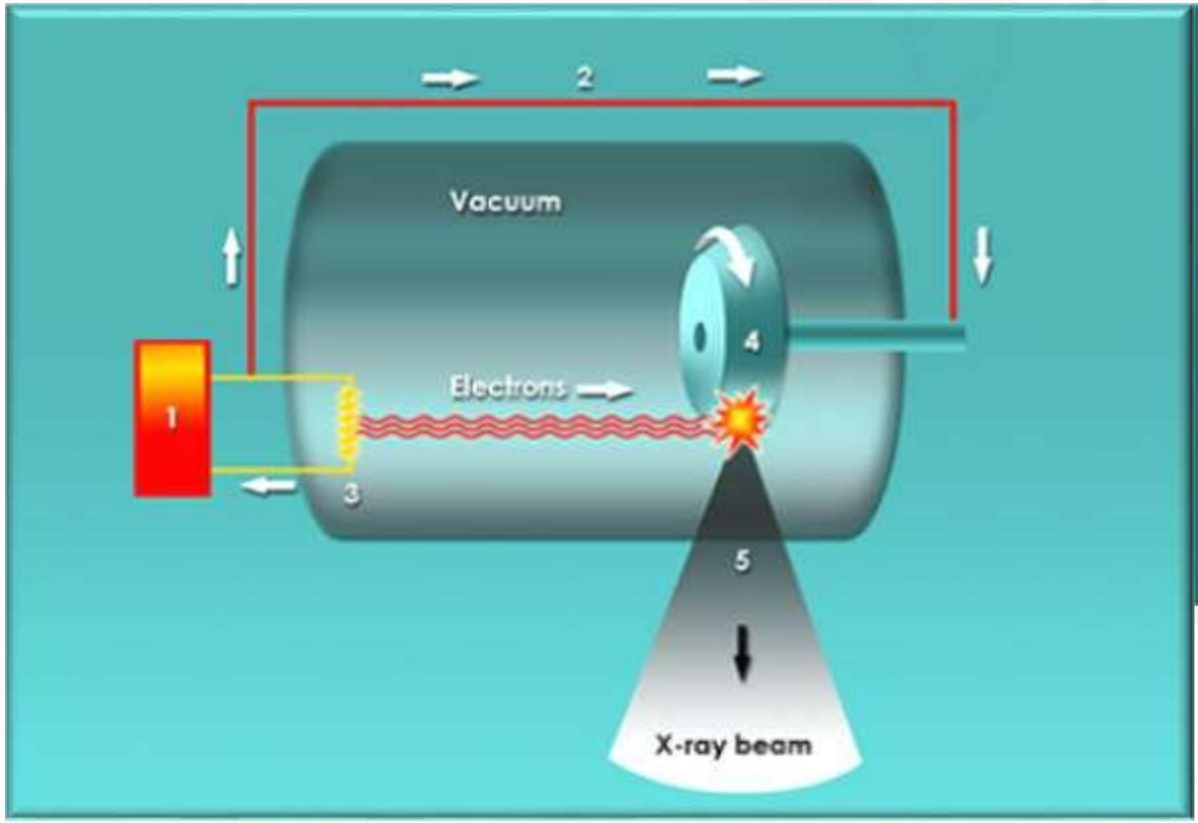
X-RAYS

Generation of different types of XRAYS

Production of x-ray

HOW IT ALL BEGINS

- X-rays are produced when fast moving electrons are stopped by means of a target material.
- When the electron is suddenly stopped, its kinetic energy is converted into heat and x-rays.
- This conversion takes place within the target material, interaction of electron with the target is the basis for x-ray production.



The X-ray tube

- A small increase in the filament voltage (**1**) results in a large increase in tube current (**2**), which accelerates high speed electrons from the very high temperature filament negative cathode (**3**) within a vacuum, towards a positive tungsten target anode (**4**). This anode rotates to dissipate heat generated. X-rays are generated within the tungsten anode and an X-ray beam (**5**) is directed towards the patient.

Current to the filament

Thermionic emission

- When a metal is heated, the atom absorbs thermal energy and some of the electrons in the metal acquire enough energy to allow them to move a small distance from the surface

Potential difference applied

- A high potential difference is applied between the cathode and the anode to accelerate the electrons

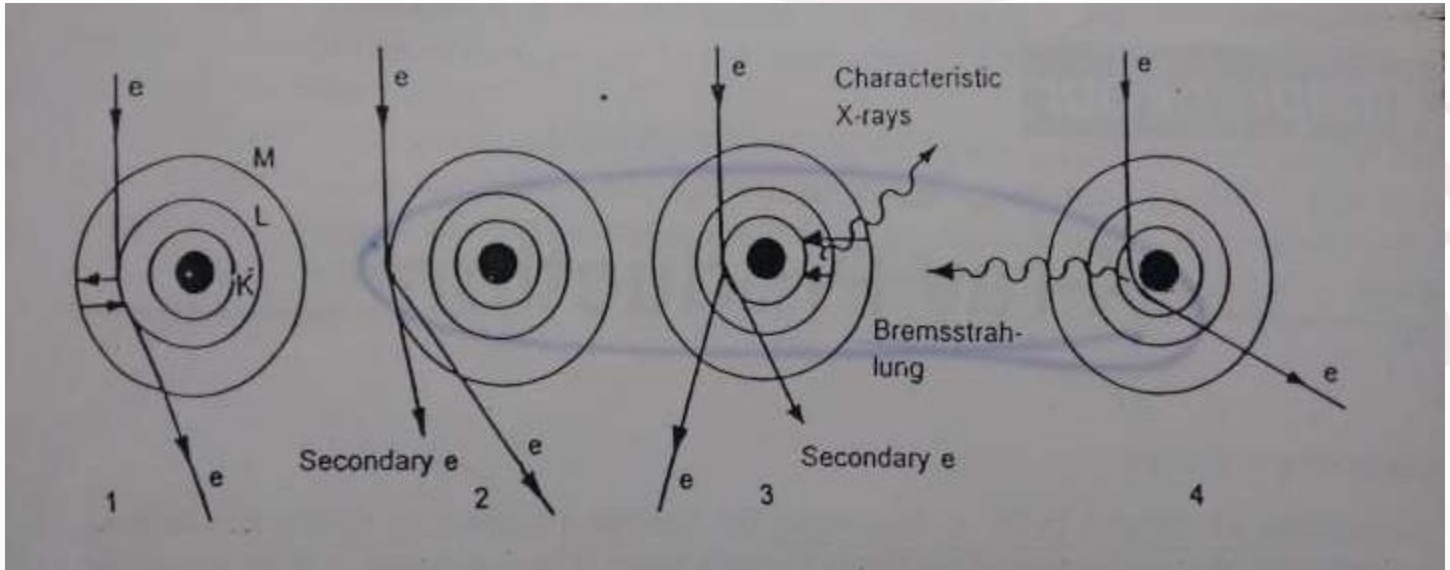
Interaction of electron with target

- Due to the potential difference the electrons rush towards the anode

Production of x-rays

INTERACTION OF ELECTRONS WITH THE TARGET (ANODE)

