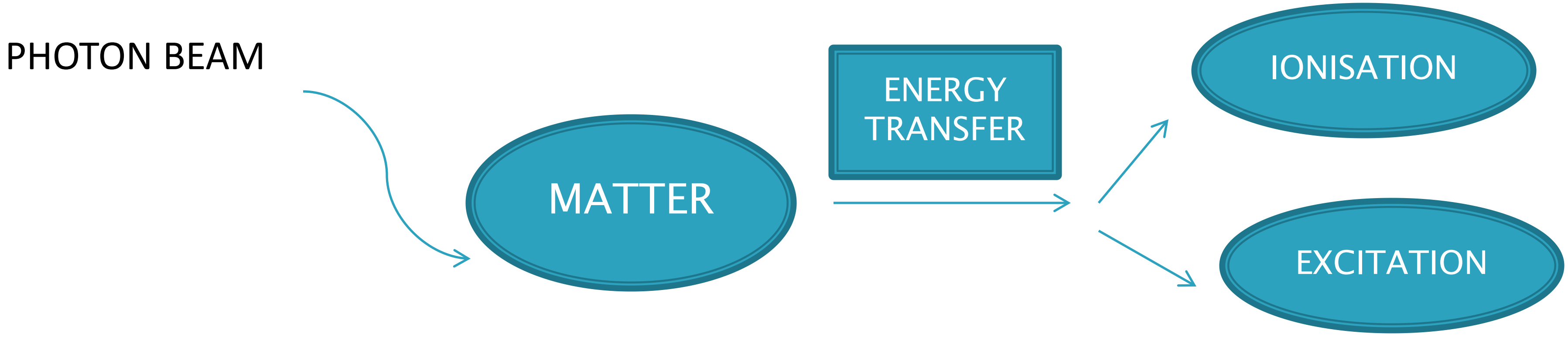
INTERACTION OF PHOTON WITH MATTER

PHYSICAL , CHEMICAL AND BIOLOGICAL EFFECTS

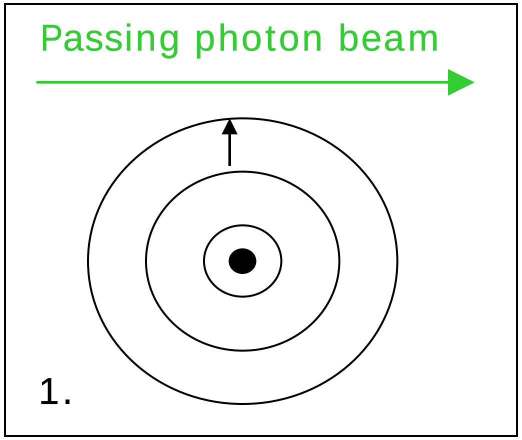
DR KAZI SAZZAD MANIR

INTERACTION OF PHOTON WITH MATTER

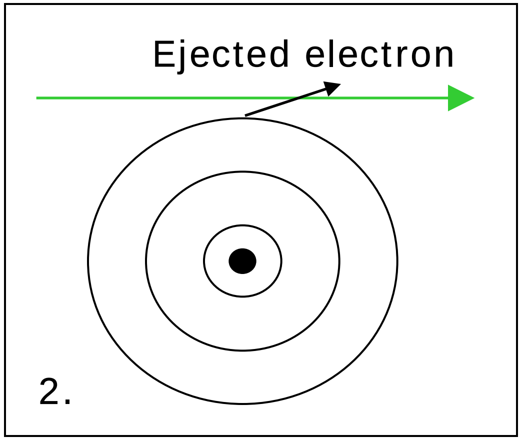


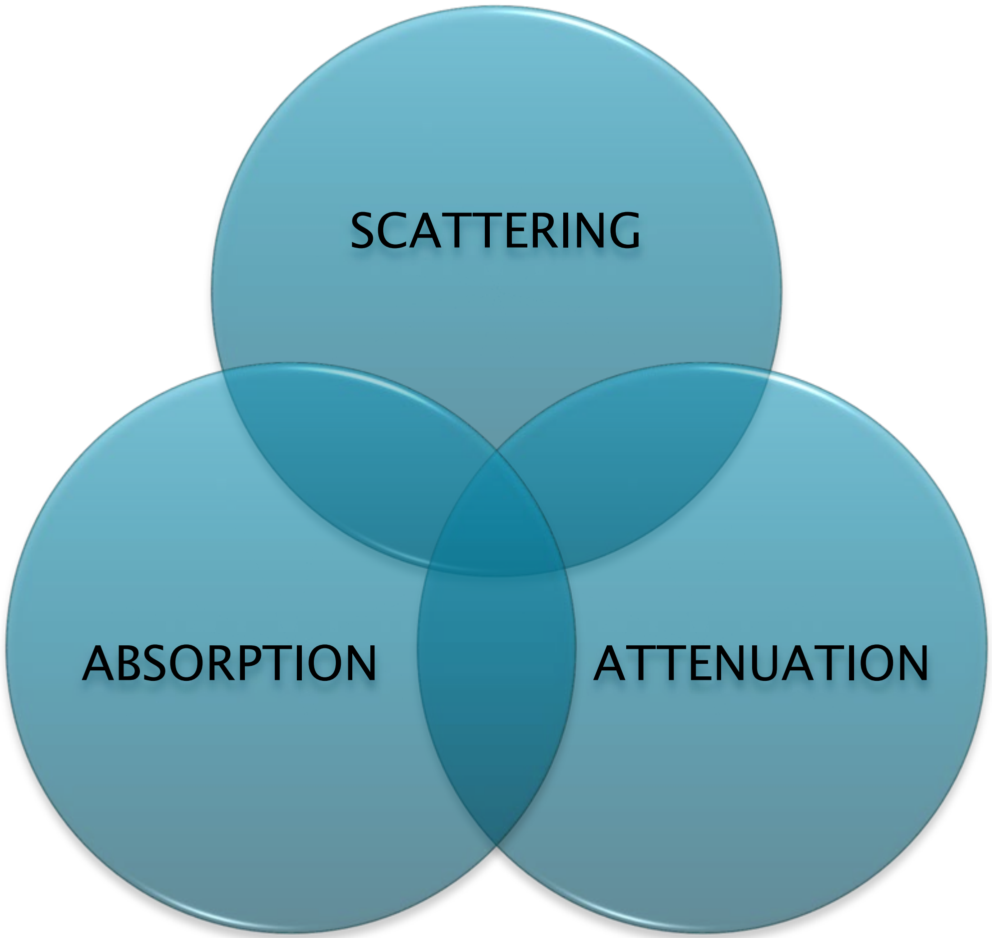
ATTENUATION	removal of photons from the beam by the matter.
ABSORPTION	Taking up the energy from the beam by the radiating material: **RADIOBIOLOGICAL EFFECTS**
SCATTERING	Change in the direction of photon beam
TRANSMISSION	Not suffering any of the interactions

- Excitation



- Ionisation




SCATTERING
ABSORPTION
ATTENUATION

INTERACTION OF PHOTON WITH MATTERS :

- PHYSICAL EFFECTS
- CHEMICAL EFFECTS
- BIOLOGICAL EFFECTS

BIOCHEMICAL EFFECTS OF RADIATION:

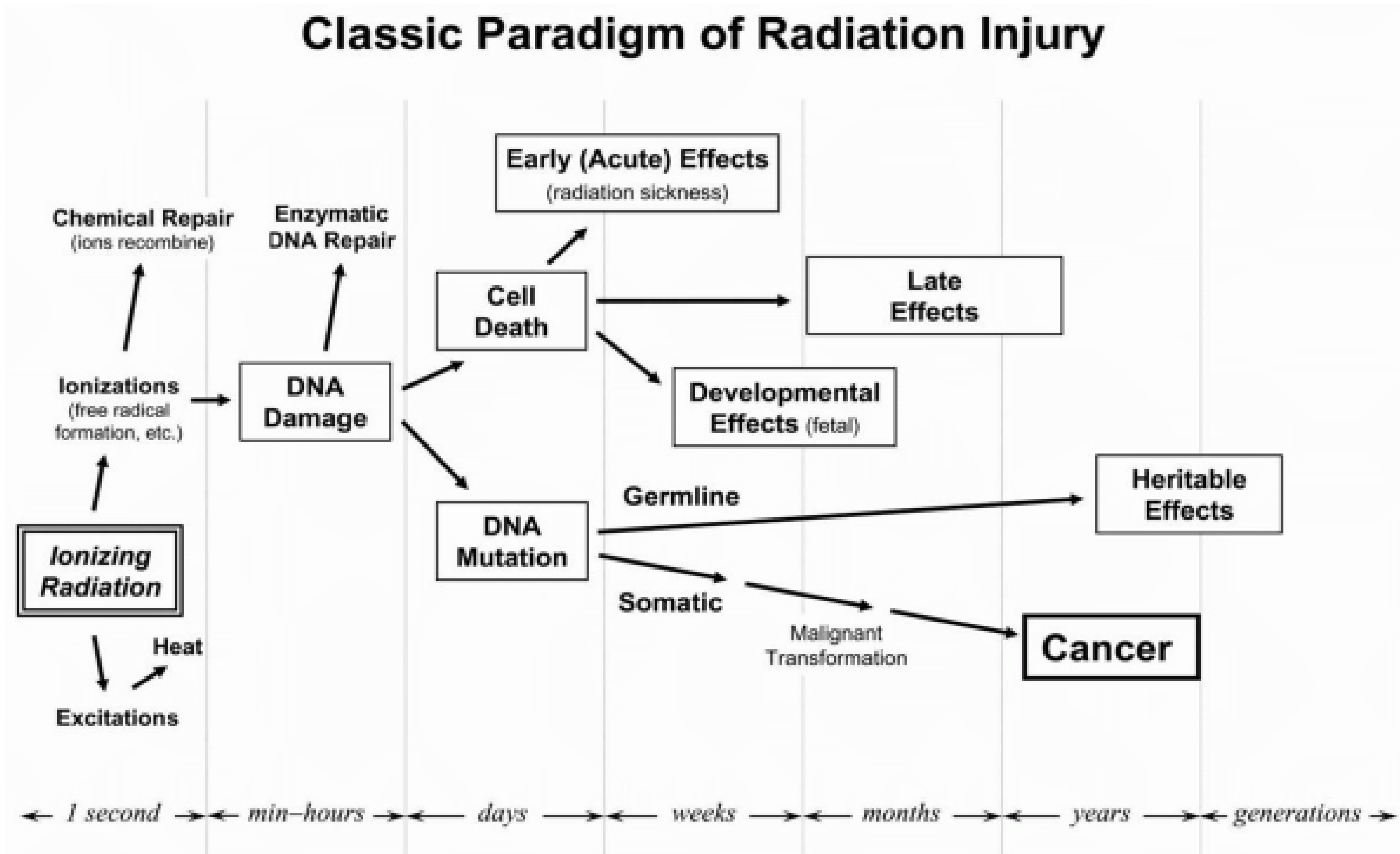


FIGURE 1.9 • Illustration of the generally accepted sequence of events from the absorption of radation to the expression of the various forms of biolo

Department of Energy.)

CHEMICAL EFFECTS

Ionising Radiation	Non-Ionising Radiation
Electron beams (directly)	Lasers
Protons (directly)	Ultra-violet
α-particles (directly)	Infra-red
β-particles (directly)	Ultrasound
Neutrons (indirectly)	MRI
X-rays (indirectly)	
γ-rays (indirectly)	

CHEMICAL EFFECTS :

ABSORPTION OF RADIATION :

- DIRECTLY IONISING:

Particles having sufficient kinetic energy to hit absorber atom directly

Eg: electron, proton, neutron, alfa particle

- INDIRECTLY IONISING:

PHOTON BEAM

↓

Absorbing medium

↓

Fast moving charged particles

↓

DAMAGE

CHEMICAL EFFECTS:

- DIRECT ACTION :

Secondary electron directly hits DNA

- INDIRECT ACTION:

Incident x-ray photon

↓

Fast electron (e^-)

↓

Free radical (Hydroxyl radical)

