X-RAY

Historical background

On Nov, 1895, Wilhelm Conrad Röntgen (accidentally) discovered an image cast from his cathode ray generator, projected far beyond the possible range of the cathode rays (now known as an electron beam). Further investigation showed that the rays were generated at the point of contact of the cathode ray beam on the interior of the vacuum tube, that they were not deflected by magnetic fields, and they penetrated many kinds of matter. Röntgen named the new form of radiation X-radiation (X standing for "Unknown").

What are X-Rays

X-rays are electromagnetic radiation of very short wavelength (0.1Å and 100Å) and high energy which are emitted when fast moving electrons or cathode rays strike a target of high atomic mass.

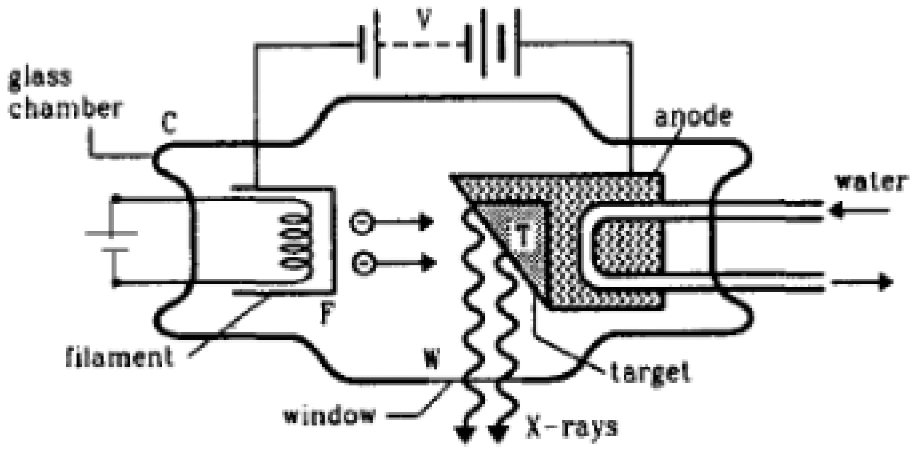
The X-Rays extends from the ultraviolet band to gamma rays band. Although their is very thin line between the X-ray and gamma rays but they are distinguished by the source of their generation. In the older days the X-Rays were distinguished from gamma rays by the wavelength and frequency but with time it has been observed that their exists X-Rays and gamma rays overlapping band and hence it is then understood that the distinction between them is source of generation.

Coolidge tube

William Coolidge invented the X-ray tube popularly called the Coolidge tube. His invention revolutionized the generation of X-rays and is the model upon which all X-ray tubes for medical applications are based.

The characteristic features of the Coolidge tube are its high vacuum and its use of a heated filament as the source of electrons. There is so little gas inside the tube that it is not involved in the production of x-rays, unlike the situation with cathode gas discharge tubes.

The operation of the Coolidge tube is as follows. Due to filament current the cathode filament is heated, it emits electrons. The hotter the filament gets, the greater the emission of electrons. A constant potential difference of several kilovolts is maintained between the filament and the target using a DC power supply so that the target is at a higher potential than the filament. These electrons are accelerated towards the anode with a very high speed and when the electrons strike the anode and emit x-rays. These X-rays are brought out of the tube through a window W made of thin mica or mylar or some such material which does not absorb X-rays appreciably. In the process, large amount of heat is developed, and thus an arrangement is provided to cool down the tube continuously by running water.



Note

(i) An increase in the filament current increase the number of electrons it emits. Larger number of electrons means an intense beam of X-rays is produced. This way we can control the quantity of X-rays i.e. Intensity of X-rays.

(ii) An increase in the voltage of the tube increase the kinetic energy of electrons ($eV = 1\ 2mv^2$). When such highly energetic beam of electrons are suddenly stooped by the target, an energetic beam of X-rays is produced. This way we can control the quality of X-rays i.e. penetration power of X-rays.

(iii) Based on penetrating power, X-rays are classified into two types. HARD-rays and SOFT-x-rays. The first one having high energy and hence high penetration power are HARD-X-rays and another one with low energy and hence low penetration power are SOFT-X-rays.

Continuous X-rays

When electron strikes target an electron loses a part of its kinetic energy and continues to move with the remaining energy until it hits another atom of the target. Part or whole of the energy lost by the electron is converted into a photon. This process is known as bremsstrahlung (breaking radiation)- as it leads to the electron getting decelerated by the target. There is existence of a minimum wavelength (or maximum frequency) in x-ray spectrum. This is called the cutoff wavelength or the threshold wavelength.

If the potential difference between the filament and the target is V, then the kinetic energy of the electron just before it hits the target is

$$K.E. = eV$$

Energy of the X-ray photon, $\Delta E = \frac{hc}{\lambda}$

ΔE is the fraction of K.E. of electron that gets converted into photon. l is the wavelength of the photon. Wavelength of the X-ray's photon

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

as

$$\Delta E \le eV \qquad \Rightarrow \qquad \lambda \ge \frac{hc}{eV}$$

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

This minimum wavelength does not depend on the target material and depend on the potential difference between the filament and the target.

Characteristic x-ray

When the high energy lectrons "knock off" the innermost electrons of the atoms of the target material causing a vacancy. This vacancy is filled by a electron that 'jump' from one of the outer shells. If the vacancy is created in K shell and electron from the L shell fills the vacancy then the emitted photon is a K_α X-ray. If a vacancy is creasted in the K-shell and an electron from the M shell fills this vacancy then the x-ray emitted is known as a K_β X-ray.

