NUCLEAR RADIATION DETECTION

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PREFACE

There has been a rapid growth in nuclear science and technology during the past decade. To bring this about, many scientists and engineers have pooled their various disciplines and experiences to develop what in many cases have been new and strange gadgets and techniques. Many more technical personnel will be joining this effort in the future.

The detection of nuclear radiation is involved to a certain extent in all nuclear science and technology. While only a few people are called upon to develop new detection methods and equipment, many are continually faced with the application of existing techniques to their own problems. Still a larger group are indirectly but still intimately connected with nuclear-radiation detection because their own responsibilities depend on the correct measurement of nuclear radiation by others.

In this book the attempt has been made to collect the basic information on all the important nuclear-radiation detectors in use today. Included with the description of the detectors is sufficient specific information on applications to enable the reader to select his own detection equipment and, in many cases, to apply it.

Practically all the detection equipment which is discussed in this book is available from commercial sources; the reader is referred to a very comprehensive buyers' guide published annually by *Nucleonics* magazine. Nevertheless, sufficient emphasis has been given to the principles on which the detection systems depend that the book should also prove useful to the reader who desires to design his own equipment.

This book was developed for use in the Nucleonics Instrumentation Course at the Air Force Institute of Technology. This course is given to Air Force officers enrolled in the Nuclear Engineering Curriculum at that Institute. It is hoped that this book will be useful to future students planning to enter the very fascinating field of nuclear science and technology as well as to many of the engineers and scientists presently engaged in these activities.

The author would like to express his thanks for the kind permission to use illustrations and data which has been given to him by many editors and scientists. The author would also like to express deep gratitude to his colleagues and students who have helped in various ways in the preparation of this book, to W. H. Jordan of Oak Ridge National Laboratory who read an earlier manuscript and offered many valuable criticisms and suggestions, to Miss Beulah McCray and others for their painstaking efforts in typing the manuscript, and to his wife, Betty N. Price, for her encouragement and able assistance.

William J. Price

CONTENTS

CHAPTER 1

PROPERTIES OF NUCLEAR RADIATION

The study of nuclear-radiation detection requires an understanding of the interaction of radiation with matter. This first chapter covers the essential aspects of that subject.

Nuclear radiation emanates from systems undergoing nuclear transformations, from particle accelerators, and as cosmic rays from outer space. This emanation includes subatomic and atomic particles as well as X and gamma rays. In Table 1–1 the common types of nuclear radiations are listed, along with several of their more important properties.

There are several obvious omissions from Table 1–1. One is the long list

TABLE 1–1. SOME CHARACTERISTICS OF NUCLEAR RADIATION

Type of Particle	Symbol	Charge (relative)	Approximate rest mass (relative)	Rest mass, amu
Neutron	n	0	1	1.008982
Proton	p	1	1	1.007593
Deuteron	d	1	2	2.014187
Triton	t	1	3	3.01645
Alpha particle	α	2	4	4.002777
Positron*	β^+, e^+	1	1/1,840	0.000549
Electrons or beta particles†	β^-, e^-	−1	1/1,840	0.000549
μ meson	μ	±1	210/1,840	0.115
π meson	π	±1	276/1,840	0.152
Gamma ray‡	γ			
X ray‡	X			
Neutrino	η	0	Small or zero	?
Fission fragments, average light	...	~20	~95	
Fission fragments, average heavy	...	~22	~139	

* The first symbol is used when the radiations are emitted from nuclei; this is sometimes referred to as beta-plus emission. The second symbol refers to the same particles when they occur in other connections.

† The term beta minus and the symbol β^- refer to electrons emitted from nuclei; usually these are called simply beta (β) particles.

‡ Gamma and X rays differ only in their origins; the former originate in the nucleus while the latter do not.

of particles of a more transient nature, such as neutral π mesons, τ mesons, κ mesons, and V particles. A discussion of the properties of these particles is beyond the scope of this book. However, the detection of this class of radiation is based on the principles covered in this text. Of the particles with atomic number greater than 2, only fission products are entered in Table 1–1. The omissions include those heavy particles which are given energy in modern particle accelerators and which are found as components of cosmic radiation.