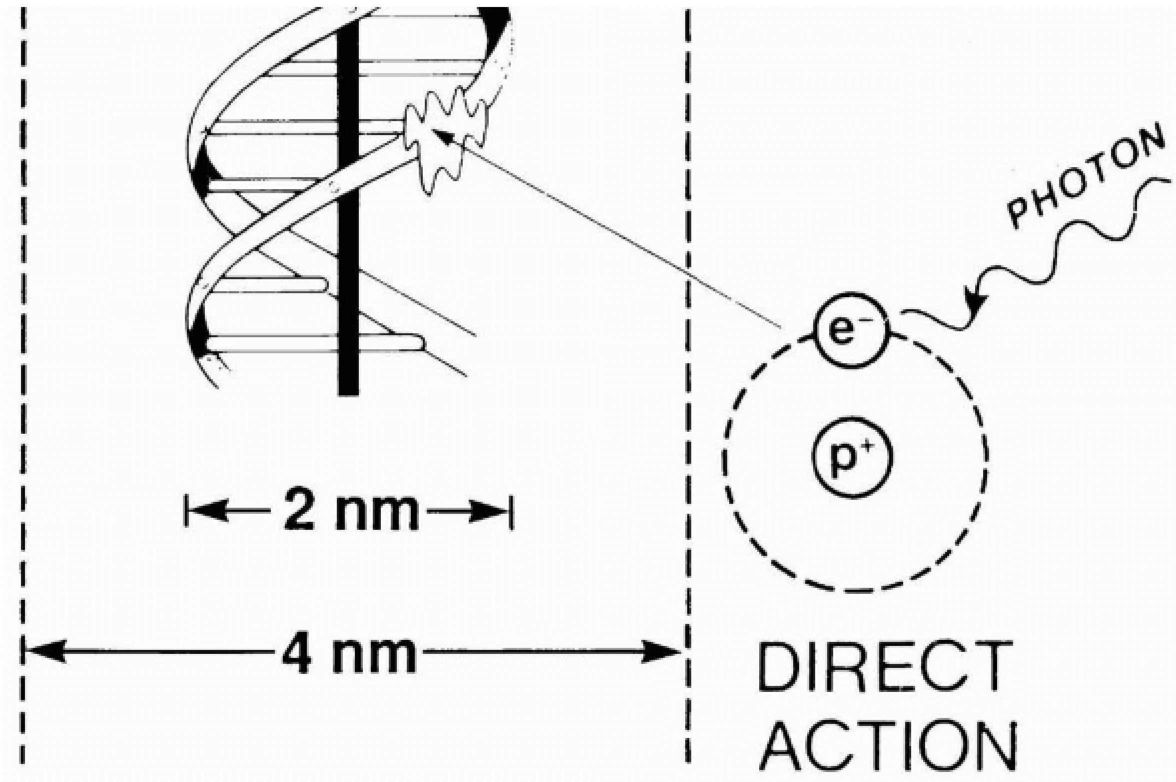
↓

Chemical changes from the breakage of bonds

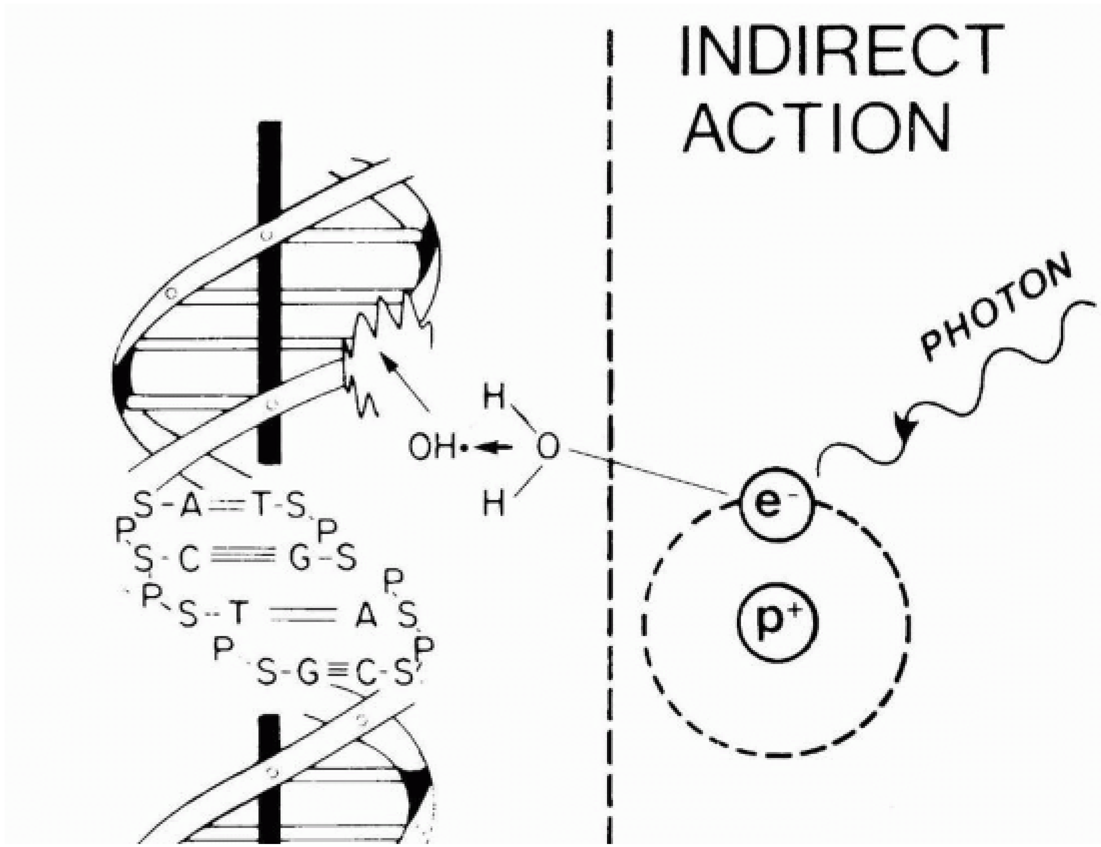
↓

Biologic effects

CHEMICAL EFFECTS :

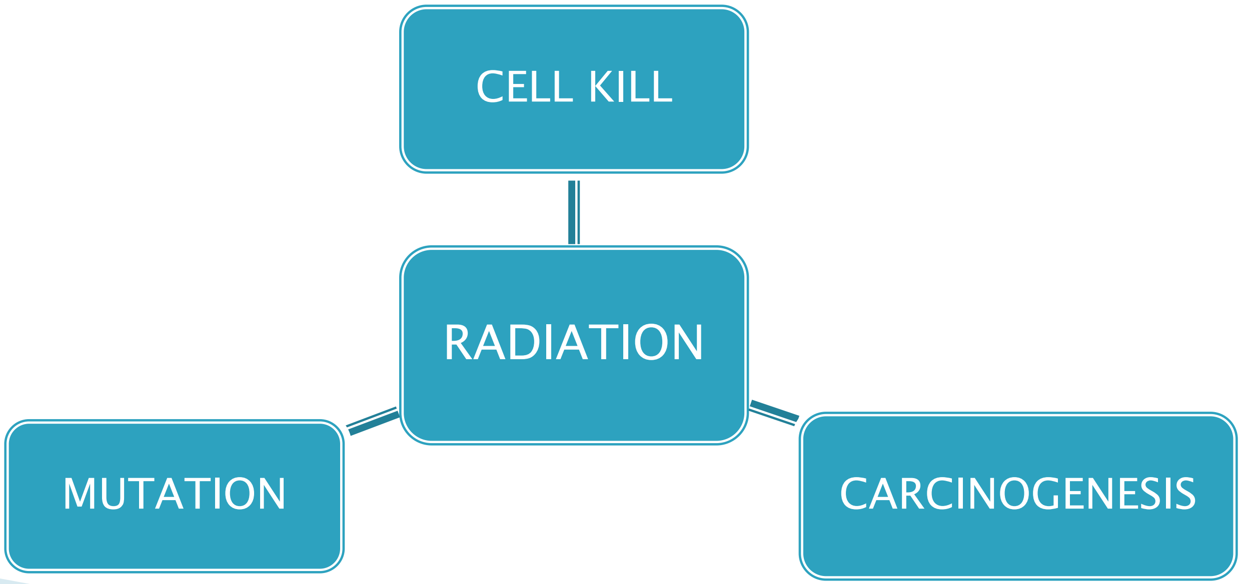


CHEMICAL EFFECTS:



BIOLOGICAL EFFECTS :

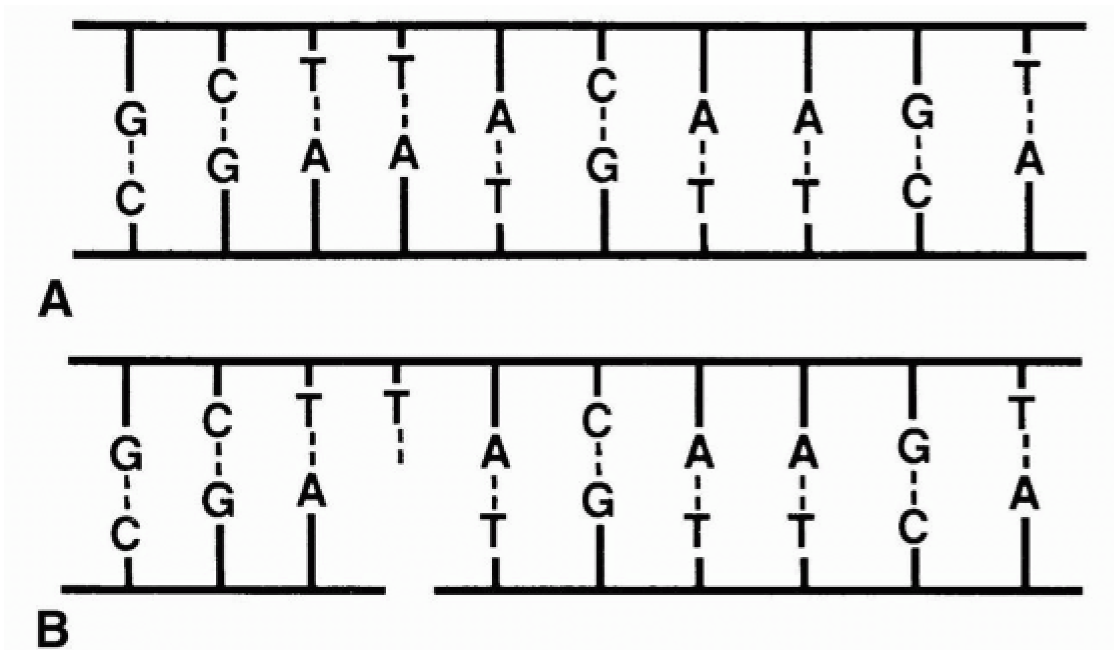
- DNA IS THE PRINCIPAL TARGET.



BIOLOGICAL EFFECT :

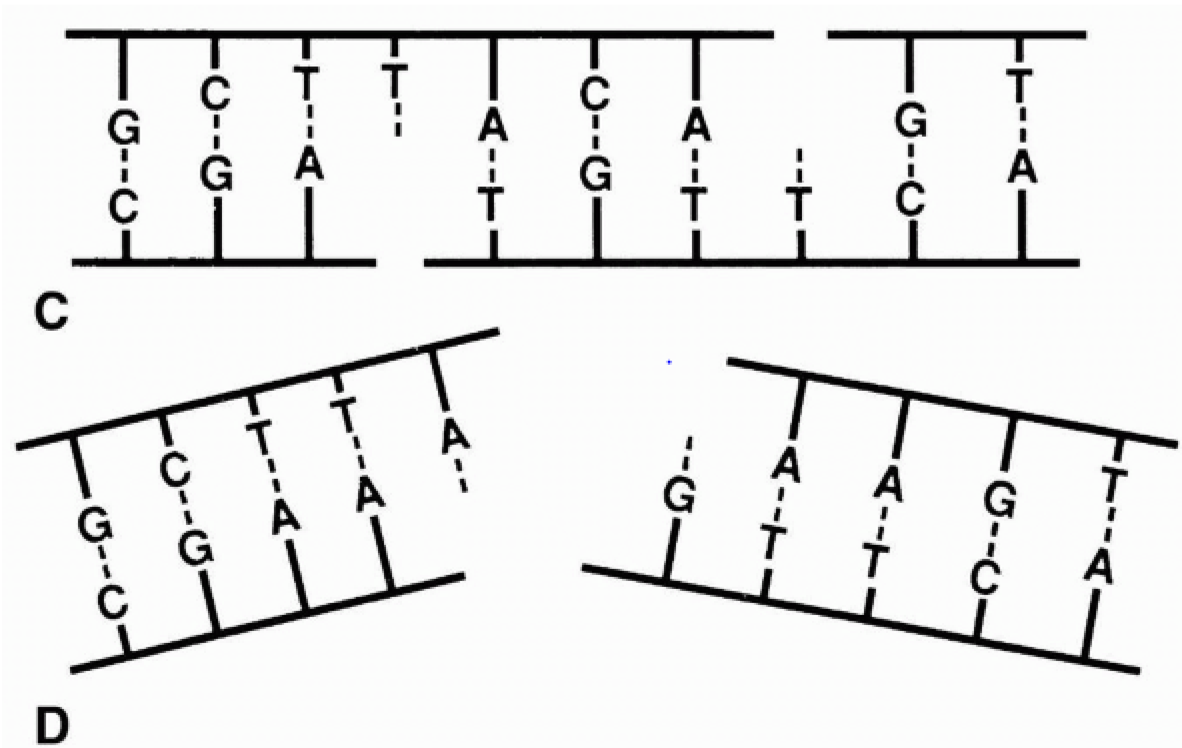
- DNA STRAND BREALS:

1.SINGLE STRAND BREAKS



BIOLOGICAL EFECTS :

2.DOUBLE STRAND BREAKS:



BREAKS : FATE :

1.restitute, rejoin in original configuration

2. fail to rejoin : ABERRATION

3. Broken end may rejoin with ends of other broken segments. Distorted chromosome.

- RADIATION INDUCED ABERRATIONS:

LETHAL:

1.DICENTRIC

2.RING

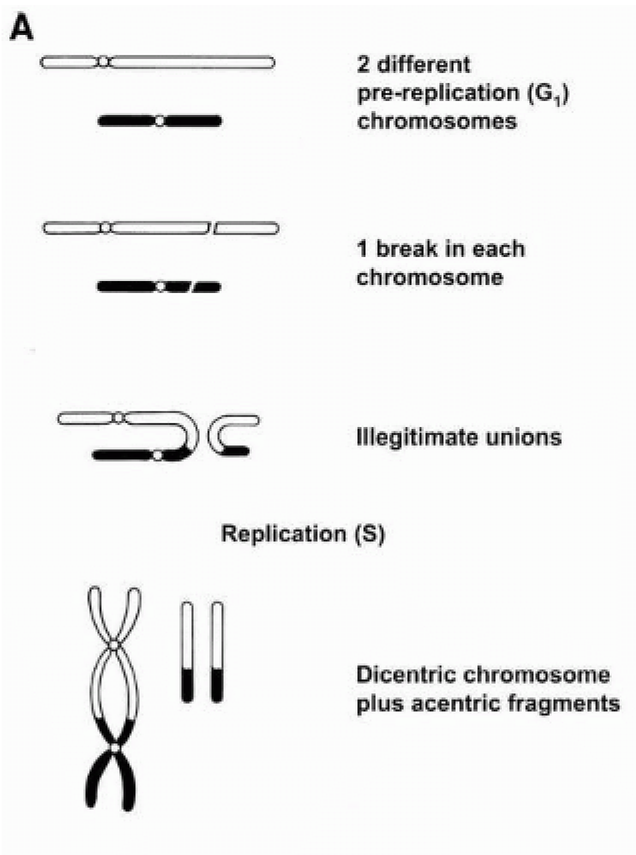
3.ANAPHASE BRIDGE

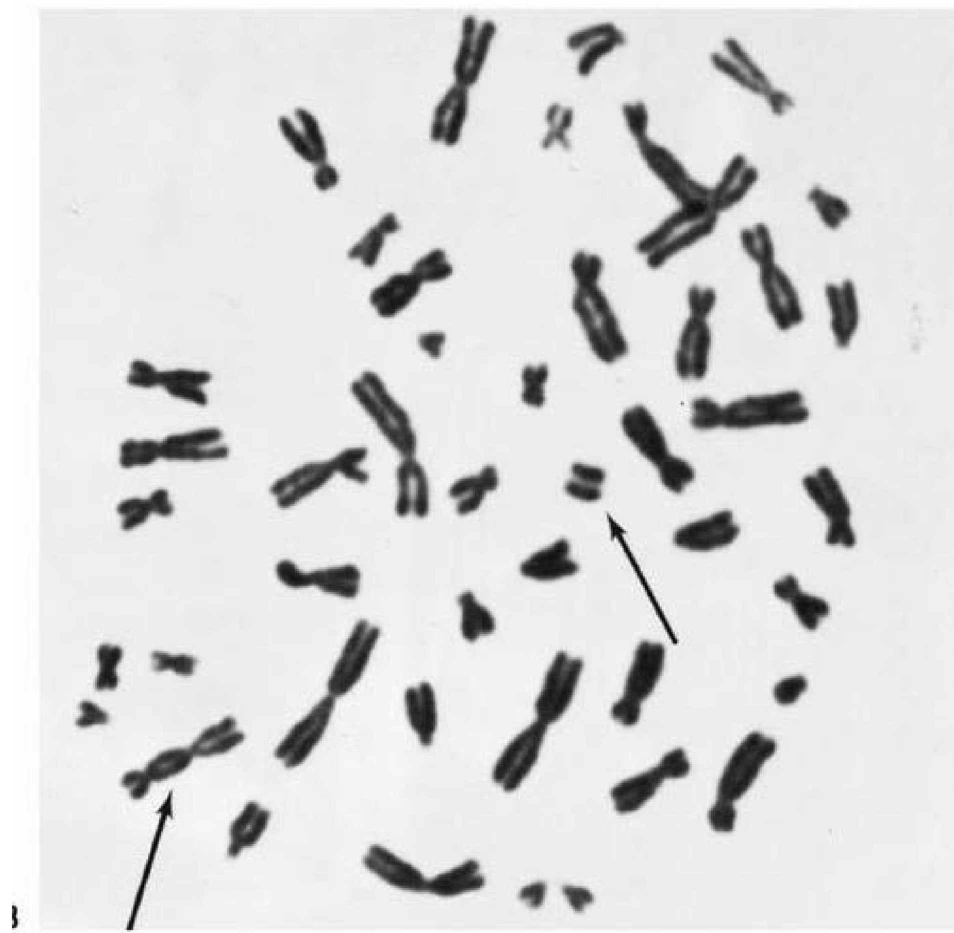
NONLETHAL:

