TRACKS OF NUCLEAR PARTICLES IN PHOTOGRAPHIC EMULSIONS

JOSEPH L. DELAWARE

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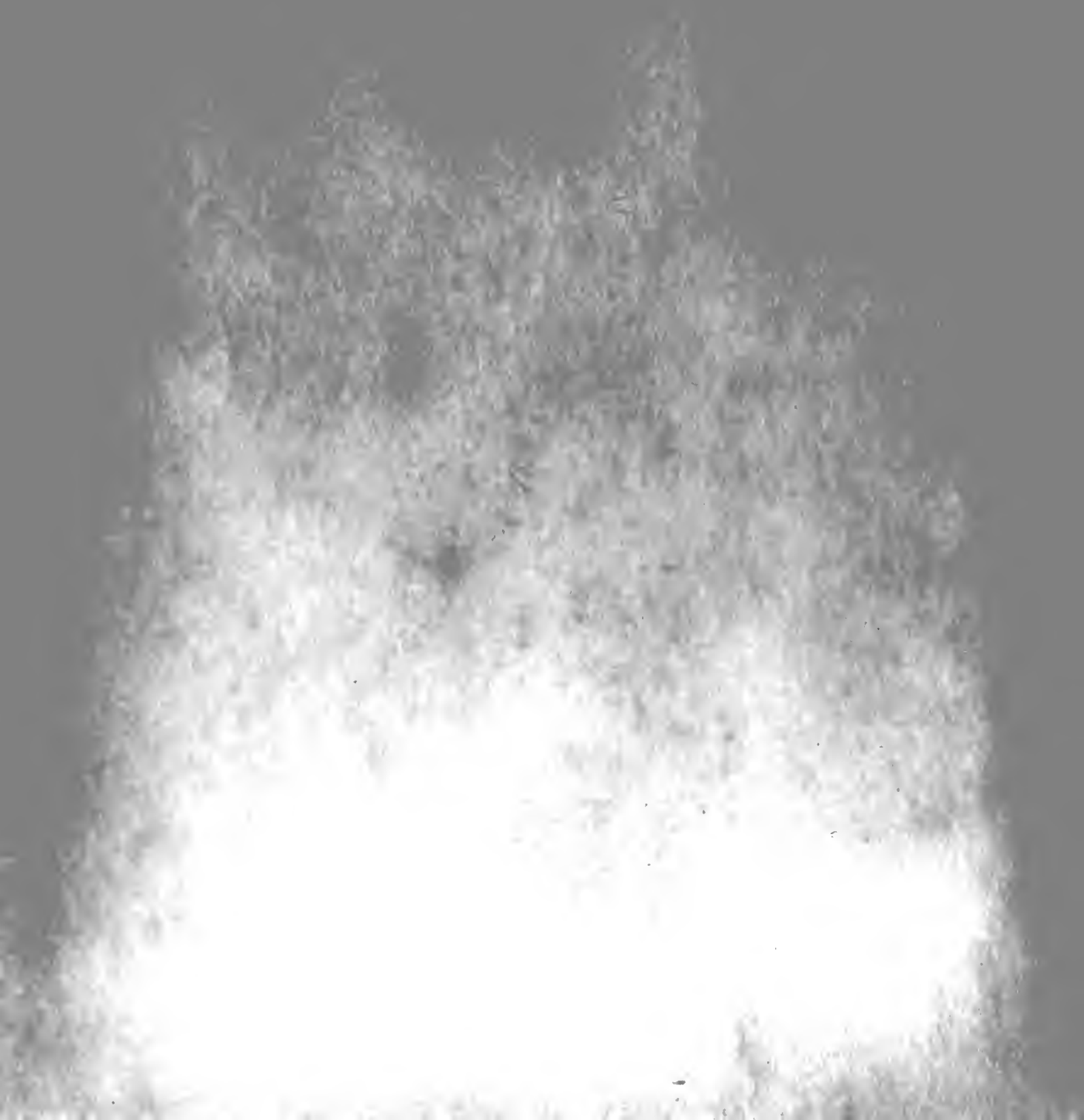PRINTED HERE.

