Interaction of Radiation with Matter

In order for health physicists to understand the physical basis for radiation dosimetry and the theory of radiation shielding, they must understand the mechanisms by which the various radiations interact with matter
the several radiations, depends on the type and energy of the radiation as well as on the nature of the absorbing medium.

Beta Particles (beta rays)

Range–Energy Relationship

The attenuation of beta particles (beta rays is used synonymously with beta particles) by any given absorber may be measured by interposing successively thicker absorbers between a beta source and a suitable beta detector, such as a Geiger–Muller counter(Fig. 1), and counting the beta particles that penetrate the absorbers. When this is done with a pure beta emitter, it is found that the beta-particle counting rate decreases rapidly at first, and then, as the absorber thickness increases, it decreases slowly. Eventually, a thickness of absorber is reached that stops all the beta particles; the Geiger counter then registers only background counts due to environmental radiation. If semilog paper is used to plot the data and the counting rate is plotted on the logarithmic axis while absorber thickness is plotted on the linear axis, the data approximate a straight line, as shown in Figure 2.

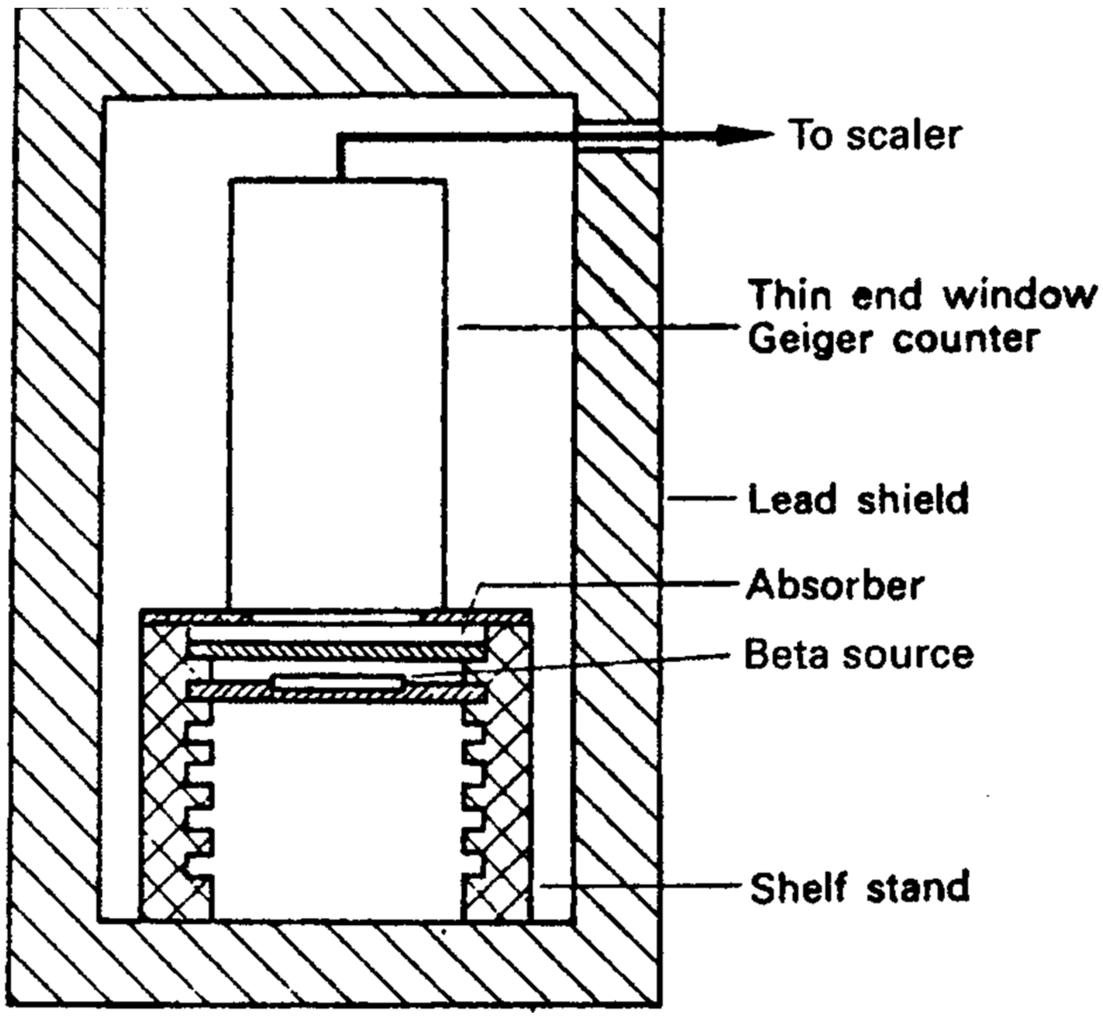


Figure 1. Experimental arrangement for absorption measurements on beta particles

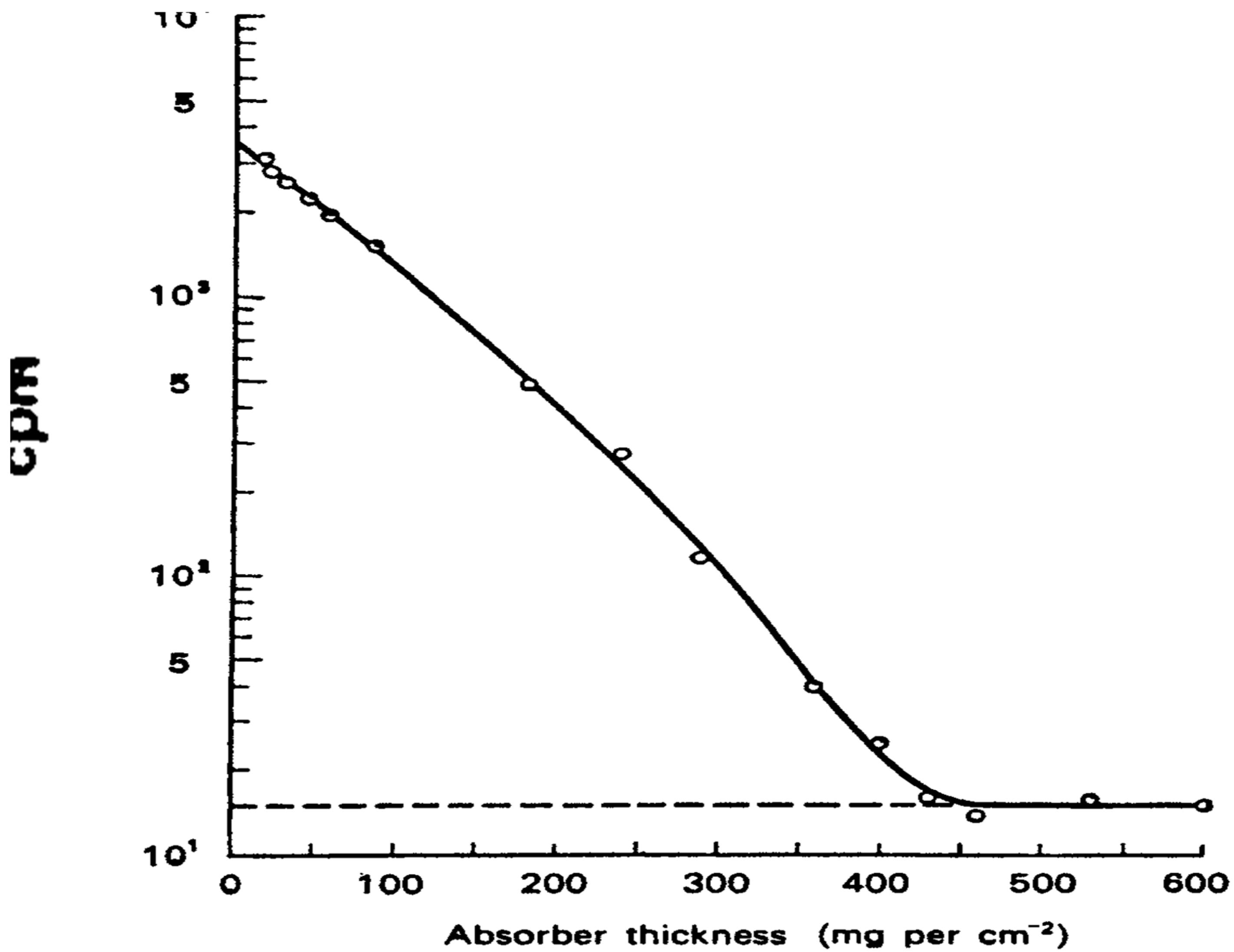


Figure 2: Absorption curve (aluminum absorbers) of ^{210}Bi beta particles, 1.17 MeV.

