B.Sc. (Semester - 4) Subject: Physics

Course: US04CPHY21

Electromagnetic Theory and Spectroscopy

Part 1

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UNIT - IV X-ray and X-ray Spectra

Topics

- Production of X-rays
- Origin of X-Radiations according to electromagnetic theory
- X-rays, Light and Electromagnetic Spectrum
- Measurement of X-Radiations
- Diffraction of X-Radiations
- Bragg’s law,
- Laue spots
- Bragg's spectrometer
- Continuous X-ray spectrum,
- Characteristic Emission Spectrum,
- Characteristic absorption Spectrum,
- A Close Survey of Emission Spectrum,
- Explanation of Emission and Absorption Spectra,
- Energy levels,
- Comparison of Optical and X-ray Spectra,
- Moseley’s Law,
- The Fluorescence yield and Auger Effect
- Satellites

UNIT - IV X-ray and X-ray Spectra

Reference Book:

Elements of Spectroscopy,
S L Gupta, V Kumar, R C Sharma, (20th Edition)
Pragati Prakashan

Production of X-rays- Principle:

X-rays are produced by

electrons → accelerated by10^3 to 10^6 V

electrons with high speed strike a metal target → produces x-rays.

Less than 1 % of the energy supplied is converted into X-radiation during this process.

The rest is converted into the internal energy of the target.

Production of X-rays- Principle:

It is also observed that under certain conditions the primary X-rays, on being absorbed in the matter, give rise to the generation of **secondary X-rays**.

Requirements: Parts in apparatus:

(1) A source of electron (Cathode + Filament)
(2) A target to impart the electrons (Anode)
(3) A power supply with high potential difference

Production of X-rays- Principle:

Method – I *Gas Tube Method:*

Requirements:

(1)	A source of electron (Cathode)	**Al**
(2)	Target Materials	**Pt, Mb**
(3)	Power supply	**30 to 50 KV**
(4)	Pressure	**0.001 mm**

Production of X-rays- Principle:

Method – I *Gas Tube Method:*

*In the **gas tube** the electrons are produced by the ionization of the gas in the tube.*

In this case applied potential between cathode and target depends critically on the pressure in the tube, which is variable at the low pressure used.

Production of X-rays- Principle:

Method – I *Gas Tube Method:*

Disadvantages -1:

It is very difficult to maintain the intensity and quality of emitted X-rays constant.

Disadvantages -2 :

The wall of the tube absorb the residual gas. Thus, The number of electron produced by ionization decreases and hence it is hard to operate after few times.

In view of these shortcomings, the gas tube has become obsolete and the **Coolidge tube** is now used for the production of X-rays.

Production of X-rays- Principle:

Method – II Coolidge Tube

Requirements:

(1) A source of electron (Cathode)	***Tungsten Filament***
(2) Target Materials	***Pt, Mb***
(3) Power supply	***60 KV to 2 MV***
(4) Pressure	***1.0 μmm***

Production of X-rays- Principle:

Method – II Coolidge Tube

Requirements:

(1) A source of electron (Cathode)	***Tungsten Filament***
(2) Target Materials	***Pt, Mb***
(3) Power supply	***60 KV to 2 MV***
(4) Pressure	***1.0 μmm***

Production of X-rays- Principle:

Method – II Coolidge Tube

Construction

Vacuum Tube: The tube is evacuated to **1 μm** of Hg.

Cathode: An independent source of electrons, electrons are emitted from a hot wire cathode. The cathode C is a **tungsten filament** which is fitted in a metal cup, in order to focus the electrons in a narrow beam. This filament is heated by a current of **3 to 5 amp** taken from a **battery**. The filament thus emits electrons at a temperature between **1800 K to 2540 K**.

Production of X-rays- Principle:

Method – II Coolidge Tube

Construction

- **Target A** is fixed to a **copper rod** which projects outside the tube and is water-cooled since there is generation of a large amount of heat when the tube operates for a long time.

Production of X-rays- Principle:

Method – II Coolidge Tube

Advantages :

Intensity and Quality of x-rays can controlled.

Intensity of x-rays can controlled by Changing the temperature of the filament.

Quality of x-rays can controlled by changing the PD between the cathode and the target.

Production of X-rays- Principle:

Method – III

Hot cathode Coolidge Tube,

Advantages :

High precision and accuracy

Production of X-rays- Principle:

Method – IV Betratrone:

Accelerate the electrons in a range of ***2 MeV to 210 MeV***

X-rays of extremely high energy are produced.
Useful to investigates the study of atomic nuclei and in medicine and therapeutic purpose

Origin of X-radiations according to electromagnetic Theory:

The electrons in the cathode stream when stopped by some solid material such as walls of the discharge tube or by some target upon which they fall experience some retardation. According to electromagnetic theory, such retarded charges radiate energy.

Thus, due to random velocities of cathode ray electrons, the pulses of radiations come out with random intervals.

It is observed that higher the velocity of colliding electrons, higher is the frequency of the radiations, and also that higher the frequency of radiations, higher is the penetrating power.

Origin of X-radiations according to electromagnetic Theory:

Later, on the basis of same concept, J. J. Thomson gave an expression for the energy radiated by the target as

$$\frac{2 e^2 v^2}{3(4 \pi \varepsilon_0)c^3 t}$$

all symbols have their usual meaning with t being **time of stoppage of the electron by the target**. Now it is very reasonable to assume that **electrons of given velocity will be more easily stopped by a heavy atom** than by a lighter one; hence energy radiated by using **a target of large atomic weight will be larger.** All the above facts, as we will see, have been experimentally confirmed.

Comparison between X-rays and Ordinary Light

- The X-radiations are invisible, travel in straight lines without transference of matter.
- They are transverse electromagnetic vibrations and are non-electrical in nature.
- They are reflected, diffracted, refracted and polarized just as light.
- They are differentially absorbed by the matter.
- They ionize gases and affect the electrical properties of solids and liquids.
- The X-radiations are produced by the impact of cathode rays upon matter and are characterized by a wide range of wavelengths (10^{-4} ^{o}A to 100 ^{o}A).
- X-rays are capable of acting photo-chemically. They are also capable of damaging living cells and produce genetic mutations.

Comparison between X-rays and Ordinary Light

- If the energy of X-radiations is above 1 MeV, they are capable of producing electron positron pairs.
- X-radiations are emitted in the form of continuous spectrum whose short wave-length limit is determined by the voltage on the tube.
- They also exhibit line spectrum which is characteristic of the element of the anode.
- The absorption spectra of X-radiations are characteristic of chemical elements.
- X-radiations show dual nature.
- They are diffracted by crystal in accordance with Bragg's law.
- The total reflection of X-radiations is used to construct X-ray microscopes.

MEASUREMENT OF X-RADIATIONS

MEASUREMENT OF X-RADIATIONS

X-rays are characterised by

Quantity (dosage and intensity) and

Quality (hardness).

Now, if we want to measure X-radiations, we must measure **both** quantity and quality.

Let us take them one by one.

MEASUREMENT OF X-RADIATIONS

Intensity and Dosage:

- The two terms intensity and dosage are sometimes loosely used to have the same meaning.
- But, in fact, the two words **are not exactly synonymous.**

MEASUREMENT OF X-RADIATIONS

Intensity of X-radiations:

- ***The energy carried by radiations in a unit of time per unit of area in a direction, perpendicular to the direction of radiation propagation.***
- It is the **energy flux**
- **Unit : ergs per square centimeter per second**

MEASUREMENT OF X-RADIATIONS

The dose:

- It is defined in terms of **intensity of X-radiations and its duration.**

- Dose is the ***energy absorbed in a particular region of a specimen.***

- ***Unit :*** **erg per gram**. It means **the intensity is dose rate.**

Dose rate *refers to the* ***quantity of radiation absorbed per unit of time.***

MEASUREMENT OF X-RADIATIONS

"Roentgen

It is the quantity of X- or γ - radiation such that associated corpuscular emission per 0.001293 gram of air produces in air, ions carrying 1 esu of quantity of electricity of either sign."

MEASUREMENT OF X-RADIATIONS

Rontgen (r)

It is equal to the amount of radiation that will produce an electric charge of 0.000258 coulomb per kilogram of dry air.

