Interaction of Radiation with Matter

The detection, characterization and effects of radiation are almost entirely dependent upon their interaction with matter.

Types of radiation are direct ionizing radiation and indirect ionizing radiation. The flows of charged particles, such as alpha particles, beta particles, electrons, are phenomena of direct ionizing radiation, because though coulomb interaction with matter it directly causes ionization and excitation of atoms. Indirect ionizing radiation (neutrons, γ-quantums) is radiation of particles or photons, which have no charge and during interaction with matter can transfer energy to charged particles, nuclei and atom electrons due to electromagnetic or nuclear interaction.

Interaction of ionizing Radiation with Matter

α

bremsstrahlung

charged particles interact strongly and ionize directly

β

δ-Electron

γ

n

Recoil Proton

n capture photon

neutral particles interact less, ionize indirectly and penetrate farther
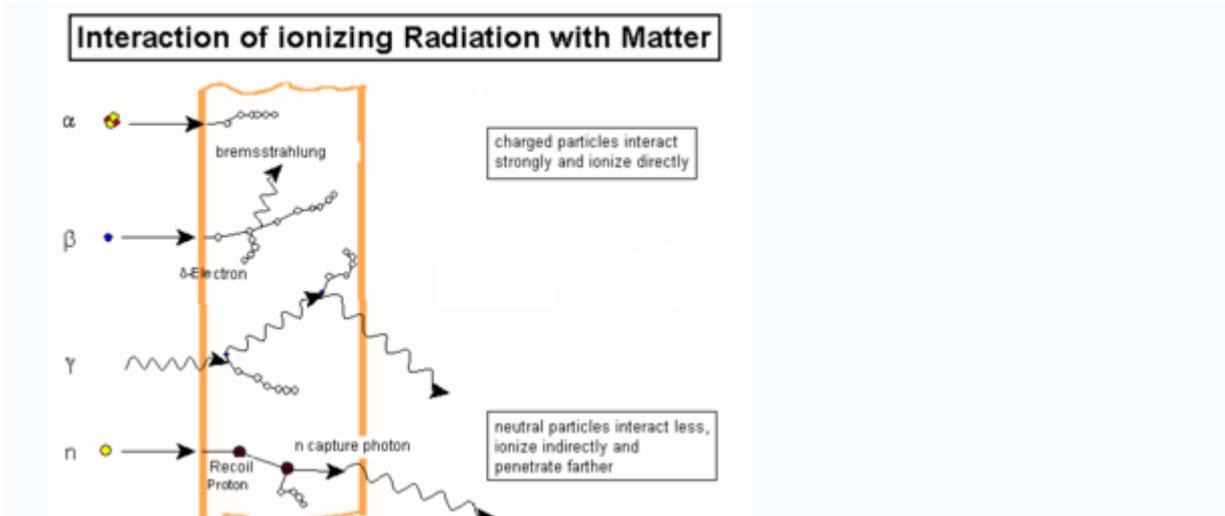
1. Alpha particles

Because alpha particles are comparatively heavy and have a charge, they react strongly with matter, producing large numbers of ions per unit length of their path. As a result, they are not very penetrating. For example, 5 MeV alpha particles will only travel about 3.6 cm in air and will not penetrate an ordinary piece of paper. For the other materials the average travel distance with respect to air is approximately inversely proportional to the respective densities of each material. 5 MeV alpha particles will only travel about 4 μm in mammal tissue.

Alpha particles can interact with either nuclei or orbital electrons in any absorbing medium such as air, water, tissue or metal. An alpha passing in the vicinity of nucleus may be deflected with no change in energy (Rutherford scattering), deflected with small change in energy or absorbed by nucleus, causing nuclear transformation (this process is negligible for alphas).

The most probable process involved in the absorption of alphas, however, are ionization and excitation of orbital electrons. Ionization occurs whenever the alpha particle is sufficiently close to electron to pull it out from orbit though coulomb attraction. Each time this occurs, the alpha loses kinetic energy and is thus slowed. The alpha also loses kinetic energy by exciting orbital electrons with interactions that are insufficient to cause ionization. As it becomes slowed, the alpha has tendency to cause ionization at an increasing rate. As the alpha nears to the end of its track, its rate of ionization peaks and within very short distance, it stops, collects two electrons and becomes helium atom.

Since alphas are low in penetration ability, they themselves are usually not hazardous for external exposure, unless the alpha-emitting nuclide is deposited to organism. When internally deposited, alpha particles are often more damaging than most other types of particles because comparatively large amounts of energy are deposited within a very small volume of tissue.

2. Beta particles

Beta particles can interact with electrons as well as nuclei in the medium through which they are travelling. Beta particles passing near nucleus will be deflected by the coulomb forces and losses of the beta particles kinetic energy may or may not (Rutherford scattering) occur.

The interactions of beta particles with orbital electrons are most important. Coulomb repulsion between beta particles and electrons frequently results in ionization. In the ionization process, the beta particles lose an amount of energy equal to the kinetic energy of the electron plus the energy used to free it from the atom. A beta particle may produce 50 to 150 ion pairs per centimeter of air before its kinetic energy is completely dissipated. The characteristic X-rays are emitted, when the vacant internal electron orbits are refilled with other electrons. Beta particles also cause excitation of external orbital electrons, which in turn leads to the emission of ultraviolet photons.