1.TRANSLOCATION

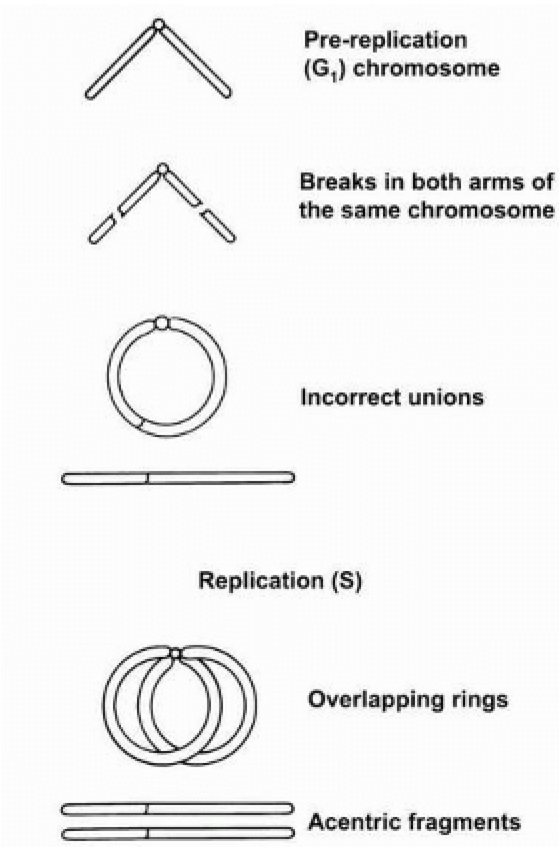
2.DELETION

DICENTRIC:

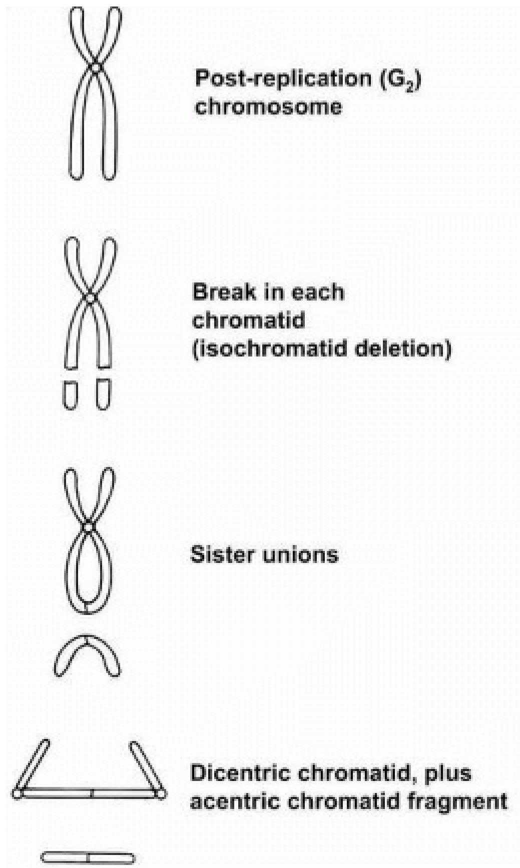

A
2 different
pre-replication (G_1)
chromosomes
1 break in each
chromosome
Illegitimate unions
Replication (S)
Dicentric chromosome
plus acentric fragments


B

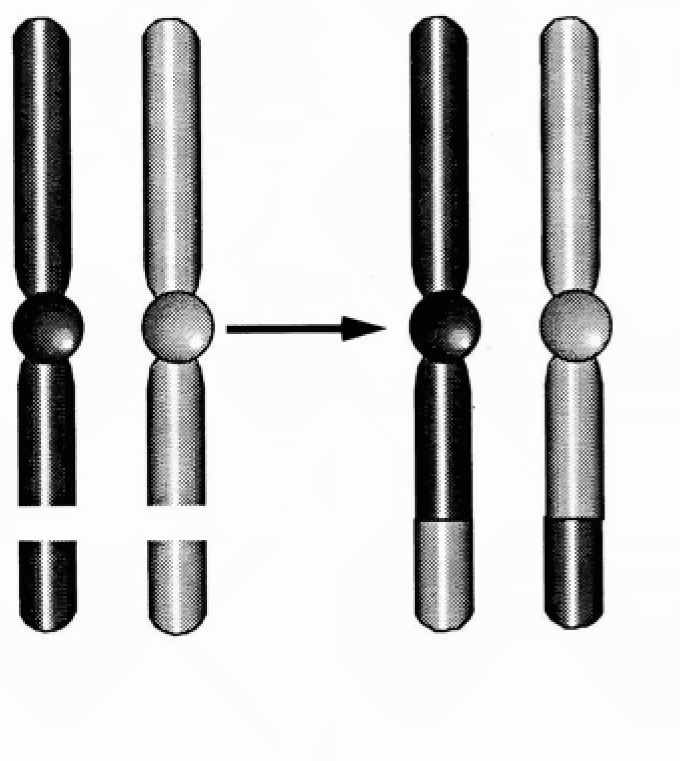
RING FORMATION:



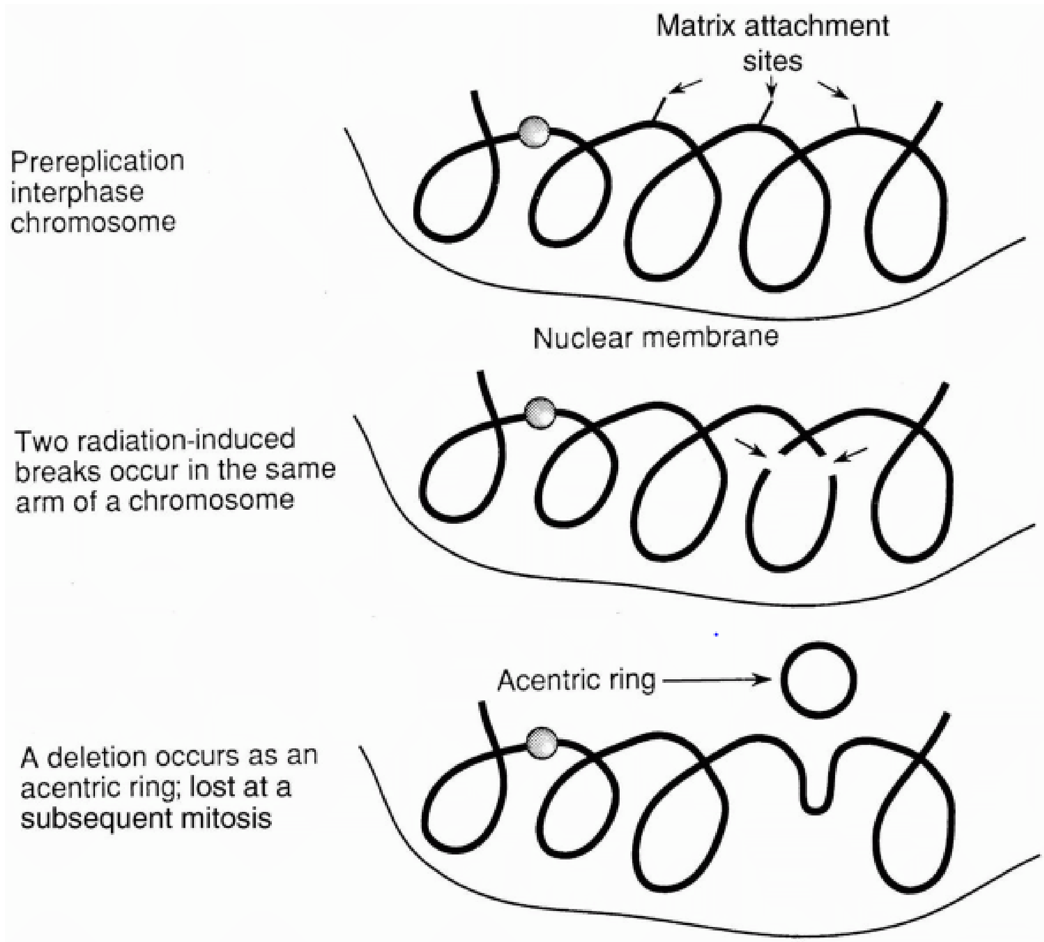
ANAPHASE BRIDGES :



SYMMMETRIC TRANSLOCATION :



DELETION :


Matrix attachment sites
Prereplication interphase chromosome
Nuclear membrane
Two radiation-induced breaks occur in the same arm of a chromosome
Acentric ring
A deletion occurs as an acentric ring; lost at a subsequent mitosis

OPERATIONAL CLASSIFICATION OF RADIATION DAMAGE

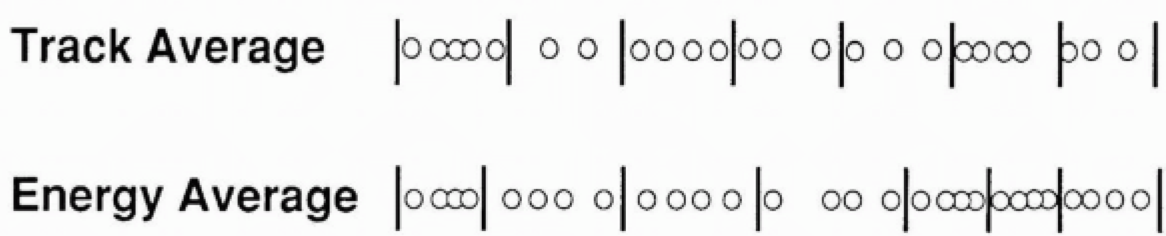
DAMAGE	PROCESS
LETHAL DAMAGE	Irreversible and irreparable
POTENTIALLY LETHAL DAMAGE (PLD)	Can be modified by post radiation environmental conditions
SUBLETHAL DAMAGE (SLD)	Can be repaired in hours

LINEAR ENERGY TRANSFER (LET)

- After radiation absorption in matter ionisation /excitation occurs not at random but…

ALONG TRACKS , patterns depending on nature of radiation

LET = Average energy deposited per unit length of track (keV/μm)



L E T

TABLE 7.1 Typical Linear Energy Transfer Values

Radiation	Linear Energy Transfer, keV/μm
Cobalt-60 γ-rays	0.2
250-kV x-rays	2.0
10-MeV protons	4.7
150-MeV proton	0.5
14-MeV neutrons	Track Avg. 12 Energy Avg. 100
2.5-MeV α-particles	166
2-GeV Fe ions (space radiation)	1,000

RELATIVE BIOLOGIC EFFECTIVENESS (RBE)

- The RBE of some test radiation (r) compared with x-rays is defined by the ratio D_{250}/D_r,

D_{250} = the doses of x-rays and

D_r = the test radiation required for equal biological effect.

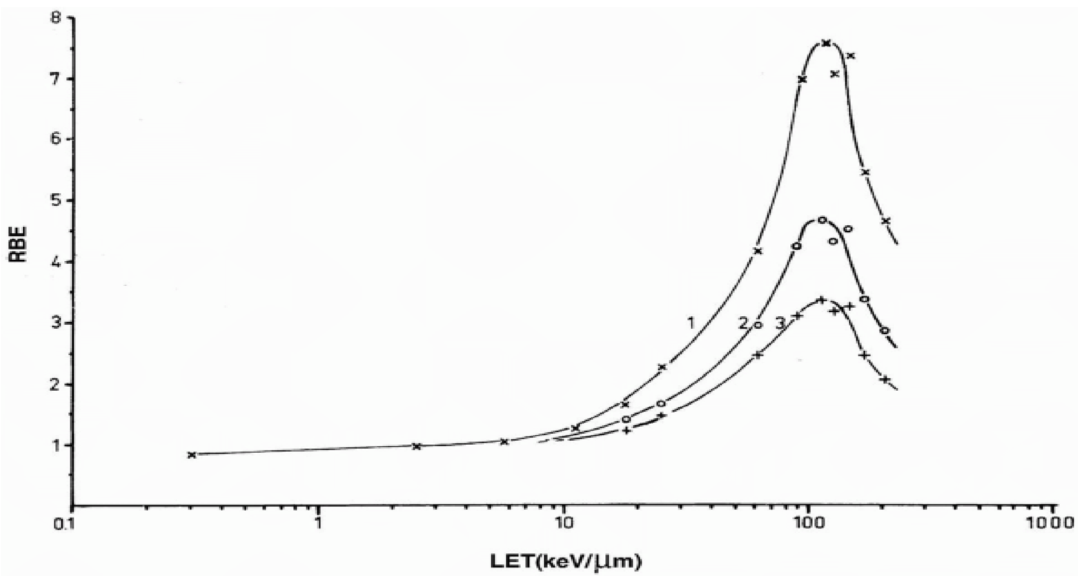


FIGURE 7.6 • Variation of relative biologic effectiveness (RBE) with linear energy transfer (LET) for survival of mammalian cells of human origin. The RBE rises to a maximum at an LET of about 100 keV/µm and subsequently falls for higher values of LET. Curves 1, 2, and 3 refer to cell survival levels of 0.8, 0.1, and 0.01, respectively, illustrating that the absolute value of the RBE is not unique but depends on the level of biologic damage and, therefore, on the dose level. (From Barendsen GW: Responses of cultured cells, tumors, and normal tissues to radiation of different linear energy transfer. Curr Top Radiat Res Q 4:293-356, 1968, with permission.)

