X-RAY PRODUCTION

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OBJECTIVES

- Discuss the process of x-ray being produced (conditions)
- Explain the principles of energy conversion in x-ray production (how energy being converted into x-rays)
  - Bremsstrahlung radiation
  - Characteristic radiation
Introduction

- X-rays are produced when rapidly moving electrons that have been accelerated through a potential difference of order 1 kV to 1 MV strikes a metal target.
- Electrons from a filament are accelerated onto a target anode.
- When the electrons are suddenly decelerated on impact, some of the kinetic energy is converted into EM energy, as X-rays.
- Less than or 1% of the energy supplied is converted into X-radiation during this process. The rest is converted into the internal energy of the target or heat.
Properties of X-ray

- X-rays travel in straight lines.
- X-rays cannot be deflected by electric field or magnetic field.
- X-rays have a high penetrating power.
- Photographic film is blackened by X-rays.
- Fluorescent materials glow when X-rays are directed at them.
- Photoelectric emission can be produced by X-rays.
- Ionization of a gas results when an X-ray beam is passed through it.
What is an atom?

- All matter consists of atoms.
- An atom is the smallest part of an element which retains the chemical properties of the element.
- An atom can be thought of as having a central nucleus surrounded by a cloud of particles called electrons.
High frequency / short wavelength photons have higher energy than low frequency / long wavelength photons.

X-rays are produced when electrons (i.e. from the filament) lose a proportional amount of energy.

This energy may be lost by the deceleration of fast moving electrons or by electron transitions between inner shells of an atom.

Both of these above processes occur within the x-ray tube.
High Voltage 80 - 140 kV

Tube housing

Vacuum tube

Anode

Rotor

Stator

Filament

Electron beam

Thin window

Collimator

X-ray beam
**X-ray Tube Design**

- The x-ray tube is a large diode valve, which is designed to produce fast moving electrons & then cause the electrons to decelerate rapidly in a vacuum environment.
- The purpose of this session is to assess what happens at the anode
- How are the x-rays produced?
X-ray Production

- X-rays are produced when high energy electrons bombard a metal target, interacting with its atoms.
- The potential difference (pd) across the x-ray tube accelerates the electrons from the cathode to the anode, increasing their kinetic energy (KE).
- The PD across the tube may not be constant (hence use of the term kVp for peak), therefore the amount of kinetic energy gained by each electron may differ.
- This is why we get an energy spectrum.
Interactions between incident electrons & orbital electrons

Binding energy

- This is the energy which binds the electron to the nucleus
- It is the energy that must be supplied to the electron in order to remove it from its orbital shell
- It is NOT the energy of the electron
- The electron binding energy depends upon it’s shell (orbit) & atomic number (Z) of the atom

Examples:

- Binding energy of Tungsten = L shell – 111 keV, K shell – 70 keV
- Binding energy of Copper = L shell – 1.1 keV, K shell – 9.0 keV
What are the processes?

- Elastic collisions with atoms
- Inelastic collisions with electrons in the outer shell of an atom
  a) Excitation
  b) Ionisation
- Inelastic collisions with electrons in the inner shell of an atom (Characteristic)
- Inelastic collisions with the nuclei of the atom (Bremsstrahlung)
Elastic collision with target

- Incoming electron (i.e. from filament) is attracted by strong positive charge on nucleus of heavy atom
- The electron is deflected but loses very little kinetic energy because its mass is negligible
- The electron continues in tortuous path because of successive interactions
Interaction between filament electron & outer shell electron (1)

- Excitation
  i) This results in an outer shell Electron gaining energy & Being raised to a higher level.
  ii) Heat is produced as the electron Falls back into its original path.
- The filament electron may repeat this process many times
- No contribution to x-ray production
Interaction between filament electron & outer shell electron (2)

- Results in an outer shell electron being completely removed from the target atom. Both the filament & the ejected electrons may interact in either the first or second of these interaction processes with other target atoms.
- Ultimately, this type of interaction may cause the target material to heat up.
Inelastic collisions with electrons in the inner shell of an atom (characteristic radiation)