'Roentgen', the unit of a dose, is used upto the energies of the value 3 MeV.

The **effective intensity** and **dose rate** is expressed as ***roentgen per second***.

MEASUREMENT OF X-RADIATIONS

'**rep**' (= roentgen-equivalent-physical)

At higher energies its measurement becomes difficult, and at high frequencies it is expressed as '**rep**' (= roentgen-equivalent-physical) which represents

The energy absorption of approximately 93 ergs per gram of tissue.

MEASUREMENT OF X-RADIATIONS

For calculation purpose, a **β - ray dose of one rep** is said to be **physically equivalent to an X-ray dose of 1 *r* at a given point.**

rad

The absorbed dose unit, 100 ergs per gram, is known as 'rad'.

MEASUREMENT OF X-RADIATIONS

Ionization method for the measurement of X-ray intensity:

Principle:

- The air and gases which are insulators under normal conditions become conductors under the action of X-rays.
- When X-radiations are passed through a gas **secondary radiations** are emitted by the gas. The **frequencies of emitted radiations are greater than the frequencies of incident radiations**.
- The secondary radiations, when strike the atoms and molecules of the gas, break them into positive and negative ions.
- The positive and negative ions by their motion constitute the **ionization current**.

MEASUREMENT OF X-RADIATIONS

Ionization method for the measurement of X-ray intensity- Principle:

MEASUREMENT OF X-RADIATIONS

Ionization method for the measurement of X-ray intensity- Principle:

- The **saturation ionization current** depends upon the rate of production of ions, which, in turn, depends on the **intensity of X - radiations**.

- Thus, **measurement of saturation ionization current** offers a means of measuring the intensity of X-radiations.

MEASUREMENT OF X-RADIATIONS

T metal tube
O **thin sheet of aluminum**
aa rod

The chamber is filled in by one of the H_2, CO, air, CO_2 gases.

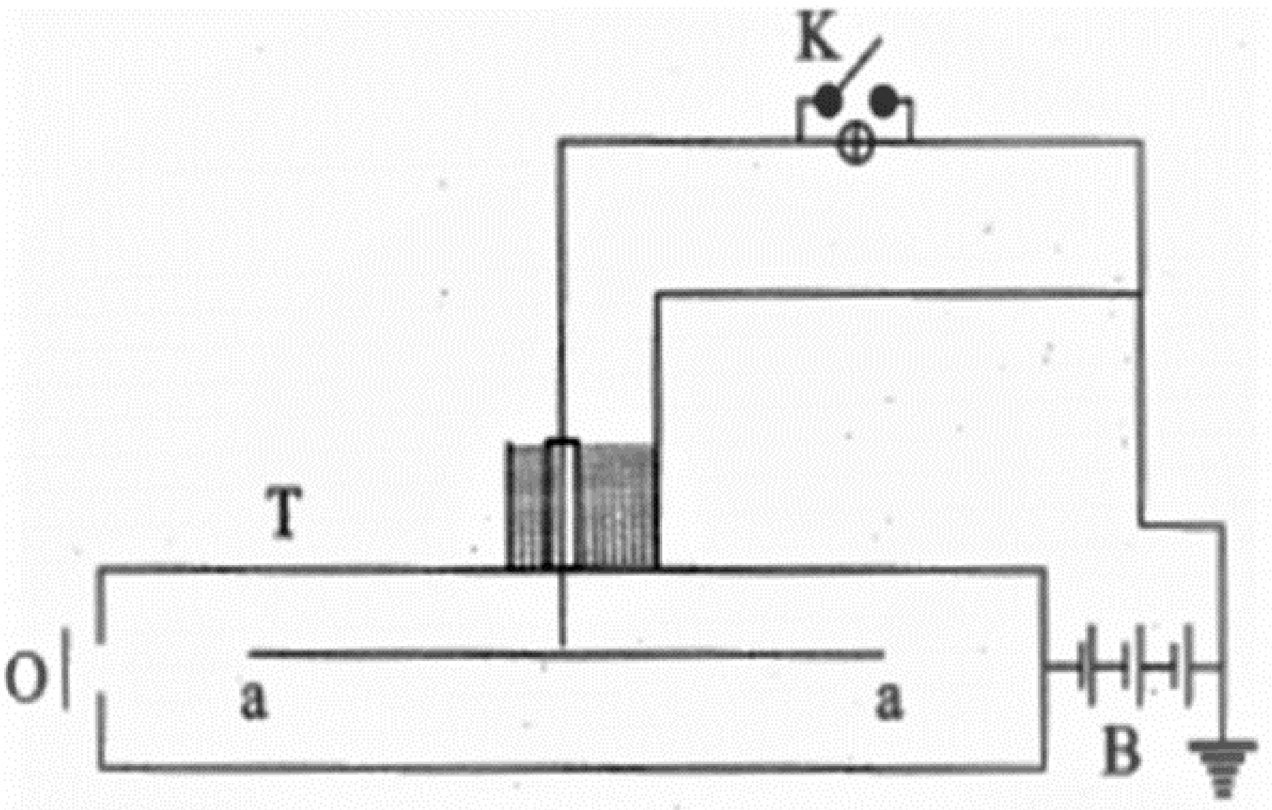

Fig. 1.2. Ionization chamber.

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- By X-ray quality (hardness) we mean **spectral energy distribution** or **constitution of beam** with regard to wavelength.

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- As the **white light** consists of many wavelengths of visible region corresponding to different pure colours, in the similar fashion a beam of X-radiations consists of a **spectrum of X-rays** and this **spectral distribution of X-radiations**, previous to the analysis, was identified as **quality of X-radiations**.

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- The measurement of quality of X-radiations is done with the help of two types of methods:

- [1] It depends upon the properties which are the **same** as those of the orbital ranges of the electromagnetic spectrum, and

- [2] It depends upon the properties which are **different**.

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- The measurement of quality of X-radiations is done with the help of two types of methods:
- [1] It depends upon the properties which are the **same** as those of the orbital ranges of the electromagnetic spectrum, and
- [2] It depends upon the properties which are **different**.

Here we shall use the later method for a brief description. The method depends upon the **property of X-ray absorption, HALF value layer** and **Mass absorption coefficient.**

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- The X-radiations, in traversing the matter of all kinds, are absorbed in accordance with the exponential law which is expressed as

$$I_x = I_0 \, e^{-\mu x},$$

where

- I_x is intensity after passage through homogeneous matter of thickness x.
- I_0 is the initial intensity
- e is the natural base of logarithms, and
- μ is the absorption coefficient.

MEASUREMENT OF X-RADIATIONS-Hardness:

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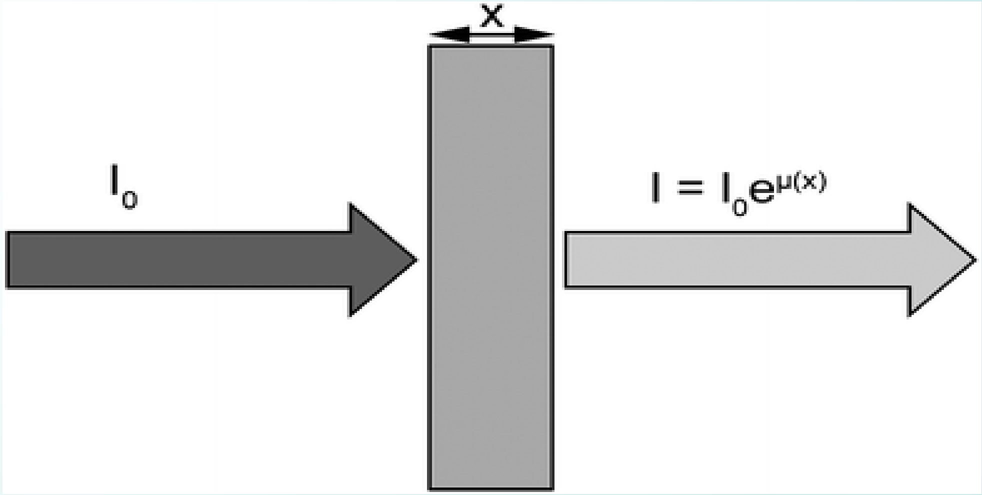

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- The absorption coefficient of any material is defined in terms of ***half-value layer*** (HLV) or the **thickness of an absorbing material which diminishes the intensity of a parallel bundle of rays to one half the initial value**.

