Properties of X-rays

- Very short wavelength (~ the same size as the diameter of an atom).
- They cause ionisation (adding or removing electrons in atoms and molecules).
- They affect photographic film in the same way as visible light (turning it black).
- They are absorbed (stopped) by metal and bone.
- They are transmitted (pass through) healthy body tissue.
- Very useful for medical diagnosis and treatment.

Generation of X-rays

- Low pressure gas filled glass tube (10^-6 bar ~ 0.13 Pa)
- Due to the high voltage between the anode and cathode electrons leave the material of the cathode.
- e accelerated by the anode voltage.
- They hit the target, giving off energy mostly as heat, but 1% is given off as X-rays.
- The target would rapidly melt.
- Electrons impact the ant cathode (anode)
- Generation of X-ray radiation
Production of X-rays

X-rays are produced by:

I) removing an inner electron. As electrons replace the inner electron, photons are emitted as the electrons undergo transitions from energy level to energy level.

CHARACTERISTIC X-RAY RADIATION

Linear spectrum

II) slowing the electron down

BRAKING RADIATION (BREMSTRAHLUNG)

Continuous spectrum

Two independent mechanisms → composite spectrum (linear and continuous).

Characteristic x-ray

Charles Glover Barkla: Nobel Price in Physics 1917: discovery of the characteristic x-ray

An incoming high-energy electron removes a k-shell electron in the anode (vacancy in the shell)

A characteristic x-ray is produced (E equals the energy difference between the shells = discrete difference between the energy levels)

Line spectrum (Characteristic of the anode material)

BRAKING RADIATION (BREMSTRAHLUNG)

Braking radiation or “deceleration radiation” (“Bremsstrahlung”)

In an x-ray tube an electrically charged particle (electron) is slowed down by the electric field of an atomic nucleus.

The energy loss from the interaction results in the release of x-ray photons.

The energy (“wavelength”) will equal to the energy loss during the deceleration → a broad band of continuous radiation generated.

Continuous spectrum

Spectrum of X-ray radiation

Breaking: continuous emission radiation

Characteristic: line type emission radiation

Duane-Hunt rule

(braking radiation)

Maximum released energy of electron equals to energy gained by an accelerating voltage.

Maximal energy of photon; minimal wavelength

Intensity decreases linearly towards the lower frequency (greater wavelength)

it is $E$ at energy of the accelerating voltage (limit frequency; Duane-Hunt rule)

William Duane (1873–1935, USA)

\[
\begin{align*}
E_{\text{max}} &= \frac{e \cdot V_{\text{anode}}}{h} \\
\lambda_{\text{min}} &= \frac{h \cdot c}{e \cdot V_{\text{anode}}} \\
\end{align*}
\]

$E_{\text{max}} = \text{Planck's constant} = 6.626 \times 10^{-34}$ Js

c = speed of light = $3 \times 10^8$ m/s

e = elementary charge = $1.602 \times 10^{-19}$ C

Henry Moseley (1887 – 1915)

Frequency of the main characteristic peaks in the x-ray radiation is proportional to the atomic number of the element [1913].

First link between the atomic number and a measurable physical quantity.

Lending important experimental support to Bohr’s atom model.

\[
A = c \cdot \frac{1}{\lambda_{\text{min}}} = c \cdot \frac{h}{E_{\text{max}}} \\
A = \frac{2.19 \times 10^{-18}}{\lambda_{\text{min}}} \text{ m}^{-1} \text{ shell}^{-1} \text{ shell}^{-1} \text{ } \text{ for } \text{shell} \text{ number quantum number}
\]

Determination of the place of the atom in periodic table.
Applications

- Diagnostic imaging
- Skeleton
- Teething
- Mammography
- Angiography
- Nephrolith
- Chest screening
- X-ray diffraction
- Investigation of painting originality
- Matter faults of metals
- Luggage scanning

X-ray shielding: Pb(82) - lead

Why is it useful in radiation shielding?

- Compact, and dense atomic structure
- High probability that the electrons will collide with the incident photons.
- Cheap (gold, silver)
- Less toxic than thallium or bismuth
- Readily available

Important X-ray Interactions with matter

- Photoelectric effect or photoelectric absorption
  - Responsible for the contrast on the image
  - Compton scatter
  - Contributes to no useful information: reduces contrast

Photoelectric effect

- Inner shell ionization
- The energy of the photon is totally absorbed
- Photoelectron is removed from the atom (E = E_{incident} photon - E_b - binding energy)
- Orbital vacancy
- An electron from the above shell jumps down to fill the vacancy energy is released.
- The photoelectric effect is more likely to occur in absorbers of high atomic number (e.g. bone, contrast media)
- Significantly contributes to patient dose (exposure)
- Is mainly responsible for the production of contrast on the image

Compton Effect (Compton Scattering)

- X-ray photon ejects an outer shell electron.
- The x-ray photon is deflected (changed direction) with reduced energy.
- Compton e^- is also released.
- Both the scattered x-ray and the Compton electron have enough energy to cause more ionization before losing all their energy.
- Compton effect occurs in any tissue.
- Scattered photons provide no useful diagnostic information.
- Reduces image contrast.

how the X-ray beam can be directed: Controlling the X-ray Beam

Unlike light or electron beams, X-rays cannot be focused. So they can only make shadow images. If you use a small point source of light, you get sharp shadows. If it’s a wide source of light, the shadows become fuzzy. Obviously the doctor wants a sharp shadow.

There are various ways in which an X-ray source can be made into a point source:

- The beam is made narrow by the geometry of the anode to about 1 mil.
- The beam can be limited by using apertures. This can be a simple diaphragm or a cone made from lead.
- Scattering in the tissues can make the picture fuzzy. A grid made of strips of lead will absorb any scattered X-rays.
X-ray imaging

- Addition of absorption of elements behind each other in the direction of x-ray propagation.
- 2D summation imaging
- No depth information
- Elements with higher contrast cover those with smaller
- Scattered x-ray is exposing, too (gray background).

- Examined part of body is placed between the source and detector
- Absorption of individual tissues/ organs is different
- A better penetration makes the photographic plate become darker
- Higher atomic number elements in bones:
  - Mg Z=12, P Z=15, K Z=19, Ca Z=20
- In soft tissues chiefly: H Z=1, C Z=6, O Z=7, N Z=8
- Bone absorbs radiation better than e.g. muscle (higher electron density), therefore causes less darkening of the photographic plate.