RBE ,LET AND OER: RELATION

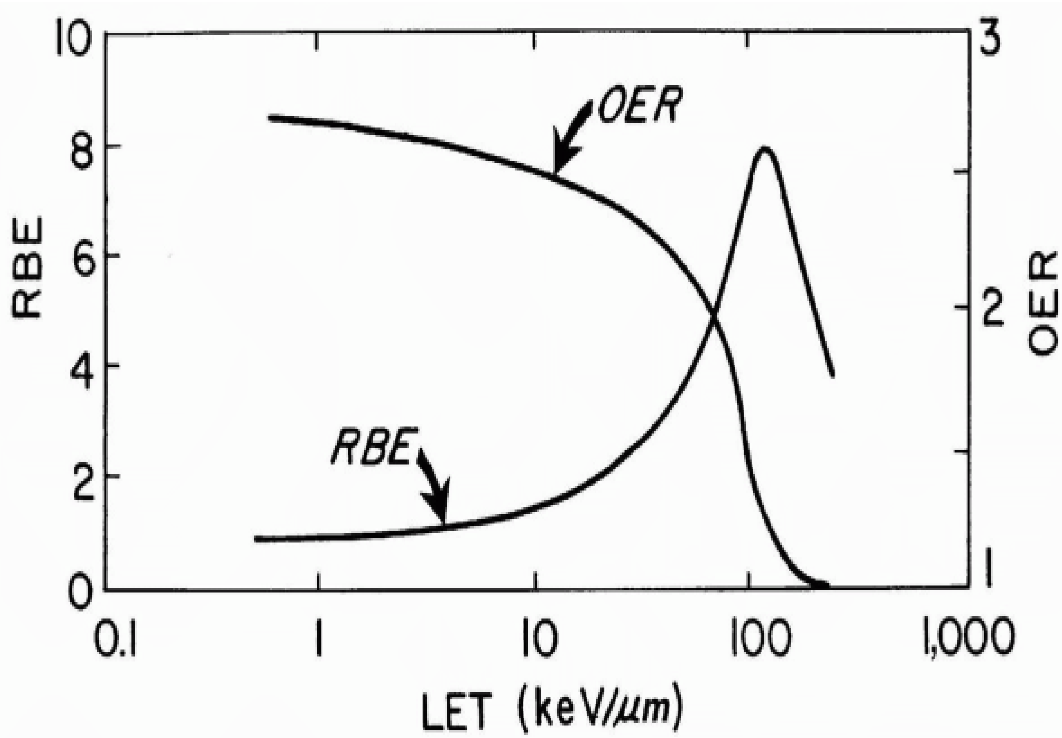
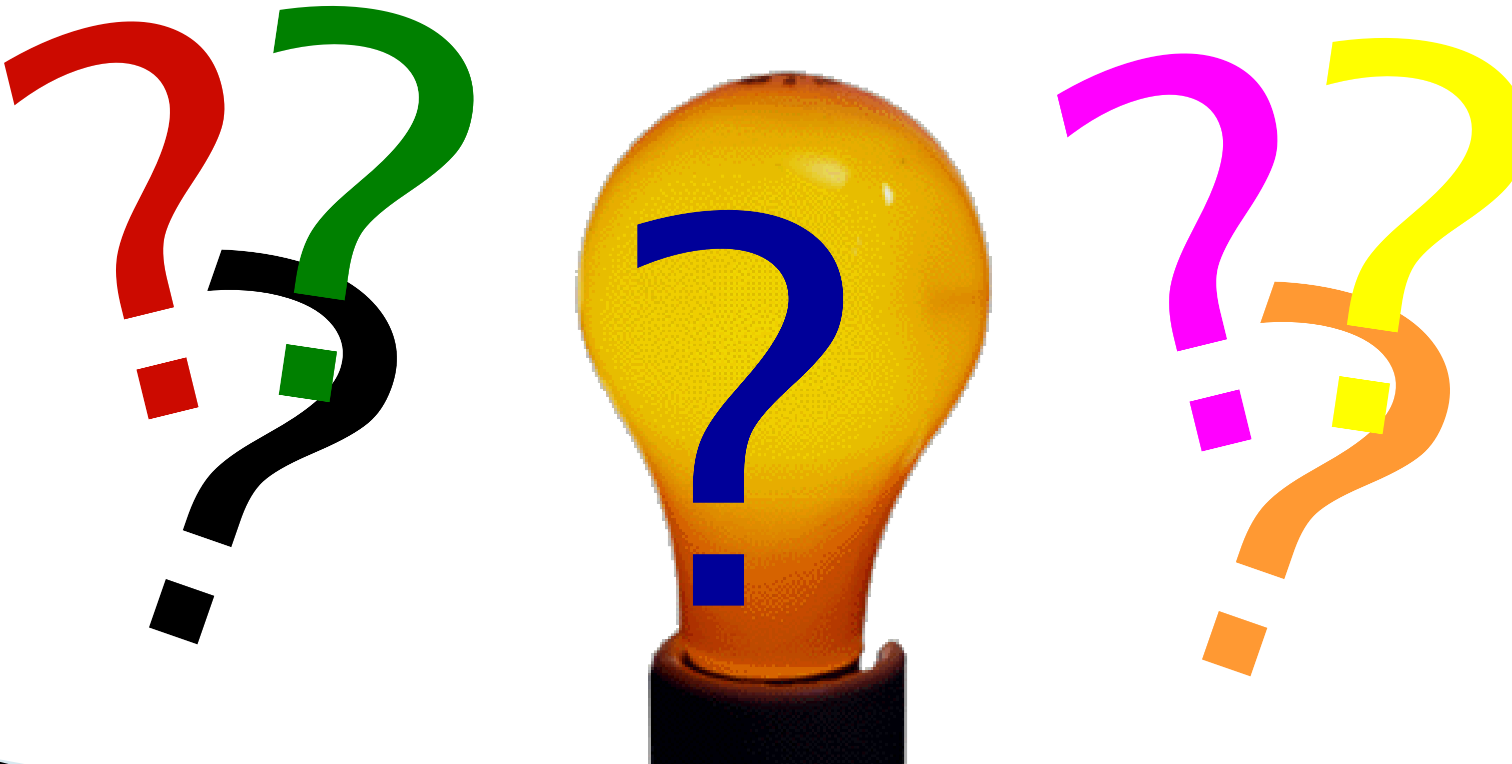


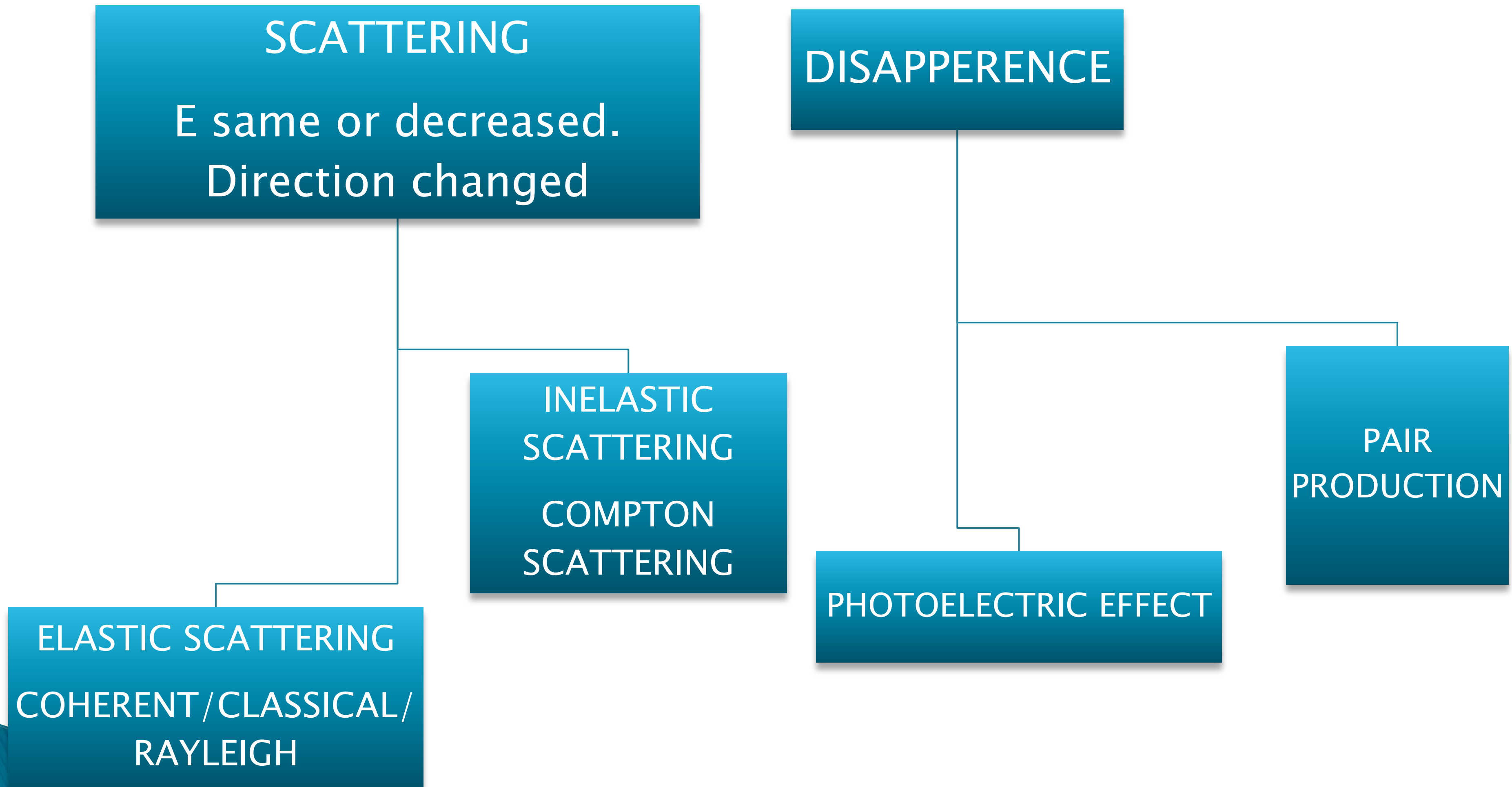
FIGURE 7.10 • Variation of the oxygen enhancement ratio and the relative biologic effectiveness as a function of the linear energy transfer of the radiation involved. The data were obtained using T1 kidney cells of human origin irradiated with various naturally occurring α-particles or with deuterons accelerated in the Hammersmith cyclotron. Note that the rapid increase in relative biologic effectiveness and the rapid fall of the oxygen enhancement ratio occur at about the same linear energy transfer, 100 keV/μm. (Redrawn from Barendsen GW: In: Proceedings of the Conference on Particle Accelerators in Radiation Therapy, pp 120-125. LA-5180-C. US Atomic Energy Commission, Technical Information Center, 1972, with permission.)

PHYSICAL EFFECTS :

What is Physics?