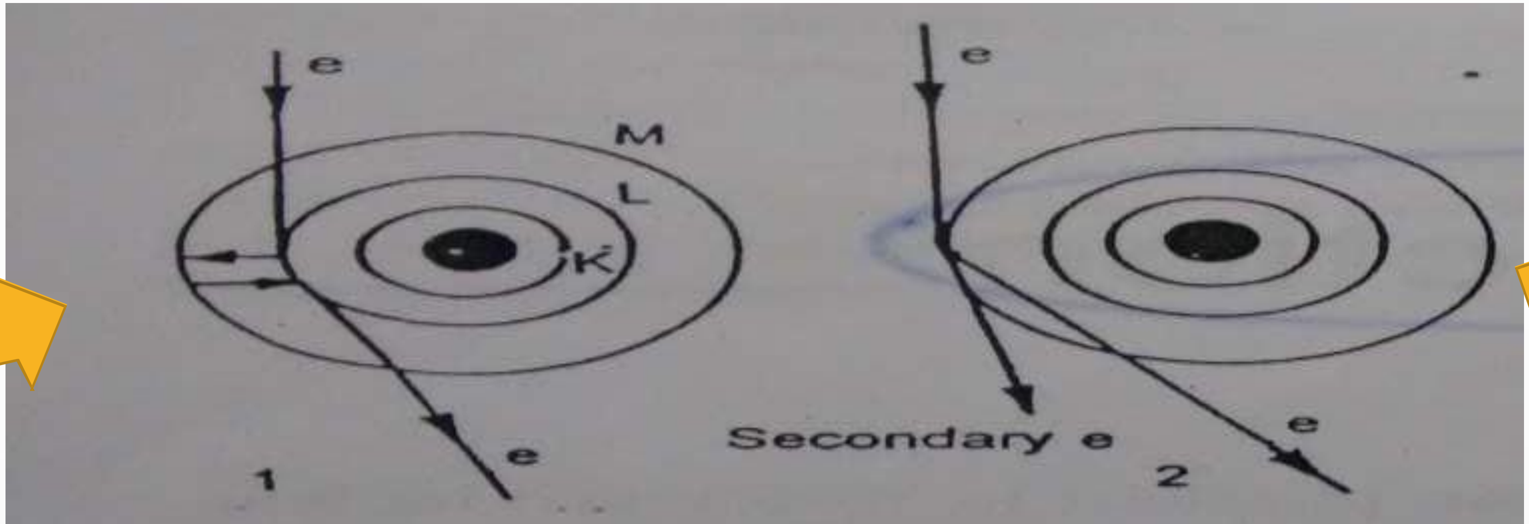
- Electron interacts with the target in four different ways
  - Excitation of outer shell (heat)
  - Ionization of outer shell (heat)
  - Ionization of inner shell (k-characteristic spectrum)
  - Interaction with the nuclear field (Bremsstrahlung/continuous spectrum)



NOT SO USEFUL INTERACTIONS

- **Excitation of outer shell**
  - The incident electron interacts with an electron in the outer shell of the target.
  - It transfers a small amount of energy to the outer shell and displaces it to a higher energy level
  - The excited electron returns to the original shell and the difference in energy appears as heat in the target.

- **Ionization of outer shell**
  - The incident electron interacts with an outer shell electron of the target.
  - It transfers sufficient energy and removes an electron from the outer shell.
  - The displaced electron is called as secondary electron which may further produce ionization or excitation in other atoms of the target and result in heat production.



