Chapter 2

Radiation Interactions

The operation of any radiation detector basically depends on the manner in which the radiation to be detected interacts with the material of the detector itself. An understanding of the response of a specific type of detector must therefore be based on a familiarity with the fundamental mechanisms by which radiations interact and lose their energy in matter. Many general reference works are available concerning this broad topic; the classic text by Evans,[1] to mention only one, has served as a standard reference for several decades.

To organize the discussions that follow, it is convenient to arrange the four major categories of radiations introduced in Chapter 1 into the following matrix:

Charged Particulate Radiations		**Uncharged Radiations**
Heavy charged particles (characteristic distance $\cong 10^{-5}$ m)	$\Leftarrow$	Neutrons (characteristic length $\cong 10^{-1}$ m)
Fast electrons (characteristic distance $\cong 10^{-3}$ m)	$\Leftarrow$	X-rays and gamma rays (characteristic length $\cong 10^{-1}$ m)

The entries in the left column represent the charged particulate radiations that, because of the electric charge carried by the particle, continuously interact through the coulomb force with the electrons present in any medium through which they pass. The radiations in the right column are uncharged and therefore are not subject to the coulomb force. Instead, these radiations must first undergo a "catastrophic" interaction (often involving the nucleus of constituent atoms) that radically alters the properties of the incident radiation in a single encounter. In all cases of practical interest, the interaction results in the full or partial transfer of energy of the incident radiation to electrons or nuclei of the constituent atoms, or to charged particle products of nuclear reactions. If the interaction does not occur within the detector, these uncharged radiations (e.g., neutrons or gamma rays) can pass completely through the detector volume without revealing the slightest hint that they were ever there.

The horizontal arrows shown in the diagram illustrate the results of such catastrophic interactions. An X- or gamma ray, through the processes described in this chapter, can transfer all or part of its energy to electrons within the medium. The resulting *secondary electrons* bear a close similarity to the fast electron radiations (such as the beta particle) discussed in Chapter 1. Devices designed to detect gamma rays are tailored to promote such interactions and to fully stop the resulting secondary electrons so that their entire energy may contribute to the output signal. In contrast, neutrons may interact in such a way as to produce secondary heavy charged particles, which then serve as the basis of the detector signal.

Also listed in the diagram are order-of-magnitude numbers for the characteristic distance of penetration or average path length (range or mean free path) in solids for typical energy radiations in each category.

I. INTERACTION OF HEAVY CHARGED PARTICLES

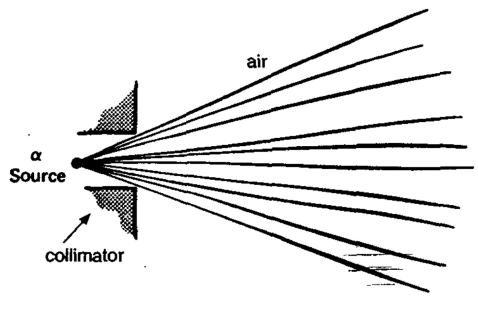
A. Nature of the Interaction

Heavy charged particles, such as the alpha particle, interact with matter primarily through coulomb forces between their positive charge and the negative charge of the orbital electrons within the absorber atoms. Although interactions of the particle with nuclei (as in Rutherford scattering or alpha-particle-induced reactions) are also possible, such encounters occur only rarely and they are not normally significant in the response of radiation detectors. Instead, charged particle detectors must rely on the results of interactions with electrons for their response.

Upon entering any absorbing medium, the charged particle immediately interacts simultaneously with many electrons. In any one such encounter, the electron feels an impulse from the attractive coulomb force as the particle passes its vicinity. Depending on the proximity of the encounter, this impulse may be sufficient either to raise the electron to a higher-lying shell within the absorber atom (*excitation*) or to remove completely the electron from the atom (*ionization*). The energy that is transferred to the electron must come at the expense of the charged particle, and its velocity is therefore decreased as a result of the encounter. The maximum energy that can be transferred from a charged particle of mass m with kinetic energy E to an electron of mass m_0 in a single collision is $4Em_0/m$, or about $1/500$ of the particle energy per nucleon. Because this is a small fraction of the total energy, the primary particle must lose its energy in many such interactions during its passage through an absorber. At any given time, the particle is interacting with many electrons, so the net effect is to decrease its velocity continuously until the particle is stopped.

