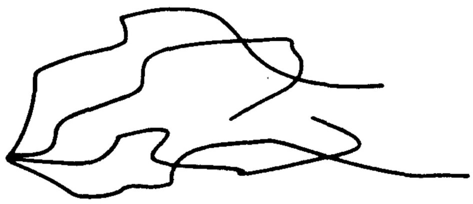
particle is incident on or emerges from a solid surface, some of these electrons may migrate to the surface and have sufficient energy to escape. The term *secondary electrons* is conventionally applied to these escaping low-energy electrons. (*Note*: The same term is often used to characterize the much more energetic electrons formed in the gamma-ray interactions described later in this chapter—a very different type of secondary electron.)

A single heavy ion such as a fission fragment can produce hundreds of these escaping secondaries, whereas lighter alpha particles might typically result in 10 or fewer secondaries per particle.[16] Fast electrons such as beta particles are much less likely to create escaping secondaries, and only a few percent will result in secondary emission. To a first approximation, the yield of secondaries will be proportional to the energy lost within a near-surface layer whose thickness represents the maximum distance an electron will tend to migrate from its point of origin and still retain enough energy to escape from the surface. Thus, the dE/dx value of the particle is a reasonable predictor of secondary yield from a given material. Those materials with low work function and large escape distance will have the largest yield. Thin films of alkali halides, and cesium iodide in particular, are observed to produce secondaries with high yield. Models of the electron transport in alkali halides[17] confirm their suitability as prolific sources of secondary electrons.

The energy spectrum of these escaping secondary electrons is a continuum with a mean value that is very low compared with the primary particle energy. For example, the energy of secondaries from a carbon surface average 60–100 eV for alpha particles and 290 eV for fission fragments.[16] The energy of secondary electrons produced by lighter particles such as fast electrons is even lower. Thus it is normally difficult or impossible to observe the secondaries since they are readily reabsorbed even in air. If they are emitted into a vacuum or low-pressure gas, however, they can be accelerated and easily guided by electric fields because of their low initial velocity. For example, an electric field created by the application of 1000 V with respect to the surface would have a strong influence on the trajectory of a 100 eV electron, but almost no effect on a 1 MeV fast electron. This property has led to the successful use of secondary electron emission from surfaces as a means of detecting the positions at which beta particles emerge from a surface[18] and in the imaging of X-rays and fast electrons.[19] Secondary electrons emitted from a thin foil and directed to an external electron detector such as a microchannel plate have also served as the basis for fast timing measurements with heavy ions.[20,21] One special application of the secondary electron emission process will be detailed in Chapter 9, where a typical electron in a photomultiplier tube is accelerated to a few hundred eV before striking a solid surface, causing the emission of 5–10 secondaries in a charge multiplication process.

II. INTERACTION OF FAST ELECTRONS

When compared with heavy charged particles, fast electrons lose their energy at a lower rate and follow a much more tortuous path through absorbing materials. A series of tracks from a source of monoenergetic electrons might appear as in the sketch below:



Large deviations in the electron path are now possible because its mass is equal to that of ~~the~~ orbital electrons with which it is interacting, and a much ~~larger~~ fraction of its energy can be lost in a single encounter. In addition, electron–nuclear interactions, which can abruptly change the electron direction, sometimes occur.

A. Specific Energy Loss

An expression similar to that of Eq. (2.2) has also been derived by Bethe to describe the specific energy loss due to ionization and excitation (the " collisional losses") for fast electrons:

$$-\left(\frac{dE}{dx}\right)_c = \frac{2\pi e^4 NZ}{m_0 v^2}\left(\ln\frac{m_0 v^2 E}{2I^2(1-\beta^2)} - (\ln 2)(2\sqrt{1-\beta^2} - 1 + \beta^2) + (1-\beta^2) + \frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right) \tag{2.10}$$

where the symbols have the same meaning as in Eq. (2.2) and $\beta \equiv v/c$.

Electrons also differ from heavy charged particles in that energy may be lost by radiative processes as well as by coulomb interactions. These radiative losses take the form of *bremsstrahlung* or electromagnetic radiation, which can emanate from any position along the electron track. From classical theory, any charge must radiate energy when accelerated, and the deflections of the electron in its interactions with the absorber correspond to such acceleration. The linear specific energy loss through this radiative process is

$$-\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z+1)e^4}{137 m_0^2 c^4}\left(4\ln\frac{2E}{m_0 c^2} - \frac{4}{3}\right) \tag{2.11}$$

For the particle types and energy ranges of interest in this text, only fast electrons can have a significant yield of bremsstrahlung. The yield from heavy charged particles is negligible as indicated by the presence of the m_0^2 factor in the denominator of the multiplicative term in Eq. (2.11). The factors of E and Z^2 in the numerator of Eq. (2.11) show that radiative losses are most important for high electron energies and for absorber materials of large atomic number. For typical electron energies, the average bremsstrahlung photon energy is quite low (see Fig. 1.6) and is therefore normally reabsorbed fairly close to its point of origin. In some cases, however, the escape of bremsstrahlung can influence the response of small detectors.