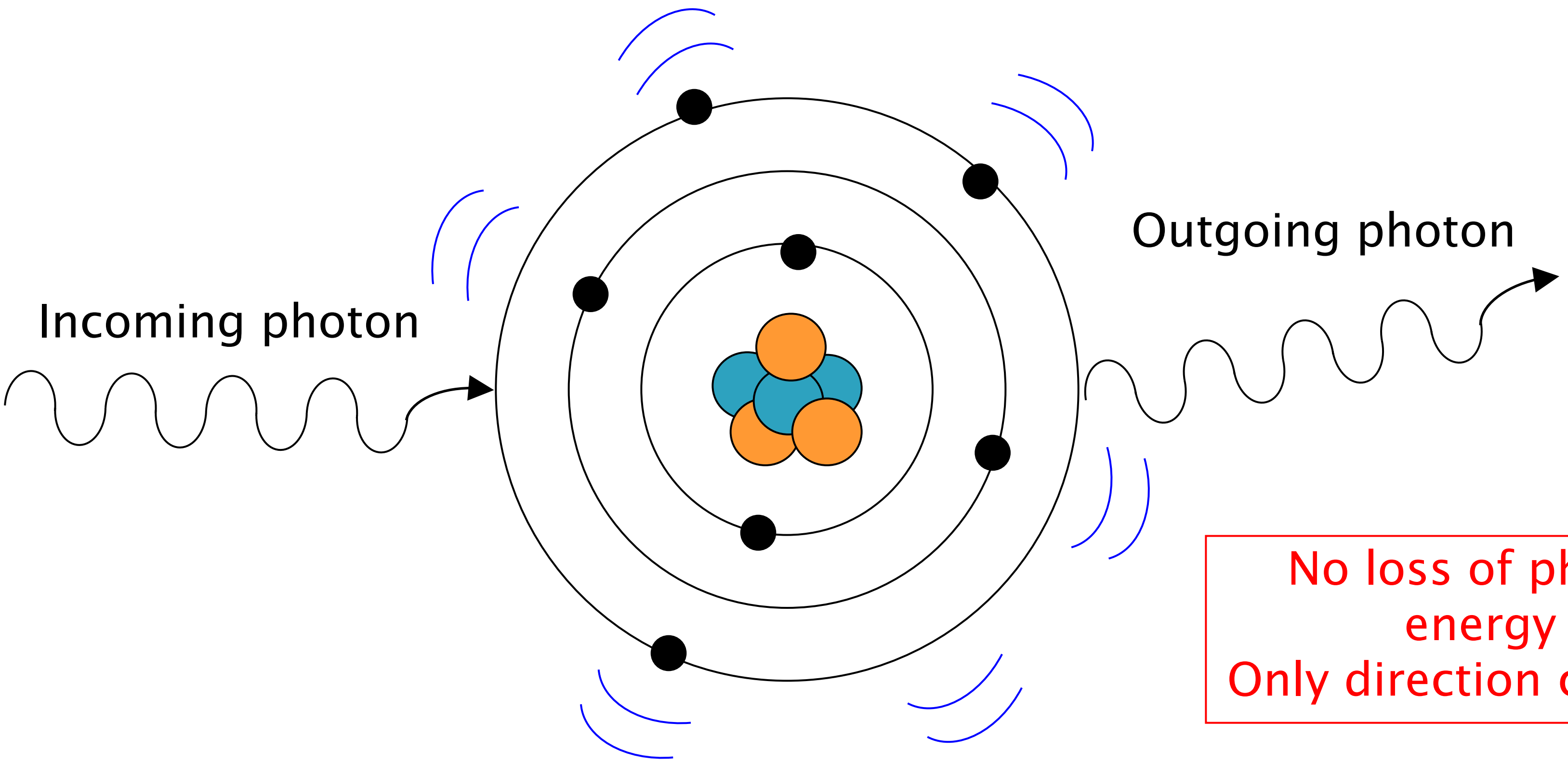


PHOTON BEAM ATTENUATION



ELASTIC/COHERENT/CLASSICAL/ RAYLEIGH SCATTERING

ELASTIC SCATTERING

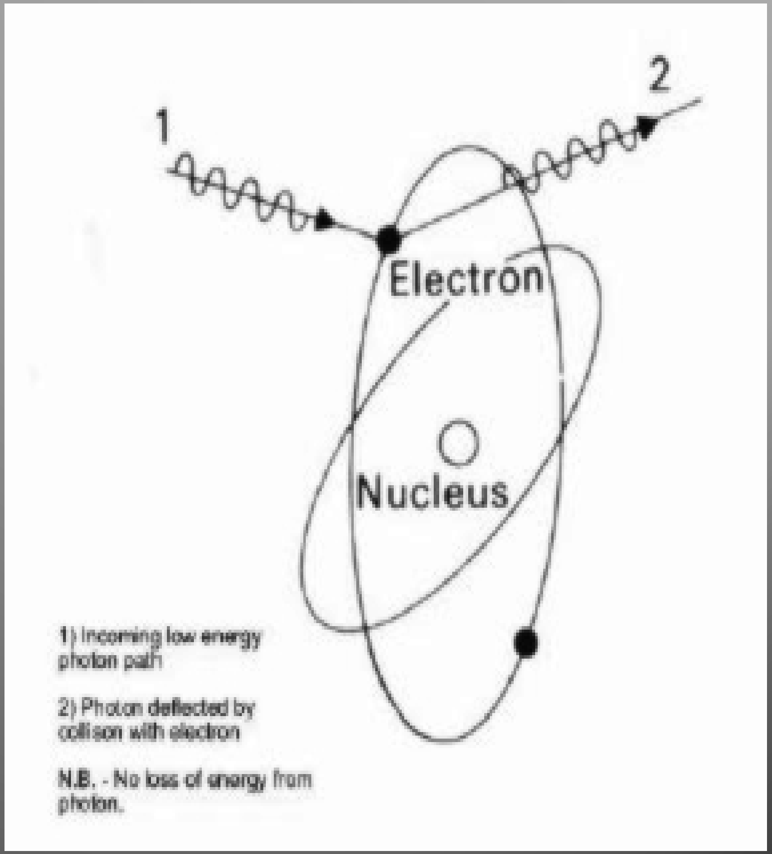


No loss of photon energy
Only direction changed

$$h\nu_{in} = h\nu_{out}$$

COHERENT SCATTERING

- Radiation is considered as WAVES.
- For BOUND electrons
- No E changes to electronic motion
- No E absorption
- No net E loss
- Only direction changed
- High Z material
- Low E photons
- $\varepsilon/\rho \propto Z^2/(h\nu)^2$



ELASTIC SCATTERING

- Photon scattering angle depends on Z and $h\nu$

$h\nu$	0.1 MeV	1 MeV	10 MeV
Al	15^o	2^o	0.5^o
Pb	30^o	4^o	1.0^o

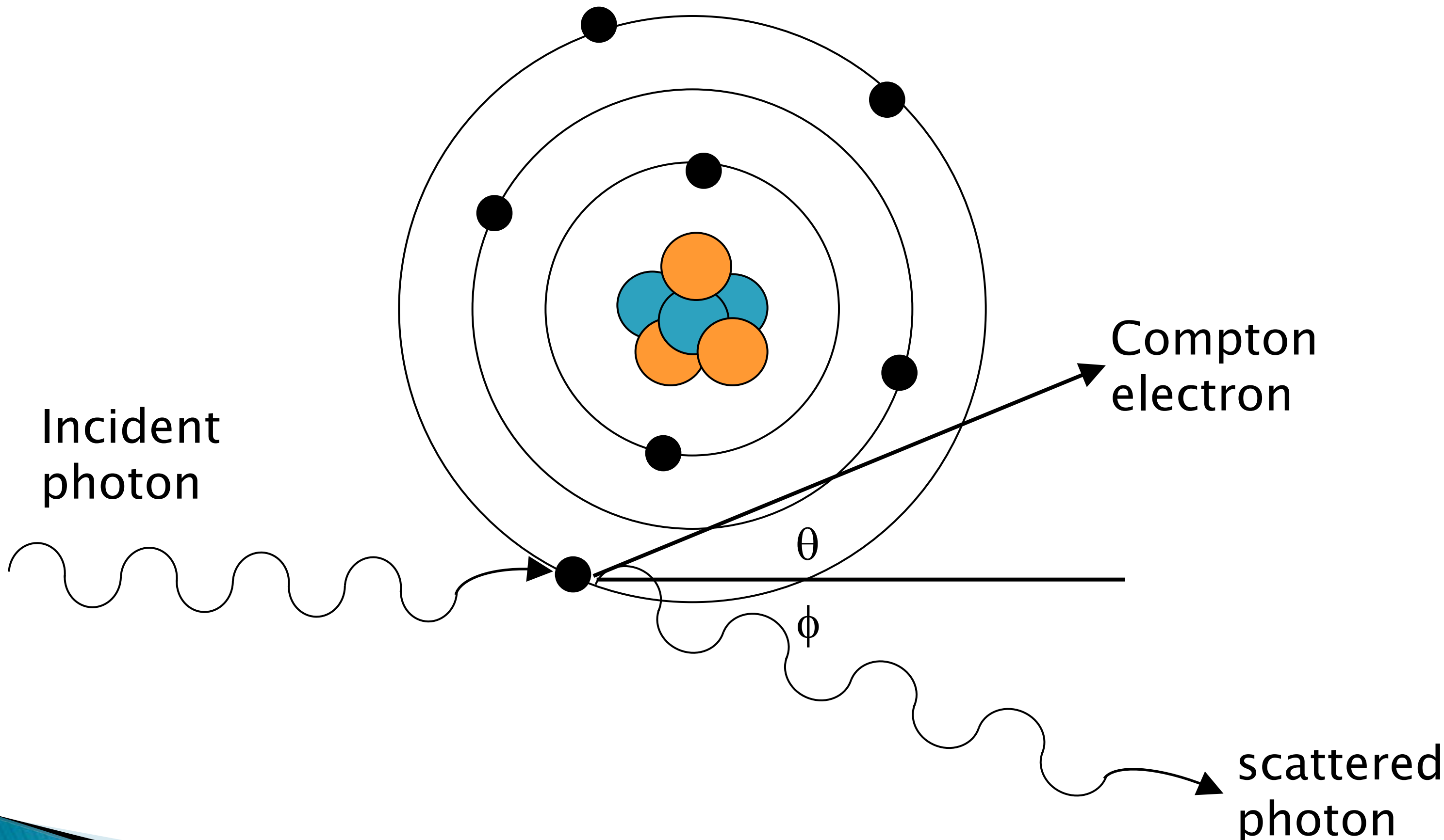
- No real importance in radiotherapy
- Used in X RAY crystallography

COMPTON EFFECT

INELASTIC SCATTERING

PHOTONS WITH FREE ELECTRON

COMPTON EFFECT



COMPTON EFFECT

Interact with **free electrons.(** binding energy of the electron is much less than the energy of the bombarding photon.)

The photon collides with electron and hands over part of its energy to it.

- The Compton effect results in **both attenuation and absorption**
- Wavelength change depends **only** upon the **angle** through which the radiation is scattered

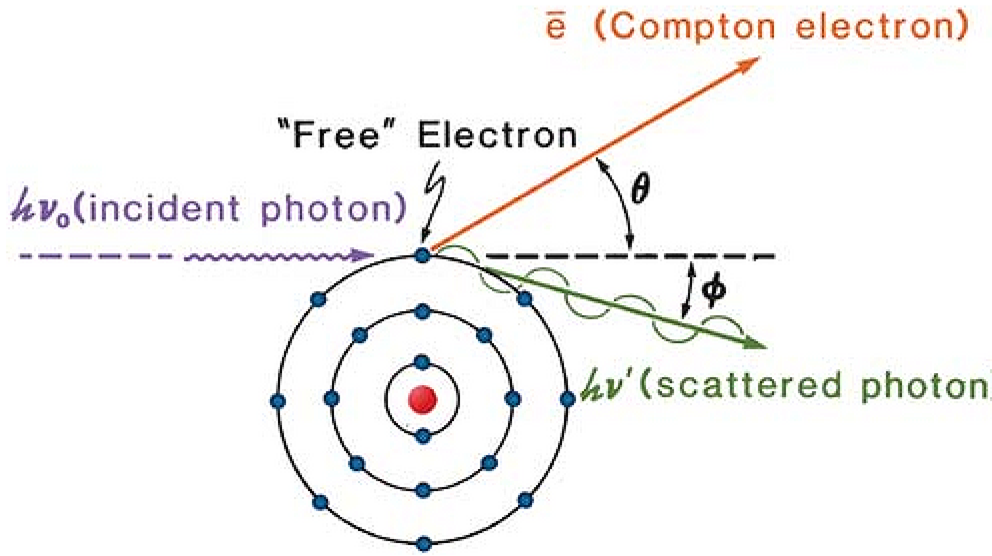


Figure 5.7. Diagram illustrating the Compton effect.

- $\lambda_o - \lambda_{'} = \boldsymbol{\delta\lambda}$ **=** constant x (1– Cosϕ)
- $h\nu_o = h\nu' + E$

- $h\nu_0$, $h\nu'$, and E are the energies of the incident photon, scattered photon, and electron, respectively,

$$E = h\nu_0 \frac{\alpha(1 - \cos\phi)}{1 + \alpha(1 - \cos\phi)}$$

$$h\nu' = h\nu_0 \frac{1}{1 + \alpha(1 - \cos\phi)}$$

$$\cot\theta = (1 + \alpha)\tan\phi/2$$

- $\alpha = h\nu_0/m_0c^2$,
- where m_0c^2 is the rest energy of the electron (0.511 MeV). If $h\nu_0$ is expressed in MeV, then $\alpha = h\nu_0/0.511$.

Photon energy: $h\nu = hc/\lambda$

where:

h = Planck's constant ($6.63e^{-34}$ J.s)

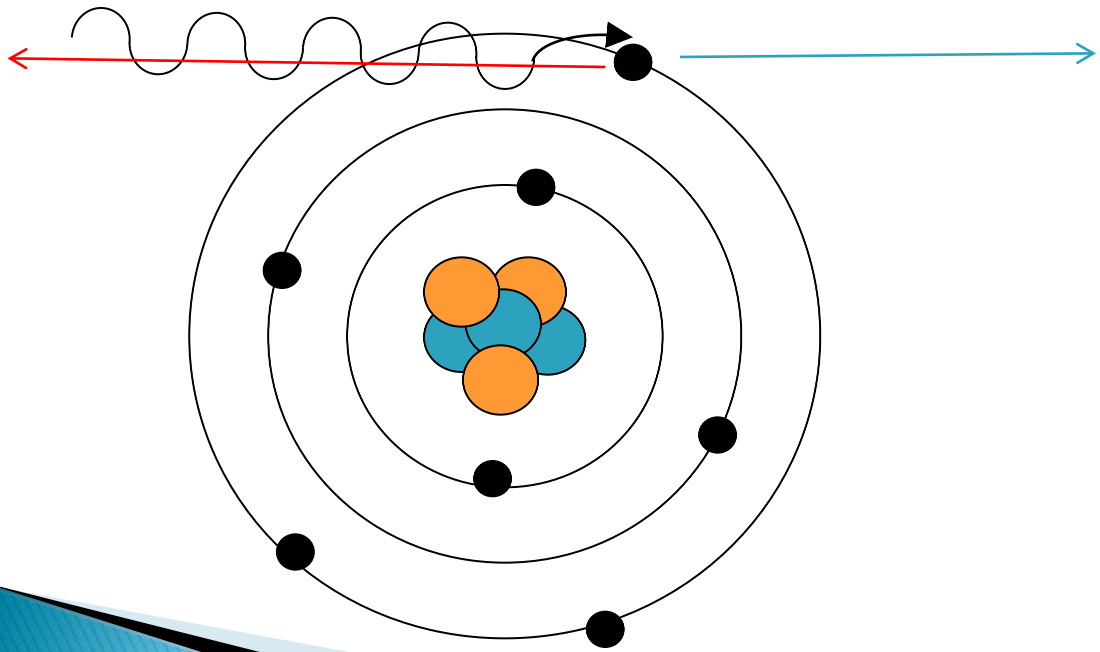
ν = frequency

λ = wavelength

SPECIAL CASES OF COMPTON EFFECT

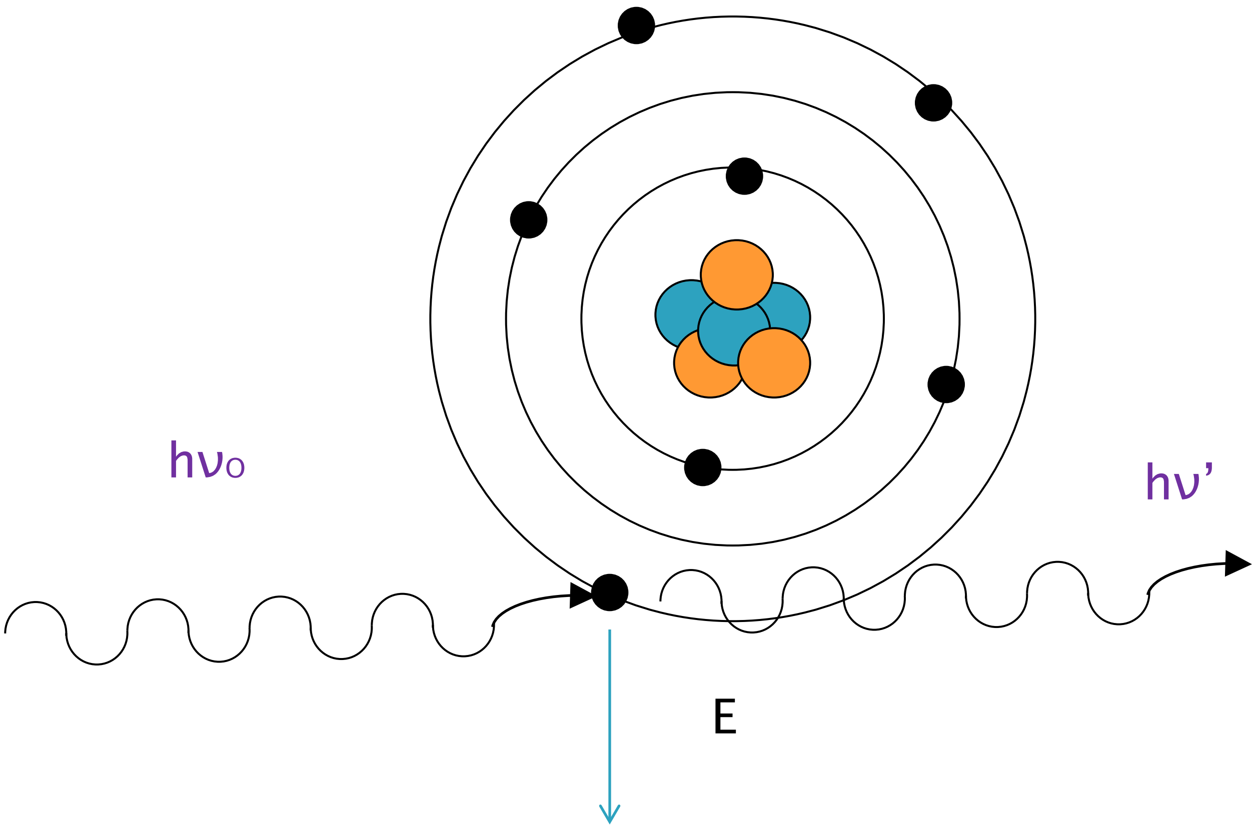
- DIRECT HIT:
- $\Phi = 180$
- $\Theta = 0$

