INTERACTION OF NUCLEAR RADIATION WITH MATTER

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Contents

Summary

The interaction of radiation with matter is briefly reviewed. The concepts are restricted to the relatively low energy regime characteristic of nuclear emissions. In these conditions, atomic ionization plays a major role in explaining the energy- transfer mechanisms occurring during the passage of this type of radiation through mater. The basic theoretical formulas used in this field are given for the interaction of both, charged particles (heavy and electrons) as well as photons and neutrons. A brief description is also given about how to detect these radiation fields and quantity their effect on inert and living matter.

1. Introduction

Unstable nuclei can emit a variety of electrically charged and neutral, particles as well as electromagnetic radiation known as γ-rays (energetic photons). The best known particle emission modes are the α-decay, in which a helium nucleus is produced, and β-decay where an energetic electron e^-(or a position, e^+)and an anti-neutrino (or a neutrino) are created. However, sufficiently excited, or very unstable, nuclei are capable of other forms of particle, radiation, such as the direct emission of neutrons of protons. Low energy nuclei can also be produced as the result of nuclear decay and nuclear fission. All these emissions are generically referred to as *nuclear radiation*. Their interaction with matter may occur via the electromagnetic, the strong and /or the week nuclear forces. The gravitational force is insignificant at the nuclear level. Although neutrinos are important nuclear –decay residues, their interaction probability with matter is too small to be of practical interest. An important issue in studying the passage of energetic nuclear radiation through matter is in understanding the transfer of energy produced. Energy transfer mechanisms depend on a number of factors, such as the type of radiation and its energy, as well as the physical properties of the irradiated material. Electrically charged particles, and γ-rays, of nuclear origin interact with highest probability with atomic excitation and dissociation. On the other hand, neutrons interact almost exclusively with nuclei, what explains their characteristic penetrability. however , when they occur, nuclear interactions by neutrons, or other nuclear radiation, involve energy transfer mechanisms in which energetic charged particles and /or γ-rays are eventually produced as the result of nuclear decay. Hence, neutron reactions, as well as rare nuclear interactions by other radiation are, too, ultimately associated to atomic excitation and ionization. In many of those processes, secondary electrons are produced which spread the energy deposition away from the primary interaction region. Measuring the effects of radiation on matter and finding out the relationship between them and the energy lost by the original radiation is the basis of all nuclear detection methods. When dealing with leaving matter, the biological impacts of such phenomena are the subject of much concern and study.

2. Basic Concepts

The probability of a given interaction to occur is measured by the *cross section*. Consider a current I of particles incident on a thin slab of material , and let $dI_s(\theta)/d\Omega$ represent the fraction of those particles scattered at an angle θ(relative to the incident particle direction), within a solid angle $d\Omega$,then

$$\frac{d\sigma(\theta)}{d\Omega}=\frac{dI(\theta)/d\Omega}{I} \qquad (1)$$

defines the *differential* (scattering) *cross section* , and its solid –angle integral is the total (scattering) cross section σ .Both quantities are measured in units of area and in general , are functions of the incident kinetic energy E .

The cross section depends on the nature of the forces involved. An important example is that of Coulomb (electric) interactions between charged particles, given by the Rutherford formula:

$$\frac{d\sigma_R(\theta)}{d\Omega}=0.52\left(\frac{zZ}{\mu c^2\beta\sin^2\frac{\theta}{2}}\right)^2 \qquad (1)$$

where $\beta=v/c$ is the ratio of the incident particle speed v to speed of light c; z and Z are the atomic numbers of the scattered, and of the scattered, particles of masses m and M are respectively, and $\mu=mM/(m+M)$ is the system's reduced mass, given in

MeV/c^2.The $MeV-10^6 eV=1.602\times10^{-13}$ *Joules* is the standard nuclear energy unit. The units of σ_R are fm^2,where $fm=10^{-15}$m, is also a characteristic nuclear length.

When dealing with compound matter, mean cross sections, as well as other mean quantities, can be estimated using *Bragg's Rule* in which a weighted average is obtained using the mass fractions of each element in the medium. If a_i is the number of atoms of the *i*-th element in the molecule, the corresponding weight factor is:

$$\omega_i=\left(\frac{a_iA_i}{\mu c^2\beta\sin^2\frac{\theta}{2}}\right)^2 \qquad (2)$$

where A_i is the atomic number of the *i*-th element and $A_m=\sum a_iA_i$ is the mean molecular number.

The actual number of scattered particles at a given angle, and of a total number particles removed from the incident current depends on the number N of scattering centers (the scatters) thus, as a result of scattering ,the current of unscattered particles decreases as a function of the distance *x* travels across the material according to :

$$\frac{dI}{dx}=IN\sigma \qquad (4)$$

which results in the exponential attenuation law:

$$I(x)=I(0)e^{-\mu_{1x}} \qquad (3)$$

where $\mu_1=N\sigma=1/\lambda$ is known as the *linear attenuation* coefficient and λ as the *mean free path.*

To avoid reference to the physical state of a material, it is convenient to replace the distance *x* by the *mass thickness* $t=xp$,where *p* is the medium density. This leads to the concept of a mass attenuation coefficient $\mu_m=\mu 1/p$.

The kinematics of collisions between incident charged particles and medium constituents (electrons and nuclei) reveal that the largest energy transfers occur in collisions with atomic electrons because of their lower mass. Yet the energy gained by medium electrons is limited to

$$E_{\max}=\frac{2m_ec^2\beta^2\gamma^2}{1+2\gamma m_e/M+\left(m_e/M\right)^2} \qquad (4)$$

where $\gamma = \left(1-\beta^2\right)^{-\frac{1}{2}}$, is the Lorentz factor , measuring the importance of relativistic effects. For typical nuclear radiation, in the MeV energy range, γ takes the value of ≈ 1 (the minimum) for the most nuclear radiation, except electrons and positrons. The large mass-difference between nuclei and electrons, now seen as incident radiation, also imply that the latter undergo large deviations from the original direction (angular *straggling)* as well as an increasing spread from a mean energy (energy *straggling*). Both forms of straggling are smaller for heavy charged particles, allowing a fairly simplified description of the phenomenon. Because of this, it is convenient to deal separately with the energy loss mechanisms of these two types of particles.

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Arturo menchaca-Rocha is working is a Professor, Experimental Physics Department at Institute of Physics, Universidad Nacional Autonoma de Mexico, México, since 1985. He was an Associate Professor Experimental Physics Department, Institute of Physics, 1975-1985.
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