# PHY 142

## PART- 6 LECTURE NOTE

his part of the lecture note contain only two topics

- Millikan's Experiment and
- X-ray

<u>Varning</u>

1. **Do not print this lecture note, read it on your PC Tablet**
2. **This lecture note is <u>not for sale</u>**

<u>ecturer Details</u>

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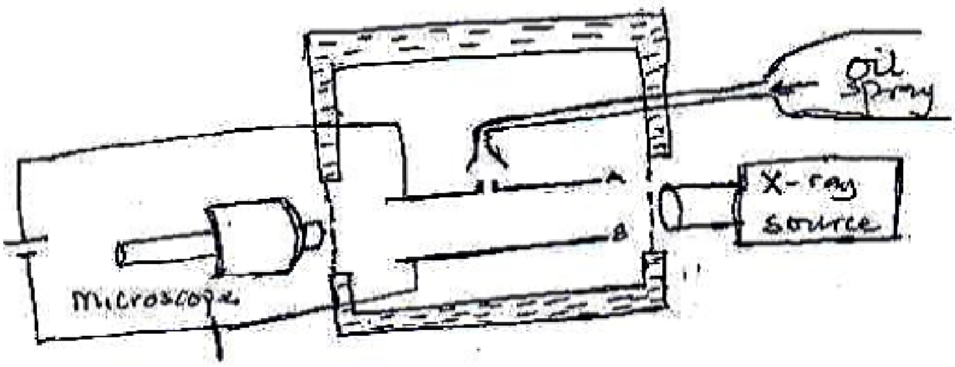
## Millikan's Experiment

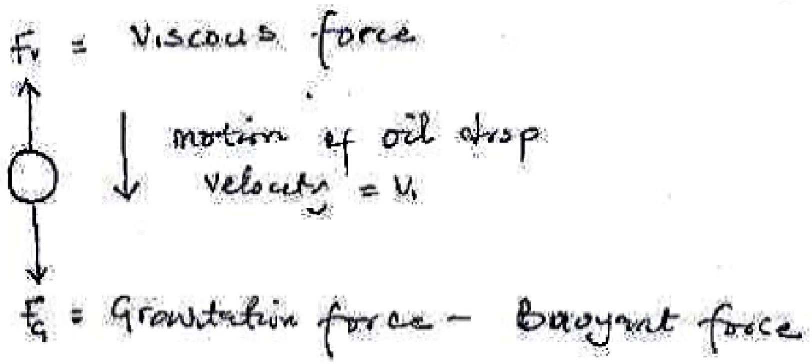
### Introduction

In 1909 Millikan started a series of experiments lasting many years which supplied evidence for the atomic nature of electricity and provided a value for the magnitude of the electronic charge. The principle of his method is to observe very small oil drops, charged either positively or negatively, falling in air under gravity and then either rising or being held stationary by electric field.




With no electric field between the plates (A & B), one drop is selected and its velocity ($v$) of fall found by timing it over a convenient number of divisions on a scale in the eyepiece of the microscope.

For a spherical drop of radius $r$, moving with uniform velocity $v$ through a homogeneous medium having coefficient of viscosity $\eta$, Stoke's law states that the viscous force retarding its motion is $6\pi\eta rv$. In falling the drop attains its terminal velocity almost at once because it is so small. The retarding force acting up then equals its weight given by $\frac{4}{3}\pi r^3\rho g$, where $\rho$ is the density of the oil and $g$ the acceleration due to gravity.




When the oil drop with constant velocity, it means that there should be no force acting on it.
Meaning that:

$$F_v = F_g$$

and $F_v = 6\pi \eta r v_1$ ——— (1)

$F_g = \frac{4}{3}\pi r^3 \rho g$ ——— (2)

$\therefore$ $6\pi\eta r v_1 = \frac{4}{3}\pi r^3 \rho g$ ——— (3)

and $r^2 = \frac{9\eta v_1}{2g\rho}$ ——— (4)

where, $r$ = radius of the oil drop
$\eta$ = coefficient of viscosity
$g$ = acceleration due to gravity
$v_1$ = velocity of the oil drop
$\rho$ = density of oil

