Nuclear Physics

Particle Behavior / Gamma Interactions

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INTRODUCTION

The various types of radiation: alpha particles, beta particles, gamma rays, neutrons, etc., produced by nuclear radioactive decay, or whatever source, are generally thought of as moving through empty space. However, in all practical situations radiation must encounter material substances, solids, liquids and gases. The interaction of the various types of radiation with matter is of basic interest for understanding the behavior of the radiation itself and for understanding radiation induced effects on materials. In the most general terms, the various radiation particles (including photons) transfer some of their kinetic energy to the material through which they are passing. This transferred energy causes changes in the observable properties of the medium, which is of interest for itself, but also signifies the presence of the particles and provides the basis for "particle detection." It is of great importance to understand in detail just how such energy transfers, from rapidly moving particles to the electrons and nuclei of matter, occur.

One factor, which is known to be important in such energy transfers to material electrons and nuclei, is the amount of time a moving particle (radiation particle) spends in the vicinity of a given atom of matter. Generally speaking, the longer the time spent the more likely is a significant energy transfer.
OBJECTIVES

TERMINAL OBJECTIVE
The Contractor Health Physics Technician will describe the characteristics of each type of radiation. The Contractor Health Physics Technician will also describe the concepts of range, specific ionization, and radiological thickness.

ENABLING OBJECTIVES
Upon completion of this lesson, the Contractor Health Physics Technician will be able to:

1. Define ionization and ion pairs.

2. Describe the various types of radiation, their structure, source, approximate range in air, energy levels, charge, and method of interaction/attenuation.

3. Recognize the characteristics of pair production, Compton Scatter, and photoelectric absorption.
1.0 IONIZATION

Atoms are mostly empty space. Thus, when passing through matter, the various particles of radiation normally encounter only the electron clouds of atoms. Charged particles such as alphas, betas, or protons interact with the electron clouds and can be expected to transfer energy to almost every atom transversed. Conversely, neutrons have no charge and thus can pass through a large number of atoms (unaffected by electron clouds) before having a significant encounter with a nucleus.

When a high energy (high speed) charged particle passes through (or near) an atom, one or more outer shell electrons are ejected. The entity left behind, an atom with less electrons than is required for neutrality, is called an "ion". The general process of producing ions by the passage of high energy particles is called "ionization". When an atom is ionized, the resultant products are a positive ion and a free electron referred to as an "ion pair". The number of ion pairs produced by a particle in a unit length of travel is called the "specific ionization". The specific ionization of a given particle varies with the material in which the ionization takes place and with particle energy. Specific ionization is measured in units of ion pairs/cm.

2.0 ALPHA PARTICLE INTERACTIONS

Alpha particles are the most ionizing form of radiation. That is, the specific ionization for alphas is very large. This is due to the fact that the alpha particle has a +2 charge, a large mass and thus a small velocity. An alpha particle forms ion pair when its electric field "pulls" electrons out of an atom it passes. In this process energy is transferred from the alpha particle; an alpha particle loses about 35.5 eV for each ion pair formed. To ionize a hydrogen atom requires 13.6 eV. The excess energy lost by the alpha is given to the electron as kinetic energy. Therefore, in addition to being freed, an electron is set into motion when an ion pair is formed.

It is also possible for an alpha particle to lose energy without causing ionization. Often electrons will only receive enough energy from a passing alpha to jump to a higher energy state, without being freed. This is most probable when the alpha is moving rapidly. The faster that the alpha moves, the less time spent in the vicinity of a particular atom. As a result, the specific ionization of alpha particles decreases at higher energies, as shown in Figure NP-4-1.

NP-4-1 Specific Ionization of Alpha Particles
It follows then that as a high energy alpha particle passes through a material its specific ionization will increase as velocity decreases. It is continually slowing down which increases its ionizing ability. This concept is illustrated in Figure NP-4-2.

NP-4-2 Specific Ionization versus Range for $\alpha$ Particles

3.0 BETA INTERACTIONS

Beta particles are capable of ionization in much the same manner as alpha particles. However, the specific ionization of beta particles is much lower than that of alpha particles (about 1/100th). This is due to the fact that betas have less charge and much less mass. Because it has less mass, a beta particle travels at a higher velocity than an alpha with the same energy. Therefore, to ionize an atom, a beta particle will have to come much closer to the atom than an alpha since its electric field is weaker and its velocity is greater.

Figure NP-4-3 plots specific ionization versus beta energy. Note that below 1 Mev specific ionization decreases with increasing energy, similar to alpha particles. With beta energies greater than 1 Mev, the specific ionization increases slowly with increasing beta energy. This may be explained by a distortion of the betas electric field at very high velocities (relativistic effect).

NP-4-3 Typical Plot of the Specific Ionization of $\beta$ Particles versus Energy
The electric field around a slow moving particle is symmetrical. When velocity is increased near the speed of light the field becomes strengthened so that the beta will interact with atoms that would have been unaffected by a slower moving beta.

