Chapter 2

RADIATION INTERACTION WITH CONDENSED MATTER

Diana Adlienė
Kaunas University of Technology, Physics Department, Studentų g. 50, LT-51368 Kaunas, Lithuania

1. INTRODUCTION

Radiation processing of materials is conducted with the aim of modification of material properties (bulk, surface) and the creation of new materials and structures. Radiation that can alter material properties and structures are energetic fundamental particles, ions and electromagnetic waves.

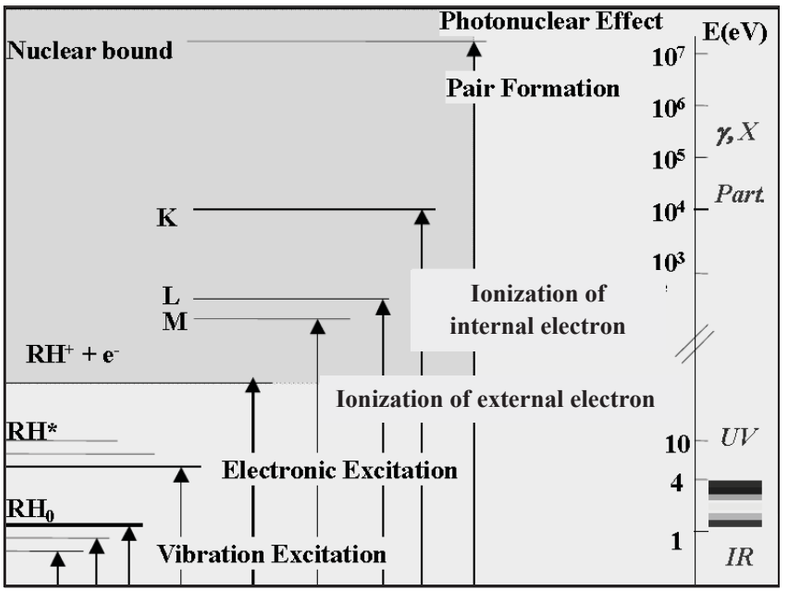

Fig.1. Energy-dependent radiation-induced processes in matter [1].

Radiation interaction mechanisms with matter depend on the type and energy of the bombarding particles, on the target material and energy imparted,

and on other physical and technical parameters. The most important parameter in discussing radiation-induced processes in matter is the energy of radiation. The energy dependency of different radiation-induced processes in materials is schematically shown in Fig.1.

Interaction mechanisms are distinguished between heavy charged particles (protons, alpha particles and heavy ions), heavy neutral particles (neutrons), charged particles (electrons and positrons) and virtual particles/electromagnetic waves (gamma and X-ray photons). Depending on the energy imparted radiation interaction with matter may lead to:

- initiation of chemical reactions,
- excitation of electrons and molecules,
- ionization of matter,
- nuclear reactions (this topic was covered in the Chapter 1).

Knowledge of the radiation interaction processes related to the energy transfer to the irradiated target is fundamental to radiation detection, measurement, and control, as well as to understanding the biological effects of radiation, when working with biomaterials.

2. INTERACTIONS OF CHARGED PARTICLES WITH MATTER

2.1. INTERACTIONS OF HEAVY CHARGED PARTICLES WITH MATTER

2.1.1. Ion beams

Ion beam interactions with matter (ion implantation, ion beam mixing, plasma assisted ion implantation or ion beam assisted deposition, *etc.*) are very complex processes that cover a broad area of different phenomena initiated by penetrating ions (Fig.2).

The energy transfer mechanisms are common for all charged particles, but ion beam induced radiation processes are quite different from those observed when fundamental particles such as electrons, protons or neutrons interact with matter. Many radiation defects are produced along a path of penetrating ions that contribute significantly to the properties of irradiated materials. Ion beam induced phenomena provides an important link to the application of energetic ions for the modification and creation of new materials.

This book is aimed at providing knowledge on material processing and modification using energetic electron or photon beams, so the energy deposition processes of heavy ions will be covered in this chapter without going into details on further processes induced in matter by bombarding it with ions.

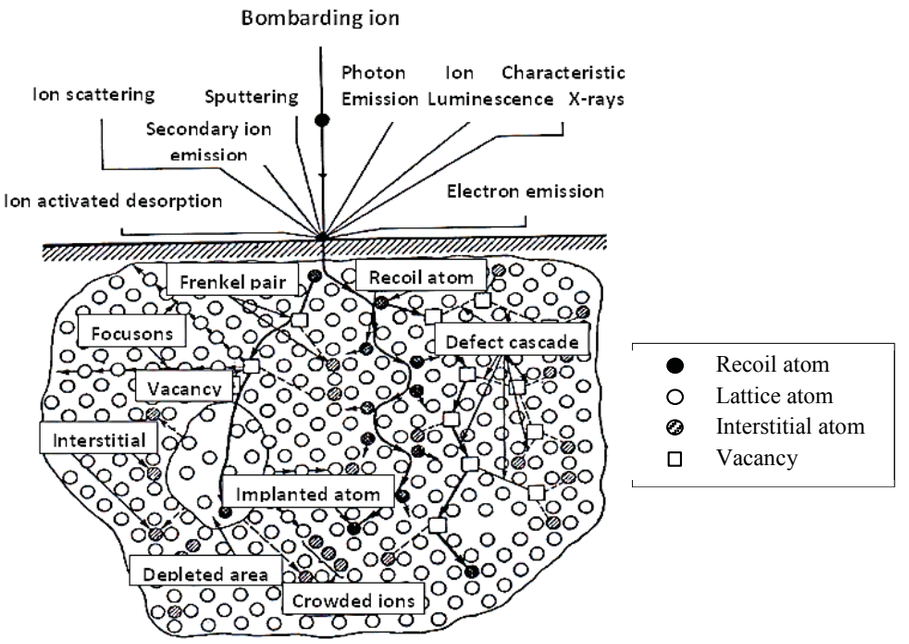

Fig.2. Primary processes induced in matter due to its bombardment with ions. (Adapted from Ref. [2]).

Useful information on ion beam interaction processes and ion beam applications can be found in Refs. [3-5].

2.1.2. Interactions mechanisms

A heavy charged particle traversing matter loses energy primarily through the ionization and excitation of atoms. The moving charged particle, being surrounded by its Coulomb electric force field, interacts with one or more electrons or with the nucleus of practically every atom it passes. In most of these interactions only a very small fraction of the incident particle's kinetic energy is transferred. For example: a 1 MeV charged particle would typically undergo 10^5 interactions with electrons before losing all of its kinetic energy. Heavy charged particles travel an almost straight path through matter since any deflection in electron collisions, which is most probable, is negligible. Nevertheless the energy transferred may be sufficient to knock an electron out of an atom and thus ionize it, or it may leave the atom in an excited state when the electron is moved to the higher energy level.

