I
NATIONAL BUREAU OF STANDARDS REPORT

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**PRINCIPLES
OF
RADIOLOGICAL PHYSICS**

**BY
U. FANO**

**U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS**

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II

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The scope of activities of the National Bureau of Standards is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section is engaged in specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant reports and publications, appears on the inside of the back cover of this report.

1. **ELECTRICITY.** Resistance Measurements. Inductance and Capacitance. Electrical Instruments. Magnetic Measurements. Electrochemistry.
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10. **BUILDING TECHNOLOGY.** Structural Engineering. Fire Protection. Heating and Air Conditioning. Exterior and Interior Coverings. Codes and Specifications.
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12. **ELECTRONICS.** Engineering Electronics. Electron Tubes. Electronic Computers.
13. **ORDNANCE DEVELOPMENT.** Mechanical Research and Development. Electromechanical Fuzes. Technical Services. Missile Fuzing Research. Missile Fuzing Development. Projectile Fuzes. Ordnance Components. Ordnance Tests. Ordnance Research.
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NBS PROJECT

2925

III

NBS REPORT

1002

201

**PRINCIPLES
OF
RADIOLOGICAL PHYSICS**

BY

U. FANO

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This report provides for interim circulation of a manuscript which has been prepared as a chapter of the three volumes on "Radiation Biology" edited by A. Hollaender of the Oak Ridge National Laboratory and to be published by the McGraw-Hill Book Co. under the auspices of the National Research Council.

The chapter is designed for a dual purpose. It should serve workers in biology and medicine as an introduction to the principles of radiological physics. To this end it includes brief summaries of the elements of atomic and radiation physics. The second purpose is to strive for an elementary but all-inclusive treatment of the broad question: what happens when radiation strikes a material? The attempt to present such a treatment has pointed up large gaps in our knowledge.

The filling of these gaps is a main goal of the current program of research in basic radiation physics at the National Bureau of Standards. This report includes several new results of research, which was supported by the CNR and the AEC. In particular, the Biophysics Branch of the AEC is supporting a project directed to survey and disseminate information regarding the action of radiations on matter. Much work which was specifically required for the preparation and illustration of this report has been carried out as a part of that project.

This report represents only a first step in the attainment of the author's goal. Criticism and suggestions by the readers regarding the content and the presentation of the report as well as its distribution to additional laboratories or individuals will be appreciated.

Lauriston S. Taylor

Chief Radiation Physics Laboratory

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Contents V

1. PROPERTIES AND PRODUCTION OF RADIATIONS	2
1.1 Corpuscular radiations	4
a. Methods of detection	5
b. Types of corpuscular radiation	7
c. Potency of corpuscular radiations	10
1.2 Production of corpuscular radiations	12
a. Sources of charged particles	12
b. Acceleration of charged particles	13
c. Nuclear sources of fast charged particles	15
d. Neutron sources	16
1.3 Electromagnetic radiation	18
a. Frequency and wavelength	19
b. Potency of electromagnetic radiation	23
c. Classification of electromagnetic radiation	26
d. Detection of electromagnetic radiation	28
1.4 Production of electromagnetic radiation	29
a. Optical radiation	29
b. X rays	30
2. ACTION OF RADIATIONS UPON ATOMS AND MOLECULES	33
2.1 Summary of Information on atoms and molecules	35
a. Structure of atoms	35
b. Aggregates of atoms	39
c. Effects of excitation	42
d. Nuclear disintegrations	46
2.2 Elementary processes involving radiation and free particles	48
a. Compton scattering	49
b. Pair production	51
c. Elastic collision of charged particles (Rutherford scattering)	53
d. Magnetic effects	55
e. Effect of nuclear forces	56
f. Summary table	57
2.3 Action of light & X rays upon atoms & Molecules	58
2.4 Action of charged particles upon atoms & molecules	63
a. Mechanism of inelastic collisions	66
b. Energy dissipated in inelastic collisions	68
c. Probability of inelastic collisions	71
d. Excitation of atomic nuclei	73
2.5 Nuclear collisions	74
3. THE DISSIPATION OF RADIATION ENERGY IN MATTER	77
3.1 Activation by charged corpuscular radiations	81
a. Characteristics of glancing collisions	84
b. Ionization yield	85
c. Energy dissipation by lower energy heavy particles	88
d. Dissipation of energy by secondary electrons	90
3.2 Activation by X rays and γ rays	91

3.3 Activation by neutrons	93
3.4 Activation by infrared, visible and ultraviolet light	96
3.5 Action of far infrared and radiofrequency radiation	97
3.6 Spatial distribution of activations	100
a. Collision distance along the tracks of fast particles	102
b. Distribution of activations produced by secondary electrons	105
c. Overall distribution of activations around the tracks of fast particles	107
3.7 Summary	110
4. PENETRATION OF RADIATIONS IN MATTER	112
4.1 Heavy charged particles	114
a. Straggling	116
b. Deflection of the track	116
c. Effect of nuclear collisions	117
4.2 Electrons	117
a. Moderate energy: penetration limited by deflection	119
b. Intermediate energy: predominance of energy loss by collision	123
c. Extremely high energy: predominance of radiation losses, cascade shower effects	125
d. Positive electrons	128
e. Penetration of thin foils	130
f. Penetration of thick foils	131
g. Data on electron penetration	132
h. Penetration of β rays through thick foils	133
4.3 X rays	134
a. Law of penetration for monochromatic X rays ("Narrow beam" penetration)	134
b. Penetration of non monochromatic X rays	139
c. Scattered and secondary X rays	139
d. Energy distribution	143
4.4 Neutrons	145
a. "Narrow beam" penetration	146
b. Scattered and secondary neutrons	147
c. Energy distribution	148
4.5 Light	151
5. KINETICS OF RADIATION ACTION	153
5.1 Introduction	153
a. The radiation dose	154
b. Methods of expressing macroscopic effects	157
5.2 Simple dose-effects relationships	159
a. Exponential curves	160
b. Range of validity of exponential curves	163
c. Effective volumes and effective areas	165
d. Target theory	169

- cont'd -

VII

5.3 "Sigmoid" dose-effect curves	173
5.4 Time-intensity factor	176
5.5 Comparative effectiveness of different radiations	179
a. Equal effectiveness	180
b. Higher effectiveness of densely ionizing radiations	182
c. The "saturation effect"	183

CHAPTER I

-1-

PRINCIPLES OF RADIOLOGICAL PHYSICS

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This chapter deals with facts and concepts of physics which underlie the action of radiations upon matter in general and upon biological materials in particular. It stresses the line of thought which may be followed in analyzing the radiation effects, but the reader will be often referred to other sources for technical details.

Physics has attained a fairly satisfactory understanding of the nature of radiations. The direct action of radiations upon single atoms or small groups of atoms is also rather well understood. Moreover, one may draw an adequate over-all picture of the processes through which the action of radiations becomes distributed over macroscopic portions of matter.

The nature of radiations and their action on small groups of atoms are the subject of the first sections (#1 and 2) of this chapter. The over-all picture of the action on sizeable amounts of matter constitutes the central and main section (#3). The next section (#4) deals with the penetration of radiations to various layers of an irradiated material. Knowledge of this field is far from satisfactory.

It should be clear from the outset that no detailed information exists regarding the effect of radiations upon any but the smallest groups of atoms. Even less is known, of course, regarding the effects on complex biochemical substances or on the far more highly organized biological materials. The present treatment does not attempt to cover

these topics which are more properly classed as radio-chemistry or radio-biology.

Nevertheless the relationships between the physical characteristics of a radiation treatment and its eventual biological effects may be analyzed to some extent without any detailed knowledge of the mechanisms of radio-biological actions. The last section (#5) deals with the methods of this analysis.

1. PROPERTIES AND PRODUCTION OF RADIATIONS

The term "radiation" usually indicates a physical phenomenon in which energy travels through space, even though that space be empty of matter.

There are two classes of radiations, namely:

(1) Corpuscular radiations, consisting of streams of various kinds of atomic or subatomic particles, which can transfer their kinetic energy to anything they strike.*

* A stream of macroscopic particles such as pebbles fits, strictly speaking, the above definition of radiation but it is not generally understood to be covered by that name.

(2) Electromagnetic radiations, consisting of self propagating electric and magnetic disturbances, which affect the internal structure of matter and thus dissipate their energy.

Sound phenomena depend for their propagation upon the presence of an elastic material medium (e.g., air) and accordingly are not classified as radiations.

Table 1 shows a classification of radiations with references to the pertinent sections of the following treatment. Corpuscular radiations are classified according to the nature of the constituent particles. The classification of electromagnetic radiations has practical rather than intrinsic significance (see p. 26). Notes are appended regarding other radiations of lesser biological importance.

Table 1 - Classification of Radiations

Corpuscular			Electromagnetic		
Electrically charged		Electrically			
Light	Heavy	Neutral			
Cathode rays (electrons) Positrons P. 8, 13ff	Protons, deuterons and other ion beams P. 9, 13ff	Neutrons P. 9, 20ff	Radio- waves Micro- waves P. 27, 29ff	Light (infrared, visible and ultra- violet) P. 27, 29ff	X rays (or roentgen rays) P. 27, 29ff
β -rays	Special names of radiations from atomic nuclei (P. 15)				γ -rays
	α -rays (=beams of He ions)				

Cosmic rays consist of a complex of radiations which flow constantly through the earth's atmosphere in a general downward direction and achieve some penetration in the earth's crust. Several components of this complex are identical with corpuscular and electromagnetic radiations studied in the laboratory. Other components include particles of energies still not attained in the laboratory. Cosmic rays seem to have little biological significance because their over-all intensity is quite low.

Mesons include a variety of subatomic particles heavier than electrons but lighter than protons or neutrons. Mesons arise from the collision of very high energy radiations with atomic nuclei but have only a brief existence and presumably no biological significance.

Neutrino is the constituent of a radiation which is presumed to arise from the emission of β rays and from other subatomic processes (see p.). A certain amount of energy and momentum remains unaccounted for in these processes. The circumstances indicate that the balance of energy and momentum is removed by a still undetected but otherwise well-defined radiation whose carrier element is electrically neutral and is called neutrino. The circumstances also indicate that this radiation ought to exert an exceedingly small action on matter and thus explain why this action has not yet been detected.

Molecular rays are beams of mono- or poly-atomic molecules which escape from an enclosure into a high vacuum carrying little energy and no electric charge.

1.1 Corpuscular radiations

Material corpuscles (or "particles") are physical entities endowed with a mass. On account of their mass, atomic particles behave like macroscopic bodies, at least in so far as their velocity can be varied to a great extent by physical means. Any change of velocity is accompanied by energy transformations. Acceleration of a particle is effected by a force which imparts to the particle a certain amount of energy to be stored in the form of kinetic energy. This energy is returned when the particle slows down owing to the action of a force opposing its motion. The storage of kinetic energy constitutes the main mechanism for energy transport by corpuscular radiation. (The internal structure of each traveling particle may contain additional energy.)

The deflection of radiation particles is effected by a force perpendicular to their line of motion. The observation of such deflections

serves to analyze the radiation response to various forces and thereby to analyze the nature of the radiation. For example, the α and β rays ejected by certain radioactive substances turn in opposite directions when they traverse a magnetic field (see Fig. 1). The deflection indicates that the α rays carry a positive charge, and, in these cases, the β rays a negative charge.

The analysis of corpuscular radiations progresses also through the study of their penetration in various materials (see parts 2, 3, and 4). Determination of the nature and velocity of the constituent particles marks the completion of this analysis.

1.1a METHODS OF DETECTION. Corpuscular radiations are detected by the effects produced by their impact on matter. For instance, one can measure the electric charge delivered to a body by a radiation, the heat dissipated in the body, the luminescence caused in certain materials, or the blackening of photographic films. Electrically charged radiation particles are generally easier to detect than electrically neutral ones, because they interact electrically with the atoms of matter even from a considerable distance.

It is possible to demonstrate directly that a radiation consists of discrete particles, for example by detecting the arrival of individual particles upon a luminescent screen. This method of observing "scintillations" served as a basis for the early study of α rays. It has become much more practical since the introduction of improved luminescent materials and of devices which record the scintillations automatically.

Two other very effective methods for detecting and studying individual fast charged particles are the Wilson cloud chamber and the Geiger counter.

They rely on the ability of radiation particles to eject electrons when they collide with gas molecules and thus to create pairs of separated charges of opposite sign, i.e., pairs of "ions".

The cloud chamber (Fig. 2) is a vessel filled with a gas saturated with water vapor. The chamber is suddenly expanded, at intervals, and each time the vapor becomes supersaturated. The Vapor cannot condense into water droplets, in the absence of impurity particles which act as condensation nuclei. However, ions can serve as condensation nuclei and hence a thin cloud marks the trail of any particle which has recently traversed the chamber (Fig. 3). (Gentner et al, 1940).

A Geiger counter consists essentially of a wire and of a tube surrounding it. An electric potential difference is established between wire and tube, which is not quite sufficient to cause a discharge under normal conditions. When a particle traverses the counter and creates a pair of ions in the filler gas, the electric force accelerates the ions and thereby starts a sudden discharge. After this, the wire and the tube recharge and no discharge passes until a new ionizing particle comes by. Thus, one counter detects the passage of a single particle at a time while a set of counters may serve to trace the path of a particle.

For information on counting devices the reader is referred to a report by Wilson, Corson and Baker (1950).

Another method of observing radiations, similarly based on the ejection of electrons from gas molecules, becomes possible at somewhat higher levels of intensity when the total separation of positive and

negative electric charges ("ionization") is adequate for measurement by electric techniques. One measures ionization by attracting the charges of opposite sign toward two electric terminals (Fig. 4). Vessels designed for this purpose are called "ionization chambers" and constitute basic dependable tools for radiation detection and measurement, see e.g. Halliday (1951) p. 170.

Neutrons are detected indirectly, through the effect of secondary radiations arising from the capture of neutrons by atomic nuclei (see p. 74)

1.1b TYPES OF CORPUSCULAR RADIATIONS. As stated before, any stream of atomic or subatomic particles constitutes a corpuscular radiation.

The main characteristics of the various kinds of particles are their mass and their electric charge. The masses are conveniently expressed in the scale of atomic weights in which

$$1 \text{ unit atomic weight} = \frac{1 \text{ gram}}{\text{Avogadro's number}} = 1.66 \times 10^{-24} \text{ gram} \quad (1)$$

The electric charges are conveniently expressed in terms of the charge of an electron, whose sign is negative and whose magnitude is usually indicated by the symbol

$$e = 4.80 \times 10^{-10} \text{ e.s.u.} = 1.60 \times 10^{-19} \text{ coulomb} \quad (2)$$

The charges of atomic particles may be positive or negative but are always integral multiples of the charge of an electron.

The corpuscular radiations listed in Table 1 fall in the following three groups:

I. Light charged particles, namely:

(a) Electron, with atomic weight $1/1823$ and a negative charge equal to e . Electrons are a normal constituent of all kinds of matter. They spring out from matter when sufficient energy becomes available for them to overcome the attraction of the positive charges carried by the atomic nuclei. This energy may be supplied by radiation or simply by heat. Classical studies have been made of electrons as they emerge from the negative terminal ("cathode") of an electric circuit inserted in an evacuated vessel and form a beam of cathode rays (see e.g. Richtmeyer & Kennard, 1942, p. 92 ff). Electrons are also called negative β particles.

(b) Positron, with atomic weight $1/1823$ and a positive charge equal to e . Positrons are the positively charged counterpart of the electrons and are also called "positive electrons" or positive β particles. They are not a normal constituent of matter because they quickly vanish by combining with one of the ever present electrons of matter (see below and p. 52). Positrons may emerge from atomic nuclei as a result of nuclear transformations (see below) or from matter exposed to high energy radiations (see p. 51). For further data see Richtmeyer & Kennard (1942) p. 610 ff.

II. Heavy charged particles are atoms of any kind of matter stripped of some or all of their electrons, i.e., turned into positive ions. They are produced and studied conveniently when an electric discharge passes through a rarefied gas or vapor in a suitable arrangement, see e.g. Richtmeyer and Kennard (1942) p. 406, 556. The following ions are widely used as the constituents of radiations:

(c) Protons, bare nuclei of the common isotope of hydrogen, with atomic weight 1.008 and a positive charge equal to e .

(d) Deuterons, bare nuclei of the heavy isotope of hydrogen, with atomic weight 2.015 and a positive charge equal to e .

(e) Alpha particles, bare nuclei of helium, stripped of both electrons, with atomic weight 4.003 and a positive charge equal to $2e$.

III. Neutral particles, one of which has great practical importance, namely the:

(a) Neutron, with atomic weight 1.009 and no electric charge. Neutrons are a normal constituent of the nuclei of all kinds of matter, except the common isotope of hydrogen. They are released from nuclei only in the course of transformations induced by high energy radiations, see e.g. Richtmeyer & Kennard (1942) p. 615 ff.

The constituent particles of radiations are by no means strictly unchangeable entities, even though some of them are normal constituents of matter. In fact, none of the particles is strictly unchangeable and some have only a fleeting existence under ordinary conditions. Thus, any positron quickly vanishes, together with an electron, giving rise to high energy radiation. (Similarly, electrons would disappear quickly if the world contained an excess of positrons.)

Isolated neutrons are intrinsically unstable. They can turn into protons ejecting at the same time a negative electron and, presumably, a "neutrino" (see note on table 1). Neutrons, if left to themselves, undergo this transformation at random, now one neutron and then another, at irregular intervals. On the average, half of the neutrons existing at any one time are expected to turn into protons in approximately $1/4$ of an hour. However, the great majority of free neutrons disappear by capture in some atomic nucleus in a much shorter time, i.e. before transforming into protons.

Protons may turn into neutrons through a similar transformation ejecting a positive electron and, presumably, a neutrino. However, this transformation is energetically impossible unless the proton is part of a nucleus and the rest of the nucleus supplies the necessary energy.

The transformations of protons into neutrons and of neutrons into protons within a nucleus constitute the processes of " β disintegration".

1.1c POTENCY OF CORPUSCULAR RADIATIONS. The ability of a corpuscular radiation to affect the properties of matter clearly depends not only on the nature of its constituent particles and on their total energy but also on the kinetic energy of each single particle. A few particles of high kinetic energy can produce effects which a far larger number of particles of low kinetic energy cannot possibly achieve. Therefore an indication of the speed or of the kinetic energy of individual particles serves as a measure of what we may call the "potency" of the radiation.

The basic unit employed with reference to the kinetic energy of atomic particles is the "electron-volt" (ev), that is, the increase of kinetic energy experienced by an electron while being accelerated across a potential difference of 1 volt. This unit has a direct significance when applied to a particle carrying the same quantity of electric charge as an electron but it is currently used as a unit of energy with reference to particles carrying any quantity of charge or no charge at all.

$$1 \text{ ev} = 1.6 \times 10^{-19} \text{ joule} = 1.6 \times 10^{-12} \text{ erg} \quad (3)$$

When the kinetic energy, E , of a particle is expressed in ev and its mass, M , in units of atomic weight, its velocity is given by

$$v = 1.4 \times 10^6 \sqrt{E/M} \text{ cm/sec} \quad (4)$$

(This formula is valid only if its result is much less than 10^{10} cm/sec, otherwise it must be replaced by a more complicated formula of relativistic mechanics.)

The kinetic energy of individual particles may also be expressed in terms of the chemical energy unit "calorie per mole". One mole of a substance consists of Avogadro's number, $N = 6.0 \times 10^{23}$, of molecules. If each of these molecules has, for example, a kinetic energy of 1 ev, the entire mole has a kinetic energy equal to

$$6.0 \times 10^{23} \times 1.6 \times 10^{-12} \text{ ergs} = 9.6 \times 10^{11} \text{ ergs} = 23,000 \text{ calories.}$$

In the same way if a chemical reaction yields 1,000 cal/mole, this means that each molecule participating in the reaction has yielded $1/23$ ev.

The equation

$$1 \text{ ev} = 23,000 \text{ cal/mole} \tag{5}$$

serves to estimate the chemical "potency" of a radiation. For example, if a certain gas reaction requires an activation energy of 50,000 cal/mole, each molecule can be activated by the impact of a particle only if this particle has a kinetic energy equal to at least $50/23 = 2.2$ ev.

There is yet another method of expressing the "potency" of a radiation with reference to familiar thermal concepts. The kinetic energy of vapor molecules which filter out of an oven at a temperature of T degrees absolute have a kinetic energy of the order of magnitude of kT ($k = 1.4 \times 10^{-16}$ erg/degree $= 8.5 \times 10^{-5}$ ev/degree represents the "Boltzmann constant"). The formula indicates that it would take an oven at about 12,000 °C to emit particles with a kinetic energy of the order of 1 ev. One may thus characterize any radiation source from the thermal standpoint by means of an "equivalent temperature" which is proportional to the kinetic energy of the radiation particles at a

rate of

12,000 °C/ev.

A comparison of the various scales of radiation potency is shown in Fig. 5.

1.2 Production of corpuscular radiations

Electrically charged particles can be directed into a beam and then accelerated to a desired velocity under the action of electric forces. Neutral particles, on the contrary, cannot be controlled easily; the main device to form a beam of neutral particles is to let the particles pass from the space where they are produced to another portion of space through collimating holes or slits.

1.2a SOURCES OF CHARGED PARTICLES. Electrons are easily produced in a vacuum by heating a metal. The hot metal emits electrons in quantities limited only by the mutual repulsion of the electrons in the surrounding space ("space charge effect"). Rates of emission of the order of amperes, i.e., of 10^{19} electrons per second, are practicable.

Positrons have to be emitted by radioactive nuclei or produced by X rays. Their rate of production is much smaller than that of electrons from a hot wire. For example, a "strong" radioactive source, of the order of curies, yields only 10^{11} positrons per second, i.e. about 10^{-8} amperes.

Protons and other positive ions are produced by stripping electrons off the atoms or molecules of a gas at low pressure. The stripping results from the violent atomic collisions which accompany an electric

discharge. Usable ion beam intensities of the order of a milliamperere have been obtained.

Charged particles produced by these methods can be formed into a beam by attracting them toward a conductor charged with electricity of opposite sign. Thence they can be canalized into empty space. Suitably distributed electric and magnetic forces also serve to concentrate or "focus" beams of charged particles. Still, the achievement of good focussing at a high intensity level offers difficulties.

1.2b ACCELERATION OF CHARGED PARTICLES. The simplest method for accelerating charged particles is to subject them to the electric force between two conductors with a sufficiently large potential difference. For example, if a source of singly ionized atoms lies at an electric potential 1 million volts above that of a target and if the ions can move freely, their kinetic energy increases to 1 million electron volts (Mev) by the time they reach the target. This method serves, for example, to provide beams of high energy cathode rays in the ordinary cathode ray or X-ray tubes (Fig. 6). The main limitation to this method lies in the technical difficulty of generating and maintaining potential differences as large as might be desired.

Large potential differences are produced by a suitable arrangement of a.c. transformers followed by rectifying stages, or by electrostatic generators (Van de Graaff machines). The main component of an electrostatic generator is a mechanically driven insulator belt which picks up electric charges at one point and deposits them onto a high voltage conductor (see Fig. 7). Multi-million-volt accelerators are normally enclosed in high pressure tanks which make it easier to maintain a high voltage without discharge through the surrounding space. The highest performance yet attained by this method is a steady potential difference of approximately 5 million volts.

In the acceleration of charged particles one should distribute the voltage difference in such a way that the particles follow paths concentrated in a narrow beam. Fig. 8 shows the usual method for achieving this end in the construction of very high voltage accelerator tubes. The voltage differences between successive metallic sections are about equal.

In order to achieve very high kinetic energies without having to produce correspondingly high voltage differences, one subdivides the acceleration of the particles in a large number of steps, each step involving only a moderately high potential difference. For example, a group of particles traveling along the axis of a series of cylindrical electrodes (see Fig. 9b) can receive one step of acceleration at each gap between successive electrodes. For this purpose one need not maintain a steady very high potential difference distributed along the set. The potential difference at each gap may oscillate (see Fig. 9a) provided the oscillations are timed to apply the acceleration in the correct direction whenever a group of particles arrives at the gap. An arrangement of this kind with a large number of gaps in a straight line constitutes a "linear accelerator" (Fig. 9c).

However, most frequently the particles are made to return again and again to the same gap by forcing them to follow a closed path by means of a deflecting magnet. A machine built on this principle, in which the deflecting field remains constant and the particles turn in larger and larger circles as they gather momentum, is called a "cyclotron", (Fig. 10). A "synchrotron" is a machine in which the particles are kept on a constant path by a magnetic field whose strength increases as the particles gather momentum. A number of combinations of these principles have been developed under various names.

Another type of machine relies on the principle of the familiar a.c. transformer and is called "induction accelerator" or also "betatron" (because it is particularly suited to the acceleration of electrons, i.e. of β particles). A transformer consists of an electromagnet excited by an alternating current in a primary winding. The alternating magnetic force induces, in turn, a current in another coil, the secondary winding. The voltage developed at the terminals of the secondary is proportional to the number of turns in the winding. A betatron is, in effect, a large transformer whose secondary current consists of electrons circulating in an evacuated ring-shaped tube, called the "donut". (see Fig. 11). Each electron circulates a very large number of times (e.g. 1,000,000 times) and thus gathers an energy corresponding to the voltage that would be achieved in a secondary winding with a similarly large number of turns.

The main obstacle to the development of high performance linear accelerators is found in timing accurately the voltage oscillations at many different gaps. The necessary length of the machine and the

problems of keeping the particles in a focused beam also cause difficulties. The main limitation in the development of cyclotrons and synchrotrons arises from the necessity of maintaining very high energy particles on a closed steady path. The deflection of the particles requires very large deflecting magnets. Moreover, particles being deflected along a closed path constitute a variable current which emits electromagnetic radiation; the energy loss by radiation is expected to become very serious at energies of the order of 10^9 ev. Finally, the problem of keeping the particle beam focused and of timing the variations of all fields are not indifferent.

Various types of accelerators yielding energies of several hundred million electron volts were in operation in 1950. For further information on high energy accelerators see e.g., Halliday (1950) Chapt.9.

1.2c NUCLEAR SOURCES OF FAST CHARGED PARTICLES. Many substances emit electrons or alpha particles with energies of the order of a few Mev as a result of spontaneous transformations of their atomic nuclei. The substances whose nuclei undergo such transformations are called "radioactive." These spontaneous transformations or "disintegrations" occur now and then at random in the nuclei of different atoms of a substance at an average rate which is characteristic for each kind of nucleus.

The substances found in nature contain between 300 and 400 species of atomic nuclei, among which nearly 50 were known to be unstable, i.e. radioactive, by the end of 1950. The best known of these radioactive substances are the elements heavier than bismuth. A few radioactive isotopes of lighter elements are also found in nature. One of these is an isotope of potassium.

Nearly 1,000 other species of nuclei have been produced artificially as the result of nuclear collisions. These are generally unstable, i.e., radioactive, and emit either electrons, or positrons; some of them emit α particles, or neutrons.

Natural radioactive substances were for a long time the only sources of fast charged particles. Natural and artificial radioactive substances are still very useful as steady and finely divisible sources of fast particles.

An amount of radioactive material, whose nuclei disintegrate at a rate of 3.7×10^{10} per second is called "one curie". A radioactive source of one curie is regarded as intense, but sources of much greater intensity have been prepared occasionally.

For a collection of data on radioactivity see Way et al (1950); for data on availability of radioactive materials, see Isotopes catalogue (1949).

1.2d NEUTRON SOURCES. Neutrons become available as by-products of nuclear collisions. They remain available for a short time only since they have a considerable chance of being captured by any nucleus with which they collide. These conditions make it difficult to provide large numbers of neutrons.

Collisions between ordinary nuclei cannot be produced very easily because nuclei repel one another electrically. Therefore nuclei collide only if they are shot against one another with high energy. Most kinds of nuclear collisions are likely to result in the ejection of one or more neutrons (see p. 46). The bombardment of atoms by a beam of fast deuterons is a particularly efficient source of neutrons, since the

neutron contained in the deuteron is loosely bound and easily splits off. Neutrons of energy beyond 100 Mev have been produced by this method.

Collisions between neutrons and other nuclei are not hindered by electrostatic repulsion and can therefore occur in large numbers if only the neutrons are available in the first place. The "fission reaction" of the heaviest nuclei, that is their splitting into nearly equal parts, results frequently from the impact of a neutron and liberates on the average about 2.5 neutrons as a by-product. Therefore the fission reaction can take place on a large scale under appropriate conditions, leading to the incidental release of large amounts of neutrons. The principle is that, on the average, one of the neutrons produced by a fission must terminate in production of another fission. If this is so, fissions will follow one another in a self-sustaining chain reaction. The difficulty lies in preventing an excessive waste of neutrons in parasitic processes.

A device where a chain reaction of fissions proceeds and is kept at a desired level of operation by controlled absorption of any excess neutron production is usually called a "nuclear reactor" or "pile", see e.g. Halliday (1950) p. 422. The neutrons produced by fission have various energies of the order of magnitude of 1 Mev. A very intense beam of neutrons can be obtained by simply opening a port through the shielding that normally surrounds a pile.

Neutrons flow in all directions within a pile. A neutron flux of 10^{13} neutrons/cm² sec. has been reported.

1.3 Electromagnetic radiation

Light, ^Xrays and radio waves have a common nature. Therefore we may well regard electromagnetic radiation as a single phenomenon. This radiation originates from a change of intensity of an electric current in the course of time, like the more familiar phenomenon of electromagnetic induction. In fact, electromagnetic radiation may be regarded as a persistent and far-traveling offshoot of ordinary induction. A brief review of the phenomenon of induction yields some indication of the mechanism of electromagnetic radiation, and of the main factors that influence its production.

The onset of a current in an electric circuit is never abrupt but is marked by a lag due to the phenomenon of "self-induction." During this lag the current generator performs work to establish the current against the opposition of self-induction. As the current is established, the surrounding space becomes the seat of magnetic forces.

The whole phenomenon is reversed when the current generator is switched off: self induction keeps the current running for ^awhile thus returning to the current the extra energy that had been spent in setting it up. The current intensity as well as the magnetic forces die off gradually.

Both the starting and the disappearance of magnetic forces in the space surrounding the wire are associated with further electric actions. Thus an electric current is driven temporarily in a closed loop of wire lying next to the wire where a current starts or dies off. This effect of electromagnetic induction underlies the common a.c. transformer action, in which one pumps an oscillating current in a coil of wire (the "primary" winding) and one obtains another current in another coil (the "secondary" winding).

Little energy is dissipated in the course of induction phenomena if the rates of change of current intensity are kept rather low, as in ordinary alternating current phenomena. Roughly speaking, the dissipation remains low because the electromagnetic equilibrium in the space surrounding a current is never greatly disturbed by rather slow variations of the current. This does not hold true in the case of sharp current variations.

A mechanical analogy may help to illustrate this point. A slow compression of gas in a cylinder proceeds reversibly without dissipation of energy. But a substantial amount of energy is dissipated into sound waves if the gas is acted upon by a rapidly oscillating piston.

Similarly, rapid variations of electric currents lead to a substantial energy dissipation. One may visualize the situation thus: the more rapid are the current variations, the less readily can the magnetic and electric forces in the surrounding space readjust to follow the current variations. This unbalance leads to a larger energy transfer away from the current. It looks as though a very rapid increase of current requires an especially large expenditure of energy but a very rapid decrease yields an especially low return of energy. The reactions caused by the electromagnetic unbalance in the surrounding space overshoot the equilibrium, just as it happens in the phenomena of elastic unbalance, and thus the disturbance propagates farther and farther away.

In conclusion: electromagnetic radiation arises from the induction effects associated with any variable current. The energy radiated by a current is an increasing function of the rate of variation of the current; in fact it is proportional to the fourth power of this rate of change.

A radiative disturbance exerts the same kind of action upon matter as electromagnetic induction. It exerts an electric force upon all electric charges within matter, and a magnetic force which tends to push all currents sideways.

However, the effects produced by these actions vary greatly depending upon the rapidity with which the electric and magnetic forces vary in the course of time. Not only the methods of detection of electromagnetic radiation but also the classification of the various types of this radiation depend on the analysis of the time variations of radiative disturbances. Therefore this analysis deserves first consideration.

1.3a FREQUENCY AND WAVE LENGTH. Electromagnetic disturbances frequently follow an oscillatory, almost perfectly sinusoidal, course. This

obtains, for example, for light of a definite color. For this reason sinusoidal radiative disturbances are called "monochromatic."

Monochromatic radiation arises from a current that performs sinusoidal oscillations. In turn, monochromatic radiation induces sinusoidally oscillating currents within matter. The rate of variation of a sinusoidal disturbance is characterized by the number of its cycles of oscillations per unit time, that is, by its frequency.

The study of monochromatic radiations of different frequencies serves as a basis for the study of any electromagnetic radiation, because any radiation may be regarded as the combination of monochromatic components. In fact, no radiation ever follows a perfectly sinusoidal course; actual "monochromatic" radiations are, at best, aggregates of ideally monochromatic components whose frequencies are very nearly equal.

At any instant during the propagation of a disturbance away from an oscillating current, the effect of successive pulsations of the current have reached points at various distances from the source. Fig. 12 represents diagrammatically the strength and direction of the force that acts on electric charges placed at various positions around a vertical "antenna". The diagram displays the wave-like character of the propagation of radiation.

The distance between successive layers of points where the electric force has, for instance, maximum strength and equal direction is called the wave length of the radiation. The wave length λ equals the product of the velocity of propagation of the radiation

and of the duration of one oscillation of the current. The velocity of propagation equals very approximately

$$c = 3 \times 10^8 \text{ meter /sec} = 3 \times 10^{10} \text{ cm/sec} \quad (7)$$

in empty space, in air and in other gases. The duration of one oscillation is the reciprocal of the frequency ν of oscillations per second. Consequently the basic relationship between wavelength and frequency is

$$\lambda = \frac{c}{\nu} \quad (8)$$

The frequency of electromagnetic radiation can have any value, in principle, according to present knowledge. Radiations of frequencies up to more than 10^{23} cycles/sec, whose wavelengths range down to about 10^{-13} cm, have been studied experimentally.

Radiation of "low" frequency succeeds in driving electric currents back and forth through macroscopic portions of matter such as wires or other conductors. If the frequency is higher than, say, 10^{12} cycles/sec the currents can not travel over macroscopic distances within a cycle of oscillation of the disturbance, but currents confined within atoms become important. Low mass and high rigidity make atomic and sub-atomic structures particularly apt to oscillate with very high frequencies (above 10^{14} cycles/sec). Atomic charges perform forced oscillations under the driving influence of a monochromatic radiation. The intensity of these oscillations depends on the same circumstances which govern the forced oscillations of any mechanical system.

