Photoelectric Effect: Liberation of electrons from a metal surface when EM radiation of sufficiently high frequency is incident on it. Provides evidence of the particulate nature of EM radiation.

Experimental observations supporting the photon theory

Experimental Observation	Failure of wave theory to explain	Ability of photon theory to explain
No electrons emitted if incident light falls below a certain frequency.	Electrons should be emitted at any frequency as long as radiation is intense enough or enough time is given for electrons to accumulate energy.	If $hf < \Phi$, no emission whatever the intensity. Threshold frequency, $f_0 = \frac{\Phi}{h}$ Threshold frequency is the minimum radiation needed to cause electron emission.
Stopping potential independent of radiation intensity (int)	Higher intensity means more energy per unit time supplied and therefore emitted electrons should have higher KE_{max} and require a larger stopping potential.	Higher intensity just means more photons incident per unit time. Since $P = \frac{E}{t} = \frac{nhf}{t}$ $\frac{n}{t} = \frac{p}{hf} = int. \times \frac{area}{hf}$
Instantaneous emission of photoelectrons	Time delay expected (especially at low intensities) as electrons take time to accumulate energy which is spread over metal surface.	Each photon passes its entire quantum of energy to a single electron, enabling the electron to escape with no delay.
Stopping potential increases with increasing *f*.	No relationship between KE_{max} and therefore stopping potential f.	With a larger photon energy and the same wok function to overcome, KE_{max} would be larger.

Einstein's photoelectric equation:

$$hf = \Phi + KE_{max}$$

Photon energy: is a discrete packet of energy of EM radiation. Energy:

$$E = hf = \frac{hc}{\lambda}$$

Work function energy: is the Minimum energy needed to remove an electron from metal surface.

Max KE of emitted electrons (called photoelectrons)

- Determines the stopping potential, V_s
- V_s is the minimum potential difference between the emitter and collector (with emitter being positively biased with respect to collector), that will prevent even the most energetic photoelectron from reaching the collector.

$$KE_{max} = \frac{1}{2} m v_{max}{}^2 = eV_s$$

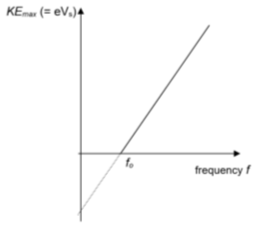
Note that electrons are actually emitted with a range of KE. Those most loosely-bound electron will be emitted with more KE while the more tightly bound will be emitted with smaller KE.

Note that the amount of KE is not so much a function of depth, but a function of how tightly bound the electron is.

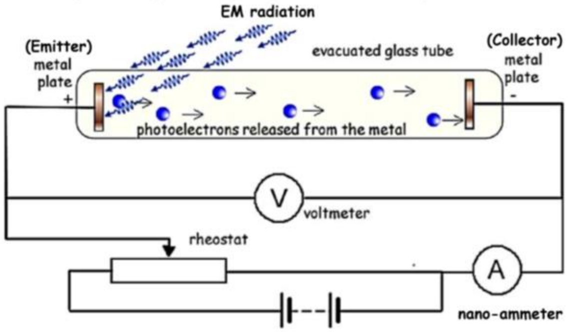
$KE_{max} = hf$ Graph

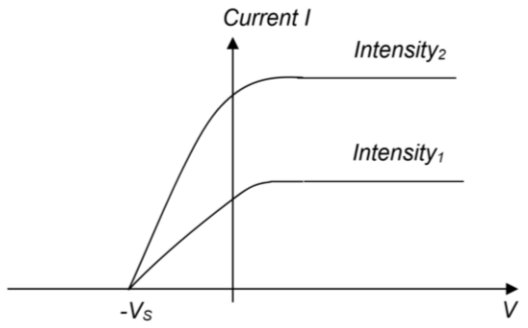
Where h is the gradient

And Φ is the y-intercept.



Basic Experimental Set-up.

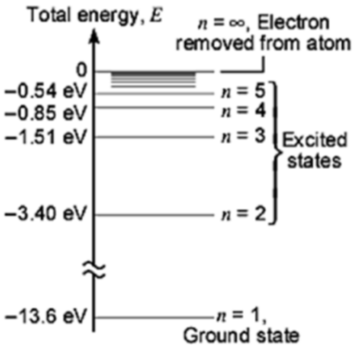




The energy of each photon is still hf and since each electron interacts with only one photon, KE_{max} is unchanged.

What results will be an increase in current because there is a proportionate increase in number of electrons emitted per unit time.