The following approximate empirical formulas can be used to estimate the mean excitation energies, $\bar{I}$, for the element with atomic number Z [6]:

- $\bar{I} \approx 19.0$ eV, $Z = 1$ (hydrogen);
- $\bar{I} \approx 11.2 + 11.7 \times Z$ eV, $2 \leq Z \leq 13$;
- $\bar{I} \approx 52.8 + 8.71 \times Z$ eV, $Z > 13$.

The mean excitation potential, $\bar{I}$, is the geometric-mean value of all the ionization and excitation potentials of an atom of the absorbing medium.

Assuming that the particle moves rapidly compared with the electron and that the energy transferred is large compared with the binding energy of the electron in the atom, the electron is free and at rest and the collision is elastic. The simplest way to calculate the maximum energy transfer is:

$$Q_{max} = \frac{4mME_k}{(M+m)^2} \tag{1}$$

But the exact relativistic expression for the maximum energy transfer, with m and M denoting the rest masses of the electron and the heavy particle, is:

$$Q_{max} = \frac{2\gamma^2 mv^2}{1 + 2\gamma m/M + m^2/M^2} \tag{2}$$

where $E_k = Mv^2/2$ is the initial kinetic energy of the incident particle, $\gamma = 1/\sqrt{1-\beta^2}$, $\beta = v/c$, c is a speed of light.

Since the electrons are bound in the discrete energy states of the medium, the minimum, or threshold, energy transfer $Q_{min} \geq \bar{I}$ is required, which is sufficient to ionize or excite the atom when heavy particle interacts with a bound electron.

The average linear rate of energy loss of a heavy charged particle passing through matter is of fundamental importance in radiation physics and dosimetry. This quantity, designated S = dE/dx, is called the stopping power of the medium for the particle, where dE is the loss in kinetic energy of the particle as it travels a distance dx.

For a given type of charged particle at a given energy, the stopping power is given by:

$$-\frac{dE}{dx} = \mu Q_{avg} = \mu \int_{Q_{min}}^{Q_{max}} QW(Q)dQ \tag{3}$$

where μ is the probability per unit distance of travel that an electron collision occurs (also called macroscopic cross section, attenuation coefficient) and Q_{avg} is the average energy loss per collision, expressed as a product of energy loss and probability W(Q)dQ, that a given collision will result in an energy loss between Q and Q + dQ.

Stopping power, S, depends upon the type of particle, its energy and the medium traversed. It is common to express the distance in terms of mass per unit area of the material, giving the mass stopping power, S/ρ:

$$\frac{S}{\rho} = \frac{1}{\rho}\frac{dE}{dx} \tag{4}$$

where ρ is the mass density of material.

Using relativistic quantum mechanics, Bethe derived the following expression (as it is provided in Ref. [6]) for the stopping power of a uniform medium for a heavy charged particle:

$$-\frac{dE}{dx}=\frac{4\pi k_0^2 Z^2 e^4 n}{mc^2\beta^2}\left[\ln\frac{2mc^2\beta^2}{\bar{I}(1-\beta^2)}-\beta^2\right] \tag{5}$$

where: $k_0 = 8.99 \times 10^9$ Nm^2·C^{-2}, Z – the atomic number of the heavy particle, $e = 1.6 \times 10^{-19}$ C, n – the electron concentration in medium, m – the rest mass of electron, c – speed of light in vacuum, $\beta = v/c$, $\bar{I}$ – mean excitation energy of the medium. The multiplicative factor in the formula can be written with the help of constants [5]:

$$\frac{4\pi k_0^2 Z^2 e^4 n}{mc^2\beta^2}=5.08\times10^{-31}\frac{Z^2 n}{\beta^2}\left[\mathrm{MeV}\cdot\mathrm{cm}^{-2}\right] \tag{6}$$

When the material is a compound or mixture, the stopping power can be calculated as follows:

$$n\ln I=\sum_i N_i Z_i \ln \bar{I}_i \tag{7}$$

where: n – the total number of electrons/cm^3 in the material ($n = \Sigma_i N_i Z_i$), N_i – the number of atoms/cm^3 of an element with atomic number Z_i, $\bar{I}_i$ – mean excitation energy.

General formula for calculation of the stopping power for any heavy charged particle in any medium is:

$$-\frac{dE}{dx}=\frac{5.08\times10^{-31}Z^2 n}{\beta^2}\left[F(\beta)-\ln I_{eV}\right] \tag{8}$$

where in the dimensionless $\ln I_{eV}$, the excitation energy values (in eV) are inserted; and $F(\beta)$ is calculated as:

$$F(\beta)=\ln\frac{1.02\times10^6\beta^2}{1-\beta^2}-\beta^2 \tag{9}$$

The reciprocal of the stopping power gives the distance of the heavy charged particle travelled per unit energy loss. The integral of this quantity down to zero kinetic energy defines an absolute travelling distance of the particle before coming to rest. This distance is called particle range in material:

$$R(E_k)=\int_0^{E_k}\left(-\frac{dE}{dx}\right)^{-1}dE \tag{10}$$

The Bethe (stopping power) formula for heavy charged particles is valid at high energies, as long as inequality $\gamma m/M << 1$ (see Eq. (2)) holds, but there are some limitations for low and very high energies.

2.2. INTERACTIONS OF ELECTRONS AND POSITRONS WITH MATTER

Electron and proton interaction processes and interaction products (Fig.3) are different as compared with ion interaction processes (see also Fig.2). Electron and positron energy loss processes are usually treated together, referring to both particles as "electrons" or "beta particles" and distinguishing between them only where it is necessary.

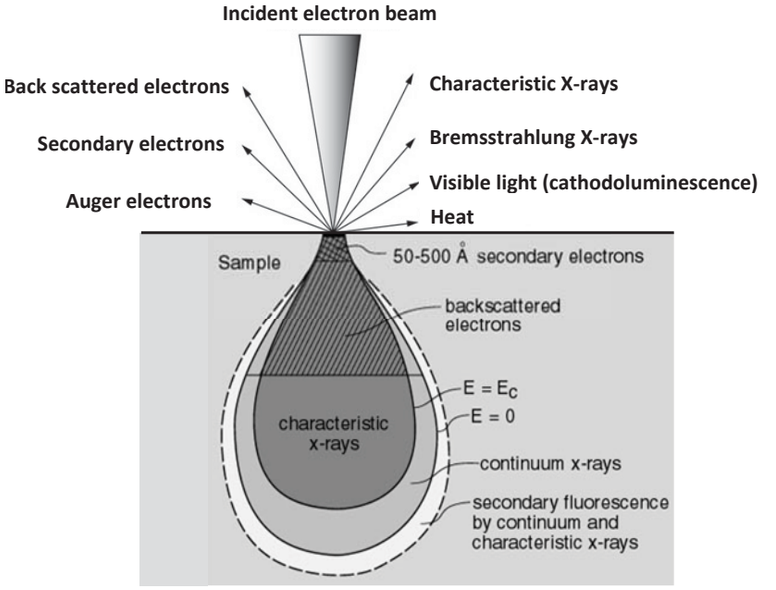

Fig.3. Schematic illustration of interaction volumes for various electron-specimen interactions (E_c – the energy required to produce X-rays in a bombarded target of interest).

