$$\text{Thickness density} = R \times \rho \text{ g/cm}^2 \qquad (2.14)$$
$$= 1000R \times \rho \text{ mg/cm}^2,$$

according as the value is expressed in g/cm² or mg/cm². The latter is generally used because the numbers are then of a reasonable magnitude. Physically, the thickness density is the mass per unit area of absorbing medium required to stop (or absorb) the given alpha particles, i.e., having a linear thickness equal to the range of the particles.

ABSORPTION OF BETA PARTICLES

2.39. The passage of beta particles through matter has some features in common with the behavior of alpha particles, e.g., production of ion-pairs at the rate of about 34 ev per ion-pair in air, but there are some important differences. As stated earlier, the smaller mass of the beta particle means that the specific ionization is less than that due to an alpha particle of the same energy. Furthermore, all the alpha particles from a given source have essentially the same energy, or they fall into two or three groups of definite energy. Beta particles, on the other hand, have a continuous distribution of energies, i.e., a continuous energy spectrum, up to a definite maximum for each particular source (Fig. 2.5).

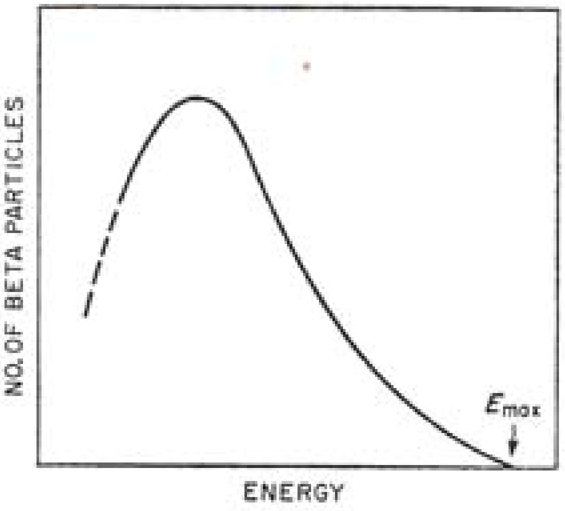

FIG. 2.5. Energy spectrum of beta particles

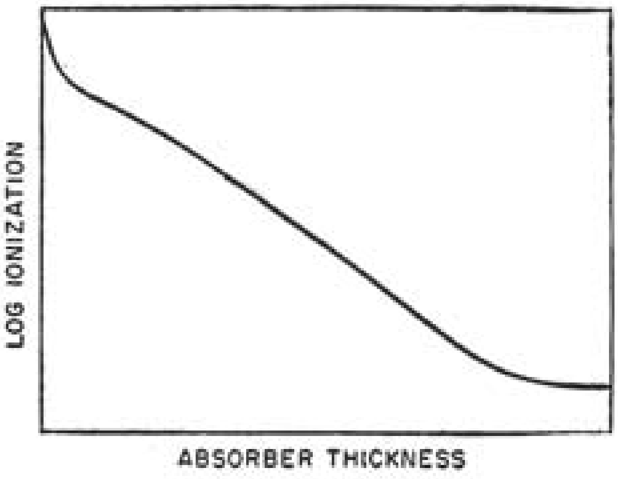

FIG. 2.6. Absorption of beta particles

This maximum is known, from the isotopic masses of the parent and daughter nuclides, to be equal to the total energy of the radioactive change. The reason why few (if any) beta particles have this amount of energy is that, in any given transition, the available energy is divided between the beta particle and the accompanying neutrino (§ 1.26). On the average, the beta particles carry about one-third, and the neutrinos the remaining two-thirds, of the total energy.

2.40. Because of their relatively large mass, alpha particles do not, on the whole, undergo any marked change of direction in their passage through matter. In other words, the majority travel in straight lines, thus leading to a fairly definite range for a given energy. Beta particles, however, are subject to considerable scattering, with frequent changes in direction as a result of electrostatic interactions with atomic nuclei and electrons. Consequently, beta particles which have passed through the same thickness of a given absorber may come out in widely different directions, so that they will actually have traversed paths of different lengths in the material.

2.41. The combined effect of the continuous energy spectrum of beta particles and their scattering means that these particles do not have a definite range, as do alpha particles from a given source. However, due to a fortuitous combination of circumstances, which are too complex for complete theoretical analysis, it is found experimentally that the ionization caused by beta radiation from a given source falls off in a roughly exponential manner with distance. The general form of the plot of the logarithm of the ionization produced against the thickness of the absorbing material is shown in Fig. 2.6; except for small or large thicknesses, the curve is approximately linear. At large absorber thicknesses the curve becomes almost horizontal, indicating a more or less constant ionization. This "tail" of the curve is due to the presence of the highly penetrating bremsstrahlung (§ 2.25) resulting from the loss of energy by the fast-moving beta particles in their passage through the absorbing medium.

2.42. The energy loss as bremsstrahlung per unit path length by beta particles (or electrons) is approximately proportional to the square of the atomic number of the absorber and to the energy of the particles. The association of bremsstrahlung with the passage of beta particles of given energy through matter is thus most marked with elements of high atomic number. The radiations cover a range of energies up to a maximum equal to the initial (maximum) energy of the beta particles. If gamma rays are emitted from the beta-particle source they will, of course, also contribute to the "tail" in Fig. 2.6. After passage through considerable thicknesses of material, both gamma radiation and bremsstrahlung will be absorbed.