The nature of the interactions with matter varies between the different types of nuclear radiation. In this discussion certain types are taken as prototypes and are discussed in detail. The properties of other types of radiation are then obtained from those of the prototype to which they are the most similar. The criteria for determining similarity are primarily charge and mass when the interest is in such properties as absorption. However, one should not overlook the fact that particles belonging to a given prototype may differ greatly in such important properties as spin and magnetic moment.

The radiations which have been selected here for the prototypes are alpha particles, fission fragments, electrons, gamma rays, and neutrons.

PROPERTIES OF ALPHA PARTICLES

1–1. *Alpha Particles as a Prototype*

The rate of energy loss of charged particles in passing through matter is shown in the next section to depend on the mass and the charge of particles. In the group of particle types consisting of alphas, tritons, deuterons, and protons, the masses differ by no more than a factor of 4, and the charges differ only by a factor of 2. Consequently, the ranges of these several particles can be related accurately. In addition, mesons may be included in this group; however, the large mass differences decrease the accuracy of the relationships.

Over a period of many years, extensive measurements have been made of alpha-particle ranges. These particles are emitted by radioactive nuclei and were among the first radiation types available. The energy with which these particles are emitted is dependent on the radioactive species, ranging up to about 10 Mev. In addition, alpha particles can be accelerated in several types of particle accelerators and are available with energies up to several hundred Mev.

1–2. *Absorption of Alpha Particles*

When alpha particles pass through absorbers, they lose energy by excitation and ionization of the absorber atoms. The mechanism which is mainly responsible for this energy loss is the interaction of the Coulomb fields of the particle with those of the bound electrons of the absorber. Because of the relative masses of the particles involved, the deflections of the alpha particles are negligible.

Two other processes occur by which alpha particles can be absorbed or removed from a beam of collimated alpha particles. These are nuclear transmutation and scattering by atomic nuclei. However, the contribution of these processes to the attenuation of a beam of alpha particles is negligible compared with that of the excitation and ionization processes.

Calculations of the charged-particle energy loss due to ionization and excitation have been made by Livingston and Bethe [1]. The energy loss per unit path, dE/dx, is known as the stopping power of the material. It can be expressed as

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 ZNB}{mv^2} \qquad (1\text{–}1)$$

where E, ze, and v = kinetic energy, charge, velocity, respectively, of primary particle
N = no. of absorber atoms per cm^3
Z = atomic no. of absorber
B = stopping number

The symbols e and m have the usual meanings of the electronic charge and the electronic mass, respectively.

The stopping number B is a logarithmic function of v and Z in the nonrelativistic energy range. Therefore, in this range, dE/dx depends on the particle velocity primarily through the $1/v^2$ term. The increase in the rate of energy loss with the decrease in velocity is to be expected because of the increase in the time required for the alpha particle to pass the bound electrons; this results in a larger impulse on the electrons and a larger probability for excitation and ionization.

Equation (1–1) breaks down for alpha particles when energies as low as 0.1 Mev are reached. This breakdown occurs because the velocity of the particles becomes so low that their charges fluctuate, owing to the alternate capture and loss of electrons. There is no theoretical expression for dE/dx in this region.

The dependence of the rate of energy loss on the atomic number of the absorber is primarily through the term outside the logarithmic function B. Thus, for a constant velocity, dE/dx is nearly proportional to NZ, the electron density in the absorber.

In the relativistic range of particle energy, dE/dx passes through a minimum which is followed by a slow increase with increasing particle energy. This is illustrated in Fig. 1–1, where the energy loss per centimeter of path in air is plotted for several particle types over a wide range of energy.