Energetic electrons lose their kinetic energy in matter almost continuously through Coulomb interactions with atomic orbital electrons and atomic nuclei (collision and radiative losses) or change their direction of motion (scattering). In contrast to heavy charged particles, beta particles do not generally travel through matter in straight lines. The interactions between incident electron and an orbital electron or nucleus may be elastic and inelastic.

In an elastic interaction the incident electron is deflected from its original path but no energy loss occurs. This process has a significant effect on electron penetration and diffusion in matter at low energies.

The type of inelastic interaction that an electron undergoes with a particular atom of radius a, depends on the impact parameter of the interaction, b (distance between the trajectory of the electron and nucleus) [7]:

- b >> a, soft collisions of electrons with the whole atom; small amount of its kinetic energy (a few per cent) transferred to orbital electrons;

- b ≈ a, hard collision of electron with an orbital electron and a significant fraction of its kinetic energy (up to 50%) transferred to the orbital electron;
- b << a, radiation collision of an electron with the atomic nucleus; emission of a bremsstrahlung photon with energy between 0 and the incident electron kinetic energy.

In an inelastic collision with orbital electron the incident electron is deflected from its original path and loses part of its kinetic energy which is used for ionization or excitation of absorbing atoms [8]. As it was already discussed in Chapter 1, ionization is related to the ejection of an orbital electron from the absorber atom (Fig.4A) and excitation is related to the transfer of an orbital electron of the absorber atom from an allowed orbit to the higher one (higher shell) (Fig.4B). Atomic ionization and excitation result in collision energy losses and are characterized by collision stopping power.

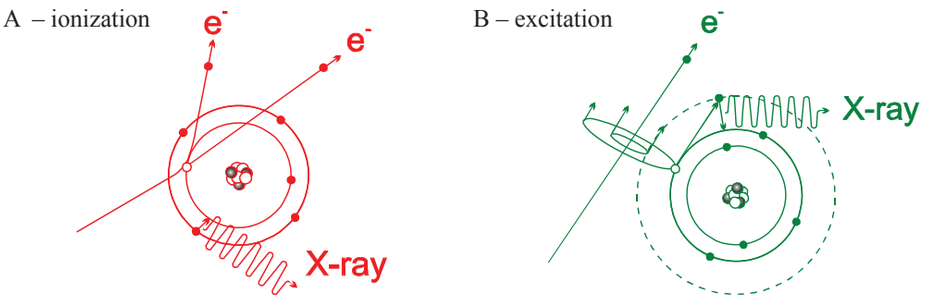

Fig.4. Inelastic collision schemes for the incident electron [9].

Elastic scattering is the dominant process at the lowest energies. Slow electrons undergo almost a random diffusion, changing direction through frequent elastic collisions without energy loss. Eventually, the occasional competing inelastic excitation and ionization collisions bring the energies of the electrons down into the region where they can react chemically with water molecules or became hydrated. At about 200 eV, ionization and the elastic scattering are comparable and considerably more probable than excitation. The attenuation coefficient curves do not cross. Elastically scattered electrons (which include backscattered electrons) are generally scattered through larger angles than are inelastically scattered electrons. At the highest energies, elastic scattering occurs increasingly in the forward direction. While elastic scattering affects electron transport through redirection of the electron paths, it does not contribute to the stopping power, because there is no associated energy loss.

The relative importance of ionization, excitation, and elastic scattering for electrons in water at energies up to 1 MeV are shown in Fig.5.

In an inelastic collision with an atomic nucleus the incident electron is deflected from its original path (scattered electron) and loses part of its kinetic energy in the form of X-ray photons (bremsstrahlung). This type energy loss is characterized by a radiative stopping power.

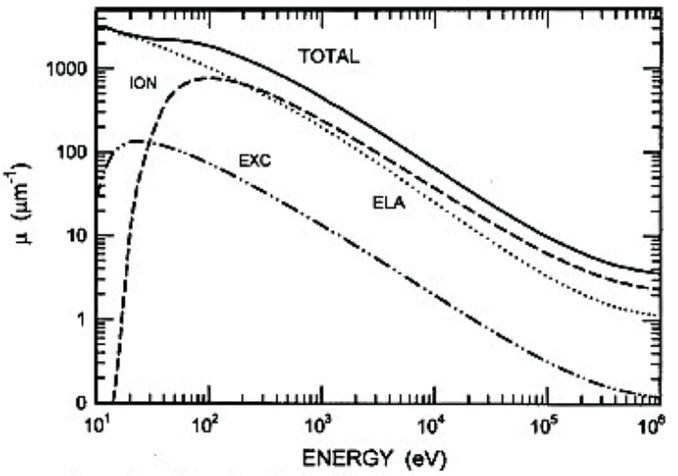

Fig.5. Attenuation coefficients μ (see Eq. (3)) for excitation (EXC), ionization (ION), elastic scattering (ELA) and total interaction for electrons in liquid water as a function of energy. (Adapted from Ref. [6]).

Coulomb interactions with the bound atomic electrons are the principal way that charged particles lose energy in the materials and energies of interest. The particle creates a trail of ionizations and excitations along its path as it is shown in Fig.6.

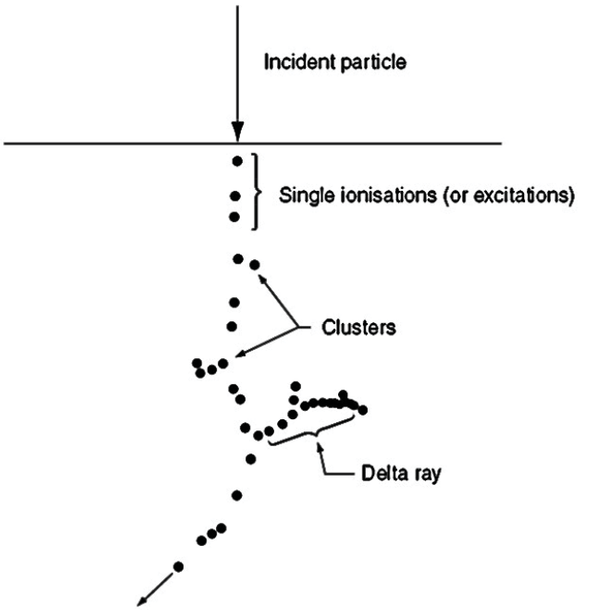

Fig.6. Schematic representation of the track of a charged particle in matter. (Adapted from Ref. [10]).