$h\nu'$ = min
E = max

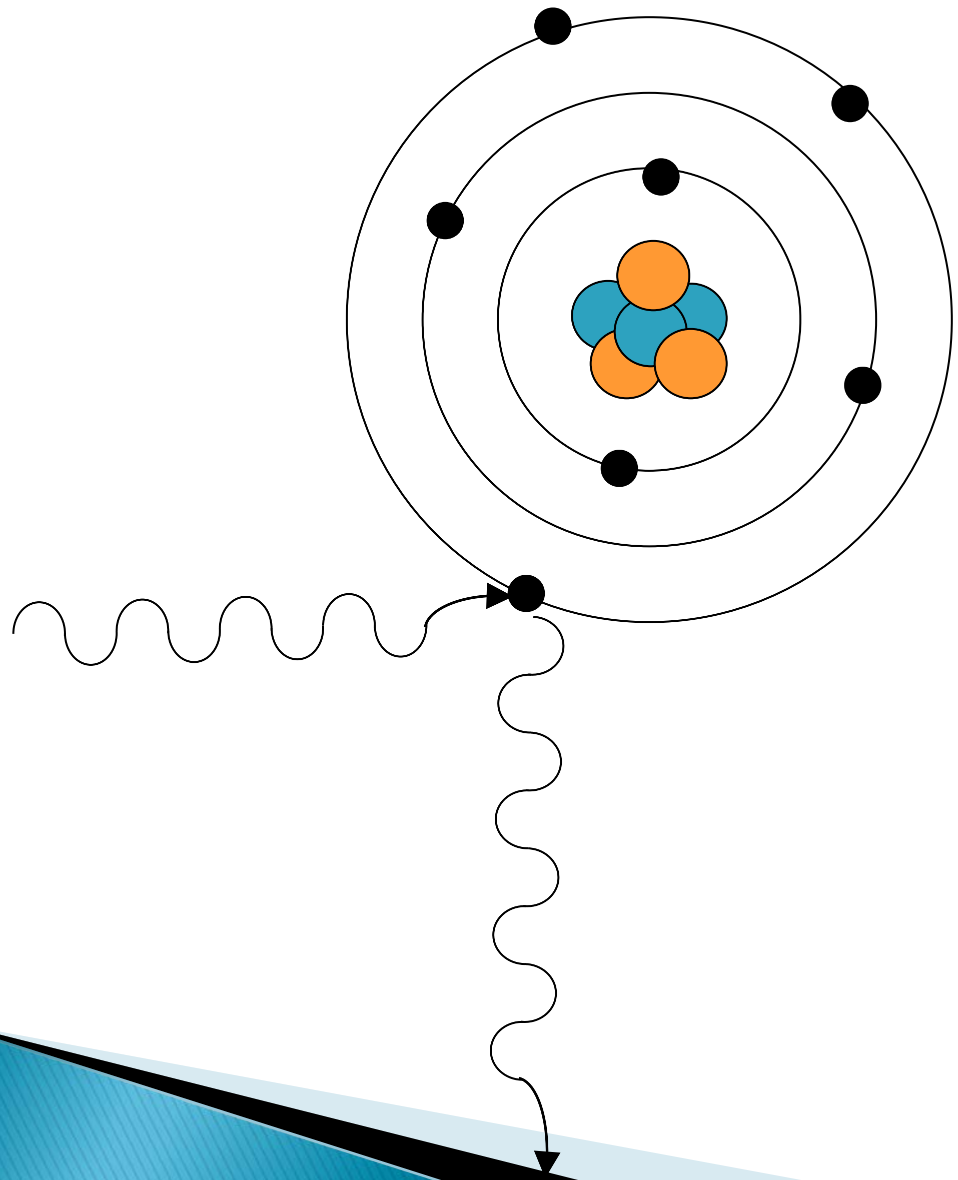


GRAZING HIT:

$\phi = 0$
$\theta = 90$
$h\nu' = MAX$
$E = 0$



90 DEGREE PHOTON SCATTER:



ϕ = 90

θ Depends on α

COMPTON EFFECT :DETERMINIG FACTORS: INCIDENT PHOTON ENERGY

- ENERGY:

hv >> binding energy of e

- $h\nu_0$ lower = maximum energy shifting to $h\nu'$
- $h\nu_0$ higher = maximum energy shifting to E

Incident photon energy	Scattered photon energy	Recoil **e** energy
51.1keV	42.58 keV	8.62 keV
5.11 MeV	0.24 MeV	4.87 MeV

COMPTON SCATTER: DETERMINING FACTORS

- Independent of Z
- depends only on the number of electrons /gram.(same for all material except H_2)
- So depends on electron density (no of e $\times$ p/gm)
- So on DENSITY of the material
- Mass attenuation coefficient

$$\sigma/\rho \propto \rho_e / h\nu$$

PRACTICAL IMPLICATIONS:

Attenuation doesn't depend on the atomic number	1. Thus **concrete** is as good as lead in shielding of megavoltage equipment! 2. The **absorption** in bones doesn't exceed that produced in the soft tissues – unlike in PE effect seen in orthovoltage radiation era. 3. There is no **Bone shielding** phenomenon unlike that seen in orthovoltage radiation. **4. Port films** produced in megavoltage equipment have very little detail.
The fraction of the energy imparted to the recoil electron increases as the beam energy increases	This means that higher beam energies allow **greater absorption** of the dose in the body with **less** scattering of energy. Thus with increasing photon energy greater absorption occurs relative to attenuation.
Direction of the scatter depends on the energy of the incident photon beam	This implies that as the photon energy increases there is a corresponding increase in the **forward scatter** of the beam. This results in better dose distribution.
Energy of the scattered radiation is independent of the incident beam energy	This has several important implications in designing radiation protection. The maximum energy of photons with 90° scatter is **0.511** MeV while that for 180° scatter (i.e.. Back scatter) is **0.255 MeV**. The energy of the photons scattered at angles <90 ° will be more than .511 MeV and will gradually approach the incident photon energy.

COMPTON SCATTER : 90 & 180 DEGREE : RADIATION PROTECTION

- For higher E photon
- when ϕ= 90 degree $h\nu' = 0.511$ MeV
- when ϕ= 180 degree $h\nu' = 0.255$ MeV

  - Radiation scattered at right angles is independent of incident energy and has a maximum value of 0.511 MeV;

  - the radiation scattered backwards is independent of incident energy and has a maximum value of 0.255 MeV.

  - $<$ 90 degree then scattered radiation $>$ o.511 MeV

  - **Concept helps in calculating barrier or wall thicknesses against scattered radiation.**

DISAPPERENCE PHENOMENA

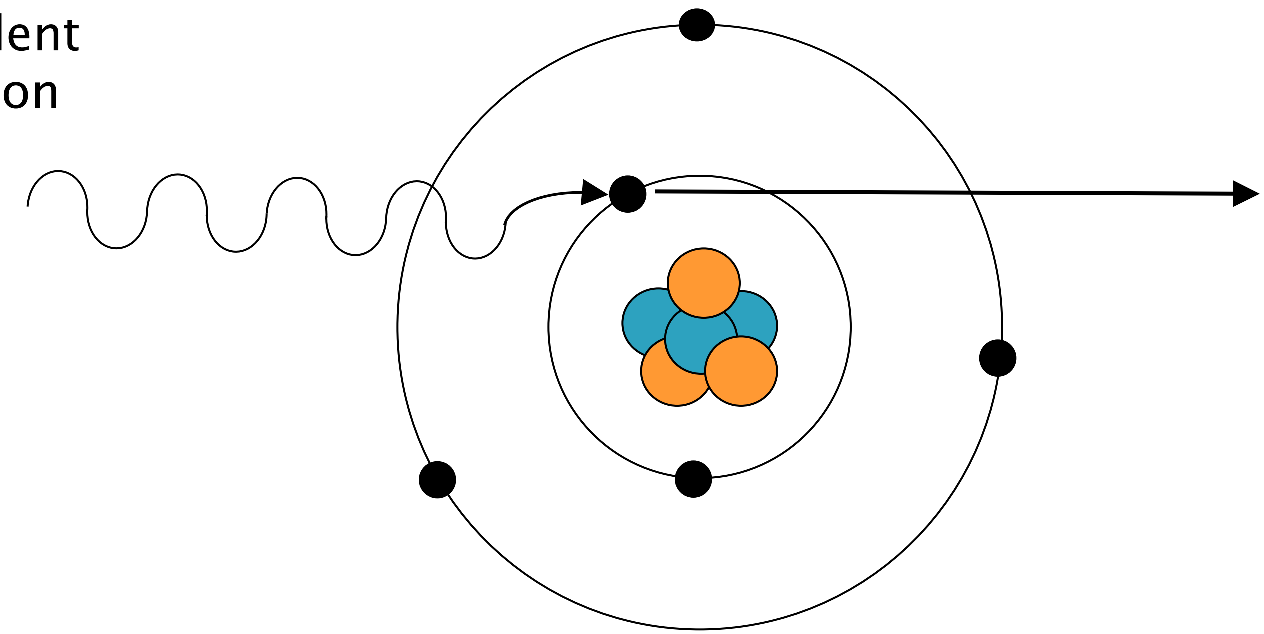
- PHOTO ELECTRIC EFFECT
- PHOTO DISINTEGRATION
- PAIR PRODUCTION

PHOTOELECTRIC EFFECTS

PHENOMENA OF BOUND ELECTRONS eg K,L,M,N shells

PHOTO-ELECTRIC EFFECT:

STEP 1:



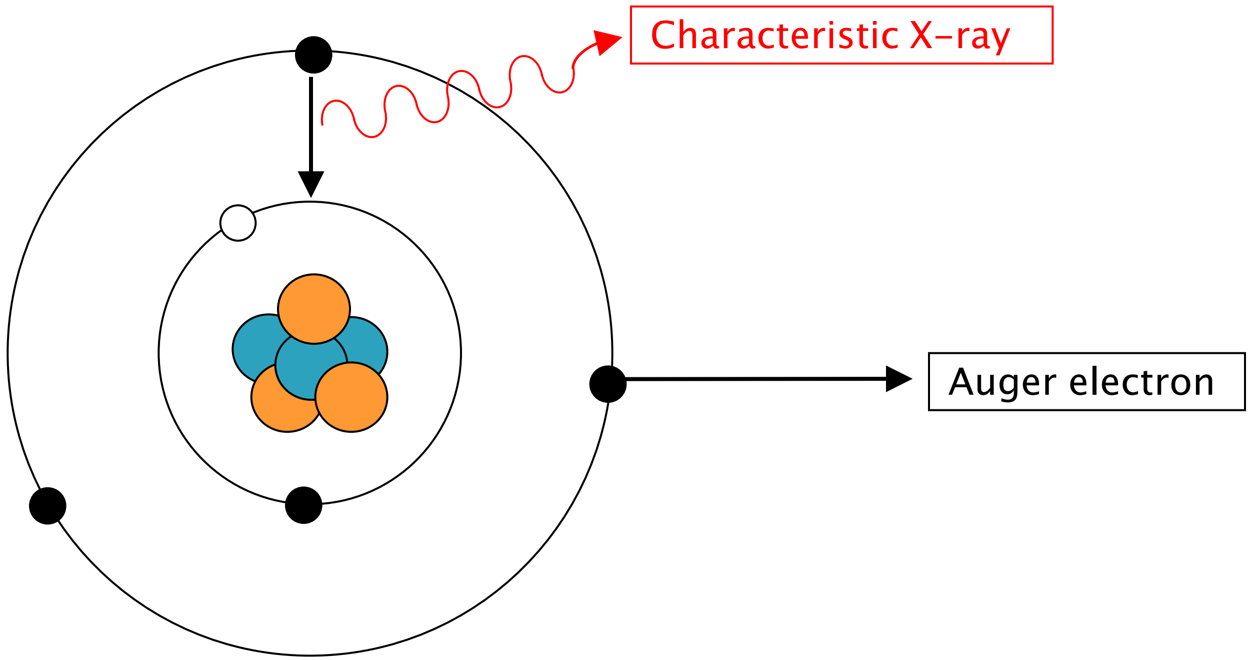
$$h\nu = E_e + E_B$$

E_e : maximum kinetic energy of the photoelectron : **½ mv^2**

E_B : binding energy of that e

PHOTO-ELECTRIC EFFECT:

STEP 2:



- Photoelectron emitted leaving atom in unstable, excited state
- Atom relaxes by
  - X-ray emission
  - Auger electron emission (The Auger Effect)

PHOTO ELECTRIC EFFECT :

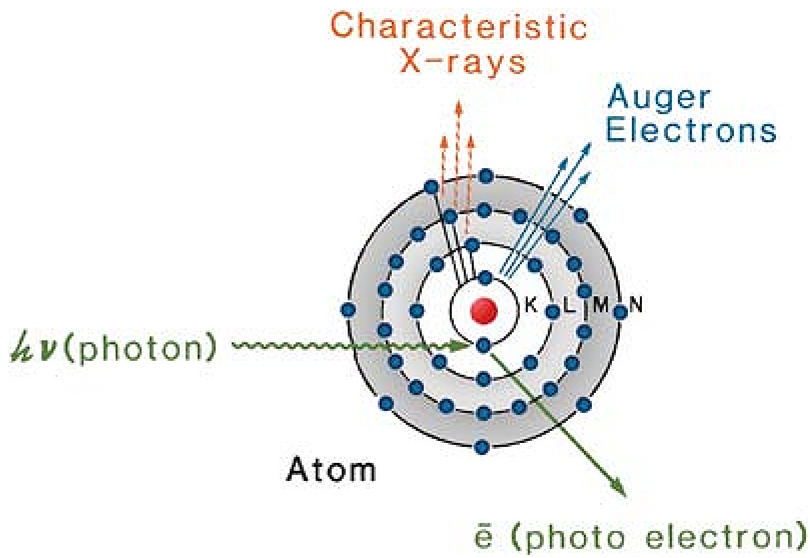
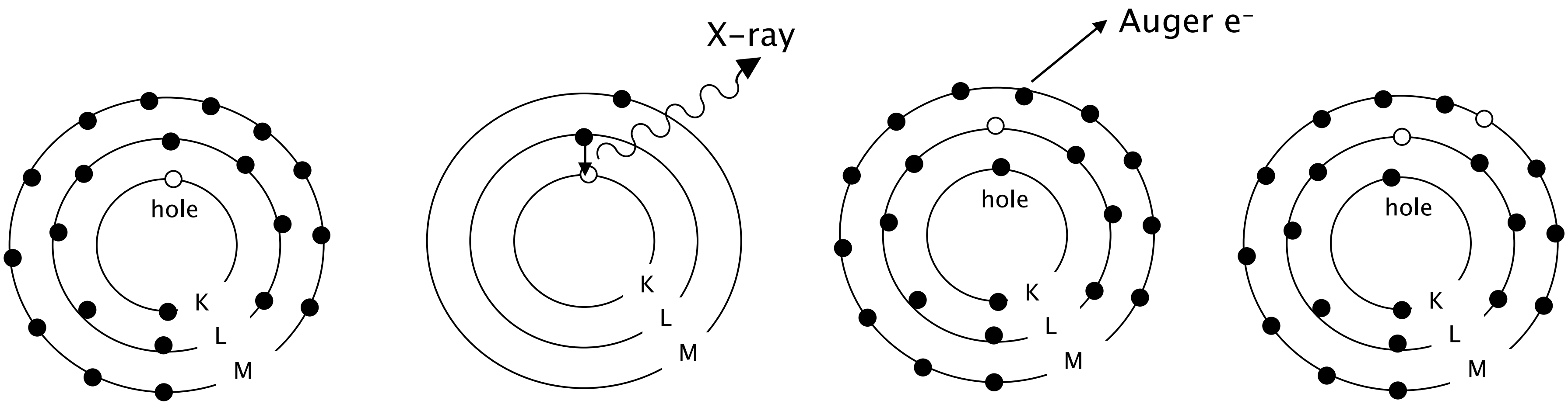


Figure 5.5. Illustration of the photoelectric effect.