The status of the investigations of the stopping power of various materials has been reviewed by Allison and Warshaw [2]. The review contains values of dE/dx in several solids and gases; data for alpha particles and a number of similar particles are included.

The absorption of alpha particles may be studied experimentally by measuring the number of ion pairs produced per unit path length; this quantity is known as the specific ionization. The energy loss is related to the ionization through the quantity w which is the ratio of the energy lost by a charged particle to the total ionization produced by it. Values of w

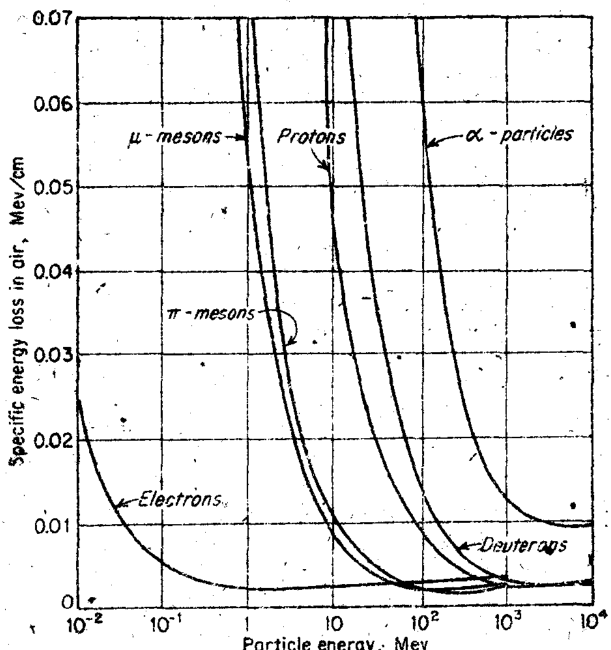

FIG. 1–1. Specific energy loss of various particles in air as a function of energy. [*From A. Beiser, Revs. Mod. Phys.*, **24**:273 (1952).]

have been found to depend on a number of factors, including the absorber material, particle type, and particle energy. This dependence has been reviewed by Uehling [3]. However, all values for gases appear to lie in a range from about 25 to 50 ev per ion pair. A number of different values of w for various conditions are collected in Table 1–2. An additional compilation of values of w appears in the review article by Bethe and Ashkin [4]. For condensed media, w is about 5 ev per ion pair.

The energy loss by a particle in the production of an ion pair in a gas is considerably in excess of that required only to ionize the atom. The addi-

TABLE 1–2. ENERGY LOSS PER ION PAIR*

Gas	w, ev	Particle	Energy, Mev
Air	32.0†	Electron	>0.3
Air	36.0	Proton	2.5–7.5
Air	35.1	Alpha	7.8
Air	35.6	Alpha	5.3
Hydrogen	36.0	Alpha	5.3
Helium	31.0	Alpha	5.3

* From L. H. Gray, *Proc. Cambridge Phil. Soc.*, 40:72 (1944).

† The recommendation that w be taken as 34 ev is made in the publication Report of the International Commission on Radiological Units and Measurements (ICRU) 1956, *Natl. Bur. Standards* (*U.S.*) *Handbook* 62, 1957.

tional energy goes into the dissociation of the gas molecules and the excitation of the atoms and molecules.

Example 1–1. Compute the charge of either sign which is released in an air ionization chamber by a 5-Mev alpha particle if it dissipates its entire energy in the air of the chamber.

