exists a certain minimum frequency of the incident radiation called *threshold frequency* (ν_o) below which no emission of photoelectrons takes place.
- Work function (energy required to liberate electron from photometal) depends on the photometal used
- For a given photometal and frequency ($\nu > \nu_o$) of incident radiation, photoelectric current increases with intensity of incident light.
- For a given photometal and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation
- *Stopping potential* i.e. the minimum potential to make photo current zero, is independent of intensity of radiation
- Above threshold frequency, stopping potential (and therefore KE_{max}) increases linearly with the frequency of the incident radiation, but is independent of its intensity

Einstein's photoelectric equation

$$h\nu = KE + \phi$$

- Electrons absorb a quantum of radiation
- If the absorbed quantum of radiation is greater than work function then the electron escapes the metal surface.
- When the intensity is increased, the number of photons increases and hence the photoelectric current also increases
- When frequency of incident radiation is increased the energy of each photon increases and hence the *KE* of photoelectron increases.
- Increases in kinetic energy in corresponding increased stopping potential

Millikan's verification of Einstein's photoelectric equation

Starting with Einstein's equation

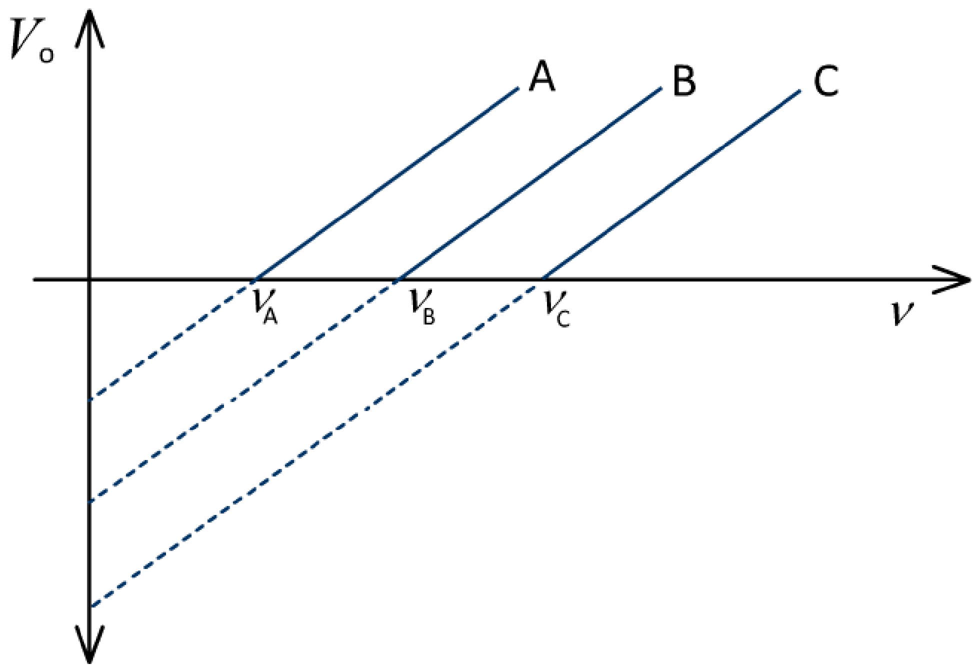
$$h\nu = KE + \phi$$

Denoting KE in terms of stopping potential (V_o) and work function (ϕ) in terms of threshold frequency (ν_o)

$$h\nu = eV_o + h\nu_o$$

$$V_o = \frac{h}{e}\nu - \frac{h}{e}\nu_o$$

$$y = mx \pm c$$



- Plot of V_o as a function of ν is a straight line
- Slope of the graph is same for all metals and is given by h/e
- x-intercept gives the threshold frequency

The photon nature of light

- Interactions of radiation with matter, can be understood by assuming that radiation behaves as if it is made up of particles called photons
- Each photon moves with the speed of light (c)
- All photons of light of a particular frequency ν or wavelength λ have the same energy E ($h\nu$ or hc/λ) and momentum p ($h\nu/c = h/\lambda$)
- Increasing the intensity of the source increases the number of photons emitted per second by the source (while frequency, energy & momentum of each photon remains same)
- Photons are electrically neutral and are not deflected by electric and magnetic fields.
- In a photon-particle collision (such as photon-electron collision), the total energy and total momentum are conserved.
- The number of photons may not be conserved in a collision / interaction / phenomena. Photons may be absorbed or new photons may be created.