Discrete energy levels:



- We are talking about the outermost electrons. Transitions take place in the outermost energy levels of the atom, unlike the characteristic X-ray lines which are due to transitions close to the nucleus. The former transitions are out of smaller energy change than the latter.
- Ordinarily all atoms are in ground state. To be excited the atom needs to absorb an amount of energy equal to the difference in energy between the ground state and an excited state, e.g. E_3-E_1.
- The difference between E_∞ and E_1 is the ionization energy. Once an electron leaves the atom, it can take on any value of energy (no more discrete value).
- Atoms in excited states are very unstable and the electron would almost immediately fall back to a lower energy level, emitting a photon corresponding to the energy difference in the process. E.g. for an electron excited to level E_4, the following six transitions are possible: (E_4-E_3, E_4-E_2, E_4-E_1, E_3-E_2, E_3-E_1, E_2-E_1)

Line Spectra: Evidence for the existence of discrete energy levels in atom. Conditions of experiment:

- Atoms sufficiently isolated so that they do not interact with one another and the energy levels remain discrete.
- Low-pressure gas is needed.

Absorption Spectrum: Appearance: dark lines on bright coloured (rainbow) background

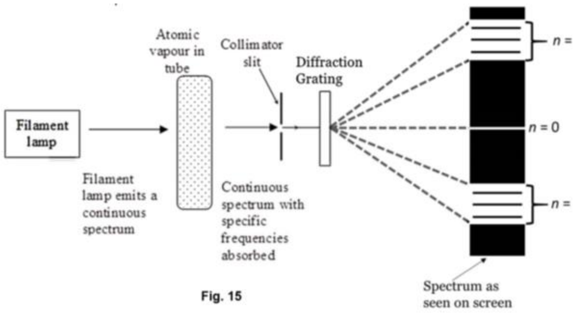


Fig. 15

- Gas atoms in tube are cool, therefore in ground state.
- Only frequencies corresponding to the difference between energy intervals, can be absorbed. All other frequencies pass straight through, in other words, for excitation by photon, the photon energy hf must be strictly equal to E_{final}-$E_{initial}$.
- Transitions for absorption are typically from ground state to higher energy states, e.g. E_1 to E_4, E_1 to E_5.
- While the excited atoms will quickly de-excite and emit the frequencies absorbed, the emitted photons are in all directions. Thus the intensity in the forward direction (towards the grating) is low.
- The grating is just to separate the different frequencies for deflection purpose. A prism could be used too.

Emission Spectrum: Appearance: Bright coloured lines on dark background

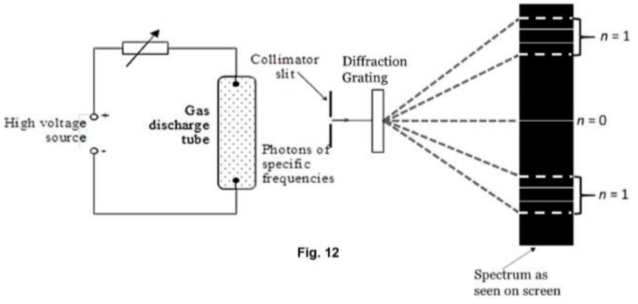
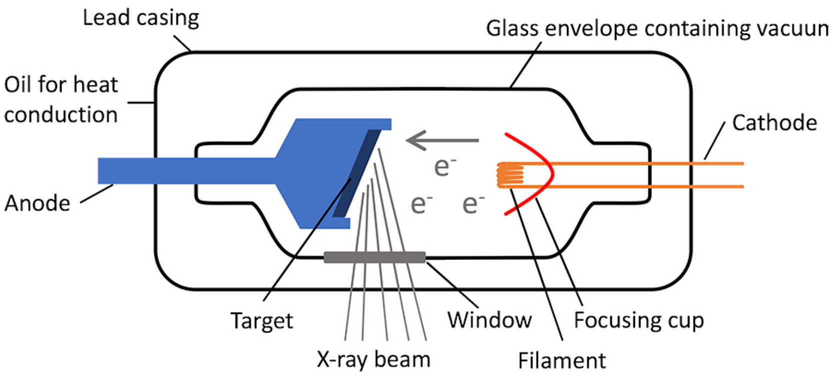


Fig. 12

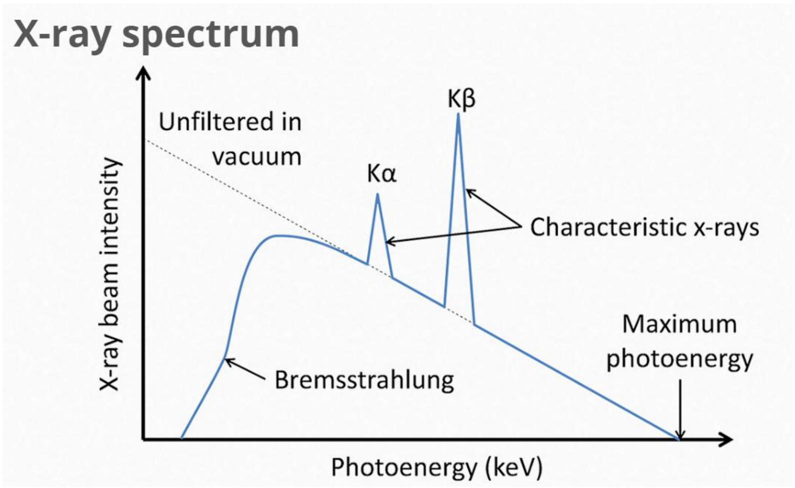
- In discharge tube, gas atoms are excited through bombardment by energetic electrons. For excitation to happen, the bombarding electron must have $KE \geq E_{final} - E_{initial}$. The excess remains as the KE of the bombarding electron.
- Atoms can also be excited through thermal means (by heating the gas).
- Bright coloured lines are due to the photons produced when de-excitation takes place from higher to a lower energy state, e.g. E_3 to E_1.
- The grating is just to separate the different frequencies for detection purpose. A prism could be used in place of the grating.