Representative paths taken by heavy charged particles in their slowing down process are schematically represented in the sketch below. Except at their very end, the tracks tend to be quite straight because the particle is not greatly deflected by any one encounter, and interactions occur in all directions simultaneously. Charged particles are therefore characterized by a definite *range* in a given absorber material. The range, to be defined more precisely below, represents a distance beyond which no particles will penetrate.

The products of these encounters in the absorber are either excited atoms or *ion pairs*. Each ion pair is made up of a free electron and the corresponding positive ion of an absorber atom from which an electron has been totally removed. The ion pairs have a natural tendency to recombine to form neutral atoms, but in some types of detectors, this recombination is suppressed so that the ion pairs may be used as the basis of the detector response.



In particularly close encounters, an electron may undergo a large enough impulse that after having left its parent atom, it still may have sufficient kinetic energy to create further ions. These energetic electrons are sometimes called *delta rays* and represent an indirect means by which the charged particle energy is transferred to the absorbing medium. Under typical conditions, the majority of the energy loss of the charged particle occurs via these delta rays. The range of the delta rays is always small compared with the range of the incident energetic particle, so the ionization is still formed close to the primary track. On a microscopic scale, one effect of this process is that the ion pairs normally do not appear as randomly spaced single ionizations, but there is a tendency to form many "clusters" of multiple ion pairs distributed along the track of the particle.

B. Stopping Power

The *linear stopping power S* for charged particles in a given absorber is simply defined as the differential energy loss for that particle within the material divided by the corresponding differential path length:

$$S = -\frac{dE}{dx} \tag{2.1}$$

The value of $-dE/dx$ along a particle track is also called its *specific energy loss* or, more casually, its "rate" of energy loss.

For particles with a given charge state, S increases as the particle velocity is decreased. The classical expression that describes the specific energy loss is known as the *Bethe formula* and is written

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB \tag{2.2}$$

where

$$B \equiv Z\left[\ln\frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

In these expressions, v and ze are the velocity and charge of the primary particle, N and Z are the number density and atomic number of the absorber atoms, m_0 is the electron rest mass, and e is the electronic charge. The parameter I represents the average excitation and ionization potential of the absorber and is normally treated as an experimentally determined parameter for each element. For nonrelativistic charged particles ($v \ll c$), only the first term in B is significant. Equation (2.2) is generally valid for different types of charged particles provided their velocity remains large compared with the velocities of the orbital electrons in the absorbing atoms.

The expression for B in Eq. (2.2) varies slowly with particle energy. Thus, the general behavior of dE/dx can be inferred from the behavior of the multiplicative factor. For a given nonrelativistic particle, dE/dx therefore varies as $1/v^2$, or inversely with particle energy. This behavior can be heuristically explained by noting that because the charged particle spends a greater time in the vicinity of any given electron when its velocity is low, the impulse felt by the electron, and hence the energy transfer, is largest. When comparing different charged particles of the same velocity, the only factor that may change outside the logarithmic term in Eq. (2.2) is z^2, which occurs in the numerator of the expression. Therefore, particles with the greatest charge will have the largest specific energy loss. Alpha particles, for example, will lose energy at a rate that is greater than protons of the same velocity but less than that of more highly charged ions. In comparing different materials as absorbers, dE/dx depends primarily on the product NZ, which is outside the logarithmic term. This product NZ represents