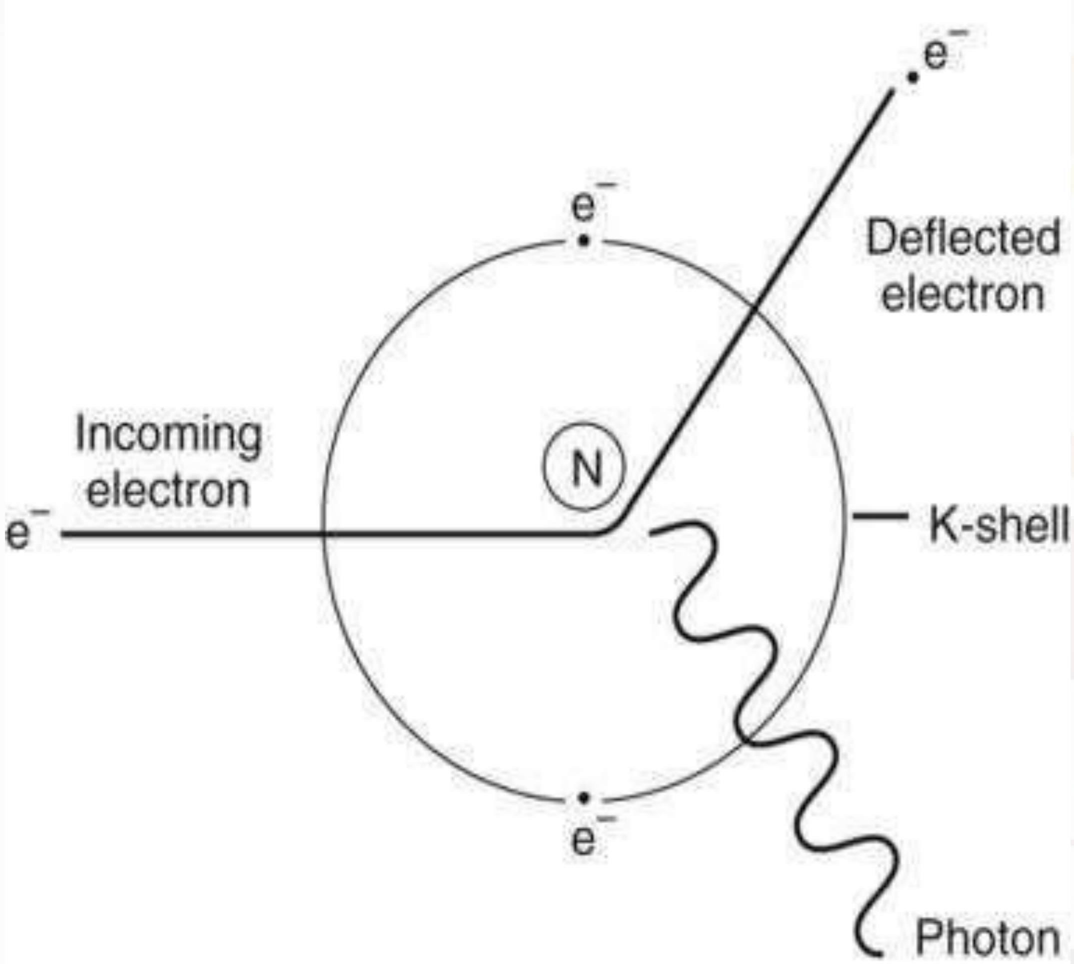
IONIZATION IN AN INNER SHELL

- This is the interaction between the incident electron and the electron in the inner shell.
- The incident electron transfers sufficient energy and removes an electron from the inner shell.
- The displaced electron further produces ionization and excitation in other atoms.
- The vacancy created is filled by an electron moving inwards from the outer shell.
- During this transition the difference between the binding energies of the two shells is given out as x-ray photon.

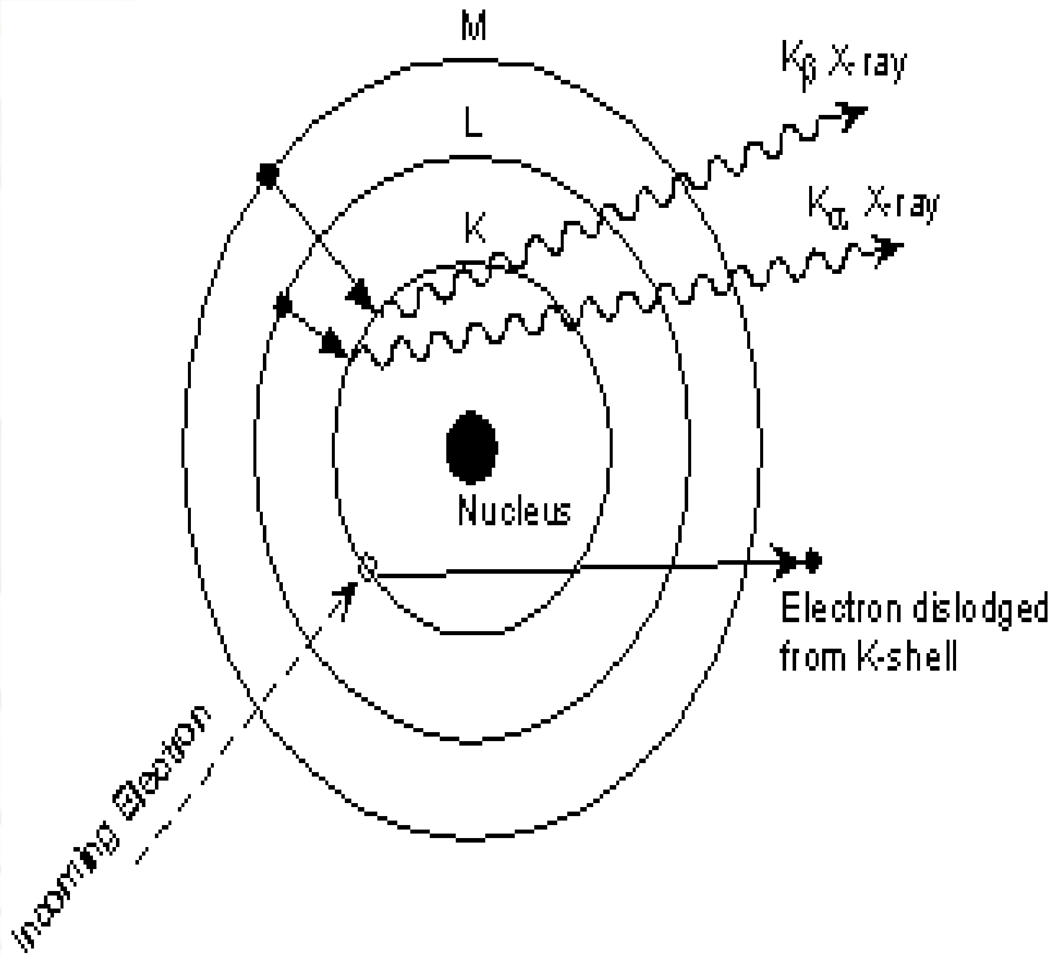
INTERACTION WITH NUCLEAR FIELD

- The incident electron passes close to the nucleus of an atom in the target. Since electron is a negative particle, it is attracted towards the positive nucleus.
- Therefore, the electron decelerates and loses energy in the form of x-ray photon.
- The energy of the x-ray photon depends upon the degree to which the electron is decelerated by the nuclear attraction.
- The x-ray photon are known as continuous x-ray or bremsstrahlung. The bremsstrahlung is a German word meaning 'breaking radiation'.