- The incoming electron transfers sufficient energy to remove an inner shell electron from its atom in the target.
- In order for this to occur the electron must possess energy at least as great as the binding energy of the inner shell.
- Any surplus energy appears as additional kinetic energy in the ejected electron.
- The inner shell vacancy is quickly filled by an electron falling inwards from a shell further out from the nucleus.
- This transition is accompanied by a burst of electromagnetic radiation with energy equal to the difference in binding energies of the two shells.
- This type of x-ray production is termed characteristic because the exact photon energy is characteristic of the element of which the target is made.
Inelastic collisions with electrons in the inner shell of an atom (Characteristic Radiation)

Let’s see this happen

1 – Inner shell electron ejected from atom
2 – Electron falls to occupy vacancy
3 – Burst of EMR (Characteristic)
- Characteristic x-rays contribute less than 10% of an x-ray beam.
- The majority of x-ray production results from inelastic collisions of incoming electrons with the nuclei of the target atoms.
Inelastic collisions with the nuclei of the atom (Bremsstrahlung Radiation)

- The incoming electron passes very close to the nucleus of a target atom (1).
- The attraction causes the electron to deviate in its course (2).
- The sudden change of direction stimulates the electron to release energy in the form of a photon of electromagnetic radiation (3).
- The emission of radiation results in a reduction in the electron's kinetic energy causing it to slow down.
- The energy of the radiation depends on the degree of deviation the electron suffers.
- In an extreme case the electron may actually be brought to rest.
- Thus the photon energy can be of any value from zero up to a maximum equal to the initial kinetic energy of the incoming electron.
- This gives rise to a continuous spectrum of x-radiation and is known as braking (Bremsstrahlung) radiation.
Photon of x-radiation emitted

Track of electron from filament
Relative incidence of the interactions

- Inelastic processes are much more likely to occur than characteristic or Bremsstrahlung processes.
- Less than 1% of the energy in a diagnostic x-ray tube is converted into x-rays (the rest is heat).
- At the higher voltages (i.e., radiotherapy) the efficiency is higher (up to 30%) & relatively less heat is produced.
- Characteristic x-ray production cannot take place at all if the x-ray tube voltage is insufficient to give electrons enough energy to remove an inner shell electron from the target atom.
With a tungsten target, voltages below about 68 kVp cannot produce tungsten characteristic radiation.

In other materials, such as molybdenum (which is used in mammography X-ray tubes) the voltage value required to produce characteristic radiation is much less (approx 27 kVp).

The amount of heat produced within an X-ray tubes can cause problems.
The X-ray Spectrum – Important Points

- Characteristic radiation & Bremsstrahlung radiation produce line & continuous spectra respectively.
- Line spectra can **never** be produced alone in an x-ray tube.
- If present, it is **always** superimposed on the continuous spectrum.
Intensity

L-shell transitions

Photon energy

L-K transition

M-K transition
The two most prominent line spectra from a tungsten target are caused by electrons filling vacancies in the K shell.

- One line from L-K shell transitions
- One line from M-K shell transitions

(**There is a line produced from vacancies being filled in the L shell, however the photon energy here is too low for it to leave the X-ray tube**)
Another feature of the X-ray spectrum is the presence of an upper photon energy limit (or min $\lambda$)

For any particular tube voltage there will be a corresponding upper photon energy limit (or min $\lambda$)

i.e. for a tube voltage of 75 kVp, the maximum photon energy will be 75 keV
Quality of X-rays

- Quality describes the penetrating power of an x-ray beam
- X-ray beams are invariably heterogeneous & to describe completely the quality of such a beam it would be necessary to give the spectrum of the radiation.
Intensity of X-rays

- A measure of the quantity (amount) of radiation energy flowing in unit time.
- “The quantity of energy flowing in unit time through a unit area when measured at right angles to the direction of the beam” (Ball & Moore 1992)
Example MCQ

- Elastic collisions of incoming electrons with atoms of the X-ray tube

A involve the transfer of energy to the target
B result in a tortuous path
C produce heat and light
D rarely occur
E produce X-ray photons
Bremsstrahlung radiation is

A emitted when an incoming electron interacts with a bound electron

B is responsible for the line spectrum of X-rays emitted from the target

C is emitted when an incoming electron interacts with a bound electron

D has a maximum photon energy in keV

E has a minimum photon energy, which varies with the kVp set
X-ray beams are always

A heterogeneous  
B exponential  
C characteristic  
D homogeneous  
E logarithmic
Which of the following processes is primarily responsible for the emission of X-ray photons from the X-ray tube

A characteristic radiation  
B Bremsstrahlung radiation  
C photoelectric effect  
D Compton effect  
E electron capture