Duality used by nature : Gathering & focusing mechanism of light by the eye-lens is well described in the wave picture. But its absorption by the rods and cones of the retina requires the photon picture of light !

De-Broglie relation

De Broglie proposed that the wave length (λ) associated with a particle of momentum (p) is given by the relation

$$\boxed{\lambda = \frac{h}{p}}$$

Nobel Prize (Physics) 1929 for discovery of the wave nature of electrons

Other forms

$$\lambda = \frac{h}{mv}$$

$$\lambda = \frac{h}{\sqrt{2mE}}$$

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

$$\lambda = \frac{h}{\sqrt{3mkT}}$$

v : velocity of the particle

h : Planck's constant (6.63 x 10 $^{-34}$ Js)

E : Kinetic energy

q : charge of the particle

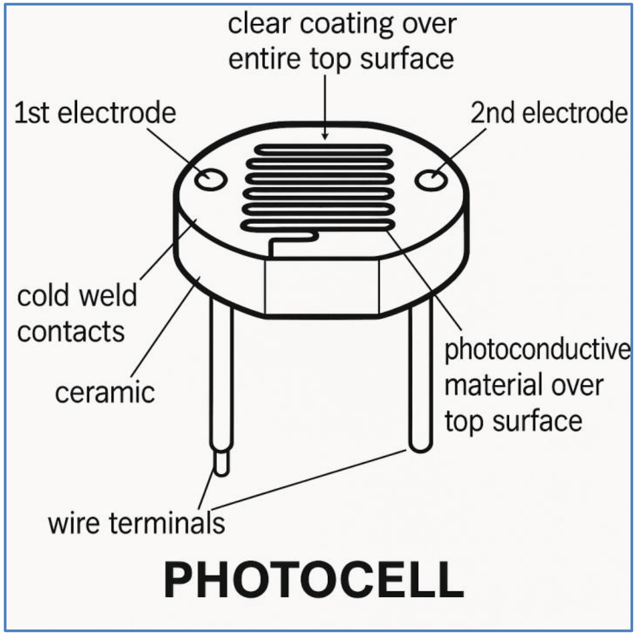
h : potential difference

k : Boltzmann's constant

T : absolute temperature

Photocell

- A photocell work n the principle of photoelectric effect.
- A thin layer of photosensitive metal in it emits photoelectrons in response to the radiation incident on it
- A high tension battery is used to gather the photoelectrons and a micro-ammeter measure the photocurrent
- Emission depends on the frequency and photocurrent depends on intensity of radiation



Applications / uses of photocells

- Lead sulphide based photocell is used for IR radiation detection
- Digital cameras, automatic door openers, currency counters, intruder alarms etc
- Reproduction of sound, scanning & telecasting in digital media
- For detecting minor flaws or holes in metal sheets.

Heisenberg's uncertainty principle

it is not possible to measure both the position and momentum of an electron (or any other particle) at the same time exactly.

The product of uncertainty (Δx) in the specification of position and uncertainty (Δp_x) in the specification of momentum is always greater than reduced Planck's constant.

$$\boxed{\Delta x \, \Delta p_x > \hbar}$$

Max Born suggested a *probability interpretation* to the *matter wave amplitude*. According to this, the intensity (square of the amplitude) of the matter wave at a point determines the *probability density* of the particle at that point. Probability density means probability per unit volume.

The uncertainty inherent in the probabilistic interpretation is evidenced by Heisenberg's principle.

Davisson and Germer experiment

Davisson-Germer experiment provides direct experimental evidence for the wave nature of electrons and confirms the de Broglie relation.

- An electron gun with a tungsten filament emits electrons.
- Electrons are accelerated by applying a suitable high voltage and directed onto a nickel crystal which acts as a diffraction grating for the electrons.
- A movable detector measures the intensity of electrons scattered at various angles.
- The experiment is conducted in a vacuum chamber to prevent interaction with air molecules.

- Intensity of scattered electrons shows peaks at certain angles when the accelerating voltage is around 54 V, with a peak observed at a scattering angle of 50°.
- This peak corresponds to constructive interference of electrons scattered from different crystal planes, analogous to X-ray diffraction and confirming wave behavior.