Hence, $\mu = \log_e 2 / HVL.$ (1)

Thus, if HVL is measured, μ, can be calculated.

MEASUREMENT OF X-RADIATIONS-Hardness:

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Hence, $\mu = \log_e 2 / HVL.$ (1)

Thus, if HVL is measured, μ, can be calculated.

In other words, we measure the intensity for different thickness of absrobing material and the HLV, which, in turn, gives the value of μ.

MEASUREMENT OF X-RADIATIONS-Hardness:

Hardness:

- The quality of X-radiations is determined by their absorption coefficient in **aluminium**.

- The rays are **hard** for **large** μ (have great penetrating power)
- The rays are **soft** for **small** μ (they are easily absorbed).

- Alternately, if we plot a graph between I_x and x, a **linear** relation holds.
- The **slope of the curve** indicates the **quality**;
- the **steeper the slope, the softer the ray**.

Diffraction of X-rays

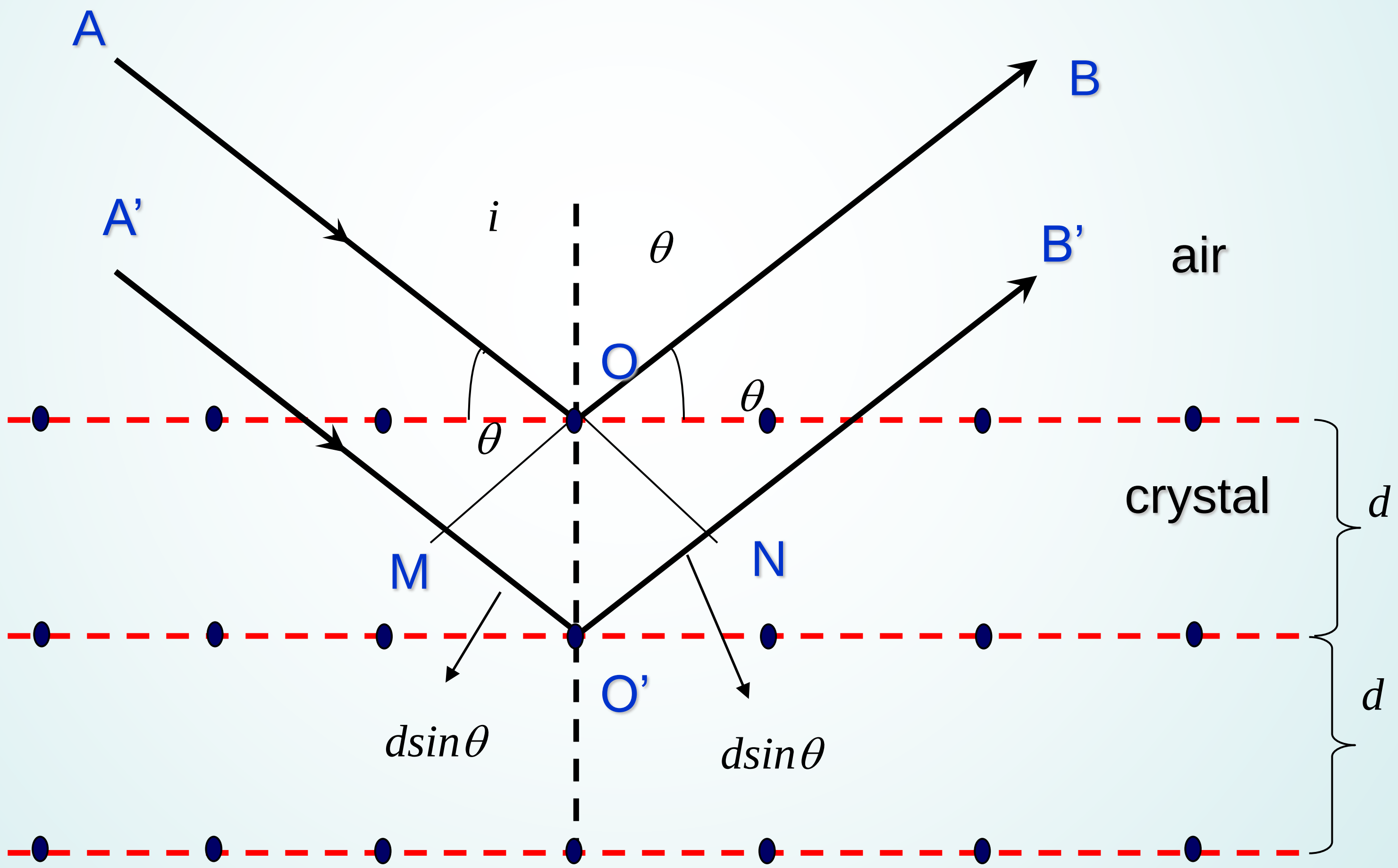
BRAGG'S LAW

BRAGG'S LAW

- After the experiments of Friedrich Knipping and **Laue W. H.** and **W. L. Bragg** started further investigation in this direction.
- They pointed out that through any crystal a set of equidistant parallel planes can be drawn, which pass through all the atoms of the crystal.
- In fact, a large number of such families of planes can be drawn. The planes of each family are separated from the other by a characteristic distance. The planes are called Bragg planes and their separations, **Bragg spacings**.

Bragg's Law

- The x-ray diffraction is shown by the diagram in Figure.

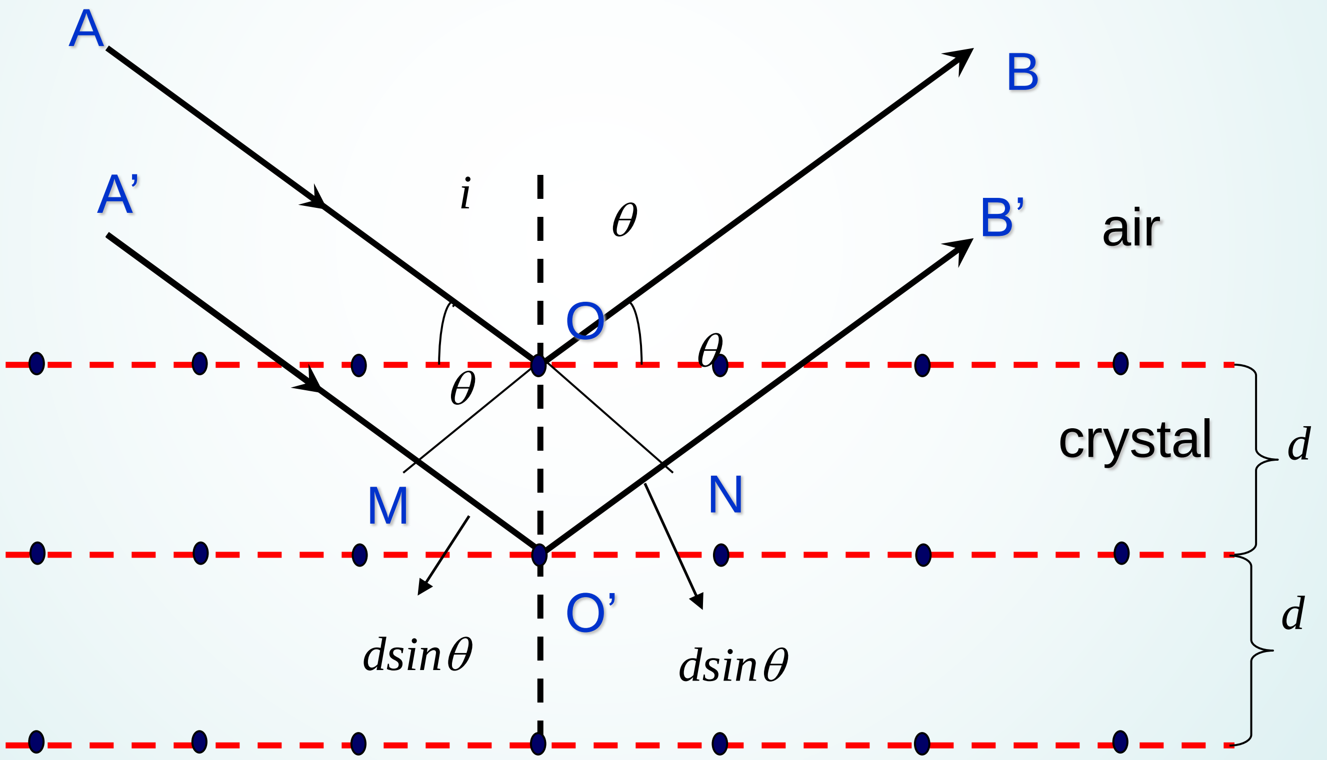


BRAGG'S LAW

- **d**: Bragg spacing
- λ : wavelength of monochromatic beam of X-radiations
- Since X-radiations are much more penetrating than ordinary light, it is essential to consider the reflection at several such layers.