THE AUGER ELECTRON



Initial state:
hole in K-shell

$h\nu = E_K - E_L$

$E = h\nu - E_M$
$E = E_K - E_L - E_M$

holes in L- and
M-shell

- Mono-energetic Auger electrons will carry away any surplus energy of excited atom

P.E. EFFECT :

- Process = attenuation and absorption
- Total absorption of photon energy
- **Photoelectric attenuation coefficient** *(τ/ρ)*

Predominates at low energies

- Is highly Z dependent

$$\left.\begin{array}{l}\text{Predominates at low energies}\\ \text{Is highly Z dependent}\end{array}\right\} \tau/\rho \propto Z^3/(h\nu)^3$$

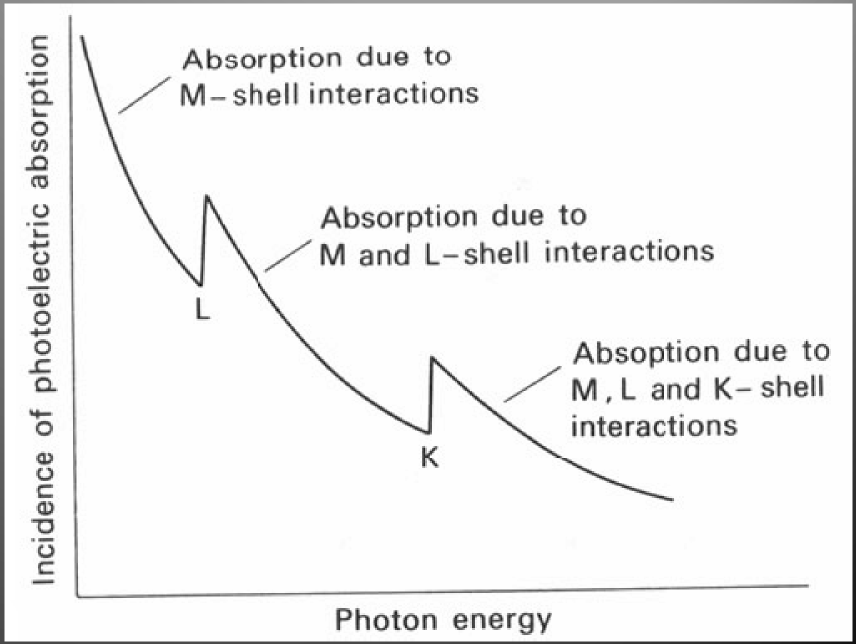
- Example: t_{Pb}/r_{Pb} is 300 times greater than $t_{bone/}r_{bone}$

P E EFFECT:

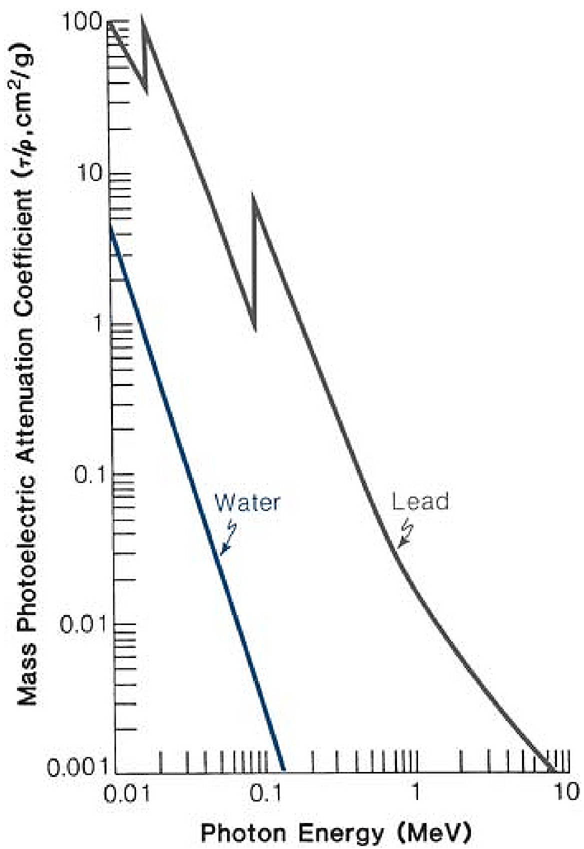
- The energy of the characteristic radiation (**fluorescent radiation**) for low z elements is probably absorbed by the same cell in which the initial event occurs.
- Auger electron is mono energetic
- The **angular distribution** of electrons emitted in the photoelectric process depend upon the photon energy.
- As the photon energy increases the photo electrons are emitted in a more **forward** direction.

P.E. EFFECT : FEATURES:

- PE Coeff is **discontinuities** at specific photon energies.
- These are known as **absorption edges**.
- These absorption edges, correspond to the **binding energies** of the electrons in different shells.



P.E. EFFECT : FEATURES: WITH Z



Mass photoelectric attenuation coefficient (t/r) plotted against photon energy. Curves for water (Z_{eff} = 7.42) and lead (Z = 82).

P.E. EFFECT : PRACTICAL IMPLICATION

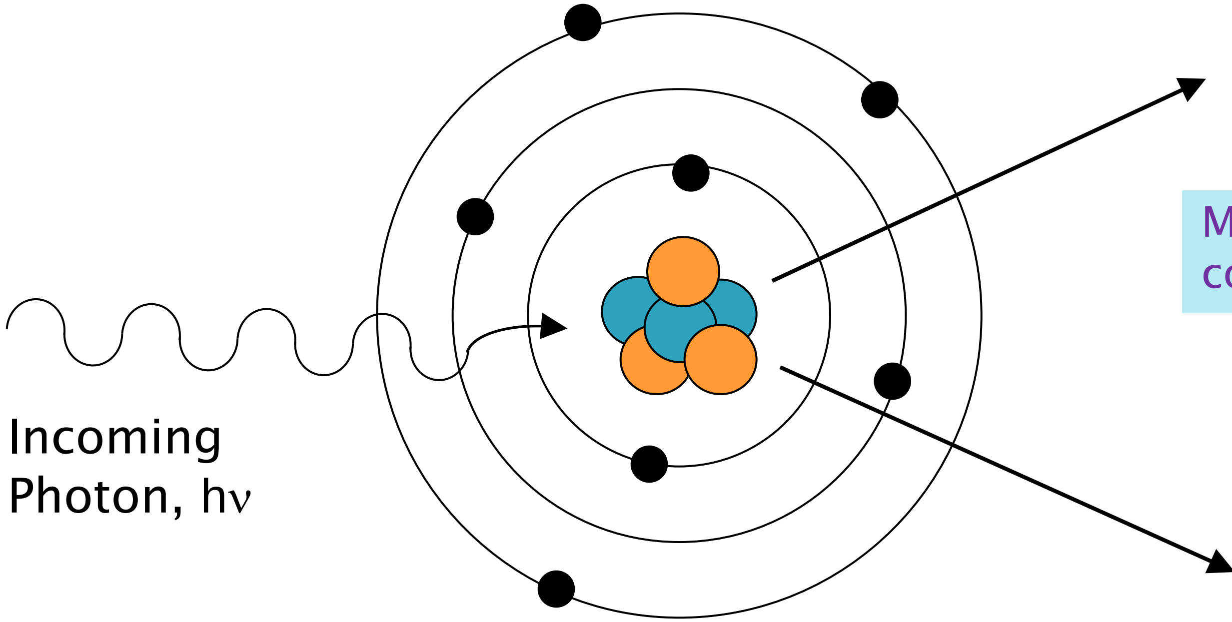
- In **diagnostic radiology**, the primary mode of interaction is photoelectric. It is also responsible for the contrast effect.

  - In **therapeutic radiology**, low-energy beams in orthovoltage irradiation caused excessive absorption of energy in bone.

PAIR PRODUCTION

Photon interacts with nuclear EM field

PAIR PRODUCTION:



- $h\nu \geq 1.022$ MeV
- $h\nu - 1.022 = E_- + E_+$
- E_-, E_+ are the kinetic energies of the electron and positron resp.

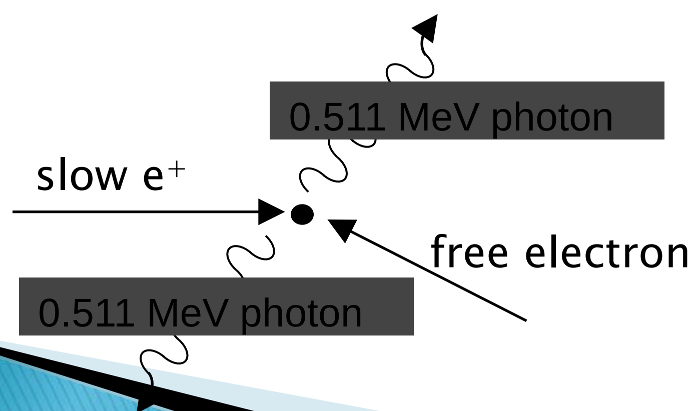
PAIR PRODUCTION

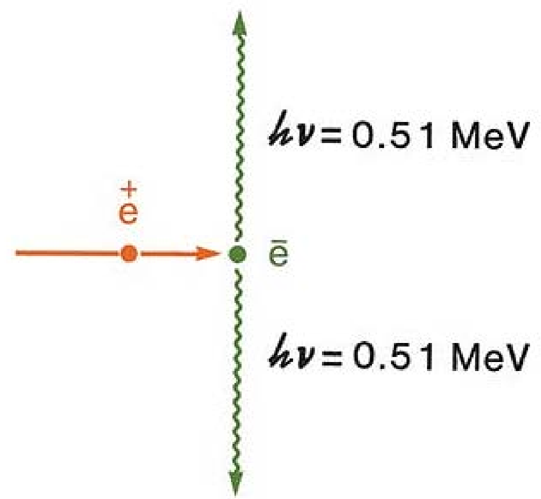
- When $h\nu_0 > 1.02MeV$ (rest E of electron 0.511MeV)
- ATTENUATION + ABSORPTION
- Example of conversion of energy into mass: $E = mc^2$
  - Energy equivalent of one electronic mass is 0.511 MeV
  - As e^+ & e^- produced, incoming photon must have energy: 2 x 0.511 MeV
  - e^+ and e^- can receive any fraction of photon energy

PAIR PRODUCTION

- e^+ produced in Pair Production dissipates energy locally

- It is annihilated by combining with a free electron producing two photons of energy 0.511 MeV





PAIR PRODUCTION:

- the energy absorbed from the beam (with incident energy, E) is given by:

  $$E - 1.02\ MeV$$

- the probability of this process:

- **increases** rapidly with the atomic number (**Z^2**).

- **increases** as the photon energy **increases** in contrast to the Compton effects and the photoelectric effect.

- The pair production coefficient (π) is directly proportional to Z^2 and log of incident photon energy.

- **$\pi = k\ Z^2 \log(E)$**

PAIR PRODUCTION: PRACTICAL IMPLICATION

PET SCAN

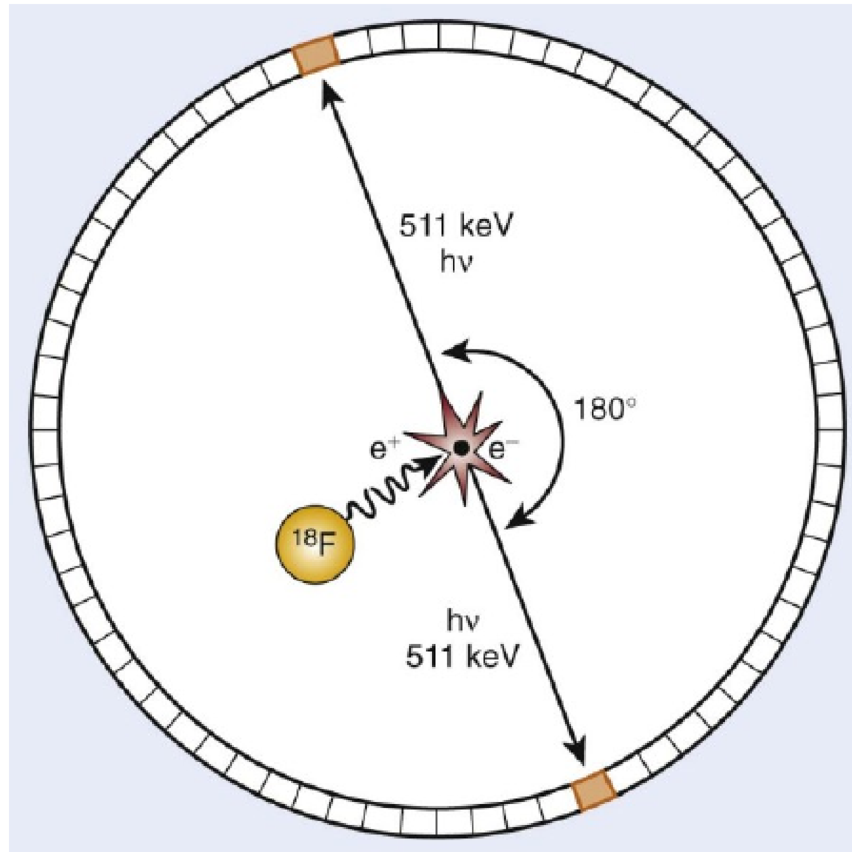


FIGURE 9-1 • Positron emission and its use in tomography. An unstable radionuclide (here, ^{18}F) decays via the emission of a positron from the nucleus. The positron travels some distance before annihilating with an electron, resulting in the production of two 511 keV traveling i opposite directions. A detector array may be used to record the arrival of two "coincidence photons" within a short time of each other.

