PROPERTIES AND APPLICATIONS OF X-RAYS

INTRODUCTION

On November 8, 1895, a German physicist Conrad Wilhelm Roentgen made a discovery which will remain forever one of the most important milestones in the history of humankind.

Roentgen, who had generally been a highly esteemed scientist known for the meticulousness and thoroughness of his research, had noticed a phenomenon that escaped the attention of many other researchers who at that time worked with the so-called cathodic rays. Cathodic ray is the name used to refer to electrons emitted from the negative electrode (cathode) of a discharge tube (Crooks's tube).

Having placed a flat plate covered with barium platinocyanide next to the CRT (Cathode Ray Tube), Roentgen had discovered that the plate would emit light (fluoresce), even if it were shielded from the direct light, both visible and ultraviolet, stemming from the gaseous discharge in the tube.

Roentgen deduced that the fluorescence of barium platinocyanide was caused by certain invisible radiation capable of passing through air and even through solid material screens.

Roentgen had named the radiation he discovered, X-rays. This name has been preserved in English to this day, while in some other languages, the X-rays are deservedly called Roentgen's Rays.

In four articles published in 1895 and shortly thereafter, Roentgen provided a classical description of the properties and behavior of X-rays, based on his ingenious and simple, Faraday-style experiments. Roentgen had stated the following facts:

a) Besides barium platinocyanide, many other materials would fluoresce after an exposure to X-rays.

b) A photographic emulsion is affected by X-rays in the same manner as by visible light.

c) X-rays cause a discharge of electrically charged particles.

d) X-rays propagate along straight lines like visible light.

e) Different materials have different degrees of 'transparency' with regard to X-rays.

f) A Magnetic field does not affect X-ray propagation (hence, X-rays are not charged particles).
g) Each time a cathode ray strikes an obstacle, X-rays are produced.

h) Obstacles made of heavy elements are more efficient producers of X-rays than those made of light elements.

i) No reflection, diffraction or interference of X-rays was observed. (As was discovered later, X-rays can be reflected, and undergo diffraction and interference under certain conditions).

The modern concept of X-rays is that they are electromagnetic waves with short wavelengths (in the range from about 0.1 x 10^{-10} to about 5 x 10^{-10} meters, for the so called characteristic radiation, and in a much wider range for the so called continuous or braking radiation. The meaning of these terms will be explained later). As well as all other parts of the spectrum of the electromagnetic waves, X-rays display both the properties of waves and of particles (X-ray photons). The energy of X-ray photons range from about 2 KeV to about 5 KeV for the characteristic radiation and from less than 1 eV to several MeV, for braking radiation.

The ability to pass through solid materials is the basis of the wide use of X-rays in medical diagnostics. The application of Roentgen's discovery to medical purposes had virtually caused a revolution in medicine.

As it was found in the course of subsequent research, X-rays may have a serious detrimental effect on living tissues if the exposure exceeds certain levels, both in regard to the rays intensity and the exposure duration. Therefore, rigorous protective measures are always necessary whenever X-ray equipment is being operated.

When a beam of cathode rays (electrons) strikes a material, two types of X-rays are generated. One type has a continuous spectrum and is called either continuous X-rays or Brehmsstrahlung which is a German word meaning braking radiation. This name is due to the mechanism of the generation of this type of X-ray. Continuous X-rays are produced by moving electrons which are losing their kinetic energy in the course of their deceleration while entering the material of the obstacle. If the decrease of an electron energy is E, the frequency ν, of the emitted ray is determined by the X-ray photon energy, as per the equation:

\[ hv = \Delta E \]

Obviously, as the electrons energies are distributed over a certain range, the values of \( \Delta E \) may be anything within that range, and therefore a continuous spectrum of photon energies, i.e. of wavelengths/frequencies is present in the braking radiation.
If the cathode ray beam is comprised of electrons which have been subjected to an acceleration voltage $V$, then the short wave cut-off wavelength $\lambda_0$ is determined by $V$, as expressed by the so called Duane-Hunt law, as follows:

$$\frac{hc}{\lambda_0} = eV$$

and this cut-off wavelength is independent of the material of the obstacle. (Another name for the Duane-Hunt law is inverse photoelectric effect).

