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X-Ray and production of X-Ray

Lecture 3

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X-Rays

1-Introduction

X-rays was discovered by Wilhelm Conrad Roentgen at the University of Würtzburg in Germany. He, like many others in those days, was studying electric discharges in glass tubes filled with various gases at very low pressures. In experiments on November 8, 1895, Roentgen had covered the tube with

some black paper and had darkened the room. He then discovered that a piece of paper painted with a fluorescent dye, at some distance from the tube, would glow when he turned on the high voltage

between the electrodes in the tube. Realizing the importance of his discovery, Roentgen focused all his attention on the study of this new radiation that had the unusual property of passing through black paper. He found that the radiation not only could penetrate black paper but also thick blocks of wood,

books and even his hand. In the dark room, he observed shadows of the bones in his own hand. This was the first x-ray image.

The German anatomist von Koel liker (see his hand below) proposed that the new type of radiation be called Roentgen rays. Although this term is used in many countries, the most common name used is that coined by Roentgen himself, x-rays. The letter “x” is often used by physicists to indicate something “unknown.” Since the nature of these rays was unknown, Roentgen called them x-rays. All x-rays on earth are from man-made sources. There are x-rays from natural sources in outer space. They are, however, absorbed by the upper atmosphere and do not reach the earth’s surface.

Wilhelm Roentgen
1845 -1923
Discovered X-rays

2. Basic Requirements for Production of X-Rays

X-rays are produced when some form of matter is struck by a rapidly moving electron. To accomplish this, there are basic requirements must be met.

2.1 Supply of Electrons

There must be a supply of the electrons. Fortunately, they can be supplied by simply raising the temperature of a suitable material. An electron source is readily obtainable in as much as all matter is generally considered to be composed of electrons and other minute particles. All that is necessary to sufficiently heat the proper material. As the temperature rises, the electrons become more and more agitated until finally they escape or "boil off" the material, surrounding it in the form of an electron cloud. This is known as thermionic emission. In an X-ray tube the heated material is known as the filament, which is similar to the filament in a light bulb. Just as in a light bulb the filament is heated by passing electrical current through it. This cloud of electrons simply hovers around and returns to the emitting substance unless some external action or force pulls it away.

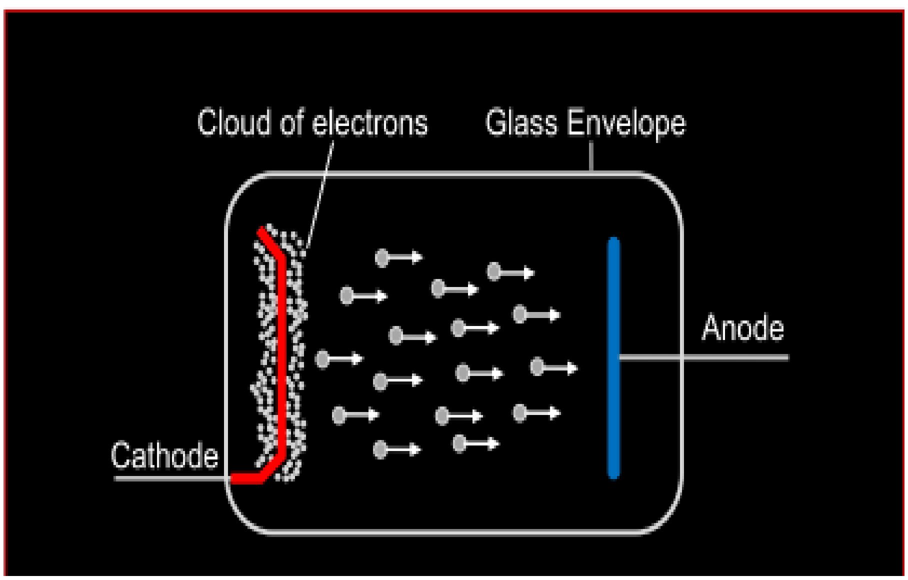

Figure 1.1 : Electrons cloud surrounds the filament

2.2 Movement of the Electrons

Movement of the emitted electrons is the second step in producing X-rays. This movement is brought about by the repelling and attracting forces inherent in electrical charges. The fundamental law of electrostatics states that like charges repel each other and unlike charges attracts each other. Electrons are negative charges, thus repel each other. However, a stronger attracting force is needed to accelerate the electrons to a higher velocity. Therefore, a strong opposite (positive) charge is used to move the electrons from one point to another. It is important that this movement is conducted in a good vacuum; otherwise the electrons collide with air molecules and lose energy through ionization and scattering. In an X-ray tube the anode is given a positive charge with respect to the filament, which is part of the cathode.