~~eqn~~ eqn (4) can be re-written as

$$r^2 = \frac{9\eta v_1}{2g(\rho_{oil} - \rho_{air})}$$

Where $\rho_{oil}$ = density of oil
$\rho_{air}$ = density of air / medium

Some of the oil drops becomes charged either by friction in the process of spraying or from ions in the air. Suppose the drop under observation has a negative charge q. When a p.d. is applied to the plates so that the top one is positive, an electric field is created which exerts an upward force on the drop at rest, then the electric force experienced by it is ~~Eq~~ (Since, $E = F/q$)

Here,

$F_E$ = Electric force and

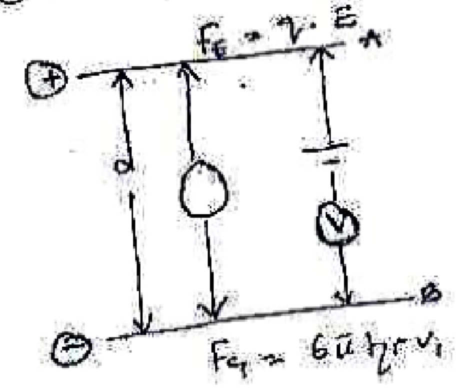
$F_E = qE$

q = Charge on the oil drop

E = magnitude of the electric field

This electric force can do two

① Stop the motion of the oil drop.




where,

d = distance of seperation between plates A and Plates B

V = p.d or voltage supply

Here,

$F_G = F_E = q.E$

and $E = \frac{V}{d}$

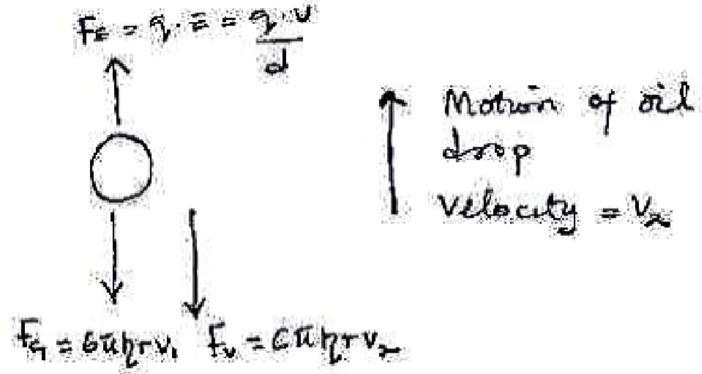
$\therefore F_G = q \times \frac{V}{d}$

$q = \frac{F_G \times d}{V}$

$q = \frac{6\pi\eta r v_1 d}{V}$ or $q = \frac{4\pi r^3 \rho d}{3V}$

(2) The oil drop may rise up with constant velocity $V_2$ which may be experimentally calculated by recording the time required for the oil drop to rise to a certain distance.

Now, the viscous force act downward because the oil drop is moving up.




Since the oil drop is rising up with constant velocity all the forces acting on the oil drop should balance each other.

$$F_E = F_g + F_v$$

and

$$\frac{q.V}{d} = 6\pi\eta r v_1 + 6\pi\eta r v_2$$

$$q = \frac{6\pi\eta r (v_1 + v_2) \times d}{V}$$

Millikan found that the charge on an oil drop, whether positive or negative, was always an integral multiple of a basic charge. He studied drops having charges many times the basic charge and by using X-rays he was able to change the charge on a drop. The same minimum charge equal to that on a monovalent ion, was always involved. The value of the atom of electric charge, i.e. the electronic charge $e$ is

$$e = 1.60 \times 10^{-19} C.$$

From J. J. Thomson's experiment on Cathode ray tube:

Charge to mass ratio $= \frac{e}{m} = 1.76 \times 10^{11}$ C/kg

and $m = \frac{e}{e/m} = \frac{1.602 \times 10^{-19}}{1.76 \times 10^{11}} = 9.1 \times 10^{-31}$ kg

Example

Calculate the radius of a drop of oil, density 900 kg m$^{-3}$, which falls with a terminal velocity of $2.9 \times 10^{-2}$ cm s$^{-1}$ through air of viscosity $1.8 \times 10^{-5}$ Nsm$^{-2}$. Ignore the density of the air.