Any mechanical system which is stable but susceptible of elastic deformation, is capable of performing free elastic oscillations with characteristic frequencies of its own. An electrically charged

particles within matter, primarily the atomic electrons, constitute an elastic system whose characteristic frequencies are very high. Forced oscillations become extremely intense when the frequency of the driving force coincides with a characteristic frequency of the oscillating system. This particularly strong reaction of atomic charges to a specific radiation is called "resonance." Similarly a very intense current is induced in the wire of an oscillating circuit by the action of lower frequency radiation when the circuit is "tuned" to oscillate with the radiation frequency.

The induction of intense resonating currents within the atoms of a material or within the wires of a macroscopic circuit requires the expenditure of energy by radiation. Therefore the occurrence of resonance is associated with the absorption of radiation.

Radiation of any particular frequency propagates easily only through those materials whose internal currents do not respond easily to radiation of that frequency.

Even in the absence of resonance, the proximity of the radiation frequency to the characteristic frequencies of internal currents determines the speed of propagation of the radiation.

Thus the mode of interaction of radiation with any material appears to depend to a great extent on the radiation frequency. Therefore it appears natural to classify electromagnetic radiation according to its frequency or wavelength.

Newton utilized first the different refraction of light of different frequencies to resolve light into its multicolored components. He called the resulting pattern of colors a "spectrum." The analysis

of radiation into its monochromatic components is now generally called "spectral analysis".

1.3b THE POTENCY OF ELECTROMAGNETIC RADIATION. The effects of resonance establish a connection between the frequency of radiation and its ability to affect various portions of matter, because the energy of radiation is absorbed selectively when the internal currents happen to resonate with the radiation.

However, a much more striking connection between the frequency and the "potency" of radiation appears when one observes the effect of radiation on individual atomic particles. Such observations can be made, for example, in the study of the "photoelectric effect" in which electrons escape from matter under the influence of monochromatic light. Each ejected electron turns out to have received from the light a definite amount of energy which is proportional to the light frequency. The proportionality constant has always the same value

$$h = 6.62 \times 10^{-27} \text{ erg sec} = 4.14 \times 10^{-15} \text{ ev sec.} \quad (9)$$

which is called the "Planck constant."

For example: Ultraviolet light with a wavelength of 2500 Angstrom units (A) equal to 2.5×10^{-5} cm, has a frequency ν of $3 \times 10^{10} / 2.5 \times 10^{-5} = 1.2 \times 10^{15}$ cycles/sec, according to (7) and (8). The energy which this light imparts to an electron equals the product

$$h\nu = 4.14 \times 10^{-15} \times 1.2 \times 10^{15} = 4.96 \text{ ev.} \quad (10)$$

A certain minimum amount of energy is required to eject any electron from the atoms of matter. Therefore low frequency radiation, which can impart only a small amount of energy to an electron, may be wholly incapable of ejecting electrons. For example, light of 2500 Å which imparts to electrons 4.96 ev at a time, can produce no photoelectric effect in any monoatomic vapor except cesium (for which 3.87 ev are sufficient). However, this light is capable of extracting electrons from a number of solid metals, because electrons are less strongly bound within solid metals than within vapor atoms of the same elements. The lowest frequency of radiation capable of ejecting electrons from a material is called the "photoelectric threshold" of that material.

The amount of energy $h\nu$ which electromagnetic radiation of frequency ν is capable of transferring to an electron in a single process is called a "photon" or "radiation quantum."

All pertinent experiments of atomic physics show that electromagnetic radiation always transfers energy to matter in finite lumps, that is, one photon at a time. In fact, all experiments which can indicate the size of energy transfers with sufficient accuracy confirm that the transfer of energy "photon by photon" is a general law.

The discontinuous absorption of radiation energy in lumps is not detected in macroscopic systems such as radio antennas for the following reasons. In the first place radio circuits respond only to electromagnetic radiation whose frequencies are many orders of magnitude lower than the frequency of light. The photons absorbed by radio circuits have correspondingly lower energies. In the second place, even an amount of energy whose absorption has a substantial effect upon a single atom has a wholly negligible effect on a wire circuit. Radiofrequency circuits in practice absorb or emit huge numbers of photons within short time intervals. Therefore the discontinuity of the energy transfers escapes detection.

Thus the frequency of electromagnetic radiation is a clearcut index of its "potency." The photon energy $h\nu$ determines the ability of a radiation to accomplish or not to accomplish any given effect on matter. Low frequency radiation cannot eject electrons from atoms. Higher frequency radiation is photoelectrically active but the amount of kinetic energy which it imparts to an ejected electron is limited by the magnitude of each photon.

Electromagnetic radiations are entered in the chart of radiation potencies (Fig. 5), by equating the potency of radiation of frequency ν to that of a corpuscular radiation whose particles have a kinetic energy equal to $h\nu$.

The following example illustrates the interconnection of the potencies of corpuscular and electromagnetic radiations. Consider an X-ray tube to which is applied a potential difference of 85 kv. The electrons within the tube strike the target with an energy of 85 kev. The target radiates X-rays consisting of a variety of monochromatic components whose frequencies range up to a maximum value $\nu_{\max}$. This value is fixed by the condition that an electron cannot possibly radiate any more energy than it possesses initially. Therefore the maximum photon energy equals the kinetic energy of the electron:

$$h\nu_{\max} = 85 \text{ kev}$$

$$\nu_{\max} = \frac{85,000}{4.15 \times 10^{-15}} = 2.05 \times 10^{19} \text{ cycles/sec.} \quad (11)$$

The X-ray wavelengths exceed a corresponding minimum value:

$$\lambda_{\min} = \frac{c}{\nu_{\max}} = \frac{3 \times 10^{10}}{2.05 \times 10^{19}} = 1.46 \times 10^{-9} \text{ cm} = 0.146 \text{ \AA}$$

The X-ray photons can in turn eject electrons by photoelectric effect from any material around the X-ray tube. The kinetic energies which these "photoelectrons" receive from the radiation range up to 85 kev.

Thus the energy of the corpuscular radiation in the tube is transferred by intermediary X rays to a new corpuscular radiation generated outside the tube. The decrease of potency involved in the transfer may be quite small.

1.3c CLASSIFICATION OF ELECTROMAGNETIC RADIATIONS. There are two frequency ranges at which electromagnetic radiation is very strongly absorbed by practically any kind of matter.

One is the range between approximately 10^{11} and 10^{13} cycles/sec (corresponding to photon energies of 0.0004 to 0.04 ev, or wavelengths of 0.3 cm to 0.003 cm). Electromagnetic radiation of these frequencies induces resonating currents associated with the motion of whole atoms with respect to one another.

The other range of strong absorption runs approximately from 10^{15} to 10^{17} cycles/sec (corresponding to photon energies from 4 to 400 ev or wavelengths of 30 Å to 3000 Å). Oscillating currents associated with the motion of electrons within atoms are responsible for this absorption.

Radiation in these two ranges of strong absorption is unwieldy. Therefore the frequency spectrum which finds most practical application

consists of three separate portions lying below, between and above the ranges of strong absorption (see Fig. 5).

Radiation of the lower frequency range, up to 10^{11} cycles/sec, propagates freely through insulators (but drives oscillating currents through conductors, and is absorbed in doing so). It is usually called "radio waves" or "hertzian waves"; radiation whose frequency lies in the upper part of this range (above 10^9 cycles/sec) is usually called "microwaves."

Radiation of the frequency band 3.85 to 7.7×10^{14} cycles/sec affects the human eye and is called "light." The term "ultraviolet light" applies to radiations of higher frequency, perhaps up to 4×10^{15} cycles/sec. "Infrared light" applies to radiation of frequency lower than visible light and higher than radio waves. Infrared, visible and ultraviolet light together cover the middle or "optical" portion of the spectrum. Radiations of this range penetrate easily through homogeneous pure substances in which the external electrons of each atom or molecule are held comparatively tight.

Radiation of such high frequency as to be poorly absorbed by most atomic electrons (see p. 61-62) is called X rays and covers the third main frequency range, above 10^{16} - 10^{17} cycles/sec. X rays emitted by oscillating currents within the atomic nuclei are usually called " γ rays." The oscillating currents within nuclei cause the absorption of X rays, but to a very low extent. Cosmic rays include electromagnetic radiation of the highest frequency known; this radiation may be called the " γ -ray component of cosmic rays."

1.3d DETECTION OF ELECTROMAGNETIC RADIATION. The detection relies directly or indirectly on the effects of the electric currents which electromagnetic radiation induces within matter.

In the range of radio or microwave frequencies, i.e., of wave - lengths from miles down to millimeters, the currents induced in a receiving antenna or in an equivalent circuit are studied conveniently by electrical engineering techniques.

In the range between the radio and the optical frequency, i.e. of wavelengths between 1 mm and a few microns, the detection is less sensitive and specific. It is usually based on the observation of small temperature rises caused by the dissipation of radiation energy in any material.

Beginning with the optical frequency range, radiation becomes capable of exerting lasting effects on individual atoms or molecules. Some of these effects result in chemical transformations. In particular the photographic effect is convenient and fairly sensitive. The electric effects, due to the separation of atomic charges or even to the generation of secondary charged corpuscular radiations, are often still more convenient and sensitive. For example, photoelectrons ejected from atoms can be scored one by one (see p. ⁶). It is generally also possible to measure the energy of these electrons.

In general, high frequency radiations are studied, through the secondary electrons which they release, by the methods indicated at p. 5 ff.

1.4 Production of electromagnetic radiation

The general method of producing electromagnetic radiation of given frequency is, naturally, to produce electric currents in systems apt to oscillate with that frequency. This is done in the radio frequency range by electrical techniques which are highly developed but whose discussion is beyond our present concern. Suitable techniques of the same nature are not available to generate electric currents of frequency much above 10^{11} cycles/sec (100,000 Megacycles/sec). Hence resort is made to methods which utilize the properties of atoms.

1.4a PRODUCTION OF OPTICAL RADIATION. Infrared, visible and ultraviolet light of all frequencies is emitted in substantial amounts by the atoms of any condensed material at a sufficiently high temperature. The average frequency of the radiation emitted increases in direct ratio to the absolute temperature of the emitting body as indicated by the correspondence of temperature and frequency in Fig. 5. Fig. 13 shows an example of the "spectral distribution" of intensity among radiation components of different frequencies at various temperatures. (The characteristic frequencies of oscillation of the individual atoms in the material do not appear in this spectrum because the atoms are not isolated but are continuously and variously disturbed by other adjacent atoms under the influence of thermal agitation.)

Radiation of frequency falling within narrow limits can be selected from a beam containing a wide variety of frequencies, by means of "monochromators" such as a spectroscope. A cruder chromatic analysis

can be performed with filters which absorb light of different frequencies to a different extent. These methods are naturally wasteful of energy since they utilize only a small fraction of the radiation available.

For better efficiency one takes advantage of the fact that excited atoms or molecules in rarefied gases emit light of characteristic frequencies. The atoms are excited by the impact of electrons, usually in an electrical discharge. With suitable technical arrangements it is possible to convert into radiation of desired wavelengths a substantial fraction of the energy imparted to the discharge (Fig. 14). This method is now being used increasingly also for illumination purposes.

Certain substances have the property of absorbing light of comparatively high frequencies and of re-emitting it as light within a limited range of lower frequencies. This phenomenon is called "fluorescence". In the fluorescent lamps a gas emits primary radiation which is ultraviolet and is turned into visible by a fluorescent material which is part of the lamp wall.

1.4b PRODUCTION OF X RAYS. The internal electrons of atoms radiate X rays of definite frequencies when they are set in oscillating motion. These frequencies are characteristic for each kind of atom and are much higher for heavy than for light atoms (because the internal electrons are held the more stiffly the higher is the nuclear charge, see pp. 38-39). The corresponding photon energies range up to 120 kev. Oscillating motions of internal electrons arise when an internal atomic electron is knocked off by the impact of a fast electron or other particle.

Atomic nuclei also emit monochromatic X rays, or rather γ rays, of characteristic frequencies determined by their internal oscillating currents. This happens only when the nuclei have been excited by a collision or as the consequence of a spontaneous disintegration. The monochromatic γ rays obtained in this way usually have very low intensity. The highest photon energies are released in the formation of He^4 and Be^8 nuclei and amount to approximately 20 and to 17.6 Mev respectively. They are obtained by bombarding with protons the unstable isotope of hydrogen H^3 or the stable isotope of lithium Li^7 .

Whether these monochromatic X rays originate from internal atomic electrons or from nuclei, the primary agent is always a high energy corpuscular radiation. On the other hand, whenever high energy electrons strike a target material, X rays are also produced directly by the electrons through an entirely different mechanism and in much larger amounts, at least if the material has high atomic weight.

In the course of their flight through the atoms the electrons experience sudden accelerations as they find themselves momentarily attracted by the atomic nuclei. Such a jerky motion of charged particles constitutes the source of pulsed, irregular, rapidly variable electromagnetic disturbances, namely the X rays. This is actually the main practical mechanism of X ray production.

A typical X-ray tube is shown in Fig. 15. Electrons emitted by the filament are attracted by the positive pole which is usually called "anticathode" or "target". Potential differences up to several million volts may be applied to tubes of this general type.

Most of the kinetic energy acquired by the electrons in flight is turned into heat. Hence the anticathode usually becomes red or even white hot. Water or oil cooling of the anticathode is frequently employed to allow for increased electron bombardment and higher X-ray intensity. (When the anticathode is cool it releases far fewer electrons than the filament. Therefore electrons can easily flow only from the filament to the anticathode even if the applied voltage is reversed and the tube may be employed as a self-rectifying unit with an applied a.c. potential.) For technical data, see e.g. Medical Physics (1944) p. 1395 ff.

The faster the electrons, the sharper are the variations of their motion and the more intense the emission of X rays. The higher the atomic number of the target material, the stronger is the attraction exerted by the nuclei on the electrons and the more intense the emission of X rays. Under ordinary conditions only a small fraction of the energy of all incident electrons is radiated. This fraction y is approximately proportional to the atomic number Z of the target material and to the accelerating voltage V applied to the electrons in the tube according to the formula:

$$y \sim 10^{-9} ZV. \quad (12)$$

(The value of y approaches 1 in the case of a tungsten target ($Z = 74$) for an applied voltage of 10 Mev. The formula no longer holds at higher electron energies.)

The X rays emitted by the electrons as they move jerkily across atoms consist of a continuous spectrum of monochromatic components whose frequencies range up to a maximum value $\nu_{\max}$. The maximum energy $h\nu_{\max}$ of the X-ray photons equals the kinetic energy of the electrons which strike the anticathode in the X-ray tube. Fig. 16 shows the intensity of the components of different frequencies in a typical X-ray spectrum.

Electrons accelerators of the types described at p. 14 (betatrons and synchrotrons) serve to produce X rays of very high frequencies and high photon energies. The X rays are generated when the electrons, after acceleration, hit a target, preferably of heavy metal.

The X rays emitted by electrons in the multimillion volt range propagate mainly in the original direction of the electrons since they carry most of the momentum which was previously possessed by the electrons themselves. X rays of lower frequency are emitted more uniformly in different directions (see Fig. 17).

When the voltage applied to an X-ray tube is rather low and the anticathode material rather light, the intensity of the "characteristic" X rays arising from oscillating currents within the atoms compares with the intensity of the "continuous" spectrum generated directly by the

incident electrons. Fig. 18 shows a spectrum of the intensity of the X-ray components of different frequencies emitted by a tube with a molybdenum anticathode operated at 35 kv.

Monochromatic X rays of wavelengths ranging down to less than 10^{-10} cm = 0.01 Å corresponding to photon energies of more than 1 Mev, have been separated from continuous spectra by means of crystal spectrometers. The intensity obtained in this way is quite low and the method serves only for purpose of analysis.

Radioactive materials often prove very convenient as sources of gamma rays, especially because the spectrum of this radiation consists of a single or at most of a few frequencies. For data on radioactive sources see p. 16, Way et al. (1950), Isotopes Catalogue (1949).

2. ACTION OF RADIATIONS UPON ATOMS AND MOLECULES

The action of radiations on matter can be analyzed into a succession of separate "elementary processes" each of which involves only one or a few atomic particles. For example, individual electrons spring out from air molecules here and there in the space exposed to X rays. (Fig. 74). All air molecules located in equivalent positions with respect to the X-ray source have an equal chance of experiencing the loss of an electron. Not only the ejection of electrons but many other types of "elementary processes" occur as random events among the atoms of a portion of matter exposed to radiation.

Atoms exhibit a remarkable statistical behavior in a great variety of phenomena. For example, the radioactive transformation in which an α particle springs out of a radium atom may take place with equal chance in each atom of a sample during any given interval of time. Even though all conceivable care is exerted in placing all atoms of a material under identical experimental conditions, the individual atoms act erratically in statistical fashion. Therefore the laws which describe the behavior of atoms are necessarily formulated in statistical language. For example: each radium atom has probability of 2.7×10^{-11} of ejecting an alpha particle during each 1 second interval. This is

to say that: (a) out of a very large number, N , of atoms, $2.7 \cdot 10^{-11} N$ disintegrate, on the average, every second; (b) all remaining atoms are equally likely to disintegrate in the next second and, all atoms being identical, there is no conceivable way of predicting which atoms will disintegrate next; (c) the probability of disintegration of any one atom remains constant in the course of time and does not increase in relation to the duration of previous survival of the atom. The value of the probability of disintegration is subject to no external influence.

Statistical laws are encountered in various fields of knowledge. The observed randomness of events is usually understood to result from circumstances in preceding operations which have been disregarded either deliberately or owing to practical circumstances. For example, the dealing of a certain "hand" in a game of cards depends on the details of the mechanism of shuffling. One disregards these details with the implication that it would be actually possible to keep track of all details and thereby to predict the result of the subsequent deal.

On the contrary the randomness of atomic events does not appear to reflect circumstances that are controllable in principle but it is regarded as a primitive fact of nature. Thus the electromagnetic disturbance which propagates away from an X-ray tube truly appears to disturb all air molecules evenly; the equal disturbance eventuates in the ejection of electrons from a few random molecules but no lasting effect results in the other molecules.

The uncontrolled random behavior of atoms is regarded altogether differently from the uncontrolled behavior of other objects. The "biological variability" of a population usually appears to stem from a complex of circumstances that seem too difficult to control in practice even though controllable in principle. Therefore biological variability is looked upon as a practical obstacle to be overcome. On the contrary the variability of the reactions of different atoms is taken at face value as an inherent property of the atoms rather than as the expression of hidden determining influences.

Since exposure to radiation leads to observable effects which are localized in separate molecules, atoms or even in portions of atoms, it is convenient to study the various kinds of localized effects separately. These local effects may be called "elementary processes" and represent the component elements of the complex action of radiation on matter.

The important elementary processes will be outlined here, following a summary of data on the properties of atoms.

2.1 Summary of Information on Atoms and Molecules

2.1a THE STRUCTURE OF ATOMS. Each kind of atom is identified by two whole numbers: the atomic number Z and the mass number A. The mass number is the integer nearest to the atomic weight. An atom consists of the following components, when it is electrically neutral:

(1) A nucleus which bears a positive charge equal to Z times e (see eq. 2) and includes practically the whole mass of the atom. The nucleus is a compact aggregate of Z protons and A - Z neutrons. Its radius does not exceed 10^{-12} cm. The aggregate holds together stiffly owing to strong attractive forces which operate only between particles very close to one another, i.e., no more than a few times 10^{-13} cm apart. These forces are still known only imperfectly and are called nuclear forces.

(2) A cloud of Z electrons which occupy a volume with an approximate radius of $1 A = 10^{-8}$ cm. The cloud holds together owing to the electric attraction exerted by the nuclear charge upon the electrons. This attraction predominates over the repulsion between electrons because of the magnitude of the nuclear charge.

For example, ordinary sodium consists of a single kind of atoms with atomic weight 22.997. These atoms have the atomic number $Z = 11$ and the mass number $A = 23$. Their nuclei consist of 11 protons and of $23 - 11 = 12$ neutrons. The body of the atoms consists of 11 electrons which move about the nucleus. Ordinary nitrogen consists of two kinds

of atoms, namely the "isotopes" of atomic weight 14.008 and 15.005. Both isotopes have the atomic number $Z = 7$ but their mass numbers are respectively, 14 and 15. Nitrogen nuclei of mass number 14 consist of 7 protons and 7 neutrons; those of mass number 15 consist of 7 protons and 8 neutrons. All nitrogen atoms contain a cloud of 7 electrons.

Nuclei can absorb or eject protons, neutrons and other particles, as well as photons of electromagnetic radiation. Nuclear processes involve the uptake or release of energy amounts which are generally of the order of 1 Mev or more, that is, far larger than the amounts involved in most extranuclear processes.

The energy required to extract an electron from an atom is called the "binding energy" or also the "ionization potential" of that electron. The order of magnitude of the electronic binding energies can be estimated from a knowledge of the electric charges of the atomic particles and of their average distances. Two particles bearing an electric charge of magnitude e and lying 1 Å apart have a potential energy of 15 ev. This energy is comparable to the lower ionization potentials of atomic electrons and a little larger than the energies of chemical bonds between atoms.

Each electron of a neutral atom is attracted by the positive charge Ze of the nucleus and repelled by the other $Z-1$ electrons. However, the repulsions exerted by the other electrons act in different directions and cancel each other in part. One may state with good approximation that each electron is effectively repelled away from the nucleus

only by that portion of the total electronic charge which is closer to the nucleus than the electron itself (Fig. 19). The remaining portion of the electronic charge does not exert any substantial net force. Therefore any electron appears to be attracted toward the nucleus by an "effective charge", Z_{eff} which is smaller than the actual charge and depends on the distance of that electron from the nucleus.

An electron on the edge of the atom is kept away from the nucleus practically by all its fellow electrons, so that $Z_{\text{eff}} \sim Z - (Z - 1) = 1$. Hence the binding energy of this electron must be comparable to the binding energy of the single electron of an H atom ($Z=1$), i.e., ~ 10 ev.

The actual value of the binding energy of the outermost electron in different atoms depends on the number of electrons in the external layers of the atom (see Fig. 20). This number depends, in turn, on the total number Z of electrons and therefore on the position of the atom in the periodic system. In general, the properties of the external electrons of an atom are identified with its chemical characteristics.

Electrons with $Z_{\text{eff}} > 1$ are attracted by the nucleus Z_{eff} times more strongly and held approximately Z_{eff} times closer to the nucleus than an electron with $Z = 1$. Consequently the binding energy is approximately Z_{eff}^2 times larger than in the case of the H atom.

The innermost electron experiences the full attraction of the nucleus, consequently $Z_{\text{eff}} \sim Z$.

In conclusion: The binding energy of individual electrons within an atom of atomic number Z varies between ~ 10 and $\sim 10 Z^2$ ev.

It follows from these data that physical phenomena taking place in the inner and outer portions of an atom remain rather independent of one another. On the one hand the motion of the inner electrons is hardly affected by the presence, absence or arrangement of the outer electrons but it is affected predominantly by the strong nuclear attraction. On the other hand the outer electrons experience a weaker attraction and move more slowly; they "see" the inner electrons as forming a fixed cloud of negative charge around the nucleus.

The motion of the atomic electrons can proceed steadily according to a variety of possible patterns, which are called the characteristic "stationary states" of each kind of atom (Fig. 21). The stationary state in which the total energy of all electrons is lowest is called the "fundamental" or "normal" state of the atom.

The other stationary states of motion of the atomic electrons are called the "excited" states. The "excitation" consists of an excess kinetic energy which is usually concentrated on a single electron. The excited electron keeps farther away from the nucleus than it would do if it were not excited, on account of its more active motion. The binding energy of an excited electron is accordingly reduced.

The excitation of an external electron requires a certain minimum amount of energy which varies from a few to about twenty electron-volts depending on the number of electrons in the external portion of the atom.

This energy is, normally, 2-4 ev lower than the binding energy of the electron. The excitation of internal electrons requires a much larger amount of energy which is very nearly equal to their binding energy.

Although each atomic electron is in constant motion according to a fixed pattern, while an atom remains in a stationary state, the statistical average of its motion yields no net oscillating current. However, an oscillating current arises while the motion of the electrons changes over from one to another stationary state. The frequency ν of this current is proportional to the energy difference ΔE gained or lost by the atom in connection with the change of motion, according to the basic relation:

$$\Delta E = h\nu \quad (12a)$$

where h indicates the Planck constant (see eq. 9). No change of motion from one to another stationary state would occur but for disturbances caused by other atoms or by radiation.

Oscillating currents accompany also the transitions of an atom from a stationary state to the "ionized" states in which an electron moves away with sufficient energy to overcome the attraction of the nucleus. The frequency of these currents relates to the energy difference of the initial and final states according to eq. (12a). Here the energy ΔE gained by the atom in the process of ionization may have any value larger than the binding energy of the outermost electron, because an electron which breaks loose from an atom may carry away any amount of excess energy.

2.1b AGGREGATES OF ATOMS. Chemical bonds arise when the combined external electrons of two or more adjacent atoms can take up a coordi-

nated motion such that their total energy is lower than it would be if the atoms remained separate. The bond formation may involve an excess concentration of electrons on some atoms and an equivalent defect on other atoms. The energy released by the formation of a chemical bond is of the same order of magnitude as the energy differences of the stationary states of outer electrons in an atom, that is of the order of a few electron volts.

Molecules and crystals of various constitution and stability result from the aggregation of atoms through chemical bonds. Rather general arguments of atomic mechanics suffice to explain why and under what conditions chemical bonds are actually formed.

Other types of atomic aggregates such as liquids, plastics or colloidal systems, are less rigid and stable than molecules or crystals. They result from cohesive forces among atoms and molecules, which are weaker and less specific than chemical bonds. These forces result from a suitable mutual adjustment of the electric charges within separate but adjacent molecules. In essence, the electrons of each atom or molecule draw particularly close to one of the nuclei of another atom. In some substances like water, the center of mass of the electrons of each molecule does not normally coincide with the center of mass of the nuclei; therefore there results an excess concentration of negative charge on one side of the molecule and an excess positive charge on the opposite side. Intermolecular attraction arises then merely from a suitable orientation of adjacent molecules (see Fig. 22). This attraction is called a "polar force". In other substances, where

the electrons tend to remain more evenly distributed about the nuclear charges, the electronic distribution becomes nevertheless distorted by the very proximity of adjacent molecules. These distortions give rise to a net attraction which is still weaker than polar forces and is called a "Van der Waals force". Notice that both kinds of cohesive forces are of electric nature even though they act between molecules that do not carry any net charge.

The various kinds of aggregates of atoms are treated e.g. by Pauling (1940), Rice and Teller (1949), Slater (1939) chapt. 22 ff.

The motion of electrons within a molecule or crystal can proceed steadily in a variety of stationary states, as in atoms. Moreover the atoms within a molecule or crystal move bodily with respect to one another in oscillatory or rotatory fashion in a variety of stationary states. Therefore the combined set of stationary states is far more numerous and varied for an aggregate of atoms than for a single atom.

The energy required to "excite" the bodily motion of atoms in a molecule with respect to one another equals only a small fraction of the energy released by the formation of chemical bonds. This excitation energy is smaller than the excitation energy of electrons, in general by one or more factors of 10. It is always smaller, often much smaller, than 1 ev.

In fact many forms of excitation of interatomic motion require an energy comparable with the kinetic energy of gas molecules at room temperature, 0.1 ev or less. The heat, i.e. the thermal energy which

is contained in any material, enables these forms of motion to spend most of the time in one or another excited state.

2.1c EFFECTS OF EXCITATION. Radiations act upon atoms and molecules, in essence, by delivering energy to single atomic particles, that is, by exciting various forms of internal motion. The consequences of the various kinds of excitation depend on the internal mechanics of the atom or molecule and on the amount of excitation but do not depend on the source of the excitation.

An electron which has been excited to a sufficiently high level of energy quickly leaves the atom or molecule to which it belongs. This process is called "ionization" because it results in an outright separation of electric charges. The electron has little chance of sharing its excitation energy with any one other particles because its kinetic energy is generally large as compared with the electric force of interaction with any one of the other electrons.

Nuclear particles are much more apt than electrons to subdivide their energies, because each particle interacts strongly with its immediate neighbors. Therefore a neutron or proton which receives sufficient energy to break out of the nucleus has little chance of doing so at once (unless the nucleus consists of a very few particles only and each particle lies practically on the outer surface). If and when a particle eventually breaks loose from the nucleus, as a result of an excitation, the remaining nucleus is likely to keep some energy of excitation. The ejection of a particle from a nucleus is called a "disintegration". The relative likelihood of different kinds of disintegration is discussed separately at p. 43.

The excitation of the motion of a whole atom in a molecule or crystal with respect to its neighbors is also apt to be subdivided quickly among many atoms. However, an atom which belongs to a small molecule has a good chance of breaking loose at once if it acquires a sufficient energy. The separation of an atom from its molecule is called a "dissociation".

When the excitation of an atomic structure does not suffice to overcome the bonds which hold the structure together, the excitation normally can subside through the emission of electromagnetic radiation. The nucleus, atom or molecule "drops" from an excited stationary state to another stationary state of lower energy. The energy difference radiates away as a photon of electromagnetic radiation. The radiation arises from the oscillating current of characteristic frequency which accompanies the changeover from one pattern of internal motion to another (see p. 39). According to eq. (12a) one photon of the emitted radiation amounts to an energy $h\nu$ exactly equal to the energy difference ΔE between the initial and final state of the atom.

The excitation may subside in one or more steps depending on whether the atomic structure returns to its normal state directly or through a succession of intermediate stationary states.

Alternately, the excitation energy may be released by direct transfer to an adjacent atomic structure. A direct transfer is quite possible not only in liquids and solids but also in gases unless the density is so low that intermolecular collisions become exceedingly rare. Nuclei, being more sheltered from the environment and less

subject to external disturbances, find it difficult to transfer their excitation directly to other atomic structures.

The excitation of the external atomic electrons subsides through the emission of electromagnetic radiation within a time ranging from 10^{-8} second upward. Direct energy transfers compete effectively with the emission of radiation if they take place at a faster rate.

The larger the energy amount to be released, the higher is the frequency of the oscillating current and the higher is the rate of emission of radiation (see p. 19). Therefore the excitation of the motion of atoms within a molecule, which involves smaller amounts of energy, requires a time longer than 10^{-8} sec to subside through the emission of radiation. On the contrary, the excitation of internal electrons may lead to the emission of high energy X rays within a time as short as 10^{-14} sec.

The release of nuclear excitation energy through the emission of γ rays requires a time which is most frequently of the order of 10^{-14} sec. Occasionally the release of γ rays may require a period of seconds or hours. (An unusually long duration of an excitation is more frequently observed in nuclei than in the electronic portion of atoms and molecules, because the chance of direct energy transfer from nuclei is smaller. A long excitation results when the oscillating currents in various portions of a nucleus or of an atom neutralize one another's radiative effectiveness.)

By and large, the excitation of an atomic particle does not become easily subdivided, or "degraded", within a single atom or molecule. The excitation of a nuclear particle spreads easily to the other nuclear particles but remains within the nucleus. The excitation of an electron does not even spread easily to other electrons.

This circumstance, which simplifies the analysis of excitation, relates to the organization of the atomic structure in successive levels or layers. These layers have decreasing rigidity and remain fairly independent of one another:

(a) The nucleus is most rigid and its excitation requires a larger amount of energy. Therefore the intranuclear motions are hardly affected by the extranuclear phenomena.

(b) The structure of internal electrons has next higher rigidity. It is affected very little by intranuclear phenomena owing to the smallness of the nucleus, and hardly at all by the motion of external electrons which involves small amounts of energy.

(c) Similarly, the motion of external electrons is affected very little by the events within the nucleus or within the small hard core of internal electrons or by the weaker action of the molecular motion.

(d) The makeup and the vibrations of molecular structures do depend upon the motion of the external electrons, but only upon the average pattern of motion rather than upon the location and velocity of each electron at any particular instant. The influence of the electronic motion upon the attachment and the motion of whole atoms may be described comprehensively as the action of chemical forces exerted by each atom on the adjacent ones.

The remarkable independence of different layers of the atomic structure does not imply that transmission of energy from an inner layer to a more external one is extremely rare. However, when this transmission occurs, the energy received by the outer layer is quite excessive with respect to the bonds that hold particles within that layer. Therefore the transmission results in the immediate ejection of one particle which carries away from the atom most of the excess energy.

Nuclei sometimes transfer their energy directly to atomic electrons and thereby eject them from the atom. This phenomenon, called "internal conversion", occurs particularly when the nuclear excitation is small.

Similarly, a rearrangement of internal electrons may lead to the ejection of an outer electron. This phenomenon, called "Auger effect", is also the more frequent the lower is the energy amount to be transferred.

Some energy is frequently transferred from an outer electron of a molecule to the interatomic motion at the time when the electron radiates a photon. This is to say that the photon gets only a part—though normally a very large one—of the energy released by the electron. Another, less frequent but more effective, mechanism is a "radiationless transition" in which an outer electron changes its motion and transfers the excess energy directly to the interatomic motion. This process occurs more frequently in larger atomic aggregates than in smaller ones. It constitutes nearly the sole channel for the conversion of electronic energy into interatomic, i.e., thermal, agitation.

2.1d NUCLEAR DISINTEGRATIONS. The neutrons and protons which constitute atomic nuclei tend to escape, singly, or even in small aggregates, whenever a nucleus is excited by a sufficiently large amount of energy.

When the substitution of a neutron with a proton or of a proton with a neutron yields an energetically more stable nuclear aggregate this substitution takes place spontaneously through the process of β disintegration (see p. 10).

When different modes of disintegration are possible, each of them may take place in a nucleus with a characteristic rate of probability per unit time. If the rates are comparable, part of the

nuclei disintegrates in one way and part in another. For example: 65% of the nuclei of Bi^{212} (commonly called Thorium C) experience a β disintegration to Po^{212} ($\text{Th C}'$) whereas the remaining 35% disintegrate to Tl^{208} (Th C) by α particle emission.

As mentioned before, neutrons become attached to nuclei more easily than protons or other positively charged particles, because the approach of a neutron is not hindered by electric repulsion. Similarly, the ejection of neutrons is favored over the ejection of charged particles. All around a nucleus there is a zone where a positively charged particle experiences a strong electric repulsion but is beyond the reach of attraction of nuclear forces (see Fig. 23). The particle finds it difficult to penetrate this zone, whether it is on its way in or out of the nucleus. Therefore the zone is called the "potential barrier" of the nucleus. One may say that the capture or the ejection of a charged particle requires that a certain activation energy be available to traverse the potential barrier. The "activation energy" ranges approximately from 1 to 13 Mev for the capture or ejection of a proton depending on the atomic number of the nucleus.

Aside from the barrier effect, the ejection of an α particle generally requires the least amount of excitation energy, because the two neutrons and two protons which form an α particle become attached to each other far more strongly than to the rest of the nucleus. Therefore the ejection of α particles results quite frequently from the excitation of light nuclei, where the barrier effect is small.

