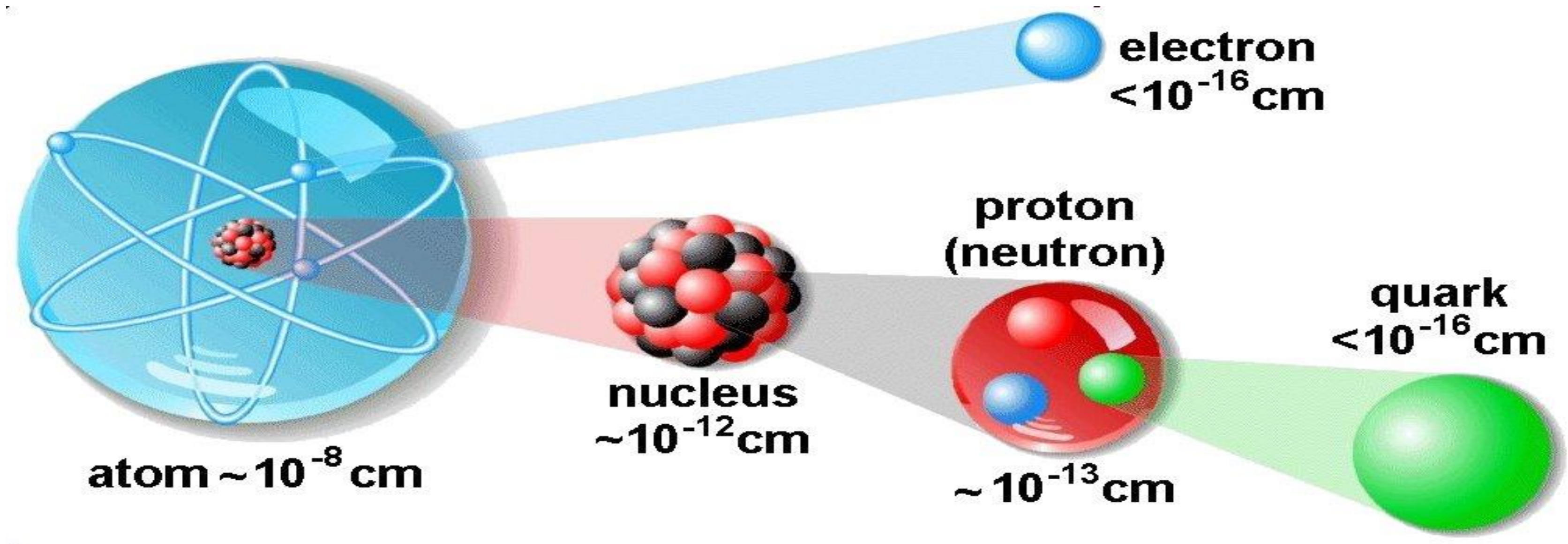
Basic Atomic Physics and Measurement of Ionizing Radiation and Absorbed Dose

Dr. Sunil Dutt Sharma

Head, Medical Physics Section

RPAD, BARC, Mumbai - 400094

Atomic and Nuclear Structure



Atomic Number Z, Mass Number A, Number of Neutrons N = A - Z

- Isotopes: Nuclei having same Z, different A (^{1}H, ^{2}H, ^{3}H)
- Isobars: Nucleai having same A but different Z & N (^{3}H,^{3}He)
- Isotones: Same N but different Z and A (^{3}H, ^{4}He,^{5}Li)
- Isomers: Different energy states of same atom (^{99m}Tc,^{99}Tc)

Mass Defect and Binding Energy (BE)

- **Mass defect (Δm) =**

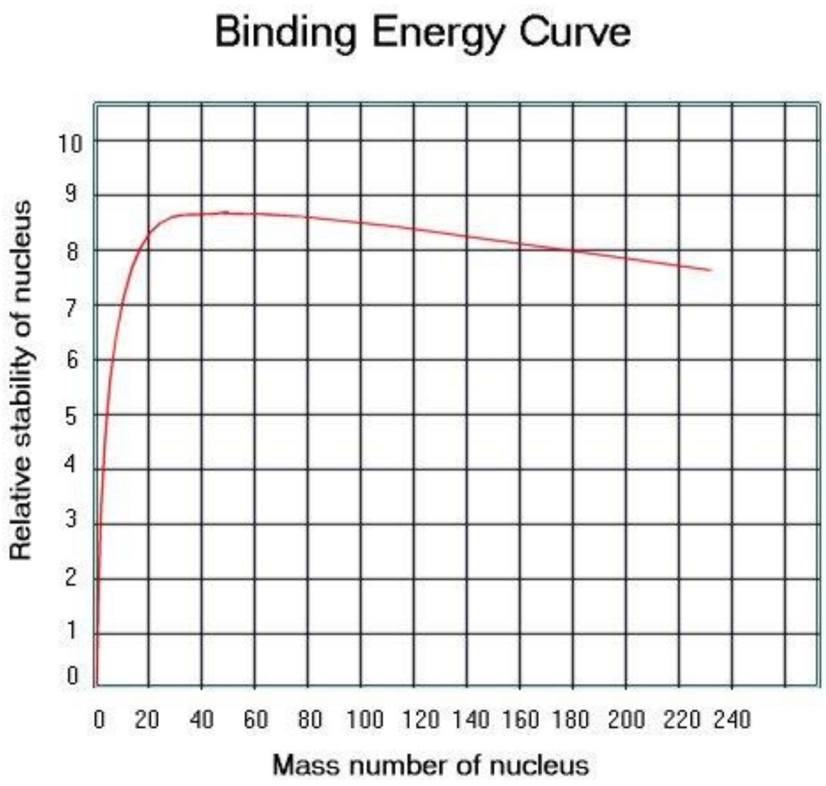
sum of masses of constituents of an atom - mass of the atom

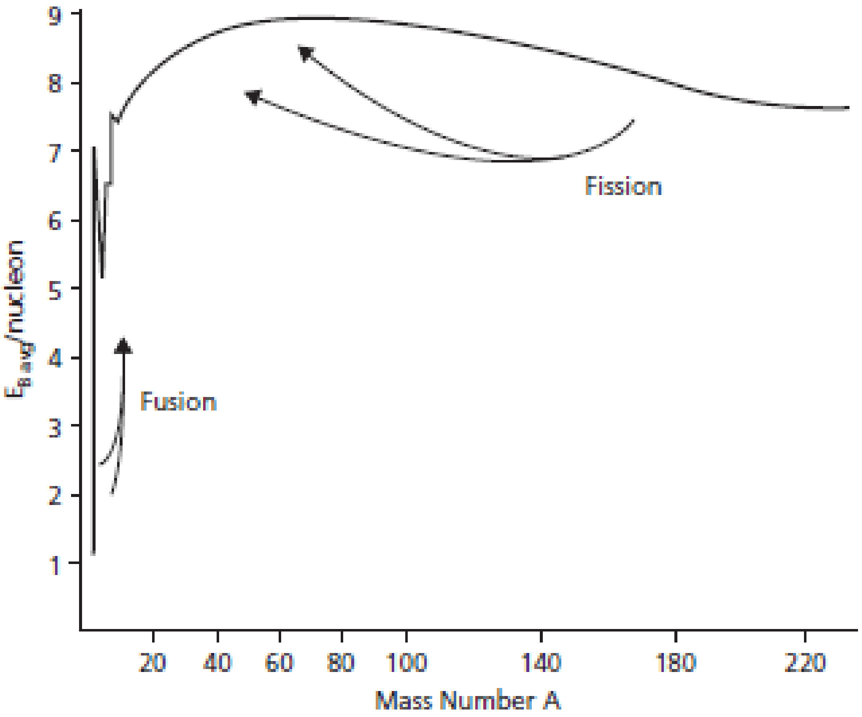
$$\Delta m = (m_e + m_p + m_n) - m_{atom}$$

- **As per Einstein's mass energy equivalence ($E = mc^2$), energy equivalent to mass defect Δm is binding energy i.e. the energy required to break a nucleus or to hold nucleons together**

- **Greater BE/nucleon, higher is the stability of the nucleus**

Avg. BE per Nucleon & Nuclear Stability



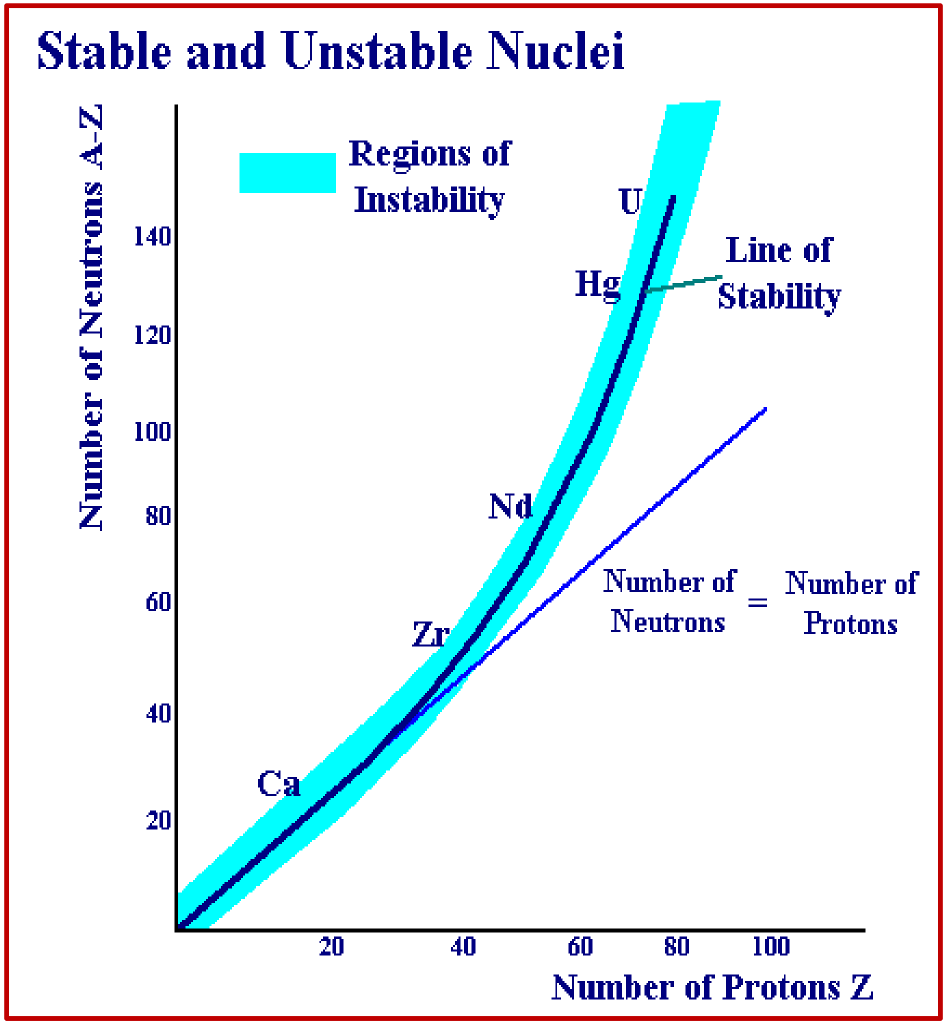


Peak value is about 8.5 MeV/nucleon

Greatest BE/nucleon occurs for Mass Number 50 to 100

Nuclear Stability

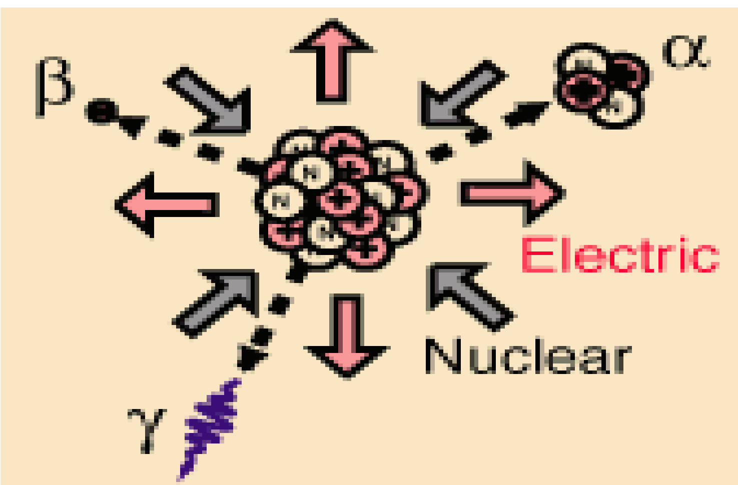
- enough BE to hold the nucleons
- n/p≈1 for low Z stable nuclei
- n/p>1 for high Z stable nuclei
- Most stable nuclei have even N and Z