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IN PHOTOGRAPHIC EMULSIONS

JOSEPH L. DELAWARE

TRACKS OF NUCLEAR PARTICLES
IN PHOTOGRAPHIC EMULSIONS

By

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''
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Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 5 4

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

PHYSICS

from the

United States Naval Postgraduate School

ABSTRACT

A brief historical background of the application of photosensitive emulsions to studies in radioactivity is presented. The mechanism of latent image formation is considered from the standpoint of ion-pair production in the grain. The advantages and limitations of the photographic technique are discussed, and data on the composition, physical characteristics, and sensitivity, as well as recommended uses of some of the commercially available nuclear research emulsions are presented. The registration of charged particles by the photographic emulsion is considered from the standpoint of their space rate of energy loss on passage through-matter, and a theoretical formula which permits the calculation of specific energy loss is discussed. Grain density and its variation in the recorded tracks of nuclear particles are discussed. A calculation is made of the range-energy relation of a given particle in a stopping material, and useful deductions of a general nature based on this relation are considered. Range-energy curves for alpha-particles, protons, deuterons, and mesons in nuclear emulsions are furnished, and range-energy relations for various particles in different emulsion types are compared. A theoretical calculation of the stopping power of the photographic emulsion relative to that of air is given. Curves of stopping power versus energy for alpha-particles and protons in nuclear emulsion are furnished. The measurements to be performed on the tracks themselves are examined, and a discussion of the various techniques employed to obtain these measurements is included. The search techniques for observing tracks of nuclear
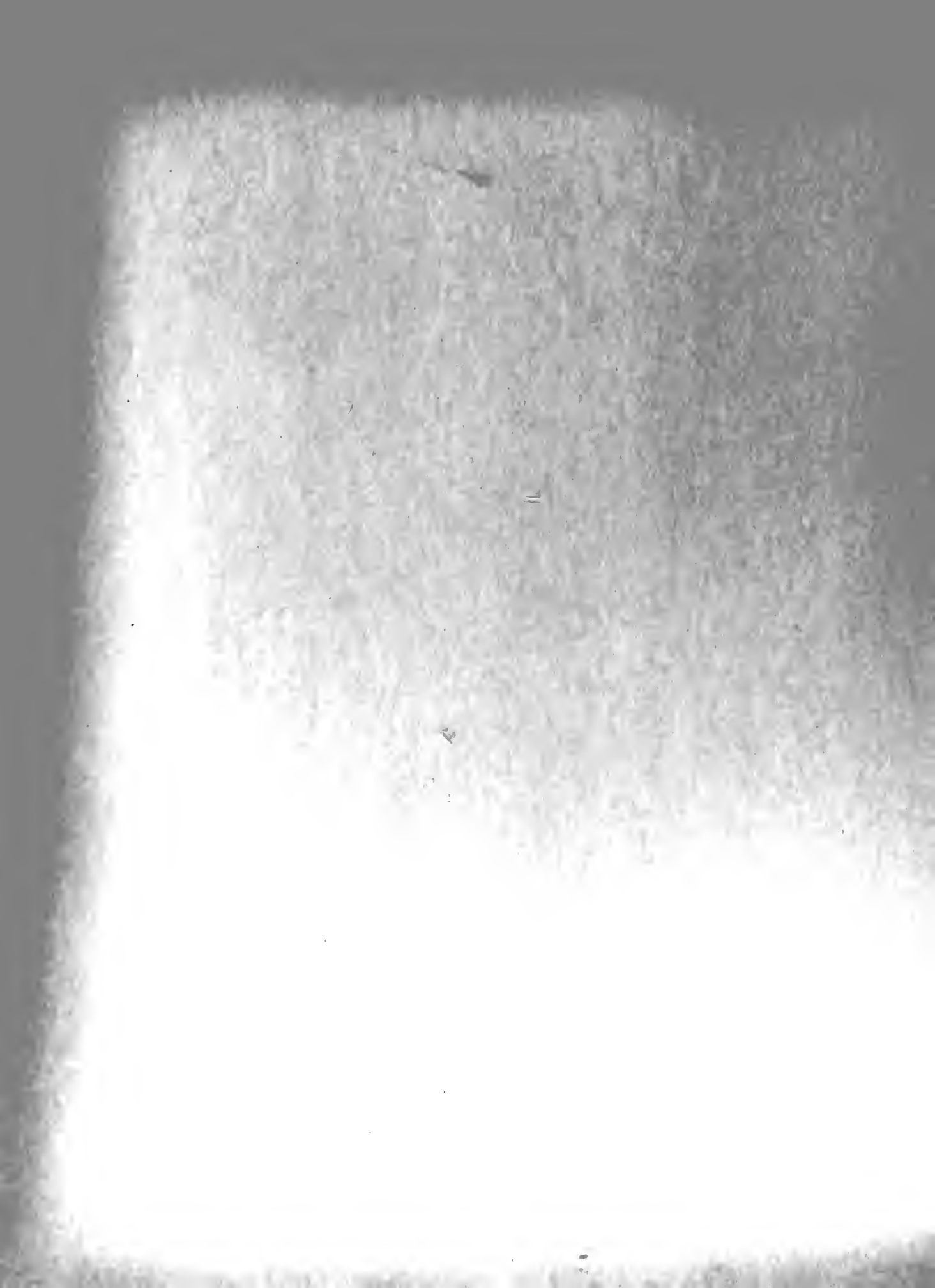
particles in photographic emulsions are discussed with emphasis mostly centered on the major progress of recent years in automatic instruments. Finally, selected microphotograph reproductions of tracks produced by fast charged particles in passing through nuclear research emulsions are shown to give an indication of the wide scope of the photographic method.
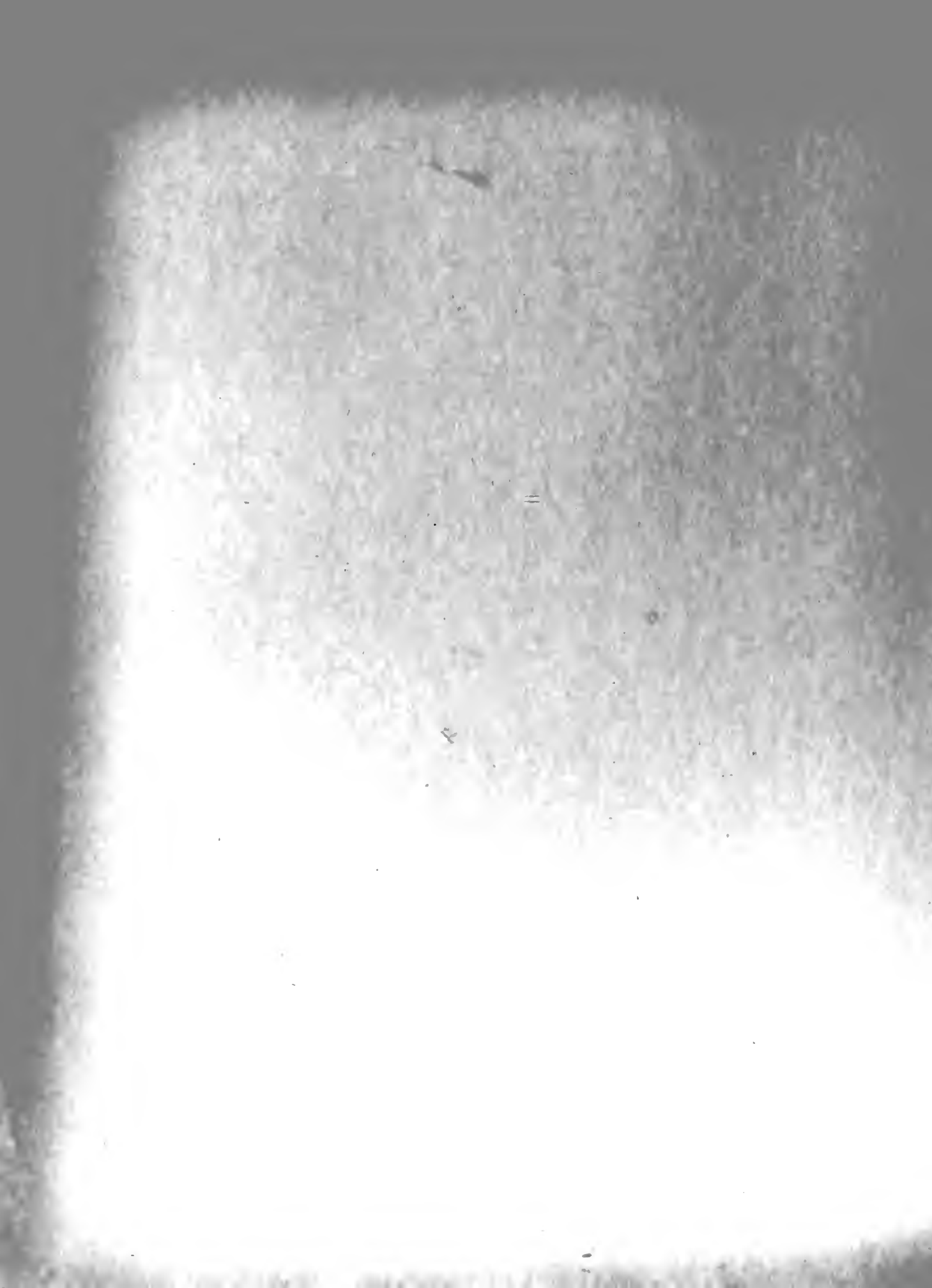
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CHAPTER I