Nuclear disintegration by the emission of an α particle does not require any excitation energy for most heavy nuclei with a mass number above 210. The immediate disintegration is prevented by the barrier effect. The spontaneous ejection of α particles observed in many radioactive elements is due to occasional penetration of particles through the barrier.

The ejection of a neutron or a proton from a nucleus requires, an excitation energy which lies, with few exceptions, between 5 and 10 Mev. The ejection of a proton is hindered by the barrier effect. Therefore the ejection of a neutron constitutes the most likely result of moderate excitation for nuclei of medium or high atomic weight.

Excitation with energies from 15-20 Mev upward may lead to the ejection of two or more particles. Owing to the subdivision of energy among the particles of a nucleus particles are unlikely to take away much energy in excess of the energy required to leave the nucleus.

Neutrons usually escape with a kinetic energy of the order of 1 Mev, protons with a similar energy in addition to the energy required to overcome the barrier effect. The successive escape of a number of particles with moderate kinetic energies is called "evaporation" by analogy to the escape of molecules from a liquid.

The analysis of multiple evaporations resulting from excitation energies of the order of 100 Mev is in progress at the time of this writing (1950). Neutrons and protons, as well as larger aggregates of nuclear particles, are ejected in these processes. Very high energy particles (with 100 Mev or more) appear to escape from nuclei without sharing much, or even any, of their energy with other particles. In general, the coupling of nuclear particles becomes less effective in the range of very high energies.

"Fission" is a form of nuclear disintegration in which a nucleus breaks up into two or more fragments of comparable size. Fission occurs when the electric repulsion among the positive charges of the protons within a nucleus overcomes the cohesion due to the nuclear forces. Therefore fission is a characteristic mode of disintegration of the nuclei containing highest numbers of protons. A substantial level of excitation is required to "activate" fission in all the nuclei present in nature. The necessary excitation energy equals 5-6 Mev for uranium ($Z = 92$) but is already much higher, possibly 50 Mev, for bismuth ($Z = 83$). Fission is the most likely mode of disintegration when the activation is adequate.

2.2 Elementary processes involving radiation and free particles.

Radiation may transfer to a single electron or nucleus within matter, in a single elementary process, an amount of energy far in excess of the amount required to remove the particle from the atom or molecule to which it belongs. When this happens, the forces between the particle and the rest of the atom do not have much influence on the effect of radiation. The process can then be treated with considerable accuracy under the simplifying assumption that the particle is totally free at the start.

In the following discussion atomic nuclei are regarded as single heavy charged particles, under the assumption that the radiation does not disturb their internal structure.

2.2a COMPTON SCATTERING. Electromagnetic radiation exerts a rapidly variable electric force on any charged particle and drives it to oscillate according to the variation of the electric force. The forced motion of the particle constitutes a variable current and therefore it acts as an antenna which sends out radiation in all directions. Consequently, energy from the incident radiation becomes diffused or "scattered" all around in new directions.

Nuclei, being much heavier than electrons, respond far less than electrons to the driving force of the radiation. The scattering effect of nuclei should be roughly a million times less intense than the scattering due to electrons and has in fact not yet been observed. All the observed scattering of electromagnetic radiation by free particles is attributable to electrons.

The response of an electron to the driving force of radiation is limited by the inertia of the particle and accordingly it decreases as the radiation frequency increases. On the other hand, a particle radiates energy away the more effectively the more rapid are the variation of its motion. These two circumstances have compensating effects and tend to make the net scattering effectiveness of an electron independent of the frequency of the radiation (Fig. 24).*

* The probability of processes such as Compton scattering, due to the interaction of a beam of radiation with individual atoms or atomic particles within a material, is represented conveniently as a "cross section" according to the following argument. The frequency of processes which are observed experimentally or expected theoretically is

proportional to the flux of particles or photons in the incident radiation and to the density of atomic particles in the irradiated material. Therefore this frequency equals the frequency with which a particle, or a photon as the case may be, would traverse a target area of suitable size attached to each of the pertinent atomic particles (e.g. electrons) within the material. The area of such imaginary targets measures the probability of the process under consideration and is called the "effective cross section" or simply the "cross section" of the process.

When scattered radiation emerges sidewise from an incident beam and one detects a photon of the scattered radiation, the electron which has caused the scattering recoils on the opposite side of the beam, see Fig. 25. The simultaneity of the scattering of a photon with the recoil of an electron has been carefully checked. The kinetic energy of the recoiling electron is supplied by the incident radiation; the scattered photons have actually lower energy than the incident ones.

The energy loss associated with scattering of a photon by a free electron is borne out by a corresponding decrease of frequency and increase of wavelength of the scattered radiation with respect to the incident one. This change of properties is called "Compton effect" after its discoverer.

The exact sharing of energy between the scattered photon and the recoiling electron depends on the detailed balance of the energy and momentum (Fig. 26). The recoil is appreciable only when the photon has sufficiently high energy, i.e., when it is an X-ray photon, and is

deflected by a sufficiently large angle. Otherwise, when the recoil is weak, the scattering electron may not be regarded as free from its bonds within an atom and no Compton effect is observed.

The probability of scattering in different directions is indicated in Fig. 27. More complete data and formulas are given e.g. by Heitler (1944), sect. 16.

2.2b PAIR PRODUCTION. According to general experience, electromagnetic radiation is not affected by the electric or magnetic forces prevailing in the space where the radiation propagates. However, a radically new experience occurs when very high frequency radiation, with photons above 1 Mev, traverse the space within atoms which is the seat of strong forces varying rapidly from point to point.

The propagation of high frequency X rays in the space surrounding a charged particle leads to the simultaneous outright generation of an electron and a positron, i.e. of two particles, one bearing a negative and one bearing a positive charge. (Fig. 28) An X-ray photon disappears per every electron-positron "pair" which is produced. The energy of the absorbed photon equals the combined energy of the end products of the process, namely: (a) the kinetic energy of the electron and of the positron; (b) the energy associated with the very existence of an electron and a positron, i.e., the so-called "rest energy", which amounts to 0.5 Mev per particle; (c) the kinetic energy acquired by the preexisting charged particle as it is forced to recoil.

The minimum photon energy required for pair production amounts to $2 \times 0.5 = 1.0$ Mev, since the kinetic energies (a) and (c) may be negligible. A photon energy of 1.0 Mev corresponds to an X-ray frequency of 2.4×10^{20} cycles/sec. and to a wavelength of 1.2×10^{-10} cm. The minimum energy requirement increases by a factor of two for pairs produced in the proximity of an electron, because the electron always recoils violently (item c above) on account of its low mass.

The phenomenon of pair production has a curious history. Its discovery by Anderson in 1932 was wholly unexpected, but the observed facts were soon found to fit in with a preexisting theory by Dirac. This agreement with theory implies that pair production is the logical consequence of previously established facts. Nevertheless, the logical connection has not yet been presented in non-mathematical language.

The probability of pair production relates directly to the strength of the electric forces in the space surrounding the charged particle. Therefore pair production is far more efficient in the proximity of nuclei of high atomic number than in the proximity of nuclei of low atomic number or of electrons (Fig. 29).

The production of pairs is confined to the immediate proximity of the charged particles if the frequency of the incident radiation barely exceeds the minimum required value. The fraction of space within each atom where pairs may arise increases progressively as the X-ray frequency and the photon energy increase, until it includes the whole atom.

Pair production is reversible: A positive and a negative electron may neutralize, or "annihilate," each other in the space surrounding another charge and thereby irradiate all their energy in the form of a high energy photon. More frequently, however, a positive electron

ends its life by combining with a negative electron through a somewhat different process which does not require the proximity of another charge. This process releases the energy of the two particles by the simultaneous emission of two photons.

Pair production may also result, with low probability, from the collision of two charged particles. For further details on pair production see e.g. Heitler (1944), Sect. 20.

2.2c ELASTIC COLLISION OF CHARGED PARTICLES ("RUTHERFORD SCATTERING"). When an electrically charged particle of a corpuscular radiation approaches another charged particle within a material, the electrical attraction or repulsion tends to deflect the incident particle off its path and exerts an opposite pull upon the other particle (Fig. 31). Collisions of this kind have the effect of spreading out, or "scattering", the particles of an incident beam.

We speak of "elastic" collisions when the total kinetic energy of the two particles has the same value after as before the collision. (An inelastic "radiative" collision occurs when an X-ray photon is emitted as described at p. 32.)

Rutherford was the first to analyze the elastic collisions of charged particles experimentally and theoretically. He exposed a thin metal foil to a beam of α particles and observed whether and how many particles emerge in various directions (Fig. 32). The overwhelming majority of α particles experience hardly any deflection, a few are deflected by a small angle and some occasional particle is even deflected backwards. Rutherford realized that the chance of a large

deflection depends on whether a particle happens to approach some atomic nucleus within the foil so closely as to experience a particularly strong repulsion. (In fact, the observations on the α particle scattering supplied the first and main evidence of the concentration of positive atomic charges within small nuclei.)

Rutherford and his co-workers showed experimentally and theoretically (see e.g. Rutherford et al 1930) that:

(a) The probability of deflection by any given angle is proportional to the square of the electric charges carried by the incident particle and by the scatterer particle.

(b) The probability of deflection by any given angle is inversely proportional to the square of the kinetic energy of the incident particle.

(c) The relative probability of large and small deflections does not depend on the energy of the incident particle.

(d) The probability of any given deflection is inversely proportional to the fourth power of the momentum change experienced by the particle (Fig. 33). Accordingly, small deflections are far more likely than large ones.

The following formula summarizes these results. Consider an incident particle having a mass m , a velocity v and an electric charge e_1 which traverses a thin layer of matter of thickness t containing N scatterer particles of charge e_2 per unit volume. Assume that the scatterer particles are fixed in space or else that they have an exceedingly large mass so that they do not recoil at all. The probability for the particle to be deflected by an angle between θ and $\theta + d\theta$ equals:

$$P(\theta)d\theta = Nt \frac{e_1^2 e_2^2}{(mv/2)^2} \frac{2\pi \sin \theta d\theta}{\sin^4(\theta/2)} \quad (13)$$

$$= Nt \frac{4 m^2 e_1^2 e_2^2}{(2mv \sin(\theta/2))^4} 2\pi \sin \theta d\theta$$

The expression $2mv \sin(\theta/2)$ represents the momentum change, according to the diagram of Fig. 33.

In practice the scatterer particles recoil as a result of the collision. When this is considered, Rutherford's analysis still applies to the motion of the particles with respect to one another rather than with respect to a fixed frame of reference. The speed of recoil of the scatterer particle and the energy which it acquires depend on the ratio of the masses of the two particles.

If the incident particle is much lighter than the scatterer, as e.g. when an electron is scattered by a nucleus or when an α particle is scattered by a heavy nucleus, the scatterer hardly recoils at all and takes up hardly any energy.

If the incident particle is much heavier than the scatterer, as e.g. when a proton hits an electron, the scatterer offers little resistance to the incident particle and is unable to deflect it greatly or to take up much of its energy. The transfer of some energy to the scatterer is comparatively likely but the amount of energy transferred cannot exceed a rather low limit.

If the two particles have comparable masses, the speed and energy of recoil may be comparable to the speed and energy of the incident particle.

The probability that the scatterer receives a recoil energy comprised between Q and $Q + \delta Q$ is given by a rather simple formula, in which the symbols are the same as in (13) except that m indicates the mass of the scatterer instead of the mass of the incident particle:

$$P(Q)\delta Q = Nt \frac{2\pi e_1^2 e_2^2}{mv^2} \frac{\delta Q}{Q^2} \quad (14)$$

Notice that this probability depends on the velocity v but not on the mass of the incident particle.

These results are modified when the speed of approach of the particles is comparable to the speed of light and also when the two particles are identical.

2.2d MAGNETIC EFFECTS. Electrically charged particles in motion generate magnetic forces and are themselves subject to magnetic forces produced by other currents. The magnetic effects increase in proportion to the speed of the particles.

Magnetic effects are generally obscured by the accompanying effects of electric forces in the processes we have been considering, unless the particles move with velocities approaching the speed of light. The study of processes involving high speed particles requires a detailed treatment of magnetic as well as of electric effects.

Besides the magnetic effects due to the bodily motion of charged particles one must also consider the magnetic effects due to internal currents inherent in the structure of the particles. Magnetic effects of this nature are exhibited not only by complex particles such as nuclei but also by the so-called "elementary particles" such as electrons, protons and neutrons. (Notice that neutrons show evidence of internal currents even though they bear no electric charge.) The magnetic effects are particularly conspicuous in the interaction of neutrons with other particles just because neutrons do not exert any electric action.

2.2e EFFECT OF NUCLEAR FORCES. The "nuclear forces" which act among protons and neutrons and hold a nucleus together also act upon any neutron or proton which happens to get close to a nucleus. These forces are exceedingly strong (much stronger than electric forces between two protons at comparable distances) but they act only among particles separated by no more than a few times 10^{-13} cm.

Nuclear forces have secondary importance in the collision of protons with nuclei, unless the incident proton has sufficient energy to overcome the electric repulsion and get close to a nucleus. No such force resists the approach of incident neutrons. In fact the travel of neutrons is affected almost exclusively by close range collisions with nuclei.

Nuclear forces exert only a minimal influence on electrons.

A nucleus may behave as a rigid body even when nuclear forces are effective in the course of a close range collision. The collision is then "elastic", meaning that no energy is transferred to the internal motion of the nucleus.

Neutrons of moderate energy (up to a few Mev) when they experience elastic collisions with nuclei, rebound evenly in all directions.

Elastic collisions are predominant, in general, for neutrons with a kinetic energy below 1 Mev (see also p. 74ff). The frequency of collisions along the path of neutrons frequently becomes quite large for very low neutron energies.

2.2f SUMMARY TABLE. The following table summarizes the main elementary processes which result from the interaction of incident radiations with "free" atomic particles.

Table 2

Particle Radiation	Electron	Nucleus
Electromagnetic	Compton scattering	Negligible Compton Scattering
	Weak pair production (when $h\nu > 2 \text{ mev}$)	Pair production (when $h\nu > 1 \text{ mev}$)
Electrons	Rutherford scattering with important recoil	Rutherford scattering
	Weak β -ray emission	β -ray emission
	Very weak pair production	Weak pair production
Protons	Rutherford scattering with limited energy transfer	Rutherford scattering (modified by nuclear forces) Negligible β -ray emission
Neutrons	Very weak magnetic interaction	Scattering (with recoil and possible capture due to nuclear forces)

2.3 Action of light and X rays upon atoms and molecules.

Electromagnetic radiation acts upon atomic systems by inducing internal oscillating currents within them. The induction of currents may subtract from the energy of the incident radiation either by dissipating energy within the atomic system ("absorption" proper) or by reradiating energy in a new direction ("scattering").

The process of absorption of one photon of light or X rays is generally localized within the particular atom or molecule which takes up the energy. (The absorption in larger crystalline aggregates of atoms may be localized less closely.) Therefore the absorption of light or X rays by a material may be fairly resolved into separate "elementary processes" which take place within particular atoms or groups of atoms. The absorption of radiofrequency radiation constitutes a macroscopic process and will not be considered here.

The process of scattering of one photon by a portion of matter can be localized within a particular atom or molecule if the atom or molecule shows some after-effect of the scattering. For example, the Compton scattering of a high energy X-ray photon results in the ejection of an electron from an atom.

However, the scattering of light or of low energy X-ray photons generally leaves no after-effect, for the following reason. Unless the recoil of an electron due to the scattering of a photon is sufficiently strong to eject the electron, the recoil is absorbed by the whole atom or molecule to which the electron belongs. Owing to the large mass of

atoms their recoil would entail a very small energy uptake which does not even overcome the cohesion of adjacent molecules. Therefore the scattering of each photon does not necessarily leave a mark on a particular atom or molecule (except in gases of sufficiently low density).

The scattering of radiation may also produce a localized effect on a molecule by modifying its internal motion. The "Raman effect" is a well known phenomenon of this type in which the scattering of light causes a change in the vibration or rotation of the atoms of a molecule with respect to one another.

On the whole, the localized effects of radiation scattering other than the Compton effect, do not seem important for the action of radiation on biological materials. Therefore the attention will be confined here to the absorption of radiation.

Atoms and molecules behave like antennas whose internal electric charges are tuned to oscillate with any one of the characteristic frequencies ν_0 pertaining to the changeover from the initial to another stationary state (see p.39). The internal charges "resonate" when driven by a radiation whose frequency coincides with one of the values ν_0 . The intensity of the induced currents is then limited by the dissipation of energy required to raise atoms from one to another stationary state. Within a population of atoms subjected to this action, individual atoms suddenly appear to have actually absorbed one radiation photon and changed over to a new stationary state. (A photon is emitted if the change-over releases energy instead of absorbing it.)

After an atom or molecule has been "excited" it can return to the fundamental state (see p.42ff.) by releasing energy in one or more steps through two main channels:

(a) "Fluorescence", i.e. emission of radiation of one of the characteristic frequencies of the atom equal to or smaller than the frequency of the absorbed radiation.

(b) Internal rearrangements in which the excitation energy is transferred from one to other particles and is split up in smaller fractions.

The fundamental state which is eventually attained need not be identical with the state preceding the absorption of radiation, because the excitation may have induced a lasting rearrangement of atoms ("photochemical reaction").

The atomic electrons can also "resonate" under the influence of any radiation whose photons have sufficient energy to remove an electron from the atom or molecule. As indicated at p. 39, oscillating currents accompany transitions from stationary to ionized states. The transition to an ionized state under the influence of electromagnetic radiation takes place simultaneously with the absorption of a photon and constitutes a photoelectric effect (see p. 24ff).

An atom or molecule remains ionized until it acquires a new electron. The eventual capture of an electron releases energy which had been originally provided by the photon absorbed at the time of the ionization. (The remaining portion of the energy of that photon is carried away as kinetic energy of the ejected electron.)

When the absorption of radiation results in the ejection of an internal electron, the place of this electron is usually taken by an outer electron which drops in closer to the nucleus. This internal

rearrangement is equivalent to a loss of excitation. The energy released may radiate away as an X-ray photon ("X-ray fluorescence") or may serve to eject another outer electron ("Auger effect", see p. 46).

An atomic electron does not respond strongly to high frequency radiation whose photon energy greatly exceeds the energy required to remove the electron from its atom. In other words, the photoelectric effect becomes unlikely when the radiation frequency is far higher than the threshold frequency. The reason is that the own inertia of the electron, rather than its attraction by the nucleus, presents the main obstacle to oscillations with excessive frequency. Therefore the electron behaves practically as a free electron which scatters but does not absorb radiation.

Fig. 34 illustrates diagrammatically the absorption of radiation of different frequencies by the atoms of a monoatomic gas or vapor. It represents the so-called "absorption spectrum", i.e., the fraction of the intensity of different spectral components which remains unabsorbed after traversing a certain thickness of vapor. The sharp "lines" correspond to the excitation of particular stationary states of the electrons and constitute the characteristic "line spectrum" of the substance. The broad bands on the high frequency side constitute the "continuous spectrum" and correspond to absorption processes leading to ionization of the atoms. The "edges" of successive broad bands correspond to the onset of the ejection of electrons of higher and higher binding energy. The edges corresponding to the ejection of

the innermost electrons lie in the X-ray region, whereas the line spectrum and the beginning of the continuum lie in the visible and ultraviolet region.

The absorption spectrum of the molecules of non-monoatomic substances appears to consist of a succession of bands of limited width followed, in the ultraviolet range, by a continuous spectrum which corresponds to ionization of the molecules. Absorption bands in the infrared range correspond to various forms of excitation of the vibration and rotation of the atoms with respect to one another. The absorption bands in the visible and ultraviolet correspond to the simultaneous excitation of an electron and of interatomic vibrations and rotations. These bands can be resolved in a multitude of "lines" with a good spectroscope, provided the absorbing substance is in a gaseous state and at a low pressure; otherwise the adjacent molecules disturb one another's internal motion and smear out the characteristic absorption frequencies. Molecules and atoms of the same element have identical X-ray absorption because this absorption is due to internal electrons which are unaffected by chemical bonds.

Each kind of atomic nucleus possesses a characteristic absorption spectrum. This spectrum consists in general, like the spectrum of an atom, of a succession of "lines" pertaining to the excitation of various stationary states. The lines correspond to the absorption of definite photon energies which range from about 100 kev upward. The spectrum of light nuclei consists of a number of lines followed by a

broad band which corresponds to the break-up or disintegration of the nucleus. (The nuclei of mass numbers up to 4 and of mass number 9 have no excited stationary state and correspondingly no absorption lines.) The spectrum of heavier nuclei shows an extremely large number of lines which get closer and closer at large energies and finally blend into a broad absorption band at an energy of the order of 5-10 Mev. Maximum absorption seems to obtain at an energy of the order of 20 Mev.

Detailed data on the absorption spectra of nuclei are still extremely scarce.

Table 3 summarizes the elementary processes which occur in atoms or molecules under the influence of electromagnetic radiation of various frequencies.

2.4 Action of charged particles upon atoms and molecules.

When a charged corpuscular radiation traverses matter, the radiation particles exert an electric disturbance over all the atoms and molecules which surround their paths. Most of the atoms thus disturbed exhibit no after effect due to the passage of radiation. Observable after-effects, for example excitations or ionizations, appear here and there, at random.

The atoms which experience an excitation or an ionization need not have been traversed directly or approached very closely by the path of a particle. A close approach by a particle causes a particularly strong disturbance and therefore a particularly high probability of excitation or ionization. Nevertheless an intrinsic randomness governs the actual occurrence of definite processes in one or another atom, as explained at p. 33ff.

Table 3

Absorption and scattering of electromagnetic radiation in different frequency ranges.

		Absorption		Scattering
Increasing photon energy Increasing frequency ↓	INFRARED Energy of lowest electronic excitation (mostly ~2-5 ev) ULTRA-VIOLET AND VISIBLE Binding energy of outermost electron (mostly 10ev) X RAYS Binding energy of innermost electron (10 Z ² ev)	No absorption by single atoms	Molecular absorption of characteristic frequencies concentrated in bands. (Excitation of inter-atomic motion).	Weak scattering
		No absorption (Range of optical transparency)		Scattering increases rapidly with increasing frequency.
		Absorption of optical line spectra by single atoms. (Excitation of external electrons).	Absorption of optical band spectra by molecules. (Excitation of external electrons plus interatomic motion).	Range of maximum scattering. (Intensity of scattering has sharp maxima in the proximity of characteristic frequencies of internal currents)
		Absorption of large numbers of characteristic frequencies		
		Absorption of all frequencies by many electrons. (Range of maximum absorption associated with ejection of external electrons).		
		Weaker absorption by internal electrons		
		Absorption only by innermost electrons		
Atomic electrons behave as free electrons.		Compton scattering proportional to electron number.		
Negligible absorption				
Weak absorption of characteristic frequencies by intranuclear currents.	Pair production in the space around the nuclei.	Extremely weak scattering by nuclear currents.		

The interaction of an incident charged particle with an atom or group of atoms can yield three types of effects, namely: elastic collisions, radiative collisions and inelastic collisions.

Elastic collisions are those in which the atom or molecule recoils bodily, the incident particle is deflected, but no energy is transferred to the internal motions within the scatterer. These collisions result mostly from the electric force between the incident particle and the atomic nuclei. They are particularly apt to cause a deflection of the incident particle, but unlikely to absorb most of its energy, owing to the large mass of the nuclei. An elastic collision reduces to a simple Rutherford scattering (see p. 53 ff.) when the incident particle comes close to an atomic nucleus. Otherwise the negative electronic charge which surrounds the nucleus effectively cancels the electric force due to the nuclear charge and reduces the probability of scattering (see Fig. 35).

Radiative collisions involve the emission of electromagnetic radiation by the incident particle in the course of an otherwise elastic collision. They have already been discussed with regard to the production of X rays (see p. 30 ff.).

Inelastic collisions involve the excitation or ionization of an atom or molecule and result primarily from the interaction of the incident particle with the atomic electrons. Since electrons are light and yield easily to the incident particle these collisions are particularly frequent and take up, on the whole, most of the energy of the incident particle even though each collision usually leads only to a small energy transfer.

As we shall see further on, the inelastic collisions of charged particles constitute the most important mechanism for the action of all high energy radiations on matter.

A given collision may appear to be elastic or inelastic depending on how one looks at it. Therefore some care is required to gauge the meaning of these terms in a particular context. A collision between two specified bodies is called "elastic" if no part of the initial kinetic energy is transferred to the internal energy of the bodies. Thus if an incident proton knocks an electron off an atom, the collision between the proton and the electron may be regarded as elastic. On the other hand, the same collision appears to be inelastic if one regards the whole atom as undergoing a collision with the proton, because the energy taken up by the outgoing electron is then classed as internal energy of the atom which has been raised to a highly excited state.

2.4a MECHANISM OF INELASTIC COLLISIONS. The electric force exerted by an incident charged particle upon each atomic electron increases in strength as the particle approaches and then decreases as the particle moves away. This disturbance acts as a sudden blow if the incident particle moves sufficiently fast and passes sufficiently close to the atomic electron. We speak then of a "fast" collision.

On the contrary we speak of a "slow" collision when the electric force increases and decreases rather slowly and the motion of the atomic electron has time to readjust itself reversibly to the proximity of the incident particle. The reversibility of this disturbance implies that a slow collision is inherently an elastic one. A collision may generally be regarded as "slow" when the incident particle moves more slowly than the atomic electron, but even a fast particle exerts a slowly variable disturbance if it passes too far away.

The electric force between the incident particle and each atomic electron tends to produce an effect basically similar to that of Rutherford scattering. In fact, if the electron receives a recoil energy much larger than its binding energy, it recoils just about as though it were free (see p. 48), according to the law of Rutherford scattering indicated at p. 53ff. A collision where the electron recoils with a large energy may be called a "knock-on" collision. It implies a close approach of the incident particle to the recoiling electron and therefore it occurs rather infrequently.

A high velocity incident particle still exerts a sudden blow, which may result in a fast inelastic collision, even though it passes far away from an atom. The effective "radius of action" may range up to distances of the order of 10^{-5} cm = 1000 Å, i.e. a thousand times as large as the size of an atom. The action of such "glancing collisions" resembles the action of electromagnetic radiation, because it results from an electric force whose strength is fairly uniform over a whole atom but varies rapidly in the course of time.

The sudden blow received by an atomic electron in a glancing collision causes the electron to start oscillating with any of its characteristic frequencies. The electron may therefore land in any of its excited stationary states, or else it may leave the atom as in the photoelectric effect, according to chance. Still, most of the atoms exposed to a glancing disturbance remain eventually in their normal state, as is the case when they are exposed to electromagnetic radiation.

2.4b ENERGY DISSIPATED IN INELASTIC COLLISIONS. The qualitative arguments just presented regarding the mechanism of inelastic collisions serve also as a basis for evaluating the quantitative effect of these collisions.

The average amount of energy dissipated by a particle in a great many collisions is an important index of the total effectiveness of the particle. As pointed out by Bohr, the total energy dissipation does not depend much on the binding of the atomic electrons but can be calculated, in essence, "as though" the electrons were free and all fast collisions were of the knock-on type.

Accordingly, in order to calculate the energy dissipated by a particle, one may start from the expression (14), p. 55, for the probability of collisions which cause a free particle to recoil with energy Q . The expected energy dissipation in collisions where the recoil energy ranges from Q to $Q + \delta Q$ is the product of Q and of the probability $P(Q) \delta Q$ of this kind of collisions. The expected energy dissipation in collisions ranging between wide limits $Q_{\min}$ and $Q_{\max}$ equals the sum, or rather the integral, of $Q \delta Q$ over all intervals δQ from $Q_{\min}$ to $Q_{\max}$. The result of this calculation, starting from eq. (14), is

$$Nt \frac{2\pi e_1^2 e_2^2}{mv^2} \ln (Q_{\max}/Q_{\min}).$$

Large values of the recoil energy Q correspond to knock-on collisions in which the atomic electrons actually behave as free electrons. Therefore the value of the maximum recoil energy $Q_{\max}$ follows from elementary considerations on the mechanics of collisions between free particles. Low values of the recoil energy Q correspond to glancing collisions where the bond of the recoiling electron within an atom is very important. Therefore the determination of the effective value of the lower limit $Q_{\min}$ requires a more sophisticated treatment. However,

any error in the determination of this limit tends to have only a minor influence on the final result because the logarithmic function in the formula above is a slowly varying function of its variable $Q_{\max}/Q_{\min}$.

The factor in front of the logarithm describes the principal influence of the pertinent variables upon the energy dissipation by fast particles traversing matter. It represents the energy absorbed by free electrons in collisions where the recoil energy lies between two limits Q_1 and Q_2 such that $\ln(Q_1/Q_2)=1$. This factor serves as an arbitrary standard of reference for the energy dissipation. The remaining, logarithmic, factor measures the ratio of the actual energy dissipation to the arbitrary standard and embodies the results of the finer details of the calculation.

In the formulae regarding the energy dissipation we shall indicate the charge of the incident particle by ze , rather than by e_1 as in (14), and its speed by v . The charge and the mass of the atomic electrons will be indicated by e (instead of e_2) and m respectively, the number of electrons per unit volume by NZ (instead of N) representing N atoms per unit volume with Z electrons per atom. The factor $\ln(Q_{\max}/Q_{\min})$, which represents the ratio of the actual energy dissipation to a convenient standard, is often indicated by the single letter $\bar{E}$. Using these symbols we express the average energy W dissipated by a particle through inelastic collision while it traverses a layer of matter of thickness t in the form:

$$W = tNZ \frac{2\pi z^2 e^4}{m v^2} \bar{E} \quad (17)$$

The ratio:

$$W/t = NZ \frac{2\pi z^2 e^4}{m v^2} \bar{E} \quad (18)$$

represents the average rate of energy loss per unit distance traveled by the particle and is called the "stopping power" of the material for the particles under consideration. The value of $\bar{B}$ is called the "stopping number" of the atomic electrons for the pertinent incident radiation.

Since $\bar{B}$ depends upon the binding of the atomic electrons one should more properly introduce a separate value $B_1, B_2, B_3, \dots, B_Z$ for each of the Z electrons. The sum of these values can then be entered in equation (17) or (18) in place of the factors Z and $\bar{B}$. (The symbol $\bar{B}$ actually represents the mean of the values of B for all electrons.) Therefore we write

$$W/t = N \frac{2\pi z^2 e^4}{mv^2} (B_1 + B_2 + B_3 + \dots + B_Z). \quad (19)$$

Values of B for various conditions are not as readily available as one may desire. Most of the effort has been devoted to the preparation of data of greater technical interest, namely range-energy relations, see p. 116, 132. Fig. 36 shows some illustrative data with special regard to the variation of B as a function of the energy of the incident particle. The value of B vanishes when the incident particle is much slower than the atomic electron and the collisions are all elastic. Thereafter B increases steadily because inelastic collisions can occur under an increasing variety of conditions. The increase is rapid at first then slows down; it follows approximately a straight line if the energy is plotted on a logarithmic scale.

The variation of the stopping power as a function of the energy of the incident particle results from the combined variations of the factor $2\pi z^2 e^4/mv^2$ and of the stopping numbers B for the different electrons. The stopping numbers increase monotonically as the energy increases, beginning from zero and then levelling off gradually. The factor $2\pi z^2 e^4/mv^2$ decreases at first in inverse ratio to the energy, since it is inversely proportional to v^2 , but then it stops decreasing as the velocity v approaches the speed of light. The increase of B predominates at very low energies, where B tends to vanish, and at very high energies, where $2\pi z^2 e^4/mv^2$ becomes constant; the decrease of $2\pi z^2 e^4/mv^2$ causes a characteristic decrease of the stopping power at intermediate energies. Fig. 37 shows illustrative data. Notice that the main factor $2\pi z^2 e^4/mv^2$ depends only on the charge and on the velocity but not on the mass of the incident particle.

Modifications to the theory are required when the velocity of the incident particle approaches the speed of light (see p. 55) but they are not too important. The necessary corrections are usually incorporated in the value of the stopping number B .

A considerable uncertainty still exists concerning the effect upon the stopping power of the presence of atoms located between the path of the incident particle and the atoms which actually absorb energy. The presence of such atoms tends to reduce the probability of energy absorption in proportion to the density of the material, but only when the velocity of the incident particle approaches the speed of light, and thus to flatten the curve of B vs. energy (see Fig. 36).

2.4c PROBABILITY OF INELASTIC COLLISIONS. The energy dissipation by a particle as it traverses matter results from the product of the number of inelastic collisions and of the average energy dissipated per collision. Since we have already given formulas for the energy dissipation, we may express the number of collisions as the ratio of the total energy dissipation to the average energy loss per collision.

This detour proves convenient because the average energy $\bar{E}$ dissipated in a collision depends only on the relative probability of different outcomes of the collision. This probability, in turn, depends primarily on the characteristic reaction of atomic electrons to a sudden blow and only a little on the nature and speed of the incident particle. Therefore $\bar{E}$ is approximately constant for each kind of atom or molecule, and the variations of the expected number of collisions, N , parallel the variations of the energy dissipation W . We write:

$$N = W/\bar{E} \quad (20)$$

The mean energy transfer has different values $\bar{E}_1, \bar{E}_2, \dots, \bar{E}_Z$ for the different atomic electrons 1, 2, ... Z. One may also consider separately the energies $W_1, W_2, \dots, W_Z$ dissipated to the different electrons in a whole series of collisions and the corresponding numbers $N_1, N_2, \dots, N_Z$ of collisions which affect the different electrons.

For example:

$$\mathcal{N}_1 = W_1/\bar{E}_1 = Nt \frac{2\pi z^2 e^4}{mv^2} \frac{B_1}{\bar{E}_1} \quad (21)$$

The mean energies $\bar{E}_1, \bar{E}_2 \dots$ are of the same order of magnitude as the binding energies of the corresponding electrons and decrease very slowly as the energy of the incident particle increases.

The expected number of collisions $\mathcal{N}_1$ may be further subdivided according to the relative frequency with which the electron 1 is excited to the stationary state a,b,c, ... as a result of the collision. We indicate the relative frequency as $g_{1a}, g_{1b}, g_{1c} \dots$, so that, e.g.:

$$\mathcal{N}_{1a} = \mathcal{N}_1 g_{1a} = Nt \frac{2\pi z^2 e^4}{mv^2} \frac{B_1}{\bar{E}_1} g_{1a} \quad (22)$$

Similarly, the relative frequency of ionizing collisions in which the electron escapes with an energy between E and $E + \delta E$ can be indicated as $g_1(E) \delta E$. Then

$$\mathcal{N}_1(E) \delta E = \mathcal{N}_1 g_1(E) \delta E = Nt \frac{2\pi z^2 e^4}{mv^2} \frac{B_1}{\bar{E}_1} g_1(E) \delta E. \quad (23)$$

Fig. 38 shows sample data on the coefficients g and on their slow dependence on the energy of the incident particle. These coefficients can be estimated fairly readily from data on absorption spectra, relying on the similarity of the action of glancing collisions and of electromagnetic radiation and on a sharp subdivision of collisions into glancing and knock-on ones.