Solution. The total number of ion pairs produced is

$$\frac{E}{w} = \frac{5 \times 10^6}{35.6} = (1.41 \times 10^5) \text{ ion pairs}$$

The value of w given in Table 1–2 for 5.3-Mev alpha particles has been used. The charge which is released is

$$\frac{Ee}{w} = (1.41 \times 10^5)(1.60 \times 10^{-19}) = (2.25 \times 10^{-14}) \text{ coulomb}$$

A plot of the specific ionization versus the particle energy is known as the Bragg curve. Figure 1–2 is a Bragg curve for alpha particles. In this

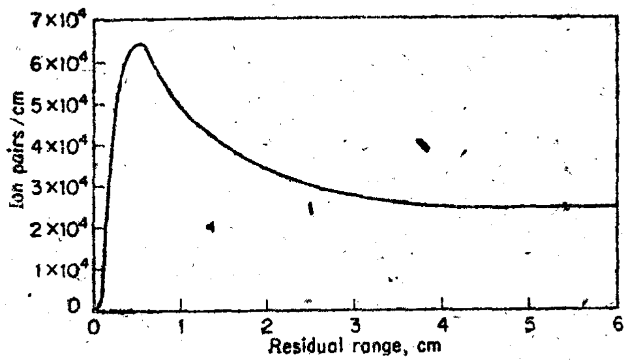

FIG. 1–2. Bragg curve for specific ionization in air at 15°C and 760 mm Hg.

curve the residual range of the particles in air is used as a measure of the particle energy.

1-3. *Range of Alpha Particles*

Alpha particles which are initially monoenergetic all are found to travel nearly the same distance in a given medium before coming to rest. This can be studied experimentally through the use of a collimated beam of alpha particles from a thin radioactive source. A thin source is one in which the loss of energy within the source is negligible. Measurements of the number of particles reaching a given distance versus the distance result in curves similar to those in Fig. 1-3. The ordinate of the integral curve is the

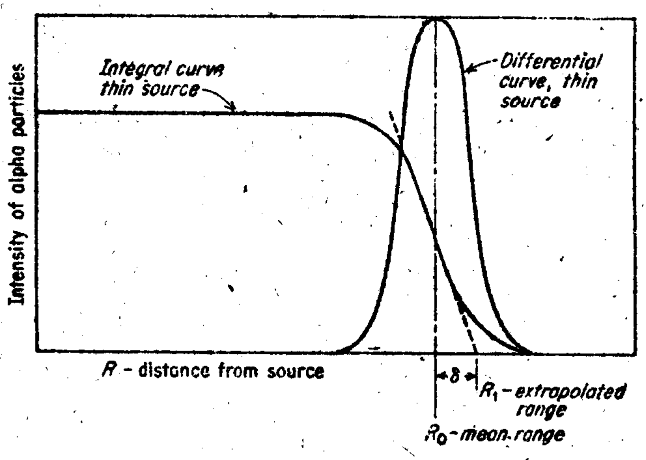

FIG. 1-3. Integral and differential range-distribution curves for alpha particles.

number of alpha particles per unit time which travel the distance R from the source or farther. The ordinate of the differential curve multiplied by dR is the number per unit time which have paths ending between the distances R and $R + dR$ from the source. The differential curve is Gaussian in form, with its maximum occurring at the mean range R_0 of the particles. The range R_1, which is obtained from the integral curve by a straight-line extrapolation from the point on the curve determined by R_0, is known as the extrapolated range.

The variation in the ranges of monoenergetic particles arises because of the statistical nature of the process by which the particles lose their energies. The energy loss occurs in a large but finite number of events. There are fluctuations in both the energy lost per event and the number of events per unit path length. Consequently there is a statistical fluctuation in the range of the particles.

The difference between the extrapolated and the mean ranges is referred to as the straggling and is designated as δ. The straggling amounts to about 1 per cent of the total range for 5-Mev alpha particles [3].

Extensive measurements have been made of the range-energy relationship of alpha particles in air. These results are commonly expressed with the normal conditions of temperature and pressure taken as 15°C and 760 mm Hg, respectively. Figures 1–4 and 1–5 show these relationships for the energy ranges of 0 to 8 Mev and 8 to 15 Mev, respectively.