If the charge on the drop is $-3e$, what p.d. must be applied between two plates 5 cm apart for the drop to be held stationary between them? ($e = 1.6 \times 10^{-19}$ C and $g = 10$ m/s$^2$)

Solution

$\eta = 1.8 \times 10^{-5}$ Nsm$^{-2}$
$\rho = 900$ kgm$^{-3}$
$v = 2.9 \times 10^{-2}$ cm s$^{-1}$
$v = 2.9 \times 10^{-4}$ ms$^{-1}$
$g = 10$ m/s$^2$

$$r^2 = \frac{9\eta v}{2g\rho}$$

$$r^2 = \frac{9 \times 1.8 \times 10^{-5} \times 2.9 \times 10^{-4}}{2 \times 10 \times 900}$$

$$r = 1.6 \times 10^{-6} m = 1.6 \times 10^{-4} cm$$

$$F_e = qE = q \times \frac{V}{d}$$

and $q = 3e$ (given in the question).

and since $F_e = F_g$

$$qE = \frac{4}{3}\pi r^3 \rho$$

$d = 5$ cm $= 5 \times 10^{-2}$ m

~~Ex3e~~

$$E \times 3e = \frac{4}{3}\pi r^3 \rho$$

Since $E = \frac{V}{d}$

$$E = \frac{4\pi r^3 \rho}{9e} = \frac{V}{d}$$

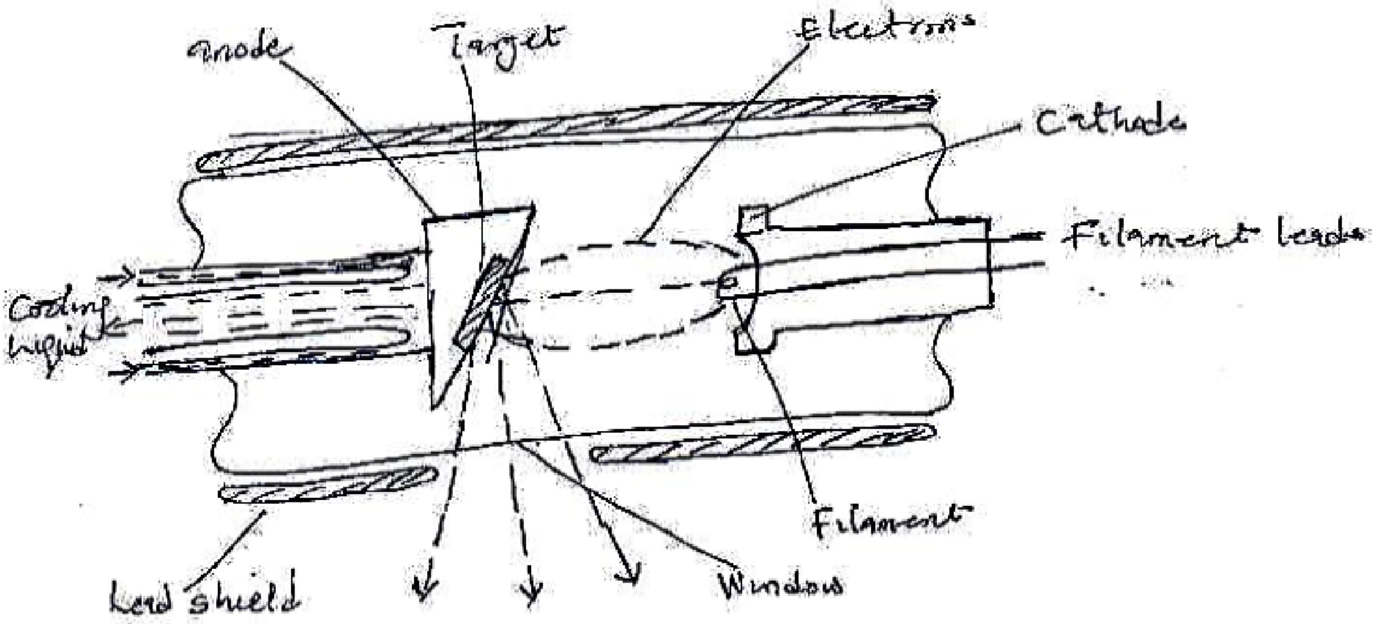
$$V = \frac{4\pi r^3 \rho d}{9e}$$

$$V = \frac{4\pi \times (1.6 \times 10^{-6})^3 \times 900 \times 5 \times 10^{-2}}{9 \times 1.6 \times 10^{-19}} = 1600 V$$

## X-rays

X-rays, so named because their nature was at first unknown, were discovered in 1895 by Röntgen. They are produced whenever cathode rays (electrons) are brought to rest by matter.