The endpoint in the absorption curve, where no further decrease in the counting rate is observed, is called the *range* of the beta in the material of which the absorbers are made., a useful relationship is that the absorber half thickness (that thickness of absorber which stops one-half of the beta particles) is about one-eighth the range of the beta. Since the maximum beta energies for the various isotopes are known, by measuring the beta ranges in different absorbers, the systematic relationship between range and energy shown in Figure 3 is established. Inspection of Figure 3 shows that the required thickness of absorber for any given beta energy decreases as the density of the absorber increases. Detailed analyses of experimental data show that the ability to absorb energy from beta particles depends mainly on the number of absorbing electrons in the path of the beta—that is, on the areal density (electrons/cm^2) of electrons in the absorber, and, to a much lesser degree, on the atomic number of the absorber. For practical purposes, therefore, in the calculation of shielding thickness against beta particles, the effect of atomic number is neglected. (It should be pointed out that, for reasons to be given later, beta shields are almost always made from low-atomic-numbered materials.) Areal density of electrons is approximately proportional to the product of the density of the absorber material and the linear thickness of the absorber, thus giving rise to the unit of thickness called the *density thickness*. Mathematically, density thickness

$$t_d \; g/cm^2 = \rho \; g/cm^3 \times t_l \; cm \text{---------(w)}$$

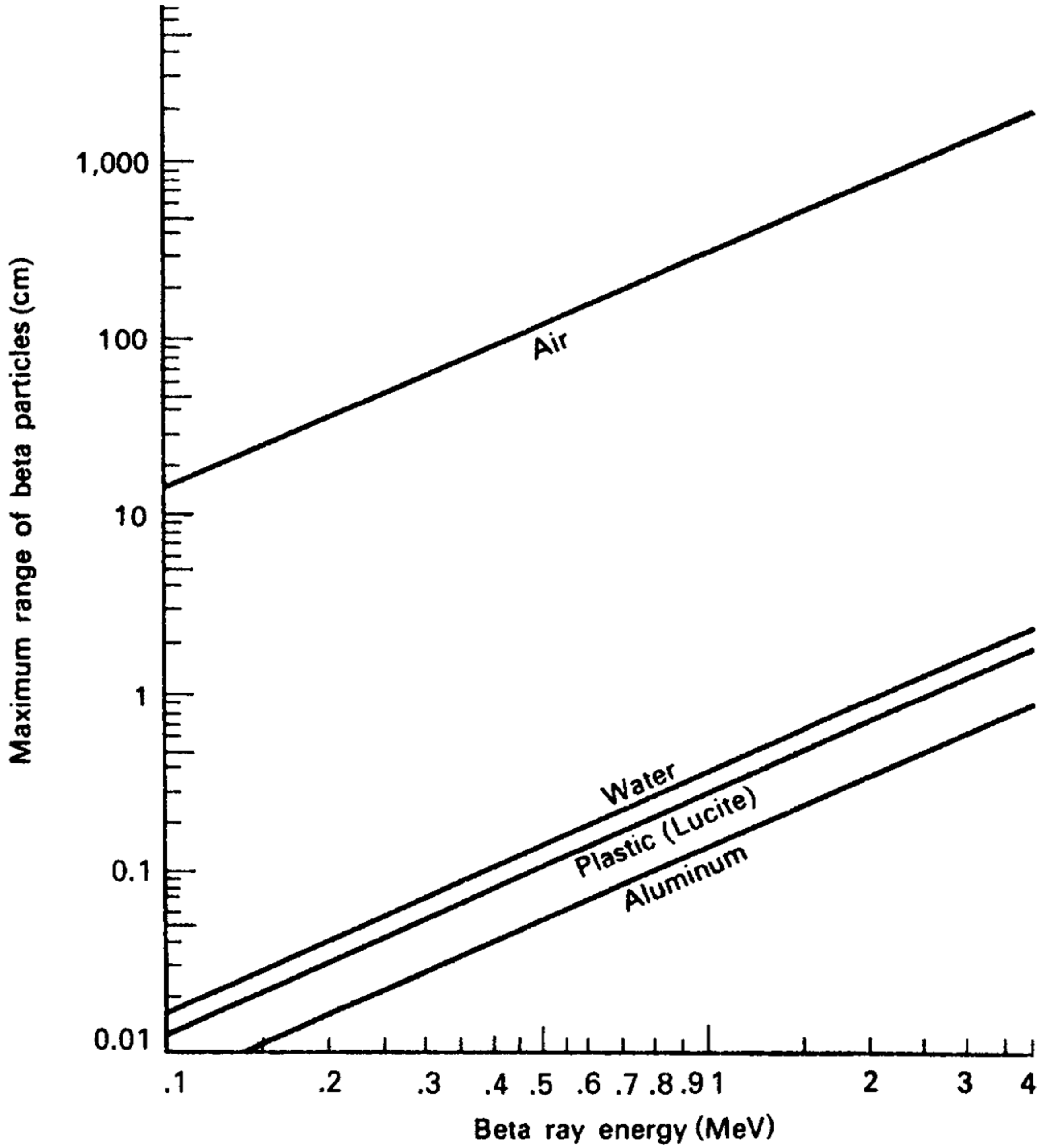


Figure 3. Range–energy curves for beta particles in various substances. (Adapted from Radiological Health Handbook. Washington, DC: Office of Technical Services; 1960.)

If a sheet of Plexiglas whose density is 1.18 g/cm^3 is to have a beta absorbing quality very nearly equal to that of the 1-cm-thick sheet of aluminum-that is, 2.7 g/cm^2-its linear thickness is found, from Eq. (w), to be

$t_1 = t_d/\rho = 2.7 g/cm^2 / 1.8 g/cm^3 = 2.39$ cm.

The quantitative relationship between beta energy and range is given by the following experimentally determined empirical equations:

$E = 1.92R^{0.725}$ $\quad R \leq 0.3\ g/cm^2$ (a)

$R = 0.407E^{1.38}$ $\quad E \leq 0.8 MeV$ (b)

$E = 1.85R + 0.245$ $\quad R \geq 0.3$ g/cm2 (c)

$R = 0.542E - 0.133$ $\quad E \geq 0.8 MeV$ (d)

where

R = range, g/cm^2 and

E = maximum beta energy, MeV.

An experimentally determined curve of beta range (in units of density thickness expressed as mg/cm^2) versus energy is given in Figure 4.