The electrons which escape with an amount of energy E much larger than their binding energy I_1 , should be regarded as resulting from knock-on collisions. Therefore the expected number of these electrons must be given directly by eq. (14). The number of knock-on electrons which receive an energy between $Q = E + I_1$ and $Q + \delta Q = E + I_1 + \delta E$ equals:

$$[\mathcal{N}_1(E)]_{K.O.} \delta E = Nt \frac{2\pi z^2 e^4}{mv^2} \frac{\delta E}{(E+I_1)^2} \quad (24)$$

The comparison of (23) and (24) indicates the following relationship:

$$g_1(E) \sim \frac{\bar{E}_1}{B_1} \frac{1}{(E + I_1)^2}, \text{ when } E \gg I_1. \quad (25)$$

The value of the right hand side of (25) is indicated by the dotted line in Fig. 38.

The excess of lower energy electrons over the number expected on the basis of knock-on processes only, may be loosely regarded as the result of glancing collisions. This excess is very large because the total number of glancing collisions is much larger than the number of knock-on collisions (roughly in a ratio of 8 to 1). Glancing collisions are unlikely to result in the ejection of electrons with energies $E \gg I$; for the same reason which makes the ejection of high energy photoelectrons unlikely (see p. 6-61).

The maximum energy of the ejected electrons is set by the conditions of conservation of momentum and energy in a knock-on collision. If the incident particle is heavy (proton, α particle, etc.) it can impart to an atomic electron up to twice its own speed, and therefore only a small fraction of its own kinetic energy. Thus, e.g., if the incident proton has an energy of 1 Mev the maximum energy of ejected electrons equals 2200 ev.

On the contrary, if the incident particle is itself an electron, it may share any fraction of its energy with an atomic electron in the course of a collision. When the two energies are comparable after the collision, one usually calls "primary" the faster of the two electrons and "secondary" the slower one; this convention amounts to fixing the upper limit to the energy of the ejected electrons at one half the energy of the primary.

The ejected electrons constitute a new, "secondary", corpuscular radiation and therefore receive the name of "secondary electrons". The aggregate energy of this radiation amounts approximately to $2/3$ of the energy dissipated by the incident, or "primary", radiation. This fraction is a little lower than $2/3$ when the dissipation takes place in the lightest elements, which have no internal electrons, and amounts to about $1/2$ in hydrogen.

2.4d EXCITATION OF ATOMIC NUCLEI. We consider here the effect of the impact of fast electrons upon atomic nuclei, and also the effect of the impact of protons and other heavy particles if they remain outside the range of attraction of nuclear forces. Electrons cannot impart a strong recoil to individual nuclear particles because of their low mass, protons cannot either unless they come close to the nucleus. Therefore the collisions we are dealing with can be treated as glancing collisions.

The probability of these glancing collisions can be estimated utilizing data on the absorption of electromagnetic radiations. This probability turns out to be small, mainly on account of the heavy mass of nuclear particles. The excitation of nuclei by the impact of electrons has been detected experimentally. Excitation due to glancing collisions of heavy charged particles has not been distinguished clearly from the excitation due to the effect of nuclear forces.

2.5 Nuclear collisions.

There remains to be considered the direct effect of nuclear particle radiations (protons, neutrons, deuterons, etc.) on atomic nuclei.

Since the nuclear forces are very strong, an incident particle tends to lose its identity and to become mixed with the other particles of the nucleus immediately upon impact, unless its kinetic energy is excessively high. Therefore it is generally convenient to analyze the processes of nuclear collision into two steps. First the incident particle becomes incorporated into the nucleus. Thus a new "compound nucleus" arises from the old one.

This nucleus finds itself in an excited stationary state because much energy normally results from the attraction which the nucleus exerts upon the incoming particle. The excitation energy normally amounts to about 6-10 Mev-- roughly 8 Mev on the average-- for every neutron or proton added to the nucleus. The compound nucleus disposes of its excitation energy, usually by disintegration, according to the principles discussed on p. 46ff.

Once a particle hits the nucleus the formation of a compound nucleus in an excited stationary state is always possible, no matter what the kinetic energy of the incident particle, provided this energy is sufficiently high. At lower energies the excited energy levels of the compound nucleus are still clearly distinct from one another and do not yet blend into a continuous band (see p. 62). No compound nucleus can then be formed unless the kinetic energy of the incident particle added to the energy released by the capture happens to coincide with one of the excited energy levels of the compound nucleus.

This difficulty generally hinders the capture of neutrons of energy below 1 Mev by nuclei of medium or high atomic weight. The corresponding capture of comparatively slow charged particles is hindered anyhow by the electric repulsion. When the energy of the incident particle happens to be just right for the formation of an excited state one speaks of a "resonance effect", by analogy with the resonance of characteristic oscillations induced by electromagnetic radiations. The whole concept of formation of a compound nucleus applies less characteristically to the capture of particles by light nuclei.

No detailed systematics of the results of nuclear collisions has been worked out. The qualitative understanding of the general course of the phenomena does not yield quantitative predictions on the probability of nuclear transformations. The complication of nuclear phenomena is akin to the complication of chemical phenomena which still defies detailed theoretical prediction in the majority of cases.

A fairly large amount of experimental information on nuclear transformations is available (see e.g. Way et al 1950, Hornyak et al 1950).

The various possible types of nuclear transformations are usually indicated by a symbol in parentheses which contains an indication of the incident particle followed by a comma and by an indication of the particle or particles ejected. For example:

(n, α) means a reaction consisting of the capture of a neutron followed by the ejection of an α particle.

(n, pn) means capture of a neutron followed by ejection of one proton and one neutron.

(d, 2n) means capture of a deuteron followed by the ejection of two neutrons.

(n, n) means capture and ejection of a neutron and implies the outward appearance of an inelastic scattering since the nucleus generally remains in an excited state.

Similar symbols apply also to the absorption and emission of electromagnetic radiation. For example (n, γ) means the simple capture of a neutron followed by release of the excitation energy by γ radiation and (γ , p) means the ejection of a proton induced by the absorption of a photon.

The ordinary symbols of the initial and final nuclei, including their atomic and mass number, serve to complete the identification of the transformation. For example $^{63}_{\text{Cu}}(n, 2n)^{62}_{\text{Cu}}$ indicates the production of copper of mass number 62 by the bombardment of copper-63 with neutrons leading to capture of one neutron followed by the ejection of two neutrons.

The preceding discussion pertains to nuclear collisions in which the energy of the incident particle does not exceed 50 or 100 Mev. Higher energy particles seem to move more freely across nuclei, in a manner a little more similar to the motion of particles across atoms. The production of mesons results from nuclear collisions above approximately 150 Mev but does not become very frequent up to much higher energies. The study of high energy collisions has just been passing through its initial stages in the years 1948-1950.

3. THE DISSIPATION OF RADIATION ENERGY IN MATTER.

In this section we begin the discussion of the over-all process of action of radiation on matter, which constitutes the main topic of our treatment.

The biological effects of radiation which are accessible to observation derive presumably from some disturbance of the atomic structure of living matter. What general information does physics contribute regarding the nature and the production of such disturbances by radiation?

We may think of two kinds of permanent or semipermanent changes in the structure of matter, namely "chemical" changes in which some atoms are regrouped to form different molecular or colloidal aggregates, and "nuclear" changes in which the nuclear constituents are regrouped to form different nuclei. Chemical changes do not affect the over-all crude chemical composition of a material but nuclear changes do.

Some changes of structure release energy, others require a net supply of energy. In either case, however, a structural transformation can proceed only through an intermediate structure whose energy is considerably higher than that of both the initial and the final structure. Therefore a rapid transformation must be "activated" by a temporary loan of energy. Radiations act on matter, in the main, just by carrying a flow of energy and distributing it so as to produce a large number of activations.

Chemical changes require activation energies of the same order of magnitude as the energies of chemical bonds, which is also the order of magnitude of the binding energies of external atomic electrons. The bond energies range from about 1 to about 10 ev. The activation energy is effectively supplied to an atom within matter by shaking the atom as a whole or, more frequently, by shaking its external electrons.

An excitation of the external electron brings about a change of the chemical forces which bind an atom within a molecule. This change of forces may or may not lead to a regrouping of the atom in a different molecular arrangement. Thus the excitation of external electrons appears as an indirect method of inducing chemical changes. (The excitation of internal electrons does not even influence chemical bonds directly.)

Excitation of the motion of an atom with respect to its neighbors by a few electron volts constitutes a more direct way of tearing up chemical bonds. However, whole atoms respond to the action of a radiation much less easily than electrons, because of their high mass (see, however, pp. 86 ff.).

The chance of inducing a chemical change improves if an atom receives an amount of activation energy somewhat in excess of the minimum requirement. However, a large excess of activation energy increases the chance of a chemical change no further, because the excess energy leaves the atom in short order, for example through the emission of an electron.

The actual occurrence of one or another chemical change after activation energy has been provided raises problems of molecular mechanics which are treated in later chapters of this collection. Here we are concerned with the distribution of activation energy, both as regards its mechanism and its eventual location in space.

Many radiations, such as X-rays for example, have a potency greatly in excess of that required to produce chemical changes. These radiations are easily capable of ejecting electrons from all kinds of atoms, i.e., of forming ions, and are therefore called ionizing radiations. An X-ray photon may transfer a considerable share of its energy to an electron in a process of Compton scattering. After this process both the photon and the electron constitute an ionizing radiation. All ionizing radiations undergo repeated processes here and there in various atoms as they traverse matter. As a result, their energy is progressively broken down into smaller and smaller packets, that is, it is degraded.

Energy packets of the order of magnitude of 1 to 10 ev., suffice to activate chemical changes. Therefore the energy of ionizing radiations is most effective, for the purpose of activating the largest number of atoms, when sub-divided into packets of this order of magnitude or, as we shall say loosely, when it has been "degraded to the chemical range."

The degradation of the energy of ionizing radiations down to the chemical range constitutes a complicated but rather well understood process. Most of the following discussion deals with this process.

All ionizing radiations turn out to produce the large majority of activations through the same mechanism. Therefore all ionizing radiations produce, on the whole, strikingly similar effects.

The potency of light falls in the lower portion of the chemical range. Infrared light has a low chemical potency, because its photons amount to approximately 1 ev only. The potency of visible light is a little higher and that of ultraviolet light considerably higher. Light in the far ultraviolet range of the spectrum (beyond 1500 or 2000 Å) has full chemical potency but low practical importance because it is absorbed too strongly and therefore it must be handled in a vacuum (see p.23).

Since light has no excess potency, its chemical action must be exerted directly, or nearly directly, without many intervening processes which would cause loss of potency.

Radiations whose potency lies initially, or has subsequently fallen, below the chemical range can still produce chemical changes but with low efficiency. In fact thermal energy from any source may occasionally happen to concentrate upon one or a few atomic particles in amounts adequate to produce a chemical change. This concentration constitutes a statistically unlikely accidental reversal of the general process of degradation of energy. The chance of such unlikely events depends greatly upon the absolute temperature of the material. Small accidental concentrations are far less unlikely than larger ones. Because of the unlikelihood of accidental concentrations, thermochemical transformations proceed slowly as compared to the speed of reaction of atoms activated by radiation, even though they may appear fast on a

macroscopic scale of time.

One may ask whether the chemical and biological effects of any radiation could be regarded as thermal effects taking place after the radiation energy has already been degraded to the thermal range, i.e. into "heat", though not quite down to the ambient temperature. (See e.g. the concept of "point heat" introduced by Dessauer, 1922.) The answer seems to be negative, because the heat conduction, away from the small region where a packet of radiation energy was absorbed and degraded, takes place much faster than a thermochemical reaction.

Nuclear changes can be produced by radiations of very high potency and also by slow neutrons, since neutrons always end up by being attracted and captured by some nucleus. These changes do not depend on the extranuclear state of aggregation of the material but take place--with unimportant exceptions--as though each nucleus were free (see pp. 74ff). A fairly extensive production of nuclear changes results from the action of neutrons in nuclear reactors (see p. 18) and also from the action of high potency radiations.

However, the direct biological significance of the nuclear effects of radiations is normally overshadowed by the simultaneous and far more extensive occurrence of chemical changes. Accordingly, the production of chemical activations calls for a more detailed discussion than the production of nuclear changes.

The following sections describe the chains of elementary processes through which ionizing radiations exert their "chemical" action. The action of non-ionizing radiations is the object of a few additional notes.

3.1 Activation by charged corpuscular radiations.

The over-all action of high speed charged particles upon a material consists, in the main, of a succession of "fast" inelastic collisions (see pp. 63 ff). The atoms and molecules along and around the path of each incident particle react to the passage of the particle in a manner essentially independent of the presence of adjacent atoms. A very large number of inelastic collisions takes place along the path of a charged particle. The energy of the particle is thus progressively used up and transferred to various atoms and molecules within the material.

A large number of the collisions experienced by a fast charged particle may be regarded as "glancing collisions" affecting the external electrons of atoms (see pp. 67 and 71 ff). The energy transferred in each of these collisions is of the order of magnitude required to produce chemical activations, or slightly in excess of that magnitude.

Therefore glancing collisions against external electrons afford a mechanism for degrading high potency radiation directly down to the chemical range. In fact, these collisions constitute the main mechanism of chemical activation by ionizing radiations because, as we shall see, all other elementary processes result primarily in the production of new secondary radiations.

Knock-on collisions against external electrons lead to a larger energy transfer. Most of the energy is carried away by the ejected electron. The collision leaves an atom in an ionized state, that is, in a particular state of chemical activation.

Similarly, any collision which affects internal electrons results in an energy transfer large as compared to the energy required for chemical activations. As discussed at pp. 42-46 most of the energy imparted to internal electrons of an atom leaves the atom again in short order, without suffering any too great degradation. The electron originally ejected carries away much of the energy received; the rest comes out in the form of X rays or as kinetic energy of Auger electrons. In any event, the atom originally affected remains singly or multiply ionized, that is, it undergoes a strong activation, but most of the energy is carried away by new secondary ionizing radiations.

Radiative collisions of an electron and an atom (see pp. 30ff) may lead to the emission of a large fraction of the electron's energy in the form of an X-ray photon. This mechanism, too, has the effect of converting energy from one kind of ionizing radiation into another one. It contributes to the degradation of the radiation energy but does not dissipate much of the energy in chemical activation.

Sample data on the frequency of different kinds of collisions and on their energetic import have been given in eq. 20 ff and in Fig. 37 and 38. Those data pertain to the collisions within layers of matter consisting of a single kind of atoms or molecules. When a material consists of different chemical substances one may calculate the numbers of collisions affecting each substance along the path of a particle as though the other substances were not there. Figs. 39 and 40 give some data on the course of energy degradation in water.

The average fraction of energy spent by electrons in the production of X-rays has been indicated at p. 32. Notice that an occasional electron may release nearly all of its energy in the form of a single photon even when the average X-ray production by a large number of electrons is small. The X-ray production accounts for most of the energy dissipation by high energy electrons traveling through materials of high atomic number. The degradation of energy proceeds then mostly through the process of "cascade showers" which is described at p. 93.

3.1a CHARACTERISTICS OF GLANCING COLLISIONS. As we have seen, fast charged particles transfer energy to atoms in packets of chemical activation size mostly through collisions against the external electrons, which may be loosely referred to as "glancing" collisions. The other types of collision transfer energy primarily from one radiation to another; the energy thus transferred is eventually dealt out to atoms in packets of "chemical" size through further glancing collisions by secondary particles.

According to the discussion at pp. 68 and 71, the atomic electrons "feel" the glancing passage of a fast charged particle as a quick pulse of electric force. The action of this pulse is equivalent to the action of a complex electromagnetic radiation whose intensity is distributed evenly among all frequencies.

The external electrons are thus in a position to absorb just those amounts of energy which correspond to their own characteristic frequencies of oscillation. There results no preferential or selective absorption of energy by the electrons of any particular group of atoms. In

other words, ionizing radiations exert through glancing collisions an entirely non specific action.

Since atomic electrons are not very apt to absorb photons of energy greatly in excess of their own binding energy (see p. 60-61), the energy absorbed by external electrons through glancing collisions is generally of chemical or nearly chemical scale. Finally since the glancing passage of a charged particle acts only as a quick electric pulse, the relative frequency of different energy absorptions in any particular atom does not depend upon the charge, mass and velocity of the incident particle (see p. 71). These quantities affect equally the probability of each absorption. Here is a further reason why all kinds of ionizing radiations act in the same way, if not to the same extent.

3.1b IONIZATION YIELD. Ionization constitutes a particularly drastic form of **chemical** activation. When an electron is ejected from an atom, the resulting separation of electric charges lasts for a much longer time than the minor dislocations of atomic electrons which accompany simple excitations. It is uncertain whether the somewhat larger energy involved in the ionization processes than in excitations and the greater permanency of charge separation have a particularly great significance with regard to biological effectiveness.

The separation of charges which results from ionization processes in gases affords a convenient and sensitive method for the physical measurement of radiation effects. It is frequently assumed, on somewhat uncertain grounds, that a radiation produces essentially

equal amounts of ionization in a given amount of matter whether the matter is in gaseous, liquid or solid state. Present information on the subject of ionization concerns mostly the occurrence of this phenomenon in gases.

The ratio $\bar{\epsilon}$ of the energy dissipated in a gas to the number of ionizations produced is approximately equal for different ionizing radiations, since most ionizations originate from a single mechanism, namely charged particle collisions affecting the external electrons. Therefore the number of ionizations produced in a gas frequently serves as a measure of the energy dissipated within it. Table 4 shows the numerical values of the ratio $\bar{\epsilon}$, which represents the average energy dissipated per every ionization produced by various radiations in different gases.

The energy $\bar{\epsilon}$ dissipated per ionization does not depend immediately on the ionization potential (the energy actually required to rip off an electron from an atom) but results from a grand average over all collisions, among which some produce an ionization and some do not. In fact, the values of $\bar{\epsilon}$ vary within narrow limits from one substance to another and lie in the neighborhood of 30-35 ev per ionization for most gases.

The value of $\bar{\epsilon}$ for each substance depends on how often external electrons are raised to different levels of excitation and ionization as a result of collision. As indicated at pp. 71-72, the probability of different outcomes of a collision depends on the readiness of electrons to start oscillating with different frequencies after a glancing disturbance. Electrons that are attached rather loosely, that is, electrons with a low ionization potential, are generally apt to oscillate with comparatively low frequency and with great intensity, while being raised to low excited states, but the opposite obtains for electrons that are held more stiffly. Therefore, excitations are relatively more probable than ionizations just in those atoms and molecules

Table 4

Typical values of $\mathcal{E}$, the energy dissipated per ion pair produced.

340 Mev protons in H ₂	34.9 ev
340 Mev protons in air	32.2 ev
5.2 Mev α particles in H ₂	36.0 ev
5.2 Mev α particles in air	31.1 ev
5.2 Mev α particles in He	31.0 ev
50 kev electrons in air	32.4 ev

For additional data and discussion see e.g.

Rutherford, et. al. (1930) p. 80, Gray (1944)

Bethe (1950) Bakker and Segré (1951)

which require least energy to be ionized. In other words, just in those substances where an ionization can be produced cheaply, in terms of energy, a larger amount of energy has to be spent in excitations. (In substances whose ionization potential has a typical average value, around 10 ev, the relative frequency of excitations and ionizations is of the order of two to one.) This argument accounts for the remarkable similarity of the values of ξ for different substances (Fano, 1946).

As a particle begins to slow down, there is no longer a great excess of glancing collisions over collisions which involve a larger momentum transfer. Therefore one observes a somewhat paradoxical result: The probability of excitation tends to decrease, as compared to the probability of ionization (see Fig. 38); the over-all yield of ionization increases and the value of ξ decreases a little.

3.1c ENERGY DISSIPATION BY LOWER ENERGY HEAVY PARTICLES. Inelastic collisions tend to become extremely unlikely when the incident particle slows down to and below the velocity of atomic electrons (see pp. 66). A heavy particle may move more slowly than any atomic electron within a material and still retain a substantial kinetic energy. This obtains, for example, for protons whose energy falls below approximately 20 kev or for nitrogen ions below 300 kev. The energy dissipation by such "slow" particles does not appear important, on the whole, in ordinary phenomena of radiobiology because most of the radiation energy is dissipated by fast particles. Dissipation by slow particles is of importance under special circumstances, especially with regard to the action of neutrons.

"Slow" heavy particles dissipate most of their energy by forcing atomic nuclei to recoil as a result of "elastic" collisions. Even though the particle be slower than the atomic electrons, it may possess a momentum and energy more than adequate to force its way through the atoms of a material. The atomic electrons do not have sufficient mass to deflect the incident particle but the atomic nuclei do. Therefore the elastic collision reduces, in a sense, to a Rutherford scattering of the incident particle by the nucleus of the atom (see pp. 63-65 and 53 ff.).

As the kinetic energy of the incident particle becomes comparable to the binding energy of the internal atomic electrons within the material, the penetration of the particle through the atoms becomes more difficult. Thus an increasing portion of the atomic volume behaves as an impenetrable body and the elastic collisions acquire progressively the character of bodily impacts such as take place among the atoms and molecules of a gas.

The rate of energy dissipation by elastic collisions along the path of a particle is rather low. It can be estimated by the same methods as the rate of dissipation by inelastic collisions. Fig. 40 shows some illustrative data.

The energy dissipated through elastic collisions tends to escape detection by ordinary radiation measuring devices such as ionization chambers, cloud chambers or Geiger counters. Nevertheless, this energy is imparted directly to the motion of the massive portions of atoms (the nuclei) with respect to the adjacent atoms. Therefore it may more easily cause a substantial dislocation in the structure of matter and thus may turn out to be particularly effective.

It should also be noticed that "slow" heavy particles tend to pick up electrons, as they traverse atoms, up to the point of becoming electrically neutral atoms. For example, an α particle which picks up two electrons becomes a neutral helium atom. The capture of electrons by positively charged radiation particles reduces their charge and thereby reduces their chance of producing inelastic collisions. Nevertheless it does not reduce, in essence, their dissipation of energy by elastic collisions once the particles are quite slow.

Under what conditions can an electron travel along attached to a positive ion without being stripped off in the course of collisions with atoms? Consider, for example, an electron which is combined with an α particle to form an He^+ ion. This electron "sees" the atoms of matter rushing on toward it with a speed equal to the speed of the He^+ ion. Therefore if the He^+ ion as a whole moves faster than the electron within the ion the collisions with matter are "fast", as far as the electron is concerned, and lead soon to a stripping of the electron. A He^+ ion, that moves along as fast as its electron moves about the nucleus, has a kinetic energy of 0.4 Mev. An α particle of this energy is liable to pick up an electron and to carry it along through several collisions. An α particle of much lower energy normally holds on to an electron and travels as a He^+ ion. At still lower energy, the particle picks up a second electron.

Observations show that the density of ions along the tracks of comparatively slow heavy charged particles varies at intervals, indicating a change of the net charge carried by the particle. For example, the charge of an α particle of less than 1 Mev appears to jump back and forth between $2e$ and e and eventually settles at the lower value. A proton may also capture an electron and travel on as a neutral hydrogen atom when its energy falls near to 0.025 Mev or less. The loss and gain of charge of ions of moderate velocity is at present (1950) under experimental study by Allison and co-workers at the University of Chicago.

The nuclear fission of uranium or other very heavy atoms (see p. 48) results in the ejection of "fragments" which are ions of medium atomic weight with kinetic energies of the order of 100 Mev. Despite their high energy, these ions move more slowly than their internal electrons, because of their high mass and high atomic number and therefore hold on steadily to quite a number of electrons during their flight.

Even the "elastic" collisions of very "slow" heavy particles may lead to the capture or loss of an electron by the particle. Therefore the particle may never remain steadily neutral. This persisting exchange of electric charge at low energies may be regarded as a residual ionization. Quantitative data on this subject are scarce.

3.1d DISSIPATION OF ENERGY BY SECONDARY ELECTRONS. As pointed out at p. 73, the "secondary" electrons which are ejected from atoms all along the track of a fast charged particle carry away an aggregate $2/3$ of the total energy of the particle. These electrons constitute a new charged corpuscular radiation which dissipates its energy, by and large, as described in the preceding sections.

The action of the secondary electrons differs from that of the primary charged particles only in so far as most of the electrons are comparatively slow (see p. 71). Therefore the inelastic collisions experienced by secondary electrons affect solely the external electrons of atoms within a limited radius of action. The qualitative effect of these collisions differs somewhat from the effect of collisions by very fast particles, in so far as the secondaries produce comparatively more ionizations and fewer excitations. Nevertheless this circumstance does not affect the great similarity of action of different ionizing radiations, since the secondaries themselves are produced according to the same pattern no matter what the primary radiation.

Secondary electrons whose energy no longer suffices to disturb the external electrons of other atoms, undergo a large number of elastic collisions thus slowly losing their energy in packets of "thermal" size. The electrons are eventually captured by some atom or molecule with formation of a negative ion. The formation of negative ions constitutes in itself a semi-permanent change whose chemical and biological effectiveness is uncertain.

Only highly electronegative atoms, or groups of atoms, such as F, Cl, O and O₂, are capable of capturing electrons. Moreover the chance of electron capture is quite small, at best; capture occurs, on the average, only after thousands of elastic collisions with electronegative atoms.

3.2 Activation by X-rays and γ rays.

X-rays or γ rays, traversing matter produce three main types of phenomena, namely: (a) photoelectric effect (pp. 60-61), (b) Compton effect (p. 49 ff), and (c) pair production (p. 51 ff).

These phenomena take place here and there through any material exposed to X-rays. The laws of atomic physics predict the probability that any one of these phenomena will take place in any given atom, but otherwise the actual occurrence of these phenomena proceeds at random.

Each individual process of photoelectric effect or of pair production causes the disappearance of one X-ray photon. The energy of this photon is transferred to one or two electrons which are thereby violently ejected and constitute a new corpuscular ionizing radiation. A part of the photon's energy may be reemitted in the form of lower potency

X rays, namely by X-ray fluorescence (see p. 60) following a photoelectric effect or by positron annihilation following pair production (see p. 53).

Each process of Compton effect causes the transfer of a part of one photon's energy to an electron, which is thereby violently ejected and constitutes a new corpuscular radiation. The energy transferred to the electron is almost invariably far in excess of the chemical range. The energy which remains in the scattered X-ray photon is subject again to further transformations, like the energy of the initial photon.

All processes produced by X rays have therefore the main effect of replacing X rays with fast electrons. The chemical action of X-rays is exerted almost entirely through secondary fast electrons, which act, in turn as described at p. 82 ff.

The relative frequency of photoelectric effect, Compton effect and pair production depends greatly upon the energy of the X-ray photons and upon the atomic number of the material traversed. Photoelectric effect predominates greatly at lower energies, Compton effect at intermediate ones and pair production at higher energies. Data on this subject are shown in Fig. 41. Fig. 42 shows a diagram of a chain of degradation processes and gives results on the overall effects of degradation of Cobalt-60 gamma rays in water.

When the photoelectric effect is most important, the energy of each X-ray photon is primarily distributed by a single photoelectron. When Compton effect is most important each X-ray photon produces in succession a series of secondary electrons.

At high photon energies, where pair production is most important, the electron and the positron which arise by pair production from one photon are likely to lose most of their energy in the production of more X rays. If these X rays have a still sufficiently high photon energy, they produce more pairs. The process may go on and on: X rays make pairs, the pairs make more X rays, the X rays make more pairs (see Fig. 43). The group of particles and photons which results from this process is called a "shower", or, more specifically, a "multiplicative shower" or "cascade shower." A cascade shower can be started by a single high energy electron (see p. 84) as well as by an X-ray photon (Fig. 44).

When a high energy electron or positron transfers a large share of its energy to a newly emitted X-ray photon and then the photon produces a pair, this pair added to the initial particle gives a total of three particles. By the time the pair is generated by the photon, the initial particle has an even chance, on the average, of emitting still another photon. Thus the total number of particles and photons doubles, on the average, after each step of the phenomenon, as shown schematically in Fig. 43.

The finer and finer subdivision of the total energy available, into packets of comparable size, stops when the energy of the electrons and positrons reduces to the level where it is spent mostly in inelastic rather than in radiative collisions.

3.3 Activation by Neutrons

Neutrons traversing a material interact almost exclusively with the atomic nuclei. Nuclear collisions occur here and there throughout

the material, according to the general rules indicated at p. 74 ff.

The collisions result in the production of secondary radiations which may include charged corpuscular radiations, γ -rays and also neutrons of lower energy than the incident ones. In any event, the great majority of chemical activations results from the action of charged particles since also the secondary γ -rays and neutrons act only indirectly. A delayed emission of secondary radiation results when the capture of a neutron leads to the formation of a metastable nucleus, e.g. β -radioactive.

Elastic collisions of neutrons against hydrogen nuclei (protons) absorb most of the neutron energy whenever a hydrogen-rich material, such as tissue, is exposed to neutrons. In the first place a neutron-proton impact has a much greater chance of yielding an elastic collision than capture. In the second place protons, being no heavier than neutrons, are capable of recoiling violently under the impact. The recoiling proton may take up any fraction of the neutron energy. Each elastic collision leads, on the average, to an even sharing of energy between neutron and proton. As a result, a material containing hydrogen, which is exposed to neutrons, is traversed by protons of all energies from zero up to the initial kinetic energy of the neutrons. Elastic collisions also result with highest frequency from the impact of neutrons on the nuclei of other light elements, notably helium, carbon and oxygen.

Table 5

Components of the energy absorbed in 1 gram (1 cc) of Tradescantia tissue, at constant flux of 1.25×10^9 thermal neutron/cm² sec. (Reprinted from Conger and Giles, 1950)

SOURCE OF COMPONENT	TYPE OF RADIATION	REP/MIN	REP PER 1×10^{11} n_{th}/cm^2	PERCENT of TOTAL REP	PERCENT of CAPTURE REP
(1) Fast neutron contamination	p^+ recoil	negligible	negligible	---	---
(2) Inherent gamma-ray contamination	γ	6.0 r max.	8.0	82	---
Capture processes					
(3) H capture	γ	0.195	.260	2.7	15
(4) N capture	p^+	.628	.837	8.6	48
(5) B capture	α^{++}	.394	.525	5.4	29
(6) Induced Radioactivity (from Cl^{38})	β^-, γ	$\sim .100$ (.52 max)	.133 (.69 max)	1.4	7.5
Sub totals:					
all capture:					
H+N+B+Cl	$\gamma + p^+ + \alpha^{++} + \beta^- + \gamma$	---	1.75	18.0	---
from N+B only	$p^+ + \alpha^{++}$	---	1.36	14	78
Total:					
contam. + capture	$\gamma, + \gamma + p^+ + \alpha^{++} + \beta^- + \gamma$	---	9.75		

Note: 1 "rep" has been taken by Conger and Giles as equal to 83 ergs absorbed per gram of tissue, see p. 201-202

The dissipation of energy by all possible mechanisms must be evaluated in detail, for each specific application, whenever the dissipation by proton recoil does not constitute the main mechanism or anyhow whenever an accurate knowledge is desired. For example, Table 5 summarizes the result of an evaluation of the energy dissipated by neutrons, mostly of low energy, in a biological material. The introduction in a material of an abnormally large amount of some highly neutron-absorbing element, like boron, serves to increase locally the energy dissipated by slow neutrons.

3.4 Activation by infrared, visible and ultraviolet light.

As mentioned before, the potency of light lies in the lower portion of the chemical range. Light energy is delivered directly to individual atoms and molecules by absorption of individual photons here and there throughout a material exposed to light. Photon absorption leads then generally to a simple excitation, whose possible consequences have been considered briefly at pp. 60 and 42 ff.

One further point must be considered with regard to the action of light on materials such as living matter, or even on less complex organic substances. Most pure non-electrically-conducting substances are transparent to near-infrared, visible and near-ultraviolet light. Therefore the absorption of these radiations in most organic materials takes place exclusively in special molecular groups which are called "chromophoric" and are present in greater or smaller concentration. The specific absorption of visible light of wavelength ^{between} 6000 and 7000 Å

by chlorophyll in plants offers a familiar example of this mechanism. The absorption of ultraviolet light near $2600 \text{ \AA}$ by the purine and pyrimidine groups of nucleic acids offers another well-known example.

Thus we see that special groups of atoms constitute the point of attack of the primary action of light on a large number of materials, particularly on biological materials. Different atomic groups respond to light of different wavelengths. In principle this makes it possible to channel the action of radiation by introducing suitable molecular groups which absorb specifically light of certain wavelengths. Conversely the action of certain wavelengths is understood to be channeled through groups of proper specificity. In practice, however, the absorption bands of molecular groups in liquid or solid state are not too sharp. Therefore this specificity of action does not actually serve as a tool of investigation as well as one may wish.

3.5 Action of far infrared and radio-frequency radiation.

Electromagnetic radiation can dissipate energy by inducing electric oscillations in larger amounts of matter when its frequency is too low to match the characteristic frequencies of oscillations of atoms or of atomic aggregates. This absorption, like the absorption of atoms, becomes particularly intense if the period of oscillation of the radiation matches a characteristic time of response of the material exposed to radiation.

Consider the two examples shown in Fig. 45, namely, a cylindrical conductor and a suspension of particles which are positively charged on one side and negatively charged on the other. (These particles may be

simple molecules or larger colloidal particles;

water and ammonia molecules among many others are "polar" molecules, i.e. have an uneven internal distribution of charges as shown in the figure.)

Fig. 45 shows how either of these systems becomes "polarized" by electric induction under the action of an electric force. Electrons that move freely through the cylinder accumulate at its bottom surface and leave a net positive charge on the top surface. A majority of the particles in suspension take an orientation with their positively charged side pointing upward.

Neither of these effects is achieved instantaneously: The motion of electrons through the conducting cylinder is opposed by the electric resistance of the material and by self-induction and capacity effects. The re-orientation of suspended particles is opposed by the impacts between the suspended particles and the molecules of the medium or, as it may be said, by internal friction. Vice versa the polarization does not vanish instantaneously if the field is suddenly switched out. The time in which the polarization effect decays to $1/e$, that is to 37% of its initial value, serves as a measure of the lag with which the polarization adjusts itself to variations of the field and is called the "relaxation time" of the system. Table 6 shows values of the relaxation time for a few typical systems.

If the electric force oscillates with a period much longer than the relaxation time of either system in Fig. 45, that system stays steadily polarized according to the instantaneous value and direction

Table 6

Sample data on the relaxation time of polar systems.