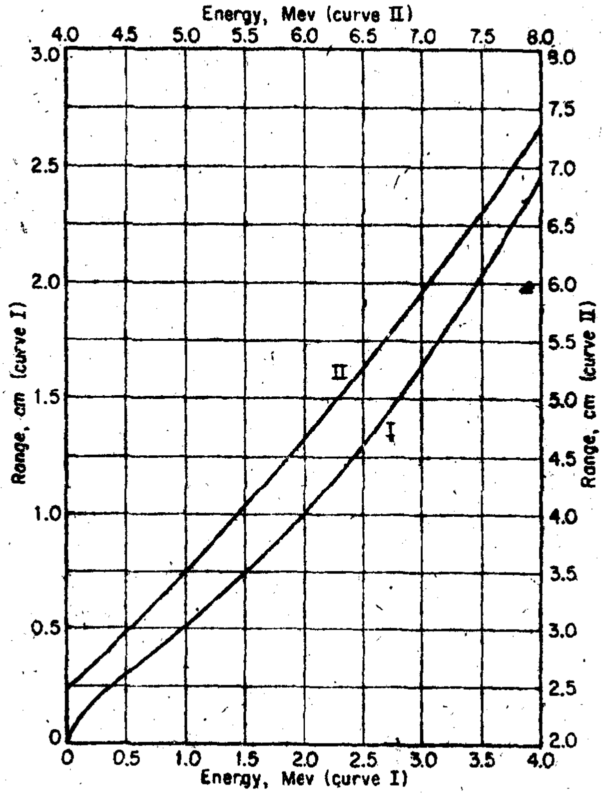

FIG. 1–4. Range-energy curves for alpha particles in air (15°C, 760 mm); energy range, 0 to 8 Mev. (*From H. A. Bethe, U.S. Atomic Energy Comm. Document BNL-T-7, 1949.*)

Empirical equations have been developed to relate the range in air and the energy of alpha particles. One such equation which fits with fair accuracy in the range from 4 to 7 Mev is

$$R = 0.309E^{3/2} \tag{1-2}$$

where R is the mean range in centimeters at normal conditions and E is the alpha-particle energy in Mev. At lower energies the dependence on energy is more nearly proportional to $E^{3/4}$, while at higher energies an E^2 dependence fits better.

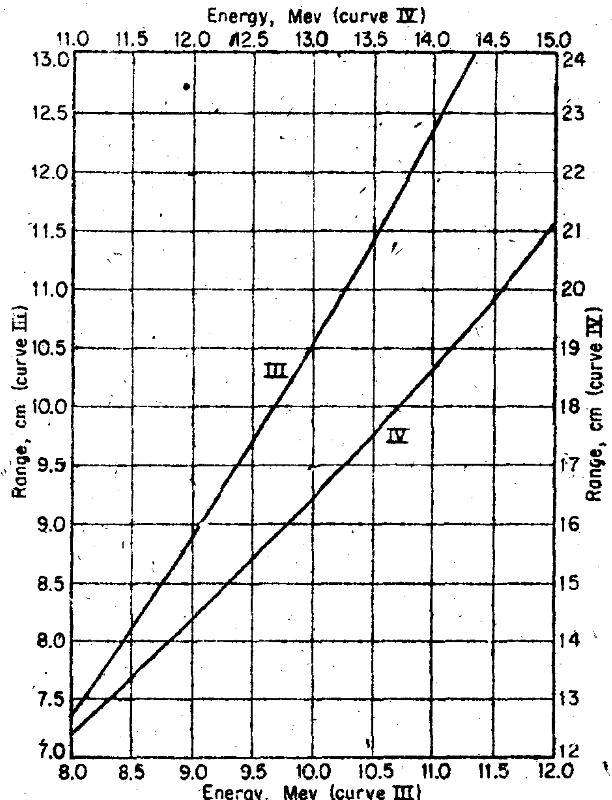

Fig. 1–5. Range-energy curves for alpha particles in air (15°C, 760 mm); energy range, 8 to 15 Mev. (*From H. A. Bethe, U.S. Atomic Energy Comm. Document BNL-T-7,* **1949.**)

1–4. *Absorption in Substances Other Than Air*

Extensive studies, both experimental and theoretical, have been made of the range-energy relationships of heavy particles in a variety of substances. Taylor [6] has reviewed the status of these investigations.