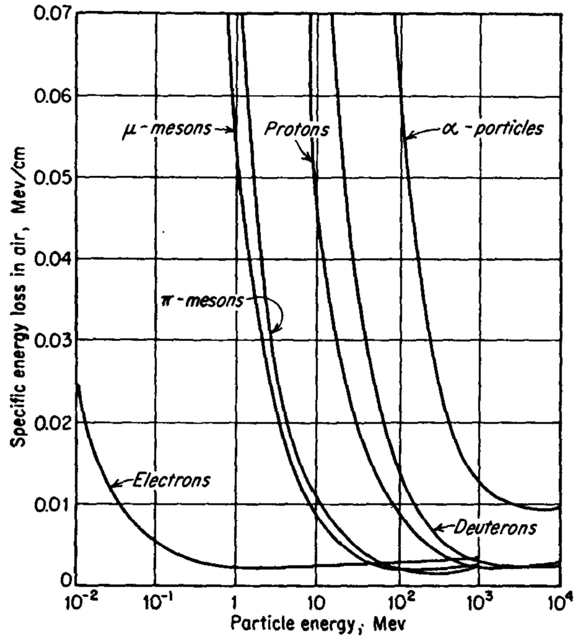


Figure 2.1 Variation of the specific energy loss in air versus energy of the charged particles shown. (From Beiser.[2])

the electron density of the absorber. High atomic number, high-density materials will co quently result in the greatest linear stopping power.

The variation of the specific energy loss for a number of different charged particl shown in Fig. 2.1 over a wide energy range. This figure shows that the value of dE/dx many different types of charged particles approaches a near-constant broad minir value at energies above several hundred MeV, where their velocity approaches the velo of light. This specific energy loss corresponds to about 2 MeV per g/cm^2 in light mater Because of their similar energy loss behavior, such relativistic particles are someti referred to as "minimum ionizing particles." Fast electrons also fall into this categor energies as low as about 1 MeV because their much lower mass results in relativistic vel ities even at such modest energy.

The Bethe formula begins to fail at low particle energies where charge excha between the particle and absorber becomes important. The positively charged particle then tend to pick up electrons from the absorber, which effectively reduce its charge consequent linear energy loss. At the end of its track, the particle has accumulated z el trons and becomes a neutral atom.

C. Energy Loss Characteristics

1. THE BRAGG CURVE

A plot of the specific energy loss along the track of a charged particle such as that shown Fig. 2.2 is known as a *Bragg curve.* The example is shown for an alpha particle of seve MeV initial energy. For most of the track, the charge on the alpha particle is two electro charges, and the specific energy loss increases roughly as $1/E$ as predicted by Eq. (2.2). Ne the end of the track, the charge is reduced through electron pickup and the curve falls c Plots are shown both for a single alpha particle track and for the average behavior o parallel beam of alpha particles of the same initial energy. The two curves differ somewh due to the effects of straggling, to be discussed below.

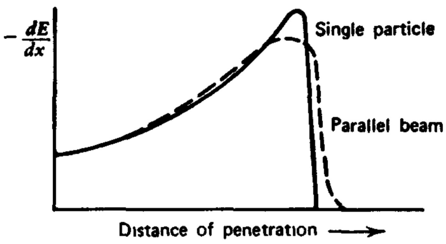


Figure 2.2 The specific energy loss along an alpha track.

Related plots showing $-dE/dx$ versus particle energy for a number of different heavy charged particles are given in Fig. 2.3. These examples illustrate the energy at which charge pickup by the ion becomes significant. Charged particles with the greatest number of nuclear charges begin to pick up electrons early in their slowing-down process. Note that in an aluminum absorber, singly charged hydrogen ions (protons) show strong effects of charge pickup below about 100 keV, but doubly charged ^{3}He ions show equivalent effects at about 400 keV.

2. ENERGY STRAGGLING

Because the details of the microscopic interactions undergone by any specific particle vary somewhat randomly, its energy loss is a statistical or stochastic process. Therefore, a spread in energies always results after a beam of monoenergetic charged particles has passed through a given thickness of absorber. The width of this energy distribution is a measure of energy straggling, which varies with the distance along the particle track.