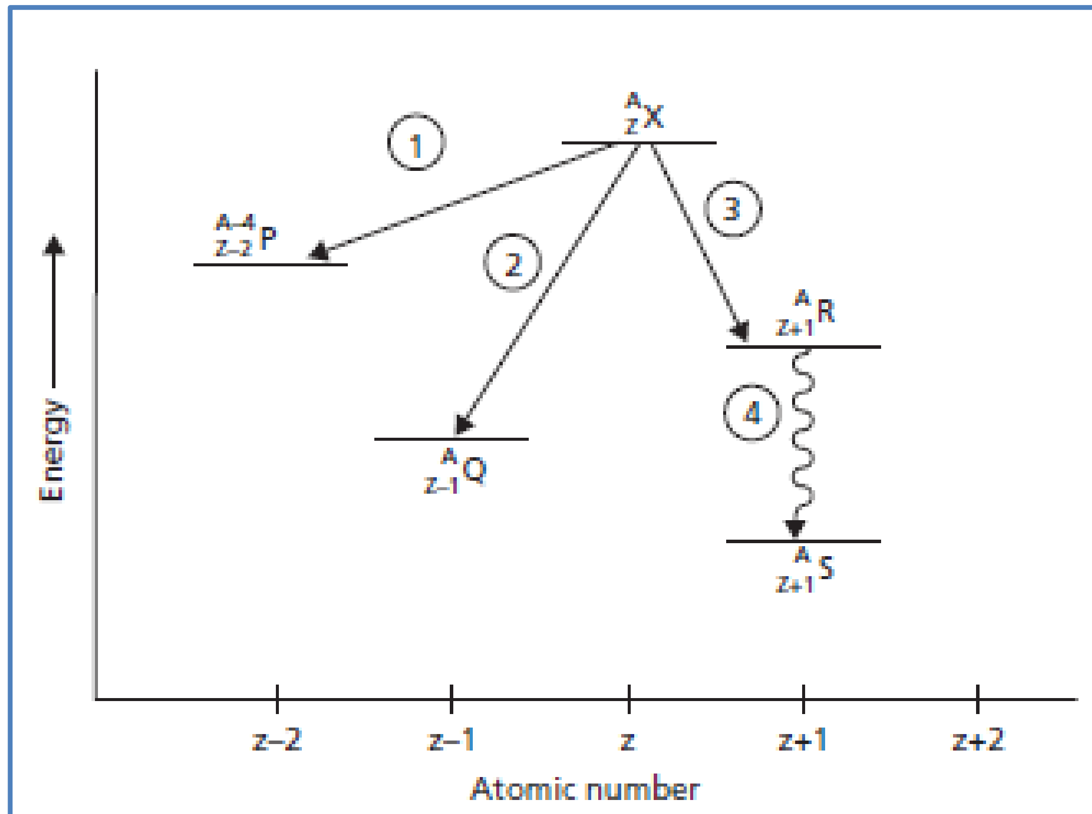
- If an atom does not have enough BE to hold the nucleus together permanently, is called a radioactive atom

Radioactive Decay

- **Spontaneous changes in the nucleus of an unstable atom that results in formation of new elements**
- **Accompanied by a release of energy, either particulate or electromagnetic or both**



α, β, γ and decay by electron capture



Radioactivity

- **Rate of decay or number of disintegrations per second is known as activity** (SI unit – Bq; old unit Ci)

- **Activity A, is directly proportional to**

  - number of atoms in a sample, N

  - decay constant, λ

$$\frac{dN}{dt} = -\lambda N(t)$$

Activity $A = \lambda N$

$$N(t) = N_0 \, e^{-\lambda t}$$
$$A(t) = A_0 \, e^{-\lambda t}$$

$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq} = 37 \text{ GBq}$

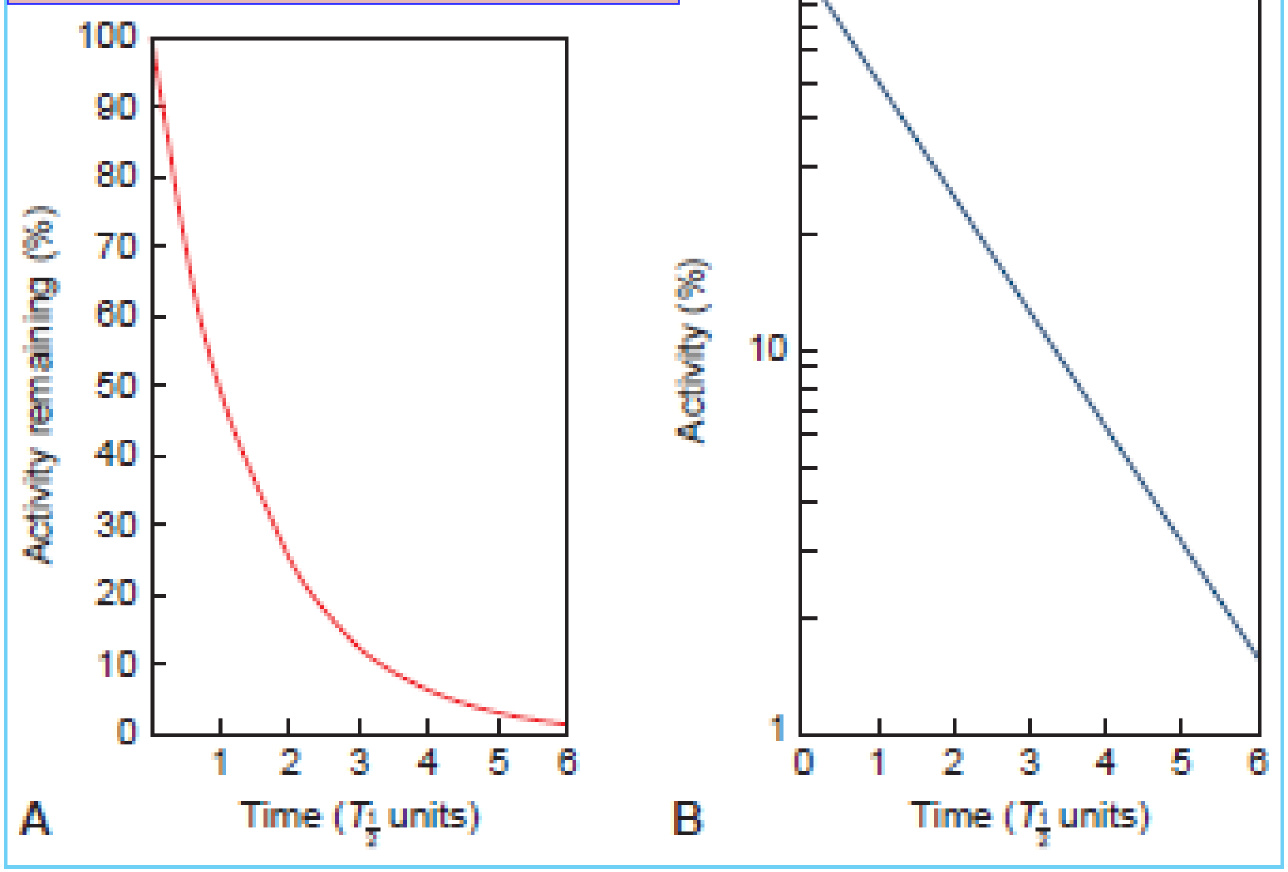
$1 \text{ mCi} = 3.7 \times 10^{7} \text{ Bq} = 37 \text{ MBq}$

Specific Activity = Activity/Mass = A/M

$$T_{1/2} = 0.693/\lambda \qquad T_{avg} = 1/\lambda = 1.44\, T_{1/2}$$

Radioactivity - contd.

$$A(t) = A_0\, e^{-(0.693\, t)/T_{1/2}}$$



$$\frac{A}{A_o} = \frac{1}{2^n}$$

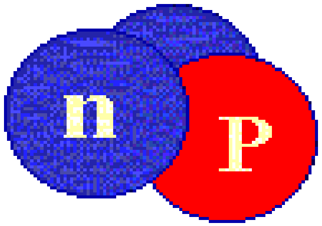
n = number of half life

Beta (Negatron, $_{-1}\beta$) Decay

- Emission of an electron from the nucleus of a radioactive atom

  $$(n \rightarrow p^{+} + e^{-1} + \bar{\nu} + Q)$$

- Occurs when neutron to proton ratio is too high (i.e., a surplus of neutrons)



a neutron changes into a proton and a fast electron

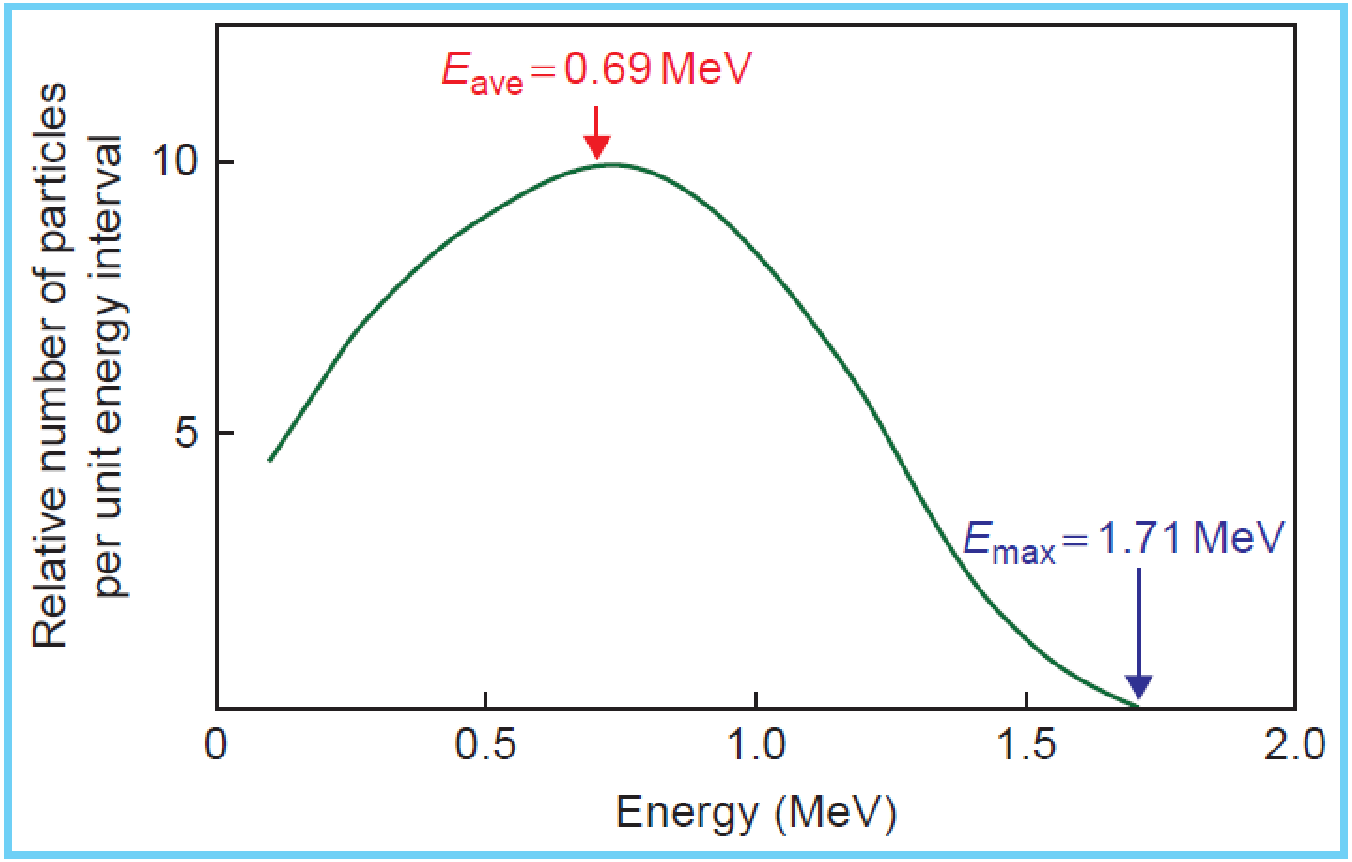
N decreases by 1, Z increases by 1, A remains same

$$_{38}Sr^{90} \rightarrow {}_{39}Y^{90} + \beta + \bar{\nu} + 2.27\ \text{MeV} \qquad T_{1/2} = 28\ \text{y}$$

$$_{15}P^{32} \rightarrow {}_{16}S^{32} + \beta + \bar{\nu} + 1.71\ \text{MeV} \qquad T_{1/2} = 14.3\ \text{d}$$

Beta Energy Spectrum: P-32

$$^{32}_{15}\text{P} \xrightarrow[14.3\text{ days}]{T\frac{1}{2}} {}^{32}_{16}\text{S} + {}^{0}_{-1}\beta + \tilde{\nu} + 1.7\text{ MeV}$$