The total linear stopping power for electrons is the sum of the collisional and radiative losses:

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_c + \left(\frac{dE}{dx}\right)_r \tag{2.12}$$

The ratio of the specific energy losses is given approximately by

$$\frac{(dE/dx)_r}{(dE/dx)_c} \cong \frac{EZ}{700} \tag{2.13}$$

where E is in units of MeV. For the electrons of interest here (such as beta particles or secondary electrons from gamma-ray interactions), typical energies are less than a few MeV. Therefore, radiative losses are always a small fraction of the energy losses due to ionization and excitation and are significant only in absorber materials of high atomic number.

B. Electron Range and Transmission Curves

1. ABSORPTION OF MONOENERGETIC ELECTRONS

An attenuation experiment of the type discussed earlier for alpha particles is sketched in Fig. 2.13 for a source of monoenergetic fast electrons. Even small values of the absorber thickness lead to the loss of some electrons from the detected beam because scattering of the electron effectively removes it from the flux striking the detector. A plot of the detected number of electrons versus absorber thickness therefore begins to drop immediately and gradually approaches zero for large absorber thicknesses. Those electrons that penetrate

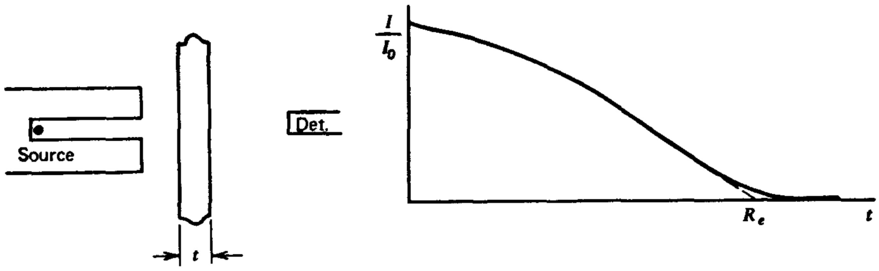


Figure 2.13 Transmission curve for monoenergetic electrons. R_e is the extrapolated range.

the greatest absorber thickness will be the ones whose initial direction has changed least in their path through the absorber.

The concept of range is less definite for fast electrons than for heavy charged particles, because the electron total path length is considerably greater than the distance of penetration along the initial velocity vector. Normally, the electron range is taken from a transmission plot, such as that given in Fig. 2.13, by extrapolation of the linear portion of the