Liquid H_2O	at	20 C°	0.4×10^{-10} sec
Solid H_2O	at	-5 C°	2.7×10^{-6} sec
Solid H_2O	at	-22 C°	18×10^{-6} sec
Liquid C_3H_7OH	at	20 C°	0.9×10^{-10} sec
Liquid C_3H_7OH	at	0 C°	1.6×10^{-10} sec
Liquid C_3H_7OH	at	-60 C°	26×10^{-6} sec

of the force. If, on the contrary, the period of oscillation is much shorter than the relaxation time, the polarization cannot possibly follow the variations of the force and necessarily remains very small. Finally, if the period of oscillation has the same order of magnitude as the relaxation time, the polarization barely succeeds in following the variations of the force; the system absorbs then a maximum amount of energy by dissipation into heat due to electrical resistance or internal friction.

Energy thus absorbed is not capable of producing chemical transformations in the irradiated matter directly, owing to the low potency of the radiation, but may do so indirectly through heating effects. These effects may be localized if a certain portion of the material exposed to the radiation has an electric relaxation time which just matches the period of oscillation of the radiation.

3.6 Spacial Distribution of Activations

We have been dealing, thus far, with the mechanisms through which radiations produce chemical activations within a material. Information on the spacial distribution of the activations within a material, that is on the proximity of adjacent activations, is also important for the interpretation of their ultimate biological effects.

It seems clear a priori that the proximity of different activations may affect the chance of biological effects. Suppose, for example, that activations result in the formation of diffusible active radicals. These radicals have a greater chance of colliding if they arise close to one another than otherwise. The collision may

conceivably yield a still more active product, or also an inactive one. Thus an increase in the concentrations of activations in a portion of matter might either enhance or depress the macroscopic effect of radiation which is observed eventually. Instances of enhancement and of depression of radiochemical or radiobiological actions have actually been found to result from crowding of activations (see p. 182 ff).

The following pages deal with the factors which govern the proximity of the activations produced by radiations. Ionizing and non-ionizing radiations behave quite differently in this respect because the action of ionizing radiations is concentrated along the tracks of charged particles but the action of non-ionizing radiation does not follow any such systematic pattern.

Since light produces activations by the direct absorption of different photons, these activations take place in different molecular groups independently, in a wholly uncorrelated random fashion. If an atom has been excited by light, adjacent atoms have a normal average chance of being excited as well, just like other similar atoms in any portion of the material equally exposed to the radiation beam. On the contrary, if an atom has been excited by an ionizing radiation, a fast charged particle must have passed in the proximity of that atom and therefore the chance of excitation of adjacent atoms by the same particle is particularly high.

Quite in general, the only systematic influence upon the proximity of activations arises from their arrangement along and about the tracks

of fast charged particles. The essential data required to describe this arrangement may be derived from the discussion of the collisions of charged particles at p. 63 ff. A picture of the distribution of activations results by considering a number of separate questions such as: the average number and kind of collisions along the track of a particle, the statistical fluctuations in the distribution of these collisions and the distribution of activations produced by secondary electrons.

3.6a COLLISION DISTANCE ALONG THE TRACKS OF FAST PARTICLES. The mean number of inelastic collisions experienced by a charged particle traversing a thickness of matter has been discussed at p. 71 ff. Formula (22) indicates the mean number of collisions leading to a particular kind of excitation. Formula (21) indicates the mean number of all inelastic collisions which affect electrons bound in a particular way within a particular kind of atom. The mean total number of all inelastic collisions is obtained by adding up the collisions which affect all the differently bound electrons in all kinds of atoms within the material.

The average distance l of two successive collisions of any specified kind along the track of a particle is the reciprocal of the mean number of those collisions per unit length of the track. This average distance varies greatly depending on the charge and speed of the particle, as shown by the formulas. For example, collisions are spaced thousands of times more closely along the track of a 1 Mev alpha particle than along the track of a 1 Mev electron. (Most of the difference stems from the far lower speed of the alpha particle, a further factor

of 4 stems from its double electric charge). An alpha particle experiences an inelastic collision, on the average, every 5-10 Å in most solids or liquids, an electron less than one every micron.

Whereas the average spacing of the collisions along the track can be controlled by varying the speed and the charge of the particles, the kind of collisions does not vary to a significant extent from one radiation to another (see p. 71 and Fig. 38).

Activations may occur in atoms lying at a substantial distance from the line of flight of a particle, as explained at p. 67. Actually the track of a particle is identified only by the position of the activations which are produced. These activations do not lie exactly on a straight line even where the track is, on the whole, straight. Nevertheless one may visualize the track of a particle as an ideal line running down the middle of the region where the activations are distributed. One may then inquire about the average number of activations at various distances from this line. The numbers are roughly equal in successive coaxial layers whose thickness increases in a geometric progression and which extend, e.g. from 5 to 10, 10 to 20, 20 to 40 Å etc. from the line. The maximum distance of activations depends on the condition that the collision be "fast", see p. 67.

Since collisions occur at random along the path of a particle, one may inquire about the probability that the actual distance by various two successive collisions depart from the average distance by various amounts. "Random occurrence" of collisions means that the chance for a collision to occur on a certain section of track is wholly unrelated to whether or not the preceding collision has taken place only a short

distance before. The law of probability which governs the actual distance between collisions may be derived from the following argument.

Suppose that a large number N_0 of particles start to travel under identical conditions and that 10% of them have undergone a collision within a distance δ . The remaining 90% travel on, still unaffected. Therefore, 10% of these 90%, ie another 9% of the initial N_0 particles, experience a collision between the distances δ and 2δ . Then 10% of the remaining 81% experience a collision between 2δ and 3δ , and so on (see Fig. 46). This reasoning applied to very small, infinitesimal, intervals of distance leads to the basic law of distribution of collisions.

Call N the number of particles which have traveled a distance x without experiencing any collision. The infinitesimal fraction df of these particles which undergoes a collision in the next infinitesimal distance interval dx is proportional to dx :

$$df = \gamma \, dx$$

and is independent of the distance x already traveled. The coefficient γ equals the expected number of collisions per unit distance, that is, the average number of collisions γ calculated according to the formulas of pp. 71-72 for a layer of thickness $t = 1$. The reciprocal of γ represents the average distance l of two successive collisions. Therefore, the number N decreases along dx by:

$$-dN = N \, df = N \, \gamma \, dx = N \, dx/l \quad (26)$$

This equation requires that the number of particles N which have traveled a distance x without any collision vary according to the law

$$\frac{N}{N_0} = f = e^{-\gamma x} = e^{-x/l}, \quad (27)$$

where e represents the number 2.71828 and N_0 indicates the initial number of particles. The ratio $f = N/N_0$ is the fraction of all particles which travel a distance x without collision, that is the probability for any particle to travel that distance without collision. The law (27) may be applied to the distance traveled without any collision whatsoever or to the distance without any collision of any given type; the appropriate value of the expected number of collisions γ must be introduced in each case.

Fig. 46 also shows that the semi-logarithmic plot on N against x follows a straight line with the slope γ which is described by the equation:

$$\log N = \log N_0 - \gamma x \quad (27)$$

The same type of considerations serves to find the probability $P_n(\gamma)$ that any one particle undergoes a given number n of collisions along a track distance x :

$$P_n(x) = \exp(-\gamma x) (\gamma x)^n / n! \quad (28)$$

* The symbol $n!$ indicates the "factorial of n ," i.e. the product $1 \cdot 2 \cdot 3 \cdot \dots \cdot n$.

This is the well known Poisson distribution law. The expected number of collisions along a track length x equals γx , the actual number is n . The calculation of the probability P_n for various values of n shows that the most probable value of n equals the next integer number below x . An estimate of the likely departures of n from x is obtained by calculating the variance or mean square deviation of n . This quantity turns out to equal γx itself, meaning that departures of the order of the root mean square deviation $\sqrt{\gamma x}$ are frequent.

3.6b DISTRIBUTION OF ACTIVATIONS PRODUCED BY SECONDARY ELECTRONS

As we have seen on pp. 73 and 90 ff., the great majority of the secondary electrons have a rather low energy, even though their aggregate energy amounts to about 2/3 of the energy lost by a fast particle. Electrons whose energy amounts to no more than 100 or 200 ev can transfer energy only to the external electrons of atoms, and this only when

passing right through or very close to an atom. On the other hand, every passage in the proximity of an atom has a fair chance of leading to a collision with energy transfer because these electrons are slow. Furthermore, low energy electrons experience frequent repeated large angle deflections.

Therefore, low energy secondaries dissipate most of their energy within a short distance from their point of origin. This distance is of the order of 10 Å in solid or liquid materials and about 1000 times as large in gases at atmospheric pressure. This energy is dealt out in the form of activations (excitations or ionizations) at points irregularly scattered in the proximity of the atoms from which each electron was ejected. These activations are said to form a "cluster".

Not all of the activations in a cluster are produced directly by the secondary electron which originates the cluster. Some are produced by other electrons which are "secondary to the secondary", that is, which are ejected with sufficient energy as a result of ionizing collisions within the same cluster.

Little detailed information is available regarding the statistical distribution of the location of activations within clusters. The distance traveled by a secondary electron depends on its initial energy, is roughly inversely proportional to the density of the material (see p. 117) but depends little on the chemical structure of the material. The clusters include the negative ions which arise by capture of very slow electrons ^{after} protracted migration (see p. 91). In the course of the migration the electrons diffuse far away from their point of origin, probably up to more than 100 Å in water and one thousand times as far in air (even though air contains much oxygen). Therefore, negative ions lie, on the whole, much farther from the center of a cluster than the positive ions or the simple excitations. It is doubtful whether the formation of negative ions has much significance with regard to the chemical and biological effects of radiation.

The number of activations or the number of ions within a cluster depends primarily on the energy of the secondary electron which generates the cluster. The number of ion pairs is roughly equal, on the

average, to the total energy dissipated within the cluster divided by 30 ev (see p. 86). Therefore, the frequency of clusters containing different numbers of ion pairs shown in Table 7 parallels the frequency of secondary electrons of different energies shown in Fig. 38. Notice that this distribution is completely skew; a large proportion of the clusters consists of a single pair of ions, corresponding to energy-poor secondary electrons. The average number of ion pairs per cluster is approximately 3 for most gases.

The larger the initial energy of a secondary electron, the longer and the more nearly straight is its path. The transition from cluster formation to an arrangement of activations along a clear track takes place gradually, of course, as the energy increases from about 100 to about 500-1000 ev. Secondary electrons whose energy amounts to at least several hundred electron volts are called delta rays.

The track length of delta rays of various initial energies is not known satisfactorily. The theoretical methods for calculating the "range" of fast charged particles (see p. 126ff) are less reliable when applied to comparatively slow electrons. Experimental evidence is scarce. Lea (1947) has given tables of the numbers and ranges of rays produced by various kinds of particles in living tissue but these data should be used with caution. The preparation of more comprehensive and reliable data requires further study.

3.6c OVERALL DISTRIBUTION OF ACTIVATIONS AROUND THE TRACKS OF FAST PARTICLES. It follows from the preceding discussion that the activations produced by a fast charged particle are grouped in clusters of different

Table 7

Frequency of ion clusters containing various numbers of ion pairs

Number of ion pairs in the cluster	1	2	3	4	>4
Frequency	0.43	0.22	0.12	0.10	0.13

Experimental data by Wilson (1923).

sizes spaced at irregular intervals along the particle's track. Many "clusters" actually consist of a single activation. The activations produced by the few secondary electrons whose energy is particularly high constitute a delta ray track which branches out from the main track.

The speed and charge of a particle determine the average spacing of clusters along its track, but the frequency of clusters of different sizes is nearly independent of the characteristics of the incident particle.

Cloud chamber pictures of charged particle tracks give a visual impression of the spatial distribution of the action along the track, but this impression is often distorted by various circumstances. Fig. 47 shows the tracks of a very fast and of several slower electrons. Spots corresponding to successive clusters are generally distinguishable along the fast electron track but not along the slow electron tracks. The separate ions in each cluster cannot be resolved in the picture unless time is allowed for the ions to diffuse apart before the chamber expands. Fig. 48 shows a magnified picture of a track with resolved clusters, but the positions of the individual ions in this picture does not correspond to the actual points of origin of the ions.

The tracks of alpha particles or protons of a few Mev are marked by collisions so closely spaced (owing to the low velocity of these particles) that the successive clusters merge to form a single compact

column (Fig. 49). It seems somewhat uncertain how well the cloud chamber pictures reflect the actual distribution of activations. Part of the observed blending of clusters certainly arises from the migration of electrons prior to the formation of negative ions (see p. 106) and thus appears as a somewhat spurious effect. Notice also that the pictures taken in increasingly rarefied gases show an increasing amount of detailed δ ray structure and give less and less the impression of an even columnar distribution of ions.

3.7 Summary

The main lasting effects of radiation of a material consist of changes in the chemical state of aggregation of the material. Changes in the aggregation of particles within atomic nuclei are overshadowed in numbers by chemical changes, by many orders of magnitude.

Chemical changes result, in the main, from the disturbance, or "activation", of the external electrons of atoms and molecules. Ripping of chemical bonds through bodily bumping of whole atoms by radiation particles is quite infrequent, under ordinary conditions.

Two phases are distinguishable in the chain of processes that follow the introduction of radiation energy into a material. (1) The first phase develops through radiation phenomena and ends when most of the energy absorbed is distributed in separate packets having the form of chemical activations. (2) The second phase of the process develops through chemical (molecular) processes and is accompanied by the eventual complete degradation of the radiation energy into heat. We have

much better information on the first phase of the process than on the second. The present treatment deals only with the first phase. The first phase is missing in the case of low potency radiations, see p.

97ff., whose initial action consists of heating and merely increases the ever-present chance of chemical rearrangements activated by thermal fluctuations.

All ionizing radiations produce the great majority of chemical activations through a single mechanism, namely through glancing collisions of charged particles against the external electrons of atoms. Therefore all ionizing radiations are expected to have essentially similar effects. In particular:

(a) There is no way of affecting the relative average amounts of energy absorbed by specific groups of atoms or by larger portions of matter (except by modifying their crude constitution, see e.g. p. 96).

(b) The average chemical potency of activations (as well as the energy involved in each individual activation) does not depend on the physical characteristics of the ionizing radiations inducing them. It exceeds considerably the potency of activations induced by ultraviolet light or by other radiations of even lesser potency.

(c) Activations induced in different atoms, or groups of atoms, are correlated in space and time because they occur along the paths of fast charged particles.

(d) Physical control of the speed of charged particles traversing matter affects the average distance between successive activations, or clusters of activations, induced by ionizing radiations. Any resulting

variation of the over-all effectiveness of the radiations should be attributed to interaction effects between the phenomena developing from neighboring activations.

The action of ultraviolet light (as well as of visible or infrared light insofar as they are chemically effective) is exerted directly on the "chromophoric" groups of atoms which absorb individual photons.

The main characteristics of the effects of optical radiations are:

(a) Limited chemical potency, in proportion to the amount of energy carried by each photon (see the chart in Fig. 5).

(b) Absence of any correlation in time and space between the activation of different atoms or groups of atoms.

(c) Selective activation of those atoms, or groups of atoms, which are best fitted to absorb the radiation used. This selective activation affords good potentialities for specific action, which find applications in nature (as e.g. in the mechanism of color vision) but have not proved very effective as tools of experimental research.

4. PENETRATION OF RADIATIONS IN MATTER

The following sections deal with the macroscopic distribution of radiation effects in various portions of a material. By and large, deep lying portions of a material are shielded from the radiation by the more superficial layers of the same material, if the radiation source is external to the material. If the source is imbedded in the material the portions distant from the source are similarly protected. An immediate question is: How far does a particular radiation penetrate within a material? More specifically, how does the chance of activation of any

atom depend on its location within a material with respect to the radiation source? This chance does not vary much between points at a short distance from one another, unless the structure of the material lacks uniformity.

Our problem is, therefore, one of macroscopic distribution and concerns really the average action of radiation over portions of matter containing large numbers of atoms. The average amount of energy absorbed per unit mass (or volume) by different portions of a material can well be taken as an index of the chance of activation of any one atom within each portion.

Beside the attenuation of radiation due to its interaction with a material, one must always consider the simple attenuation due to divergence of the radiation flow away from its source. If the source is concentrated in a narrow space, this effect alone reduces the radiation intensity in inverse ratio to the square of the distance from the source, as shown in Fig. 50. Therefore, this effect is commonly referred to as the " $1/r^2$ law".

The interactions of radiation with a material oppose the penetration to deep lying portions of the material in two different ways, namely:

- a. Progressive dissipation, or outright absorption, of radiation energy in layers of the material nearer to the source of radiation.
- b. Scattering actions which divert the flow of radiation from its initial direction. Scattering actions complicate the pattern of flow of radiation and make the study of penetration more difficult.

Scattering causes some of the radiation energy to flow sideways with respect to the direction of incidence. Nevertheless portions of a material located at equal depth below the surface receive equal amounts of energy, provided the dimensions of the surface uniformly exposed to radiation are large as compared to the penetration of the radiation. Fig. 51 and Table 8 show how the escape of radiation sideways, beyond the limits of the region directly exposed, affects the absorption at various depths, under different circumstances.

The complications due to scattering effects are minimal in the penetration of heavy charged particles.

4.1 Heavy charged particles

Rutherford's basic experiment described in Fig. 32, p. 53 shows that sharp deflections of heavy charged particles are quite rare. Hence one may assume, as a first approximation, that these particles travel through matter along straight tracks.

Heavy charged particles dissipate their energy progressively along their tracks in the course of a very large number of inelastic collisions. Since heavy particles with a kinetic energy of the order of a few Mev are not extremely fast, they experience rather frequent energy losses. As mentioned before, the average distance between successive inelastic collisions is of the order of 10 Å in a material like water and a thousand times larger in air.

As a particle dissipates its energy and slows down, its rate of energy dissipation, i. e. the "stopping power" of the material for that particle, varies as indicated in Fig. 37. When the total energy

dissipation by a beam of particles in successive layers of the material is plotted against the depth of the layer from the surface, there results a curve of the type shown in Fig. 52. This curve is called a "Bragg curve". As the depth of penetration increases, the curve of Fig. 52 is followed from left to right, the curve of Fig. 37 from right to left. The "specific ionization" along the track of particles in a gas, that is the number of ion pairs produced per unit distance, is proportional to the stopping power at a rate of approximately 30,000 ion pairs produced per Mev of energy dissipated. Fig. 52 also shows the progressive average decrease of the particle energy in the course of penetration.

Fig. 52 shows a dotted straight line extension of the steepest portion of the Bragg curve. The intercept of this dotted line on the abscissa is generally taken as the value of the effective "range" of the particles, as it is difficult and of no great interest to determine where each particle actually stops after having become "slow". Fig. 53 gives data on the effective range and on the rate of energy dissipation for a variety of particles, energies and materials.

The following rules, based on the discussion on p. 68 ff, serve as a guide to estimate the ratio of the stopping powers of different materials:

a. The stopping power is approximately proportional to the number of electrons per unit volume of material.

b. The number of electrons per unit volume equals the product of Avogadro's number, $N = 6.0 \times 10^{23}$, of the density ρ and of the atomic number Z , divided by the Atomic weight A of the material,

$$N \rho \frac{Z}{A}$$

(29)

Table 8

PERCENTAGE OF DEPTH DOSES, 1000 KV

Half-value Layer 3.8 mm Pb or 10.3 cm Pressdwood
70cm Focus-Skin Distance

Depth (cm)	IRRADIATED AREA --- SQUARE CENTIMETERS					
	20	50	100	200	300	400
	PERCENTAGE DEPTH DOSE					
0	100	100	100	100	100	100
2	91	95	98	99	100	100
5	68	72	76	78	79	80
7	55	59	63	66	67	68
10	41	44	48	51	53	54
12	34	37	41	44	45	46
15	25	28	31	33	35	36
20	16	18	20	22	23	24
25	10	12	13	14	15	16

From Quimby and Focht (1943)

c. The ratio of atomic number to atomic weight equals 1 for hydrogen, 1/2 for the other light elements and a little less than 1/2 for heavier elements (approximately 0.4 for lead). If a standard value of Z/A , e.g. 1/2, is adopted, the number of electrons appears to be simply proportional to the density of the material.

d. The internal electrons of heavy elements contribute little to the energy dissipation by heavy particles (see Fig. 36) and should be discounted accordingly.

e. When the material under consideration contains different chemical elements, the number of electrons per unit volume corresponding to the different elements must be added up. One must therefore consider separately the partial densities $\rho_1, \rho_2, \dots$ of the component elements and the corresponding values $Z_1/A_1, Z_2/A_2, \dots$ of the ratio Z/A . The number of electrons is then:

$$N (\rho_1 Z_1/A_1 + \rho_2 Z_2/A_2 + \dots) \quad (29')$$

If a standard value of Z/A is adopted, as in (c) above, then the number of electrons is again proportional to the total density:

$$N (\rho_1 + \rho_2 + \dots) Z/A = N \rho Z/A$$

f. The stopping power of a material for different heavy particles of equal velocity differs only in proportion to the square of their charges.

4.1a STRAGGLING. The actual energy dissipation along the tracks of individual particles may depart a little from its expected value, owing to statistical fluctuations of the distance of collisions and of the amount of the energy lost in individual collisions. This leads to small random variations of the total track length; for example, particles which experience a particularly large energy loss stop short of the effective range. This variability of the actual range is called "straggling". The tail end of the Bragg curve in Fig. 52 is rounded off because of straggling.

The amount of straggling can be estimated from the data on the statistics of collisions involving various amounts of energy loss. Straggling is rather small for heavy particles of moderate energy but it increases with the energy of the particles. Fig. 54 shows illustrative data on straggling.

4.1b DEFLECTION OF THE TRACK. We consider here briefly the deflections experienced by a heavy particle along its track, which we have disregarded so far. The rare occurrence of rather large sharp deflections is governed by Rutherford's formula (13). Very small deflections take place steadily, in the course of every collision, elastic or inelastic, experienced by a particle. These successive deflections are directed in

various ways and frequently tend to cancel each other.

On the whole, however, the direction of the track eventually departs more and more from the initial direction, in the same way as a particle in Brownian motion eventually gets away from its initial position. The mean square of the angle of total deflection is expected to increase linearly along the track at an average rate of

$$N \frac{z^2 Z^2 e^4}{(p v/2)^2} \approx \frac{z^2 Z^2 N t h^2}{2 \pi m^2 v^2} \quad (30)$$

per unit length of track where ze , p and v indicate the charge, momentum and velocity of the incident particle, z the atomic number of the material, m the mass of the atomic electrons h the Planck constant, N the number of scatterer atoms per unit volume and t the thickness of material already traversed. (This formula is written so that it holds also for relativistic speeds of the incident particles; notice the resemblance of its first factor with the basic Rutherford equation (13) on p. 54). Occasionally, minute deflections may not tend to average out but pile up to simulate a steady curvature of a track.

4.1c EFFECT OF NUCLEAR COLLISIONS. Particles of sufficiently high energy, of the order of 100 Mev or more, penetrate so deeply into matter that they have a considerable chance of hitting a nucleus squarely. Under these conditions the pattern of distribution of the radiation energy through matter is considerably altered. Secondary high potency radiations stem from the nuclei that have been hit (see p. 73 ff). Information on effects of this type is still fragmentary at the time of this writing (1950).

4.2 Electrons

Electrons penetrating into matter undergo, like heavy charged particles, a progressive energy loss, through inelastic collisions; they also experience repeated deflections, mostly through elastic collisions. On the other hand these two processes of absorption and scattering have different relative importance for electrons and heavy particles, because electrons are much more easily deflected, on account of their smaller mass. Since the overall process of penetration is quite complicated when the deflection effects are paramount, data on the average amount of energy delivered by electron beams to successive layers of various materials are still inadequate.

Scattering effects become comparatively less important when the electron velocity approaches the velocity of light. For electrons of very high energy, above 1 Mev, the effects of energy dissipation, i.e. of outright absorption, tend to predominate over the effects of scattering, owing to the increased inertia of very high speed particles. Therefore, the tracks of high energy electrons are more nearly straight, like the tracks of heavy particles. However, the length of electron tracks greatly exceeds the length of heavy particle tracks of equal energy, because heavy particles, being slower, dissipate energy at a higher rate (except at extremely high energies, as noted below).

The photographs of electron tracks of different energies in Fig. 47 illustrate the different importance of scattering effects in different energy ranges. The scattering effects would be much more important if the medium consisted of a high atomic number material rather than of air.

Finally, the energy loss by electrons due to X-ray emission becomes paramount at sufficiently high energies (that is, beyond 10 to 100 Mev depending upon the atomic number of the material, see p.32). This type of energy loss, which is wholly unimportant in the case of heavy particles, sets an upper limit to the penetration of electrons in a material, no matter how high their energy. However, the energy lost by the electrons is carried along in this case by the propagation of X-rays and by the resulting cascade shower production and thus reaches much farther than the electrons themselves.

In conclusion the distribution of the energy carried by an electron beam to a material takes place according to different patterns depending upon the electron energy and also upon the atomic number of the material. The following sections deal first with the various qualitative aspects of penetration and then give more specific data on the energy distribution.

4.2a MODERATE ENERGY: PENETRATION LIMITED BY DEFLECTION. The relative importance of deflection by elastic collisions against nuclei and of energy losses by collision against atomic electrons is nearly independent of the electron energy, for electrons of energy up to approximately 1 Mev. This is understandable since both processes result from impacts between charged particles.

On the other hand the relative importance of deflections and collisions varies in proportion to the atomic number of the material for the following reason. The deflections depend mainly on the square of the nuclear charge (eq. 13 p. 54), i.e. on the square of the atomic number, but the energy loss depends mainly on the number of electrons (eq. 17, p. 69), i.e. on the first power of the atomic number. The scattering effects turn out to be more important than energy losses in opposing the penetration, in all materials but those of lightest atomic number. The two effects are of comparable importance in materials like carbon or oxygen. By and large, the deflections effectively stop the initial penetration of an electron before the electron has lost all, or even most, of its energy. •

Once the electron track has been turned off its initial direction, it continues to curve in various directions at random. Sudden kinks appear here and there on the track where a large angle scattering has taken place. Since large angle scattering arises mostly from elastic collisions with atomic nuclei, its probability is given approximately by eq. (13) at p. 54.

A track may curve all the way back to the surface of the material through which the electron had entered. We speak then of a "back scattering" of the electron. Or else the changing curvature may lead to a deeper penetration. The probability of back scattering depends on the relative importance of scattering and energy dissipation and, therefore, primarily on the atomic number. Fig. 55a shows data on the probability of back scattering.

The curvature of the track and the rate of energy dissipation become greater and greater as an electron loses speed (see Fig. 47). The rate of energy dissipation varies along the track according to the Bragg curve of Fig. 52, except that it starts at a much lower level than in the case of heavy particles; therefore, the rising portion of the curve is greatly extended.

• Because of the increasing curvature, the eventual depth attained by an electron depends primarily on the depth of initial penetration, that is, on the distance covered by the electron before being turned off its initial direction. This distance may vary greatly from one electron to another due to accidental summation or cancellation of successive minute deflections along each track and to the accidental occurrence of sharp deflections.

To indicate the progress of the average deflection as the electrons dissipate their energy one may consider the progressive decrease of the cosine of the angle θ between the momentary direction of each electron and its initial direction. The mean value of $\cos \theta$ for a population of electrons decreases approximately in proportion to the power $.3 Z$ of

their kinetic energy, where Z is the atomic number of the material penetrated (Blanchard and Fano, 1951). For a heavy material this means that $(\cos \theta)_{av.}$ drops to $1/2$ by the time the electrons have dissipated only a fraction:

$$2.3/Z \quad (31)$$

of their initial energy. Even for a light material like tissue, $(\cos \theta)_{av.}$ becomes quite small by the time most of the energy has been dissipated.

Since the electrons entering a "heavy" material turn around rather soon, on the average, those electrons which are actually backscattered are likely to emerge from the material with a high residual energy.

"Light" materials yield low energy backscattered electrons (Fig. 55b).

Since the penetration of electrons follows a capricious path, the concept of "range" of penetration is not as unique for electrons as it is for heavy particles. One calls "true range" the total length of the track of an electron in an unbounded material. This length can be calculated from the stopping power of the material, like the range of heavy particles.

The dependence of the mean "stopping number" $\bar{B}$ in eq. (17) upon the energy of an electron may be disregarded over a wide range of electron energies. When this is done one finds that the true range R is proportional to the square of the initial kinetic energy T of an electron. Making use of the rules for the estimation of the stopping power indicated at pp. 115 - 116 and assuming a value of the stopping number $\bar{B}$ of approximately 10, one arrives at the following expression:

$$R = 1.25 \times 10^{-6} \frac{A}{\rho Z} T^2 \text{ cm} \quad (32)$$

Here A and Z indicate the atomic weight and the atomic number of the material, ρ the density of the material in g/cm^3 and T the electron energy in kev. This formula appears to hold satisfactorily from about 10 to 200 kev in materials of low atomic weight. In "heavy" materials the formula is less satisfactory in the lower portion of this range since $\bar{E}$ varies more rapidly.

Actually, throughout its range of validity, this formula nowhere represents the depth of penetration to be expected in a material, since it gives the length of the path which is far from straight. What matters is how much energy a beam of electrons dissipates in successive layers of a material. Some data on this question are available (Trump et al 1940, 1950). A qualitative picture emerges, for electrons of low or moderate energies, from the following very crude considerations.

Since most electrons lose the "memory" of their initial direction before they are completely slowed down, the initial penetration of a beam has the main effect of "injecting" the electrons at some depth within the material. Thereafter the electrons essentially diffuse away from the zone of injection in random directions. This zone of injection lies in "light" materials at a depth of a few times smaller than the "true" range of the electrons and in "heavy" materials at a depth some 20-50 times smaller than the "true" range.

The concentration of electrons is highest in the zone of injection. Consequently a maximum of energy is dissipated in this zone rather than right at the surface through which the beam enters the material. Furthermore the deep lying layers of the material are traversed by electrons of

lower average energy which dissipate their energy at a higher rate. This effect shifts the point of maximum energy dissipation toward greater depth. (The same effect is much stronger in the case of heavy particles and gives rise to the maximum of the Bragg curve of Fig. 52). Fig. 56 gives approximate data on the energy dissipation at various depths within a "heavy" and a "light" material.

The shape of the curves in Fig. 56 depends primarily on the atomic number of the material but rather little on the energy T of the incident electrons, so long as this energy remains well below 1 Mev. As the energy increases, other conditions being equal, the depth of penetration increases, and, therefore, the scale of abscissae in Fig. 56 is stretched, in proportion to the true range of the electrons, i.e. approximately in proportion to the square of the energy T (see eq. 32).

Extrapolation of the curve in Fig. 56 at its steepest point serves to identify a depth which may be taken as an index of maximum penetration, that is, as an effective range. The practical characterization of maximum penetration will be considered again at p. 131.

Little is known about the displacement of the electrons sidewise from the beam direction, which is of interest for the reasons indicated at p. . One may estimate that the average value of this displacement is comparable to, the average depth of penetration.

4.2b INTERMEDIATE ENERGY: PREDOMINANCE OF ENERGY LOSS BY COLLISION.

As mentioned before, the energy dissipation along the track acquires greater and greater importance as compared to the scattering effects for electrons whose speed approaches more and more closely to the velocity of light. This relates to the circumstance that the "stopping power", or rate of energy loss, of an electron depends on the **electron velocity** rather than on its energy (eq. 17, p. 69) and, therefore, no longer decreases when the energy increases beyond 1 Mev. On the contrary the probability of deflections keeps decreasing as the energy increases, approximately in inverse ratio to the square of the energy. Therefore,

electrons of increasing energy, in the multi-million volt range, dissipate a greater and greater fraction of their energy before being greatly deflected from their initial direction.

The rate of energy dissipation of these electrons is, very roughly, independent of the energy and falls within the range of

$$1 \text{ to } 2 \rho \text{ Mev/cm} \quad (33)$$

where ρ indicates the density of the material. The actual value lies nearer to the lower limit of this range for "heavy" materials, like lead, and nearer to the upper limit for "light" materials. One may also express this result with reference to the energy dissipation in a layer of material of known mass per unit area, independently of its density. The energy loss falls between 1 and 2 Mev per gram/cm² of mass of the layer.

For electrons of sufficiently high energy, only a very small fraction of the initial energy remains after an electron has undergone a substantial deflection. The initial energy required for this depends on the atomic number of the material, since the deflection effects are more important in "heavy" than in "light" materials. In "light" materials the deflection effects are not very important even at low energies, and therefore the energy loss predominates beginning at a few Mev. In "heavy" materials scattering predominates greatly at low energies; accordingly scattering becomes unimportant only at much higher energies. In fact, in materials like lead, there remains no energy range where the energy loss by collision constitutes the main obstacle to penetration, because

the radiative collisions become paramount before scattering becomes unimportant.

4.2c EXTREMELY HIGH ENERGY: PREDOMINANCE OF RADIATION LOSSES, CASCADE SHOWER EFFECTS. The energy loss by X-ray production begins to predominate over the dissipation by inelastic collision at an energy which depends on the atomic number Z of the material and is of the order of

$$10^{9/2} \text{ ev}, \quad (34)$$

according to eq. (12) p. 32. Whenever most of the electron energy goes into X-rays, most of the X-ray energy goes into pair production. A "cascade shower" of high energy electrons, positrons and X-ray photons is then formed as described at p. 92-93. There remains to be seen how the energy of a shower becomes distributed in successive layers of a material.

Scattering of the shower radiation in different directions is rather unimportant, except at the lower energy end of showers in "heavy" material. In the first place, electron deflection progresses slowly, as compared to X-ray production, at all energies above approximately 20 Mev. (The relative importance of electron scattering and X-ray production is independent of the atomic number since both effects vary mainly in proportion to Z^2). Similarly, Compton scattering of the X-rays is unimportant at high energies as compared to pair production; furthermore the photon energy drops to a low level in the unlikely event of Compton scattering by a large angle (see pp. 92 & 50). In the second place the

new particles and photons which are generated in a shower travel approximately in the same direction as the generating radiation.

As a result, particles or photons of energy E within a cascade shower normally travel within a narrow cone whose aperture is of the order of

$$2/E \text{ radians} = 115/E \text{ degrees} \quad (35)$$

where the energy E is expressed in Mev.

A shower dissipates its energy to the material traversed primarily through the inelastic collision losses of the electrons and positrons. The positrons behave essentially like the electrons, as will be discussed at p. 128. Since the rate of energy dissipation by high energy electrons or positrons is roughly independent of their energies and roughly equal to 1.5 Mev/cm (eq. 33), the rate of energy dissipation by the whole shower equals approximately 1.5 times the number of particles which traverse each particular layer of material.

The number of particles in showers which develop under identical conditions is subject to large statistical variations. The energy lost by electrons in radiative collisions is evenly distributed, on the average, among photons of all energies up to the total. However, any one electron may transfer most, or even all, of its energy to a single photon, or else it may distribute its energy among many smaller photons. Similarly, the energy of a pair-producing photon may be shared in any ratio between the electron and positron with nearly equal chance. Moreover, the radiation of a high energy photon by an electron or the pair production by a photon may take place after a flight of variable length.