Average beta energy, $E_{ave} \approx E_{max}/3$

Beta (Positron, $_{+1}\beta$) Decay

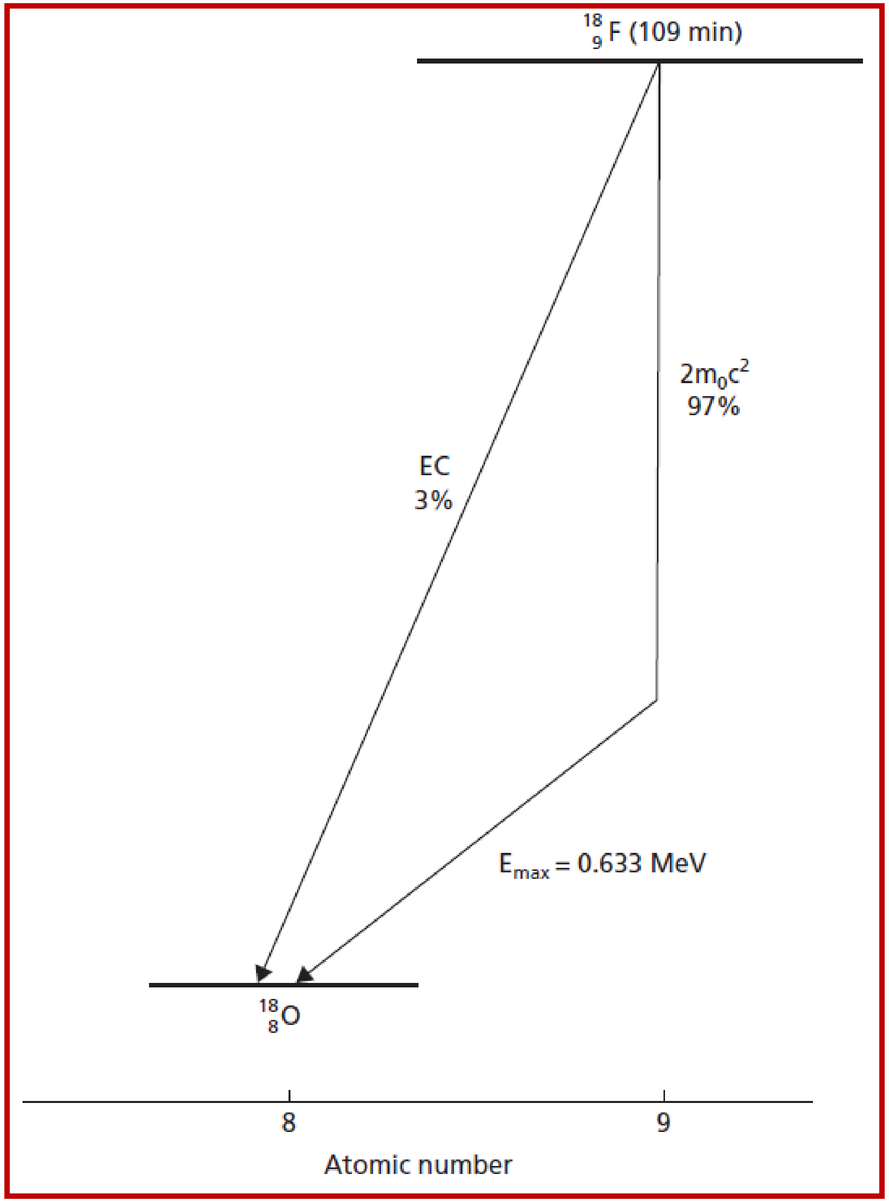
$$ {}^{18}_{9}F \rightarrow {}^{18}_{8}O + {}^{0}_{+1}\beta + \nu $$

- In this case, $M_d > M_p$

  $\Delta m = M_d - M_p \geq 1.02$ MeV

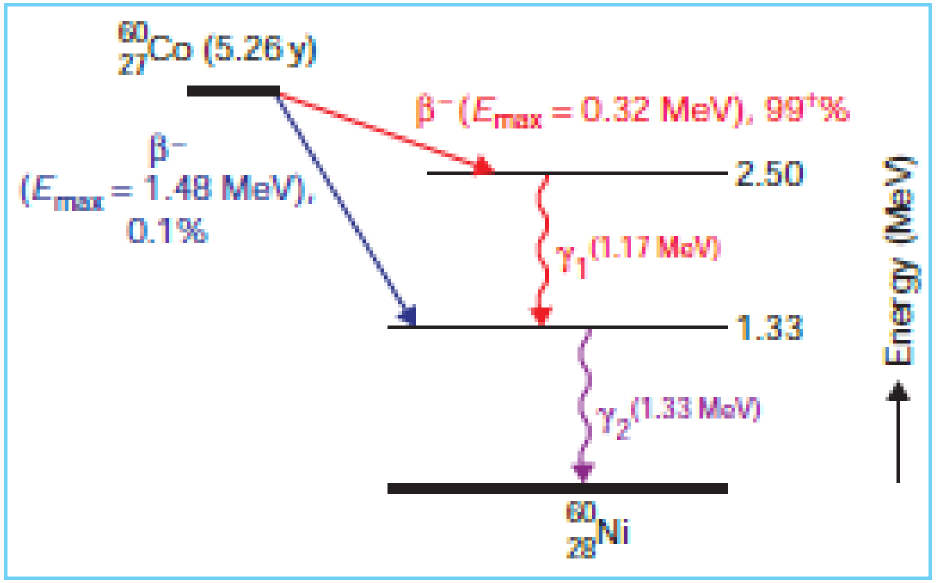
- Nuclei with transition energy <1.02 MeV cannot undergo positron decay,

- For nuclei with transition energy > 1.02 MeV, the excess energy is shared between positron and neutrino

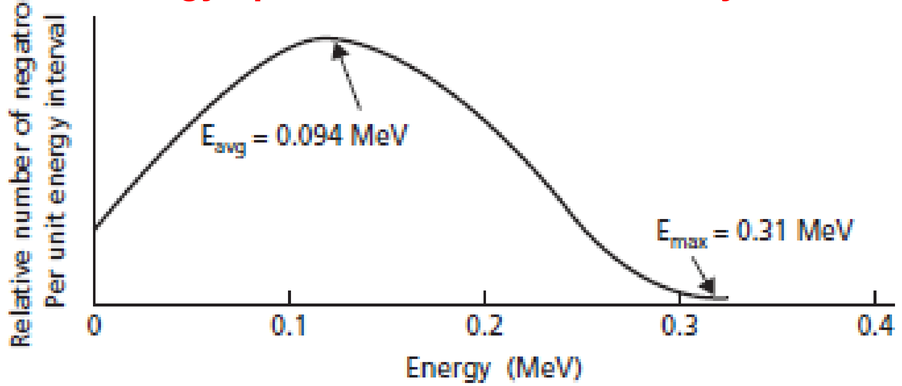


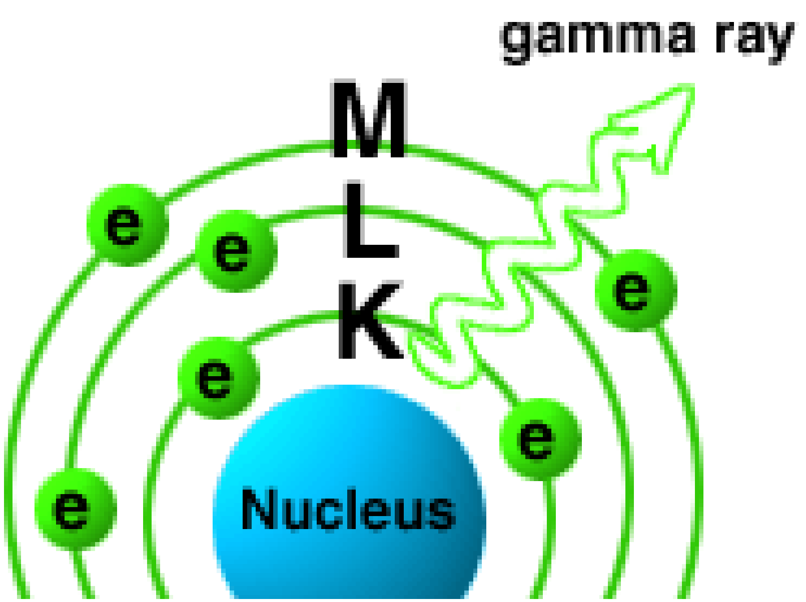
Gamma Emission

$$^{60}_{27}Co \rightarrow \, ^{60}_{28}Ni + \, ^{0}_{-1}\beta + \bar{\nu} + \text{ isomeric transition}$$



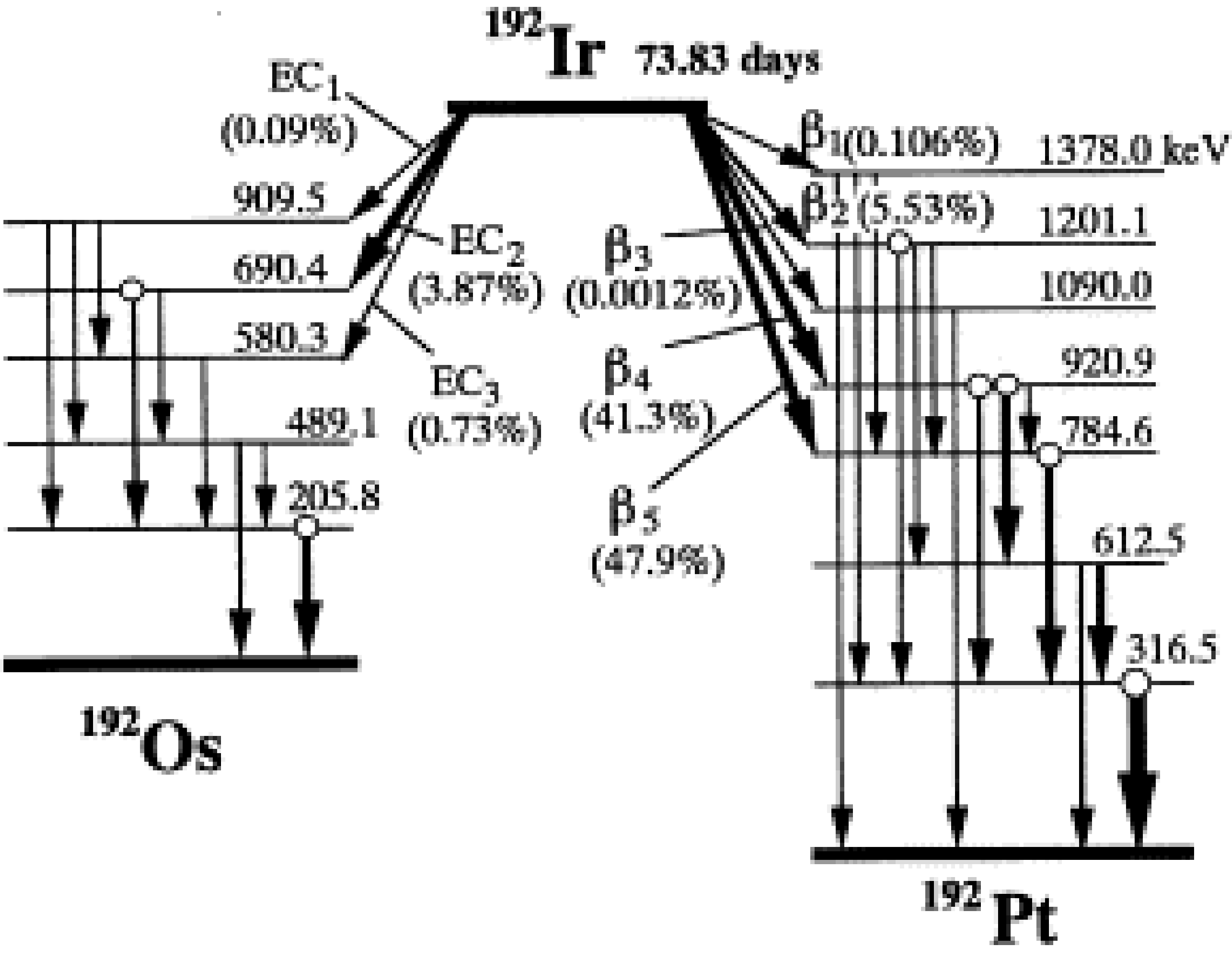
Energy spectrum of beta from decay of Co-60





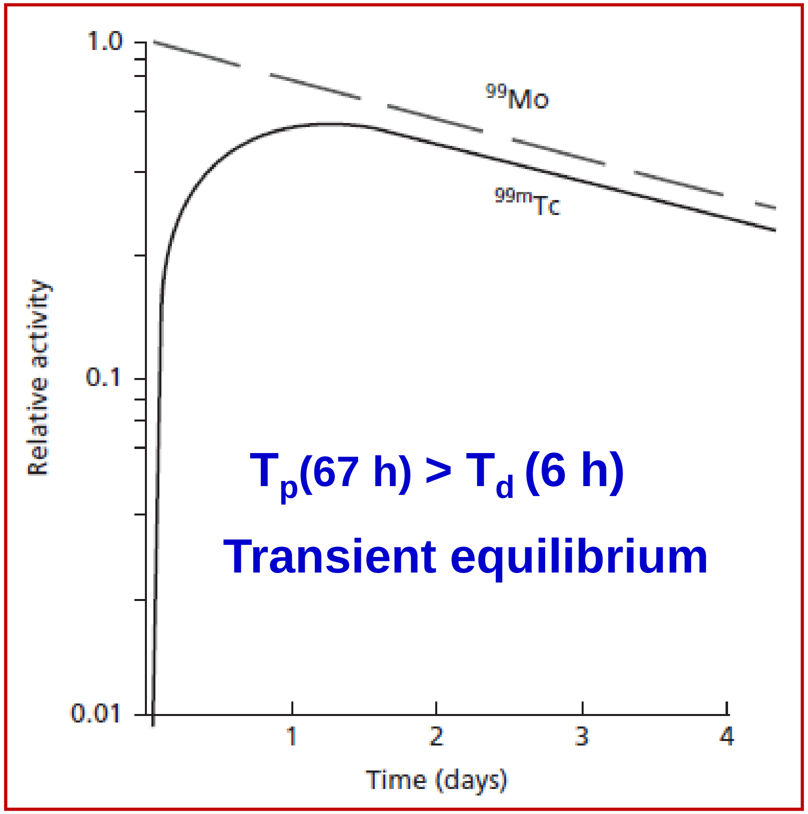
Nucleus de-excites by emitting gamma ray.