2.43. Beta particles do not have a definite range, in the same sense as do alpha particles. Nevertheless, it is possible to specify a more or less definite thickness of absorber which will reduce almost to zero the ionization, other than

TABLE 2.3. APPROXIMATE RANGES OF BETA PARTICLES IN AIR

Energy (Mev)	*Range* meters	ft
0.1	0.11	0.36
0.5	1.5	4.9
1.0	3.7	12
2.0	8.5	28
3.0	13	43

that due to bremsstrahlung, produced by beta particles of given energy. The approximate ranges in air of beta particles of various maximum energies are given in Table 2.3. It may be noted that the average maximum energy of the beta particles from fission products is about 1.2 Mev; the absolute maximum energy probably does not exceed 3 Mev and is appreciably less in most cases.

2.44. As for alpha particles, the approximate range of beta particles in an absorbing material is frequently expressed in terms of its thickness density in grams per cm^2, defined by equation (2.14). The values for aluminum as absorber have been determined experimentally for beta particles from various sources, and the results fall on or very close to the curve shown in Fig. 2.7; the ordinates are the thickness densities of aluminum in grams per cm^2 required to absorb beta particles with maximum energies indicated by the abscissae. Within the range of about 0.8 to 3 Mev, the relationship between the absorption thickness density ($R \times \rho$) of aluminum and the maximum energy (E_m) of the beta particles from the given source is linear and may be represented by the expression

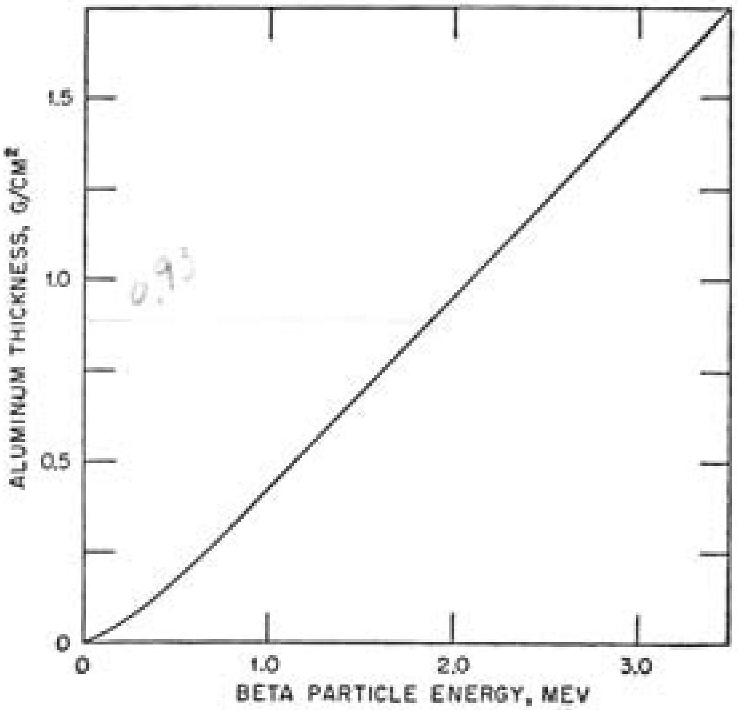

FIG. 2.7. Aluminum thickness density (g/cm^2) as function of beta-particle energy

$$R \times \rho \text{ (g/cm}^2) = 0.54E_m \text{ (Mev)} - 0.15. \qquad (2.15)$$

2.45. In the absence of other data, it may be supposed, as a first approximation, that the absorption thickness density is independent of the nature of the absorbing material; this is based on the assumption that the linear range of the beta particles in any medium is inversely proportional to the density. In this event, the values of $R \times \rho$ given by equation (2.15) would be the same for all absorbers. The (approximate) linear range in any material can then be obtained if the density is known.

Example 2.3. Estimate the maximum range in concrete of density 2.8 g/cm³ of beta particles from fission products.

As stated in § 2.43, the energy of the beta particles from fission products does not exceed 3 Mev; hence, from equation (2.15), the corresponding maximum value of $R \times \rho$ is 1.47 g/cm². Since ρ is 2.8 g/cm², it follows that

$$R = 1.47/2.8 = 0.53 \text{ cm}.$$

The maximum range is thus about 0.53 cm or 0.21 in. in concrete.

2.46. Positive beta particles, i.e., positrons, behave like negative beta particles in their interaction with matter. There is, however, another factor to be considered in the former case. Within a very short time of its liberation, a positron is likely to combine with an electron, of which large numbers are always present in matter as the outer electrons of atoms. The positively charged positron and negatively charged electron neutralize one another; the particles are thereby annihilated and energy is liberated in the form of radiation, called *annihilation radiation*. The total mass of a positron and an electron is 0.00110 amu and, by equation (1.4), this is equivalent to 1.02 Mev. To be consistent with the principle of the conservation of momentum, this energy is usually divided equally between two photons moving in opposite directions. The energy of the annihilation radiation, which has properties similar to gamma radiation, is thus mainly 0.51 Mev, although there may be a small amount of 1.02-Mev energy photons.

ČERENKOV RADIATION

2.47. Charged particles of high energy emit visible (electromagnetic) radiation in their passage through a transparent medium, provided their velocity is greater than the velocity of light in that medium. This radiation is called *Čerenkov radiation*. The bluish glow which is often observed surrounding the cores of reactors cooled and moderated by water is the Čerenkov radiation generated by Compton electrons (§2.53) produced by fission-product gamma rays.

INTERACTION OF GAMMA RAYS WITH MATTER

INTRODUCTION

2.48. Although x-rays, bremsstrahlung, and annihilation radiation are not strictly gamma rays, since they do not arise from nuclear transitions, they are essentially identical with gamma rays in their fundamental nature. As far as their interaction with matter is concerned, the only differences that may arise are the result of the higher energies, in general, of the gamma radiations. The