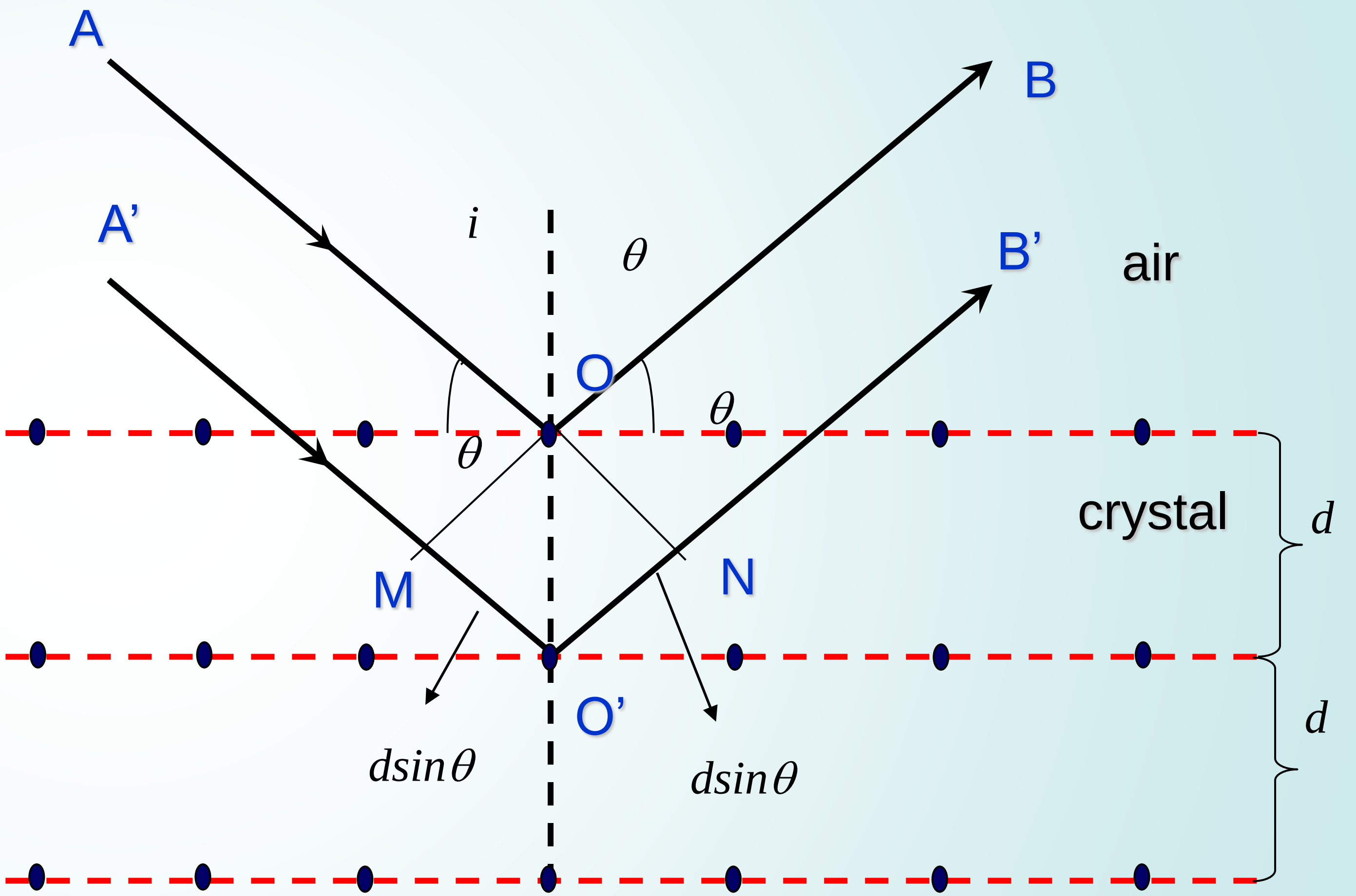
Bragg's Law

- *For constructive interference, the path difference* (***bright***) = $n\lambda$



Bragg's Law

From the Figure, the path difference is equal to MO'N between rays AOB and A'O'B' is given by



MO' + O'N = 2d sin θ

BRAGG'S LAW

- In Fig., a plane wave falls on these planes at an angle θ , between the propagation direction of incident beam and planes.

- The angle θ is known as **glancing angle**, and reflection condition require that $\theta = \theta'$.
- From Fig. the path difference is to MO'N, i.e.

MO' + 0'N.

- The geometry of Fig. 4 further gives

$$MO' + 0'N = 2d \sin \theta.$$

BRAGG'S LAW

- Now the condition for constructive interference becomes

$$2d \sin \theta = n \lambda$$

- where n is an integer called the **order of reflection**. The above equation together requirement $\theta = \theta'$ constitutes **Bragg's law** for X-ray reflection

BRAGG'S LAW

- From Bragg's law if the spacing d between adjacent Bragg planes in the crystal is known, X-ray wavelength λ may be calculated.

- d known
- λ unknown

$$2d \sin \theta = n \lambda$$

BRAGG'S LAW

- To **determine d** is simple in the case of crystals whose atoms are arranged in cubic lattices similar to those of rock salt (NaCl).
- As an illustration let us calculate the value of d in a crystal of NaCl.

Numerical:

NaCl crystal has FCC structure. The density of NaCl is 2.18×10^3 kg/m^3. Calculate the distance between the two adjacent atoms.

1.8. LAUE SPOTS:

LAUE SPOTS

- With the help of Bragg's law, it is possible to explain the **formation of Laue spots**.
- In a crystal there are great many **families of sets of parallel planes** and for each family the values of ***d*** and are different.
- The X-rays that penetrate a crystal will be reflected from **any set of parallel layers only if the incident beam satisfies the Bragg relation.**

LAUE SPOTS

- In the **production of Laue spots**, radiations used contain a **wide range of wavelengths**. Therefore, different sets of parallel layers reflect the rays of appropriate wavelengths given by Bragg's law.

- Thus, **several intense spots** will be produced on the photographic plate arranged in the regular pattern depending upon the crystal structure.

1.9 BRAGG'S SPECTROMETER

BRAGG'S SPECTROMETER:

The apparatus-Bragg's spectrometer, which is much similar to the **optical spectrometer**, is shown in Fig. 5.

- It consists of three parts, viz.,
  - a **source of X-radiations**,
  - a crystal mounted on a **table** and
  - a **detecting device**.

