

Part B

An Introduction to the Interaction of Radiation with Matter.

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We will consider two major types of radiation: charged particles and neutral particles. Charged particles will be divided into two groups. The heavy charged particles and light charged particles. Heavy charged particles are those that have a mass much greater than the mass of electron. Examples are protons that have a mass of about 2000 times that of an electron, alpha particles with a mass of about 8000 times the electron mass, & fission fragments that are even heavier. The light charged particles are the electrons and their anti-matter particles positrons. The second major group, neutral particles, will consist of, again, two subgroups, photons and neutrons. The photons we will consider will be X rays, gamma rays, annihilation radiation, & Bremsstrahlung radiation. Neutrons will be discussed when we discuss neutron detectors.

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We will start our discussion with the interaction of charged particles with matter. We will discuss three possible mechanisms for the loss of energy. First, we will talk about energy loss by interactions with atomic electrons, second energy loss by Bremsstrahlung radiation, and third energy loss by collisions with atomic nuclei. In the first case, the charged particle can transfer both energy and momentum through the electromagnetic force to atomic electrons. The electrons are then either knocked out of the atom or raised to a higher energy level resulting in either an ionized or an excited atom. In the second case, that is, energy loss by Bremsstrahlung radiation, the charged particle usually a light charged particle, such as an electron, interacts in the electric field of the nucleus. The path of the charged particle is changed, and in the process, radiation may be emitted. The radiation photons are called Bremsstrahlung radiation. The energy of the photons may range from zero energy to the full kinetic energy of the charged particle. In the third case, the energy loss by collisions with an atomic nucleus, heavy charged particles, after they have lost most of their kinetic energy through interactions with atomic electrons, may interact with one of the nuclei in the target. In this case, a large amount of momentum and energy may be transferred resulting in a large angle scattering of the charged particle.

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The Interactions of Heavy Charged Particles.

Since atoms consists of very small nuclei surrounded by electrons, when a charged particle travels through matter, it sees mostly electrons. The mass of the alpha particle is 7294 times larger than the mass of an electron, so when the alpha particle encounters an electron, it can transfer both energy and momentum

to the electron, either knocking the electron out of the atom or raising it to a higher energy level. However, because of the great difference in mass between the two particles, the energy and momentum lost is relatively small and the alpha particle will continue on its original path. After many such interactions, when the alpha particle has lost most of its energy, it is possible that it will interact with a nucleus. This is an interaction between particles of comparable mass, so that the alpha particle may undergo a large momentum transfer and change directions.

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The range of an alpha particle in air can be approximated by the following equation:

$$\bar{R}(\text{cm of air}) = 0.309 T_0^{3/2}$$

where T_0 is the initial energy of the alpha particle in MeV. A typical alpha particle has an energy of about 5 ± 1 MeV. The range of a 5 MeV alpha particle in air at atmospheric pressure is about 3.5 cm. In a solid or more dense material, the range would be much shorter. In fact, a typical 5 MeV alpha particle will be stopped by a single sheet of paper.

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The Interactions of Electrons with Matter

Beta particles, both electrons and positrons, also lose energy primarily by interactions with atomic electrons. Again, the interactions will either knock the atomic electrons out of the atom or raise them to a higher energy level. However, in this case the incoming particles and the atomic electrons have the same mass which means that a large fraction of the energy and momentum can be lost in a single collision resulting in the particle undergoing a large angle scattering. The beta particles also travel much faster than the heavy charged particles and go much greater distances between collisions. Thus the range of the beta particles is much longer than the range of the heavy charged particles.

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Bremsstrahlung Interactions

In addition to energy losses by collisions, electrons and positrons can also lose energy by bremsstrahlung radiation. When the electron passes close to a nucleus, the strong Coulomb interaction will cause the electron to change direction. In the process, the electron may radiate energy in the form of photons, called bremsstrahlung radiation. The energy of the bremsstrahlung photons can range from 0 to the full kinetic energy of the electron.

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The maximum range of an electron or positron in matter can be approximated by the equation

$$R_o \text{ (gm/cm}^2\text{)} = 0.52 T \text{ (MeV)} - 0.09$$

Dividing the range, R_o , by the density, ρ (gm/cm³) will give the range in cm for almost any material. For an electron with a typical energy of 1 MeV, the range in air is about 3.3 meters. The range in Aluminum, where the density is 2.7 (gm/cm³), the range would be something less than 2 mm.

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Positron Annihilation

Positrons are the anti-particles of electrons. Energetic positrons lose their kinetic energy in the same way that electrons lose energy, that is, by collisions with atomic electrons and bremsstrahlung radiation. After the positrons have lost most of their energy, they will find an electron and the two particles will annihilate each other, with both particles disappearing and their combined rest mass energy of 1.022 MeV forming two photons, each with an energy of one rest mass or 0.511 MeV. However, since both the electron and positron may have small amounts of kinetic energy, the energy of the two outgoing photons will be slightly different than the 0.511 MeV.

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Photon Interactions

Theoretically, there are 12 possible photon interactions, but of the 12 possible interactions, the three most probable in the energy range from 0 to 10 MeV are the

1. Photoelectric Effect,
2. Compton Scattering, and
3. Pair Production.

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Photoelectric Effect

In photoelectric events, the incoming photon interacts with the atom as a whole and the energy of the photon is transferred to one of the atomic electrons (usually one of the most tightly bound or k shell electrons). The energy of the outgoing electron is then given by: $T_e = E_\gamma - B_e$. The net result is an energetic electron and an ionized atom or ion. Within the ionized atom, however, one of the other electrons from a higher energy level will then drop down to fill the vacancy and the atom will emit an x-ray. This process will continue until finally the ion picks up a free electron and becomes a neutral atom again.