Figure 2.4 shows a schematic presentation of the energy distribution of a beam of initially monoenergetic particles at various points along its range. Over the first portion, the distribution becomes wider (and more skewed) with penetration distance, showing the

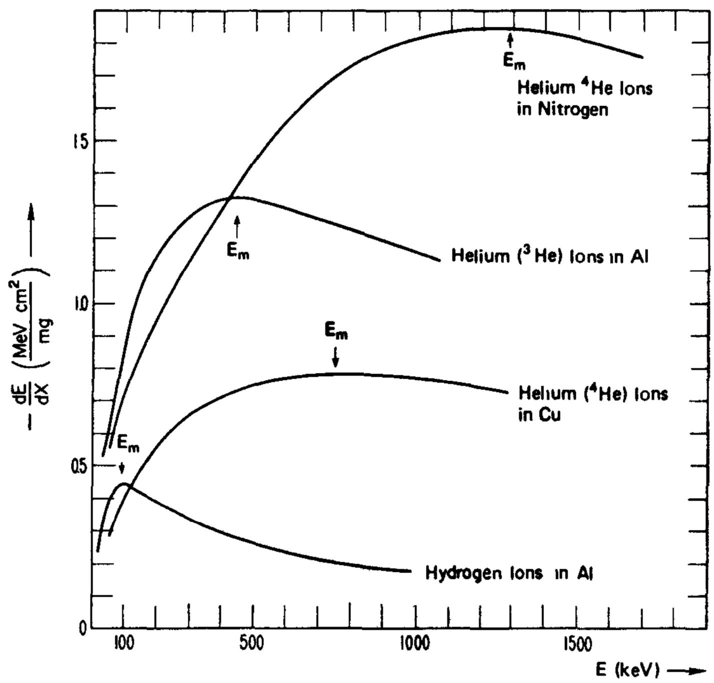


Figure 2.3 Specific energy loss as a function of energy for hydrogen and helium ions. E_m indicates the energy at which dE/dx is maximized. (From Wilken and Fritz.[3])

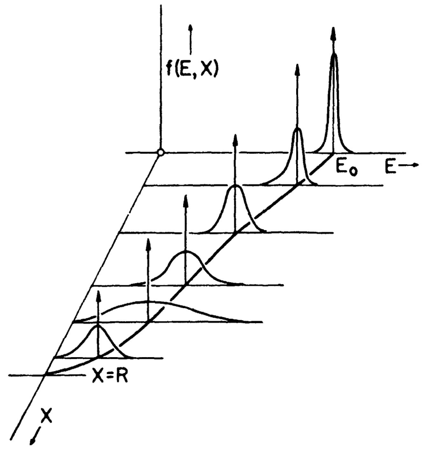


Figure 2.4 Plots of energy distribution of a beam of initially monoenergetic charged particles at various penetration distances. E is the particle energy and X is the distance along the track. (From Wilken and Fritz.[3])

increasing importance of energy straggling. Near the end of the range, the distribution narrows again because the mean particle energy has greatly been reduced.

D. Particle Range

1. DEFINITIONS OF RANGE

In order to quantify the definition of particle range, we refer to the conceptual experiment sketched in Fig. 2.5. Here a collimated source of monoenergetic alpha particles is counted by a detector after passing through an absorber of variable thickness. (We later contrast the behavior of other types of radiation when observed under similar conditions.) For alpha particles, the results are also plotted in Fig. 2.5. For small values of the absorber thickness, the only effect is to cause an energy loss of the alpha particles in the absorber as they pass through. Because the tracks through the absorber are quite straight, the total number that reach the detector remains the same. No attenuation in the number of alpha particles takes place until the absorber thickness approaches the length of the shortest track in the absorbing material. Increasing the thickness then stops more and more of the alpha particles, and the intensity of the detected beam drops rapidly to zero.

The range of the alpha particles in the absorber material can be determined from this curve in several ways. The *mean range* is defined as the absorber thickness that reduces the alpha particle count to exactly one-half of its value in the absence of the absorber.

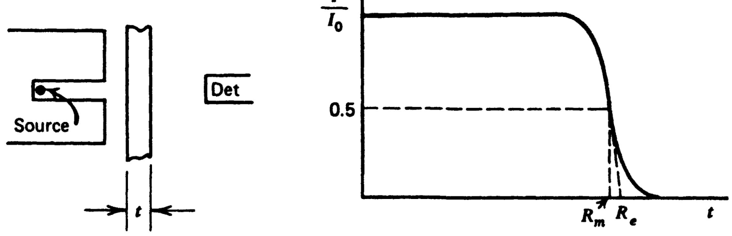


Figure 2.5 An alpha particle transmission experiment. I is the detected number of alpha particles through an absorber thickness t, whereas I_0 is the number detected without the absorber. The mean range R_m and extrapolated range R_e are indicated.