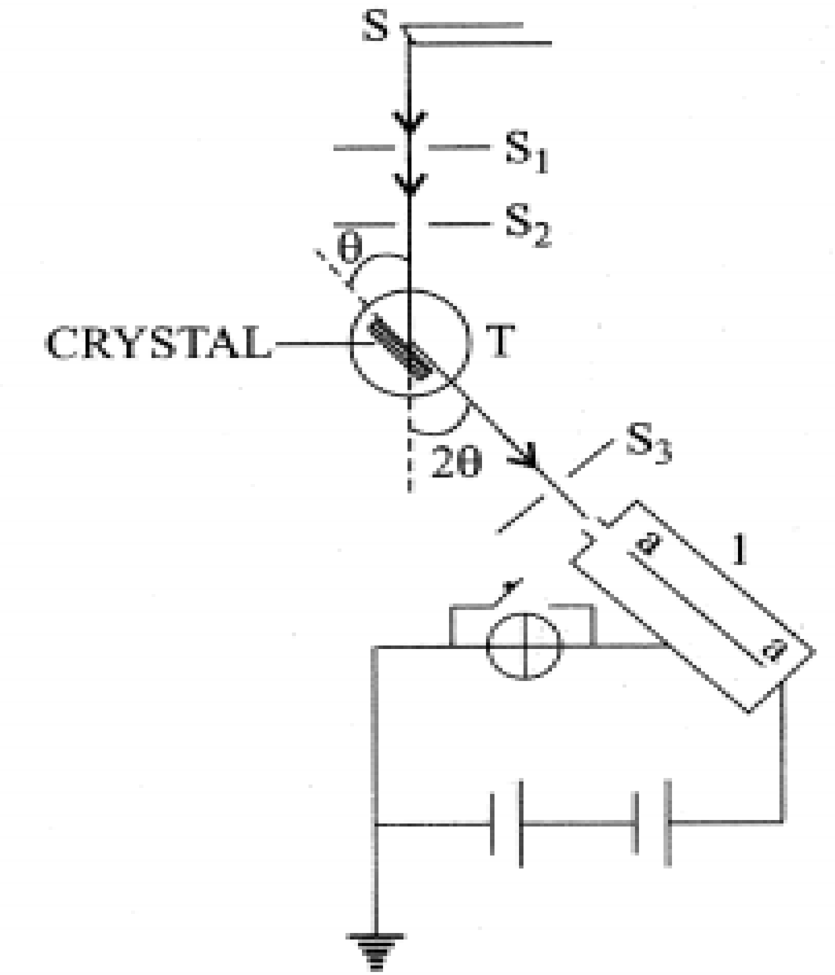


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- The X-rays from an X-ray source **S** are allowed to pass through two narrow slits s_1 and s_2 which collimate the rays into a narrow beam.
- This beam is then allowed to fall at a **glancing angle** $\boldsymbol{\theta}$ on the cleavage face of a crystal mounted on the table ***T***, the angular position of which can be read with the help of attached vernier.

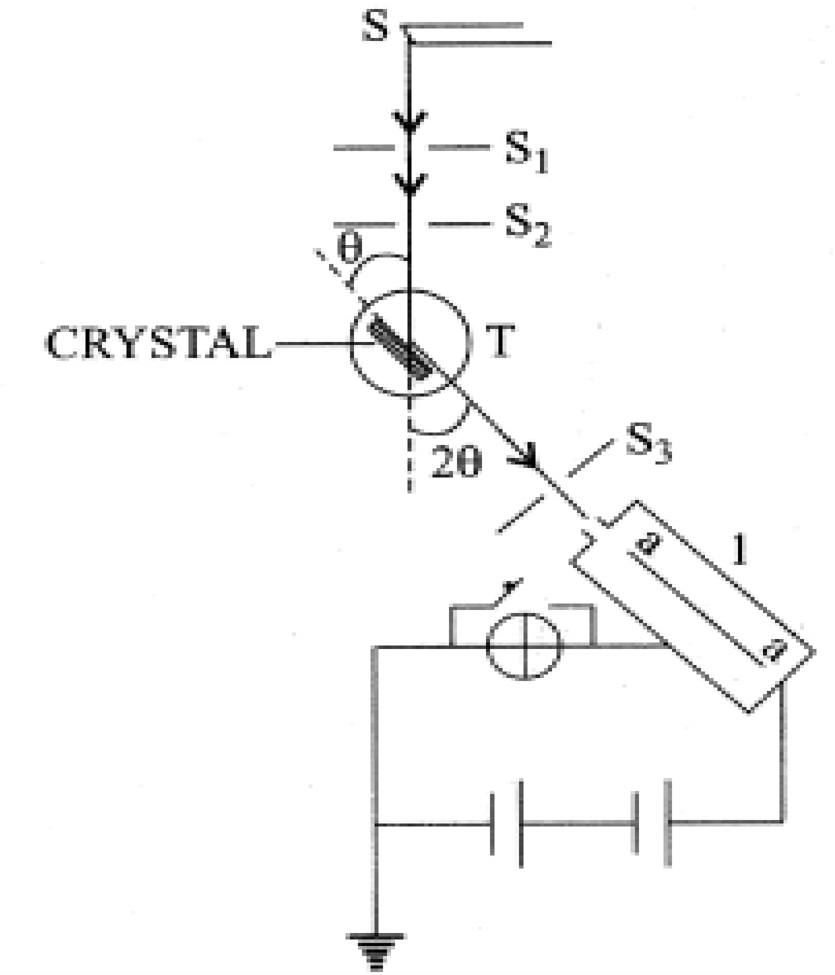


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- The reflected beam, which subtends an angle 2 θ with the incident beam, enters an ionisation chamber ***I*** by means of which the intensity is measured.
- For a photographic registration, ionisation chamber is replaced by a photographic plate.

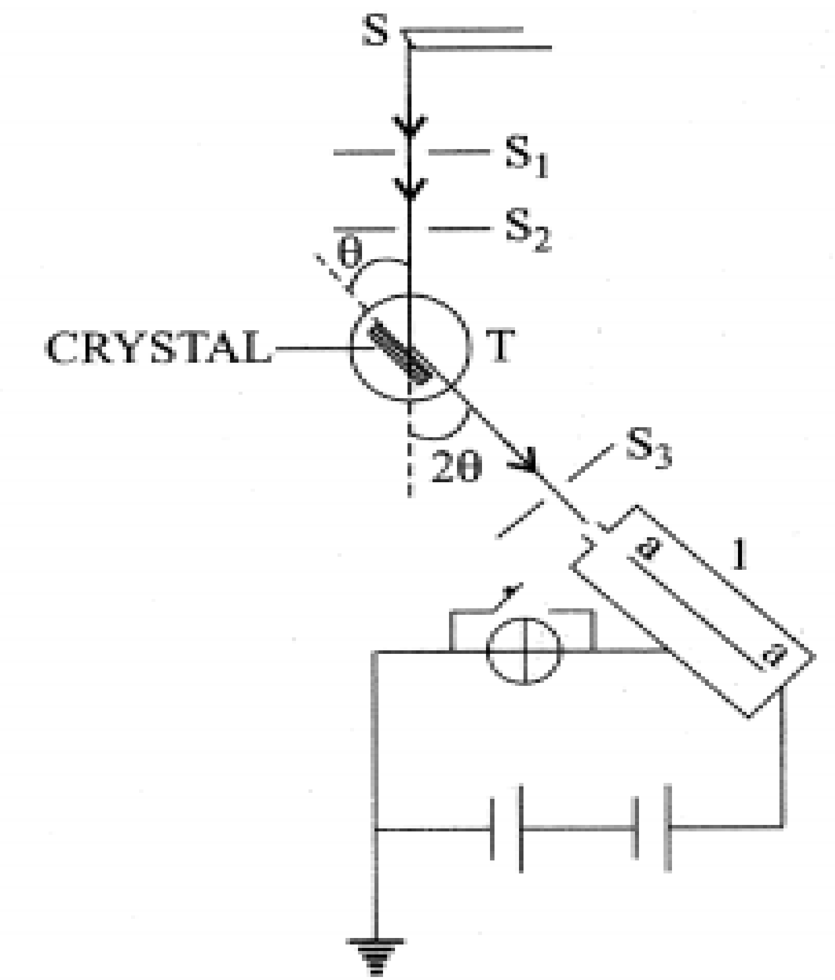


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- If a **homogeneous beam** falls on the crystal, Bragg's Law is satisfied in accordance with the following equations:

$$2d \sin \theta_1 = \lambda$$

$$2d \sin \theta_2 = 2\lambda$$

$$2d \sin \theta_3 = 3\lambda$$

…………………..