PHOTONUCLEAR REACTION

WITH ATOMIC NUCLEUS

PHOTO NUCLEAR REACTION:

- High energy photon interacts with atomic nucleus resulting in emission of a proton (p) or a neutron (n)
- incident photons with energy > BE of nucleus.
- Threshold Energy 10.8 MeV
- IMPLICATIONS:
- Used for energy **calibration** of machines producing high energy photons. For this the following reaction is used:

$$ {}_{29}Cu^{63} + \gamma \rightarrow {}_{29}Cu^{62} + {}_{0}n^{1} $$

- 25 MV X-ray beam has greater neutron contamination than 10MV

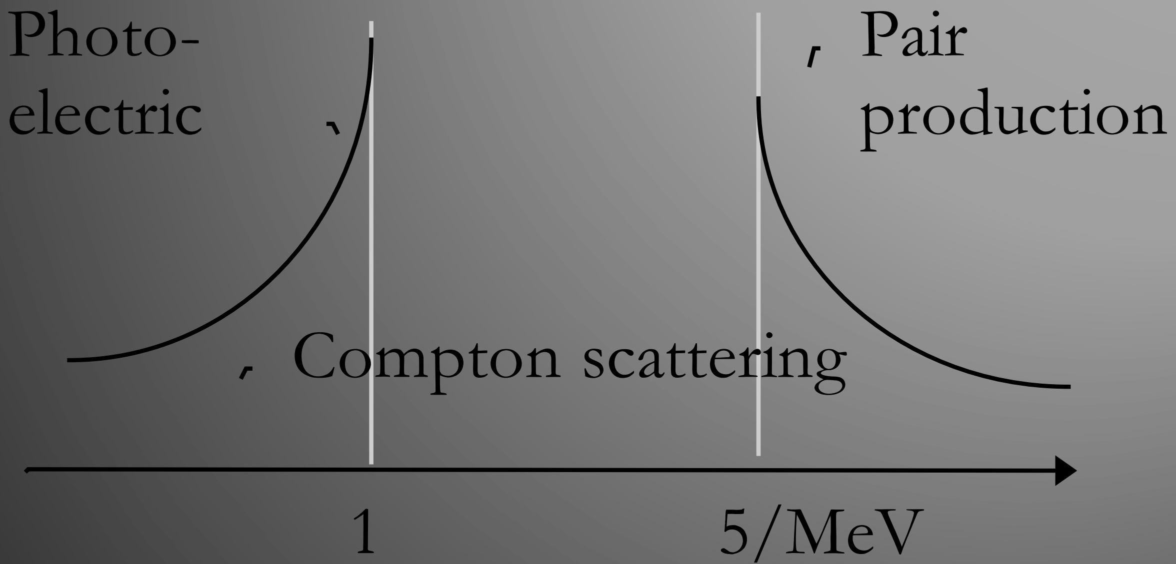
RELATION BETWEEN DIFFERENT TYPES OF INTERACTIONS

- The total mass attenuation coefficient (μ/p) is the sum of the four individual coefficients:

$$\frac{\mu}{\rho} = \frac{\varepsilon}{\rho} + \frac{\tau}{\rho} + \frac{\sigma}{\rho} + \frac{\kappa}{\rho} + \frac{\zeta}{\rho}$$

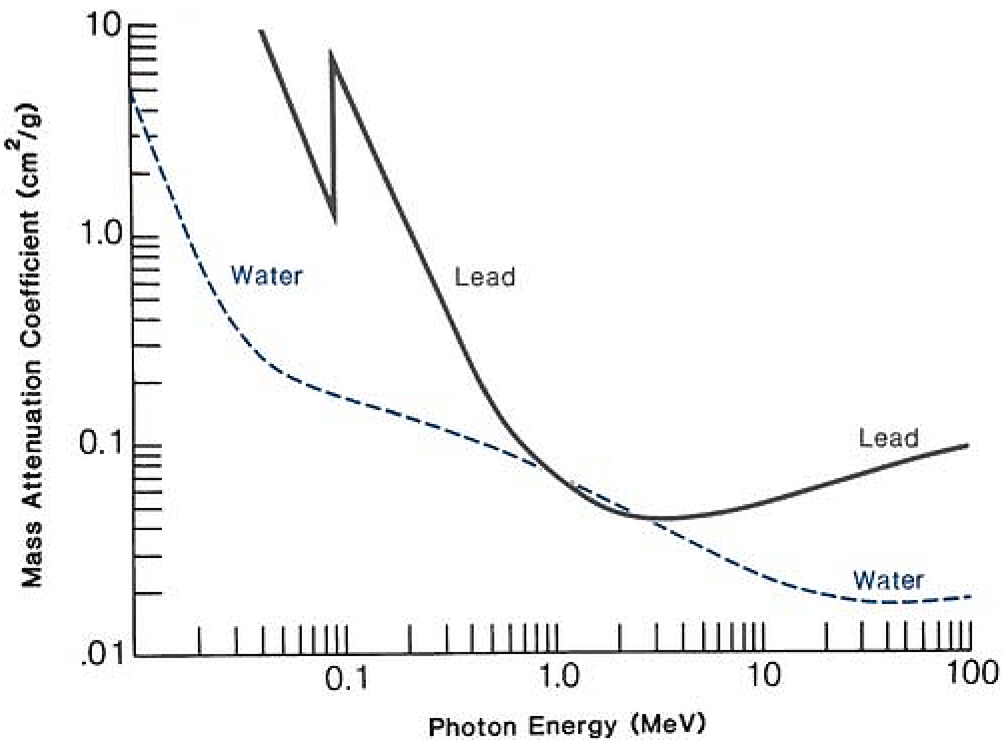
PE com pair

Interaction of Photons with Matter



Photoelectric effect **Compton scattering** **pair production**

MASS ATTENUATION COEFFICIENT VARIATION WITH ENERGY



Attenuation in Soft Tissue (Z = 7)

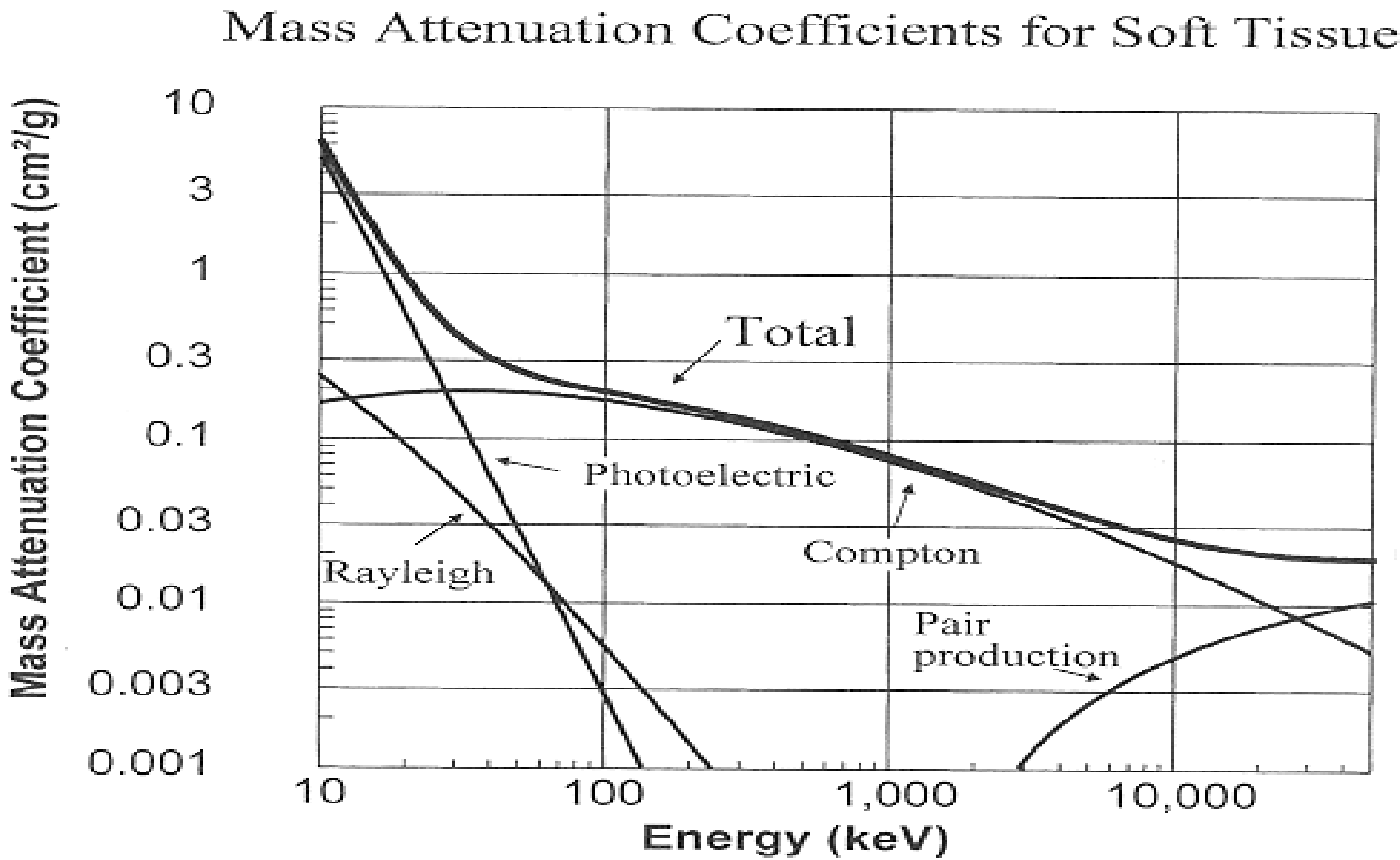
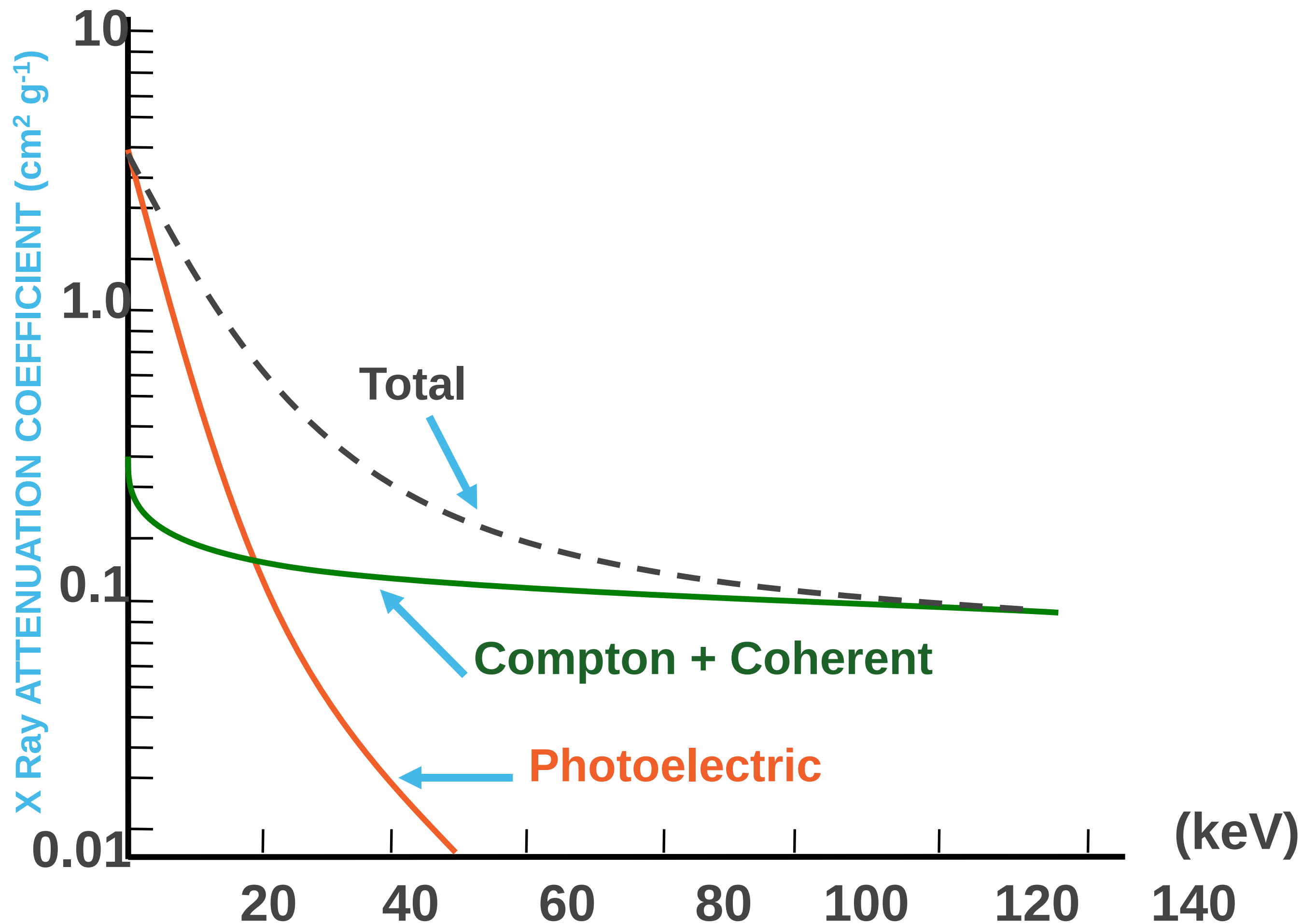


Table 5.2 Relative Importance of Photoelectric (τ), Compton (σ), and Pair Production (Π) Processes in Water

Photon Energy (MeV)	Relative Number of Interactions (%)		
	τ	σ	Π
0.01	95	5	0
0.026	50	50	0
0.060	7	93	0
0.150	0	100	0
4.00	0	94	6
10.00	0	77	23
24.00	0	50	50
100.00	0	16	84

Data from Johns HE, Cunningham JR. *The Physics of Radiology*. 3rd ed. Springfield, IL: Charles C Thomas; 1969.

Contribution of photoelectric and Compton interactions to attenuation of X Rays in water (muscle)




THANK YOU