NATURE OF THE PHOTOGRAPHIC TECHNIQUE

1-1 INTRODUCTION

Before directing our attention to the specific application of photo-
sensitive emulsions to studies of tracks of nuclear particles, it would
be well to briefly review how the photographic emulsion first came to be
employed for the investigation of radiation by atomic nuclei and why it
is termed the oldest detection instrument of nuclear physics. By means
of a photographic plate radioactivity was discovered, purely by chance,
during the course of experiments with phosphorescent bodies. In 1896
Henri Becquerel decided to investigate an hypothesis concerning the revers-
ibility of the fluorescent mechanism. It was known that X-rays cause a
fluorescent substance to shine in the dark. Becquerel reasoned that the
process may be reversible; that is, the phosphorescent body may emit in-
visible penetrating rays, similar to X-rays, capable of photographic
detection. He wrapped a Lumiére gelatin-silver bromide plate in black
paper and placed upon it a phosphorescent substance which was then ex-
posed to sunlight. Fortuitously, Becquerel selected uranyl sulfate for
this experiment. The salt, activated by sunlight, gave out penetrating
radiations which passed through the black paper and blackened the photo-
graphic plate. The experiment was repeated one day when the sun was
obscured. Becquerel set the wrapped photographic plate with the non-
activated preparation in a dark drawer for several weeks. Upon developing
the plate, he found that blackening had proceeded just as much in darkness
as in light. Further studies showed that neither phosphorescence nor

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sunlight had anything to do with the results obtained. Darkening of the plate was caused by the emission of an invisible penetrating radiation from the uranyl sulfate itself; such radiations were also capable of discharging an electroscope.

These sensational findings stimulated widespread interest in the phenomenon. It led to the isolation of polonium and radium in pitchblende by Marie and Pierre Curie in 1898 and to the formation of the concept of nuclear instability by Rutherford and Soddy in 1902. Physicists discovered that many chemical compounds are radioactive and that some minerals have radioactive properties which activate the photographic emulsion.

In 1911 Reinganum noted that an alpha-particle striking a photographic plate, at glancing incidence, could render developable a minute trail of discrete silver grains. In ensuing years the characteristic tracks of other particles were investigated. The photographic emulsion has been used by many workers for the registration and study of nuclear events. Among the pioneers in this field the names of Blau and Wambacher and Wilkins are to be especially pointed out. In many cases the technique represents the only means of recording such phenomena. The reader is referred to an excellent summary of the work along these lines in a review by Shapiro (1941).