3-The production of characteristic X rays and Auger electrons

When charged particles pass through matter, they interact with the atomic electrons and lose energy through the processes of excitation and ionization. Ionization can also be produced as photons pass through matter by interactions such as the photoelectric effect and incoherent scattering . excitation occurs when there is a transfer of some of the incident particle's energy to electrons in the absorbing material, displacing them to shells further from the nucleus (i.e. to higher energy levels) and leaving a vacancy in the original shell. if the transferred energy exceeds the binding energy of the electron, ionization occurs, resulting in the electron being ejected from the atom. an ion pair, consisting of the ejected electron and the ionized, positively charged atom, is then formed. While the smallest binding energies (ionization potentials) for electrons in carbon, nitrogen and oxygen are 11.3, 14.5 and 13.6 eV, respectively, the average energy required to produce an ion pair in dry air (mostly nitrogen and oxygen) is 33.97 eV. the energy difference (approximately 24 eV) is the result of the excitation process. Whenever a vacancy is created in an inner electronic shell, whether by excitation or ionization, it is filled by an electron from a more distant (outer) shell. this results in a vacancy in this second outer shell, which is then filled by an electron (if available) from an even more distant outer shell, and the whole process repeats, producing a cascade of transitions. the energy released in each transition is carried away by the emission of electromagnetic radiation or by an electron ejected from another outer shell, known as an auger electron. Depending on the atomic number of the material, and the electronic shells involved, the electromagnetic radiation may be in the visible, ultraviolet or X ray portions of the spectrum. the energy of this radiation is characteristic of the particular atom, since it is equal to the difference in the electron binding energies of the initial and final states for the particular transition, which depends on atomic number. X rays thus emitted are known as characteristic or fluorescent X rays. a naming convention is used in accord with the shell in which the vacancy occurred. X rays emitted in association with an electron transition to the k shell are known as k characteristic X rays, and X rays resulting from an electron transition to the l shell are known as l characteristic X rays, and so forth. subscripts are used to denote the shell from which the vacancy is filled. the subscript a is used to denote radiation emitted for a transition between neighbouring shells and subscript b to denote radiation emitted for a transition between non-neighbouring shells. hence, a k_α X ray is emitted for a transition between l and k shells and a k_β X ray for a transition between *M* or *n* and *k* shells. (fig. 1.2). further subscripts are used as necessary to indicate which subshells are involved in the transition. the lines $k_{\alpha1}$, $k_{\alpha2}$, $k_{\beta1}$ and $k_{\beta2}$ are visible in the X ray spectrum from a tungsten target X ray tube. for X ray spectra from a molybdenum target, however, the energies of the subshells are closer together and the splitting of the kα and k_β lines is often not resolved .

as noted above, the energy carried away is the difference in binding energies between the initial and final states. for example, for tungsten, the energies of the k_α and k_β X rays are given by

$E(k_{\alpha1}) = E_{LIII} - E_k = -10.2 - (-69.5) = 59.3$ keV ……………………….(1.1)

$E(k_{\alpha2}) = E_{LI} - E_k = -11.5 - (-69.5) = 58.0$ keV ……………………….(1.2)

$E(k_{\beta1}) = E_{MIII} - E_k = -2.3 - (-69.5) = 67.2$ keV ……………..………..(1.3)

$E(k_{\beta2}) = E_{NIII} - E_k = -0.4 - (-69.5) = 69.1$ keV …………………..…….(1.4)