The second type of X-ray is called a characteristic X-ray. It was first studied in England by Henry Mosley. The spectrum of this radiation consists of discrete lines, depending on the material of the obstacle (sometimes called anti-cathode or anode). The characteristic radiation is generated when an electron of a cathode ray strikes an atom of the anode's material and causes an excitation of an electron in the latter. The excited electron then delivers the absorbed energy back, emitting an X-ray photon of energy equal to the difference between energy levels of its excited and non-excited states. Since the energy levels of electrons in atoms are quantized, the energies of the emitted X-ray photons, i.e. the wavelengths of X-rays, have certain well defined magnitudes, characteristic of the anode's material.

The characteristic radiation follows Mosley's law which is mathematically stated as:

$$\sqrt{v} = B(Z - \delta)$$

where $B$ and $\delta$ are constants specific to each line of the spectrum. $Z$ is the atomic number of the anode material. $v$ is the frequency of the given X-ray.

The spectra of X-rays, like those of visible, UV and infrared light, consist of series, which are sets of lines each associated with a certain unexcited energy level of electrons in a given atom. These series are denoted by capital letters, K, L, etc. The most commonly used X-rays belong to the K series. One must distinguish between the more pronounced $K_\alpha$ line and a weaker $K_\beta$ doublet. The $K_\alpha$ line really consists of two lines, $K_{\alpha 1}$ and $K_{\alpha 2}$. The $K_\beta$ line is actually a quadruplet consisting of four lines, denoted $K_{\beta 1}$, $K_{\beta 2}$ and two $K_{\beta 2}$.

Besides the manner in which X-rays were obtained in Roentgen's experiments, X-rays are also generated in many nuclear reactions.

The use of X-rays in science is manifold. For example, the study of characteristic radiation provides information about the
structure of atoms of the anode material. The study of X-ray absorption in materials enables one to gain knowledge about the atomic structure of these materials.

In extremely sophisticated experiments, scientists succeeded in revealing, through the use of X-rays, the atomic structure of many highly complicated organic molecules, some of which contain thousands of atoms arranged in a very complicated spatial way. Among these materials are important drugs and other useful materials.

In 1912, a German scientist Max von Laue suggested that crystals may serve as natural diffraction gratings for X-rays. Hence, if an interatomic distance is known for a certain crystal, then by observing diffraction of X-rays on this natural grating, one can determine the wavelength of the ray. Inversely, if a wavelength of an X-ray is known, its diffraction can be utilized to measure the interatomic distance. Indeed, the idea of Laue was successfully applied by Friedrich and Knipping, and X-ray crystallography was born.

Soon afterwards, an English physicist, Sir William Bragg, suggested another technique for X-ray diffraction. Bragg used the interference of X-rays scattered from atomic planes of a crystal. The equation, suggested by Bragg, is as follows:

\[ n\lambda = 2d \sin \theta \]

where \( d \) is the interatomic distance in a crystal, \( \lambda \) is the X-ray wavelength, \( n \) is an integer called order of diffraction, and \( \theta \) is the diffraction angle.

Safety requirements in handling X-ray equipment.

All students are required to watch the safety presentation and to sign a statement to the effect that they have been explained the hazards inherent in the experiment and instructed as to the necessary precautions.
WAVELENGTH MEASUREMENT: BRAGG METHOD

Sir Lawrence Bragg presumed that the atoms of a crystal such as Sodium Chloride were arranged in a cubic and regular three dimensional pattern.

The mass of a molecule of NaCl is \( \mu/N \) Kg, where \( \mu \) is the molecular weight (58.46 x\(10^3\) Kg/Mole) and \( N \) is Avogadro's number (6.02 x\(10^{23}\) molecules/mole). The number of molecules per unit volume is \( \rho N/\mu \) molecules per cubic meter, where \( \rho \) is the density, (2.16 x\(10^3\) kg/m\(^3\)). Since NaCl is diatomic, the number of atoms per unit volume is 2\( \rho N/\mu \) atoms per cubic meter.

The distance, therefore, between adjacent atoms, 'd' in the lattice is derived from the equation:

\[
d^3 = \frac{1}{2\rho N/\mu}
\]

and for NaCl, \( d = 0.282 \) nm.

The first condition for Bragg "reflection" is that the angle of incidence, \( \theta \) equals the angle of reflection, this is as for optical reflection and infers that any detector of the reflected rays must move through an angle 2\( \theta \), the 2:1 spectrometer relationship.

\[
n\lambda = AB + BC = 2d \sin \theta
\]
THE TEL-X-OMETER

Figure 1
Mount slide collimator (3 mm), 562.016, at E.S.13 and collimator (1 mm) 562.015 at E.S.18.