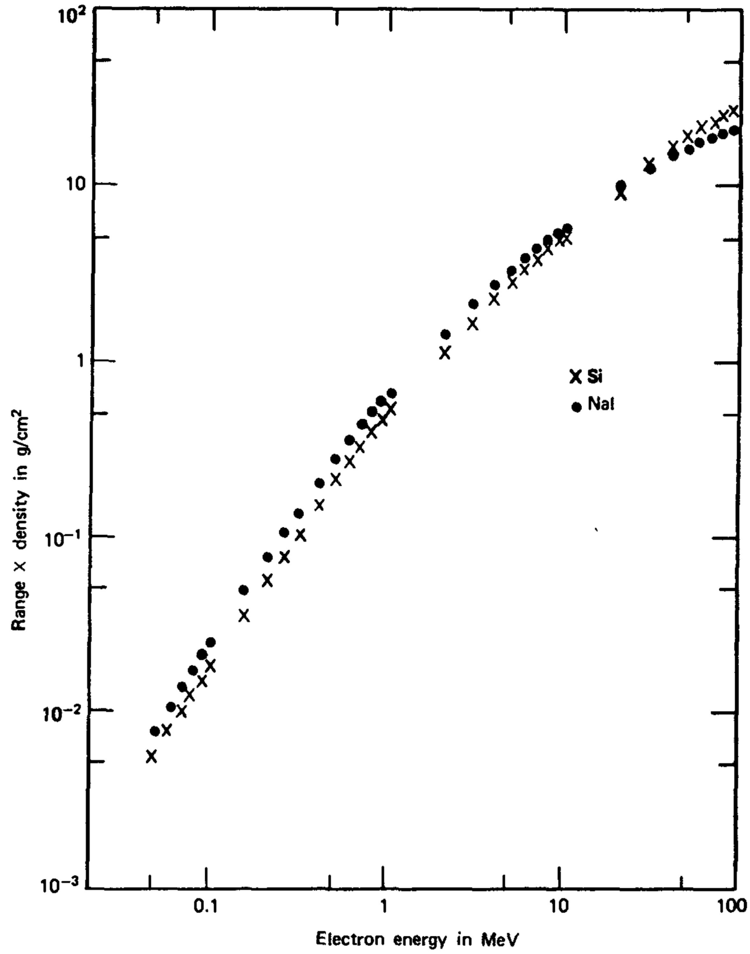


Figure 2.14 Range–energy plots for electrons in silicon and sodium iodide. If units of mass thickness (distance × density) are used for the range as shown, values at the same electron energy are similar even for materials with widely different physical properties or atomic number. (Data from Mukoyama.[24])

curve to zero and represents the absorber thickness required to ensure that almost no electrons can penetrate the entire thickness.

For equivalent energy, the specific energy loss of electrons is much lower than that of heavy charged particles, so their path length in typical absorbers is hundreds of times greater. As a very crude estimate, electron ranges tend to be about 2 mm per MeV in low-density materials, or about 1 mm per MeV in materials of moderate density.

Tabular data are given in Refs. 22 and 23 for the stopping power and range of electrons and positrons in elements and compounds, covering a large region of energy. To a fair degree of approximation, the product of the range times the density of the absorber is a constant for different materials for electrons of equal initial energy. Plots of the range of electrons in two common detector materials are given in Fig. 2.14.

2. ABSORPTION OF BETA PARTICLES

The transmission curve for beta particles emitted by a radioisotope source, because of the continuous distribution in their energy, differs significantly from that sketched in Fig. 2.13 for monoenergetic electrons. The "soft" or low-energy beta particles are rapidly absorbed even in small thicknesses of the absorber, so that the initial slope on the attenuation curve is much greater. For the majority of beta spectra, the curve happens to have a near-exponential shape and is therefore nearly linear on the semilog plot of the type shown in Fig. 2.15. This exponential behavior is only an empirical approximation and does not have a fundamental basis as does the exponential attenuation of gamma rays [see Eq. (2.20)]. An *absorption coefficient n* is sometimes defined by

$$\frac{I}{I_0} = e^{-nt} \tag{2.14}$$

where I_0 = counting rate without absorber

I = counting rate with absorber

t = absorber thickness in $\mathrm{g/cm^2}$

The coefficient n correlates well with the endpoint energy of the beta emitter for a specific absorbing material. This dependence is shown in Fig. 2.16 for aluminum. Through the use of such data, attenuation measurements can be used to identify indirectly endpoint

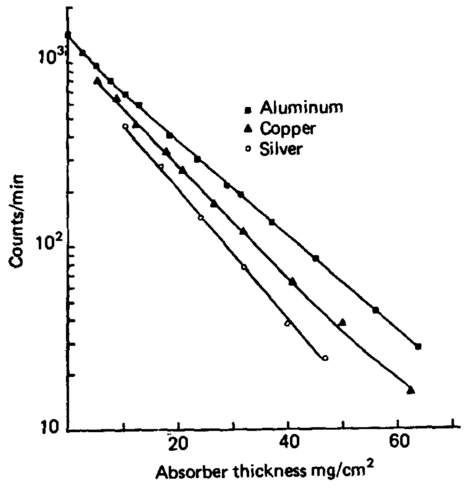


Figure 2.15 Transmission curves for beta particles from ^{185}W (endpoint energy of 0.43 MeV). (From Baltakmens.[25])

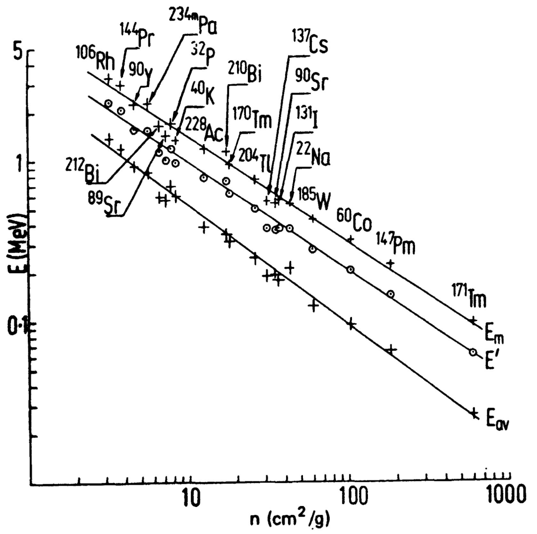


Figure 2.16 Beta particle absorption coefficient n in aluminum as a function of the endpoint energy E_m, average energy E_{av}, and $E' \equiv 0.5\ (E_m + E_{av})$ of different beta emitters. (From Baltakmens.[26])

energies of unknown beta emitters, although direct energy measurements are more common.