Occasionally, the energy transfer to the atomic electron is sufficient to create a so-called delta ray (or δ-ray). Delta rays are defined as (secondary) electrons that acquire sufficiently high kinetic energies through hard collisions which enables them to carry this energy a significant distance away from the track of the primary particle and produce their own ionization of absorber atoms.

The inelastic energy losses by electrons travelling through material are described by a total mass stopping power, which represents the kinetic energy loss by electron per unit path length, divided by the density of material (see Eq. (4)). The mass collision stopping power expresses the average rate of energy loss by a charged particle in all hard, as well as soft, collisions. Collision stopping power plays an important role in radiation dosimetry, since it is related to the dose absorbed in medium [11]:

$$D = \Phi \left(\frac{S}{\rho} \right)_{col} \tag{11}$$

where Φ is the fluence of electrons.

The delta rays resulting from hard collisions may be energetic enough to carry kinetic energy a significant distance away from the track of the primary particle. In this case, the use of mass collision stopping power may lead to an overestimation of the dose. To overcome this problem the restricted stopping power defined as a fraction of the collision stopping power that includes all the soft collisions plus those hard collisions resulting in delta rays with energies less than a cut-off value Δ shall be applied [12]:

$$\left(\frac{S}{\rho} \right)_{\Delta} = \left(\frac{1}{\rho} \frac{dE}{dx} \right)_{\Delta} \tag{12}$$

The full quantum-mechanical expression for the electron mass collision stopping power [13] is given by:

$$\left(-\frac{dE}{dx} \right)_{col}^{\pm} = \frac{4\pi k_0^2 2e^4 n}{\beta^2} \left[\ln \frac{mc^2 \tau \sqrt{\tau + 2}}{\sqrt{2I}} + F^{\pm}(\tau) - \delta \right] \tag{13}$$

where for electrons:

$$F^{-}(\beta) = \frac{1 - \beta^2}{2} \left[1 + \frac{\tau^2}{8} - (2\tau + 1) \ln I \right] \tag{14}$$

and for positrons:

$$F^{+}(\beta) = \ln \left[23 + \frac{14}{\tau + 2} + \frac{10}{(\tau + 2)^2} + \frac{4}{(\tau + 2)^3} \right] \tag{15}$$

where $\tau = E/mc^2$ with E as kinetic energy of the β^+ or β^- particle, and δ is the density effect correction factor. The other symbols in these equations are the same as it was defined in the Eq. (5).

The total mass stopping power consists of two components: the mass stopping power related to electron-orbital electron interactions (ionization and excitation) and the radiative mass stopping power related to electron-nucleus interactions (bremsstrahlung):

$$(S/\rho)_{tot} = (S/\rho)_{col} + (S/\rho)_{rad} \tag{16}$$

Both stopping powers are competing: within a broad range of kinetic energies below 10 MeV collision (ionization) losses are dominant $(S/\rho)_{col} > (S/\rho)_{rad}$, but at high kinetic energies the situation is reversed (Fig.7).

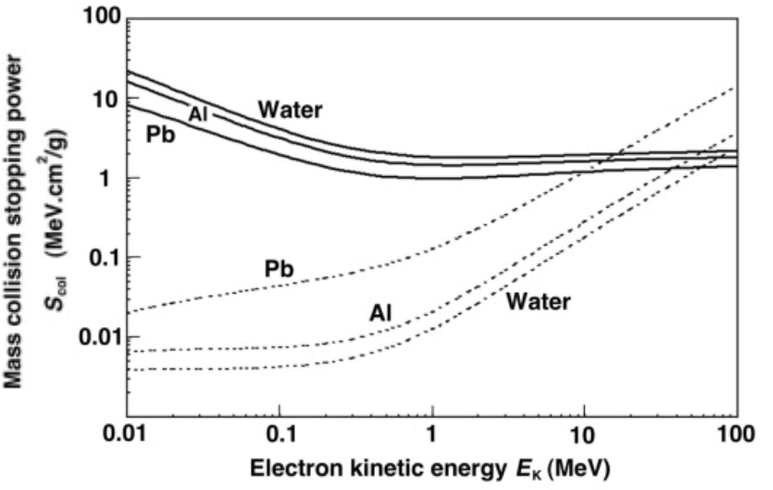

Fig.7. Mass stopping powers for electron in medium: solid lines – mass collision stopping power, dotted lines – mass radiation stopping power. (Adapted from Ref. [14]).

The energy loss rate in collision interactions depends on the kinetic energy of the electron and the electron density of the absorber. It is greater for low atomic number Z absorbers than for high Z absorbers because of lower electron density in high Z absorbers.

The energy loss rate in radiation interactions (followed by bremsstrahlung) is approximately proportional to the kinetic energy of the electron and Z^2 of the absorber. Bremsstrahlung production is more efficient for higher energy electrons and higher atomic number absorbers.

Radiative yield, also known as radiation efficiency, is expressed as:

$$Y = \frac{1}{E_i}\int_0^{E_i} \frac{(S/\rho)_{rad}}{(S/\rho)_{tot}}\, dE \tag{17}$$

The radiative yield increases directly with atomic number Z and kinetic energy of electrons. The radiation yield for low energy range electrons (~100 keV) is ~1% and for megavoltage region ~0%.

For heavy charged particles the radiation stopping power is negligible thus $(S/\rho)_{tot} \approx (S/\rho)_{col}$.

When the energetic electron travels through matter it has interactions (electron-electron or electron-nucleus) with every atom it encounters. Due to Coulomb interactions electron loses its kinetic energy and comes to the rest at a certain depth in the absorbing medium called electron (particle) range.

Since the stopping of particles in an absorber is a statistical process, several definitions of the range are possible. According to Attix [15], distinctions are made between the path length, the projected path range and the mean path length for the electron entering material with a certain amount of kinetic energy:

- The path length of an electron is the total distance travelled along its actual trajectory until the electron comes to rest.
- The projected path range of an electron is the sum of individual path length, projected onto the incident beam direction.
- The mean path length of an electron of initial kinetic energy E_0 is defined as:

$$R_{CSDA} = \int_0^{E_0} \left(\frac{S(E)}{\rho} \right)_{tot}^{-1} dE \tag{18}$$

The mean path length is called also CSDA range taking into account that the fractions of electron's kinetic energy transferred to matter in each single interaction is very small and it is convenient to assume that the electron is losing its energy gradually and continuously in a process referred to as continuous slowing down approximation (CSDA) [16]. CSDA range is purely calculated quantity representing the mean path length along electron's trajectory but not the depth of penetration in the defined direction.