Emulsions on the commonly available commercial plates intended for optical photography were used in the early radioactive studies. However, such plates do not record individually resolvable tracks; thus, more recently, emulsions manufactured especially for photographic detection of nuclear particles were introduced by Ilford Company and Kodak Ltd. in
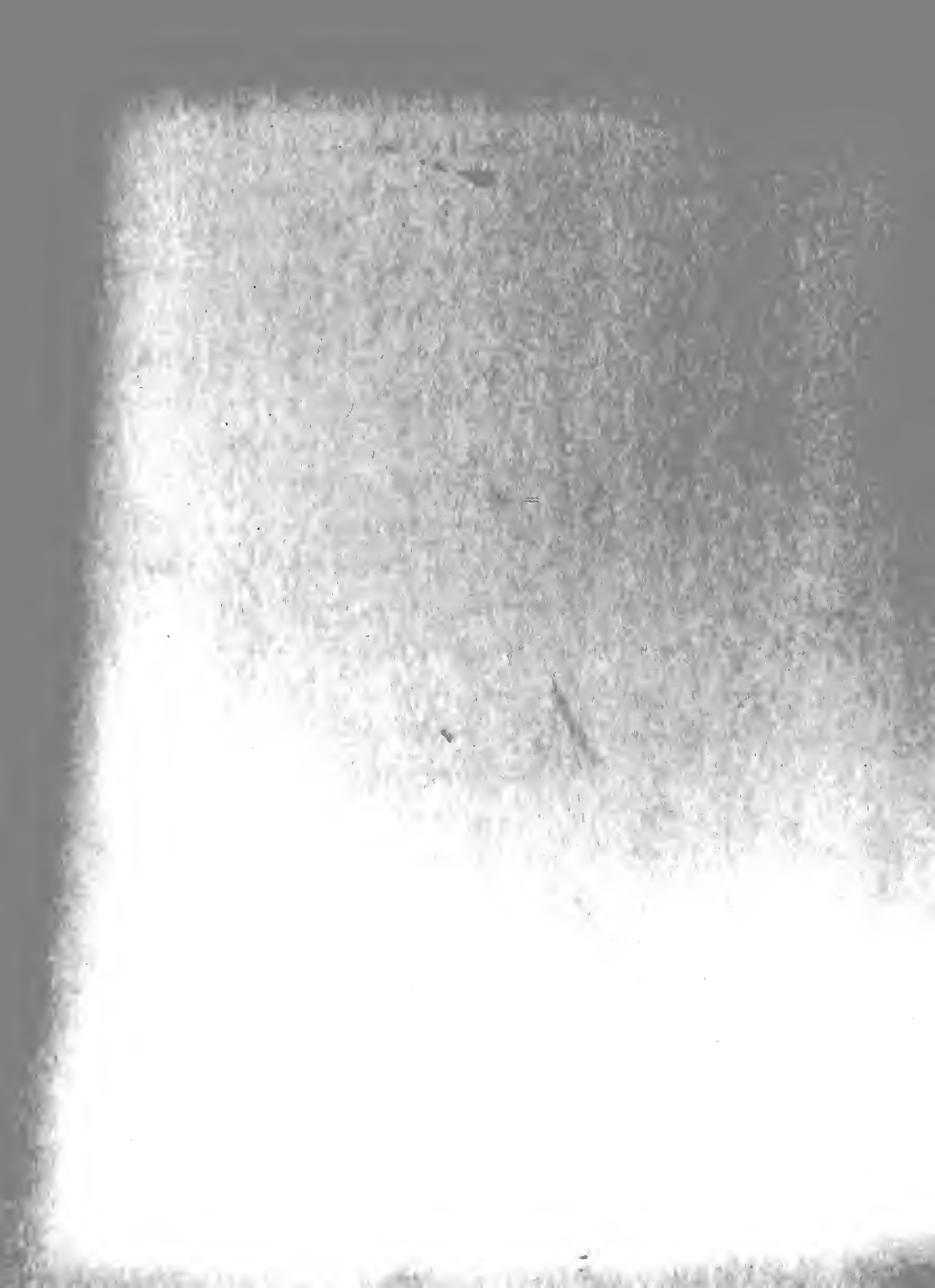
England and the Eastman Kodak Company in Rochester, New York. They are termed Nuclear Emulsions as a means of differentiating them from plates intended for optical or X-ray photography. During and since the war enormous advances have been made in nuclear emulsion manufacture and techniques, to a great extent the result of the efforts of C. F. Powell of the University of Bristol and his co-workers. Different types of emulsions are available, which can be selected according to the problem.

Nuclear track plates have wide application for investigation of problems peculiar to radioactive decay, reaction kinetics, and cosmic rays and meson physics.

The subjects treated and the experimental data presented in this paper are intended as a guide to an understanding of the action of the photographic plate as an invaluable tool in nuclear research and to show that as such it is comparable, and in some instances superior, to the many sensitive radiation detection devices presently available.

1-2 LATENT IMAGE FORMATION

The general concepts of the production of a latent (i.e., developable) image by an ionizing particle in a nuclear emulsion also apply to the photographic emulsions activated by photons of visible light. The fact that in the latter case ion pair formation occurs by the photoelectric emission of electrons by incident photons rather than as a result of direct ionization through collision of the charged particle with orbital electrons of the emulsion atoms appears to be the only significant difference between the two processes. According to the theory of Gurney and Mott (1938) the mechanism of latent image formation is as follows. By action