## Production




A modern X-ray tube is highly evacuated and contains an anode an a tungsten filament connected to a cathode as shown in the diagram above. Electrons are obtained from the filament by thermionic emission and are accelerated to the anode by a p.d., typically up to 100kV. The anode is a copper block inclined to the electron stream and having a small target of tungsten, or another high-melting-point metal, on which electrons are focused by the concave cathode.

The tube has a lead shield with a small window to allow the passage of the X-ray beam.

Less than ½ percent (0.5%) of the Kinetic energy of the electrons is converted into X-rays. The rest of the Kinetic energy becomes internal energy of the anode which has to be kept cool by circulating oil or water through channels in it or by the use of cooling fins.

The intensity of the X-ray beam increases when the number of electrons hitting the target increases and this controlled by the filament current.

The quality or penetrating power of the X-rays is determined by the speed attained by the electrons and increases with the p.d. across the tube.

Soft X-rays only penetrate such objects such as flesh, hard X-rays can penetrate much more solid matter.

Types of X-rays

(i) Hard X-ray

(ii) Soft X-ray

(i) Hard X-rays have a high penetrating power and a short wavelength. They can be produced by increasing the p.d. between the cathode and anode of the X-ray tube. The higher this p.d. the faster and more energetic the bombarding electrons.

(2) Soft X-rays have a lower penetrating power and longer wavelengths.

# Characteristics and Properties of X-rays

1. X-rays are electromagnetic waves of very high frequency. Like light, they have a velocity of $3 \times 10^8 \ ms^{-1}$ in free space

2. They have very short wavelength, much shorter than that of light waves.

3. They readily penetrate matter; they can easily pass through most solid substances which are opaque to ordinary light, e.g. flesh, wood, paper, aluminium foil, etc. Soft x-rays do not penetrate dense metals and bones.

4. They travel in straight lines

5. They are not deflected by electric or magnetic fields

6. They eject electrons from matter by the photo-electric effect and other mechanisms

7. They ionize a gas, permitting it to conduct.

8. They cause certain substances to fluorescence, e.g. zinc sulphide, barium platinocyanide.

9. They are diffracted by crystals

10. They affect a photographic emulsion in a similar manner to light.

## Uses of X-rays

The usefulness of X-rays is largely due to their penetrating power.

(i) Medicine. X-rays are used for examining the body to locate broken bones or hidden metallic objects like bullet in a patient's leg or a pin swallowed by a child. X-rays penetrate the flesh but not the bone or the metal object. They thus disclose the position of the bone or the metal objects.

(ii) They are used in airports to detect metals and contraband in a luggage

(iii) Industry. Castings and welded joints can be inspected for internal imperfections using X-rays

(iv) X-ray crystallography. The study of crystal structure by X-rays is now a powerful method of scientific research. The first crystals to be analysed were of simple compounds such as Sodium Chloride but in recent years the structure of very complex organic molecules has been unravelled

(v) Medicine. They are used in the treatment of tumours and some skin diseases. Cancer cells can be destroyed by X-rays.

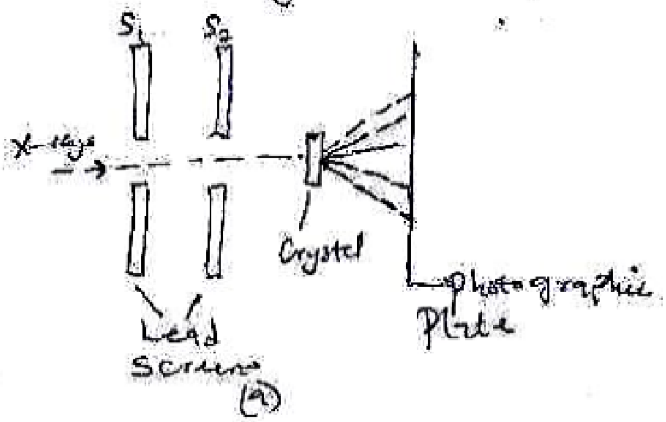
(vi) Art. They can be used to detect alterations which have been made on works of art.