The ultimate fate of a beta particle depends upon its charge. A negatively charged beta particle, after its kinetic energy has been spent, either combines with a positively charged ion, or becomes a "free electron". Positrons, however, have a different fate. In spite of the fact that they dissipate their kinetic energy just like beta particles through ionization and excitation, they cannot exist at rest in the vicinity of the electrons. When a positron has been slowed sufficiently, it will be attracted to the opposite charge of an electron. When the electron and positron collide, they are both annihilated and an amount of energy equal to the sum of the particle masses is released in the form of two photons. These photons are referred to as "annihilation radiation". Both annihilation photons carry energy of 0.512 MeV, which is equivalent to the rest mass of the electron or the positron. Because of this phenomenon, 0.512 MeV photons often provide a convenient means for measurement of positron-emitting radionuclides.

Like alpha particles, betas have a characteristic average traveling distance (range) through matter that is dependent upon their initial kinetic energy. Beta particle range may be expressed as distance traveled in a certain medium. For example, beta particle with energy about 2 MeV will travel up to 9 m in air and about 10 mm in water.

3. X- and Gamma Ray

The interaction of photons (γ-quantums) with matter involves several distinct processes. The relative importance and efficiency of each process is strongly dependent upon the energy of the photons and upon the density and atomic number of the absorbing medium. We shall first consider the general case of photon attenuation and then discuss some of the important processes separately.

Rayleigh Scattering
When a photon interacts with atom, it may or may not impart some energy to it. The photon may be deflected with no energy transfer. This process is called Rayleigh scattering and is most probable for very low-energy photons.

Compton Effect
The Compton effect is usually the predominant type of interaction for medium energy photons (0.3 to 3 MeV). In this process the photon interacts with an atomic electron sufficiently to eject it from orbit, the photon retains a portion of its original energy and continues moving in a new direction. Thus, the Compton effect has an absorption component and scattering component. The amount of energy lost by the photon can be related to the angle at which the scattered photon travels relative to the original direction of travel.

The scattered photon will interact again, but since its energy has decreased, it becomes more probable that it will enter into a photoelectric or Rayleigh interaction. The free electron produced by the Compton process may be quite energetic and behave like a beta particle of similar energy, producing secondary ionization and excitation before coming to rest.

Photoelectric Absorption
The most probable fate of a photon having energy slightly higher than the binding energy of atomic electrons is photoelectric absorption. In this process, the photon transfers all of its energy to the electron and its own existence terminates. The electron will escape its orbit with a kinetic energy equal to the difference between the photon energy and its own binding energy. Photoelectric absorption is most important for photons below 0.1 MeV if the absorbing medium is water or biological tissue. However, in high Z (atomic mass number) materials such as lead, this process is relatively important for photons up to about 1 MeV.

As with ionization produced by any process, secondary radiation are initiated, in this case, by the photoelectron which may have sufficient energy to produce additional ionization and excitation of orbital electrons. Also, filling of the electron vacancy left by the photoelectron results in characteristic X-rays.

Pair Production
Photons with energy greater than 1.024 MeV, under the influence of the electromagnetic field of a nucleus, may be converted into electron and positron. At least 1.024 MeV of photons energy are required for pair production, because the energy equivalent of the rest mass of the electron and positron is 0.51 MeV each. Pair production is not very probable, however, until the photon energy exceeds about 5 MeV. The available kinetic energy to be shared by the electron and the positron is the photon energy minus 1.02 MeV, or that energy needed to create the pair. The probability of pair production increases with Z of the absorber and with the photon energy.

Relative Importance of Photon Attenuation Processes
The various processes of photon attenuation can now be considered by examining the effects of photon energy and atomic mass number of the absorber on their relative importance (Figure 1). The lines in the figure indicate the values of the photon energy and Z where the probabilities of occurrence of two major processes are equal.
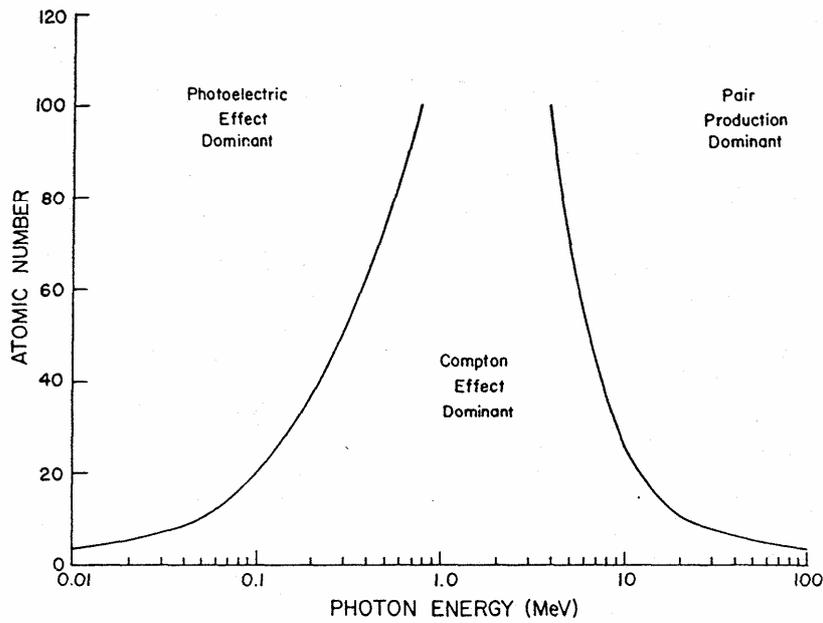
Figure 1.   Effects of photon energy and atomic mass number of absorbing medium on dominant type of photon attenuation processes.

4. Neutrons

The neutrons interact with atoms due to electromagnetic and nuclear forces. The neutrons affect living matter by the process of moderation. A high-energy neutron encountering biological material is apt to collide with a proton with sufficient force to dislodge the proton from the molecule, which held it. The proton (normally called the "recoil proton") may then have sufficient energy to travel some distance in the tissue causing secondary damage through ionization and excitation of molecules along its path.