Finally, note that precautions should be taken when handling radioactive sources. We recommend that the reader review the material on radiation safety in Appendix D before undertaking the measurements described in this chapter.

8.2. INTERACTIONS OF CHARGED PARTICLES AND PHOTONS WITH MATTER

8.2.1. General Remarks

As already mentioned the interaction of charged particles and photons with matter is electromagnetic and results either in a gradual reduction of energy of the incoming particle (with a change of its direction) or in the absorption of the photon. Particles such as nuclei, protons, neutrons, and π-mesons, are subject to a nuclear interaction as well, which is, however, of much shorter range than the electromagnetic one. The nuclear interaction may become predominant only when the particles have enough energy to overcome Coulomb-barrier effects. A nuclear mean free path, which is approximately 60 g/cm^2, is the distance over which the probability for a nuclear interaction is of order unity.

Heavy charged particles lose energy through collisions with the atomic electrons of the material, while electrons lose energy both through collisions with atomic electrons and through radiation when their trajectory is altered by the field of a nucleus (*bremsstrahlung*—see Section 8.2.6). Photons lose energy through collisions with the atomic electrons of the material, either through the photoelectric or the Compton effect; at higher energies photons interact by creating electron–positron pairs in the field of a nucleus.

A brief review of definitions will be helpful.

(a) *Cross Section.* We define the cross section, σ, for scattering from a *single* target particle as

$$\sigma = \frac{\text{scattered flux}}{\text{incident flux per unit area}}. \tag{8.1}$$

Thus σ has dimensions of area (usually cm^2) and can be thought of as the area of the scattering center projected on the plane normal to the incoming beam. If the density of scatterers is n (particles/cm^3), there will be $n\,dx$

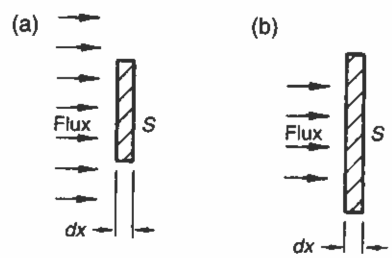

FIGURE 8.1 Scattering of an incoming flux of particles by a target: (a) Area covered by flux is larger than the target area and (b) area covered by flux is smaller than the target area.

scatterers per unit area in a thickness dx of material, and the probability $dP = I_s/I_0$ of an interaction in the thickness dx is

$$dP = \frac{\sigma(I_0/S)}{I_0}(Sn\,dx) = \sigma n\,dx, \tag{8.2}$$

where S is the area covered by the scattering material and I_0 is the total flux incident on the target; thus I_0/S is the flux per unit area as shown[3] in Fig. 8.1a. The result of Eq. (8.2) is not surprising since dP *must* be proportional to n and dx:

$$dP \propto n\,dx,$$

σ is then the factor that transforms this proportionality into an equality. Nuclear cross sections are on the order of $10^{-24}\,\text{cm}^2$ (one barn), as expected given the geometrical size (cross section) of the nucleus

$$\sigma_{\text{geom}} = \pi R^2 = 3.14 \times 10^{-26} A^{2/3}\text{cm}^2.$$

(b) *Differential Cross Section.* For a single scatterer we define[4]

$$\frac{d\sigma(\theta,\phi)}{d\Omega} = \frac{\text{flux scattered into element } d\Omega \text{ at angles } \theta,\phi}{\text{incident flux per unit area}}.$$

It follows that

$$\int_0^{2\pi} d\phi \int_0^{\pi} \frac{d\sigma}{d\Omega}\sin\theta d\theta = \sigma,$$

[3] Occasionally confusion arises because the area of the incoming beam may be smaller than the area presented by the target as shown in Fig. 8.1b. The definition of Eq. (8.1) is valid in either case and always leads back to Eq. (8.2).