(7) Agriculture. They are used in agriculture to kill germs.

on Nature of X-ray: Von Laue's experiment

X-rays cannot be charged particles since they are not deflected by electric and magnetic fields. The vital experiment which established their electromagnetic nature was initiated by Von Lau in 1912.

The arrangement of their apparatus is shown below.





A narrow beam of X-rays from two ~~Selet~~ slits $S_1$ and $S_2$ fell on a thin crystal in front of a photographic ~~radiation~~ plate. After a long exposure the plate (on developing) revealed that most of the radiation passed straight through to give a large central one. The electromagnetic wave behaviour of X rays

The electromagnetic wave behaviour of X-rays was thus demonstrated and analysis of diffraction patterns confirmed they had wavelengths of about $10^{-10}$ m (0.1nm). They are considered to be electromagnetic waves because

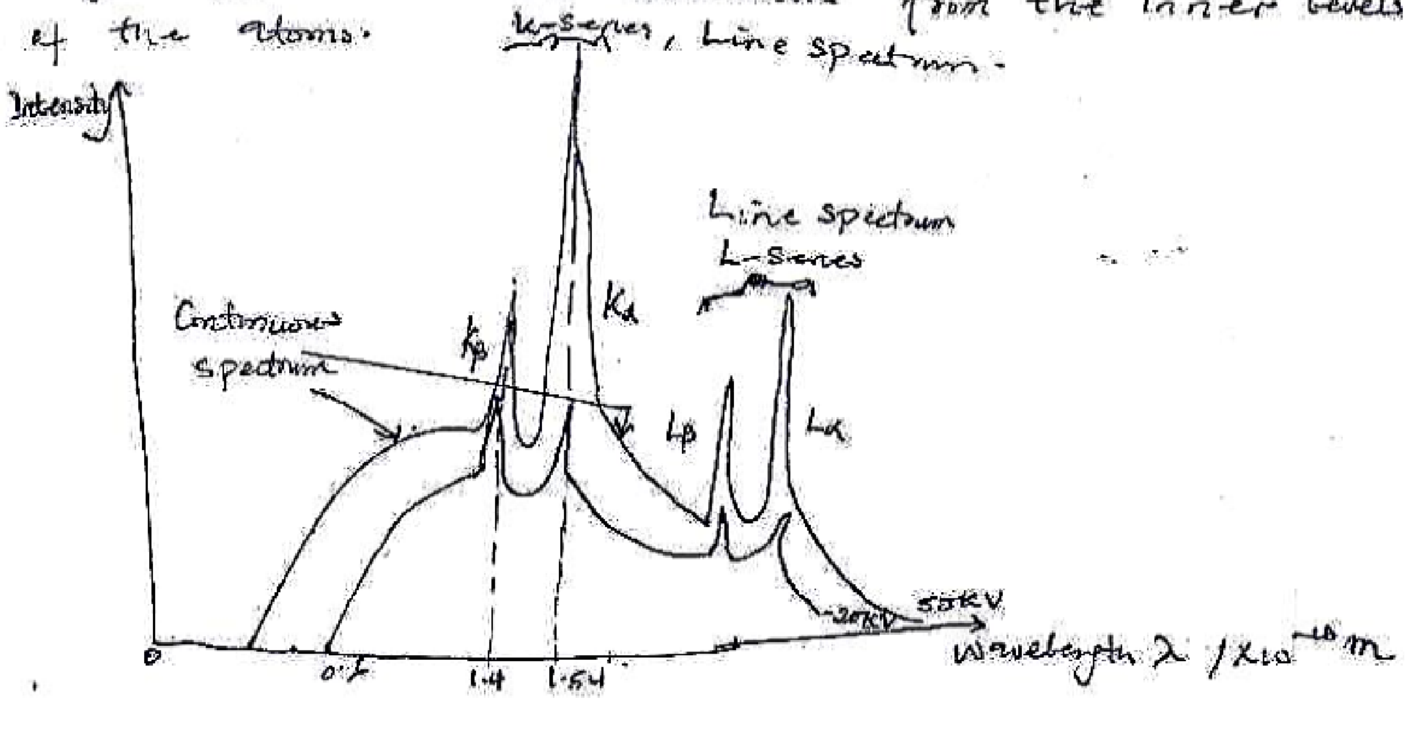
(i) Their method of production involves accelerated charges
(ii) They eject electrons from matter (implying strong electric fields)
(iii) they give line spectra similar in general character to the optical spectrum of hydrogen

~o~ The X-ray spectrum

The X-ray spectrum consists of continuous spectrum and line or characteristic X-ray spectrum.