Nevertheless, when a beam of high energy electrons strikes a material, the important quantity is the average number of particles which traverse each layer per electron incident on the material. The order of magnitude of this number may be estimated by a semi-quantitative schematic discussion of the shower phenomenon, disregarding statistical fluctuations.

Assume, for the sake of the argument, that each electron or positron travels a fixed distance d characteristic for each material, and then generates one photon carrying half of its energy. Assume also

that the photon travels an equal distance and then forms a pair of particles, each of which carries just half of the photon's energy. And so on.

If there occurs one "doubling-up" every path length d , a layer of material located at a depth n times d is traversed by approximately 2^n particles or photons. The numbers of electrons, positrons and photons tend to remain equal.

The shower multiplication stops when the energy is so subdivided that the energy dissipation by electrons and positrons through inelastic collisions exceeds the energy spent in producing new γ rays. At this point the energy of particles and photons is of the order of $10^9/2$ ev, according to eq. (34).

According to this picture an electron of energy E ev gives rise to a shower which develops up to a number of particles and photons of the order of $EZ/10^9$. This maximum number is attained at a depth of n_M times the distance d , where the number n_M fulfills the condition:

$$2^{n_M} EZ/10^9 \quad (36)$$

The distance d corresponds in essence to the so-called "radiation length". The radiation length, in turn, equals, to within a factor of the order of 1, the average distance travelled by a very high energy photon before producing a pair or the average distance travelled by an electron or positron before radiating away its energy in the form of γ rays. Table 9 gives the values of the radiation length in various materials. The results of detailed calculations or of experiments on cascade showers are usually plotted against the depth of penetration expressed in radiation lengths. For detailed results, see e.g. Janossy (1948) p. 202 ff.

Fig. 57 shows plots of the numbers of particles against the depth of penetration. The region of maximum intensity of the shower spreads out over quite a thick layer of material because of the statistical fluctuations which were disregarded in the preceding discussion. For the same reason the concentration of particles and photons never attains a value as high as that given by eq. (36) but remains some ten times lower. Fig. 58 gives experimental data on the energy dissipation versus depth of penetration for showers generated by a synchrotron.

Table 9

Radiation length in various substances expressed in g/cm^2 .

H_2	C	N_2	O_2	Al	A-	Fe	Cu	Pb	Air	H_2O
138	52	45	39.7	26.3	20.8	14.4	13.3	5.9	43	43

These values must be divided by the density in g/cm^3 to obtain the length in cm.

When the process of shower multiplication subsides, the lower energy electrons and photons travel on deeper into the material. The further penetration of the electrons and positrons proceeds as described in the preceding section (p. 123 ff). The further penetration of photons proceeds as will be described at p. 139 ff. The lower energy photons, having little chance of forming pairs, turn out to constitute the most penetrating secondary component of a shower.

4.2d POSITIVE ~~VE~~ELECTRONS. The penetration and the distribution of energy by positive electrons take place in the same manner as for ordinary negative electrons, except for a few rather minor differences.

A positron is constantly exposed to annihilation as a result of collision with an atomic electron anywhere along its track. However, the chance of annihilation remains small until the positron has spent nearly all its kinetic energy. Fig. 59 gives data on the chance of annihilation along the track.

As indicated on p. 53, positron annihilation may yield one or two X-ray photons. Emission of a single photon is comparatively more likely if annihilation occurs while the positron still moves rather swiftly. Two-photon annihilation predominates after the positron comes nearly to rest.

The elementary processes of collision of charged particles, as described in earlier sections, have equal probability irrespective of whether the charge of the incident particle is positive or negative (see p. 54 eq. 13). Accordingly, only the strength of the electric forces between the incident particle and the atomic particles matters, irrespective of their sign. This accounts for the basic similarity of the

behavior of electrons and positrons traversing matter.

However, attractive and repulsive forces do produce different effects when the forces are very strong and act on particles whose speed approaches the speed of light. The formulae of page 54 do not indicate this difference of action because they are derived under the assumption that the velocity of the incident particle remains much smaller than the speed of light. An improved analysis must take into account the special effects of inertia which arise when the speed of light is approached. These effects turn out to increase the chance of sharp deflections of electrons and to reduce the corresponding chance for positrons, when the energy of the incident particles amounts to hundreds of kev or more.

Therefore scattering effects are less important, as compared to the energy dissipation, for high energy positrons than for electrons. The probability of backscattering of positrons has been observed to lie about 30 percent below the corresponding probability for electrons (Seliger, 1950).

4.2e PENETRATION OF THIN FOILS. It is sometimes of interest to consider how the passage through a thin layer of material modifies the characteristics of a beam of electrons. For example, one may think of a beam of cathode rays which has been accelerated to a definite energy inside an evacuated vessel and then emerges from the vessel through a thin window which absorbs only a small fraction of the beam energy. Most of the electrons emerge with nearly equal energies and traveling approximately in the initial direction.

The average ^{energy} loss depends on the foil thickness and on the stopping power of the material and can be evaluated as indicated at p. 115. The departures from the average energy loss may be subdivided into two classes. Small departures, similar to the "straggling" of heavy charged particles (see p. 116), are the rule. Unusually large energy losses may arise either from an occasional knock-on collision in which an atomic electron acquires a rather large amount of energy or from the emission of an X-ray photon. As we know, X-ray emission is quite unlikely for

lower energy electrons and in "light" materials but becomes increasingly frequent as the electron energy and the atomic number of the material increase.

In conclusion, large energy straggling constitutes an occasional anomaly under most conditions but becomes the rule in the conditions which lead to the formation of cascade showers.

The accumulation of the effects of small deflections proceeds for electrons in the same way as for heavy charged particles (see p. 116). The mean square angle of deflection increases in proportion to the thickness of the foil according to eq. (30).

Occasional sharp deflections are noticeable. Their probability follows, in the main, the law of Rutherford scattering, eq. (13) p. 54.

4.2f PENETRATION OF THICK FOILS. The fraction of the electrons of a beam that passes through comparatively thick foils is frequently the object of experiments directed to evaluate the energy of the beam. Aluminum foils are mostly employed in these experiments, but foils of other light materials give comparable results.

The number of electrons which penetrate to increasing depths within a material remains fairly constant during the early stages of penetration, that is, until the effect of progressive scattering becomes important. This stage lasts longer in "light" than in "heavy" materials and is followed by a rapid decrease of the number of electrons attaining greater and greater penetrations. Therefore the curves of Fig. 60 representing the number of electrons transmitted through foils of increasing thickness resemble the curves of Fig. 56 except for the lack of an initial rise.

In fact, the plot of "number vs thickness", rather than the plot of "energy vs depth", serves usually as a basis for the definition and for the experimental determination of the "extrapolated range" of electrons (see Fig. 56).

The minimum thickness of material which lets no electron through is also of practical importance. This thickness may be called the "maximum range". It coincides, in principle, with the "true range" (see p.

126) since maximum penetration is achieved by an electron which happens to undergo no deflection and therefore travels in a straight line until its energy is fully spent; in practice the probability of a straight

line travel is vanishingly small. The maximum range is considerably larger than the "extrapolated range" for electrons of moderate energy in "heavy" materials, where scattering is most important.

"True" range, "extrapolated" range and "maximum" range are almost synonymous when energy dissipation by collision predominates over the effect of scattering (see p. 108 ff). On the other hand the concept of "range" becomes meaningless when X-ray production predominates and showers are formed.

4.2g DATA ON ELECTRON PENETRATION. It would be desirable to present sets of data pertaining to the penetration of electrons of various energies into various material and concerning:

- (a) the stopping power,
- (b) the "true" range,
- (c) the "extrapolated" range,
- (d) the dissipation of energy at various depths, including the case of shower formation,
- (e) the distribution of electrons and photons generated by shower processes.

Data of fair accuracy on items (a) and (b) can be derived from the basic theory of stopping power (eq. 19), but no extensive tabulation is available and experimental data are scarce and of low precision. Fig. 61 shows experimental data on the extrapolated range (item c) in aluminum; corresponding data on other materials are scarce. Quantitative information on item (d) is still limited (see Fig. 61 and 63), even though it would not be difficult to derive experimentally in many instances. Quantitative information on showers can be derived from theory

with fair accuracy, except at lower energies in heavy materials, but tabulations are scarce.

4.2h PENETRATION OF BETA RAYS THROUGH THICK FOILS. The β rays from any radioactive substance consist of electrons or positrons of different kinetic energies, which range from zero up to a maximum that depends on the substance. As these electrons penetrate through a material, the lower energy ones stop first and then those of higher and higher energies. The plot of the number of electrons transmitted through a foil against the thickness of the foil shows then an upward concavity, as in Fig. 62a. The penetration of the few electrons of highest energy tends to extend the "tail" of the curve, but this tail may fade into the "background" of particles which are scored by the detector even in the absence of the β ray source.

It so happens that the curves of transmission vs. depth have approximately the same shape as the graph of the exponential function e^{-x} over a fairly extended range of values of the depth. This is confirmed by the fact that the semi-logarithmic plot of the same data, in Fig. 62b, approximates a straight line. Therefore the relationship between the number N of electrons transmitted and the thickness t of a foil may be represented by the empirical equation

$$N(t) \sim N(0) e^{-\mu t} \quad (38)$$

The coefficient μ characterizes the slope of the plot in Fig. 62b, which is described by the equation

$$\ln N(t) \sim \ln N(0) - \mu t \quad (38')$$

The coefficient μ is called "absorption coefficient" by analogy with the similar coefficient which appears in the law of X-ray penetration (see p. 135). However, the coefficient μ serves merely to characterize an approximate empirical relationship for β ray absorption, whereas it has an intrinsic physical significance for the absorption of X rays.

The absorption coefficient μ may be related to the average energy or even more conveniently, to the maximum energy E_m of the electrons of each β emitting substance, by means of the approximate empirical equation:

$$\mu/\rho = 22 E_m^{1.33} \quad (39)$$

where ρ is the density of the absorber in g/cm^3 and E_m is expressed in Mev.

Alternately, and more frequently, one considers as "maximum range" R_m the abscissa of the point in Fig. 62 where the curve fades into the background. Fig. 63 gives the experimental values of R_m vs E_m for aluminum.

4.3 X rays

The penetration of γ rays into matter is limited by the same processes which serve to distribute the X-ray energy to matter, namely, photoelectric effect, Compton scattering and pair production. As seen on p. 92 the photoelectric effect predominates for lower photon energies, the Compton effect for intermediate and pair production for the higher energies.

The scattering of γ rays and the penetration of secondary electrons complicate the study of the distribution of X-ray energy in different portions of a material. The difficulties encountered resemble those met in the study of electron penetration, but our present knowledge is perhaps a little better regarding the penetration of γ rays than that of electrons.

4.3a LAW OF PENETRATION FOR MONOCHROMATIC X-RAYS ("NARROW BEAM" PENETRATION). Whereas charged particles have a large chance of experiencing minute deflections or minute energy losses as they traverse even a very thin layer of matter, X-ray photons may traverse even a thick layer of matter without being changed at all. The study of penetration becomes much simpler if one considers only what fraction of the intensity of an X-ray beam traverses a layer of matter without experiencing any change at all. Interaction with matter by photoelectric effect or pair

production leads to outright absorption of X-ray photons, interaction by Compton effect leads to deflection and to a change of photon energy. We consider here the ideally simple process of attenuation of a monochromatic X-ray beam, in which any change is regarded as a total loss.

Each X-ray photon has a constant probability of being absorbed or scattered in successive layers of equal thickness, no matter how much material it has traversed previously. This condition is the same which governs the occurrence of collisions of a particle along its track (except that particle collisions are much more frequent). Therefore the considerations developed at pp. 104 - 105 and illustrated in Fig. 43 apply to the penetration of X rays. The total intensity of a beam of monochromatic X rays decreases in the course of penetration in proportion to the probability of attaining a greater and greater depth without being absorbed or scattered.

Thus the intensity varies as a function of the depth of penetration x according to a law having the same form as eq. (27). The probability for a photon to be absorbed or scattered per unit distance of penetration in a material is usually indicated by the symbol μ and is called the "absorption coefficient". This probability μ corresponds to the probability of collision per unit length, in the discussion on p. 105, which is equal to the expected number of collisions ν over a section of track of unit length. Therefore the variation of intensity I as a function of x is described by the formula:

$$I(x) = I(0) e^{-\mu x} \quad (40)$$

$I(0)$ represents the intensity at the depth $x = 0$, that is the incident intensity.

The intensity may be expressed in any appropriate unit. From the physical standpoint the intensity is an energy flow per unit area per unit time. It may also be expressed as a flow of photons, equal to the flow of energy divided by the energy $h\nu$ of each photon.

According to the exponential law of penetration (40), the intensity does not vanish exactly, however large is the thickness of material traversed. Some minute fraction of the X-ray intensity penetrates through any barrier.

The intensity of the monochromatic beam drops to one half of its initial value after traversing a thickness of material equal to

$$x_{1/2} = \ln 2 / \mu = 0.693 / \mu \quad (41)$$

This thickness is called a "half-value layer" and its value serves frequently as an index of the penetrating capacity of X rays. Thicknesses of 2, 3, 4....half-value layers reduce the intensity to $1/4$, $1/8$, $1/16$.. of its initial value.

The reciprocal of the absorption coefficient corresponds to the quantity in eq. (27) which indicates the mean distance between successive collisions along the track of a particle. (The reciprocal of μ is sometimes called the "relaxation length"). The absorption coefficient itself represents a reciprocal distance and is expressed accordingly in inverse centimeter (cm^{-1}).

Frequently, however, it is convenient to express the thickness of the layers of material traversed by X rays according to their mass per unit area, that is, in g/cm^2 . The absorption coefficient is then called the "mass absorption coefficient" and is expressed in inverse g/cm^2 , that is, in cm^2 per gram. The value of μ in cm^{-1} is then referred to more specifically, as the "linear absorption coefficient". The ratio of the value in cm^{-1} to the value in cm^2/g is simply the density ρ of the material in g/cm^3 .

The mass absorption coefficient has a more basic significance than the linear coefficient because the X-ray absorption actually depends on the amount of material packed within a layer rather than on the thickness of the layer. A change of density affects the linear but not the mass absorption coefficient.

The absorption coefficient consists of three components: μ_{ph} which corresponds to the probability of photoelectric absorption, μ_{pair} which corresponds to the probability of pair production and μ_{sc} which corresponds to the probability of scattering.

$$\mu = \mu_{ph} + \mu_{pair} + \mu_{sc} \quad (42)$$

Scattering arises primarily from Compton effect, but up to about 100 kev photon energy there is also an appreciable probability of plain scattering which exerts no effect on matter (see p.58) and is called "coherent scattering". The probability of photoelectric effect and of Compton effect equals the sum of the probabilities that either effect result from the action of X rays on each of the various atomic electrons.

Fig. 64 shows data on the whole absorption coefficient. (Sample data on the probability of various effects are also shown in Fig. 24, 29 and 41). The mass absorption coefficient varies regularly from element to element as a function of the atomic number. Detailed tabulations of the values of the absorption coefficient for all elements are given by White (1951).

The chances of absorption and Compton scattering of X rays by adjacent atoms are quite independent. The chance of coherent scattering depends a little on the arrangement of adjacent atoms in liquid and in non crystalline solids. In crystalline solids the combined coherent scattering by many atoms gives rise to the striking phenomenon of crystal diffraction.

Therefore, except for crystal diffraction, the total attenuation of X rays in passing through any material results very approximately from the sum of the attenuations due to the separate constituent elements of the material. The mass absorption coefficients of a material equals the arithmetic mean of the mass absorption coefficients of its constituent elements #1, 2, 3...weighted according to the crude chemical composition of the material.

$$\mu = p_1 \mu_1 + p_2 \mu_2 + p_3 \mu_3 + \dots \quad (43)$$

The coefficients $p_1, p_2, \dots$ indicate the percent by weight of each element in the material.*

* For the purpose of calculating the X-ray absorption coefficient, or some other atomic property, of a material containing different elements, one often characterizes the material by an "effective atomic number". Thus, for example, if the absorption coefficient of each element happened to be proportional to the cube of its atomic number Z , one could

define the Z_{eff} of a mixture of elements, according to (43), by the formula:

$$Z_{\text{eff}}^3 = p_1 Z_1^3 + p_2 Z_2^3 + p_3 Z_3^3 \text{ ----}$$

Then one would treat the absorption coefficient of the mixture as the coefficient pertaining to a single element whose atomic number equals Z_{eff} . Naturally, the definition of Z_{eff} must be adapted in each case to the actual dependence of the coefficient under consideration upon the atomic number of each element.

As mentioned before, the simple exponential law of attenuation (40) holds when the intensity $I(x)$ includes only the fraction of the incident X rays which has traversed a material without experiencing any deflection or change of energy. This fraction may be determined experimentally provided one minimizes the reception of unwanted radiation by the device which measures the transmitted intensity $I(x)$.

The arrangement shown in Fig. 65 attains this goal to a degree which depends on the narrowness of the beam after passing the collimator and on the distance of the source and of the detector from the absorber. These geometrical characteristics of the arrangement cannot be improved indefinitely without an excessive reduction of the X-ray intensity. The geometrical requirements are not too strict at lower X-ray energies, since most of the attenuation is due to photoelectric effect. On the contrary, very small angle scattering becomes quite important at high energies and an adequate measurement requires a high precision geometry.

Since a direct measurement of μ is performed with a narrow beam of X-rays, one frequently refers to this quantity, more specifically, as the "narrow beam absorption coefficient".

4.3b NARROW-BEAM PENETRATION OF NON-MONOCHROMATIC X RAYS. When a non-monochromatic beam of X rays traverses a material, each monochromatic component is absorbed or scattered independently of the others, at a rate determined by the value of the absorption coefficient which corresponds to its energy.

Generally, the lower energy, or "softer", components are absorbed at a higher rate than the higher energy ones. (The downward trend of the absorption coefficient with increasing energy is reversed only at very high energies). Therefore the spectral composition of the beam changes progressively. The softer components disappear and the higher energy, or "harder", components become comparatively more prominent. The average rate of attenuation of the whole beam decreases in the course of penetration.

Therefore, the slope of a semilogarithmic plot of intensity vs. depth keeps decreasing, as in Fig. 66, instead of remaining constant as in Fig. 46. The slope approaches progressively the value corresponding to the most penetrating component of the incident beam.

These considerations apply to the penetration determined under the "narrow beam" conditions.

4.3c SCATTERED AND SECONDARY X RAYS. The "narrow beam" conditions of X-ray attenuation obtain only in special experimental arrangements.

Under conditions of practical interest, such as in the penetration of protective barriers or a patient's body, most of the scattered X rays travel on mixed with the incident beam. The intensity of this radiation must therefore be added to the unaltered fraction of the intensity of the incident beam at any point within or beyond an absorber.

Besides the scattered X rays one must also consider the secondary X rays which radiate away from an atom by "fluorescence" (see p. 60), following the photoelectric absorption of an X-ray photon. Table 10 gives data on the "fluorescence yield" of various elements, that is, on the probability that the photoelectric absorption of a photon be followed by the emission of another photon of characteristic energy.

Scattered and secondary X rays accumulate to an increasing extent as the penetration proceeds to deeper and deeper layers of a material. (Notice, however, that these X rays have lower energy photons and therefore are generally "softer" than the incident, or "primary", X rays). Therefore the semi-logarithmic plot of the intensity transmitted through a layer of material against the thickness of the layer no longer follows a straight line, as it does for monochromatic X rays under narrow beam conditions. The total intensity follows the downwards concave trend indicated in Fig. 67.

Notice that the curve which includes the scattered radiation does not coincide with the "narrow beam" curve even at "zero depth" of penetration. The excess radiation at the surface consists of "back-scattered" X rays which are flowing out of the entrance surface.

Table 10

Fluorescent Yield in the K Series.

<u>Element</u>	<u>Yield</u>	<u>Element</u>	<u>Yield</u>
O	0.082	Ni	0.35
Ne	.083	Cu	.40
Mg	.013	Zn	.46
Si	.038	Se	.59
S	.083	Br	.59
Cl	.108	Sr	.62
A	.149	Mo	.73
Ca	.150	Ag	.75
Cr	.263	I	.75
Fe	.29	Xe	.70

From Compton & Allison (1935) p. 489.

The downward concavity may be compensated or even overcompensated by the upward concavity due to non-monochromaticity of the incident beam (see Fig. 66). Presumably, many experimental attenuation plots which appear to follow a straight line indicate approximate cancellation of the effects of non-monochromaticity and of scattered X rays rather than good monochromaticity and adequate narrow beam conditions.

The ratio of the intensity actually observed to the intensity expected from the incident radiation alone is called the "build-up factor". The scattered radiation builds up to a very high level particularly for high primary energies and in "light" materials, where a photon frequently undergoes ten or more Compton scatterings before eventual absorption by photoelectric effect. A high build-up of X rays of lower energy than the primaries also takes place at the tail end of cascade showers, as mentioned on p. 127.

Calculations of the build-up factor are rather laborious and are possible at present only in simple geometrical arrangements. Fig. 68 shows how scattered X rays build up in a particularly simple experiment. The continued increase of the build up factor is supported by scattered components which have been deflected by a very small angle and therefore have nearly the same energy and are almost as "hard" as the primary X rays.

The travel of scattered X rays sidewise beyond the original boundaries of a beam presents particular interest for medical radiology (see Fig. 48 at p. 217). Fairly extensive data on this subject have been obtained experimentally, see e.g. Glasser et al (1944), chapter 12.

4.3d ENERGY DISTRIBUTION. Assuming that one knows the intensity and the spectrum of the X rays flowing at various points within a material, there remains the problem of finding where the X-ray energy is dissipated.

The first step in solving this problem is to calculate how much energy is transferred from the X rays to the material at each point. The transfer includes the whole energy of the photons that are absorbed photoelectrically or by pair production and a fraction of the energy of Compton scattered photons. This fraction, $f(h\nu)$, depends on the photon energy $h\nu$. Therefore the absorption coefficient adjusted to reckon the actual energy transfer equals

$$\mu_{tr} = \mu_{ph} + \mu_{pair} + f(h\nu) \mu_{sc} \quad (44)$$

To be accurate, also the energy absorption by photoelectric effect must be discounted by a suitable factor, $g(h\nu)$, to take into account the energy fraction that returns to X rays locally by fluorescence. Therefore eq. (44) should actually read

$$\mu_{tr} = g(h\nu) \mu_{ph} + \mu_{pair} + f(h\nu) \mu_{sc} \quad (44^1)$$

Fig. 69 gives some data on the values of the factors f and g .

The adjusted absorption coefficient must be multiplied by the intensity $I(h\nu)$ (energy flow per unit area per unit time) of the X rays with photon energy $h\nu$ to obtain the rate of energy transferred by these X rays per unit volume of space per unit time.

$$\mu_{tr}(h\nu) I(h\nu) \quad (45)$$

Finally, one must add up the energy transfers by all spectral components with different photon energies. The result expresses the energy transfer per unit volume or per unit mass of material depending on whether μ indicates the linear or the mass absorption coefficient.

Having completed this step of calculation one must go on to consider where the energy transferred to matter is eventually dissipated into chemical activations. This problem does not offer difficulty in the case of lower energy X rays, e.g. below 100 kev. The secondary electrons generated by these X rays have a very short range, namely a minute fraction of a millimeter in any non gaseous material. Therefore one may consider, in practice, that these electrons dissipate their energy at the very place where they received it. In other words the distribution in space of the eventual energy dissipation parallels very closely the distribution of the energy transfer from X rays to matter.

This parallelism holds in so far as the distribution of the energy transfer varies but little over the range of distances traveled by electrons. The travel of electrons all around from their points of origin tends to smooth out sharp variations in the distribution of energy transfers.

As the X ray energy increases, the range of the electrons produced increases rapidly. The surface of any material is one of the first places where the discrepancy between the distribution of energy dissipation and the distribution of energy transfer becomes apparent. Consider for example, the skin surface of a patient exposed to a beam of X rays. The density of energy transfer jumps suddenly from a very low value in the air just outside the surface to a much higher value in the tissue just inside the surface. The flow of electrons propelled by the X rays varies rapidly near the surface, without any sudden jump. Therefore the density of energy dissipation does not vary in proportion to the density of energy transfer. Since the flow of electrons is lower near the skin surface than farther in, the energy dissipation also remains abnormally low throughout a layer of tissue comparable to the range of the electrons.

Thus the energy dissipation rises from a low level, right at the surface, to a higher level farther in, which tends to equal the level of energy transfer from the X rays to the material. Fig. 70 illustrates this "transition effect" near the surface.

When the distribution of energy dissipation becomes parallel to the distribution of energy transfer we say that "electronic equilibrium" has been achieved. This equilibrium is maintained in deeper layers of the material where the energy dissipation decreases in proportion to the attenuation of the X-ray flow.

The attainment of electronic equilibrium proceeds more and more slowly for higher and higher energies of the X rays. The range of the electrons propelled by the X rays increases rapidly and eventually becomes comparable to the own range of penetration of the X rays (see Fig. 71). Moreover the electrons flow to an increasing extent in the same direction as the X rays. Eventually no form of electronic equilibrium remains possible at the highest energies when the cascade shower mechanism becomes effective.

Fig. 72 shows data on the energy dissipation as a function of depth for X-ray beams of various energies penetrating in various materials. As the energy increases the curves take progressively the appearance of curves of energy dissipation by cascade showers in Fig. 58. In fact a shower develops essentially in the same way whether it is initiated by an X-ray photon or by an electron of equal energy.

The travel of electrons contributes also to the distribution of energy sidewise from an X ray beam. Fig. 73 shows some illustrative maps of the energy dissipation produced by beams of high energy X rays.

It should be remembered, of course, that all the preceding considerations on energy dissipation pertain to the average energy dissipated within sizeable portions of matter. Microscopically, the energy is distributed along the tracks of electrons. Cloud chamber pictures of the ionizations produced by an X-ray beam in a gas (see Fig. 74) illustrate this point clearly.

Systematic collections of data on the energy distribution are not available.

4.4 Neutrons

The penetration of neutrons may be discussed along the same general lines as the penetration of X rays, since neutrons, like X rays, interact with matter through comparatively few successive elementary processes at fairly widely separated points. Quantitative information on the elementary processes caused by neutrons is less adequate than the corresponding information for X rays. On the other hand the study of the flow of neutrons through complicated masses of matter has received a great deal of attention, mostly on account of its applications to the design of nuclear reactors.

Neutron penetration is limited by collisions with nuclei (see p. 74 ff). Neutrons usually lose some of their energy in a collision but outright capture is comparatively infrequent. Final capture may take place eventually only after hundreds of collisions. As indicated at p. 76, the (n,n) type of reaction, in which neutron capture is followed by the release of a low energy neutron, is quite common in "heavy" materials and has the same effect as an inelastic scattering.

On the whole, scattering constitutes the most important process in the passage of neutrons through matter, under most conditions. Therefore the flow of neutrons takes primarily the character of a diffusion phenomenon.

4.4a "NARROW BEAM" PENETRATION. The attenuation of a "narrow beam" may be regarded as a basic phenomenon for neutrons as well as for X rays, even though it is perhaps less characteristic for neutron than for X-ray penetration.

If the neutrons are monoenergetic, the attenuation follows the law (40)

$$N(x) = N(0) e^{-\mu x} \quad (46)$$

Here $N(x)$ indicates the neutron flux (particles per unit area per unit time) after traversing a thickness x of material, and μ indicates the absorption coefficient for neutrons of the given energy.

The absorption coefficient represents the probability of collision of a neutron per unit track length in the material. If the collisions are subdivided according to their end effect, the absorption coefficient is regarded as the sum of components corresponding to the probability of the various end effects. (Compare with the analogous subdivision of μ for X rays in eq. 41). However, comparatively little detailed information is on hand regarding these various probabilities, see e.g. Way et al (1950), Adair (1950).

The absorption coefficient shows a general trend to increase as the neutron energy decreases. At lower energies the plots of μ vs. energy for "medium" or "heavy" materials generally show a series of sharp peaks corresponding to the "resonance effect" mentioned at p. 75.

Fig. 75 shows typical data on the values of μ for two chemical elements and gives references to complete sources of data.

The order or magnitude of μ for high energy neutrons relates simply to the size of atomic nuclei and to the density of nuclei in a material, owing to the elementary consideration that a collision results whenever a nucleus intercepts the path of a neutron. This argument indicates that a neutron should travel without collisions, on the average, for a distance of the order of centimeters in non-gaseous materials.

Accordingly, the value of μ should be in the general range just below 1 cm^{-1} or $1 \text{ cm}^2/\text{g}$ (see Fig. 75).

This argument no longer serves to estimate the collision frequency of lower energy neutrons. The basic experiments of atomic physics show that a beam of atomic particles behaves unlike a stream of bullets in that the particles do not appear to follow sharply defined tracks. In fact, the values of the absorption coefficient μ often rise far above the estimate indicated above, as shown e.g. in Fig. 75(c).

The trend of variation of μ for very low energies is inversely proportional to the neutron velocity. This trend sets-in already at higher energies in "light" materials, like lithium and boron where an (n, α) reaction proceeds without difficulty (see pp. -).

The chances of neutron collision with the nuclei of adjacent atoms are quite independent, except at energies well below 1 ev where diffraction effects take place in crystals and, to some extent, in non crystalline materials. Therefore the absorption coefficient for any material results by combining the coefficients for its constituent elements as it is done for X rays according to eq. (43)

$$\mu = \rho_1 \mu_1 + \rho_2 \mu_2 + \dots$$

In fact, one may analyze the absorption coefficient in greater detail by considering separately the probability of collision with the nuclei of different isotopes of each element. However, most data are available only for the naturally occurring mixtures of isotopes of each element rather than for separate isotopes.

A beam containing neutrons of different energies penetrates under "narrow beam" conditions according to the same pattern as a non-monochromatic beam of X rays (see p. 139). The slower neutrons are removed from the beam first, because of their higher absorption coefficient. Therefore the average energy of narrow-beam neutrons transmitted by an absorbing layer of matter is an increasing function of the layer thickness.

4.4b SCATTERED AND SECONDARY NEUTRONS. The accumulation of scattered neutrons in a material influences the over-all penetration even more than the accumulation of scattered X rays, because the neutrons survive a much larger number of scattering processes. Secondary neutrons are not formed very frequently except under conditions where $(n, 2n)$ processes are favored or in the presence of uranium or other fissionable materials (see p. 17).

Since neutrons are scattered in all directions more evenly than high energy X rays, scattered neutrons accumulate to a far greater extent near the place where they first enter a material or where they originate. "Back-scattering" of neutrons from the surface of a thick layer of material is quite important and may approach 100 percent. The trend of the "build-up factor" at great depths in a material depends on the same considerations as in the case of X rays (see p. 139-143).

The mathematical methods which have been developed to calculate the distribution and diffusion of neutrons have been described in the literature, see e.g. Marshak et al (1949). The results of many detailed applications are presumably still withheld for security reasons.

As indicated above, the degree of accumulation of scattered neutrons, that is, the value of the "build-up factor", depends on the duration of survival of a neutron before eventual capture. The probability of outright capture varies very greatly from one material to another. Therefore the presence of traces of highly capturing elements may have a great influence on the neutron propagation through a material. Table 11 gives data on the contribution of outright capture to the absorption coefficients of a few elements.

4.4c ENERGY DISTRIBUTION. Much of the energy released by neutrons within a material is dissipated by heavy charged particles. The tracks of these particles are quite short in non-gaseous materials, less than 1 mm except when the neutron energy exceeds 10 Mev and still shorter at lower energies. Therefore much of the complications which influence the spacial distribution of X-ray energy have little influence in the case of neutrons. The eventual distribution in space of neutron energy parallels rather closely the distribution of the energy transfers from the neutrons to heavy charged particles, except for the effect of the secondary ^{gamma} which will be discussed separately.

Table 11

Capture component of the "narrow beam" absorption coefficients for
0.025 ev neutrons.

Element	H	He	Li	Be	B	C	N	O	F
μ_c in cm^2/g	.18	0	5.8	.006	39.8	.00025	.077	4.000004	4.0003

For complete data see Way et al (1950)

To calculate the distribution of energy transfers from neutrons to heavy charged particles one must proceed, in essence, as we did for the X rays in eq. (44) and (45). One must multiply the probability of collision per unit length of path by the average kinetic energy $\bar{T}$ imparted to heavy charged particles in each collision. To calculate $\bar{T}$, one should break down the value of μ into components $\mu_a, \mu_b, \dots$ corresponding to the various possible types of collision, (a), (b), (c) ..., then evaluate $\bar{T}$ for each type of collision separately and finally add up again:

$$\mu \bar{T} = \mu_a \bar{T}_a + \mu_b \bar{T}_b + \mu_c \bar{T}_c + \dots \quad (47)$$

Data for this detailed analysis are often inadequate and one must resort to crude estimates. In the simple case of collisions with the nuclei of ordinary hydrogen (protons), $\bar{T}$ equals one half of the energy of the incident neutrons.

The rate of energy transfer to heavy charged particles per unit volume and per unit time equals the product of $\mu \bar{T}$ and of the neutron flux at the point of interest.

$$\mu \bar{T} N(x). \quad (48)$$

Since μ and $\bar{T}$ depend on the energy of the neutrons, the fluxes of neutrons of different energy must be considered separately. The contributions of the corresponding energy transfers are then added up. The result expresses the energy transfer per unit volume or per unit mass of material depending on whether μ represents the linear or the mass absorption coefficient.

A considerable amount of γ rays originates from the nuclei of a material as a result of neutron collisions. The eventual capture of a neutron by a nucleus of medium or high atomic weight takes usually the form of an (n, γ) reaction. The (n, γ) capture is normal in hydrogen and yields a photon of 2.23 Mev. Gamma rays also follow the inelastic (n, n') processes.

Detailed data on the intensity and the spectrum of these γ rays are still quite scarce. Fig. 76 gives some data on this subject.

The γ rays produced by neutron capture are, as a rule, equally or more penetrating than the neutrons themselves. Therefore the distribution in space of the energy dissipated by these γ rays does not parallel closely the distribution of the nuclei from which the γ rays originate. This can be done in the same way as one calculates the neutron production of heavy charged particles. Then one treats the γ ray penetration away from their source as an entirely separate problem, by the methods discussed under the heading of X ray penetration.

The β rays emitted by the radioactive nuclei which result from neutron collisions have energies of the order of 1 Mev. Therefore the β rays travel much farther than the heavy charged particles which are the main by-product of neutron collisions. The β rays follow the direct action of neutrons with very considerable delay; delays of days or years are not uncommon.

The distribution in space of the energy dissipation by β rays does not quite parallel the distribution of the points of direct action of neutrons, because of the appreciable range of the electrons. The situation resembles that of energy dissipation by high energy electrons arising from the action of X rays. However, the direction of the β rays does not bear any relationship to the direction of arrival of the neutrons. The distribution of the β ray energies should be studied as a problem of electron penetration starting from a knowledge of the distribution of the β -ray emitting nuclei.