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Sometimes rather than emitting an x-ray, the energy will be transferred to one of the other atomic electrons and the electron is ejected from the atom resulting in a doubly ionized atom. The ejected electron is monoenergetic and is called an Auger electron. These processes are shown on the following slide.

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Photoelectric Interactions

The incoming photon interacts with the atom and the energy is transferred to one of the atomic electrons, usually a K shell electron as shown in step 1. The electron is then ejected from the atom. An electron from one of the higher energy levels, usually the L shell, will then drop down to the K shell, emitting an X ray as shown in step 2. Sometimes, rather than emitting an X ray, the energy is transferred to another of the atomic electrons and the electron, called an Auger electron is ejected. This is shown in step 3.

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Compton Scattering

In Compton scattering, the incoming photon interacts with one of the outer shell electrons. Because the electron is only weakly bound to the nucleus, the photon can not transfer all of its energy and momentum to the electron, so a secondary or scattered photon is emitted as well as an energetic electron in the process. Technically, the secondary photon is not a scattered photon but a new photon created in the process with an energy E'_γ . The energy of the incoming gamma ray is then shared between the scattered gamma ray and the ejected electron.

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The amount of energy transferred to the electron depends on the angle at which the scattered or secondary photon is emitted. If the scattered photon is emitted at an angle of 180° from the path of the incoming photon, then the maximum energy is transferred to the electron. For a 1 MeV photon, the minimum energy that can be transferred to the electron is zero and the maximum energy is 0.796 MeV. Compton Scattering is shown in the next slide.

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Compton Scattering

The incoming photon interacts with one of the outer shell electrons, transferring part of its energy to the electron, knocking the electron out of the atom. In the process, a secondary photon is also created. The total energy of the incoming photon is shared between the secondary photon and the Compton electron.

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The energy distribution of electrons from Compton scattering will range from 0 energy to $t_{\max}$, as shown in the following diagram. $T_{\max}$ corresponds to an incoming photon transferring the maximum energy and the secondary photon going in a direction of 180° to the incoming photon. The energy of the outgoing photon is then the difference between the incoming energy, E_γ , and the energy of the outgoing electron.

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Pair Production

The third photon interaction is pair production. In this type of event, the photon interacts in the electromagnetic field of the nucleus, producing an electron and positron pair. The presence of a third body, such as the nucleus, is required to conserve momentum in the reaction. In order to create the electron/positron pair, the energy of the photon must be equal to or greater than 1.022 MeV, the mass of the two particles. Any excess energy is shared as kinetic energy between the electron and positron. Pair production is also possible in the electric field of one of the atomic electrons. However, in this case the minimum energy required is 2.044 MeV and the reaction also has a much smaller probability of happening. A diagram of pair production is shown in the following slide.

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Pair Production

In this slide, the incoming photon interacts in the field of the nucleus, creating an electron – positron pair. This requires 1.022 MeV of energy. Any additional energy appears as kinetic energy of the electron and positron.

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Probability of Photon Interactions

Unlike charged particles that undergo many interactions while giving up their energy, a photon interacts only once and disappears. In some cases such as Compton scattering, a secondary photon is created in the event, but the primary photon has disappeared. Therefore, one does not consider the “range” of photons, but rather what is the probability that a photon can pass through a thickness of material, x , without interacting. The probability of an interaction and the type of interaction depends on the energy of the photon, the charge of the target nuclei Z , the density of the target N , that is the number of nuclei per unit volume and NZ , the number of electrons per unit volume).

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The probability of a photoelectric interaction varies approximately as N , Z^5 , and $E_\gamma^{-7/2}$. The probability for Compton scattering varies approximately as N , Z , and $1/E_\gamma$. The probability for pair production is zero below $E_\gamma = 1.022$ MeV. Above this energy, the probability varies as N , Z^2 , and the log of E_γ . The total probability is the sum of the probabilities for each of the interactions. At low energies, the photoelectric process is the most likely. At energies between 0.5 and 2 or 3 MeV, Compton scattering is the most probable interaction. And, at energies above 3 MeV, pair production becomes the dominant interaction, especially in high Z targets.

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The linear attenuation coefficient or probability per unit length, μ , is the sum of the probabilities per unit length for each of the three types of interactions. The

mass attenuation coefficient, μ_o , is defined as the linear attenuation coefficient divided by the density, ρ .

The mass attenuation coefficients as a function of energy for air, aluminum, and lead are shown in the next three slides.

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On this plot for interactions in air, the horizontal axis is the energy of the incoming photon and the vertical axis is the mass attenuation coefficient. Note that at low energies up to about 0.5 MeV, the photoelectric interactions dominate the total probability while at the high energies, about 2 or 3 MeV, the pair production probability dominates the interactions. In the middle region, the Compton scattering is the most likely event.

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This plot shows the mass attenuation coefficients for aluminum.

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This is a plot of the mass attenuation coefficients for lead. Note that with $Z = 82$ for lead, that pair production begins to dominate the interaction probability at energies above 3 MeV.

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The probability of a photon passing through a target of thickness, x , is given by the equation

$$N(x) = N_0 e^{-\mu x}$$

where N_0 is the number of incoming photons. Therefore, the ratio of $N(x) / N_0$ gives the probability that a photon can pass through a target of thickness x without an interaction.

Since this is an exponential relationship, one can consider the half-thickness, or the thickness of material required to stop one half of the photons. For a 1 MeV photon, the half thickness of lead or the thickness required to stop one half of the photons is 0.95 cm. For air, the half thickness is about 83 meters and for aluminum, about 3.7 cm.

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End of Part B