X-rays in continuous part of the spectrum are emitted from a target when the bombarding electrons from the cathode are slowed down upon hitting the target. These X-rays are referred to as continuous X-rays or bremsstrahlung (from German words 'braking radiation').

Another type of X-rays emitted from a target is referred to as the line or characteristic X-rays. These X-rays are emitted when high-energy electrons from the cathode strike the atoms in the target and knock out electrons from the inner levels of the atoms.



When a bombarding electron from the cathode knocks out one of the electrons in the K-shell and the vacancy in the K-shell is filled by an electron from the L-shell, a photon of X-rays, $K_\alpha$-line, is emitted. Similarly, a vacancy in the K-shell of another atom may be filled by an electron from the M-shell. When this happens, a photon of X-ray which forms the $K_\beta$-line is emitted. The $K_\alpha$- and $K_\beta$-Lines form a series known as the K-series characteristic X-rays.

Besides the characteristic K-lines, the characteristic L-lines are also produced. The Lines are produced when vacancies in L-shell are filled by electrons from higher levels.

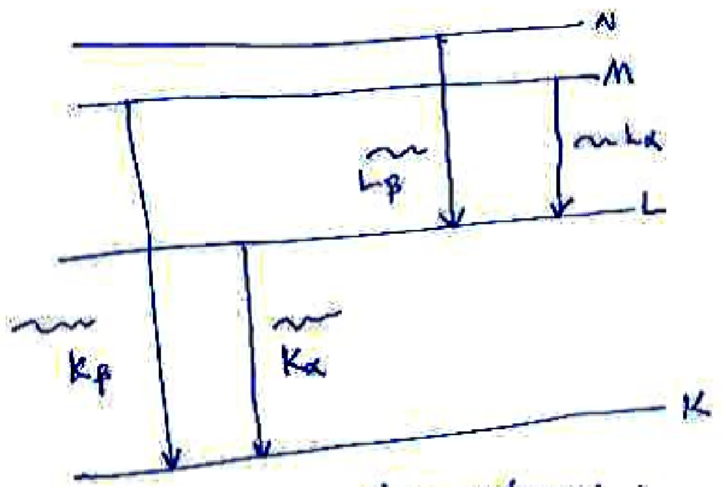



fig2: Electron transitions.

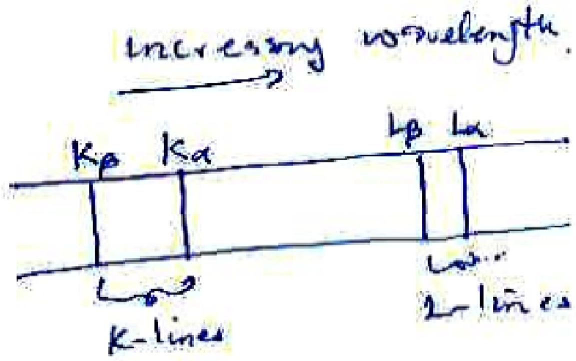



fig06: Characteristic Line X-rays.

-On Quantum theory and the Continuous Spectrum

Certain features of the continuous spectrum are readily explained by the quantum theory. Thus, the existence of a definite minimum wavelength can be justified if we assume that this radiation consists of X-ray photons produced by electrons which have given up all their kinetic energy in a single encounter with a target atom. If such an electron has mass $m$ and speed $v$ on striking the target, the energy $hf$ of the photon is given by .

$$hf = \frac{1}{2}mv^2 \quad \text{———— (1)}$$

where,

$h$ - Planck's constant i.e $h = 6.6 \times 10^{-34}$ Js
$f$ = frequency of the radiation in Hz
$v$ = ~~Ph~~ velocity of the electron
$m$ = mass of the electron.