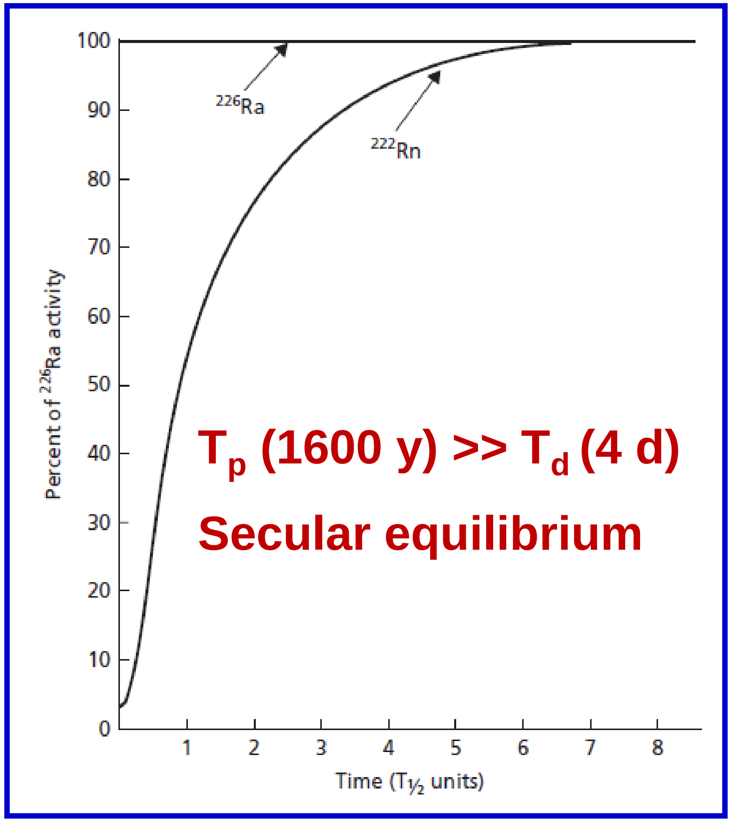
Beta Decay, Electron Capture & Gamma Emission



Radioactive Equilibrium

- Some daughter nuclei produced during radioactive decay are themselves unstable and undergo radioactive decay to obtain stability,
- In the process, a condition can be reached in which rate of production of daughter is equal to the rate of decay of the parent - the condition of (radioactive) equilibrium





Production of Radionuclides

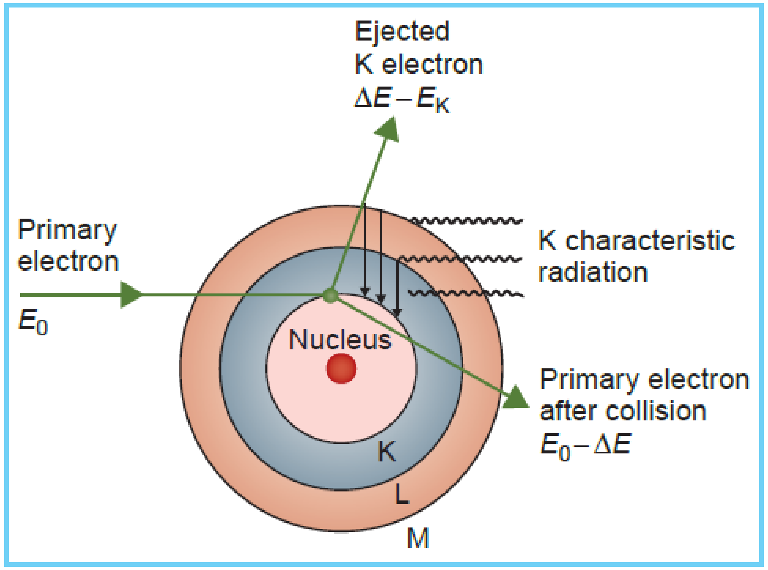
- Radioisotopes useful in biomedical research and clinical medicine may be produced by bombarding selected nuclei with neutrons or high-energy charged particles.

$$\boxed{{}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co + \gamma}$$

$${}^{32}_{16}S + {}^{1}_{0}n \rightarrow {}^{32}_{15}P + {}^{1}_{1}H$$

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

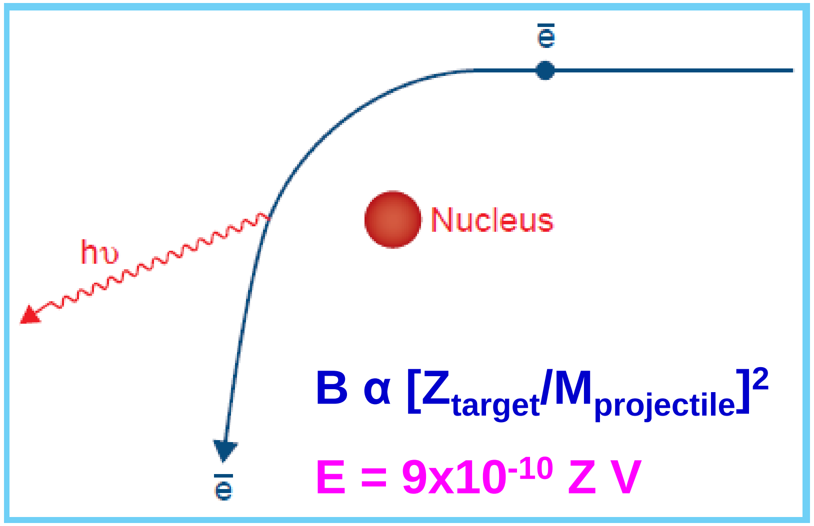
X-ray Production



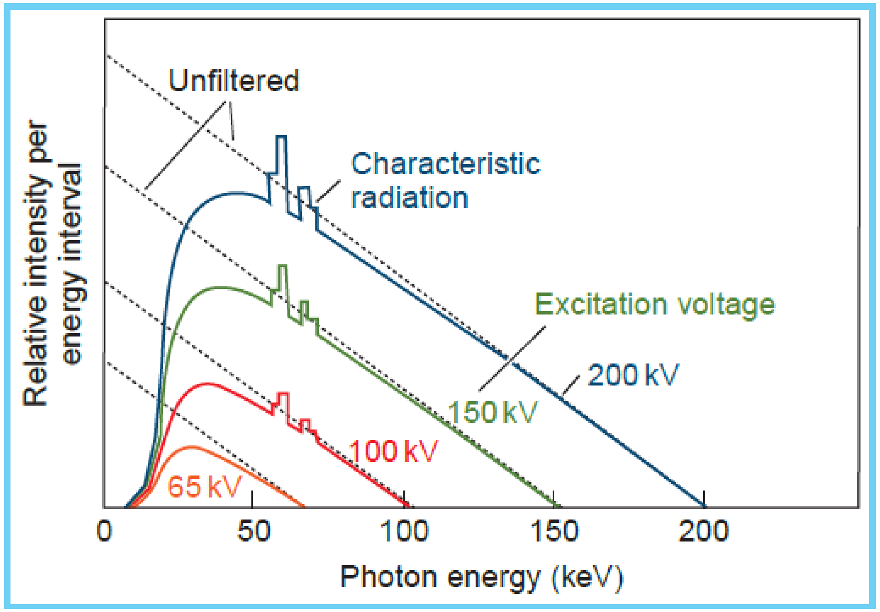
Characteristic X-rays: Interaction between high speed electron and electron of the target atom results in ejection of atomic electron and emission of EM radiation.

Properties of Characteristics and bremsstrahlung X-rays: monoenergetic/polyenergetic, …

Bremsstrahlung: Interaction between high speed electrons and nucleus of the target atom causes acceleration /deceleration to electrons which results in emission of EM radiation

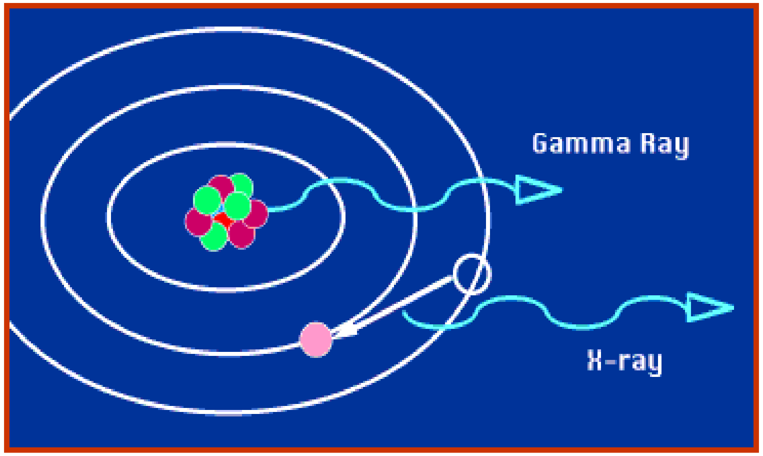


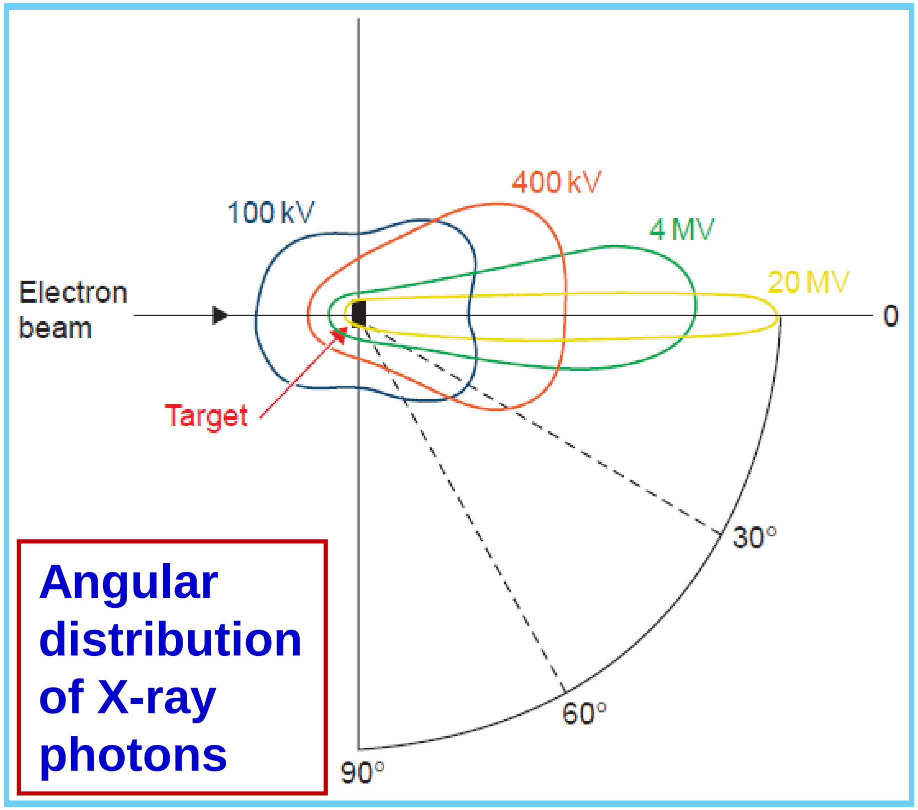
X-ray energy spectra & angular distribution



Overall nature of the x-ray energy spectrum depends on the target material, filtration and energy of projectile.