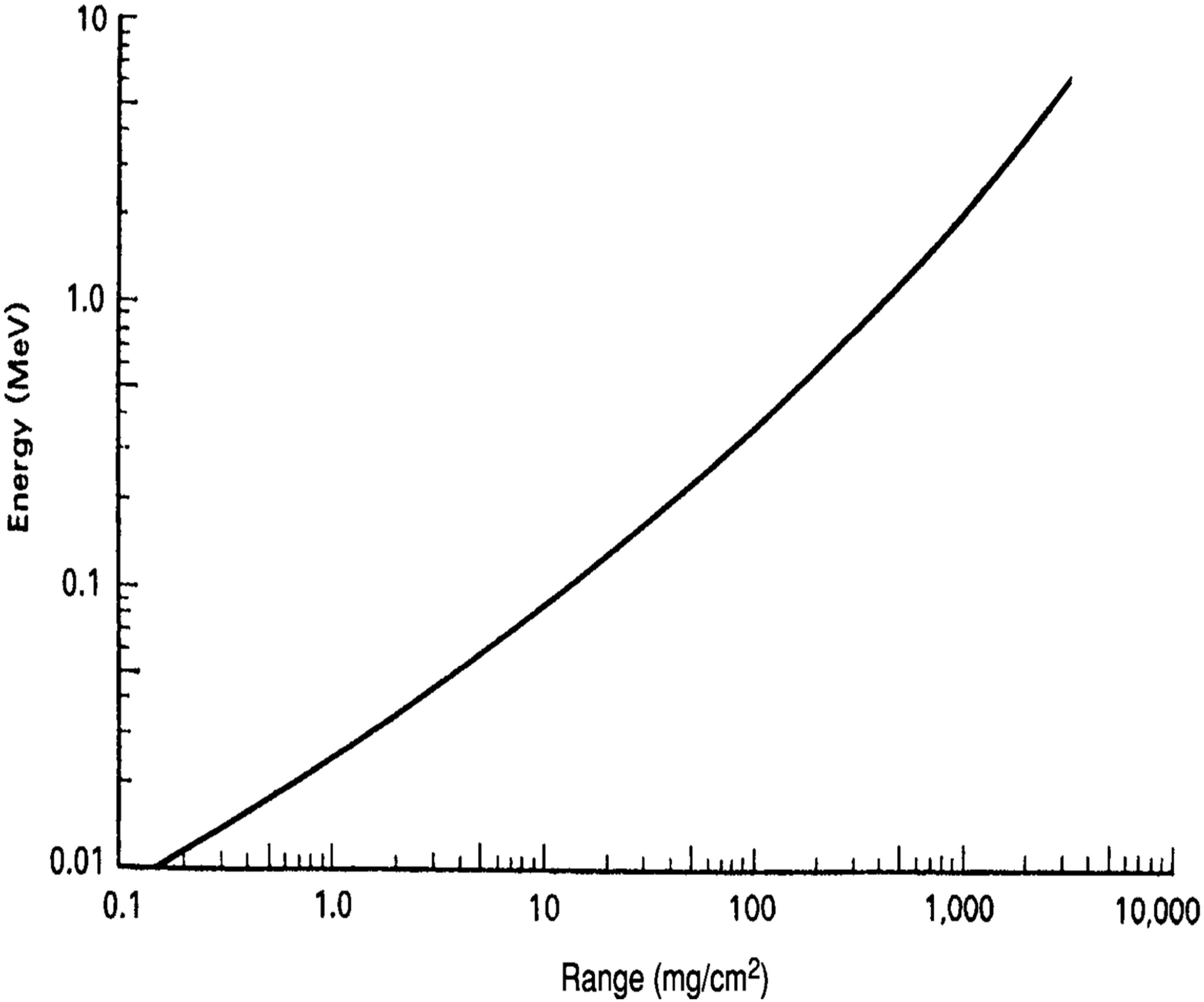


Figure 4. Range–energy curve for beta particles and for monoenergetic electrons. (Adapted from Radiological Health Handbook. Washington, DC: Office of Technical Services; 1960.)

Mechanisms of Energy Loss Ionization and Excitation

Interaction between the electric fields of a beta particle and the orbital electrons of the absorbing medium leads to electronic excitation and ionization. Such interactions are inelastic collisions, The electron is held in the atom by electrical forces, and energy is lost by the beta particle in overcoming these forces. The amount of energy lost by the beta particle depends on its distance of approach to the electron and on its kinetic energy. If φ is the ionization potential of the absorbing medium and E_t is the energy lost by the beta particle during the collision, the kinetic energy of the ejected electron E_k is

$$E_k = E_t - \varphi$$

In some ionizing collisions, only one ion pair is produced. In other cases, the ejected electron may have sufficient kinetic energy to produce a small cluster of several ionizations; and in a small proportion of the collisions, the ejected electron may receive a considerable amount of energy, enough to cause it to travel a long distance and to leave a trail of ionizations. Such an electron, whose kinetic energy may be on the order of 1000 eV (1 keV), is called a delta ray.

Beta particles have the same mass as orbital electrons and hence are easily deflected during collisions. For this reason, beta particles follow tortuous paths as they pass through absorbing media. Figure (A) shows the path of a beta particle through a photographic emulsion. The ionizing events expose the film at the points of ionization, thereby making them visible after development of the film. By using a cloud chamber or film to visualize the ionizing events and by counting the actual number of ionizations due to a single primary ionizing particle of known energy, it was learned that the average energy expended in the production of an ion pair is about two to three times greater than the ionization potential. The difference between the energy expended in ionizing collisions and the total energy lost bythe ionizing particle is attributed to electronic excitation.