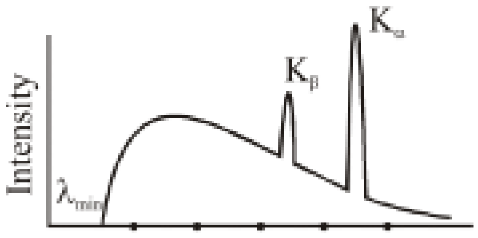
$$\lambda_{K_\alpha} = \frac{hc}{E_L - E_K}$$

$$\lambda_{K_\beta} = \frac{hc}{E_M - E_K}$$

Where E_K, E_L, E_M are the electron energy levels

These X-ray are known as characteristic X-ray as they depend on the target material (character of material), not on the applied voltage.

The adjoining graph shows the variation of the intensity of X-ray coming out of the tube with wavelengths. At some sharply defined wavelengths (K_α K_β) the intensity of the emitted radiation is very large.



Moseley's Law

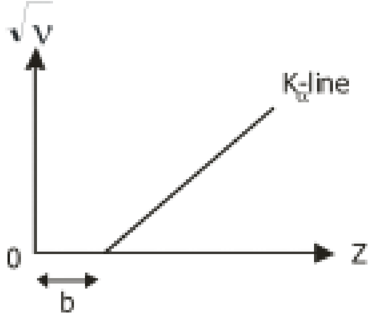
By measuring the wavelength associated with a particular line (now designated K_α), from the spectrum of each element, Moseley established that the lines from a large number of elements obeyed the relation

$$\sqrt{v} = a(Z - b)$$

Where a and b are constants with

$$a \approx \sqrt{\frac{3Rc}{4}} \quad (R = \text{Rydberg constant})$$

and $\quad b \approx 1$. (b is known as the screening constant)



Approximate explanation from Bohr's theory

Consider an atom from which an electron from the K shell been knocked out. Consider an electron from the L shell which is about to make a transition to the vacant site. If finds the nucleus of charge Ze screened by the spherical cloud of the remaining one electron in the K shell. If we neglect the effect of the outer electrons and the other L electrons, the electron making the transition finds a charge $(Z-1)$ e at the centre. One, therefore, may expect Bohr's model to given reasonable results if Z is replaced by $Z - b$

$$\Delta E = h\nu = Rhc\,(Z - b)^2 \left(\frac{1}{1^2} - \frac{1}{2^2}\right)$$

$$\Rightarrow \quad \sqrt{\nu} = \sqrt{\frac{3Rc}{4}}\,(Z - b)$$

Properties of X-Ray

1. These are highly penetrating rays and can pass through several materials which are opaque to ordinary light.
2. They ionize the gas through which they pass. While passing through a gas, they knock out electrons from several of the neutral atoms, leaving these atoms with +ve charge.
3. They cause fluorescence in several materials. A plate coated with barium platinocyanide, ZnS (zinc sulphide) etc becomes luminous when exposed to X-ray.
4. They affect photographic plates especially designed for the purpose.
5. They are not deflected by electric and magnetic fields, showing that they not charge particles.

Illustration :

To decrease the cut-off wavelength of contimuous X-ray by 25%, find the % change potential difference across the X-ray tube

Sol. $\lambda = \frac{hc}{eV}, \ \frac{\lambda_1}{\lambda_2} = \frac{V_2}{V_1}, \ \lambda_1 = \frac{3}{4}\lambda_1$

$V_2 = \frac{4}{3}V_1, \ \frac{100}{3}$ *% increases.*

Illustration :

The wavelength of K_a X-rays produced by an X-ray tube is 0.76 Å. Find the atomic number of anticathode materials.

Sol. *For K_a X-ray line.*

$$\frac{1}{\lambda_a} = R\,(Z-1)^2\left[\frac{1}{1^2}-\frac{1}{2^2}\right] = R\,(Z-1)^2\left[1-\frac{1}{4}\right]$$

$$\Rightarrow \frac{1}{\lambda_a} = \frac{3}{4}R\,(Z-1)^2 \qquad ...(1)$$

With reference to given data,

$l_a = 0.76$ Å $= 0.76 \times 10^{-10}$m; $R = 1.097 \times 10^7$ m

Putting these values in equation (1)

$$(Z-1)^2 = \frac{4}{3}\times\frac{1}{0.76\times10^{-10}\times1.097\times10^{7}} \cong 1600$$

$$\Rightarrow Z-1 = 40 \Rightarrow Z = 41$$

Pratice Exercise

Q.1 If the operating potential in an X-ray tube is increased by 1%, by what percentage does the cutoff wavelength decrease?

Q.2 When 40 kV is applied across an X-ray tube, X-ray is obtained with a maximum frequency of 9.7×10^{18} Hz. Calculate the value of Planck constant from these data.

Q.3 The K_β X-Ray of argon has a wavelength of 0.36 nm. The minimum energy needed to ionize an argon atom is 16 eV. Find the energy needed to knock out an electron from the K shell of an argon atom.

Q.4 A free atom of iron emits K_α X-rays of energy 6.4 keV. Calculate the recoil kinetic energy of the atom. Mass of an iron atom = 9.3×10^{-26} kg.

Answers

Q.1 approximately 1% Q.2 4.12×10^{-15} eV–s Q.3 3.47 keV

Q.4 3.9×10^{-4} eV