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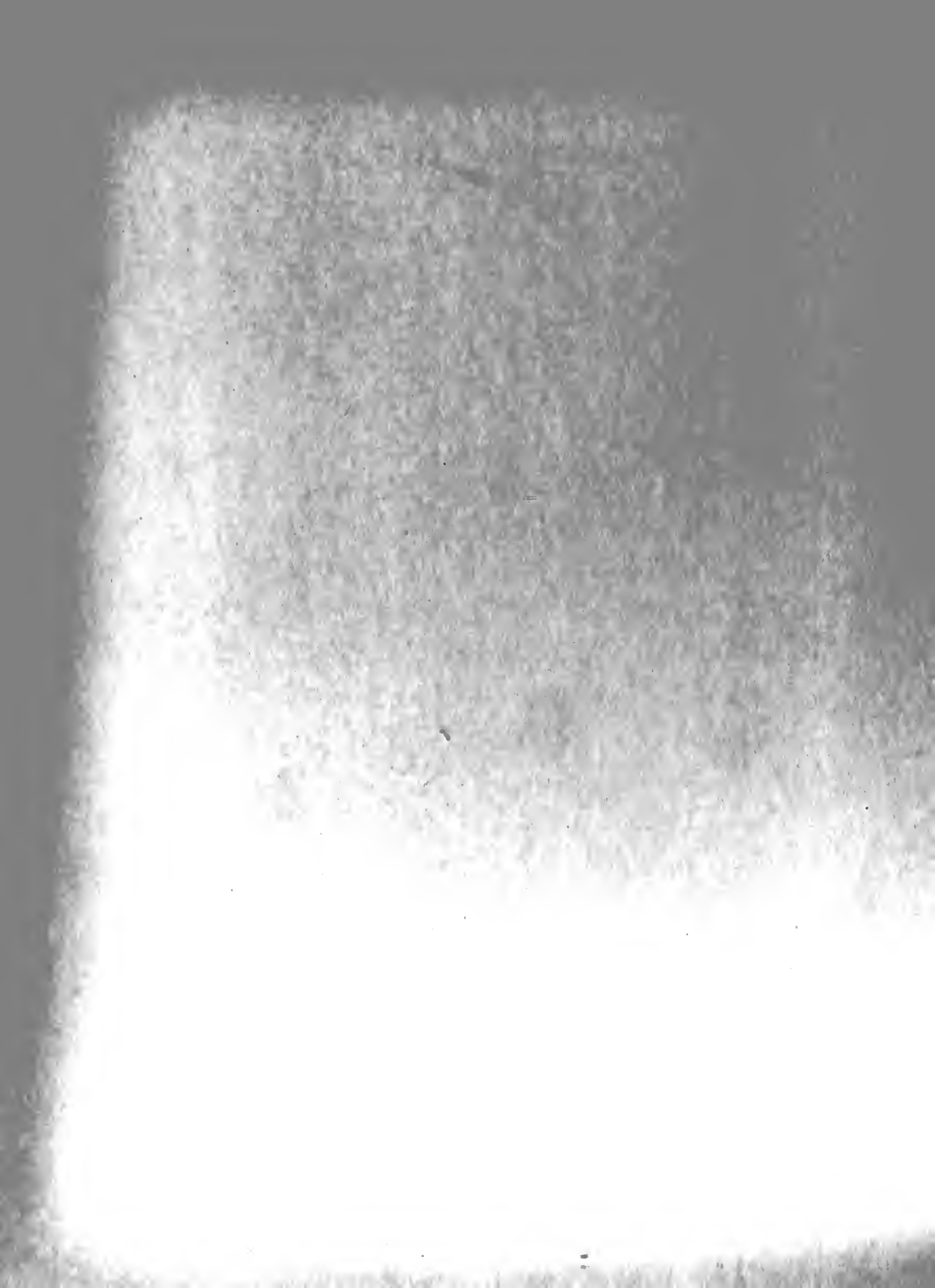
of the incident radiation, electrons are raised from their normal crystal lattice positions in the silver halide grain to vacant states in the conduction band of each crystal. These higher energy electrons move about freely in the crystal until they fall back into their normal positions or become trapped at impurity centers characterized by localized energy levels below those of the conduction band. These impurity centers or sensitivity specks, usually located on the crystal surface, thus become negatively charged. The silver halide always contains a number of free, positively charged silver ions in the crystal lattice. These migrate to the negatively charged sensitivity specks and combine with the electrons there to form silver atoms. When this process has been repeated a sufficient number of times, a speck of metallic silver (the latent image) will have been formed which will serve as a nucleus for the subsequent reduction of the entire grain by the developing solution. Hence each silver halide grain acts individually in development; if a sufficiently large latent image center exists in it, a grain will be entirely reduced. On the other hand, a grain without a latent image of sufficient size is unaffected by the developer. The fixing bath, usually sodium thiosulfate, dissolves the unaffected grains of silver halide but leaves the developed granules intact.