Difference between γ-rays & X-rays





Angular distribution of X-ray photons

Interaction of X-rays & Gamma rays

Gamma and X-ray photons are indirectly ionizing radiation. Several types of interactions of photons with matter have been observed. The most important interactions are:

- **Photoelectric Interaction – Photon interacts with tightly bound electrons of an atom resulting in complete absorption of the incident photon energy**
- **Compton Interaction – Mostly occur between photons and loosely bound electrons [outer shell (valence) electrons]**
- **Pair Production – Materialization of electromagnetic energy travelling through the matter.**

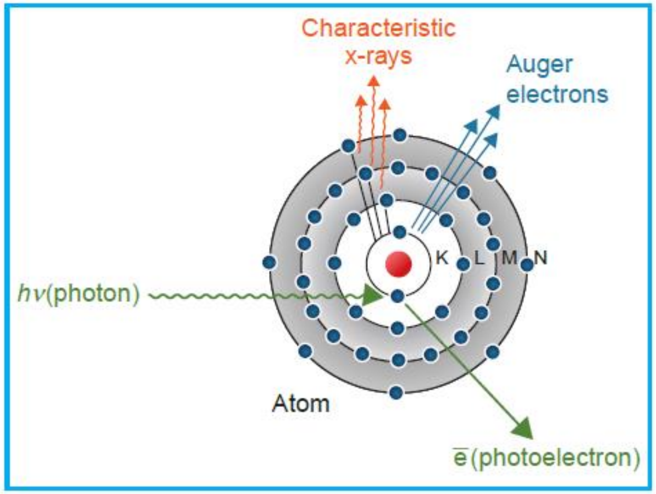
Photoelectric Effect (PE)

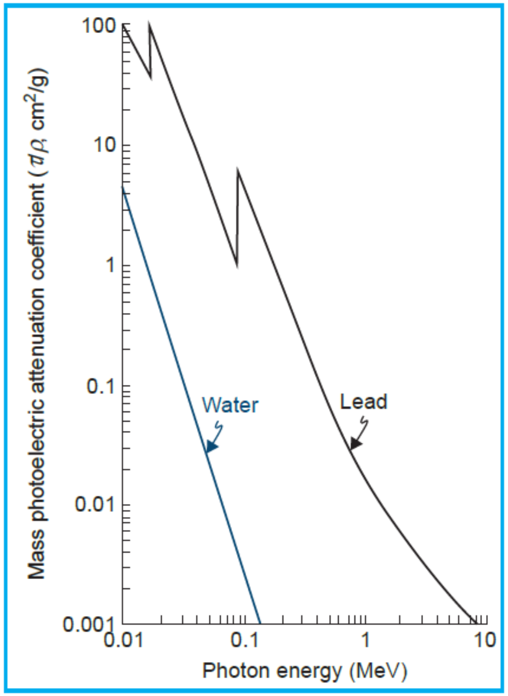
- **All of the incident photon energy is transferred to an electron (K-shell), which is ejected from the atom,**

- **KE of ejected photoelectron (E_{pe}) is equal to incident photon energy (E_0) minus the binding energy of the orbital electron (E_b)**

$$E_{pe} = E_0 - E_b$$

For PE to happen, $E_{pe} > E_b$





- **Results in emission of characteristic X-rays/ Auger electrons and probability of characteristic X-ray emission decreases with decreasing Z of the matter**

- **Probability of interaction α Z^3/E^3 i.e.** $\boxed{\tau/\rho \propto Z^3/E^3}$

Compton Effect (CE)

- **Electron ejected from the atom; photon scattered with reduction in energy**
- **Binding energy comparatively small and can be ignored**

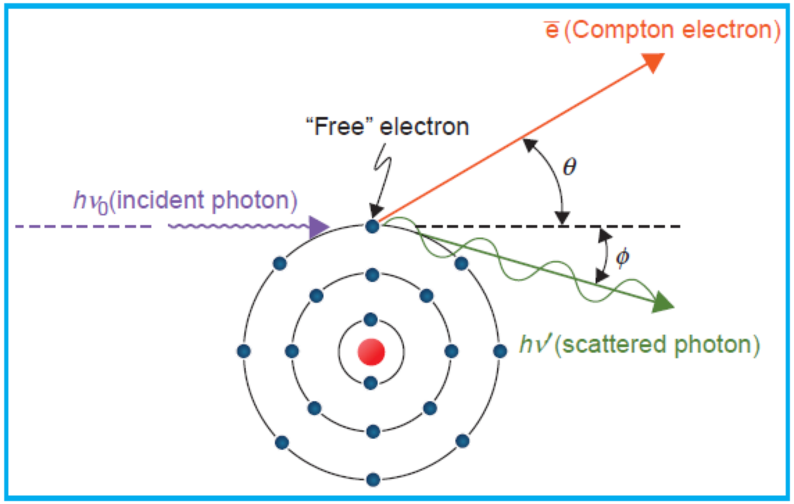
$$E = h\nu_0 \frac{\alpha(1 - \cos\phi)}{1 + \alpha(1 - \cos\phi)}$$

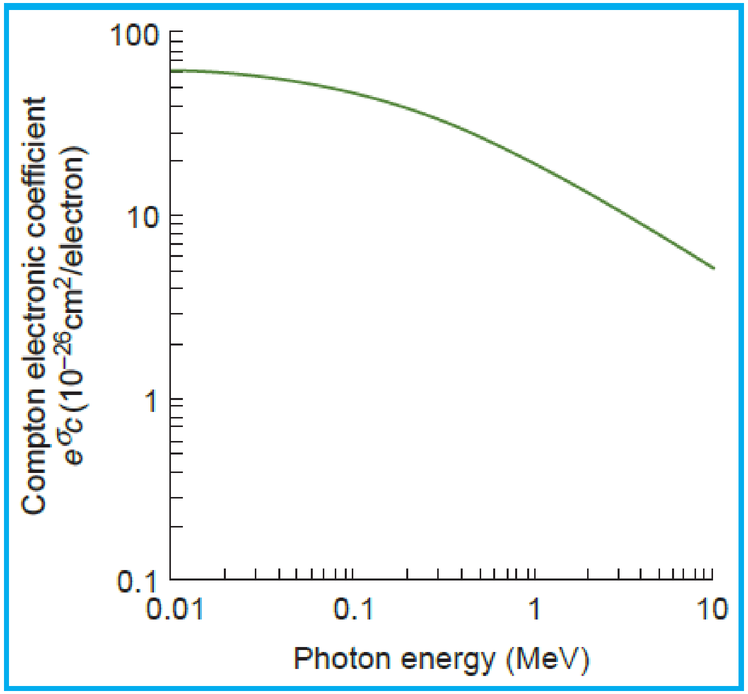
$$h\nu' = h\nu_0 = \frac{1}{1 + \alpha(1 - \cos\phi)}$$

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

$$\alpha = h\nu_0/m_0c^2$$

- **Compton mass attenuation coefficient is independent of Z and depends only on the number of electrons per gram (electron density)**





Compton Effect (CE)

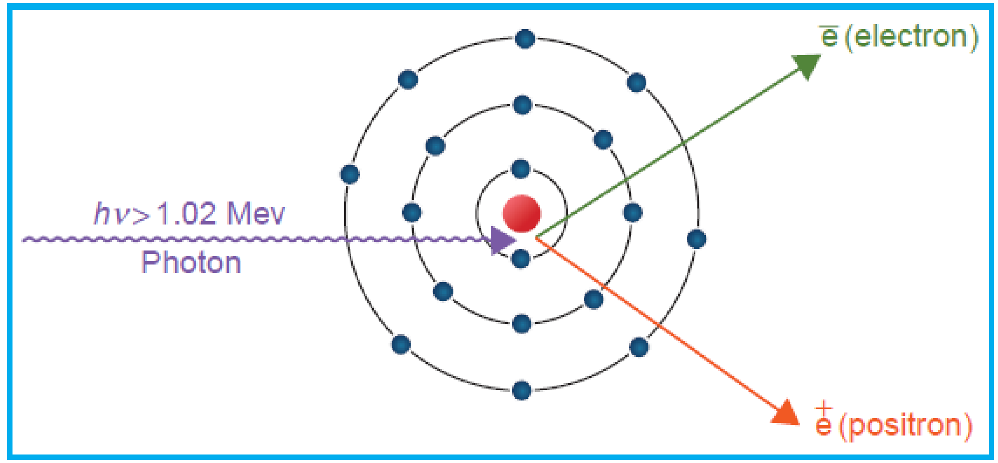
Number of electrons per gram of various materials

Material	Density (g/cm^3)	Atomic Number	Number of Electrons per Gram
Hydrogen	0.0000899	1	6.00×10^{23}
Carbon	2.25	6	3.01×10^{23}
Oxygen	0.001429	8	3.01×10^{23}
Aluminum	2.7	13	2.90×10^{23}
Copper	8.9	29	2.75×10^{23}
Lead	11.3	82	2.38×10^{23}
		Effective Atomic Number	
Fat	0.916	6.46	3.34×10^{23}
Muscle	1.04	7.64	3.31×10^{23}
Water	1.00	7.51	3.34×10^{23}
Air	0.001293	7.78	3.01×10^{23}
Bone	1.65	12.31	3.19×10^{23}

- **Probability of Compton interaction increases with increasing photon energy**
- **Number of electrons/g is fairly constant in tissue except hydrogen, σ_c/ρ is nearly the same for all materials.**

Pair Production (PP)

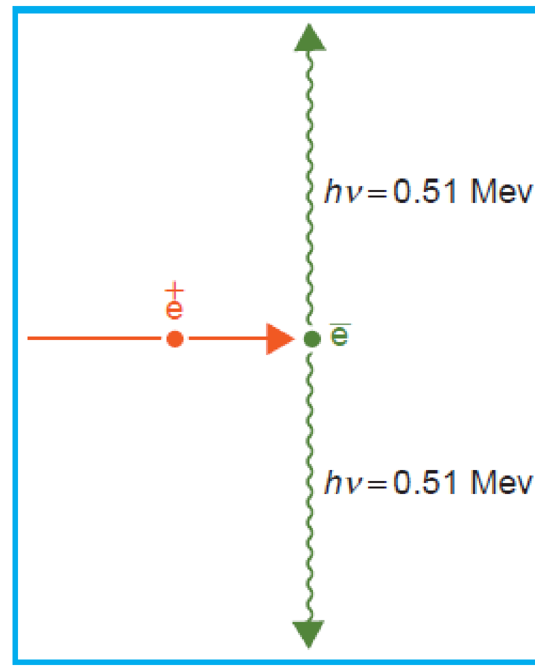
- **Pair production is direct conversion of radiant energy to matter in the vicinity of nucleus (interaction of photon with EM field of nucleus),**



- **It is one of the principal ways in which high-energy gamma rays are absorbed in matter**

$_a\Pi \propto Z^2$

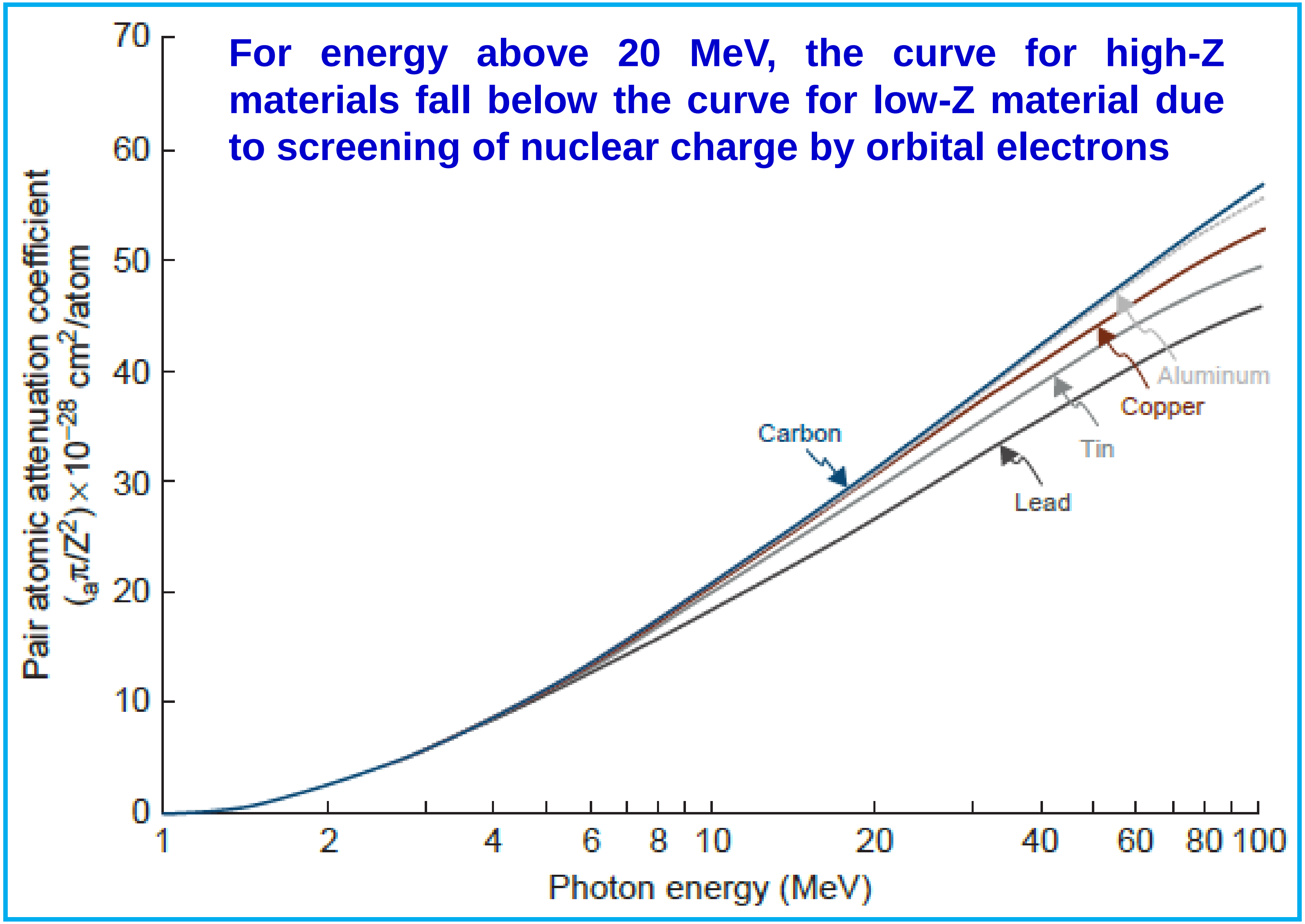
- **Threshold enery is 1.02 MeV**



- **Total KE of electron-positron pair = hv - 1.02 MeV**
- **Annihilation of positron results in production of two photons**
- **The attenuation coefficient of pair production varises with Z^2 per atom i.e.** $_a\Pi \propto Z^2$