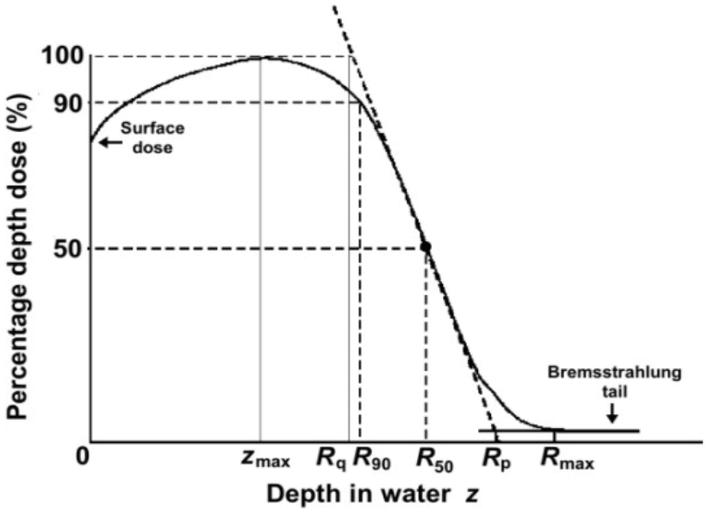

Fig.8. Typical electron beam depth-dose distribution curve with indicated penetration ranges. (Adapted from Ref. [17]). Note: Percentage depth dose (PDD) is defined as the quotient, expressed as a percentage, of the absorbed dose at any depth z to the absorbed dose at a fixed reference depth z_0, along the central axis of the beam.

Also other beam ranges are in use to define penetration depth of electron beams (Fig.8):

- The maximum range R_{max} (in cm or g/cm^2) is the largest penetration depth of an electron in an absorber. Being extrapolated from the depth-dose curve, this point is not well defined.
- The practical range R_p (in cm or g/cm^2) is defined as the depth at which the tangent plotted through the steepest section of the electron depth-dose curve intersects with the extrapolation line of the bremsstrahlung tail.
- R_{90} (most important for medical applications) and R_{50} are the depths at which the percentage depth dose values beyond the depth of dose maximum z_{max} attain of 90 and 50%, respectively.
- The depth R_q is defined as the depth where the tangent through the dose inflection point intersects the maximum dose level.

3. INTERACTION OF PHOTONS WITH MATTER

3.1. PHOTON INTERACTION PROCESSES

There are four categories of indirectly ionizing photon radiation:

- bremsstrahlung (electron-nucleus Coulomb interaction),
- characteristic X-rays (electron-orbital electron interaction),
- gamma rays (originates in nuclear gamma decay),
- annihilation radiation (positron annihilation).

If photons penetrate an absorbing medium, they may interact with the atoms of the absorbing material, with atomic nuclei or with orbital electrons. Each interaction is described by the probability or cross section which depends on the energy hν of the photon and on the atomic number Z of the attenuating material.

Direct photon-nucleus interactions lead to photodisintegration but photon interaction with an electrostatic field of the nucleus results in pair production. Thomson scattering and Compton scattering are present when photon interacts with loosely bound orbital (free) electron ($E_B << h\nu$), but the interaction between photon and tightly bound orbital electron ($E_B \leq h\nu$) is described by photoelectric effect and Rayleigh scattering [18].

During the interaction the photon may completely disappear (photoelectric effect, pair production, triplet production) or it may be scattered coherently (Rayleigh scattering) or incoherently (Compton scattering). Light charged particles (electrons, positrons) that might be produced in the absorbing medium through photon interactions behave in the way, as discussed in this chapter. A summary of photon interactions with matter is shown in Fig.9.

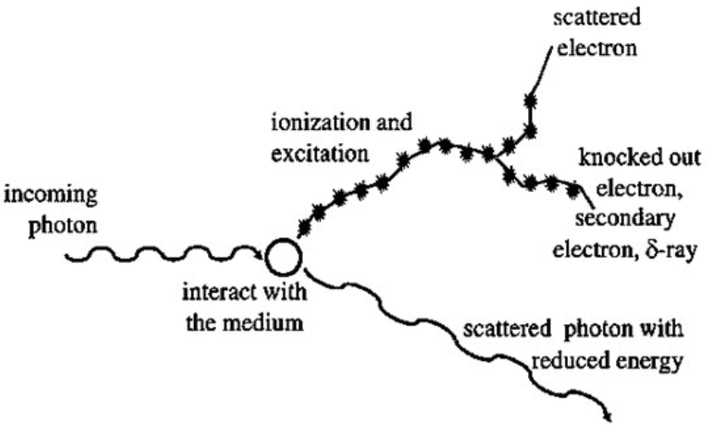

Fig.9. Schematic presentation of photon interaction processes with matter.

Photon beam is attenuated, when travelling through matter. The linear attenuation coefficient, μ, is the most important parameter used for characterization of X-ray or gamma-ray penetration into absorbing media. It is defined as the probability per unit path length that a photon will have an interaction with the absorber. It is related to the exponential decrease of the narrow monoenergetic photon beam intensity when travelling through material of the thickness x:

$$I(x) = I(0)e^{-\mu(h\nu,Z)x} \tag{19}$$

where I(0) is the original intensity of the unattenuated beam and μ(hν,Z) is the linear attenuation coefficient which depends on photon energy hν and attenuator atomic number Z.

Several specific thicknesses are used for characterization of monoenergetic photon beams in narrow beam geometry:

- Half-value layer (HVL or $x_{1/2}$) corresponds to the absorber thickness which attenuates the original beam intensity to 50%.
- Mean free path (MFP or $\bar{x}$) is the absorber thickness which attenuates the beam intensity to 1/e = 36.8%.
- Tenth-value layer (TVL or $x_{1/10}$) equals to the absorber thickness which attenuates the beam intensity to 10%.

In addition to the linear attenuation coefficient, μ (in cm^{-1}), other related attenuation coefficients and cross sections are used for describing photon beam attenuation: mass attenuation coefficient, μ_m (in cm^2/g), atomic cross section, ${}_a\mu$, and electronic cross section, ${}_e\mu$:

$$\mu_m = \frac{\mu}{\rho};\ \mu = \rho\mu_m = \frac{\rho N_A}{A}\,{}_a\mu = \frac{\rho N_A Z}{A}\,{}_e\mu \tag{20}$$

where ρ, Z, N_A and A are the density, atomic number, Avogadro's number and atomic mass number, respectively.