[4] See the discussion on "solid angle" in Section 9.1.

where the integration is over all angles. If after the scattering process the particle emerges with variable energy, then

$$\frac{d\sigma(\theta, \phi, E)}{d\Omega\, dE} = \frac{\text{flux with energy } E\text{, within } dE\text{, scattered into } d\Omega \text{ at angles } \theta, \phi}{\text{incident flux per unit area}}.$$

It follows that

$$\int_0^\infty \frac{d^2\sigma(\theta, \phi, E)}{d\Omega\, dE}\, dE = \frac{d\sigma(\theta, \phi)}{d\Omega},$$

where the integration is over all possible energies of the scattered flux.

(c) *Absorption Coefficient.* To obtain the probability for scattering in a length x of some material, we consider an incident flux per unit area I_0; $I(x)$ represents the flux at a distance x into the material. According to Eq. (8.2)

$$-dI(x) = I(x)dP = I(x)\sigma n\, dx; \tag{8.3}$$

thus

$$\frac{dI}{I} = -\sigma n\, dx, \qquad I(x) = I_0 e^{-\sigma n x}.$$

If we designate by $P(x)$ the probability for scattering in a length x, we have

$$\begin{aligned} P(x) &= 1 - (\text{probability for survival in a length } x) \\ &= 1 - e^{-\sigma n x} = 1 - e^{-\kappa x}, \end{aligned}$$

where $\kappa = \sigma n$ is the absorption coefficient. Similarly $\lambda = 1/\sigma n$, which has dimensions of length, is called the absorption length, or mean free path.

The density of scattering centers n is given by

$$\begin{aligned} n &= \rho N_0/A && \text{if we consider scattering by nuclei} \\ n_e &= \rho N_0 Z/A && \text{if we consider scattering by electrons} \\ n_N &= \rho N_0 && \text{if we consider scattering by nucleons,} \end{aligned} \tag{8.4}$$

where N_0 is Avogadro's number 6.023×10^{23} and ρ is the density of the material in grams per cubic centimeter; Z and A are the atomic and mass number, respectively.

Often we wish to express the absorption in terms of the equivalent matter traversed, namely, $\xi = \text{g/cm}^2$. Then the thickness of the material can be expressed by $d\xi$, where

$$d\xi = \rho dx.$$

The *mass* absorption coefficient is defined by

$$\mu = \frac{\kappa}{\rho}, \tag{8.5}$$

so that the fraction of a beam *not* absorbed is

$$\frac{I}{I_0} = e^{-\mu\xi}. \tag{8.6}$$

Similarly, if the region of interaction is very thin, the scattered flux is given directly by

$$I_s = I_0 \sigma n \, dx, \qquad \text{for example, for nuclei,} \qquad I_s = I_0 \frac{N_0}{A} \sigma \, d\xi.$$

8.2.2. Energy Loss of a Charged Particle

When a charged particle collides with atomic electrons, as we have already seen in the Frank–Hertz experiment (Section 1.3), it can transfer energy to them only in discrete amounts. It can either excite an electron to a higher atomic quantum state or impart to the electron enough energy so that it will leave the atom; the latter process is the ionization of the atom. Since in our present considerations the incoming particles have considerable energy, the process of ionization is by far the prevailing one, and we will use this term in the discussion.

Let us consider then an atomic electron at a distance b from the path of a heavy charged particle, of charge ze, mass M, and velocity v, as shown in Fig. 8.2a. If we assume that the electron does not move appreciably during the passage of the heavy particle, we can easily obtain the impulse transferred to it due to the electric field, $\mathbf{E}$, of the passing heavy particle:

$$\begin{aligned} I_\perp &= \int_{-\infty}^{+\infty} F_\perp(t)\, dt = e \int_{-\infty}^{+\infty} E_\perp(t)\, dt \\ &= e \int_{-\infty}^{+\infty} E_\perp(t) \frac{dt}{dx}\, dx = \frac{e}{v} \int_{-\infty}^{+\infty} E_\perp(x)\, dx. \end{aligned}$$