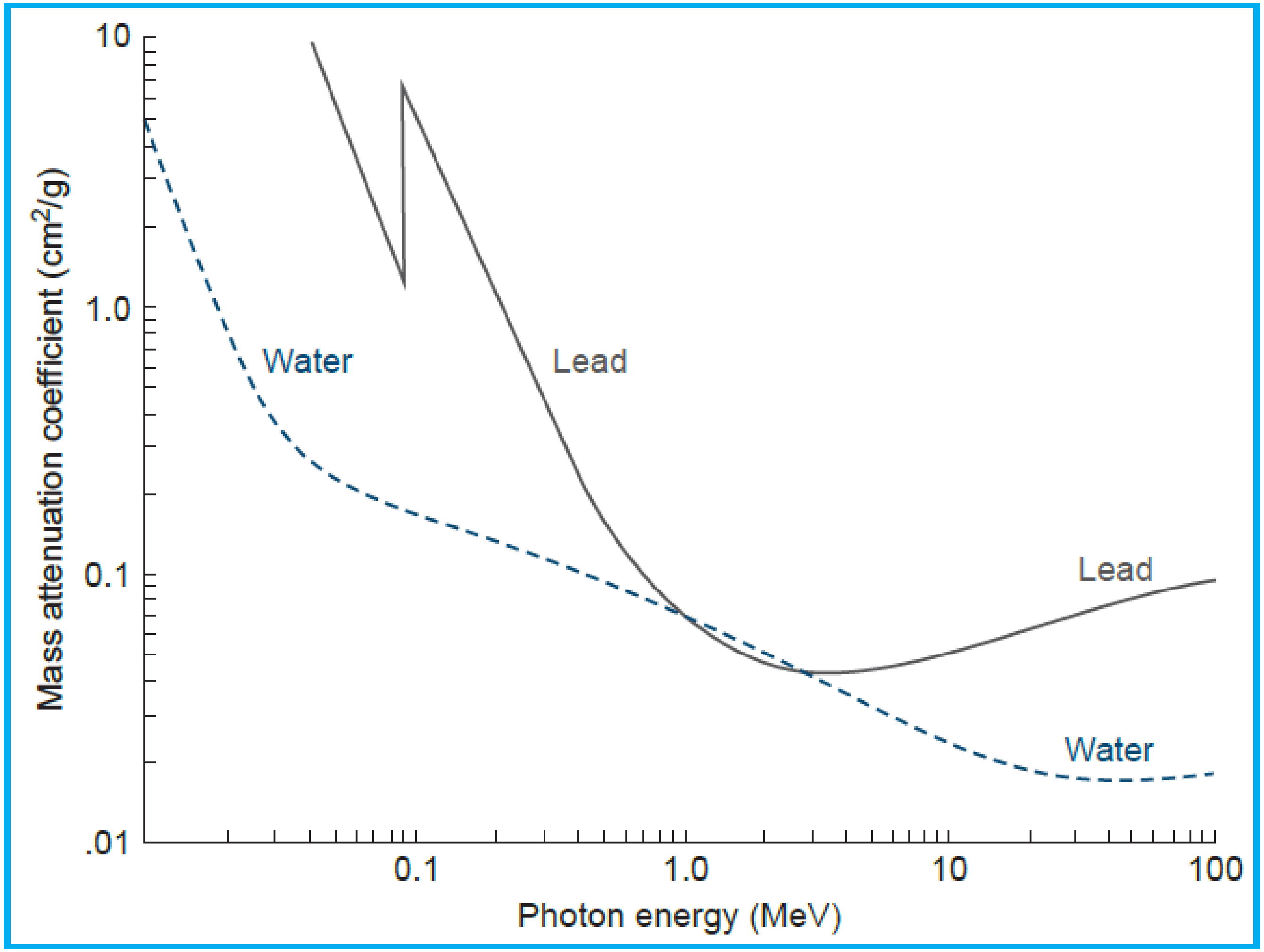
Pair Production (PP)

For energy above 20 MeV, the curve for high-Z materials fall below the curve for low-Z material due to screening of nuclear charge by orbital electrons



Relative Importance of PE, CE & PP

$(\mu/\rho) =$	$(\tau/\rho) +$	$(\sigma_{coh}/\rho) +$	$(\sigma_c/\rho) +$	(π/ρ)
total	photoelectric	coherent	Compton	pair



Relative Importance of PE, CE & PP

Photon Energy (MeV)	Relative Number of Interactions (%) in water		
	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

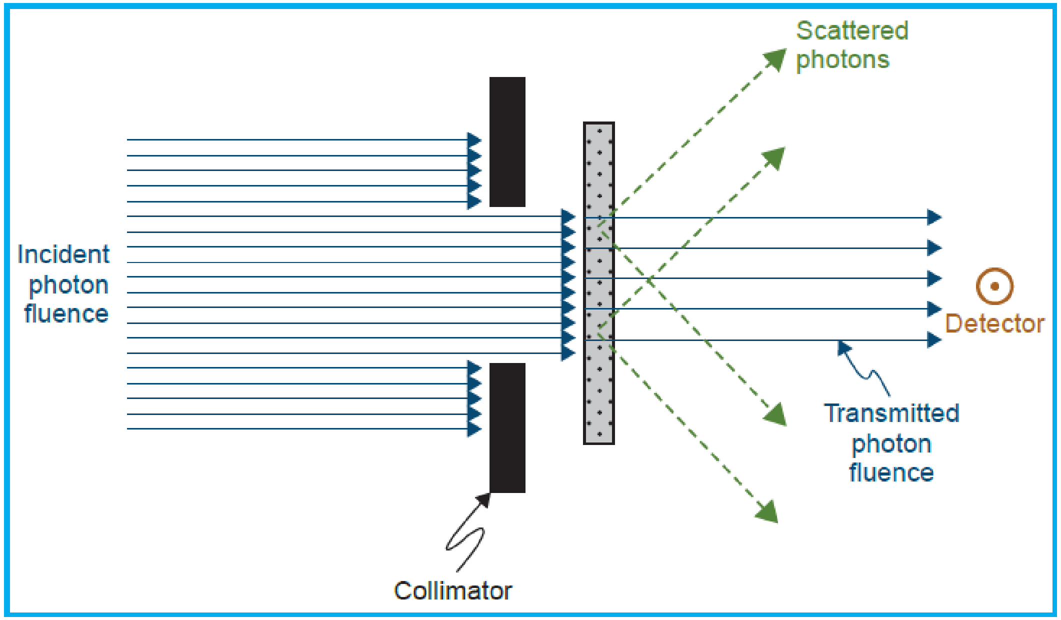
Photon Beam Attenuation – HVL & TVL

$$I(x) = I_0 e^{-\mu x}$$

x = absorber thickness (cm)

μ = linear attenuation coefficient (cm^{-1})

I = Photon beam intensity (Photon fluence)



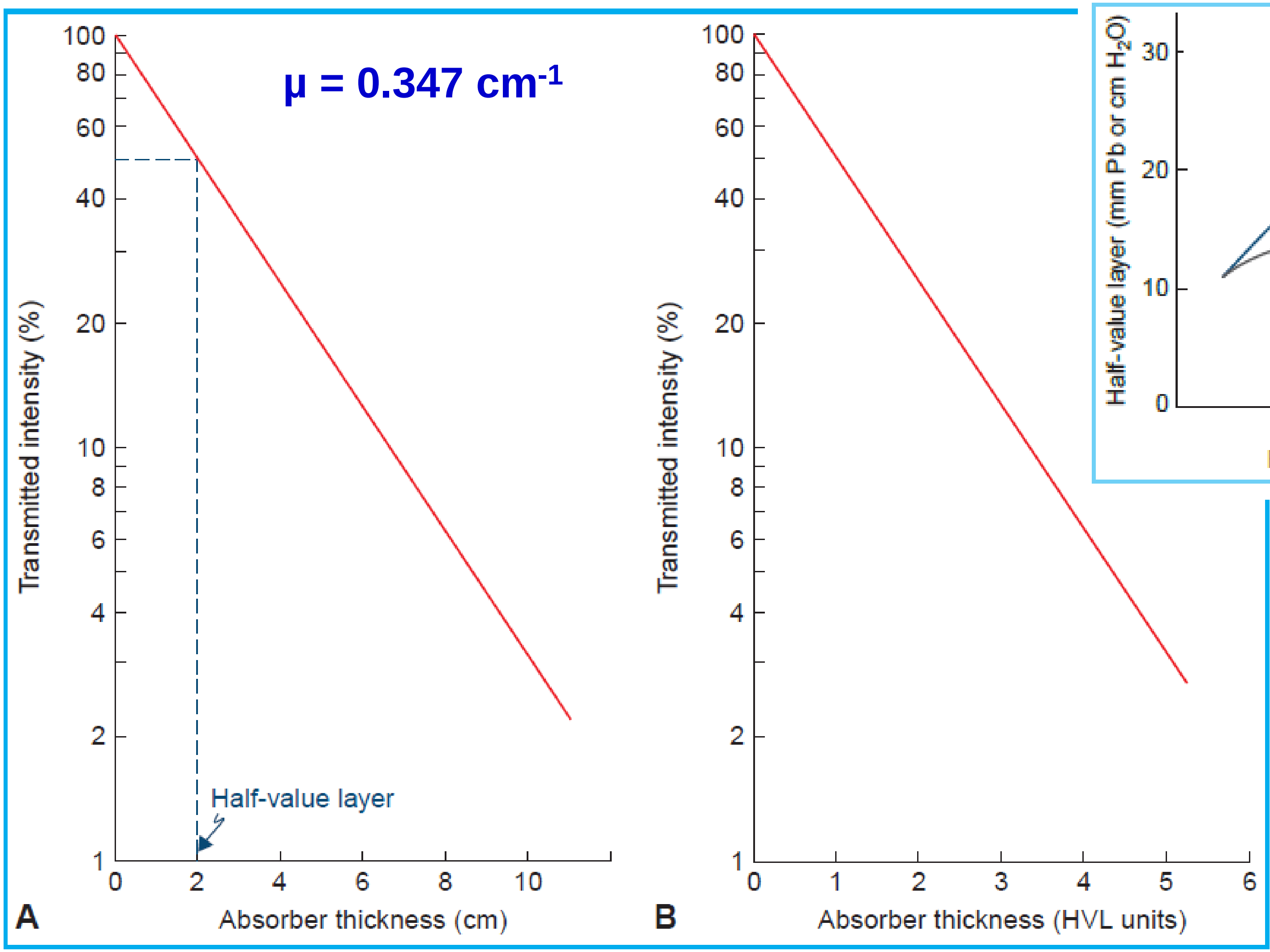
When, $I(x) = I_0/2$ the thickness x required to fulfil this condition is called Half Value Thickness/Layer (HVT/HVL)

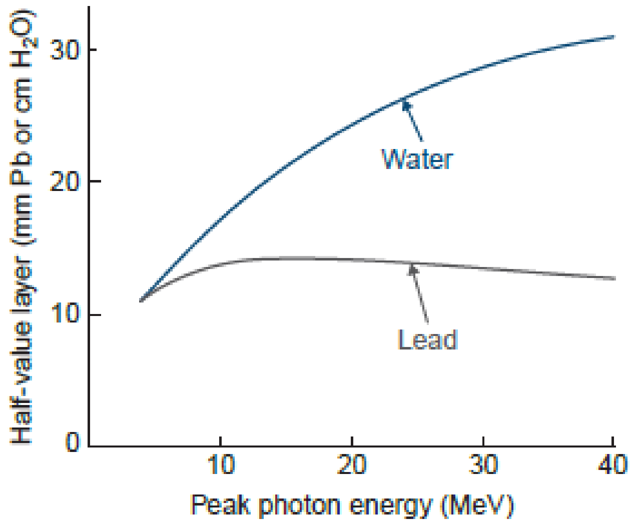
When, $I(x) = I_0/10$ the thickness x required to fulfil this condition is called Tenth Value Thickness/Layer (TVT/TVL)