This definition is most commonly used in tables of numerical range values. Another version that appears in the literature is the *extrapolated range*, which is obtained by extrapolating the linear portion of the end of the transmission curve to zero.

The range of charged particles of a given energy is thus a fairly unique quantity in a specific absorber material. In the early days of radiation measurement, experiments of the type sketched in Fig. 2.5 were widely used to measure the energy of alpha particles indirectly by determining the absorber thickness equivalent to their mean range. With the availability of detectors that provide an output signal directly related to the alpha particle energy, such indirect measurements are no longer necessary.

Some graphs of the mean range of various charged particles in materials of interest in detectors are given in Figs. 2.6 through 2.8. As one obvious application of these curves, any detector that is to measure the full incident energy of a charged particle must have an active thickness that is greater than the range of that particle in the detector material.

2. RANGE STRAGGLING

Charged particles are also subject to *range straggling*, defined as the fluctuation in path length for individual particles of the same initial energy. The same stochastic factors that lead to energy straggling at a given penetration distance also result in slightly different

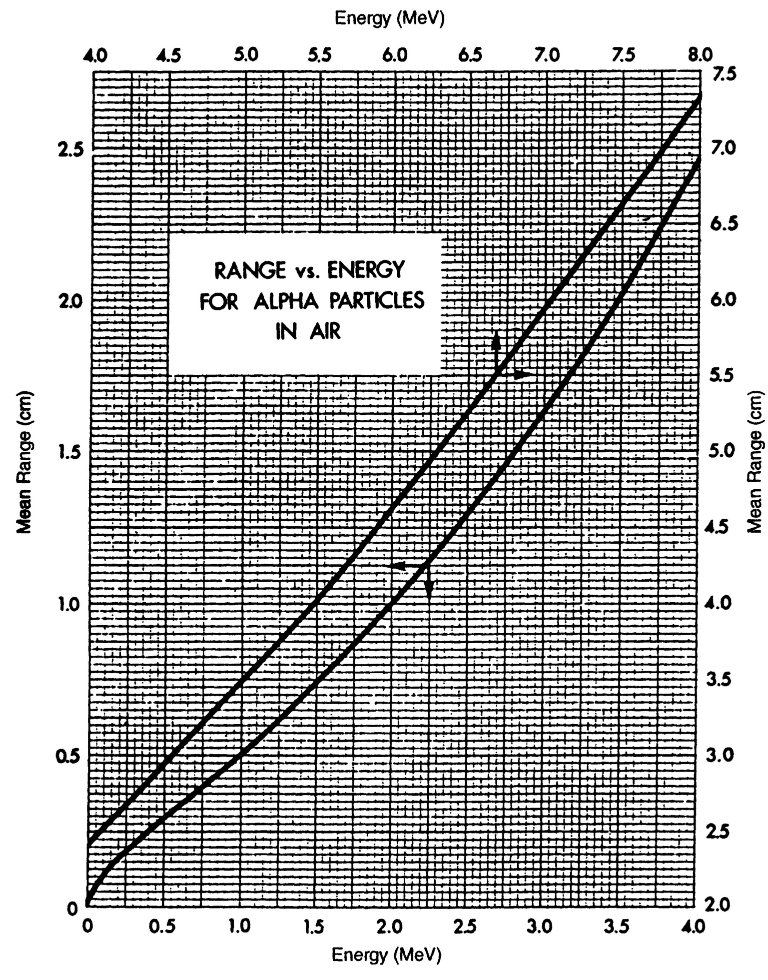


Figure 2.6 Range–energy plot for alpha particles in air at 15°C and 760 mm Hg pressure. (From *Radiological Health Handbook*, U.S. Department of Health, Education and Welfare, Washington, DC, 1970.)