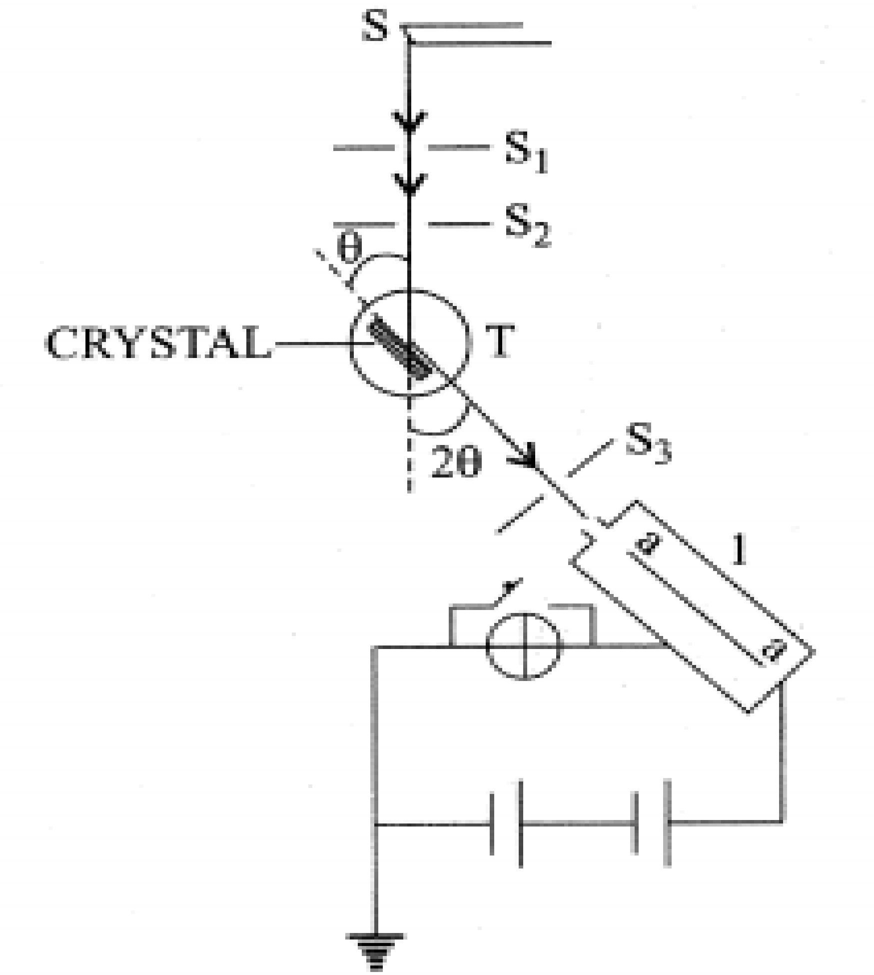


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- With n = 1, 2, 3,.. this gives

$\sin\theta_1 : \sin\theta_2 : \sin\theta_3 :: 1 : 2 : 3.$

- By measuring the glancing angle, the assumptions of Bragg are verified, if the above proportionality holds good.

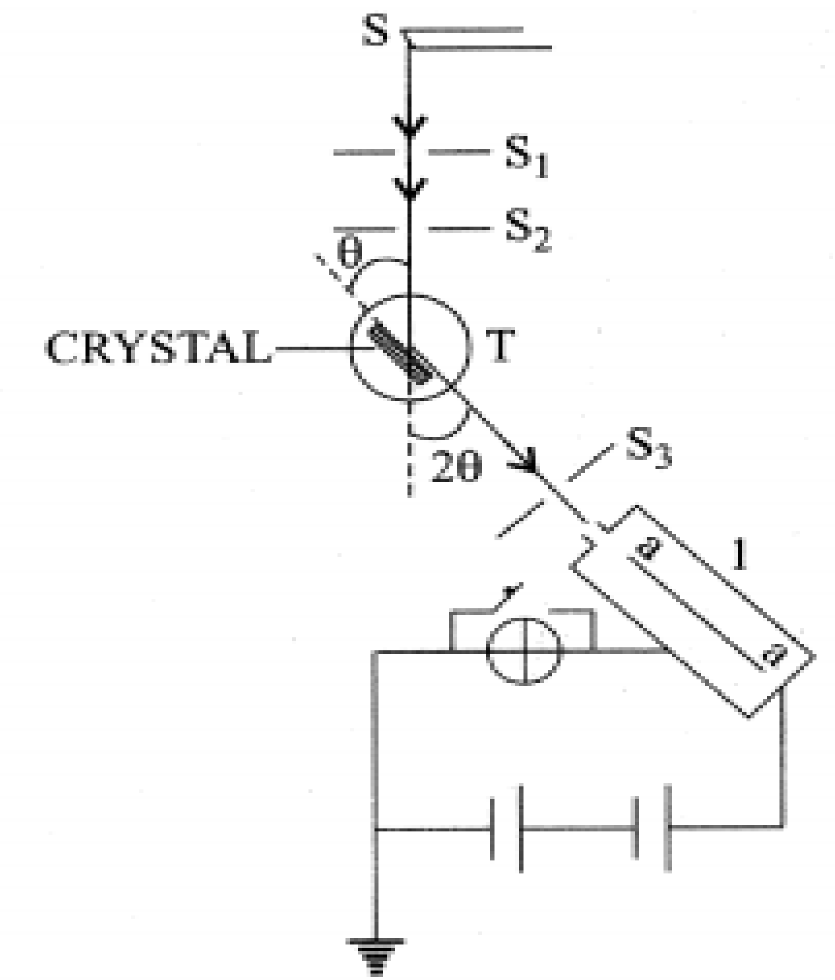


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- If the beam of X-radiations is **heterogeneous** one, only for **one** order, Bragg's equation will be satisfied for different glancing angles.
- Thus, X-ray spectrum will be obtained as with ordinary composite light.

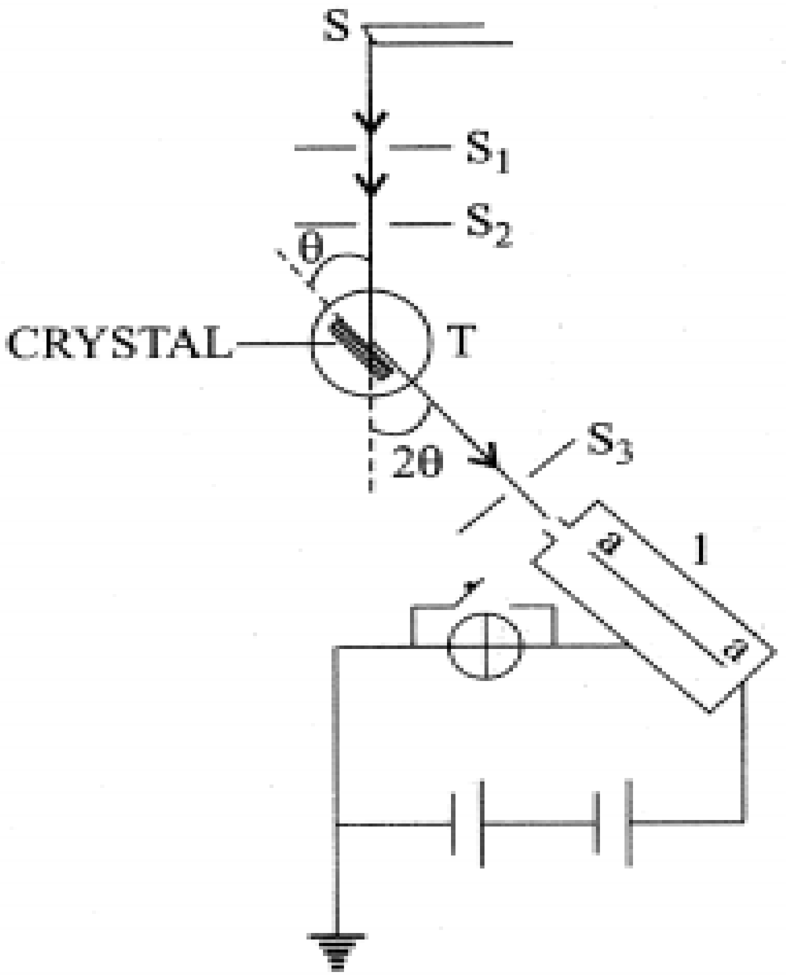


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- To start the experiment, the incident beam is allowed to fall on a small glancing angle θ.
- The rotating arm is adjusted at an angle 2θ.
- The intensity of reflected radiations is then measured by noting the rate of deflection of the needle of the electrometer.