IONIZATION IN AN INNER SHELL

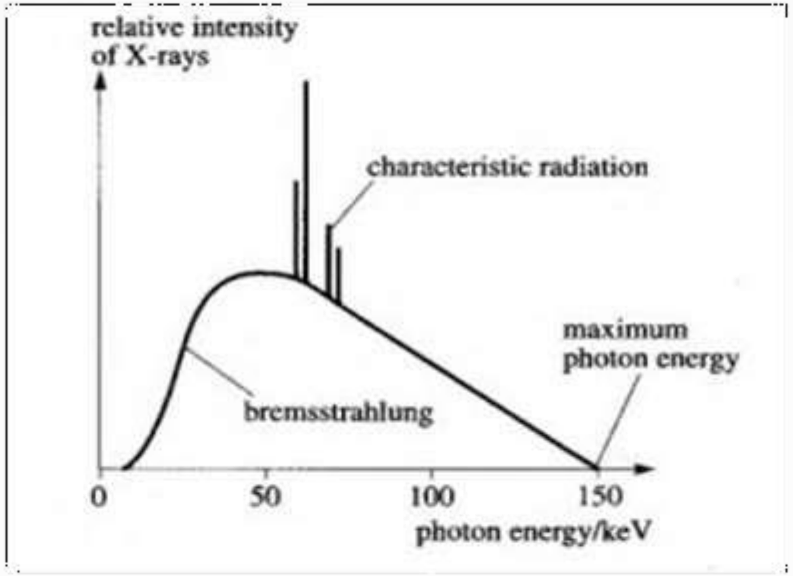


INTERACTION WITH NUCLEAR FIELD

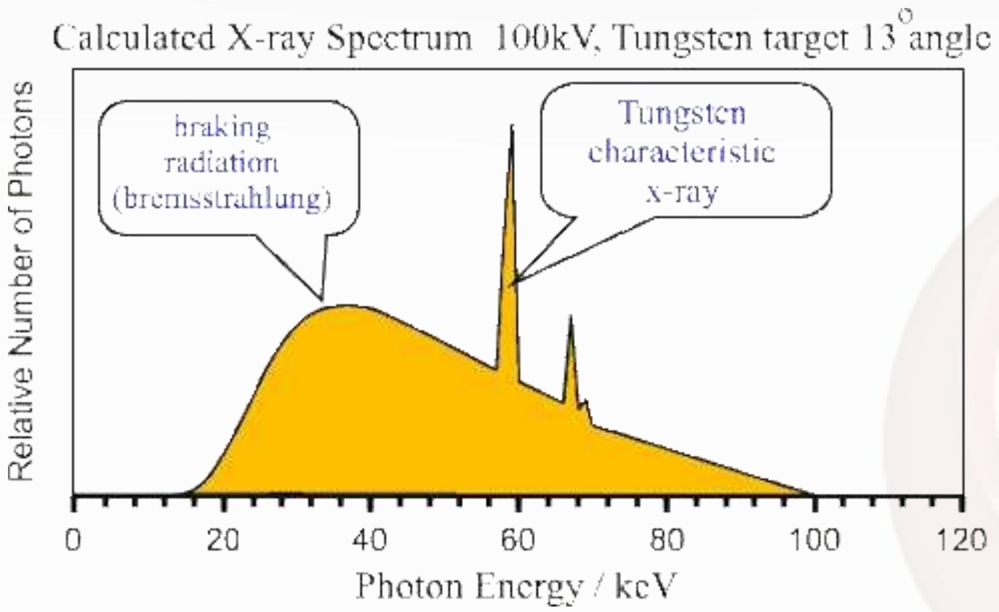


X-RAY SPECTRA

- Two types of x-ray spectrum



- X-ray spectrum
  - Continuous spectrum
    - Consists of x-ray photons of all energies up to the max.
    - Also called as white light radiation
  - Characteristic spectrum
    - Consists of x-ray photons of few discrete energies
    - Also called as line spectrum and depends on the atomic number of the target