4.5 Light

Light penetration in homogeneous media is limited by outright absorption. Therefore the light intensity decreases in the course of penetration like the penetration of X rays when only the photoelectric effect is important, that is, according to the simple exponential law (40)

$$I(x) = I(0) e^{-\mu x}$$

The absorption coefficient for light varies greatly as a function of the frequency and from one substance to another. A general discussion of the absorption of light was given on pp. 61 - 62. The absorption is exceedingly high in metals owing to energy dissipation by free electrons.

Catalogues of data of the absorption coefficients of homogeneous chemical substances are given in the International Critical Tables (1929).

The mass absorption coefficient of a homogeneous mixture of substances is obtained by combining the coefficients of the component substances #1, 2.... according to the composition in weight of the substance, as in eq. (43).

$$\mu = P_1 \rho_1 + P_2 \rho_2 + \dots$$

In calculating the light penetration in a material one should take into account, of course, the surface reflectivity of the material.

The penetration in non-homogeneous materials presents a more complicated problem. The effect of macroscopic inhomogeneities, such as e.g. a 1 mm air bubble suspended in water, constitutes a standard problem of optics. Microscopic inhomogeneities, in which the properties of the medium vary considerably over distances of the general order of magnitude of the light wave length ($0.1 - 1\mu$) produce a scattering of light.

To understand how scattering arises, one may consider in the first place, the simple propagation of light through a homogeneous medium. As mentioned at p. 58 ff, electromagnetic radiation exerts an oscillating disturbance on atomic electrons and thus induces oscillating currents within atoms and molecules. These currents constitute the source of new disturbances which tend to propagate away in all directions in the form of scattered radiation.

When atoms are distributed uniformly over a large region of space, the disturbances scattered by different atoms in any one direction neutralize each other exactly, except in the very direction of the incident radiation. The disturbances radiated by the atoms in the direction of incidence add up and combine with the incident radiation to form a single, smoothly propagating, beam. However, the characteristics of propagation of this beam depend on the intensity of the currents induced in the atoms, which thereby determine the macroscopic optical properties of the material.

When the atoms are not distributed uniformly, the disturbances scattered by the atoms in any odd direction no longer neutralize each other exactly. A macroscopic net scattering arises in this way. This scattering can be observed directly, for example from a colloidal suspension, if it is moderately weak, ("Tyndall effect"). If the scattering is too intense the medium appears outright "turbid".

Light which enters a turbid medium diffuses all about, through repeated scattering, until it escapes from a surface of the medium or it is eventually absorbed.

5. KINETICS OF RADIATION ACTION

5.1 Introduction

As mentioned earlier, our understanding of the action of radiation on matter is fairly satisfactory only up to the production of activations in single atoms or molecules. Most of the observable effects of radiation follow the initial molecular actions, probably, through a complex sequence of events which involve a large number of atoms. These effects may appear to us as chemical or biological phenomena. We refer to them loosely as "macroscopic effects" in contrast with the initial molecular effects.

Some general inferences regarding the unknown mechanisms leading to the eventual macroscopic effects may be drawn from the dependence of these effects upon the physical characteristics - quantity and quality - of a radiation treatment. Analogy with the indirect study of the reaction mechanisms in physical chemistry suggests the name of "kinetics" for the study of the manner of variation of macroscopic effects as a function of the characteristics of a radiation treatment. The principles of the kinetics of radiation action are reviewed in the following sections.

Much emphasis has been laid on studies of this kind and therefore it is of some importance to assess their significance correctly. The general inferences which can be drawn from the kinetics of radiation effects are often straightforward and well grounded. If, however, one tries to draw detailed conclusions one has to rely on elaborate hypothetical working models of uncertain significance.

The examples which illustrate the following discussion are drawn mostly from radiobiology, but chemical examples would be equally pertinent. The chemical systems, such as e.g. a solution of ferrous sulphate, on which the action of radiations has been tested have a far simpler and better known constitution than biological systems. Nevertheless, there is hardly any positive knowledge regarding the mechanisms of radiochemical reactions and studies of kinetics provide much of the available evidence. Even the understanding of many macroscopic physical effects, such as the induced emission of light by phosphorescent materials, is still rather tentative.

As a preliminary, we consider here briefly how one expresses the magnitude of radiation treatments and of their macroscopic effects.

5.1a THE RADIATION DOSE. The main quantitative characteristic of a radiation treatment is, of course, the amount of radiation received by the treated material. This amount is indicated loosely as the "dose". The concept of dose relates to the amount of action actually produced within a material rather than to the mere passage of radiation through the material.

It would be desirable to express the dose in such a way that the simple indication of the dose of a treatment give an adequate indication of its biological effectiveness, without any need for a detailed specification of the kind of radiation employed. This goal can be achieved at least for a broad range of X-ray qualities (see p. 179 ff) but certainly not for all ionizing radiations. Failing this possibility, it appears convenient to express the dose by some

quantitative index of the initial physical action of radiation on a material, which may serve as an unequivocal standard of reference. The 6th International Congress of Radiology has recommended in 1950 that the dose should be expressed, in principle, in terms of energy dissipation:

"For the correlation of the dose of an ionizing radiation with its biological or related effects the International Commission on Radiological Units recommends that the dose be expressed in terms of the quantity of energy absorbed per unit mass (ergs per gram) of irradiated material at the place of interest."

This recommendation does not exclude other methods of expressing the dose but care should be taken to avoid misunderstanding.

For example, the 1950 recommendation does not supersede the previously established practice of expressing doses in terms of the ionization produced in a standard material, namely air. This practice is quite normal for X rays of low and moderate energies (up to a few Mev), whose dose is currently expressed in "roentgen" units.

The definition of the roentgen accepted by the 5th International Congress of Radiology in 1937 relies on the following principle. The amount of electrons released in a certain mass of air, by photoelectric effect, Compton scattering or pair production, serves as an index of the dose of X or γ rays. The quantity of electricity is characterized, in turn, by the amount of ionization which they produce.

"The roentgen shall be the quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 electrostatic unit of quantity of

either sign."

The use of the roentgen will probably persist in the field of X and γ rays, for which this unit was designed and for which measuring techniques are highly developed, but attempts to extend the application of the roentgen to other ionizing radiations are likely to subside. On the other hand, measurements of ionization in air may well remain a most important method for the indirect measurement of energy dissipation, see e.g. Fano & Taylor (1950).

The quantity of X rays, expressed in roentgens, and the energy dissipation per gram of a material are related in a simple manner if the material is homogeneous and the X ray energy is low or moderate. For example, the energy dissipation in a mass of soft tissue exposed to X rays of a few hundred kev amounts to approximately 93 ergs/gram per roentgen.

Under more complicated conditions, the conversion of the value of the dose from roentgens to energy units offers some difficulty. The X ray dose in roentgen at a point depends only on the flow of X rays at that point and on the properties of a standard reference material (air). The energy dissipation depends on the properties of the material actually present at that point and in the surrounding space as well. The methods for calculating the energy dissipation in a material have been outlined in earlier sections.

The techniques for measuring radiation doses are discussed in the chapter by L. D. Marinelli in this collection.

5.1b METHODS OF EXPRESSING MACROSCOPIC EFFECTS. In order to establish and analyze quantitative relationships between the macroscopic effects of radiation and the quantity and quality of the radiation one must adopt some meaningful quantitative index of the effect under consideration.

Among the characteristics of biological systems which are subject to quantitative measurement one may mention the sizes and masses of organisms or of their various parts, the duration of certain stages of development, the chemical composition of various biological components. Many kinetic studies of the influence of radiation on variables of this kind have been made.

However, much greater emphasis seems to have been laid on biological effects where one observes the frequency of occurrence of a certain event among a population of organisms. Biological objects other than separate organisms, for example different cells of the same organism, may be regarded as the elements of a population. In some instances, as in the example of genetic mutations, the event constitutes, by its own nature, a clear cut "all or none" phenomenon. (Thus, the "white" eye or the "cut" wing mutant of a fruit fly constitutes a well defined inheritable character of the organism.) In other instances the event is defined more or less arbitrarily, as, for example, when the inability of a bacterial cell to develop into a visible colony serves as a criterion of the "death" of the cell.

In either case, the observation of the frequency of events produced by radiation seems to afford an attractive opportunity for studies of the kinetics of radiation action. Possibly, biological

phenomena which display, at least on the surface, an "all or none" character appear to be of a more fundamental nature or more readily accessible to a mechanistic interpretation. Anyhow, the following sections deal almost entirely with macroscopic effects whose magnitude is indicated by the frequency of some "event".

Chemical effects of radiation also belong to this class of macroscopic effects, since the "yield" of a radiochemical reaction represents the number of molecules which have experienced a certain well defined transformation. In other words, a chemical substance exposed to radiation may be properly regarded as a population of molecules.

In most instances, when a test population, whether of organisms, or of molecules, is exposed to radiation, only a minute fraction of the physical action of the radiation serves to affect the elements of the population. For example, when fruit flies are irradiated, their genetic material absorbs a negligible portion of the radiation. Under these conditions the frequency of "events" resulting from the treatment is determined only by the radiation dose and not by the magnitude of the genetic population treated and tested. The number of mutants detected in the offspring of treated organisms is proportional to the number of offspring tested, to within the unavoidable statistical fluctuations.

However, in some instances, when an excess material is exposed, some elements of the population treated "shield" other elements of the population. For example, if a suspension of bacteria exposed to

ultraviolet light is very thick, a further increase of the number of bacteria exposed may result in a reduction of the light absorbed by each bacterium. Allowance must, of course, be made for this effect when it occurs. In extreme cases, the radiation dose determines the total number of "events" produced in a population rather than the "percent" of the population which is affected.

This phenomenon occurs particularly in a number of radiochemical reactions produced in aqueous solutions. Even though most of the radiation energy is dissipated in the water, the resulting chemical action appears to be channeled automatically toward the solute molecules. For example, a dose of 20,000 roentgen of X rays liberates 0.00005 moles of hydrogen per liter of formic acid solution, whether the concentration of formic acid is 0.1 or 0.0001 molar (Fricke, Hart and Smith, 1938).

A similar phenomenon of channeling of radiation action occurs in certain fluorescent materials. A large fraction of the energy dissipated may reappear in the form of light radiated by special atoms or molecules which constitute only a minute proportion of the material.

These examples indicate that the dependence of a macroscopic effect upon the concentration of the reacting material may provide important information on the mechanism of action.

5.2 Simple dose-effect relationships.

The "dose-effect" relationship between the amount of energy dissipated in a material and the magnitude of the resulting effects has been the object of much study.

The interpretation of this relationship relies on the following line of argument. If the exposure of a material to successive equal amounts of radiation contributes equal increments to the overall effect, each separate amount of radiation appears to act independently of the others. This is the simplest situation.

On the contrary, if successive equal doses contribute increasingly to the macroscopic effect, the action of each portion of the treatment appears to combine with some latent effect of earlier exposure. One then tries to obtain additional evidence on the combined effect of different partial exposures from more detailed features of the dose-effect relationship.

Most chemical effects and a large number of biological effects of radiation follow simple dose-effect relationships.

For example, radiation induces a delay of cell division of cornea epithelium (Friedenwald 1951) which varies in proportion to the radiation dose from 50 to 4000 r. This and other earlier similar discoveries of simple results on time delays and other variables has not led to fully successful interpretations. As mentioned before, the attention has centered particularly on other types of effects.

5.2a EXPONENTIAL CURVES. When a macroscopic effect of radiation is measured by the frequency of occurrence of a certain event within a population, the rule of "equal effect for equal dose" leads to the following result. Suppose that a certain amount of radiation produces the event under consideration in 10 percent of the population. Then an additional equal dose would produce the event in another 10% of

The remaining 90% of the population, which were still unaffected. A third additional equal dose would produce the event in the 81% which remain unaffected after the second dose, and so on.

This situation presents a complete formal analogy with the statistical occurrence of collisions along the tracks of particles, which was discussed on p. 103 - 104. It is described by the same mathematical law as eq. (27). Here we indicate by N_0 the number of organisms exposed to the radiation treatment, by $N(D)$ the number of organism in which the event has not yet occurred after exposure to a dose D of radiation. The frequency of "non-occurrence" of the event varies as a function of the dose according to the law:

$$\frac{N(D)}{N_0} = e^{-\alpha D} \quad (49)$$

or

$$\ln N(D) = \ln N_0 - \alpha D \quad (49')$$

The plots of these equations are identical with the plots of Fig. 46 (a) and (b). Fig. 77 shows some corresponding plots of experimental data which appear to follow the equation well. The coefficient indicates the rate of action of the radiation and its value is given by the slope of the plot in Fig. 77(b).

In the exponential laws (27) and (40), which are similar to (49), the coefficients ν and μ represent the probability of a particle collision or, respectively, of photon absorption per unit distance of penetration in a material. Similarly the coefficient α in eq. (49) represents the probability of occurrence of the "event" under

consideration in an organism per unit amount of radiation treatment. This significance is particularly apparent in the differential form of eq. (49), which is analogous to eq. (26):

$$-\frac{dN(D)}{N(D)} = \alpha dD \quad (49)$$

The ratio $-dN(D)/N(D)$ indicates the frequency of events which results from the infinitesimal dose dD among the population still unaffected.

In certain experiments one may observe the occurrence of a number of similar events in the same organism. For example, many unrelated chromosome breaks may appear in a single cell. In this example, the fraction of cells which show no chromosome break may follow an exponential function of the dose. If so, the occurrence of cells showing 1, 2, 3 breaks should relate to the occurrence of no breaks in the same way as the occurrence of 1, 2, 3...collisions along a length of track of a particle relates to the occurrence of no collision (see p. 104). An example where this expectation obtains outstandingly, may be found in Table 1 of a paper by Carlson (1941). The total frequency of breaks per cell, f , may well become larger than one and, in fact, increases steadily in direct proportion to the radiation dose:

$$f(D) = \alpha D \quad (50)$$

The probabilities ν and μ pertaining to the passage of particles and X rays through matter have a primitive significance as explained at p. 33ff and do not represent the net statistical result of complex

background phenomena. On the contrary, the probability λ is introduced in the eq. (49), (49') or (49'') as a purely empirical constant, which characterizes the slope of semilogarithmic plots such as the one in Fig. 77 (b).

A more substantial understanding of the significance of λ requires an understanding of the mechanism through which the observed "events" arise from the action of radiation. This question is also often raised in the opposite way by asking: What clues does the simple law (49) give regarding the mechanism of action? How can the rate of action λ be defined in a most significant way?

5.2b RANGE OF VALIDITY OF EXPONENTIAL CURVES. In order to evaluate the significance of the simple exponential dose-effect curves one should consider first whether the mathematical expression (49) describes the observed facts over a limited range of doses only or over a very wide range.

Some experimental "survival curves" of unicellular organisms follow an exponential curve quite closely down to a very minute fraction of survival (see Fig. 77b). In other instances the semi-logarithmic survival plot flattens out at a low level, as in Fig. 78, indicating that a small proportion of the initial cell population displays a special resistance to radiation.

One may ask, in general, what is to be expected if the different organisms of the population tested are not homogeneous with respect to radiation resistance. This implies that the probability λ of a

biological event has different values for different groups of the population. If so, the survival curve has a trend similar to that of a "narrow beam absorption curve" of non-monochromatic X rays (see p. 139) whose absorption coefficients have different values for different monochromatic components. This trend shows an upward curvature in the semi-logarithmic plot of Fig. 66, and a corresponding curvature should appear in Fig. 77b. The fact that the plot of many survival curves remains straight over a large range of variation of the dose indicates a very substantial homogeneity of the population with respect to radiation resistance.

It should be realized that the interpretation of the rate of action as a probability implies from the beginning that the population tested is substantially homogeneous. "Probability" means the expected rate of occurrence of an event in a series of trials performed under identical conditions. (The exposure of each individual organism constitutes one "trial", "identical conditions" require substantially identical properties of the organisms.) The experimental fact is that, after identical irradiation, the "event" under consideration occurs in some individual organisms and not in others. These different reactions might conceivably reflect wide preexisting differences of radiation resistance among the organisms of the population rather than a statistical variability of response of identical individual.

Two reasons support the interpretation of the exponential curves in terms of some statistical variability inherent in the mechanism of radiation action. The general physiological inhomogeneity within cell populations, however considerable it may be, does not appear to be as broad or as "skew" as would be required to account for the exponential dose-action curve. Furthermore, if physiological variability had a great influence on the dose-effect curves, one would not plausibly expect this variability to follow a reproducible pattern and to yield again and again the same simple exponential dose-effect curve.

The theoretical significance of exponential dose-effect curves hinges most critically on accurate verification of the law for very small doses. The concept of a fixed probability of radiation action implies that there is a finite chance of detecting an "event" among

a large population, even for low doses where the probability of that event is exceedingly small. If a well defined macroscopical effect can result from a comparatively minute treatment, the capricious occurrence of effects in different organisms appears to reflect an inherent feature of the mechanism of radiation action. At the same time each bit of radiation, a single particle or photon, appears capable of producing an observable effect.

Very small lethal effects of radiation cannot be measured accurately under ordinary conditions because one scores the number of surviving organisms, that is, the non-occurrence of a lethal effect, rather than the effect itself. Fig. 79 shows an example of the degree of approximation with which one may determine the shape of a dose-effect survival curve for low doses.

Genetic effects can be measured accurately even at exceedingly low frequencies, such as 1 in 100,000 for fruit flies or 1 in 10,000,000 for bacteria. Here one scores directly the frequency of positive events. As long as this frequency remains small, the exponential curve is practically straight and one finds that the frequency of many classes of mutations increases in proportion to the radiation dose (see Fig. 80).

5.2c EFFECTIVE VOLUMES AND EFFECTIVE AREAS. We have been considering the rate of action λ in eq. (49) as the probability of producing a certain "event" in an organism "per unit dose of radiation". As mentioned on p. 157, the "dose" of radiation indicates

in general the amount of energy dissipated per unit volume of the material.

Energy dissipation is a comprehensive macroscopic concept which applies equally to all radiations but is unrelated to the microscopic nature of each radiation or to the mechanism of its physical action. Therefore it is also of interest to relate the number of the ultimate biological events caused by radiation to the number of primitive elements of the radiation action: particles or photons, activations or ionizations. To this end one expresses the dose in terms of the flux of particles or photons, or in terms of the number of activations of various kinds produced in the material under consideration.

A dose of monochromatic light is most simply expressed in atomistic terms. The total light energy incident on the surface of a material, divided by the energy of one photon, may be regarded as a measure of the "flux of photons". However, the number of photons absorbed in a material is more pertinent to the radiation action than the mere flux of photons. The number of light photons absorbed coincides with the number of activations produced and equals the amount of radiation energy absorbed, divided by the energy of one photon.

When the dose of light is expressed in terms of the number of photons absorbed the rate of action λ represents the probability of occurrence of the "event" under consideration "per photon absorbed". The absorption of photons is subject to statistical fluctuations, as we know. Thus the proportionality of effect to dose establishes a definite correlation between the statistically variable frequency

of biological "events" and the statistically variable number of photons absorbed in each portion of material.

One may specify this statistical relation by indicating the size of a portion of material in which photon absorptions occur as frequently as the biological "events" occur in an organism. Consider a hypothetical example in which the observed probability of bacterial "killing" by ultraviolet light equals 10^{-20} per every photon absorbed in one cubic centimeter of bacterial matter. Since photons are absorbed here and there at random, the "death" of a particular bacterium has the same probability as the absorption of one photon within a volume of 10^{-20} cm^3 of bacterial matter. The indication of this volume serves to represent the frequency of the corresponding biological event. Owing to the analogy with the corresponding formulation of the frequency of atomic phenomena (see note on p. 50) this volume is called the "effective volume" for the killing of the specified kind of bacteria by ultraviolet light of specified wavelength.

The rate of action of ionizing radiations may be represented in a variety of ways which seem equally plausible a priori.

One may represent the dose of an ionizing radiation by the total number of activations which it produces per unit volume or per unit mass of the treated material. This total number equals the energy dissipated per unit volume or mass, divided by the average energy of each activation. The rate of action is then expressed as an "effective volume" for the production of the biological "event" under consideration by an "average activation".

169

The estimation of the average energy of activations is not quite straightforward. It rests on the qualitative discussion of the production of activations on pp. 82 ff. and on data of this kind presented on p. 71 .

Instead of expressing the dose in terms of the estimated total number of activations, one may express it in terms of the number of activations of some special type. Ionizing activations are often considered in this connection. Their number is estimated from the total energy dissipation per unit volume or mass and from experimental data on the average energy dissipation per ionization in a gas having a chemical composition similar to that of the treated material (see p. 85 - 86).

Alternately, one may express the dose in terms of the flux of charged particles within the treated material. This expression is quite straightforward in some special instances, e.g. when bacteria laid on an agar surface are exposed to a beam of heavy particles. Most often the calculation of the flux of particles is subject to uncertainties, as e.g. when fast electrons of various energies are produced by X rays.

Once the flux of particles is known, one may calculate the size of an area which is crossed by a particle with a probability equal to the probability of occurrence of the biological event under consideration. For example, the frequency of "death" of bacterium coli caused by polonium α particles was found to be one per every 2×10^8 particles per square centimeter. Therefore the chance of a killing

170

effect equals the chance of crossing an area of $1/2 \times 10^8 = 5 \times 10^9 \text{ cm}^2$ laid in front of the Δ particle beam. An area of this size is called the "effective area" or the "effective cross section" for the specified killing effect by the specified kind of particles.

The alternate ways of indicating the biological effectiveness of radiation by means of effective volumes or effective areas appear equally legitimate in principle. Further considerations, to be presented in the next section and, especially, on p. 179ff indicate that one representation or another may be more significant depending on the circumstances.

5.2d TARGET THEORY. The statistical link between the frequency of the activations produced by radiation and the frequency of the ultimate biological effects has certainly something to do with the accidental distribution of activations throughout an organism. It is becoming progressively clear that macroscopic biological phenomena are steered to a great extent by submicroscopic structures, such as the genes, and also by minute amounts of some relatively simple chemicals, such as vitamins and hormones. Therefore it stands to reason that the chance of an eventual observable "event" is particularly high whenever an activation happens to occur within, or near to, the key elements of an organism. For example, a charged particle which traverses the nucleus of a cell seems a priori much more likely to produce a genetic effect than a particle which crosses the cytoplasm only and misses the nucleus.

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This concept has been elaborated upon in a variety of more or less detailed working models of the action of radiation. The core of these theoretical argumentations lies in the idea that the statistical fluctuations in the occurrence of biological effects reflect primarily the statistical accidents in the location of the primary physical effects. One visualizes the statistical fluctuations of radiobiological effects as similar to the fluctuations in the casualties among a troop of men exposed to a barrage of rifle or mortar fire. The severe casualties correspond to those individuals which happen to have been hit, and hit in some particularly sensitive spot.

Because of this analogy, the whole line of argumentation goes under the name of "hit theory" or "target theory" of radiobiological actions ("Treffertheorie" in German). The argumentation appears particularly suggestive in the circumstances considered thus far, that is when the dose-effect curves are exponential, but it can be extended to include more complicated statistical relationships. The target theory has given rise to considerable controversy. D. E. Lea's (1941) book on the "Action of radiations on the Living Cell" constitutes a major effort to describe the main results of radiation biology within the frame of the target theory (see also Timofeev-Ressowski & Zimmer, 1947, Buzzati-Traverso & Cavalli, 1948). Most of the material discussed in that book is reviewed again in the following chapters.

In a restrictive formulation of the target theory one has assumed that a definite biological effect, e.g. a specific mutation or even the death of a cell, results whenever an ionization occurs within some well defined submicroscopic structure e.g. a gene. According to this hypothesis, the structure itself constitutes a "sensitive volume", whose magnitude coincides with the "effective volume" for production of the effect by an ionization.

Thus, for example, Timofeëff-Ressowski, Zimmer and Delbruck, (1935) suggested that an ionization within a group of about 1000 atoms may produce a specific mutation from "eosin" to "white" eye color in a fruit fly sperm. The model affords an attractive opportunity for determining the size of key submicroscopic structure by means of radiobiological studies. Confirmation of the model and determination of further details concerning the submicroscopic structure was expected from comparative studies of the effectiveness of different radiations (see p. 174 ff). Thus the study of radiation action appeared as a sharp tool for the investigation of key biological structures.

Extensive studies of dose-effect curves under various conditions, stimulated by the target theory, have produced results generally consistent with the theory. However, these results are not of a crucial nature and do not lend substantial support to the rather arbitrary working models of the target theory. Thus, from this standpoint, the theoretical speculations do not appear particularly fruitful.

Moreover, indirect evidence unfavorable to the target theory has been accumulating. If the randomness of biological effects depends primarily on the random location of the primary actions, the correlation between these random events should be fixed mainly by the geometrical characteristics of the key structures of the organism. This is to say, that the slope of the "dose-effect" curves should be essentially independent of environmental factors such as the temperature or the biochemical conditions of the organisms.

To be sure, the demonstrated influence of any one environmental factor may be interpreted from the standpoint of the target theory by a suitable adaptation of the working model. Nevertheless, the accumulation of evidence which requires a special interpretation detracts from the attractiveness of the initial working hypothesis.

The detailed discussion of the pertinent evidence is beyond the scope of this chapter. It suffices to recall the demonstrated great influence of oxygen concentration on the rate of action of radiation (see e.g. Bacq, 1951, Hollaender et al, 1951).

It may also be added that closer analysis of the phenomena which display the most strikingly simple dose-effect curves has often brought to light unexplained details (see e.g. Caspari & Stern, 1948, Fano 1947). Here again, any single difficulty could probably be explained away but the collective import of the evidence seems quite considerable.

The statistical analysis of exponential dose-effect curves and the expression of the rates of action as "effective volumes" or "effective areas" derive from the original development of the target theory (Blau & Altenburger 1924). Thence also derives the name of "single-hit curves" for the exponential dose-effect curves. (Single-hit means that the observed biological event derives from a single physical process, such as, for example, the passage of an ionizing particle.)

The exponential curves and the "effective volume" were discussed on p. 165 ff without reference to the concepts of the target theory, because they involve only a deduction from experimental results (within the limits of accuracy of the observations) and afford a convenient manner of expressing those results. The introduction of more or less specific hypothetical working models and the development of deductions based on the models constitute quite different procedures of theoretical analysis.

5.3 "Sigmoid" dose-effect curves.

Most dose-effect curves are of the "sigmoid" type shown in Fig. 81. The initial flat portion of the curve indicates that no macroscopic biological effect is detected until a certain amount of latent action of radiation has accumulated. The flattening of the curve at high doses means, more trivially, that the effect is approaching completion. (The same flattening is observed also in exponential curves as shown in Fig. 77 where the ordinates are plotted in the opposite direction.)

In principle, a detailed analysis of the shape of sigmoid curves should provide substantial information on the accumulation of latent action which must precede a detectable effect. In practice such analyses have not been successful.

From the standpoint of the target theory, one visualizes an effect which follows a sigmoid curve as resulting from a definite number of latent "single-hit" effects. This interpretation appears quite plausible in a few instances, where there are good clues regarding these "single-hit" effects. For example, certain rearrangements of chromosomes which result from radiation treatments involve a breakage of two chromosomes. The individual breakages appear to constitute "single-hit" phenomena whose occurrence is a prerequisite for the completion of the rearrangement. In some instances the frequency of single breaks has been observed to follow a "single-hit" curve (see p. 161 - 162) whereas the frequency of rearrangements follows a sigmoid curve (see e.g. Sax 1940).

On the other hand, in the absence of clues regarding the nature of the prerequisite "single-hit" effects the definite model suggested by the target theory represents only a speculation of uncertain significance. Some information of the mathematical development of the target theory is given here for purpose of orientation.

Consider an observable event which results from the occurrence of a number n of latent "single-hit" events. As long as the dose D remains low each "single-hit" event has a small probability of having occurred and this probability is proportional to D . Therefore the combined probability P_n that all n latent events have occurred rises,

as a function of D, in proportion to the n^{th} power of the dose:

$$P_n(D) = kD^n \text{ (if } P_n(1) \text{)} \quad (51)$$

Thus the trend of variation of $P_n(D)$ at low doses depends only on the number n of required single hit events. The trend at higher doses depends on further details of the model which one assumes.

For example, the n single-hit events may be equivalent, or rather interchangeable, like n breaks in the chromosomes of a cell. As mentioned on p. 162 the probability that m such events result from a dose D is given by the Poisson distribution expression, eq. (28) p. 163:

$$P_m(D) = e^{-\alpha D} (\alpha D)^m / m!$$

The detectable event occurs whenever at least n single-hit events have taken place. Therefore its probability equals:

$$e^{-\alpha D} \left[\frac{(\alpha D)^n}{n!} + \frac{(\alpha D)^{n+1}}{(n+1)!} + \frac{(\alpha D)^{n+2}}{(n+2)!} + \dots \right] \quad (52)$$

Indicate by N_0 the number of organisms exposed to the radiation treatment, and by $N(D)$ the number of organisms in which the detectable event has not occurred after a dose D . The frequency of "non-occurrence" $N(D)/N_0$, equals the probability that less than n single events have taken place in an organism. Therefore:

$$N(D)/N_0 = e^{-\alpha D} \left[1 + \alpha D + \frac{(\alpha D)^2}{2!} + \dots + \frac{(\alpha D)^{n-1}}{(n-1)!} \right] \quad (53)$$

This expression reduces to the standard exponential, or "single-hit", eq. (49) when $n = 1$. It is called a "multiple-hit" curve. Fig. 82 shows regular and semilogarithmic plots of (53) for various values of the "number of hits" n .

Different trends of the dose-effect curves result from different assumptions regarding the latent single-hit events. Suppose that these events are clearly distinct from one another, as for example, when one chromosome break is required in each one of different chromosomes of a cell.

Call the rates of action for the production of the different single hit events $\alpha_1, \alpha_2, \dots, \alpha_n$. The probability of non-occurrence of these various events after a dose D are $e^{-\alpha_1 D}, e^{-\alpha_2 D}, \dots, e^{-\alpha_n D}$. The corresponding probabilities of occurrence are:

$$1 - e^{-\alpha_1 D}, 1 - e^{-\alpha_2 D}, \dots, 1 - e^{-\alpha_n D}.$$

The probability of occurrence of all events is the product of these separate probabilities:

$$(1 - e^{-\alpha_1 D}) (1 - e^{-\alpha_2 D}) \dots (1 - e^{-\alpha_n D}). \quad (54)$$

This expression is the counterpart of the expression (52) derived from a different working model. The counterpart of eq. (53) is:

$$N(D)/N_0 = 1 - (1 - e^{-\alpha_1 D}) (1 - e^{-\alpha_2 D}) \dots (1 - e^{-\alpha_n D}) \quad (55)$$

Tests have been devised, (see e.g. Curie 1929), and other tests could probably be developed, to describe an experimental dose-effect curve by one or the other of the eq. (53) and (55) and to fix the appropriate value of the "number of hits" n . However, the fitting procedures are not critical. A reliable determination of the "number of hits" and a discrimination between different types of equation such as (53) and (55), would require a higher experimental accuracy than is attained in practice.

Possible inhomogeneities within the population, with regard to the response of individual organisms to radiation, complicate the analysis of dose-effect curves. The effect of inhomogeneities tends to bend the curves of Fig. 82 b in the opposite way, i.e. to reduce their net curvature and the apparent value of the "number of hits".

5.4 The "time-intensity" factor

Thus far we have failed to consider the possible influence of the rate of delivery of a radiation treatment upon the eventual effect of the treatment. The "dose" of a treatment indicates the total amount of energy absorbed by the treated material irrespective of the total duration of the exposure to radiation and of possible variations of the radiation intensity during the exposure.

Equal doses can be delivered in very short and intense bursts or over long periods of time at a very low intensity. For example, one can deliver within less than one microsecond an X-ray dose of order of 10 roentgen, which corresponds to the absorption of 1,000 ergs per gram of tissue and has appreciable biological effectiveness (see, e.g. Slack and Thilo, 1944). The same dose can be delivered

at a steady rate by a weak radioactive source of γ rays over a period of weeks, months or years.

Control over the distribution of a radiation treatment in the course of time offers, in principle, an opportunity for investigating the mechanism of radiation effects. Studies in which this control is variously applied are often called studies of the "time-intensity factor", or simply of the "time factor". These studies have yielded thus far only moderate results.

Two simple patterns of intensity distribution appear particularly convenient for investigating the influence of the time factor. The method most commonly employed is to keep the intensity of irradiation constant throughout each treatment and to vary it in a series of experiments in inverse proportion to the duration of the treatment. Alternately, one may fractionate each treatment into two, or possibly more, short high intensity bursts and vary the interval between the bursts in a series of experiments; this method appears to offer considerable advantages (Fano & Marinelli, 1943).

No influence of the time factor is expected if the separate photons or particles of a radiation contribute independently to the eventual observable effect. Therefore, the interpretation of the exponential dose-effect curves on p. 160 ff. implies that these curves do not depend on the rate of delivery of the radiation. This expectation. This expectation obtains in practice in a substantial number of instances (provided of course that the physiological properties of the treated organisms remain constant even during protracted

exposures to radiation.) For example, the sperm cells of a fruit fly may remain under constant conditions for a period of a month; equal doses of radiation variously distributed during this period produce equal genetic effects (see Muller, 1940, Kaufmann, 1941).

On the contrary, the time factor may well be expected to influence sigmoid dose-effect curves. In a few instances the relationship of the time factor to the mechanism of origin of the biological effect seems fairly clear. One such example concerns the occurrence of two separate breaks in the chromosomes. Here it appears plausible that the two breaks may not combine to yield the final rearrangement if they arise at too distant instants of time, e.g. more than a few minutes apart (see e.g. Sax 1940, Lea and Catcheside, 1942). Therefore a given dose becomes less effective if spread over a long interval of time.

The process of degradation and distribution of radiation energy up to the production of chemical activations takes place very rapidly and involves an exceedingly small fraction of the atoms of a material. Therefore the proximity in time of the arrival of different particles or photons should not influence their immediate physical action up to the point when activations are produced. One should then expect that experimental data on the influence of the time factor supply evidence on the stages of the action of radiation which follow the production of activations. Unfortunately, so little is known in general about these stages that it is difficult to draw any conclusions from the evidence on the time factor.

5.5 Comparative effectiveness of different radiations

Two different elements influence the comparative effectiveness of radiations, namely, their initial potency and the distribution of the activations which they produce within a material.

As explained on p. 177 ff, all ionizing radiations have a potency well in excess of that required to produce any chemical activation. Accordingly, the potency of each ionizing radiation is a negligible factor. Ionizing radiations produce, in general, chemical and biological effects of comparable order of magnitude, at parity of energy dissipation.