When an auger electron carries away the energy difference between the initial and final states, a further vacancy is created in an outer shell. for example, if the initial transition is from an M to a k shell, and the auger electron is also emitted from the M shell, there will be two resultant vacancies in the M shell. the kinetic energy of the auger electron is thus determined by the difference between the binding energy of the shell with the initial vacancy and the sum of the binding energies associated with the two vacancies that are created. for example, for the transition just described for a tungsten target, the energy of the auger electron is given by:

$E(auger) = E_k – E_M – E_M = – [(–69.5) – (–2.3) – (–2.3)] = 64.9$ keV ………..(1.5)

for a molybdenum target, the equivalent energy balance for the emission of an auger electron is shown in fig. 1.2

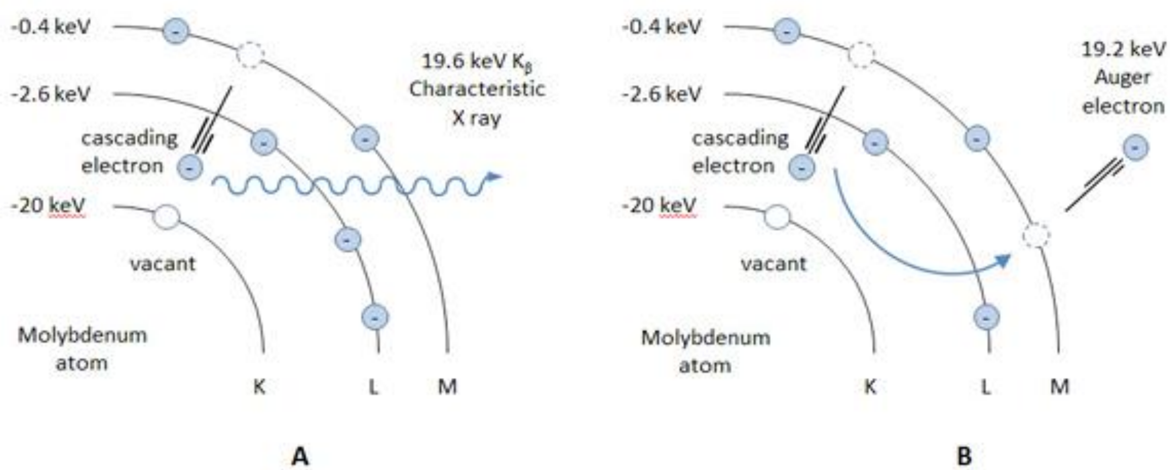

Figure 1.3. Transition of an electron in the M shell of molybdenum to fill a vacancy in the K shell followed by the emission of (a) a K_β characteristic X ray and (b) an Auger electron.

When considering energy deposition in matter following the creation and subsequent filling of a vacancy, it is important to know whether a fluorescent X ray or an auger electron is emitted. the probability of emission of a fluorescent X ray is known as the fluorescent yield, ω. since either a fluorescent X ray or an auger electron must be emitted, the probability of emitting an auger electron is 1 – ω. auger electron emission is more important for materials of low atomic number and for transitions amongst outer shells. the k fluorescence yield is close to zero for materials of low atomic number, but increases with increasing atomic number and, for example, is 0.007, 0.17, 0.60 and 0.93 for oxygen, calcium, selenium and gadolinium, respectively.

4- Radiation from an accelerated charge, bremsstrahlung

Most of the interactions that fast electrons have as they pass through matter are with the atomic electrons. they can, however, also have inelastic interactions with atomic nuclei. in such interactions, the electron path will be deflected and energy transferred to a photon, which is emitted. because the photon is emitted in association with a slowing down of the electron, it is known as bremsstrahlung, which means ‘brake radiation’ in german. The energy of the emitted photon can take any value from zero up to the energy of the initial electron, so that the passage of a beam of electrons though matter is accompanied by the emission of a spectrum of photons covering this energy range. bremsstrahlung photons are the major component of the X ray spectrum emitted by X ray tubes. the probability of bremsstrahlung emission is proportional to the value of Z_2 and is thus higher for higher atomic number materials such as tungsten (Z = 74). however, even for this material, the efficiency of bremsstrahlung production is less than 1% for 100 keV electrons. the angle of emission of the bremsstrahlung photons depends upon the electron energy. for electron energies much greater than the rest mass of the electron, the angular distribution is peaked in the forward direction, but as the electron energy decreases, the position of the peak moves so that it is at an angle to the forward direction. When the electron energy is low, the radiation is mainly emitted between 60° and 90° to the forward direction

5- Components and Properties of an X-Ray Tube

An x-ray tube consists of two electrodes sealed into an evacuated glass envelope.