The range of heavy particles in materials other than air can be calculated through the use of the theoretical formula of Livingston and Bethe [1]. An extensive compilation of such curves has been made by Aron, Hoffman, and Williams [7]. More recently, Rich and Madey [8] have extended this work.

An empirical formula which allows the calculation of the range R_A of alpha particles in a material of atomic weight A is

$$R_A(\text{mg/cm}^2) = 0.56R(\text{cm})A^{1/3} \quad (1\text{–}3)$$

where R is the range, expressed in centimeters, of the alpha particle in air at 15°C and 760 mm Hg. The range in the material, expressed in centimeters, is obtained by dividing R_A by $10^3\rho$, where ρ is the density of the material in grams per cubic centimeter. Table 1–3 contains a comparison of the values of Aron, Hoffman, and Williams and those calculated from Eq. (1–3). It is seen that the agreement is reasonably good, particularly below 10 Mev.

TABLE 1–3. RANGE OF ALPHA PARTICLES IN VARIOUS SUBSTANCES

Range in air, cm	Energy in Mev	Range in Al, mg/cm²		Range in Cu, mg/cm²		Range in Ag, mg/cm²		Range in Pb, mg/cm²	
		Eq. (1–3)	Ref. 7	Eq. (1–3)	Ref. 7	Eq. (1–3)	Ref. 7	Eq. (1–3)	Ref. 7
1	2	1.7	1.5	2.2	.....	2.7	.....	3.3	3.7
2	3.5	3.4	3.1	4.4	.....	5.4	.....	6.6	6.7
5	6.3	8.4	7.6	11.2	10.4	13.4	11.5	16.6	18.0
10	9.7	17	14.8	22	20.2	27	24.3	33	34.5
100	37	168	140	224	185	268	220	332	303
1,000	132	1,680	1,400	2,240	1,700	2,680	2,000	3,320	2,500

Example 1–2. Calculate the minimum energy which an alpha particle can have and still be counted with a Geiger-Müller tube if the tube window is stainless steel with 2-mg/cm² thickness.

Solution. To be counted, the particle must pass through the tube window. Substituting 56 as the effective atomic weight of steel into Eq. (1–3), the range of the alpha particle in air at standard temperature and pressure is

$$R(\text{cm}) = \frac{R_A}{0.56A^{1/3}} = \frac{2}{(0.56)(56)^{1/3}} = 0.94 \text{ cm}$$

This range is seen by Fig. 1–4 to be that of a 1.9-Mev alpha particle.

The ranges of particles in various materials can be related to those in air through the concept of relative stopping power. The relative stopping power S of a material is the ratio of its stopping power to that of air. The stopping power may be expressed either as the energy loss per unit path length or as the energy loss per unit of thickness expressed in mass per unit area. The corresponding relative stopping powers are designated as the relative linear stopping power S_L and the relative mass stopping power S_m, respectively. The average values of S_L and S_m are listed in Table 1–4 for several metals at different alpha-particle energies. Again the range data on which this table is based are those of Aron, Hoffman, and Williams [7].

It is seen that these quantities are dependent on energy and consequently can yield only a very approximate answer unless this energy dependence is taken into account.

It is seen from the values of relative mass stopping power presented in

TABLE 1–4. RELATIVE STOPPING POWERS OF VARIOUS SUBSTANCES FOR ALPHA PARTICLES

Particle energy, Mev	Range in air, cm	Aluminum $\rho = 2.7$ g/cm³		Copper $\rho = 8.9$ g/cm³		Lead $\rho = 11.0$ g/cm³	
		S_L	S_m	S_L	S_m	S_L	S_m
2.0	1	1,800	0.80	.....	.....	2,900	0.32
6.3	5	1,780	0.79	4,300	0.58	3,050	0.33
9.7	10	1,820	0.81	4,400	0.59	3,200	0.35
37	100	1,940	0.86	4,800	0.65	3,600	0.39

Table 1–4 that the energy loss per unit of thickness expressed in mass per unit area decreases with an increase in the atomic number of the absorber. This decrease in the absorption is due largely to the increase in the average binding energy of the orbital electrons and shows up as a decrease in B in Eq. (1–1). An additional factor is the decrease in the number of orbital electrons per unit mass of the absorber.