On the contrary, light has only limited chemical potency. Accordingly, ultraviolet light is much less effective than ionizing radiation, and the effectiveness still decreases greatly as one proceeds to visible and infrared light. Radiation of still lower potency, i.e. radio waves, acts only indirectly through the generation of heat, with still far lower efficiency.

Different radiations may display a different comparative effectiveness in the production of different effects. Therefore even the qualitative picture of the various effects produced by different radiations may differ. For example, the proportion of the genetic effects produced in fruit flies that is associated with chromosomal breaks is much greater for ionizing radiations than for ultraviolet light (see e.g., Muller, 1941, p. 160). (Incidentally, the effect of chemical mutagens of the mustard group indicates a potency intermediate between those of ultraviolet and ionizing radiation, Auerbach and Robson, 1947.) By and large, ionizing radiations duplicate all the effects of less potent radiations, as expected, but the reciprocal

is not true.

The experimental observations bearing on this point agree with expectation but do not contribute much new information.

Different ionizing radiations differ from one another in their action, depending on the average interval of collisions along the tracks of ionizing particles. Data on the comparative effectiveness of different ionizing radiations bear on the mutual influence of the after-effects of successive collisions.

X rays and fast electrons of energy greater than about 10 kev, as well as heavy particles with energies in the 100 Mev range, have essentially equal effectiveness, for equal energy dissipation. This result means that the after-effects of successive collisions do not influence each other if the collisions occur sufficiently far apart. Other, lower energy, radiations, which give rise to more closely spaced collisions, seem to be a few times more effective in most instances, but occasionally also less effective.

5.5a EQUAL EFFECTIVENESS. Consider first, phenomena which follow exponential dose-effect curves and in which different ionizing radiations produce equal effects for equal energy dissipation. The rates of action of the different radiations are equal when expressed as a probability of an "event" per unit energy dissipation. The rates of action are also equal when the dose is expressed by the number of any kind of physical processes which correspond, on the average, to equal dissipation. Thus the "effective volume" for the production of a biological event under consideration by an average activation (see p. 168) has equal values for the different radiations. Similarly, the

effective volumes for production of that effect by an ionization or by a collision of a fast ionizing particle have equal values for different radiations.

If a certain physical process is to be regarded as the independent primitive "cause" of a certain biological effect, the corresponding effective volume should have a fixed value no matter what radiation one employs. The application of this principle has been the object of much attention in the development of the target theory. One aimed at selecting one basic process among various possibilities such as: the absorption of a photon or the production of an ionization in a target region, the passage of an electron through that region, etc. Then one made experiments with different radiations, mostly with X rays of different energies, to determine the effective volume or area for the production of a biological effect by each of these processes. Since the effective volume pertaining to ionizations has an equal value for different radiations, it was argued that the production of an ionization within a target volume constitutes "the hit" which causes the observed biological effect. (The equal effectiveness of X rays of different energies and wavelengths is often referred to as "the lack of a wavelength effect".)

Actually, as mentioned above, a fixed effective volume is found for any physical process which occurs in numbers proportional to the energy dissipation. The equal effectiveness of different ionizing radiations indicates only that the after effects of successive collisions along the tracks of fast ionizing particles develop independently.

Successive collisions may dissipate widely different amounts of energy. There is no telling whether and how the effectiveness of each collision depends on the energy dissipated. For example, Lea and Catcheside (1943) have been led to think that chromosomal breaks occur only at the tail end of the tracks of fairly energetic secondary electrons (of ~ 500 ev or more). This possibility is quite consistent with the equal effectiveness of different radiations because the number of energetic secondary electrons is proportional to the energy dissipated.

5.5b HIGHER EFFECTIVENESS OF DENSELY IONIZING RADIATIONS. Ionizing radiations whose energy is dissipated by particles of comparatively low speed display, in general, a particularly high biological effectiveness. The production of genetic mutations in fruit flies appears to constitute a notable exception to this rule (see p. 184).

Since successive collisions follow one another at shorter distance along the tracks of slower particles, the greater effectiveness of these particles indicates some cooperative action of the after-effects of different collisions. There is no definite indication regarding the mechanisms of such cooperative action, but it seems quite plausible a priori that energy dissipated at a high concentration be particularly effective.

Experiments with X rays of different energies show an increase of effectiveness only when the energy of the photons, and of the photoelectrons which they release, falls below 10 kev. Catcheside and Lea (1943) demonstrated this effect in the production of chromosome breaks in the spiderwort Tradescantia.

Heavy charged particles with energies of a few Mev dissipate energy even more densely than electrons of a few kev. Most of the experimental evidence regarding heavy particles was obtained with

α particles and with neutrons (i.e. with the protons accelerated by the impact of neutrons). Table 12 shows illustrative data on the comparative effectiveness of heavy particles and of X rays.

The speed of heavy charged particles varies comparatively little over appreciable lengths of path. Therefore it is possible to study the effectiveness of beams of particles that dissipate energy at a fairly uniform and constant rate. (Low speed electrons have so little energy that they do not travel an appreciable distance). Zirkle (1935) demonstrated a progressive change of effectiveness along the path of α particles (see Table 12).

Heavy particle beams with energies up to hundreds of Mev are now available. The fastest of these particles are as effective as high energy X rays, the slower ones are generally more effective. It should be possible to determine the trend of variation of effectiveness in detail. Only preliminary results in this direction are available at the time of this writing (see Table 12).

5.5c THE "SATURATION EFFECT". It was mentioned on p. 100 that a combination of the aftereffects of different collisions may conceivably lead to a loss rather than to a gain of effectiveness. This effect seems to occur in a number of radiochemical reactions produced by α particles. Molecules, which are activated as a result of successive collisions a short distance apart, are believed to neutralize

TABLE 12 Sample results on the comparative effectiveness of ionizing radiation

Effect of radiation observed	Radiations whose effectiveness was compared	Ratio of energy dissipations having equal effectiveness	Reference
Killing of <u>Pteris longifolia</u> spores	particles at 4 μ from end of range in tissue particles at 23 μ from end of range in tissue	$\sim 1/1.7$	Zirkle (1935)
Killing of <u>E. coli</u>	high energy X rays/low energy X rays/ rays	$\sim 1/1/4$	Lea <u>et al</u> (1941)
" " <u>B. mesentericus</u> spores	" " " / " " " / "	$\sim 1/1/0.2$	
Cessation of growth of <u>Vicia faba</u> roots	-rays/neutrons/ -rays	9/1/1	Gray <u>et al</u> (1939)
Chromatid breaks in <u>Tradescantia</u>	X-rays/neutrons	$\sim 8/1$	Giles (1940)
"	15 Mev neutrons / 4 Mev neutrons (max energy)	4/1	Giles & Conger (1950)
"	X-rays/190 Mev deuterons/lower energy deuterons	1/1/.2	Giles & Tobias (unpublished)
"	80 kev X-rays/3 kev X-rays/1.5 kev X-rays	1/0.5/6	Catcheside & Lea (1943)
Sex-linked recessive lethal mutations in <u>Drosophila</u>	X rays/neutrons	0.7/1	Zimmer and Timofeeff-Ressowski (1939)
"	" "	0.4/1	Timofeeff-Ressowski and Zimmer (1944)
"	" "	0.7/1	Fano (1944)
Dominant lethals in <u>Drosophila</u>	" "	2/1	" "
Inactivation of bacteriophage T-1	3.5 Mev deuterons/1.5 Mev deuterons	1/1.5	Pollard & Forro (1949)

one another as they meet while diffusing away from their point of origin (see e.g. the chapter by W. Dale in this collection).

Another effect may contribute to reduce the effectiveness of densely ionizing radiations. If the rate of energy dissipation along the track of a particle is sufficiently high, one may imagine that this energy dissipation suffices to achieve whatever effect it was intended to produce. A further increase of the rate of energy dissipation would be wasteful.

According to this argument the effectiveness of ionizing radiations should eventually decrease provided the rate of energy dissipation along the particle tracks attains a sufficiently high value. This loss of effectiveness is generally called the "saturation effect".

Under conditions of high saturation one visualizes the action of radiation as definitely concentrated around the tracks of ionizing particles. The effectiveness of the radiation depends on the effective radius of action of the intense disturbance caused by the passage of a particle. Since the chance of production of an effect at a certain position depends primarily on the passage of a particle at a sufficiently close distance, the target theory picture of a "sensitive volume" or "sensitive area" becomes more definitely realistic:

The effectiveness of neutrons of a few Mev for the production of sex-linked lethal mutations in fruit flies is slightly ($\sim 30\%$) lower than the effectiveness of X rays. This effect is generally regarded as an example of incipient saturation. Catcheside and Lea (1943) have reported a similar drop of effectiveness for the X ray production of chromosome breaks in a spiderwort as the X ray energy

drops from 3 to 1.5 kev. (The same effect increases as the energy drops from 10 to 3 kev, see p. (82)). General indications are that heavy particles produce chromosomal breaks in this material under conditions of high saturation, i.e. that a break arises whenever a heavy particle smashes through a chromosome.

Target theory models lead to quantitative predictions regarding the decrease of radiation effectiveness as a function of the increasing rate of energy dissipation. For example one may calculate the probable "waste" of radiation energy due to the accidental occurrence of two or more ionizations within a single sensitive volume. Such predictions have been worked out by many authors, notably by Lea, (1940, 1947). They appear somewhat unrealistic because of the amount of detailed assumptions involved in the calculations.

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FIG 1

DIAGRAM OF A CLOUD CHAMBER.

FIG 2

TRACKS OF α PARTICLES IN A CLOUD CHAMBER. (FROM GENTNER, ETAL. (1940) FIG. 1.)

FIG 3

SCHEMATIC FUNCTIONING OF AN IONIZATION CHAMBER.

FIG 4

FIG 6

DIAGRAM OF A VANDE GRAAF GENERATOR.

BELT ACCUMULATES POSITIVE CHARGES ON UPPER CONDUCTOR AND CARRIES NEGATIVE CHARGES DOWN TO GROUND.

(FROM RICHTMEYER AND KENNEDY, 1942 P. 622)

FIG 7

CHART OF ENERGY SCALES

			THERMAL RANGE CHEMICAL RANGE ATOMIC ELECTRONS CORE RANGE NUCLEAR RANGE COSMIC RAYS										
THERMAL SCALE	HEAT	cal/Mol	1000	10 ⁴	10 ⁵	10 ⁶	10 ⁷	10 ⁸	10 ⁹	10 ¹⁰	10 ¹¹	10 ¹²	10 ¹³
	EQUIV. TEMP	DEGREES absolute	1000	10 ⁴	10 ⁵	10 ⁶	10 ⁷	10 ⁸	10 ⁹	10 ¹⁰	10 ¹¹	10 ¹²	10 ¹³
ELECTROMAGNETIC RADIATION SCALE	FREQUENCY	cycles/sec	10 ¹³	10 ¹⁴	10 ¹⁵	10 ¹⁶	10 ¹⁷	10 ¹⁸	10 ¹⁹	10 ²⁰	10 ²¹	10 ²²	10 ²³
	WAVE LENGTH	Angstroms	10 ⁶	10 ⁵	10 ⁴	10 ³	10 ²	10 ¹	10 ⁰	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴
ELECTRIC POTENTIAL SCALE			Electron Volts	0.01	0.1	1.0	10	100	1000	10 ⁴	10 ⁵	10 ⁶	10 ⁷

NBS

FIG 5

FIG 8

DIAGRAM OF ELEMENTS
OF A LINEAR
ACCELERATOR.
(REPRODUCED IN
PART FROM MOYER
AND CHEW, 1950)

FIG 9

DIAGRAM OF ELEMENTS OF A
CYCLOTRON (FROM RICHTMEYER
AND KENNEDY, 1942 P. 264)

FIG 10

DIAGRAM OF A BETATRON

FIG 11

NBS

SCHEMATIC DIAGRAM OF
DISTRIBUTION OF THE ELECTRIC
FIELD ABOUT AN ANTENNA.

FIG 12.

SPECTRAL DISTRIBUTION OF
RADIATION FROM OVENS AT
DIFFERENT TEMPERATURES
FIG 13

SPECTRUM OF LIGHT FROM A
MERCURY LAMP - NOTICE THE
LINES AND THE CONTINUOUS

SPECTRUM -
(FROM MEDICAL PHYSICS
1944, P. 1160)

FIG 14

DIAGRAM OF A MEDIUM
VOLTAGE X-RAY TUBE.

NBS

FIG 15

APPROXIMATE X-RAY
INTENSITY DISTRIBUTION
IN DIFFERENT DIRECTIONS
FOR OPERATION
AT DIFFERENT
VOLTAGES; AND WITH
DIFFERENT TARGET
MATERIALS (A) AL
TARGET 34 KEV
(FROM HONERJAGER, 1940);
(B) W TARGET 1.25 MEV
(BUECHNER *et al*, 1948);
(C) SAME, 2.00 MEV;
(D) SAME, 2.35 MEV.

S. 16

FIG 17

NBS

200

198

FIG 18

APPROXIMATE SPECTRAL DISTRIBUTION OF X-RAYS FROM A MOLYBDENUM TARGET TUBE OPERATED AT 35 KV. NOTICE THE TWO "LINES" OF CHARACTERISTIC X-RAYS OF THE TARGET MATERIAL.

199
 DIAGRAM OF INTERACTIONS
 AMONG ATOMIC ELECTRONS.
 THE FORCES ON THE INNER-
 MOST ELECTRON (a) TEND
 TO CANCEL OUT; THE
 FORCES ON THE OUTER-
 MOST ELECTRON (e) COMBINE
 TO YIELD A NET REPULSION
 AWAY FROM THE NUCLEUS.

FIG 19

VISUALIZATION OF THE DENSITY-
 DISTRIBUTION OF THE ELECTRONS
 OF A HYDROGEN ATOM IN VARIOUS
 STATES. (FROM WHITE, 1939
 P. 146)

FIG 21

LOWEST AND HIGHEST IONIZATION POTENTIAL OF THE ELEMENTS

200

FIG. 23

DIAGRAM OF ELECTRIC BARRIER
EFFECT AROUND A NUCLEUS.

FIG 24

PLOT OF COMPTON SCATTERING "CROSS
SECTION" FOR PHOTONS OF DIFFERENT ENERGIES

FIG 22

DIAGRAM OF MUTUAL ORIENTATION OF A GROUP OF WATER MOLECULES, WHICH YIELDS A NET ATTRACTION BETWEEN THEIR NEGATIVE AND POSITIVE CHARGES.

FIG 25

DIAGRAM OF COMPTON-SIMON EXPERIMENT FOR THE VERIFICATION OF THE LAW OF COMPTON SCATTERING.

STATISTICAL DISTRIBUTION OF THE ENERGY OF A PHOTON BY COMPTON SCATTERING INTO TWO FRACTIONS: ONE FRACTION IS LEFT WITH THE SCATTERED PHOTON, THE OTHER TO THE RECOIL ELECTRON - THE CURVES CORRESPOND TO VARIOUS ENERGIES OF THE INCIDENT PHOTON. - EXAMPLE: THE SHADED AREA,

FIG. 26

EQUAL TO THE PRODUCT OF A .05 RANGE OF ENERGY FRACTIONS AND OF THE MEAN PROBABILITY PER UNIT SCALE 1.1, MEASURES THE PROBABILITY .055 THAT A 1 MEV PHOTON KEEPS 40 TO 45 PERCENT OF ITS ENERGY AFTER SCATTERING AND TRANSFERS 55 TO 60% (i.e. .550 TO 600 KEV) TO THE RECOIL ELECTRON.

-201-

FIG 36a

APPROXIMATE PLOTS OF THE STOPPING NUMBER OF ATOMIC ELECTRONS AS A FUNCTION OF THE KIND AND ENERGY OF THE INCIDENT PARTICLE GRAPH (a) LINEAR ENERGY SCALE, (b) LOGARITHMIC ENERGY SCALE:

1	ELECTRONS	H ₂	B
2	"	H ₂ O	B
3	"	Pb	B
4	PROTONS	A	B
5	"	A	B FOR L SHELL
6	"	A	B FOR K SHELL

SEE PAGE
201A FOR
FIG 36b

201A 205

FIG. 36b

APPROXIMATE PLOTS OF THE STOPPING NUMBER OF ATOMIC ELECTRONS AS A FUNCTION OF THE KIND AND ENERGY OF THE INCIDENT PARTICLE GRAPH (a) LINEAR ENERGY SCALE, (b) LOGARITHMIC ENERGY SCALE:

(FOR FIG. 36a SEE PAGE 201)	1	ELECTRONS	H ₂ B	
	2	"	H ₂ OB	
	3	"	Pb B	
	4	PROTONS	A B	
	5	"	A B	FOR L SHELL
	6	"	A B	FOR K SHELL

FIG. 28

SKETCH OF A CLOUD CHAMBER PICTURE OF PAIR PRODUCTION (FROM GENTNER ET AL, 1940 FIG. 26.)

FIG. 27

ANGULAR DISTRIBUTION OF COMPTON-SCATTERED PHOTONS. EXAMPLE:

THE CROSS SECTION FOR SCATTERING OF A 1 MEV PHOTON, BY AN ELECTRON, AND A 1 CM^2 DETECTOR LOCATED AT A DISTANCE OF 10 CM, AT AN ANGLE OF 60° WITH RESPECT TO THE INITIAL DIRECTION EQUALS THE PRODUCT OF THE ORDINATE, $1.8 \times 10^{-26} \text{ CM}^2/\text{PER UNIT SOLID ANGLE}$, AND OF THE SOLID ANGLE, $1/10^2$ COVERED BY THE DETECTOR, NAMELY $1.8 \times 10^{-28} \text{ CM}^2$.

CROSS SECTION FOR PAIR PRODUCTION BY PHOTONS OF DIFFERENT ENERGIES IN THE SPACE SURROUNDING NUCLEI OF AL (LEFT SCALE) AND OF Pb (RIGHT SCALE). - DATA FOR OTHER MATERIALS MAY BE OBTAINED BY EXPANDING OR CONTRACTING THE SCALE OF ORDINATES IN PROPORTION TO Z^2 .

NBS

FIG. 30

CROSS SECTION FOR PRODUCTION OF PAIRS WITH POSITRON AND ELECTRON ENERGIES IN A SPECIFIC RANGE, EXAMPLE: THE SHADED AREA, EQUAL TO THE PRODUCT OF A .05 RANGE OF ENERGY FRACTION AND OF A MEAN ORDINATE OF $2.3 \times 10^{-25} \text{ cm}^2$ MEASURED THE CROSS SECTION $1.15 \times 10^{-26} \text{ cm}^2$ FOR PRODUCTION OF A PAIR BY A 5 MEV PHOTON IN THE SPACE SURROUNDING AN AL NUCLEUS WITH 30-35% OF THE AVAILABLE KINETIC ENERGY ($5 - 2 \text{ mc}^2 = 4 \text{ MeV}$) IMPARTED TO THE POSITRON AND THE REMAINING 65-70% (NAMELY 2.6 TO 2.8 MEV) TO THE ELECTRON - FOR DATA ON Pb USE THE RIGHT SCALE - FOR DATA ON OTHER MATERIALS EXPAND OR CONTRACT THE SCALE IN PROPORTION TO Z^2 .

FIG. 34

DIAGRAM OF ABSORPTION SPECTRUM

204

FIG. 31
 DIAGRAM OF DEFLECTING FORCES AS A POSITIVELY CHARGED PARTICLE PASSES NEAR A NUCLEUS. NOTICE REACTION FORCES ON NUCLEUS.

FIG. 32
 DIAGRAM OF RUTHERFORD SCATTERING EXPERIMENT.

FIG. 33
 DIAGRAM OF MOMENTUM CHANGES IN RUTHERFORD SCATTERING.

IN ABSENCE
 OF ATOMIC
 ELECTRONS

2° 4° 6°
 DEFLECTION

FIG. 35

DIAGRAM OF

CROSS SECTION
 FOR ELASTIC
 SCATTERING
 OF CHARGED
 PARTICLES IN
 DIFFERENT
 DIRECTIONS.

205

FIG. 63

THE MAXIMUM RANGE R_m IN g/cm^2 OF AL.
 FOR β -RAYS OF SOME RADIOACTIVE MATERIALS
 WITH DIFFERENT MAXIMUM ENERGIES E_m .
 (FROM EVANS, 1948, FIG. 8)

FIG. 64

TOTAL NARROW-BEAM MASS ABSORPTION
COEFFICIENT FOR X-RAYS OF DIFFERENT
ENERGIES IN AL AND Pb. (FROM WHITE 195)

STOPPING POWER OF WATER (RATE OF ENERGY LOSS BY INELASTIC COLLISIONS) FOR ELECTRONS AND PROTONS OF DIFFERENT ENERGIES.

TRAVERSING WATER
FRACTIONS OF THE ENERGY SPENT
IN DIFFERENT PROCESSES BY AN
ELECTRON AS IT SLows DOWN
FROM 500 TO 400 KEV
THE AREA NOT COVERED BY CROSS
HATCHING CORRESPONDS APPROXIMATELY
TO THE ENERGY FRACTION WHICH
REMAINS AVAILABLE FOR FURTHER
INELASTIC COLLISIONS BY SECONDARY
ELECTRONS.

NBS

FIG. 38

FRACTION OF INELASTIC COLLISIONS OF FAST ELECTRONS AGAINST H ATOMS WHICH LEAD TO VARIOUS ENERGY ABSORPTIONS - THE CURVES REPRESENT THE COEFFICIENT $g_i(E)$ OF $e_i^+(23)$. THE AREAS IN THE RECTANGULAR BLOCKS REPRESENT THE VALUES OF g_i^* OF $e_i^+(22)$ PERTAINING TO EXCITATION TO THE FIRST EXCITED LEVEL AND TO ALL OTHER LEVELS COMBINED.

FIG. 41.

RELATIVE PROBABILITY OF DIFFERENT EFFECTS FOR X-RAYS OF ALL ENERGIES IN C. AND Pb.

NUMBER OF ELECTRONS

FIG. 42(a). SCHEMATIC
REPRESENTATION OF
THE ORIGIN OF A
 δ -RAY PHOTON BY
SUCCESSIVE COMPTON
SCATTERINGS AND
INTERNAL PHOTOELECTRIC
EFFECT

NEW δ -RAY
1, 2, 3, 4, TRACKS
OF COMPTON
RECOIL ELECT-
TRONS.
5, TRACK OF
PHOTO-
ELECTRON
POINTS OF
DIRECT
ACTION

FIG. 42(b). NUMBER OF ELEC-
TRONS OF VARIOUS ENERGIES
RELEASED IN INDIC, ON
THE AVERAGE, EVERY
 δ -RAY PHOTON EMITTED BY
COBALT-60 (INITIAL
PHOTON ENERGY: 1.17 OR
1.33 MEV). THE DOTTED
LINE GIVES THE
SPECTRUM OF COMPTON
ELECTRONS.

FIG. 42(c). DISTRIBUTION OF THE
ENERGY OF COBALT-60
 γ -RAYS AMONG
THE TRACKS OF DIFFERENT
ENERGIES RELEASED BY
COMPTON & PHOTO
EFFECT

NBS

FIG. 43

Diagram of a cascade shower process - Dotted lines indicate path of X-rays; full lines the tracks of electrons and positrons.

FIG. 45

Diagram of polarization effects. Above: an electric field induces positive & negative charges on the top and bottom surfaces of a conductor.

Below: an electric field changes the initial random orientation of polar molecules in a suspension.

FIG 46

ILLUSTRATION OF THE EXPERIMENTAL LAW OF PROBABILITY FOR THE DISTANCE OF SUCCESSIVE COLLISIONS. THE STEPWISE PLOT IN (a) ILLUSTRATES THE ARGUMENT PRESENTED IN THE TEXT IN THE DERIVATION OF (27). THE SEMI LOGARITHMIC PLOT (b) CORRESPONDS TO THE FORM (27') OF THE EXPERIMENTAL LAW.

FIG 47

SKETCH FROM A CLOUD CHAMBER PICTURE OF THE TRACKS OF A FAST AND OF SEVERAL SLOWER ELECTRONS. (FROM GENTNER *et al*, 1940, FIG. 9)

FIG. 49

SKETCH FROM CLOUD CHAMBER PICTURES OF α -PARTICLE TRACKS IN A RAREFIED GAS. (FROM GENTNER *et al*, 1940, FIG. 3.)

FIG. 44

SKETCH OF A STEREOSCOPIC
CLOUD CHAMBER PICTURE OF
A SHOWER INITIATED
BY AN ELECTRON WHICH
DEVELOPS AS THE RADIATION
PASSES THROUGH SUCCESSIVE
LAYERS OF LEAD.
(FROM GENTNER *et al*, 1940 FIG. 62a)

FIG. 50

ILLUSTRATION OF THE " $1/r^2$ " LAW. - THE AREA S_1 AND S_2 INTERCEPTED BY A CONE DIVERGING FROM A SOURCE LOCATED AT V, ARE PROPORTIONAL TO THE SQUARES a_1^2 AND a_2^2 OF THEIR RESPECTIVE DISTANCES FROM V: IF THE SAME QUANTITY OF RADIATION FLOWS THROUGH S_1 AND S_2 THE AVERAGE INTENSITY ON THESE SURFACES MUST BE INVERSELY PROPORTIONAL TO THEIR AREAS, I.E. PROPORTIONAL TO $1/a_1^2$ AND $1/a_2^2$ RESPECTIVELY.

PERCENT OF SKIN DOSE PER CENT OF AIR DOSE

180 KV CONSTANT
POTENTIAL, 0.5
MM CU FILTER

100 SQ CM
50 CM DISTANCE

FIG. 51

CHARACTERISTICS OF X-RAY DOSE DISTRIBUTION, 174 IN AND AT THE EDGES OF A BEAM TRAVERSING TISSUE (FROM MEDICAL PHYSICS, 1950 VOL 2 P 745)

FIG. 52. RATE OF ENERGY DISSIPATION ("BRAGG CURVE") AND MEAN RESIDUAL ENERGY OF AN α PARTICLE ALONG ITS PATH IN AIR.

FIG. 54. STRAGGLING OF PROTONS AND α -PARTICLES. THE DIFFERENCE BETWEEN THE EXTRAPOLATED AND THE MEAN RANGE, IN PERCENT OF THE LATTER IS GIVEN AS A FUNCTION OF THE MEAN RANGE. (FROM PETHIE AND LIVINGSTON 1937 FIG. 37)

FIG. 53

RANGE OF PROTONS OF DIFFERENT ENERGIES IN WATER AND IN AIR
 FOR INTENSIVE DATA ON THE RANGES OF HEAVY PARTICLES SEE
 E. J. 420, et al. (1949), BUTLER (1944), BARKER AND SEGRE (1951)

FIG. 48

SKETCH FROM A CLOUD CHAMBER FILM OF A MAGNIFIED ELECTRON TRACK FROM GENTNER et al, 1940, FIG. 10b)

FIG. 55

(a) FRACTION OF ELECTRONS FROM DIFFERENT SOURCES BACK SCATTERED BY MATERIALS OF DIFFERENT ATOMIC NUMBER. (FROM SELIGER 1950) (b) ENERGY DISTRIBUTION OF THE ELECTRONS BACKSCATTERED BY DIFFERENT MATERIALS. (SEE BOATHE 1949)

FIG. 56

DIAGRAM OF ENERGY DISSIPATION BY AN ELECTRON BEAM AT VARIOUS DEPTHS OF PENETRATION WITHIN A MATERIAL.

NBS

FIG 57

APPROXIMATE NUMBER OF PARTICLES IN SHOWERS OF DIFFERENT TOTAL ENERGY AT VARIOUS DEPTHS WITHIN A MATERIAL. DEPTH IS EXPRESSED IN RADIATION LENGTHS (SEE TABLE 9) - SHOWER E_0 IS EXPRESSED WITH REFERENCE TO THE ENERGY ϵ DISSIPATED BY A HIGH ENERGY PARTICLE PER RADIATION LENGTH - THIS ENERGY EQUALS 98 MEV FOR AIR, 52 FOR AL, 25 FOR Fe, AND 7 FOR Pb AND IS 30-40% SMALLER THAN $10^{1/2} \epsilon$ - THEREFORE E_0/ϵ IS ESSENTIALLY THE SAME AS THE QUANTITY (36) THE NUMBER OF PARTICLES MULTIPLIED BY ϵ AND DIVIDED BY THE RADIATION LENGTH GIVES THE ENERGY DISSIPATION IN A LAYER OF 1 CM. (FROM ROSSI AND GREISEN, 1941, FIG. 19)

FIG 58

ENERGY DISSIPATION AT VARIOUS DEPTHS WITHIN MATERIALS EXPOSED TO X-RAYS FROM A 330 MEV SYNCHROTRON (FROM BLOCKER *et al*, 1950)

PROBABILITY OF ANNIHILATION
BEFORE STOPPING FOR
POSITRONS OF DIFFERENT
ENERGIES.

FIG. 59

DIAGRAM INDICATING
PROGRESSIVE REDUCTION
OF THE FRACTION OF
INCIDENT ELECTRONS
WHICH ARE TRANS-
MITTED THROUGH
FOILS OF INCREAS-
ING THICKNESS.

FIG. 60

FIG. 65

SCHEMATIC LAYOUT FOR MEASUREMENTS OF NARROW-BEAM
ABSORPTION COEFFICIENTS.

FIG. 61

THE EXTRAPOLATED RANGE R_0 FOR ELECTRONS OF DIFFERENT ENERGIES. UPPER CURVE REFERS TO THE SCALES ON TOP AND LEFT OF DIAGRAM, LOWER CURVE TO BOTTOM AND RIGHT SCALES. (FROM EVANS 1948, FIG. 5)

DIAGRAM INDICATING THE REDUCED TRANSMISSION OF β RAYS THROUGH FOILS OF INCREASING THICKNESS.

FIG. 66. NARROW BEAM
ABSORPTION CURVE IN
CU FOR NON MONO -
CHROMATIC X-RAYS
FROM A TUBE OPERATED
AT 120 KV.

FIG. 68. BUILD UP OF
SECONDARY RADIATION AT
INCREASING DISTANCES FROM
A ⁶⁰CO γ-RAY SOURCE
IN WATER. (EXPERIMENTAL
DATA FROM WHITE, 1950,
THEORETICAL CURVE FROM
SPENCER AND FANO, 1951)

FIG. 67

NARROW-BEAM AND BROAD-BEAM ABSORPTION CURVES IN CONCRETE FOR X-RAYS FROM A TUBE OPERATED AT 800 KV WITH HEAVY FILTRATION. NOTICE THE BUILD UP OF SECONDARY X-RAYS UNDER BROAD BEAM CONDITIONS.

Fraction of incident energy absorbed

224

FIG. 69

FRACTION OF THE ENERGY OF INCIDENT X-RAYS WHICH IS ACTUALLY ABSORBED IN PHOTOELECTRIC EFFECT ON THE K-SHELL (CURVES g) OR IN COMPTON EFFECT (CURVE f)

FIG. 70

A QUALITATIVE PLOT OF THE ENERGY DISSIPATED BY A BEAM OF X-RAYS AT INCREASING DEPTHS WITHIN A MATERIAL.

"RELATIVE RANGE" OF ELECTRONS AND PHOTONS OF EQUAL ENERGY, IN WATER, AS A FUNCTION OF THE ENERGY. THE QUANTITY PLOTTED IS THE PRODUCT OF THE NARROW BEAM ABSORPTION COEFFICIENT OF THE X-RAY (WHICH MAY BE REGARDED AS THE RECIPE OF A RANGE) AND OF THE TRUE RANGE OF ELECTRONS.

ENERGY DISSIPATION AT VARIOUS DEPTHS WITHIN A PRESSBOARD PHANTOM BY X-RAY BEAMS OF A BETATRON OPERATED AT DIFFERENT ENERGIES. (FROM CHARLETON & REED, 1948, FIG. 9)

FIG. 73

ENERGY DISSIPATION IN VARIOUS PORTIONS OF THE X-RAY BEAM FROM A 20 MEV BETATRON AS IT PASSES THROUGH A PRESSWOOD PHANTOM - THE BEAM HAS BEEN PASSED THROUGH A COMPENSATING FILTER WHICH SHARPENS THE EDGES OF THE BEAM (FROM ADAMS *et al*, 1948)

FIG. 74

SKETCH OF A CLOUD CHAMBER PICTURE OF THE EFFECTS OF AN X-RAY BEAM ON AIR. (FROM GENTNER *et al*, 1940 FIG. 21b)

SKETCH OF THE ENERGY SPECTRA OF THE γ RAYS EMITTED FROM ^{51}Fe , ^{35}Cl , AND ^{27}Al FOLLOWING CAPTURE OF A NEUTRON (FROM HAMER-MESH, 1950).

227

EXPONENTIAL DOSE ACTION CURVE (KILLING OF *E. COLI*) FLATTENED AT THE END THUS SHOWING THE EXISTENCE OF A MORE RESISTANT COMPONENT STRAIN. THIS STRAIN AFTER ISOLATION, YIELDS THE DOTTED DOSE-ACTION CURVE. (FROM WATKIN 1947)

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FIG. 77

EXAMPLE OF AN EXPONENTIAL DOSE-ACTION CURVE; (a) LINEAR PLOT
(b) SEMILOGARITHMIC PLOT.

FIG. 79

ATTEMPT AT A PRECISE DETERMINATION OF ^{THE} LOW-DOSE PORTION OF AN E. COLI SURVIVAL CURVE (A. HOLLANDER, UNPUBLISHED)

6×10^{-24} cross section
in cm^2/g

VARPCW -
BEAM ABSORPT-
ION CROSS

SECTIONS OF
CARBON AND
CADMIUM FOR
NEUTRONS OF
VARIOUS ENERGIES
(FROM ADAIR
1950) FIG 75C
ON NEXT PAGE.

FIG. 75a

cross section
in $\text{cm}^2/\text{NUCLEUS}$

FIG. 75b

FIG. 80

DOSE-EFFECT CURVE FOR THE PRODUCTION OF GENETIC MUTATIONS IN *DROSOPHILA*: (a) SEX-LINKED LETHALS. (b) THREE GROUPS OF VISIBLE MUTANTS (FROM TIMOFFEEFF AND ZIMMER, 1947, FIG. 16 & 17)

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235

NARROW-BEAM ABSORPTION
CROSS SECTIONS OF CARBON
AND CADMIUM FOR NEUTRONS
OF VARIOUS ENERGIES. (FROM
ADAMS 1950)

(FIG 75 A+B ON PREVIOUS PAGE.)

231

EXAMPLE OF A SIGMOID DOSE-ACTION
CURVE (KILLING OF CALLIPHORA EGGS
FROM SCOTT 1934)

FIG. 81

FIG. 82

NOTES OF 1-5 HIT DOSE ACTION CURVES ACCORDING TO
S. (53) (a) LINEAR PLOT, (b) SEMILOG ARITHMIC PLOT.

THE NATIONAL BUREAU OF STANDARDS

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I - ~~VII~~ AND
1 - 236

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