Two additional attenuation coefficients distinguish between energy transfer coefficient, μ_{tr}:

$$\mu_{tr} = \mu \frac{\overline{E}_{tr}}{h\nu} \tag{21}$$

and energy absorption coefficient, μ_{ab}:

$$\mu_{ab} = \mu \frac{\overline{E}_{ab}}{h\nu} \tag{22}$$

where $\overline{E}_{tr}$ is the average energy transferred to charged particles (electrons and positrons), and $\overline{E}_{ab}$ is the average energy deposited by charged particles in the attenuator.

Both coefficients are related through radiative fraction g as follows:

$$\mu_{ab} = \mu_{tr}(1 - g) \tag{23}$$

Usually mass attenuation coefficients, μ_m, obtained by dividing the linear attenuation coefficient by the mass density of absorber material, are used to describe photon interaction processes.

Photoelectric effect, Compton scattering, pair production (including triplet production) and photonuclear reactions are the most important photon interaction processes in materials.

In the photoelectric effect (Fig.10A) photon interacts with a tightly bound electron of absorber (from inner shells of atom mainly) and disappears, while the orbital electron is ejected from the atom as a photoelectron with a kinetic energy $E_K = h\nu - E_B$ ($h\nu$ – the incident photon energy, E_B – the binding energy of electron). Characteristic X-rays and/or Auger electrons might be also produced.

The average energy transferred from a photon of energy $h\nu > (E_B)_K$ to electrons $(\overline{E}_K)_{tr}^{PE}$ is given as:

$$(\overline{E}_K)_{tr}^{PE} = h\nu - P_K\omega_K(E_B)_K \tag{24}$$

where: $(E_B)_K$ – the binding energy of the K-shell electron (photoelectron); P_K – the fraction of all photoelectric interactions in the K shell, as compared to the total number of photoelectric events in the whole atom; ω_K – the fluorescent yield for the K shell which is defined as the number of photons emitted per vacancy in a given atomic shell. The same evaluation mechanism is valid for L-shell electrons (Fig.10B), if the incident photon energies range from $(E_B)_L < h\nu < (E_B)_K$. The fraction of Auger electrons equals to: $1 - \omega$.

The atomic attenuation coefficient, $_a\tau$, for photoelectric effect is proportional to $Z^4/(h\nu)^3$, while the mass attenuation coefficient, τ_m, for photoelectric effect is proportional to $Z^3/(h\nu)^3$, where Z is the atomic number of absorber.

In the Compton effect (incoherent scattering) (Fig.11) a photon with energy $h\nu$ interacts with loosely bound electron (from outer shells of atom). Part of the incident photon energy is transferred to a "free" orbital electron which is emitted from the atom as the Compton (recoil) electron under the angle φ. The photon is scattered through a scattering angle θ and its energy $h\nu'$ is lower

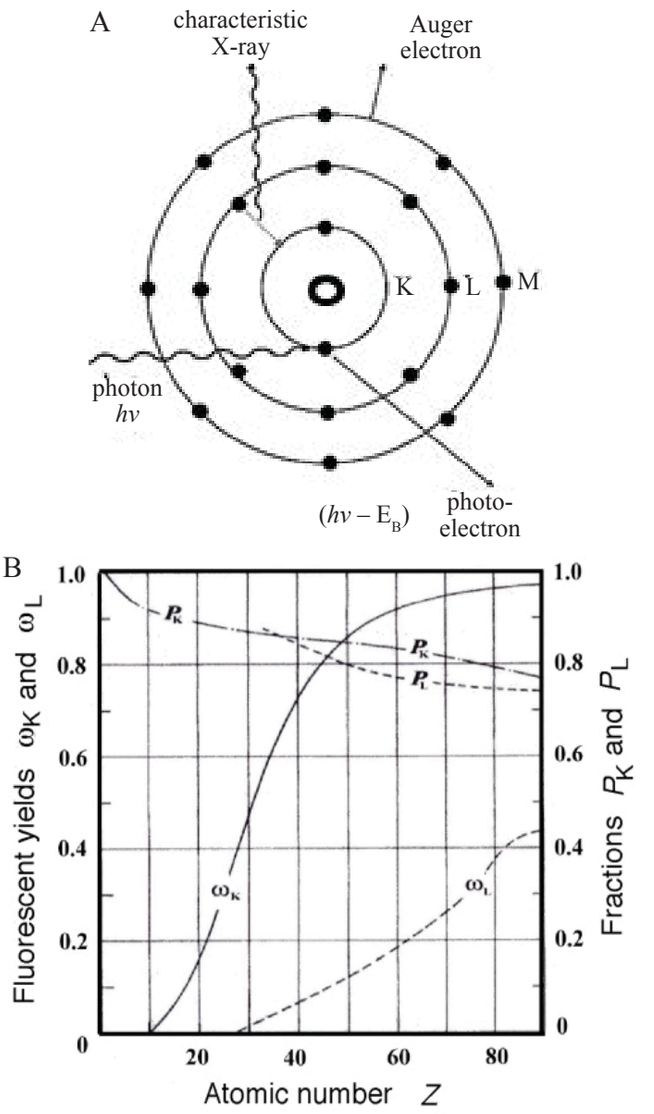

Fig.10. A – Schematic presentation of photoeffect; B – X-shell related fluorescence yields ω_X and P_X fractions against the atomic number of absorber. (Adapted from Ref. [15]).

than the incident photon energy hν resulting in the photon wavelength change after interaction:

$$\Delta\lambda = \lambda_C(1 - \cos\theta) \tag{25}$$

with $\lambda_C = 0.024$ Å as the Compton wavelength of the electron.

Taking into account energy and momentum conservation in the Compton process the scattered photon energy hν' and the kinetic energy of Compton electron E_K are given as follows:

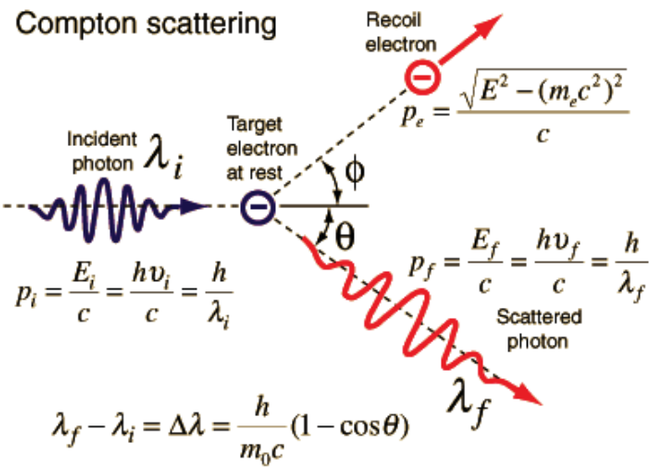

Fig.11. Schematic diagram of Compton scattering. (Adapted from Ref. [19]).

$$\nu' = h\nu \frac{1}{1 + \frac{h\nu}{m_e c^2}(1 - \cos\theta)}, \quad E_K = h\nu \frac{\frac{h\nu}{m_e c^2}(1 - \cos\theta)}{1 + \frac{h\nu}{m_e c^2}(1 - \cos\theta)} \tag{26}$$

where m_e is the rest mass of electron.