3. BACKSCATTERING

The fact that electrons often undergo large-angle deflections along their tracks leads to the phenomenon of *backscattering*. An electron entering one surface of an absorber may undergo sufficient deflection so that it re-emerges from the surface through which it entered. These backscattered electrons do not deposit all their energy in the absorbing medium and therefore can have a significant effect on the response of detectors designed to measure the energy of externally incident electrons. Electrons that backscatter in the detector "entrance window" or dead layer will escape detection entirely.

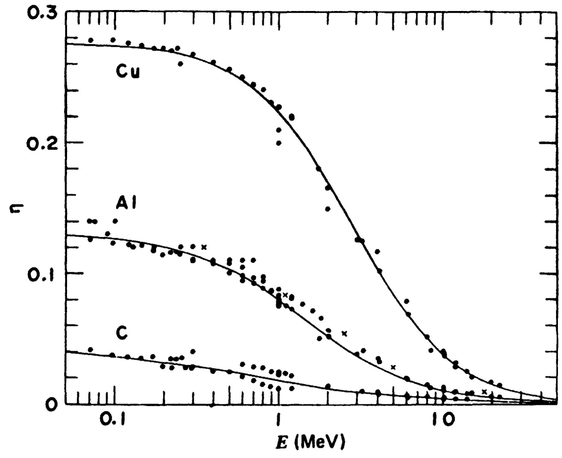
Backscattering is most pronounced for electrons with low incident energy and absorbers with high atomic number. Figure 2.17 shows the fraction of monoenergetic electrons that are backscattered when normally incident on the surface of various absorbers. Additional data for materials commonly used as electron detectors are given in Table 10.1.

Backscattering can also influence the apparent yield from radioisotope sources of beta particles or conversion electrons. If the source is deposited on a thick backing, electrons that are emitted initially into this backing may backscatter and re-emerge from the surface of the source.

C. Positron Interactions

The coulomb forces that constitute the major mechanism of energy loss for both electrons and heavy charged particles are present for either positive or negative charge on the particle. Whether the interaction involves a repulsive or attractive force between the incident particle and orbital electron, the impulse and energy transfer for particles of equal mass are about the same. Therefore, the tracks of positrons in an absorber are similar to those of normal negative electrons, and their specific energy loss and range are about the same for equal initial energies.

Positrons differ significantly, however, in that the annihilation radiation described in Chapter 1 is generated at the end of the positron track. Because these 0.511 MeV photons are very penetrating compared with the range of the positron, they can lead to the deposition of energy far from the original positron track.



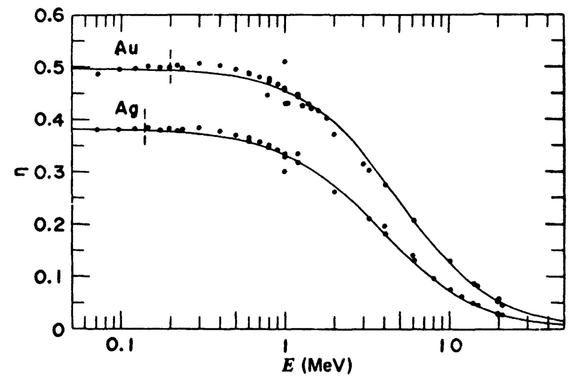


Figure 2.17 Fraction η of normally incident electrons that are backscattered from thick slabs of various materials, as a function of incident energy *E*. (From Tabata et al.[27])

III. INTERACTION OF GAMMA RAYS

Although a large number of possible interaction mechanisms are known for gamma rays in matter, only three major types play an important role in radiation measurements: *photoelectric absorption, Compton scattering,* and *pair production.* All these processes lead to the partial or complete transfer of the gamma-ray photon energy to electron energy. They result in sudden and abrupt changes in the gamma-ray photon history, in that the photon either disappears entirely or is scattered through a significant angle. This behavior is in marked contrast to the charged particles discussed earlier in this chapter, which slow down gradually through continuous, simultaneous interactions with many absorber atoms. The fundamentals of the gamma-ray interaction mechanisms are introduced here but are again reviewed at the beginning of Chapter 10 in the context of their influence on the response of gamma-ray detectors.