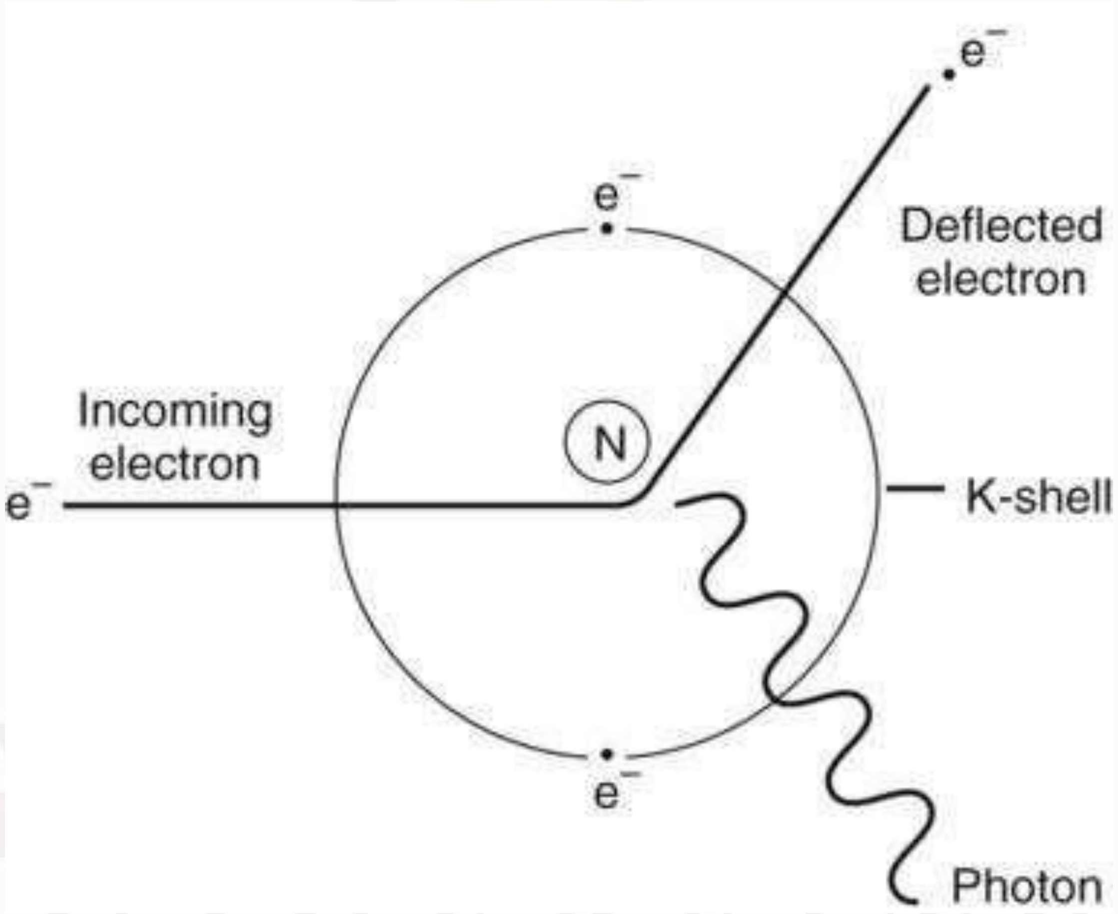


Examples

1. A K-shell electron is removed from a tungsten atom and is replaced by an L-shell electron. What is the energy of the characteristic x-ray that is emitted?
Solution: From the table below the ionization energy of a K-shell electron of Tungsten is 69.5 keV and the ionization energy of a L-shell electron of Tungsten is 12.1 keV therefore, the difference of these two energies will be the energy given off.
69.5 keV – 12.1 keV = 57.4 keV

2. A K-shell electron is removed from a tungsten atom and is replaced by an O-shell electron. What is the energy of the characteristic x-ray that is emitted?
Solution: 69.4 keV

Electron transition from shell (KeV)					
Shell	L	M	N	O	P
K	57.4	66.7	68.9	69.4	69.5
L		9.3	11.5	12	12.1
M			2.2	2.7	2.8
N				0.52	0.6
O					0.08


e⁻
e⁻
Deflected
electron
Incoming
electron
N
e⁻
K-shell
e⁻
Photon

Bremsstrahlung

- During this process, the electron while passing near the nucleus may suffer a sudden deceleration by the action of coulomb forces of attraction. As a result the electron may loose energy, in the form of Bremsstrahlung.
- The electron may have one or more such interactions and this may result in partial or complete loss of energy.
- The amount of bremsstrahlung production is determined by the distance between the electron and the nucleus.
- At very large distances, the coulombic forces are weak, only low energy x-rays are created. This has higher possibility.
- When electrons are more close to the nucleus, more kinetic energy is lost, resulting in high energy x-ray production. It has low probability of occurrence.

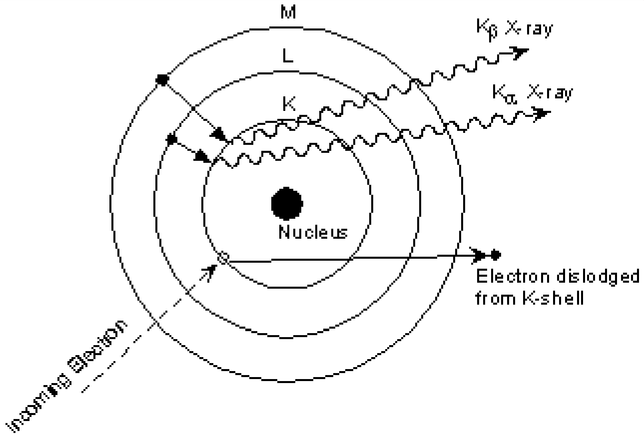
- Efficiency = $\frac{output\ energy\ emitted\ as\ x-rays}{input\ energy\ deposited\ by\ the\ electron}$ = $9\times 10^{-10} \times Z \times V$

Z – atomic number ; V – tube voltage

- X-ray production increases with increasing voltage and atomic number
- The efficiency of Tungsten target is found to be less than 1%. The rest of the input energy (99%) appears as heat.

Characteristic x-rays

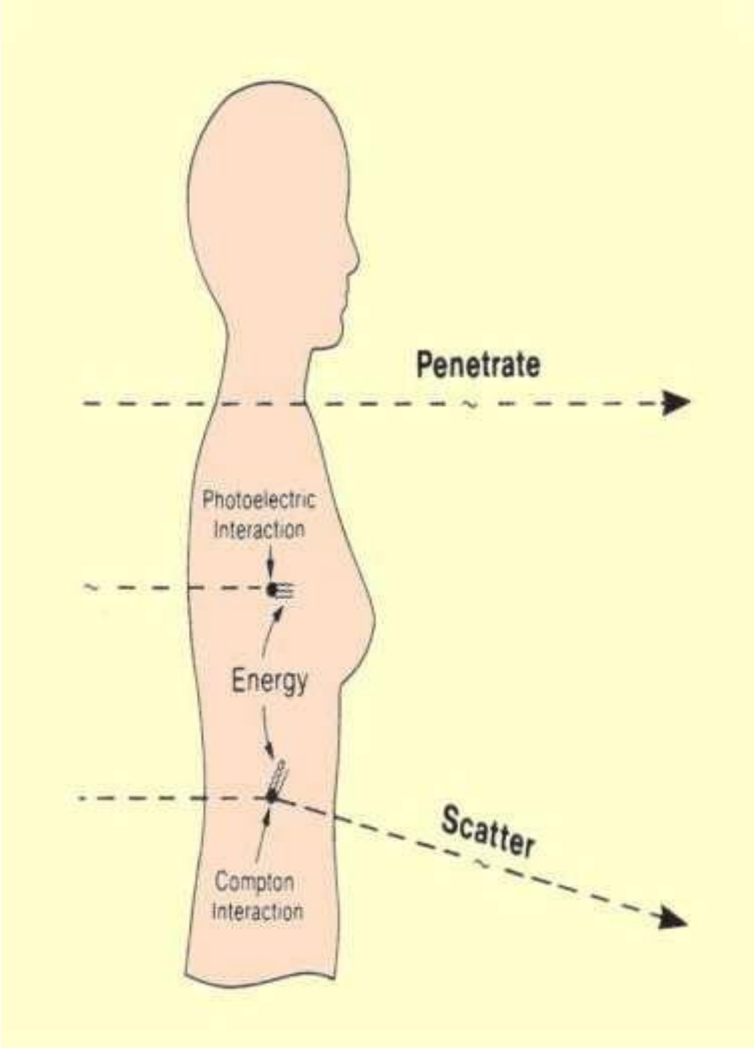
- Electron incident on the target may produce characteristic x-rays by ejecting an orbital electron from the K shell, resulting in a vacancy in that shell leading to ionization of the atom.
- The outer orbital electron will fill the vacancy at the K shell
- Difference in binding energy of the two shells is radiated as x-ray photon, which is called the characteristic radiation. It will only have discrete energies.



$$\boldsymbol{E = hv}$$
$$= E_K - E_L$$
$$= 69.5\ keV - 12.5\ keV$$
$$= 57.4\ keV$$

- K characteristic x-rays are emitted only, if the incident electron have energies greater than the binding energy of the K shell electron.
- As the energy of the incident electron increases above the threshold energy, the percentage of characteristic x-ray also increases.