Maximum and mean fractions of incident photon energy transferred to a Compton recoil electron, $(\overline{E}_K)_{tr}^{CE} = (\overline{E}_K)$, and to scattered photon are presented in Fig.12. The atomic Compton attenuation coefficient, ${}_a\sigma_C$, depends linearly on

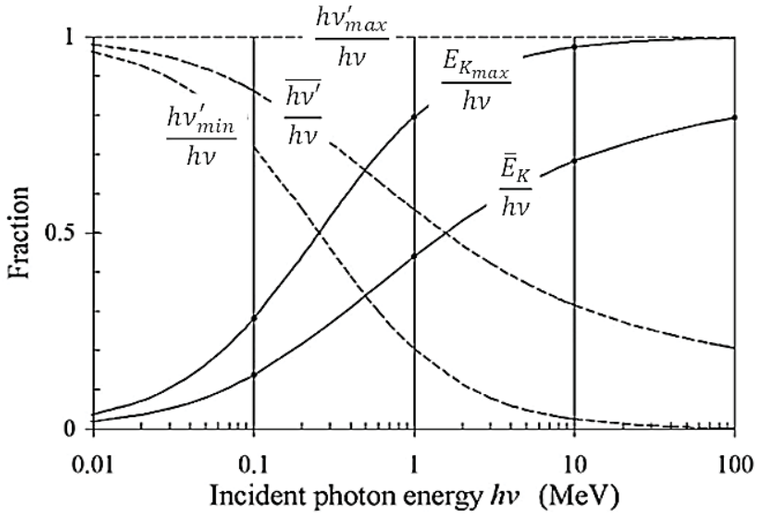

Fig.12. Fractions of incident photon energy transferred to a recoil electron, E_K, and to scattered photon, hν', during Compton process. (Data are obtained from Ref. [19]).

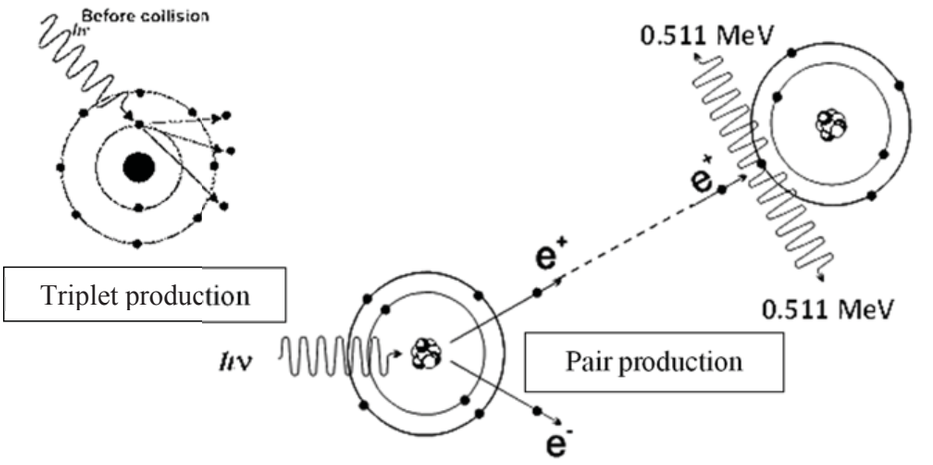

Fig.13. A scheme for pair/triplet production. (Adapted from Ref. [9]).

the atomic number Z of absorber material, while ${}_e\sigma_C$ and $(\sigma_C)_m$ – electronic and mass Compton attenuation coefficients, respectively, are independent of Z.

In pair production the photon disappears and the electron-positron pair with a combined energy $(\overline{E}_K)_{tr}^{PP} = h\nu - 2m_ec^2$ is produced in the nuclear Coulomb field [7]. Since this is an energy to mass conversion process, pair production has an energy threshold of $2m_ec^2 = 1.02$ MeV. The process is followed by positron annihilation with a "free" and stationary electron, producing two annihilation quanta, most commonly with energies of 0.511 MeV each and emitted at 180° from each other to satisfy the conservation of charge, momentum and energy (Fig.13). When pair production occurs in the field of an orbital electron, triplet (an electron-positron pair and the orbital electron) production is possible. The threshold for this effect is $4m_ec^2$. The atomic attenuation coefficient for pair production, ${}_a\kappa$, and the mass attenuation coefficient for pair production, κ_m, vary approximately as Z^2 and Z, respectively. The attenuation coefficient for pair production exceeds significantly the attenuation coefficient for triplet production at same photon energy and atomic number of absorber.

Photonuclear reactions (photodisintegration reactions) occur when a high energy photon is absorbed by the nucleus of an atom resulting in emission of neutron ((x, n) reaction) or proton ((x, p) reaction) and transformation of the nucleus into a radioactive reaction product. The threshold for a particular photonuclear reaction depends on the reaction type and nucleus and is of the order of 10 MeV for most nuclei. Photodisintegration is responsible for the nucleosynthesis of at least some heavy, proton rich elements, but the probability for photonuclear reactions is much smaller than that for other photon atomic interactions.

The probability for a photon to undergo any one of various interaction processes depends on the energy hν of the photon and on the atomic number Z

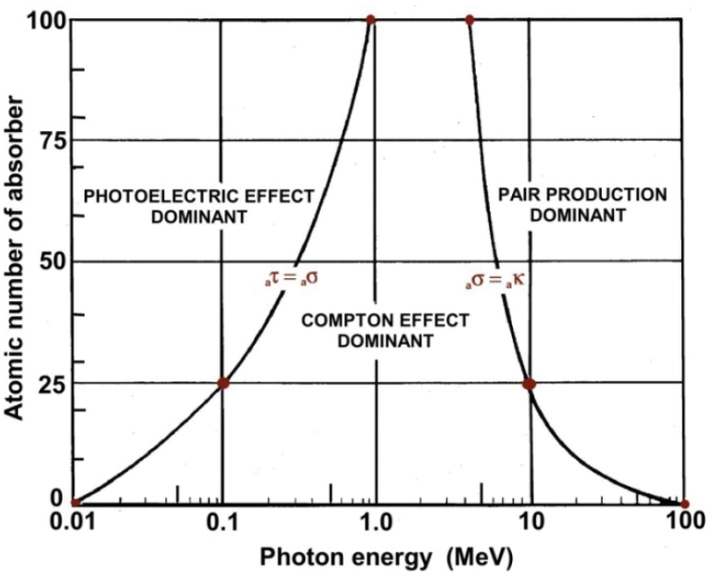

Fig.14. Regions of relative predominance of the three main forms of photon interaction with matter. (Adapted from Ref. [14]).

of the attenuating material. In general the regions of relative predominance of the most important effects are known, as it is shown in Fig.14.