X-Ray Spectra: Produced due to energy changes in electrons close to the nucleus of metal atoms (contrast with optical line spectra - which are produced when the interaction is with outermost shell electrons of isolated atoms.)

Production



- High voltage used to accelerate bombarding electrons.
- Putting the electrons through a p.d. of V will give them a KE of eV.
- To heat up the filament to produce bombarding electrons through thermionic emission.



Characteristic lines:

- Highly energetic bombarding electrons penetrate the atoms and knock out an inner shell electron from a metal atom (The inner-most shell is K, followed by L, M, N etc.).
- If a K-shell electron is removed, an electron from the L shell could fall into the vacancy in the K-shell, emitting a photon equivalent to the energy difference between the K and L shells. This is the K_α line.
- The K_α line is produced by an M-shell electron falling into a K-shell vacancy.
- One could also have electrons from shells further away falling to fill a K-shell vacancy (no shown in diagram).
- The positions of the peaks depend solely on the type of metal (different metal atoms have different energy intervals.)
- The wavelengths are so short because the energy differences between the inner-shells are very large (recall when we talked about optical line spectra due to transitions of outer0shell electrons the wavelengths were much longer and could be in the visible region.)

Continuous Radiation (Bremsstrahlung)

- The energetic bombarding electrons decelerate as they hit the metal target.
- This loss is KE is manifested in the form of a photon.
- Since the bombarding electrons can lose any fraction of its KE in a collision/interaction with a metal atom, the photon emitted can take on any value of energy.
- The maximum energy the emitted photons can have, however, is the entire KE of the bombarding electron (if the bombarding electron is brought to rest at one go).
- Hence

$$eV = hf_{max} = \frac{hc}{\lambda_{min}}$$

- The value λ_{min} of therefore depends solely on the accelerating voltage V.

Wave-Particle Duality:

waves can exhibit particle-like characteristics and particles can exhibit wave-like characteristics.

De Broglie relation:

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

Using:

$$KE = \frac{p^2}{2m}$$

One can relate the wavelength to a particle to its KE by

$$\lambda = \frac{h}{\sqrt{2m(KE)}}$$

Packets of EM radiation of wavelength λ would therefore possess a momentum:

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

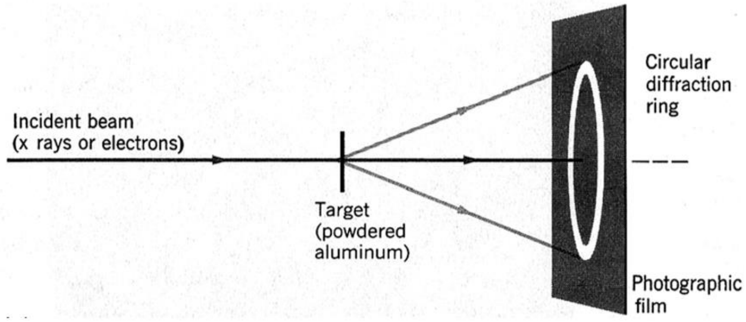
When photons are incident on a surface, they therefore exert a force on the surface, resulting in a pressure on the surface. This pressure is known as radiation pressure.

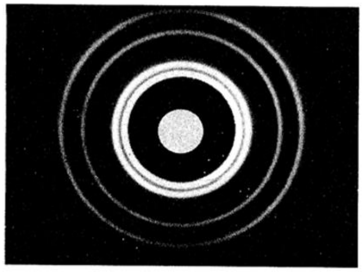
Examples of Wave-Particle Duality:

Light as waves	Diffraction, Interference, polarization
Light as particle	Photoelectric effect
Electrons as particles	Their behaviour in electric and magnetic fields
Electrons as waves	Electron diffraction through thin crystal, tunnelling.

Electron Diffraction:

The lattice spacing of the metal foil are small enough and comparable to the small wavelength of the electrons. Thus we observe the pattern below.





Heisenberg's Uncertainty Principle:

The uncertainty is not due to the measuring instrument. It is just how nature is.

Position-Momentum Uncertainty Principle: if a measurement of position of a particle is made with uncertainty Δx and a simultaneous measurement of linear momentum is made with uncertainty Δp, then the product of the two uncertainties can never be smaller than *h*.

$$\Delta x \Delta p \geq h$$

In problem-solving: just estimate Δx to be the whole range of space in which the particle moves.