Interaction with matter



Three possible fates await each photon

1.It can penetrate the section of matter without interacting.

2.It can interact with the matter and be completely absorbed by depositing its energy.

3.It can interact and be scattered or deflected from its original direction and deposit part of its energy.

ATTENUATION

- It refers to both absorption and scattering. When a photon passes through an absorber of thickness *x*, both absorption and scattering takes place.
- Attenuation results in the transmission beam having lesser number of photons

LAC (linear attenuation coefficient) = it is defined as the reduction in the radiation intensity per unit path length and is expressed in cm^{-1}

HVL (half value layer) = it is the thickness of material that attenuates an x-ray beam by 50%
TVL (tenth value layer) = thickness of material that attenuates 90% of the x-ray beam.

- The LAC depends on the energy of the photons and the nature of the material. The attenuation of photons is caused by four important processes
  i. Coherent scattering
  ii. Photoelectric effect
  iii. Compton effect
  iv. Pair production and Photo-disintegration

Coherent scattering

Thomson

A single electron is involved in the interaction

Rayleigh

Cooperative interaction with all the electrons of an atom

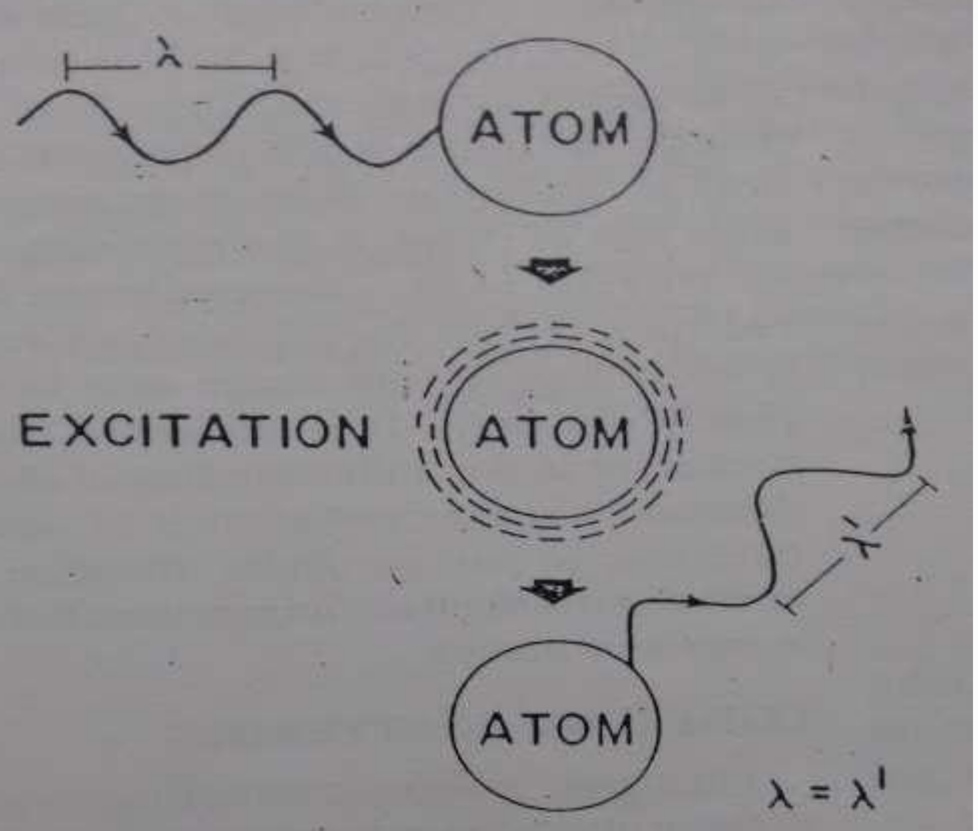
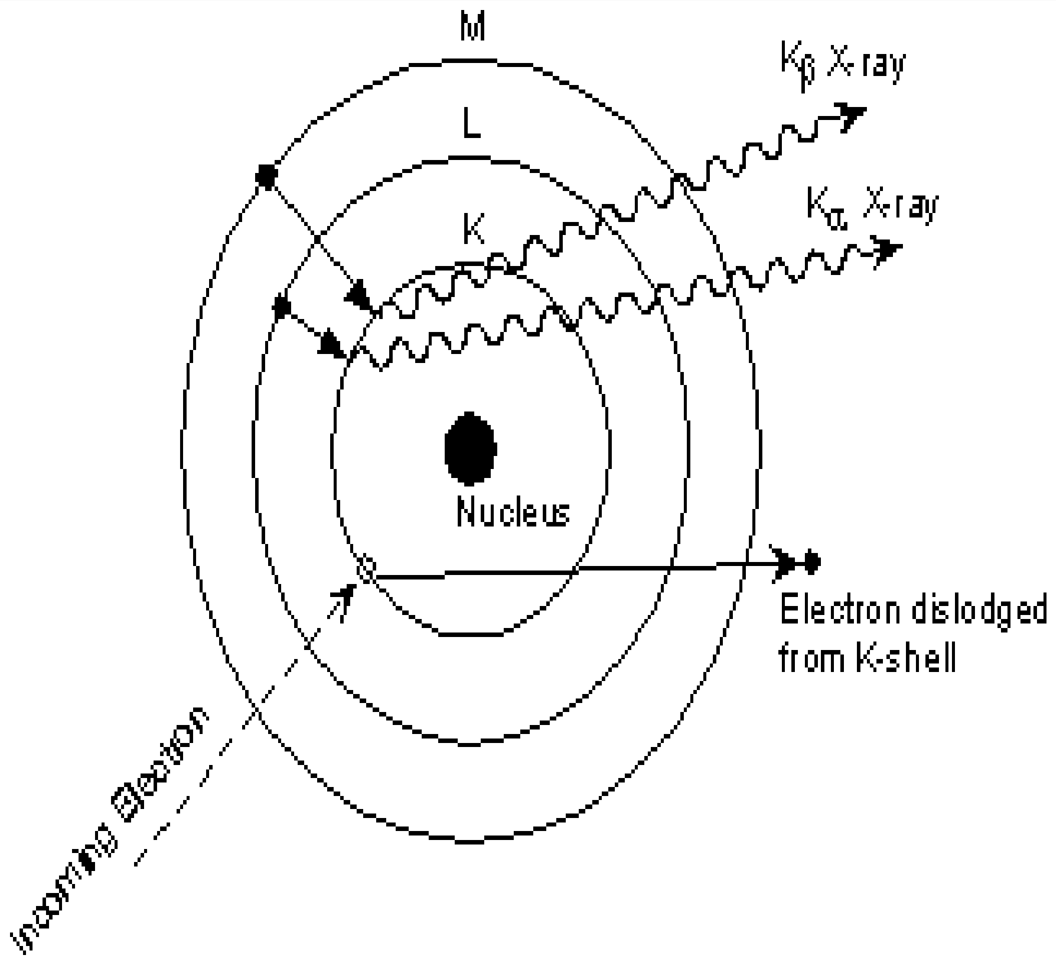