Photon Beam attenuation – HVL & TVL

HVL ≈ 0.693/μ

TVL ≈ 3.33 HVL





Interaction of Heavy Charged Particles

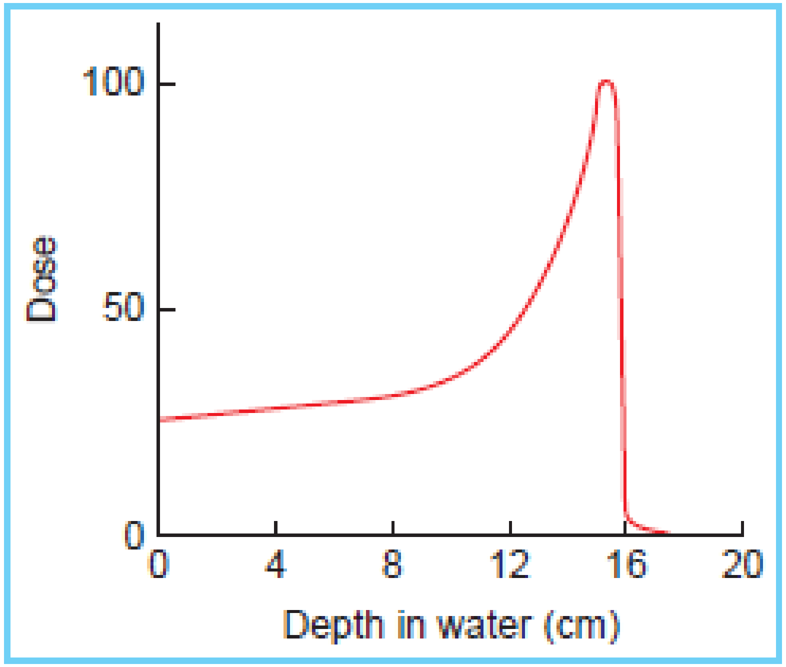
- Charged particles (electrons, protons, alpha particles, heavy nuclei) interact principally by ionization and excitation,

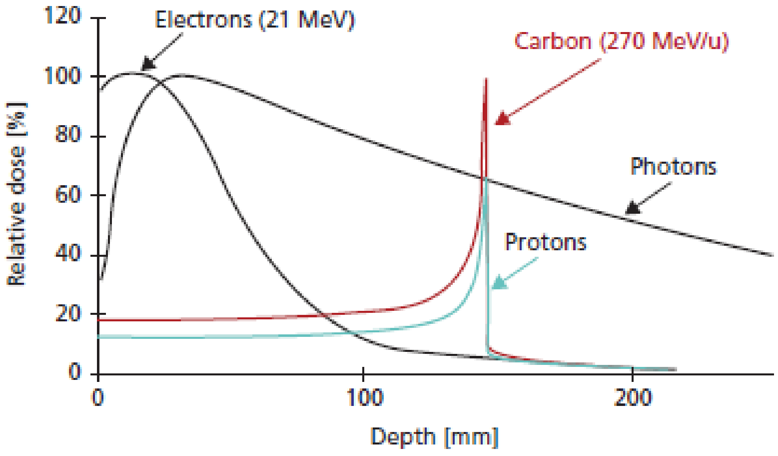
- The charged particles interactions are mediated by Coulomb force between theectric field of traveling particle and electric fields of orbital electrons and nuclei of the material,

- Interaction between charged paricles and atomic electrons results in ionization and excitation,

- Interaction between charged paricles and nucleus result in radiative loss of energy (mainly for electrons),

- Heavy charged particles give rise to nuclear reactions - production of radionuclides





Particle Fluence (Φ) & Energy Fluence (ψ)

- The fluence (Φ) of photons is the quotient dN by da, where dN is the number of photons that enter an imaginary sphere of cross-sectional area da

$$\Phi = dN/da \quad (m^{-2})$$

- Energy fluence (ψ) is the quotient of dR by da, where dR is the sum of the energies of all the photons that enter a sphere of cross-sectional area da

$$\psi = dR/da \quad (J\ m^{-2})$$

- For a monoenergetic beam, dR is just the number of photons dN times energy hv carried by each photon.

Attenuation Coefficients & Stopping Power

Mass attenuation coefficient (μ/ρ):

- **Attenuation coefficient represents the fraction of photons removed per unit thickness**

- **As μ depends on the density of the material because attenuation produced by a thickness x depends on the number of electrons present in that thickness, μ/ρ is a density independent representation of attenuation.**

Mass energy transfer coefficient **Mass energy absorption coefficient**

The stopping power (S) of the medium is defined as the energy lost by the charged particles per unit path length (dE/dx).

Mass stopping power (S/ρ) of a medium for charged particles is the quotient of dE by ρdx where dE is the energy lost by a charged particles in traversing a distance dx in a material of density ρ

$$S/\rho = dE/\rho dx \qquad \mathrm{J\ m^2 kg^{-1}}$$

KERMA (K) and Absorbed Dose (D)

- Kerma is a measure of amount of total energy transferred by photons (x-rays or gamma rays) to the medium. It is defined as the sum of the initial kinetic energies of all charged particles liberated by radiation in material of mass m.

$$K = dE_{tr}/dm = \psi\ (\mu_{tr}/\rho) \qquad \text{J/kg or Gy}$$

μ_{tr}/ρ (m^2/kg) is the mass energy transfer coefficient

- Absorbed Dose is a measure of amount of energy absorbed per unit mass of the matter at the point of interest. It is defined as the mean energy imparted to the medium of mass m, i.e.

$$D = dE/dm \qquad \text{J/kg or Gy}$$

- K represents sum of the initial KE of all charged particles liberated by radiation in the medium and whole energy need not be deposited in the medium whereas 'D' represents energy deposited by these charged particles in the medium

- Under charge particle equilibrium (CPE), $K^{col} = D$

Equations, CPE, Kerma and Dose

$$K = \frac{dE_{tr}}{dm}$$

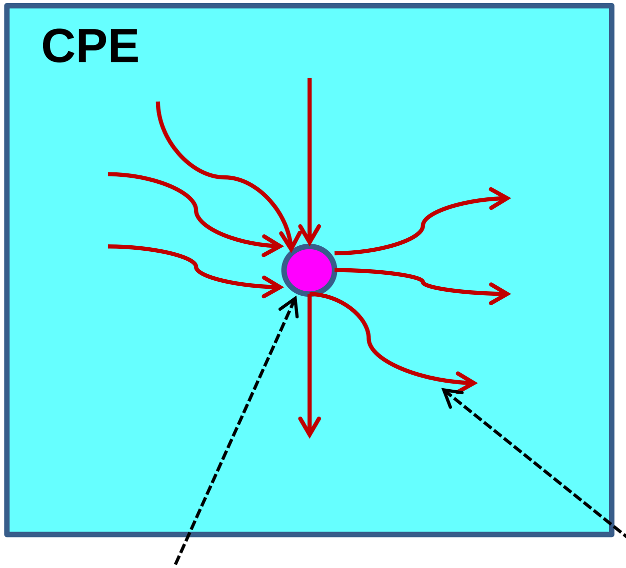
$$K = \Psi\left(\frac{\bar{\mu}_{tr}}{\rho}\right)$$

$$\left(\frac{\bar{\mu}_{en}}{\rho}\right) = \left(\frac{\bar{\mu}_{tr}}{\rho}\right)(1 - \bar{g})$$

$$K = \Psi\left(\frac{\bar{\mu}_{en}}{\rho}\right)/(1 - \bar{g})$$

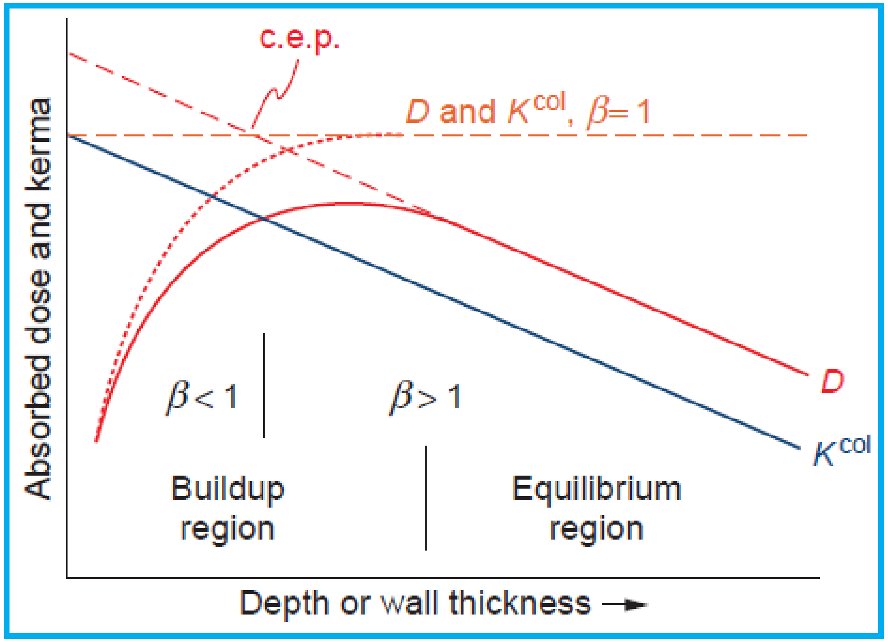
$$K^{col} = \Psi\left(\frac{\bar{\mu}_{en}}{\rho}\right)$$

$$\beta = D/ K^{col}$$



Ion chamber cavity

Electron tracks



Radiation Dosimetry - Terminology

Absolute Dosimetry

Measurement of absorbed dose using a primary standard – calorimeter, ion chambers

Reference Dosimetry

Measurement of absorbed dose under conditions defined in a recognized dosimetry protocol (i.e. reference conditions) using a dosimeter whose calibration is traceable to national/ international primary standard – secondary standard/ reference standard/ field class dosimeter (preferably ion chambers)

Relative Dosimetry (RD)

Determination of relative dosimetry parameters such as PDD, TMR, Output Factors, ………

dosimeters for RD – ion chambers, films, TLD, OSLD, …..

Calibration Factor (Coefficient)

$$\text{Calibration Factor (CF)} = \frac{\text{True value of a quantity}}{\text{Instrument reading (M)}}$$

N_X : Exposure calibration coefficient

$N_{K,air}$: Air Kerma calibration coefficient

$N_{D,air}$: Absorbed dose to air calibration coefficient

$N_{D,w}$: Absorbed dose to water calibration coefficient

[Example: 4.5×10^7 Gy/C at 20°C and 1013.2 mbar]

IAEA TRS 398: Formalism

- Reference dosimetry is carried out under the conditions of charged particle equilibrium (CPE) using ionization chambers

- The absorbed dose to water at the reference depth z_{ref} in water for a photon beam of quality Q and in the absence of the ionisation chamber is given by

$$D_{w,Q}(z_{ref}) = M_{w,Q,corr}\, N_{D,w,Qo}\, k_{Q,Qo}$$

where,

$M_{w,Q,corr}$ = dosimeter reading under reference conditions corrected for influence quantities

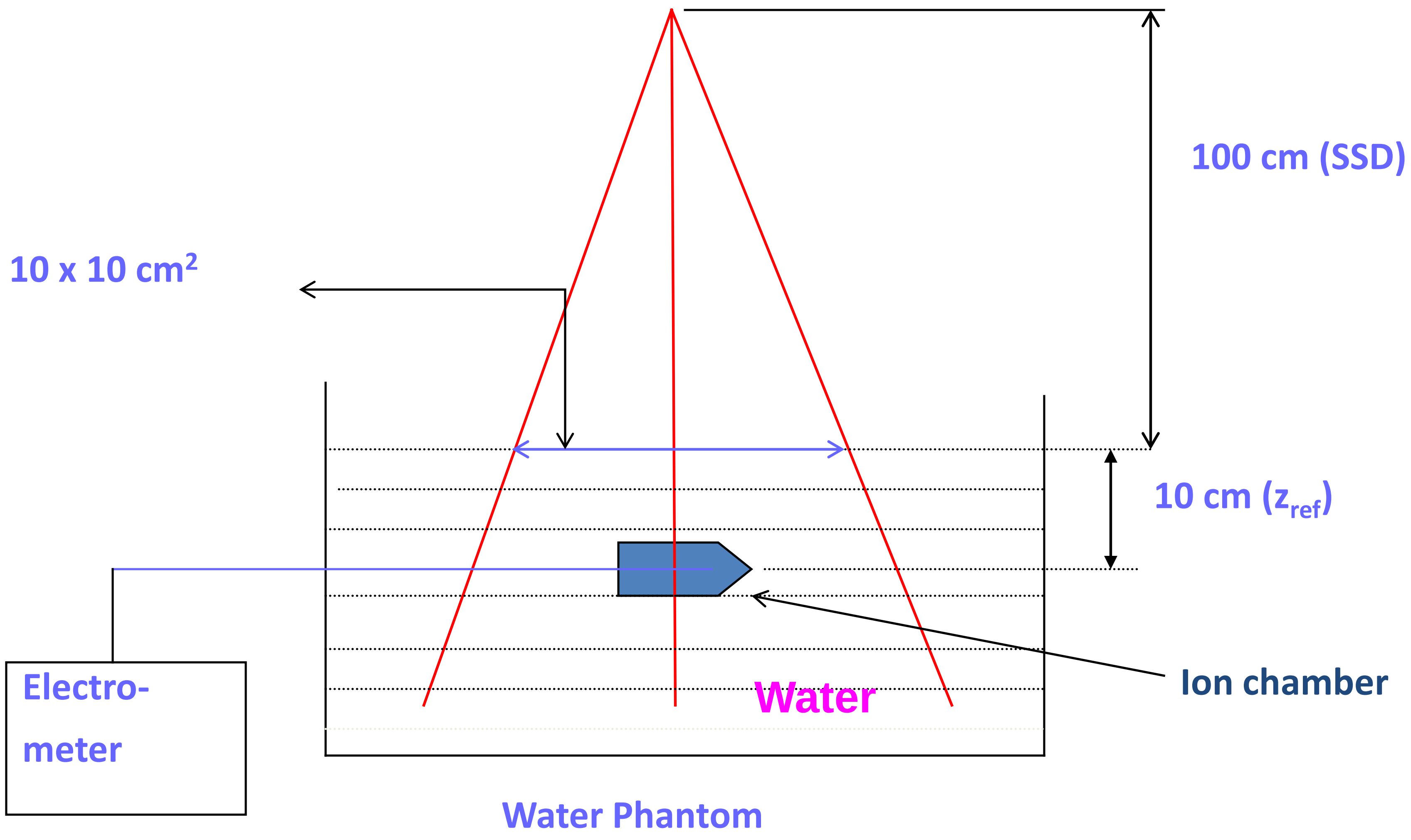
$N_{D,w,Qo}$ = absorbed dose to water calibration co-efficient of the dosimeter obtained from the standards laboratory (10 x 10 cm^2)