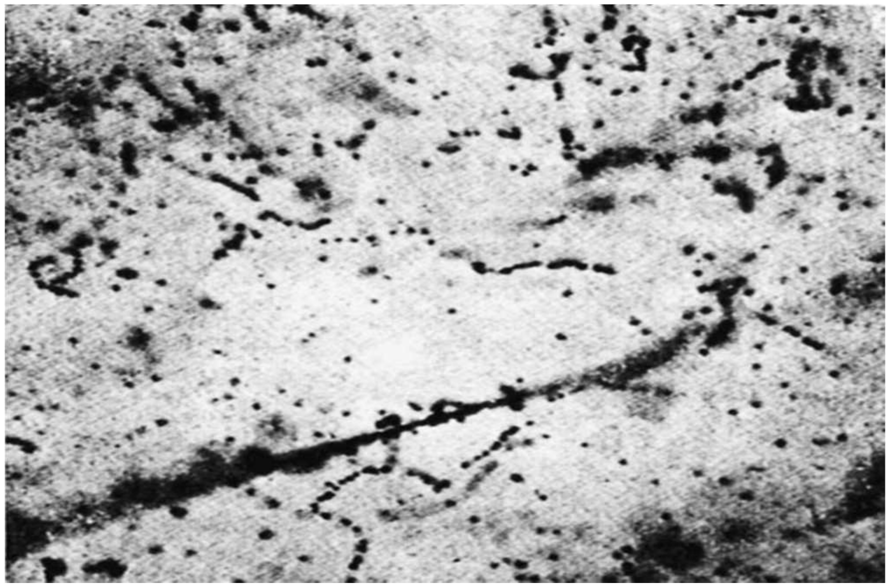
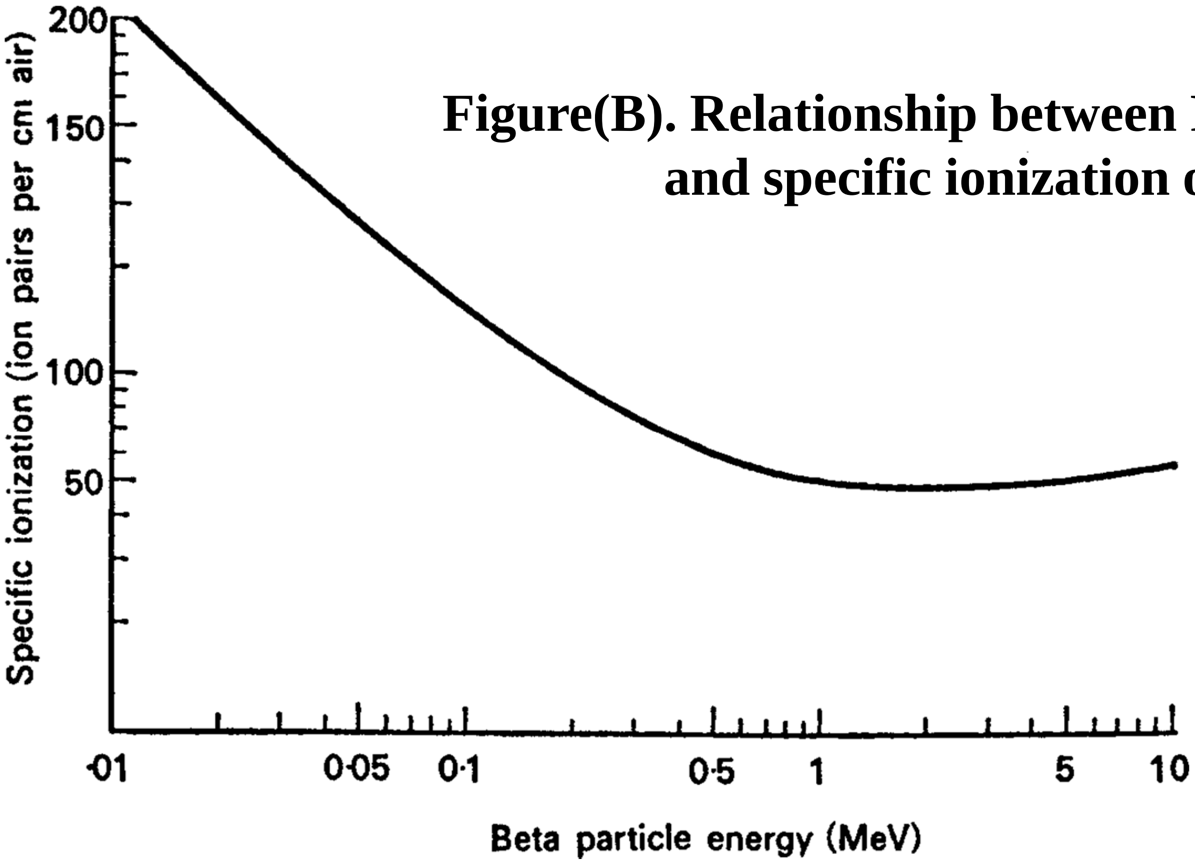