Figure 4–1 Coherent Rayleigh scattering

PHOTOELECTRIC EFFECT

- This is the interaction between the incident photon and the electron in the inner shell.
- The incident photon transfers sufficient energy and removes an electron from the inner shell.
- The vacancy created is filled by an electron moving inwards from the outer shell (L or M).
- During this transition the difference between the binding energies of the two shells is given out as x-ray photon.
- The atom after filling of the K shell void becomes a positive ion



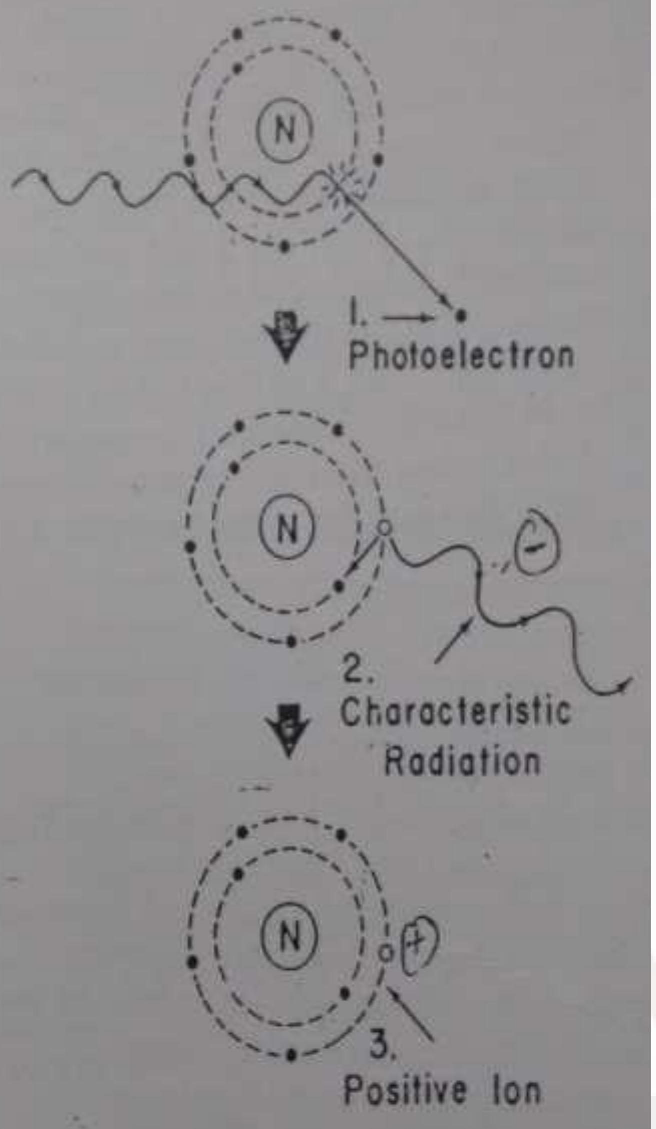


Figure 4–2 Photoelectric effect

End products

1. Characteristic radiation
2. A negative electron (the photoelectron)
3. A positive ion (an atom deficient in one electron)

Probability of occurrence

1. The incident photon must have sufficient energy to overcome the binding energy of the electron.
2.

the photon energy and electron binding energy are nearly same.

3.

the more likely it is to be involved in a photoelectric reaction.

APPLICATION IN DIAGNOSTIC RADIOLOGY

- It is used for mammography (imaging of breast tissue)

- Photoelectric effect is both good and bad

Good

- It produces radiographic images of excellent quality because
  - It does not produce scatter radiation and
  - It enhances natural tissue contrast