Another form of beta interaction is called "bremsstrahlung," which is a German word meaning, "braking radiation". When a high energy beta particle passes close to a heavy nucleus it is deflected sharply by the strong electric field. When the beta particle is deflected (and thus slowed down) it emits electromagnetic energy in the form of X rays. The energy of the electromagnetic ray is found to be directly proportional to the beta energy and also proportional to the atomic weight of the nucleus. Figure NP-4-4 shows how ionization and bremsstrahlung processes contribute to beta energy loss at different energies.

The basic behavioral difference between alpha and beta particles is due to their masses. The more massive alpha particle "plows through" the electron clouds of material atoms, so that they essentially move along a straight path while losing their energy. The much lighter beta particles are deflected by each event and end up moving in a zig-zag path.

4.0 GAMMA INTERACTIONS

Because gamma rays (photons) have no charge and zero mass, it might be expected that they do not interact with matter. Although they have a much greater penetrating distance through material atoms than alpha or beta, they do interact. There are three processes through which gamma rays transfer their energy: the photoelectric effect, compton scattering, and pair production.
4.1 PHOTOELECTRIC EFFECT

In the photoelectric effect process, an incident photon imparts all of its energy on an orbital electron. This results in ionization of the atom and disappearance of the photon. The energy of the photon is used to free the electron and give it kinetic energy. The freed particle will undergo interactions as stated in Section 3.0. Figure NP-4-5 illustrates the photoelectric effect process.

The probability of photoelectric effect is greatest with low energy photons and high Z targets.

4.2 COMPTON SCATTERING

Like the photoelectric effect, the compton scattering process involves a photon imparting its energy on an orbital electron. In the case of compton scattering the electron only receives a portion of the photon's energy. The results are a freed electron and a photon with less energy (lower frequency). Figure NP-4-6 illustrates a compton scattering event.

The scattered photon will interact with another atom; it may even undergo a series of compton scatters leaving each site at a lower energy than before. The compton scattering process extends to higher energy photons than the photoelectric effect, and in general is independent of the target's atomic number.
4.3 PAIR PRODUCTION

The third photon interaction process, called pair production, is very unique in that "pure energy" in the form of a photon is transformed into 2 particles.

When a high energy photon passes near a nucleus, the incoming photon suddenly disappears and in its place appears 2 particles an electron and a positron. This process is simply a transformation of energy into mass in accordance with Einstein's equation $E = MC^2$. It follows that the incident photon's energy must be at least the mass equivalent of the electron and positron. The mass of an electron or positron is 0.00055 AMU, converted to energy (1 AMU = 931 Mev) it equals:

$$2(0.00055 \text{ AMU}) \times 931 \frac{\text{MeV}}{\text{AMU}} = 1.02 \text{ Mev}$$

The minimum energy photon in theory for pair production then is 1.02 Mev. However, it is highly unlikely that a 1.02 Mev photon will pair produce.

In general, this type of interaction is not observed for photons having energies less than about 2.5 Mev. The excess energy of the photon (above the 1.02 Mev required to create the electron positron pair) is shared by the two particles as kinetic energy. Figure NP-4-7 graphs photoelectric effect probability vs. energy.

NP-4-7 Dependence of Pair Production on Energy
Consider now the fate of the two particles formed from the photon. The electron will continuously lose energy through ionization and bremsstrahlung processes until it is slowed and captured as an orbital electron. The positron will also cause ionization and slow down; when it loses most of its energy, the coulombic forces of some electron will capture it. The electron and positron will annihilate forming 2 photons of .511 Mev each (the equivalent energy to the Annihilation mass of each particle).

Figure NP-4-8 illustrates the complete pair production process.

NP-4-8  Pair Production and Subsequent Positron

5.0  NEUTRON INTERACTIONS

Since neutrons are electrically neutral, the mechanisms previously discussed do not apply. Neutrons do not interact with electrons and thus pass through the principal volumes of many atoms without changing energy or direction. Neutrons must interact with the nucleus of an atom in order to lose their energy. Thus, neutrons represent a highly penetrating form of radiation in contrast to the short range behavior of charged particles. For example: the range of a 1 Mev alpha particle in aluminum is 0.0003 cm, whereas a 1 Mev neutron can be expected to travel freely through several centimeters of aluminum without interaction.

The actual interactions which neutrons are capable of are presented in the next lesson.
6.0 SUMMARY

The various types of radiation interact with matter differently. However, the end result is the same, ionization and excitation of the atoms within the material. Charged particles with high velocities tend to "pull" electrons out of their orbit, thus forming ion pairs.

Gamma rays interact with atoms through three processes: photoelectric effect, compton scattering and pair production. These processes also cause ionization of material atoms. Neutrons have no charge and rely on collisions with nuclei in order to lose energy.