Figure (A). Electron tracks in photographic emulsion

Specific Ionization. The linear rate of energy loss of a beta particle due to ionization and excitation, which is an important parameter in health physics instrument design and in the biological effects of radiation, is usually expressed by the specific ionization. Specific ionization is the number of ion pairs formed per unit distance traveled by the beta particle. Generally, the specific ionization is relatively high for low-energy betas; It decreases rapidly as the beta-particle energy increases, until a broad minimum is reached at around 1-3 MeV. Further increase in beta energy results in a slow increase of specific ionization



Figure(B). Relationship between Particle energy and specific ionization of air.

The linear rate of energy loss due to excitation and ionization may be calculated from the equation

$$\frac{dE}{dX} = \frac{2\pi\, q^4 N\, Z \times (3\times 10^9)^4}{E_m \beta^2 (1.6\times 10^{-6})^2}\left[\ln\left(\frac{E_m E_B \beta^2}{I^2(1-\beta^2)}\right) - \beta^2\right]$$

q= charge on the electron, 1.6×10^{-19} C,

N = number of absorber atoms per cm3,

Z = atomic number of the absorber,

NZ = number of absorber electrons per cm3 = 3.88×10^{20} for air at 0◦ and 76 cm Hg,

E_m = energy equivalent of electron mass, 0.51 MeV,

E_B = kinetic energy of the beta particle (MeV),

β = speed of the ionizing particle/speed of light = v/c ,

I = mean ionization and excitation potential of absorbing atoms (MeV), and

I = 8.6 × 10−5 for air; for other substances, I = 1.35 × 10−5 Z.

If the mean energy, w, expended in the creation of an ion pair (ip) is known, then the specific ionization may be calculated from the equation below:

$$SI, \frac{ip}{cm} = \frac{dE}{dX} \Big/ W$$

Very often, the unit of length used in expressing rate of energy loss is density thickness, that is, in units of MeV g/cm^2 . This is called the mass stopping power; it is defined as the ratio of the linear stopping power to the density of the stopping medium:

$$S = \frac{dE}{dx} \Big/ \rho$$

Linear Energy Transfer: The term specific ionization is used when attention is focused on the energy lost by the radiation. When attention is focused on the absorbing medium, as is the case in radiobiology and radiation effects, we are interested in the linear rate of energy absorption by the absorbing medium as the ionizing particle traverses the medium. As a measure of the rate of energy absorption, we use the linear energy transfer (LET), which is defined by the equation

$$LET = \frac{dE_L}{dL}$$

where dE_L is the average energy locally transferred to the absorbing medium by a charged particle of specified energy in traversing a distance of d*l*. In health physics and radiobiology, LET is usually expressed in units of kilo electron volts per micron (keV/μm)

locally transferred" refer either to a maximum distance from the track of the ionizing particle or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered local. In either case, LET refers to energy transferred to a limited volume of absorber.

Relative Mass Stopping Power. The relative mass stopping power is used to compare quantitatively the energy absorptive power of different media. Relative mass stopping power, ρm is defined by

$\rho m = S_{medium}/S_{air}$

- For purposes of estimating the bremsstrahlung hazard from beta radiation, the following empirically determined relationship may be used:
  $f_\beta = 3.5 \times 10^{-4}$ Z Em

f_β = the fraction of the incident beta energy converted into photons,
Z = atomic number of the absorber,
E_m = maximum energy of the beta particle (MeV).

Since the average beta-particle energy is about one-third of the maximum energy, the energy E_β carried by the beta particles from the 1-Ci source that is incident on the shield is

$$E_\beta \text{ (MeV/s)} = 1/3 \ \ Em \ \times 3.7 \times 10^{10}$$

For health physics purposes, it is assumed that all the bremsstrahlung photons are of the beta particle's maximum energy, Em.
The photon flux φ of bremsstrahlung photons at a distance r cm from a point source of beta particles whose activity is 3.7×10^{10} Bq (1 Ci) is therefore given as

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$$\phi = \frac{f \cdot T_\beta}{4\pi^2 T} \qquad \frac{photon/cm^2}{\text{sec}}$$