1-3 ADVANTAGES

Photographic emulsions possess versatility in adaption to a great many methods available for experimentation in nuclear physics; their area of usefulness has been broadened to the point where they occupy a rather unique position among detection techniques. The photographic

plate resembles closely the cloud chamber in its ability to register an event permanently and in all details; however, its distinction between tracks of different types of particles is not as fine as in the latter device. It does act as a sort of continuously sensitive cloud chamber and because of its higher density allows the observation of a larger fraction of the path of high-energy particles. The plate possesses a certain simplicity, small size and weight, higher stopping power and affords a permanent record to be examined at the experimenter's leisure. These are definite advantages. If one is interested simply in recording the total number of events occurring over a certain area, the photographic plate technique is particularly adaptable. They are then in strong competition with more automatic detectors such as counters, but have the advantage of discrimination of nuclear particles against a high background of, for instance, electrons and gamma rays. This property makes them a first choice for exploratory experiments with particle accelerators of all energies. Also, combinations can be made of plates with other techniques such as absorbers of various materials or deflection in a magnetic field, thus extending even further their field of usefulness. And finally, the photographic plate technique in its less refined forms is inexpensive.

1-4 LIMITATIONS

On the other hand, the photographic method is subject to a series of disadvantages. The latent image fades; that is, the number of grains developed depends on the delay between irradiation and development. The degree of fading is a function of the conditions of humidity and temper-

ature under which the plates are stored during the delay period. Yagoda (1949) has investigated the fading phenomenon under normal ambient conditions of storage. He has found that fading is more pronounced in emulsions of low silver bromide concentration and that the fading rate increases progressively with the period of delayed development -- at the end of 20 days the photographic density is reduced from 90 to 35 per cent depending on the emulsion composition.

Within the limitations of the fading phenomena, nuclear-type emulsions record continuously the tracks of all densely ionizing radiations that traverse the plate. Though precautionary measures may be taken to reduce this background, examination of the developed plate under a microscope, even before exposure to the experimental source, reveals a great number of silver grains. This "unexposed" background originates chiefly from radioactive contaminants present in the glass support and the components of the emulsion layer. During the history of the plate prior to the development, excessive fluctuations in temperature, gamma rays from radioactive materials in the surroundings, weakly phorescent materials in the dark-room -- all these are capable of rendering silver bromide grains developable. The track contribution by cosmic radiation is negligibly small at sea level, but such rays may, nevertheless, possess sufficient ionizing power to alter single grains.