Zero set and lock the slave plate and the carriage arm cursor as precisely as possible. (See §I:10.6)

(I:10.6) The Spectrometer Mechanism:

Open the scatter shield and rotate the carriage arm until the cursor gives an accurate no-parallax zero reading on the 2θ scale.

Release the drive by unscrewing the clutch plate and push the slave plate (the inner rotating plate engraved with two datum lines, see fig.1) around until the datum lines are accurately opposite the zeros on the θ scale. It may be necessary to "mean out" small zero-reading differences on each side of the θ scale.

Check that the carriage arm cursor is still at zero on the 2θ scale and screw in the clutch plate to engage the 2:1 drive mechanism.

Now rotate the carriage arm through 90° (2θ) and note that the crystal slave plate moves through 45° (θ).

Sight through the collimating slits and observe that the primary beam direction lies in the surface of the crystal.

(Mount the GM tube and holder at E.S.26)

Using a ratemeter, track the carriage arm around from it's minimum setting about (11°, 2θ) to maximum setting about (124°, 2θ). Plot on graph paper, the count rate per second at 1°, 2θ intervals, allowing time at each reading to estimate the mean of the fluctuations of the needle. The carriage arm should be indexed to 15°, 2θ and the thumb wheel set to zero; when the scatter shield is closed, settings from 11° to 19° can be achieved using only the thumb wheel indications. If the ratemeter has a loud speaker, note the random, "quantum" nature of the beam of radiation at low count rates. Where the count rate appears to peak, plot intervals of only 10' of arc using the thumb wheel (see §I:10.8). At each peak, measure and record the maximum count rate and the angle, 2θ as precisely as possible.
(I:10.8) Fine and Coarse Controls

The carriage arm is terminated outside the shield with an orange plastic manual control. Measurements can be made at the cursor to an accuracy of 15 minutes of arc.

To achieve fine adjustment of the carriage arm, rest the hand on the base flange of the Tel-X-Ometer or on the bench top and using the thumb rotate the knurled aluminum drive wheel protruding from the manual control.

To achieve fine measurements, line up the cursor exactly on the most convenient 2θ graduation which is central within the region requiring detailed examination. Hold the manual control rigidly in this position and "slip" the thumb wheel against the friction of the drive cord until the zero on the thumb wheel scale aligns exactly with the pointer.

Now the Thumb wheel can be moved ± 4° (2θ) about the preset center line by an amount which can be measured at the thumb wheel scale to an accuracy of 5' of arc. This amount should be added or subtracted from the selected cursor setting according to the direction of movement of the arm.

Observe that the continuous spectra of "white" radiation exhibit peak intensities and intercepts on the 2θ axis which only vary with the voltage setting of the X-ray tube. The six peaks superimposed on the continuous spectrum do not vary in angle 2θ with voltage setting, but only in amplitude.

Tabulate the results from the six peaks of the graph and calculate λ and n.

Observe that the sharp peaks are a pair of emission lines which reappear in second and third orders of diffraction. The more energetic radiation, termed Kβ, is successively less intense than the longer wavelength, Kα, line.
In the absence of micro gratings, the reasonable argument was formulated by Sir Lawrence Bragg that the NaCl crystal could be used as a 3-D grating which would reveal diffraction information by means of which the wavelength of the primary radiation could be established, but previously (in the second sentence of D14) a bland assumption is made for Avogadro's number. If, however, the wavelength of the radiation is obtained by using a man-made grating, as in a previous experiment, then a contemporary approach is to reverse the sequence of the Bragg argument to provide an accurate evaluation of Avogadro's number.

Whichever didactic sequence is adapted, the Bragg experiment verifies that the incident radiation is both electromagnetic and heterogeneous and that cooperative interference can be induced using a crystal as a diffraction grating.

The crystal itself cannot be considered as the source of the dual spectrum due to photon bombardment. The continuous spectrum is modified in both minimum wavelength and general intensity only by changing the X-ray tube accelerating voltage, without any variations in crystal parameters. The emission lines are particularly discreet in angle (2θ), whereas radiation from the crystal due to photon bombardment would be multi-directional.

The radiation must be derived through some inverse photoelectric effect from the impact of the thermionic electrons on the copper target within the X-ray tube.