Bad

- Patients receive more radiation from photoelectric reaction

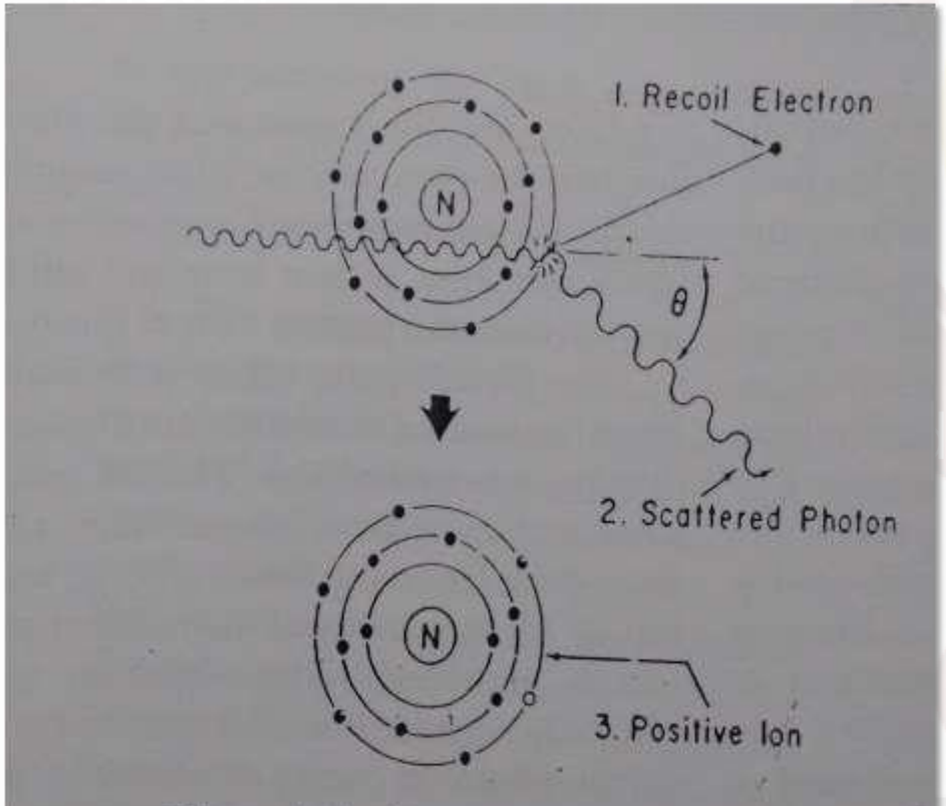


Figure 4–4 Compton scattering

End products

1. Recoil electron
2. Scattered photon
3. Positive ion

Probability of occurrence

The probability of occurrence of Compton effect depends the total number of electrons available in the outermost shell.

Pair production

initially

- High energy photon (≥1.02MeV)
- Interacts with the nuclear field

Mid phase

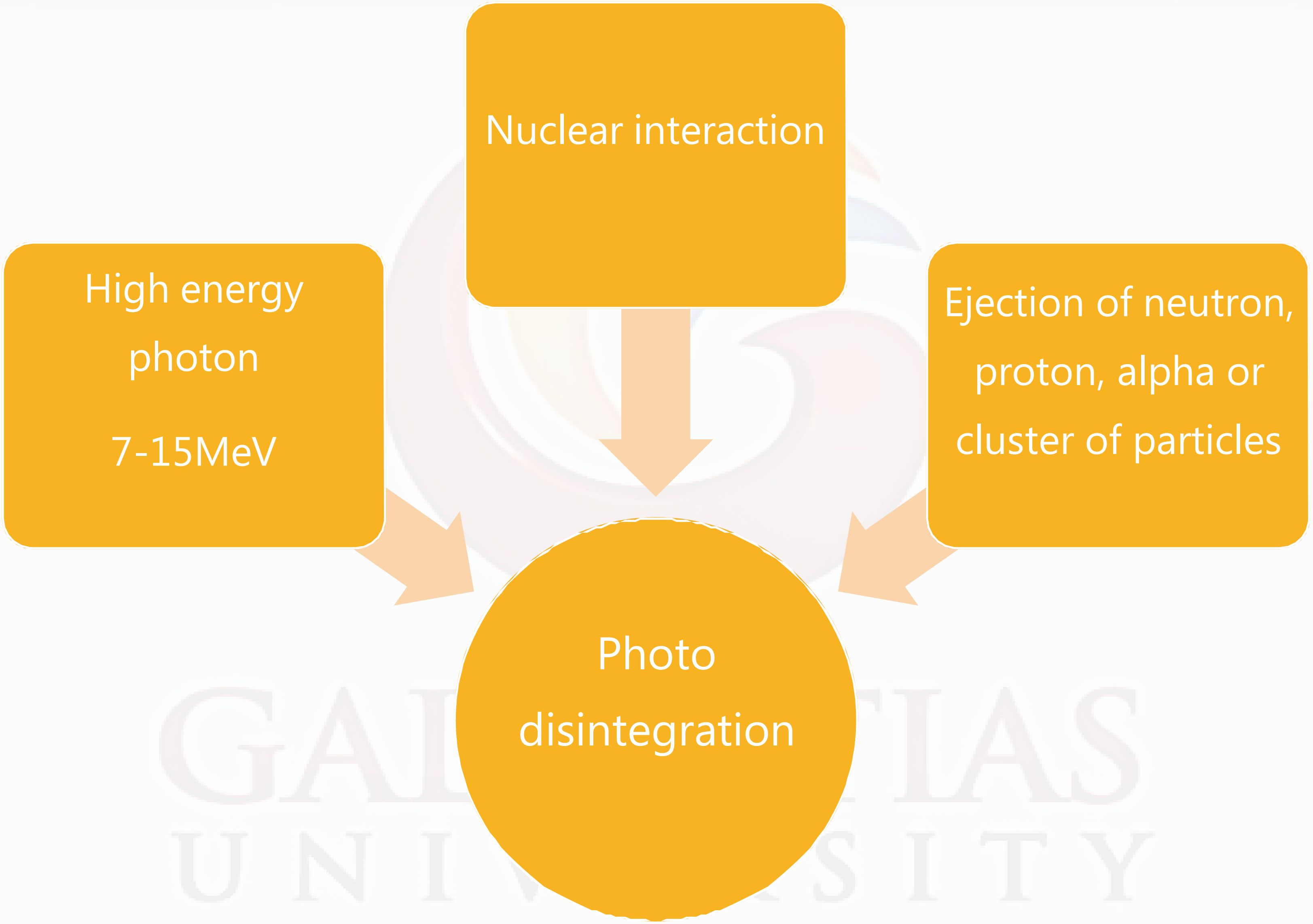
- Photon disappears
- Appearance of an electron and a positron (0.51MeV each)

later

- The positron looses its energy in the medium
- It combines with a free electron and produces two photons

Photodisintegration

- In photodisintegration, part of the nucleus of an atom is ejected by a high energy photon.
- The ejected photon may be a neutron, a proton, an alpha particle or a cluster of particles.
- The photon must have sufficient energy to over come nuclear binding energies of the order of 7-15 MeV.


Nuclear interaction
High energy photon
7-15MeV
Ejection of neutron, proton, alpha or cluster of particles
Photo disintegration

REFERENCES

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- https://youtu.be/l32YoBUqJAg

Thank you!