- A negative electrode (cathode) which incorporates a fine tungsten coil or filament.
- A positive electrode (anode) which incorporates a smooth flat metal target, usually of tungsten.

Traditionally the tube has been a glass envelope with a reduced thickness at the window, the point where the x-rays exit, to reduce x-ray absorption. The high vacuum reduces the problem of the electrons colliding with, and being absorbed by, molecules of air and provides electrical insulation between the cathode and anode.

5.1 Cathode

A structure known as the cathode serves as the electron source. Actually, it is a filament or coil of (thorium oxide, ThO_2) tungsten wire that emits electrons when heated to a high temperature. But because the filament gives off electrons in all directions, some means must be used to focus them on a target. A reflector or focusing cup within the cathode structure, into which the filament is centered, serves to focus the electron beam much as light is focused by a flashlight reflector.

5.2 Anode

As mentioned previously, there must be a target for the electron beam to strike before X-rays are actually produced. In radiographic tubes the target material is generally made of tungsten. The choice of tungsten as a target for industrial radiography is based on four material characteristics:

1- High atomic number (74). The higher the atomic number of a material the more efficient is the conversion from electrical energy into X-ray energy.

2- High melting point (3400 $^{\circ}$C). Most of the energy in the electrons bombarding the target is dissipated in the form of heat. The extremely high melting point of tungsten permits operation of the target at very high temperatures.

3- Processes Occurring in the Anode of an X-Ray Tube

Each electron arrives at the surface of the target with a kinetic energy (in kiloelectronvolts) equivalent to the kV between the anode and cathode at that instant. The electrons penetrate several micrometers into the target and lose their energy by a combination of processes:

- As a large number of very small energy losses, by interaction with the outer electrons of the atoms; constituting unwanted heat and causing a rise of temperature.

- As large energy losses producing X-rays, by interaction with either the inner shells of the atoms or the field of the nucleus.

6- X-Ray Generator Options

X-rays are produced from the small area of the target that the electrons emanating from the cathode collide with, which is called the focal spot. The area of the focal spot plays an important role in forming the x-ray image. The small size of the focal spot produces sharper image. To address this problem, the principle of linear focusing was used, where the target is tilted at a certain angle. The anode is cooled by passing oil or water through it. X-ray tubes are divided into two types depending on the type of anode used: fixed and moving anode tubes. The fixed anode cannot withstand high temperatures, so the rotating (moving) anode was invented by Philips in 1930. This anode can withstand high temperatures in order to distribute the heat over a large area of the anode.

7- Production of X-Rays

Over a century ago in 1895, Wilhelm Roentgen discovered the first example of ionizing radiation, X-rays. The key to Roentgens discovery was a device called a Crooke's tube, which was a glass envelope under high vacuum, with a wire element at one end forming the cathode, and a heavy copper target at the other end forming the anode. When a high voltage was applied to the electrodes, electrons formed at the cathode would be the anode and strike the copper with very high energy. Roentgen discovered that very penetrating radiations were produced from the anode, which he called x-rays.

X-rays are produced when very fast electrons collide with the target material inside the tube and suddenly lose their kinetic energy as the filament is heated to high temperatures, leading to the release of electrons that are attracted to the anode as a result of a high voltage difference being applied between the anode and the cathode. When these electrons collide with the target material, they lose their energy through several different ways of interactions, some of which end up producing X-rays with different energies and wavelengths.

Most of these electrons lose their energy during a series of interactions called ionic collisions, which include small transfers of energy that lead to ionization of the atoms of the target substance. Heat is also produced from the collisions, leading to an increase in the temperature of the target. The second type of these interactions occurs when the electron collides directly with one of the orbital electrons, especially The k orbital, which leads to the extraction of one of these electrons, leaving behind a void (gap) in this orbit, and when the electron descends from one of the outer orbits to fill this void, the difference in energy between the two orbits is emitted in the form of distinctive rays for this orbit called characteristic x-rays.