$k_{Q,Qo}$ = beam quality correction factor (10 x 10 cm^2)

TRS 398: Reference Conditions

Influence quantity	Reference value/characteristics
Phantom material	Water (liquid)
Chamber type	Cylindrical
Measurement depth z_{ref}	For TPR^{20}_{10} < 0. 7, 10 (or 5) g/cm^2 For TPR^{20}_{10} = 0. 7, 10 g/cm^2
Reference point of the ion chamber	On the central axis at the centre of the cavity volume
Position of the reference point of the chamber	At the measurement depth z_{ref}
SSD/SCD	100 cm
Field size	10 cm × 10 cm

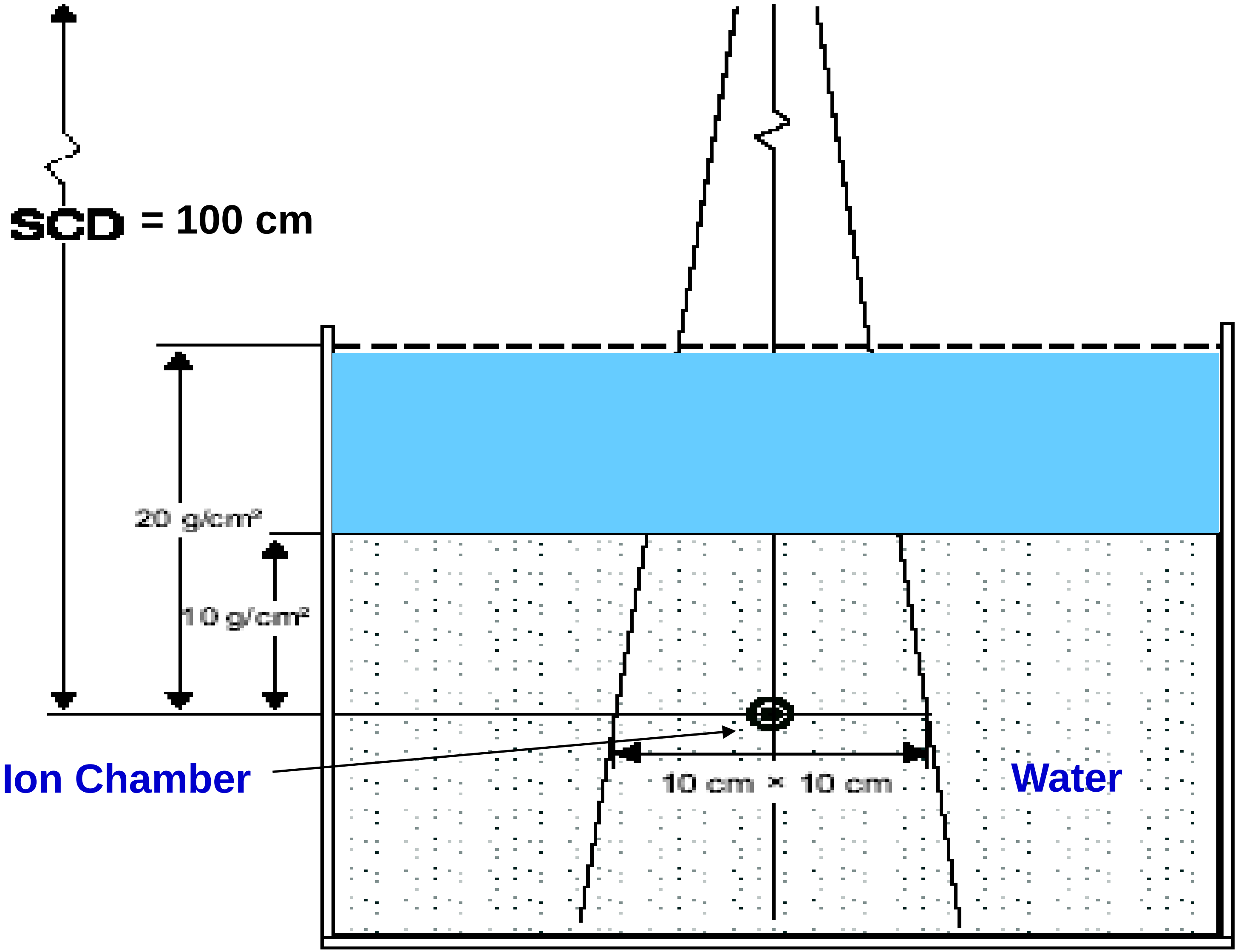
TRS 398: Experimental Set-up for Reference Dosimetry (SSD)



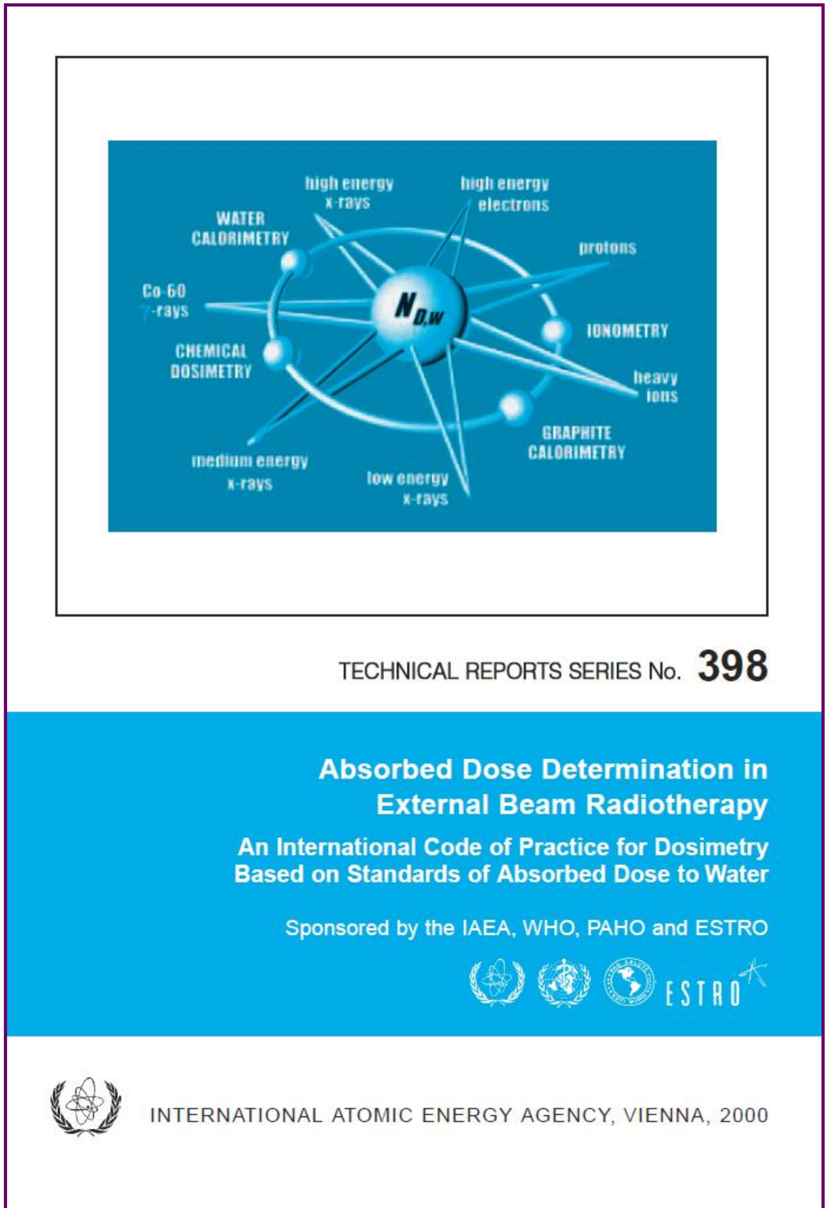
Measurement of TPR^{20}_{10} (QI)

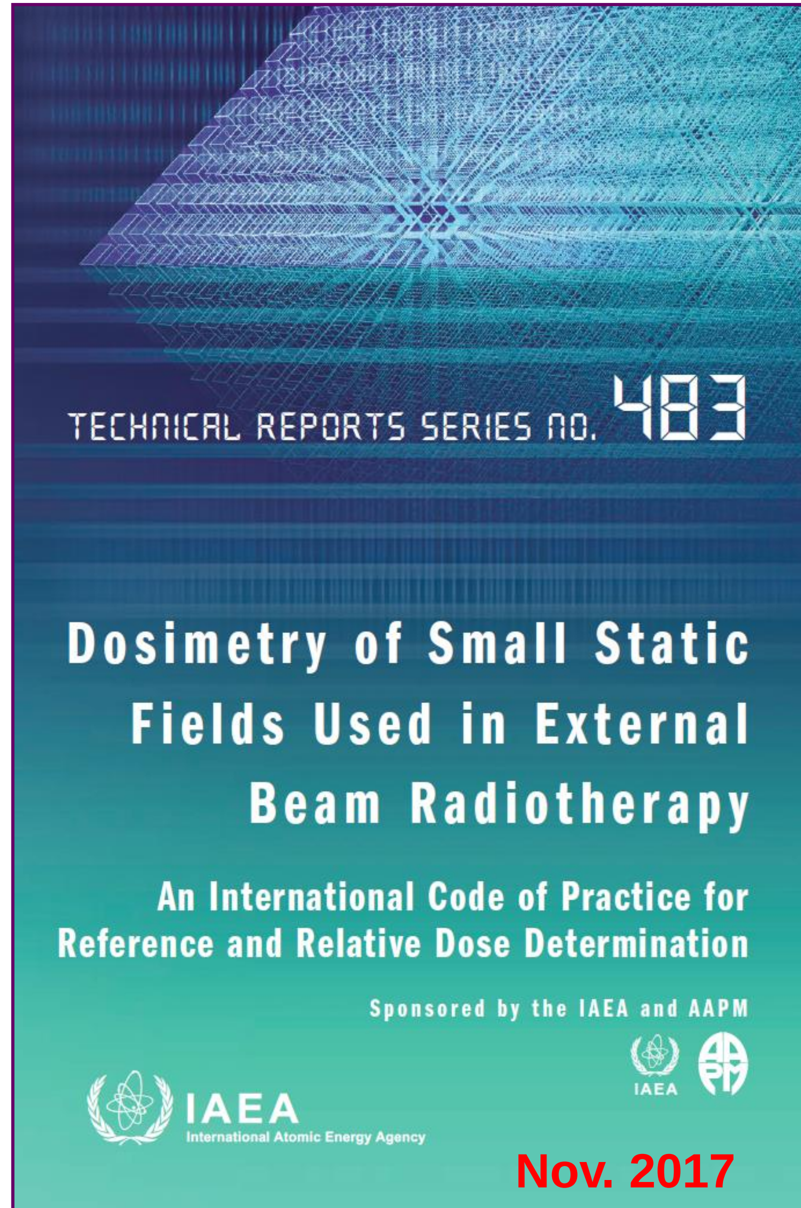
Influence quantity	Reference value/characteristics
Phantom material	Water (liquid)
Chamber type	Cylindrical or plane parallel (PP)
Measurement depths	20 and 10 g/cm^2
Reference point of ionization chamber	For cylindrical chambers: on the central axis at the centre of the cavity volume. For PP chambers: on the inner surface of the window at its centre
Position of the reference point of the chamber	At the measurement depths
SCD	100 cm
Field size at SCD	10 cm × 10 cm

Experimental Set-up for Measurement of QI



IAEA TRS 398 and TRS 483





Nov. 2017

Thank you