With the p.d. across the X-ray tube, an electron of charge $e$ has work $eV$ done on it by the electric field and so

$$eV = \frac{1}{2}mv^2 \quad \text{———— (2)}$$

and from eqn (1) and eqn (2)

$$hf = eV \quad \text{———— (3)}$$

The value of $f$ given in eqn (3) is the maximum frequency of the X-rays emitted at p.d. $V$, since all the energy of the electron is converted to the photon. The corresponding wavelength will have a minimum value, and

If this is $\lambda_{min}$ then:

$$c = f\lambda_{min} \quad \text{———— (4)}$$

where $c$ = speed of travel of x-rays = $3 \times 10^8$ m/s

It follows that

$$\lambda_{min} = \frac{hc}{eV} \quad \text{———— (5)}$$

As V increases, we see from eqn (5) that $\lambda_{min}$ decreases, meaning: X-rays of higher frequency and greater penetrating power are emitted.

The electric power input in the X-ray tube is given by:

$$\text{Power input} = VI \quad \text{———— (6)}$$

Where V is the p.d. across the X-ray tube and I is the current through the X-ray tube.

The current through the tube is given by

$$I = ne \quad \text{———— (7)}$$

Where n is the number of electrons striking the target per second and e is the electronic charge (i.e. $1.6 \times 10^{-19}$C).

## Worked example

An X-ray tube operates at 30 KV and the current through it is 2.0 mA. Calculate (i) the electric power input, (ii) the number of electrons striking the target per second, (iii) the speed of the electrons when they hit the target and (iv) the lower wavelength limit of the X-rays emitted.

**Solution**

(i) power input = VI

and $V = 30\,KV = 30\times10^{3}\,V$ and $I = 2.0\,mA = 2\times10^{-3}\,A$

$\therefore$ Power input $= (30\times10^{3}\,V)(2.0\times10^{-3}\,A)$

$= 60\,W$

(ii) Current through the X-ray tube is given by

$I = ne$

$\therefore \; n = \frac{I}{e} = \frac{2.0\times10^{-3}\,A}{1.6\times10^{-19}\,C}$

$= 1.3\times10^{16}$

(iii) If m is the mass of an electron (i.e. $9\times10^{-31}$ kg) and v is its speed at the target

$\therefore$ from eqn (2) we have:

$\frac{1}{2}mv^2 = eV$

$\therefore \; v = \sqrt{\frac{2eV}{m}}$

$= \sqrt{\frac{2\times1.60\times10^{-19}\times30\times10^{3}}{9\times10^{-31}}}$

$= 1.0\times10^{8}\,ms^{-1}$

(iv) from eqn (5)

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

$h = 6.6 \times 10^{-34}$ Js and $c = 3.0 \times 10^{8}$ ms$^{-1}$

$$\therefore \lambda_{min} = \frac{(6.6 \times 10^{-34}\ Js)(3.0 \times 10^{8}\ ms^{-1})}{(1.6 \times 10^{-19} C)(3.0 \times 10^{3} V)}$$

$$\lambda_{min} = 0.41 \times 10^{-19} m.$$

## Assignment

1) The potential difference between the target and cathode of an X-ray tube is 20kV and the current is 20mA. Only 0.5% of the total energy supplied is emitted as X-rays.

(a) What is the minimum wavelength of the emitted X-rays?

(b) At what rate must heat be removed from the target in order to keep it at a steady temperature?

2) What is the potential difference between the target and cathode when the spectrum of X-rays are produced? The minimum wavelength of the X-rays produced is $6.19 \times 10^{-11}$m. If only 0.2% of the total energy of the bombarding electrons is changed into X-rays and the X-ray tube operates at an electron beam current of 0.5A. Explain why water cooling of the target is necessary.

~~3) Find the minimum wavelength of the X-rays produce.~~

③ Find the minimum wavelength of the X-rays produced by the bombardment of electrons on the screen of a television set where the accelerating potential is 2.0 kV.

Solution

(a) The minimum wavelength $\lambda_{min}$ of the X-rays produced is given by

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

$$\therefore \lambda_{min} = \frac{hc}{eV}$$

$$= \frac{(6.6 \times 10^{-34})(3.0 \times 10^{8})}{(1.6 \times 10^{-19})(20 \times 10^{3})}$$

$$= 6.19 \times 10^{-11} m$$

(b) Rate at which heat should be removed

= rate at which heat is produced

= 99.5% of power supplied to the X-ray tube

$$= \frac{99.5}{100} \times (20 \times 10^{-3})(20 \times 10^{3})$$

$$= 398 W$$

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$P = IV$ and $V = 20 kV = 20 \times 10^{3} V$ and $I = 20 mA$