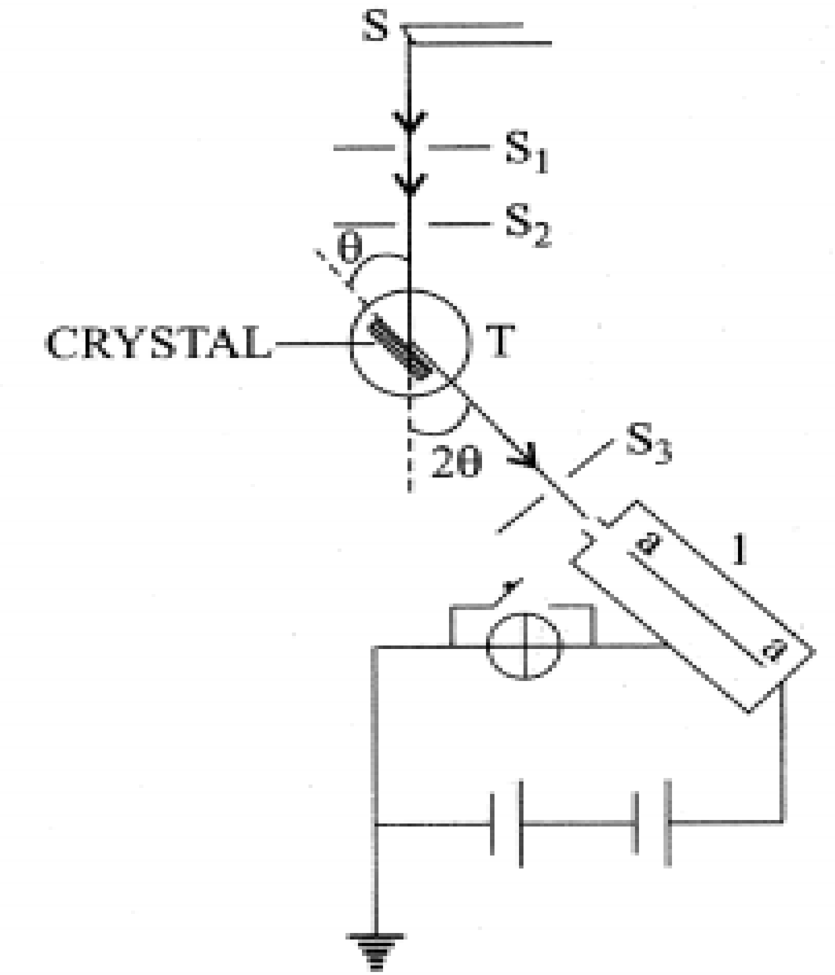


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- The glancing angle is then increased by small steps and observations are repeated.

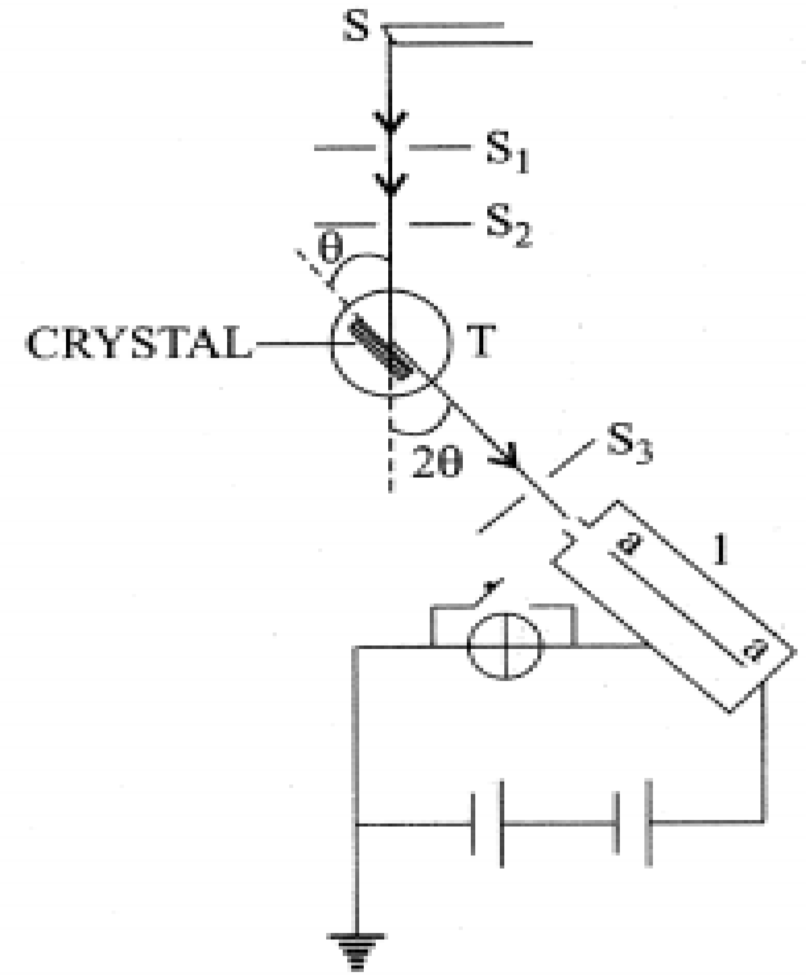


Fig. 1.5. Measurement of intensity

BRAGG'S SPECTROMETER:

- Now, if intensity of ionisation is plotted against glancing angle, the X-ray spectrum as shown in Fig. 6 is obtained

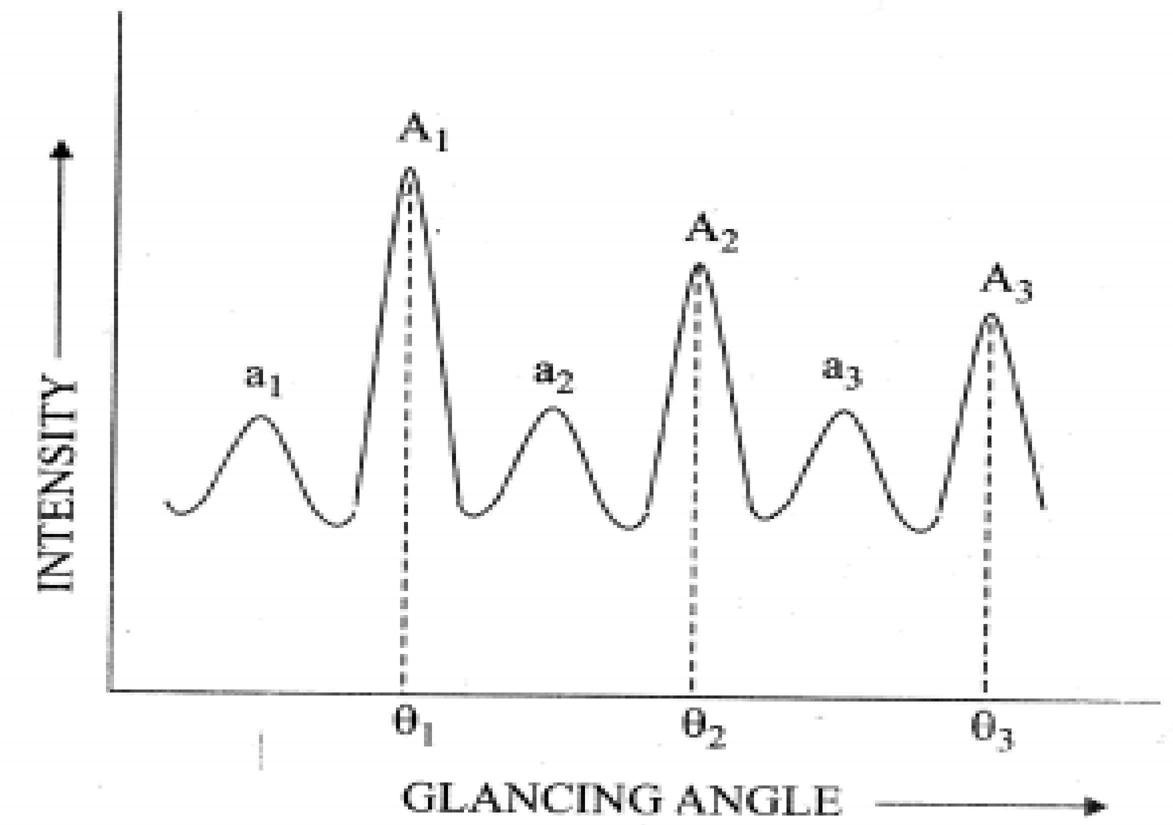


Fig. 1.6. X-ray spectrum.