Example 1–3. Compute the range of a 6-Mev alpha particle in lead.

Solution. By Fig. 1–4, a 6-Mev alpha particle has a range of 4.66 cm in air. By Table 1–4, the value of S_L for a 6.3-Mev alpha in lead is 3,050. Therefore, the range of the particle in lead is

$$R_{Pb} = \frac{R_{air}}{S_L} = \frac{4.66}{3{,}050} = (1.5 \times 10^{-3}) \text{ cm}$$

1–5. *Scaling Laws for Ranges of Similar Particles*

When the range-energy relationship is known for one type of particle in a given substance, it is possible to calculate the corresponding relationship for a different type of particle in the same substance. This calculation is made possible by the form of Eq. (1–1). The distance $R_{zM}(E_1 \rightarrow E_2)$ which a particle of mass M and charge ze travels while its energy decreases from E_1 to E_2 is

$$R_{zM}(E_1 \rightarrow E_2) = -\int_{E_2}^{E_1} \frac{dE}{dE/dx} = \frac{Mm}{4\pi e^4 z^2 ZN} \int_{v_2}^{v_1} \frac{v^3\, dv}{B(v)} \qquad (1\text{–}4)$$

where Eq. (1–1) has been used along with the relationship $E = Mv^2/2$. If the final velocity v_2 is taken as zero, one can write

$$R_{zM}(v) = Mz^{-2}F(v) \qquad (1\text{–}5)$$

where $F(v)$ is essentially the integral in Eq. (1–4) evaluated between the limits 0 to v. Equation (1–5) states that for different types of fast particles in a given absorber the range depends only upon the particle speed, its mass M, and its charge z.

By using Eq. (1–5), one can relate $R_p(v)$, the range of a proton of velocity v, to $R_\alpha(v)$, the range of an alpha particle of the same velocity; that is,

$$R_p(v) = \frac{M_p z_\alpha^2}{M_\alpha z_p^2} R_\alpha(v) - C \tag{1–6}$$

where the constant C must be used to take account of the capture and loss of electrons at low energy. Although the constant C is small, it is not zero, because alpha particles are affected differently from protons. For air at normal temperature and pressure, C has been found experimentally to be 0.20 cm when the energy is greater than about 500 kev. It gradually decreases to 0.02 cm at 6.7 kev [9]. Thus, for air at energies above 500 kev,

$$R_p(v) = 1.007 R_\alpha(v) - 0.20 \text{ cm} \tag{1–7}$$

Since for equal velocities the energies are related in the nonrelativistic case by $E_p = E_\alpha M_p/M_\alpha$, one can write

$$R_p(E) = 1.007 R_\alpha(3.972E) - 0.20 \text{ cm} \tag{1–8}$$

where $R_\alpha(3.972E)$ means the range of the alpha particle evaluated at $3.972E$.

The range-energy relationship for a particle of a given z can be obtained readily from that of a particle of different type but the same z. Since the capture and loss of electrons near the end of the range are the same for both types of particles, the correction term C disappears. Therefore the range of a particle of mass M can be calculated from that of mass M_0 when the charge is the same by the relationship

$$R_{zM}(E) = \frac{M}{M_0} R_{zM_0}(E') \tag{1–9}$$

where $E' = EM_0/M$.

The range of deuterons in air is shown in Fig. 1–6 for a large energy range. Through the use of Figs. 1–4 to 1–6 along with the scaling laws and the information in Sec. 1–4, it is possible to calculate the range-energy relationships for a number of different particle types in a large variety of substances.