The electron may approach the nucleus, and because of the large force of attraction between the positive nucleus and the negative electron, the electron is forced to rotate around the nucleus, thus changing its path. The sudden slowdown of the electron as a result and the decrease in energy leads to the emission of high-energy photons called Bremsstrahlung rays, which are X-rays.

8- The X-Ray Tube

X-rays are produced in X-ray tubes such as the one shown in Figure below. X-rays are produced when fast moving electrons are suddenly stopped by impact on a metal target. The high voltage source is typically of the order of (103 to 106 volt). The filament (cathode) is heated to incandescence and emits electrons by the process of thermionic emission. At such high temperatures (2200 oC) the atomic and electronic motion in a metal is sufficiently violent to enable a fraction of the free electrons to leave the surface, despite the net attractive pull of the lattice of positive ions. These electrons are then repelled by the negative cathode and attracted by the positive anode. The electrons are accelerated by the high voltage source toward a solid target called the anode which is made out of a metal of high atomic weight like tungsten, or metals like copper and molybdenum. Because of the vacuum they are not hindered in any way, and bombard the target with a velocity around half the speed of light.

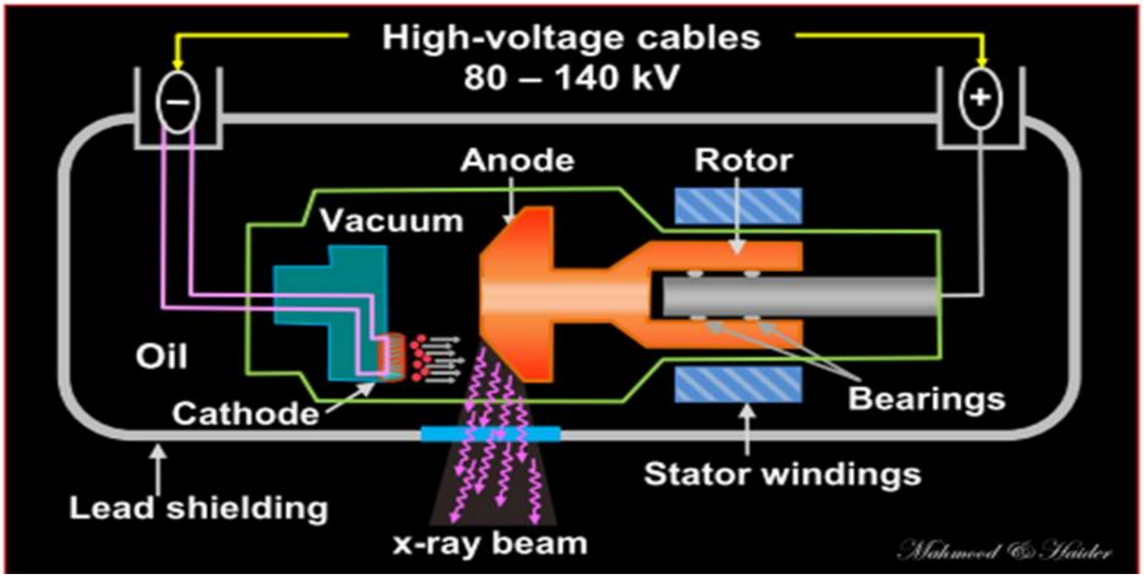

Figure 2: The X-Ray Tube

H.W

1. An X-ray tube must first accelerate the ………., in order to make X-rays through Bremsstrahlung.

a. Electrons b. neutrons c. proton d. nuclide

2. Acceleration potential is measured in……..

a. Joule b. kilovolts c. Watt d. None of them

3. The x-ray ………. that penetrate the object and reach the film can give a signal or blackening of the film.

a. Photons b. electron c. neutron d. proton

4. A structure known as ……….. serves as the electron source. Actually, it is a filament or coil of (thorium oxide, ThO_2) tungsten wire that …….. electrons when heated to a high temperature.

5. the electron path will be deflected and energy transferred to a photon, which is emitted. because the photon is emitted in association with a slowing down of the electron, it is known as ………….