BRAGG'S SPECTROMETER:

- It is observed that only for certain values of θ , the intensity is maximum.
- In the vicinity of $\theta_1,\theta_2,\theta_3$, we get more than one maxima.

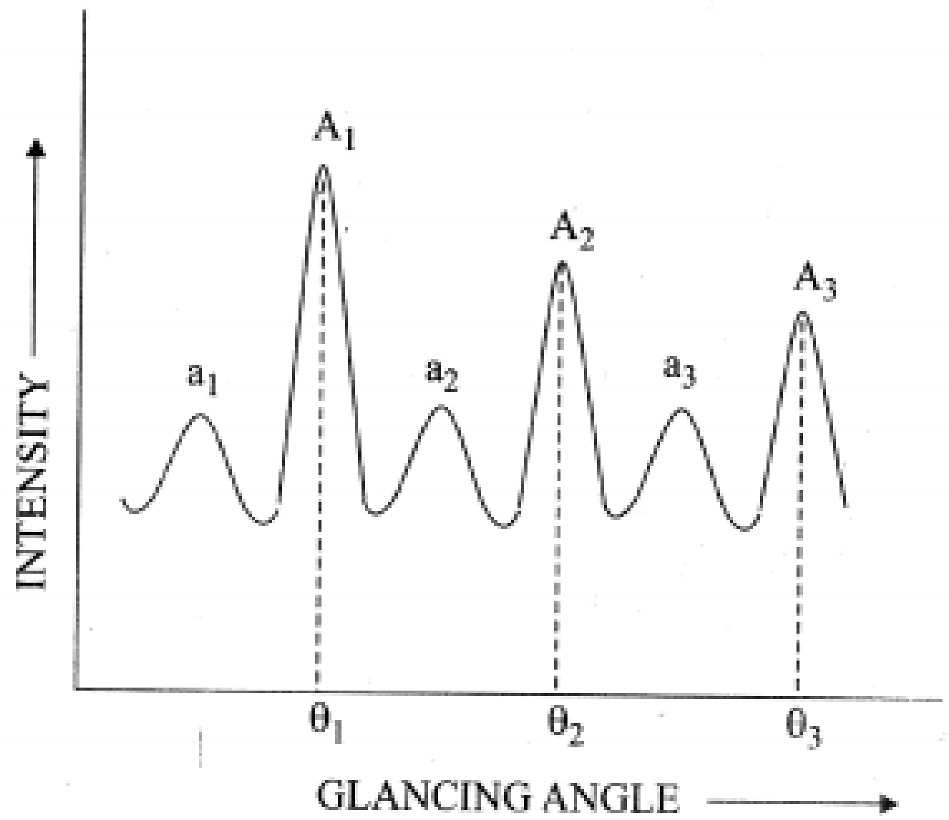


Fig. 1.6. X-ray spectrum.

BRAGG'S SPECTROMETER:

- The second maxima in the vicinity of a glancing angle corresponds to the radiations of another wavelength.

- Thus, the maxima a_1- A_1, a_2 – A_2 and a_3 – A_3 constitute the first, second and third order of X-ray spectrum.

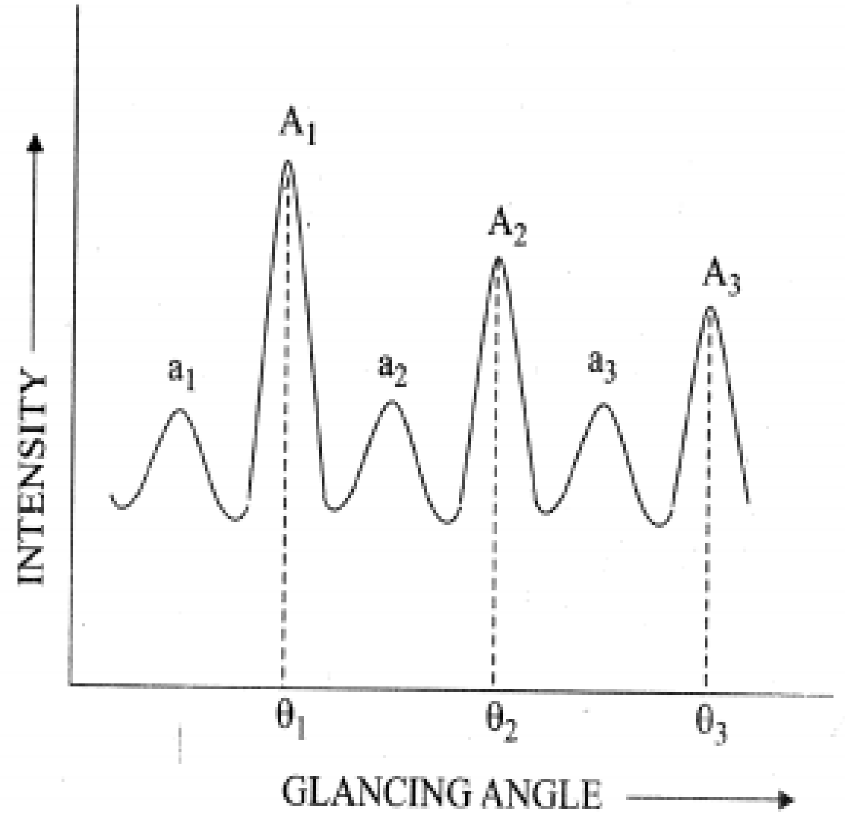


Fig. 1.6. X-ray spectrum.

BRAGG'S SPECTROMETER:

It is also noticed that

- The intensity of reflected beam decreases as the order of spectrum increases.
- The position of maxima depends on the element of the target used to produce X-radiations.
- The intensity of reflected beam never falls to zero but only to a minimum value. This shows that over a continuous X-ray spectrum, line spectrum is superposed.

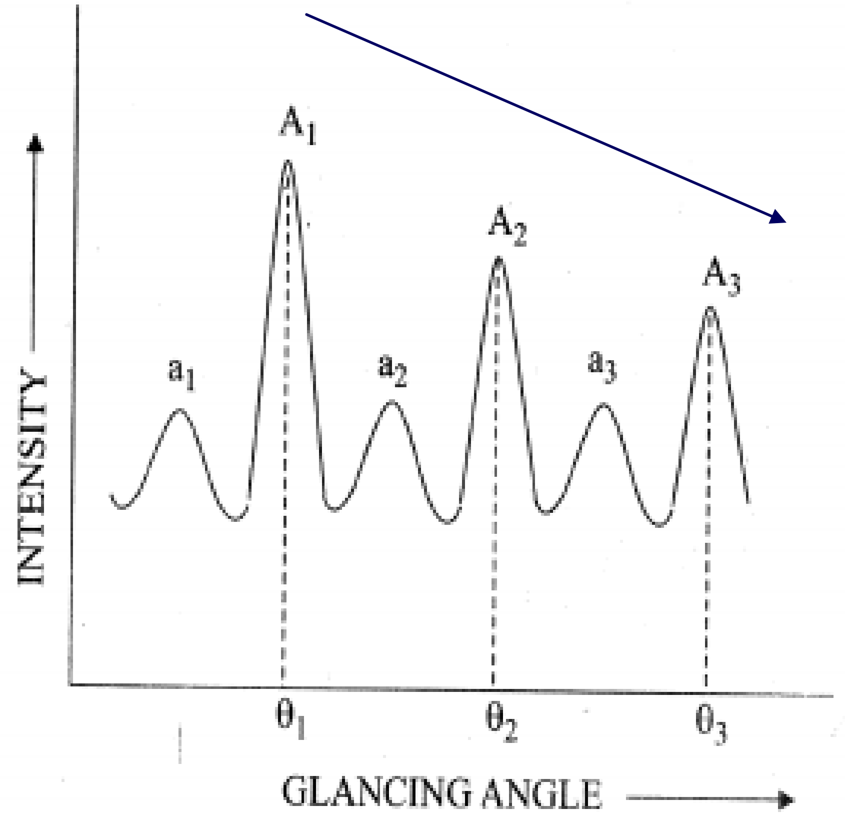


Fig. 1.6. X-ray spectrum.