Example 1–4. Use the information contained in the preceding sections to find the range of 10-Mev protons in air at standard conditions and in lead.

Solution. By Eq. (1–9) the range of a 10-Mev proton is obtained from that of a 19.9-Mev deuteron. Values of the latter for air appear in Fig. 1–6. Accordingly,

$$R_p(10 \text{ Mev}) = \frac{M_p}{M_d} R_d\left(\frac{M_d}{M_p} 10 \text{ Mev}\right) = \frac{1.008}{2.014} R_d(19.9 \text{ Mev})$$
$$= 115 \text{ cm of air}$$

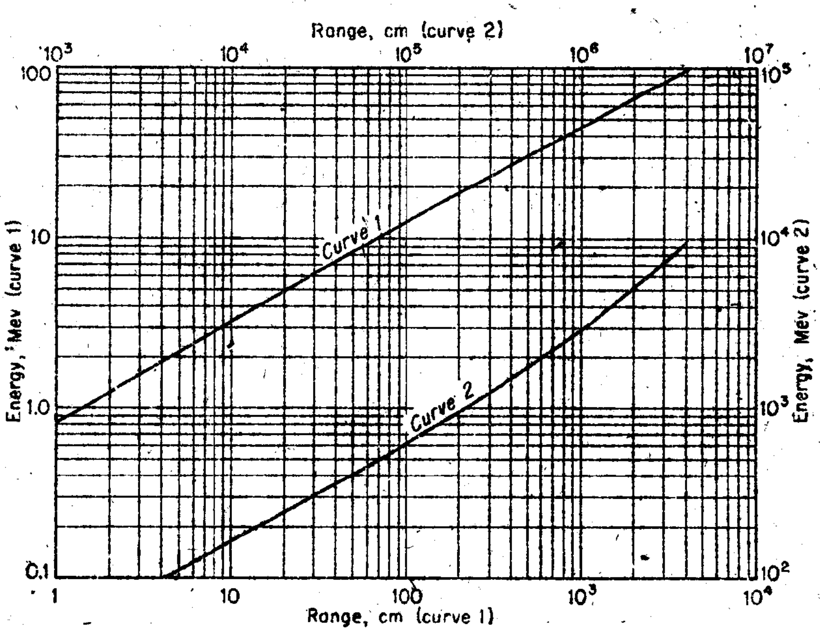

FIG. 1-6. Range-energy curves for deuterons in air (15°C, 760 mm); energy range, 1 to 10^5 Mev. (*From W. A. Aron, B. G. Hoffman, and F. C. Williams, U.S. Atomic Energy Comm. Document AECU*-663, 1949.)

The range of deuterons in lead is not available. However, the range of alphas in lead can be computed from Eq. (1-3), and the range of the protons can be obtained from that of the alphas by Eq. (1-6). The range in air of an alpha with the same velocity as a 10-Mev proton is, by Eq. (1-7),

$$R_\alpha(v) = \frac{R_p(v) + C}{1.007} = \frac{115 + 0.2}{1.007} = 114 \text{ cm}$$

By Eq. (1-3), the range of the same-energy alpha in lead is

$$R_\alpha \text{ (mg/cm}^2\text{)} = (0.56)\,(114)\,(207)^{1/3} = 378 \text{ mg/cm}^2$$

Applying Eq. (1-6) again and neglecting C lead to

$$\text{Range of 10-Mev proton in lead} = (378)\,(1.007) = 380 \text{ mg/cm}^2$$

(NOTE. A more accurate value is 340 mg/cm².)

FISSION FRAGMENTS

1-6. *Penetration of Fission Products through Matter*

Fission fragments contain elements of mass numbers from approximately 72 to 160. However, the yield curve is found to have two predominant maxima. The group around the maximum of lowest mass number is referred to as the "light fragment," while the other group is known as the "heavy fragment."