3.2. PHOTON ATTENUATION IN MATTER

Earlier in this chapter it was noted that mass attenuation coefficient, μ_m, is the main parameter used for the characterization of photons attenuation in matter. This is defined as a sum of mass attenuation coefficients for individual photon interaction events (Eq. (7)). The same is applicable for energy transfer coefficient, μ_{tr} (Eq. (28)).

$$\mu_m = \frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma_R}{\rho} + \frac{\sigma_C}{\rho} + \frac{\kappa}{\rho} \tag{27}$$

$$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho}\left(\tau\frac{h\nu - P_K\omega_K E_B(K)}{h\nu} + \sigma_C\frac{(\bar{E}_K)_C}{h\nu} + \kappa\frac{h\nu - 2m_e c^2}{h\nu}\right) \tag{28}$$

$$\frac{\mu_{ab}}{\rho} = \frac{\mu_{tr}}{\rho}(1-g) \tag{29}$$

where: τ, σ_R, σ_C and κ – attenuation coefficients related to photoelectric effect, Rayleigh scattering, Compton scattering and pair production, respectively; $(\bar{E}_K)_{tr}^{CE}$ – the averaged energy transferred to charged particles (electrons and

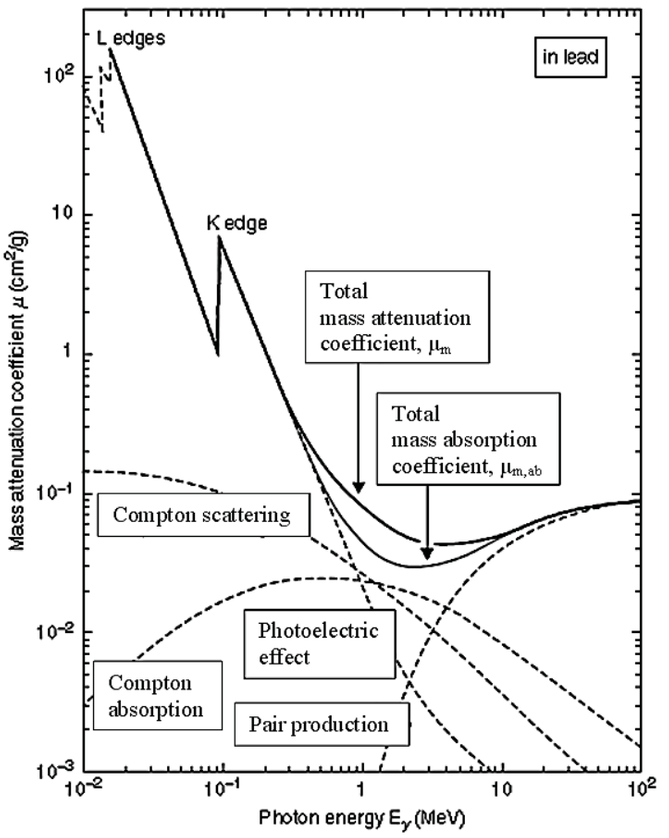

Fig.15. Mass attenuation coefficients in lead (Pb). (Data are obtained from Ref. [19]).

positrons) due to Compton effect; $E_B(K)$ – the binding energy of the K-shell orbital electron; P_K – the fraction of all photoelectric effect interaction occurring in the K shell; ω_K – the fluorescent yield of the K shell.
Mass attenuation coefficients in Pb with indicated K and L absorption edges are presented in Fig.15.
It is to notice, that the mass attenuation coefficient, corresponding to Rayleigh scattering should be also included, when calculating total mass attenuation coefficient. However Rayleigh scattering is present at low energies only; no energy transfer occurs and therefore Rayleigh scattering contributes neither to energy transfer nor to energy absorption coefficient.

3.3. PHOTON PENETRATION

Interaction processes of neutral particles (photons, neutrons) with matter are different from those of electrons or ions. Travelling through matter, neutral

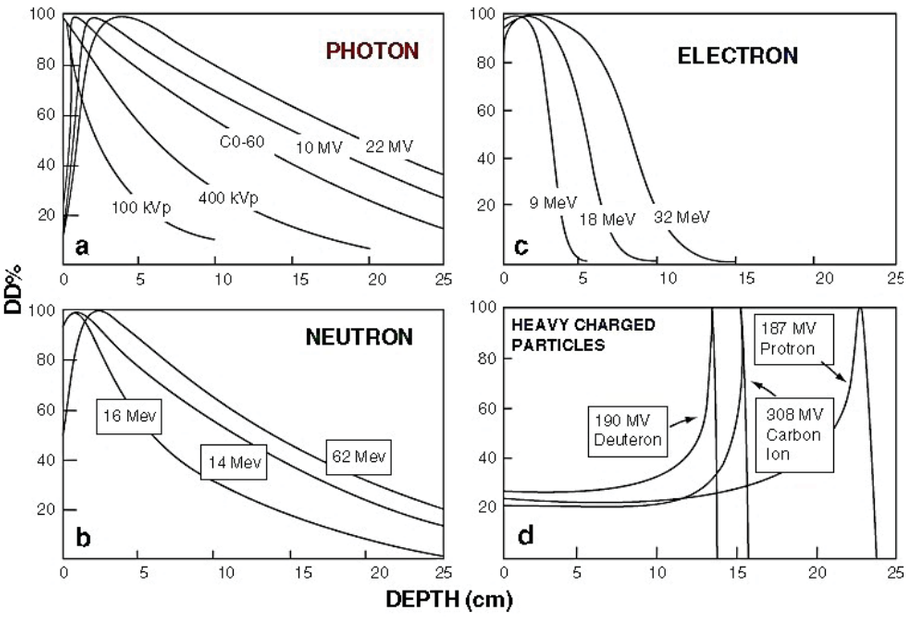

Fig.16. Typical depth-dose distribution curves for different particles with indicated penetration ranges [21].

particles are not effected by atomic Coulomb forces. Photons, representing deeply penetrating radiation, transfer their energy to the irradiated material when being attenuated in it. Photon penetration depth is limited by attenuating properties of the material and depends on the initial energy of photons. The main result of each interaction is the amount of energy imparted by ionizing radiation to matter of mass, m, in a finite volume, which is expressed as an absorbed dose, D [20]:

$$D = \frac{d\bar{\varepsilon}}{dm} \tag{30}$$

Typical dose-depth distribution curves for different energetic particles are provided in Fig.16.

Useful and more detailed information on radiation interaction with matter can be found in Refs. [22-24].

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