The tracks of nuclear particles in film emulsions are typically a fraction of a millimeter in length. The presence of a heavy background of silver grains contributes materially to the difficulty in finding and analyzing these tracks. Then again, the track patterns are such that appearance of a stray silver particle may introduce a considerable error
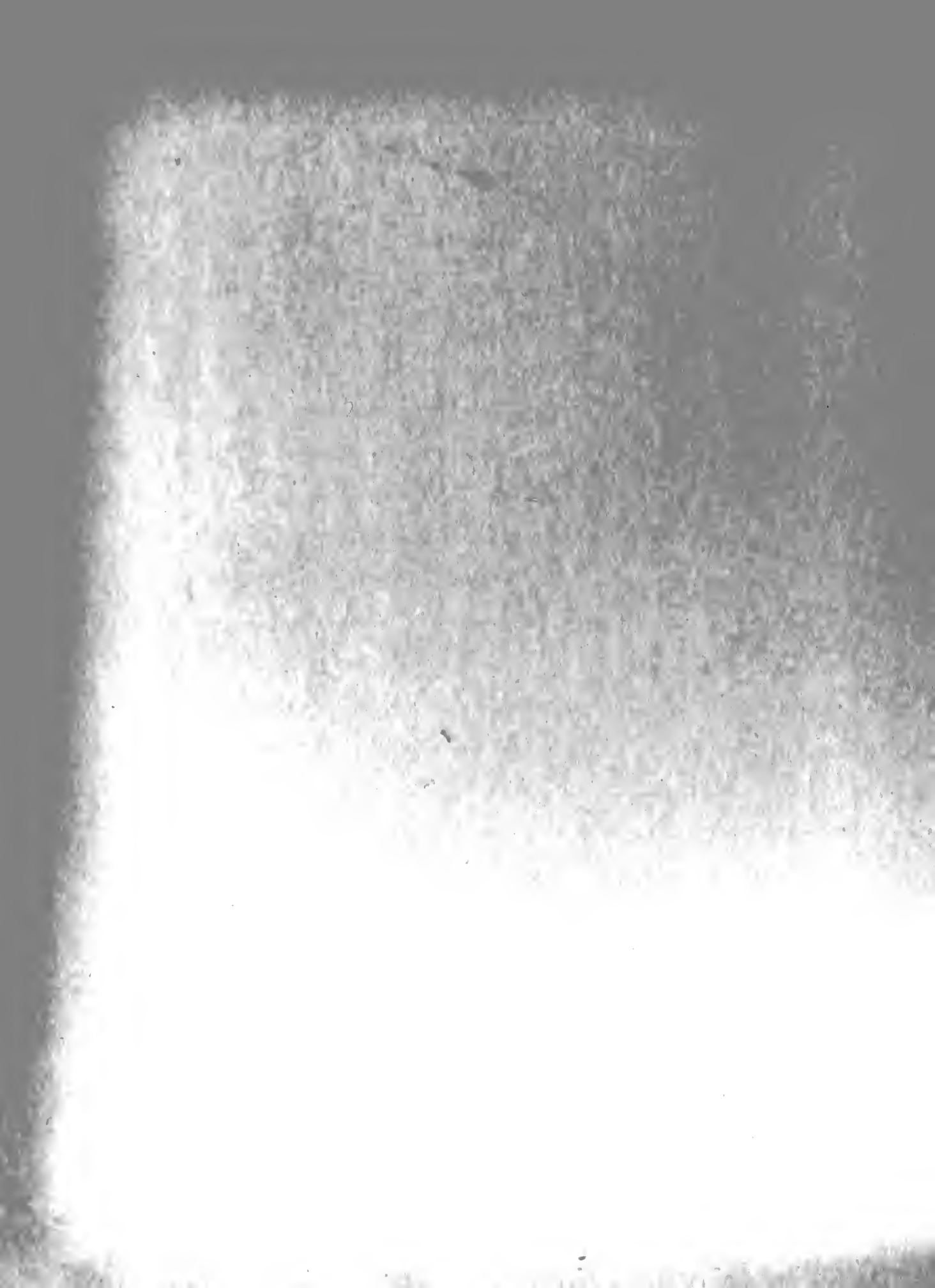
in measured range.

The composition of the emulsion may vary somewhat from batch to batch, giving rise to changes in the range-energy relations. Presence of foreign materials in the emulsion, shrinkage during processing, and changes in grain spacing during experiments where it is difficult to maintain temperature control are other sources of error.

Some of these difficulties may be overcome by selection of the proper emulsion for the problem at hand. The question then arises as to what are the differences in composition which give nuclear emulsions certain characteristics and render them suitable for specific application.

CHAPTER II

PROPERTIES OF NUCLEAR EMULSIONS

2-1 PHYSICAL CHARACTERISTICS

Early emulsions were prepared by several experimenters and for the most part were subject to fluctuations in properties. This writer has chosen to describe in a general sense the nuclear-research emulsions commercially available. The reader will find more specific data on a number of emulsions of different sensitivities in the pamphlets issued by the various laboratories.* These emulsions, as noted previously, are manufactured by the Ilford Company and Kodak Ltd. in England and by the Eastman Kodak Company in America.

The special photographic emulsions used for work in nuclear physics contain about ten times as much silver halide for a given quantity of gelatin as an ordinary optical emulsion. They are normally supplied coated on glass plates 1.25 to 1.40 mm. thick, with emulsion thicknesses of from 25 to 600 microns regularly available in most cases. Plate sizes range from one by three inches to a maximum of perhaps eight by ten inches, with the smaller sizes permitting microscopic examination without further cutting. Although these are established convenient standard sizes, physicists are able to obtain plates of almost all sizes and shapes upon special order to the manufactures. It is of interest

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*Kodak Nuclear Track Plates and Pellicles (Eastman Kodak Company, Rochester, N. Y.).
   Kodak Nuclear Track Emulsions (Kodak Limited, Research Laboratories, Wealdstone, Harrow, England, 1949).
   Ilford Nuclear Research Emulsions (Ilford Research Laboratories, Ilford, London, England, 1949).
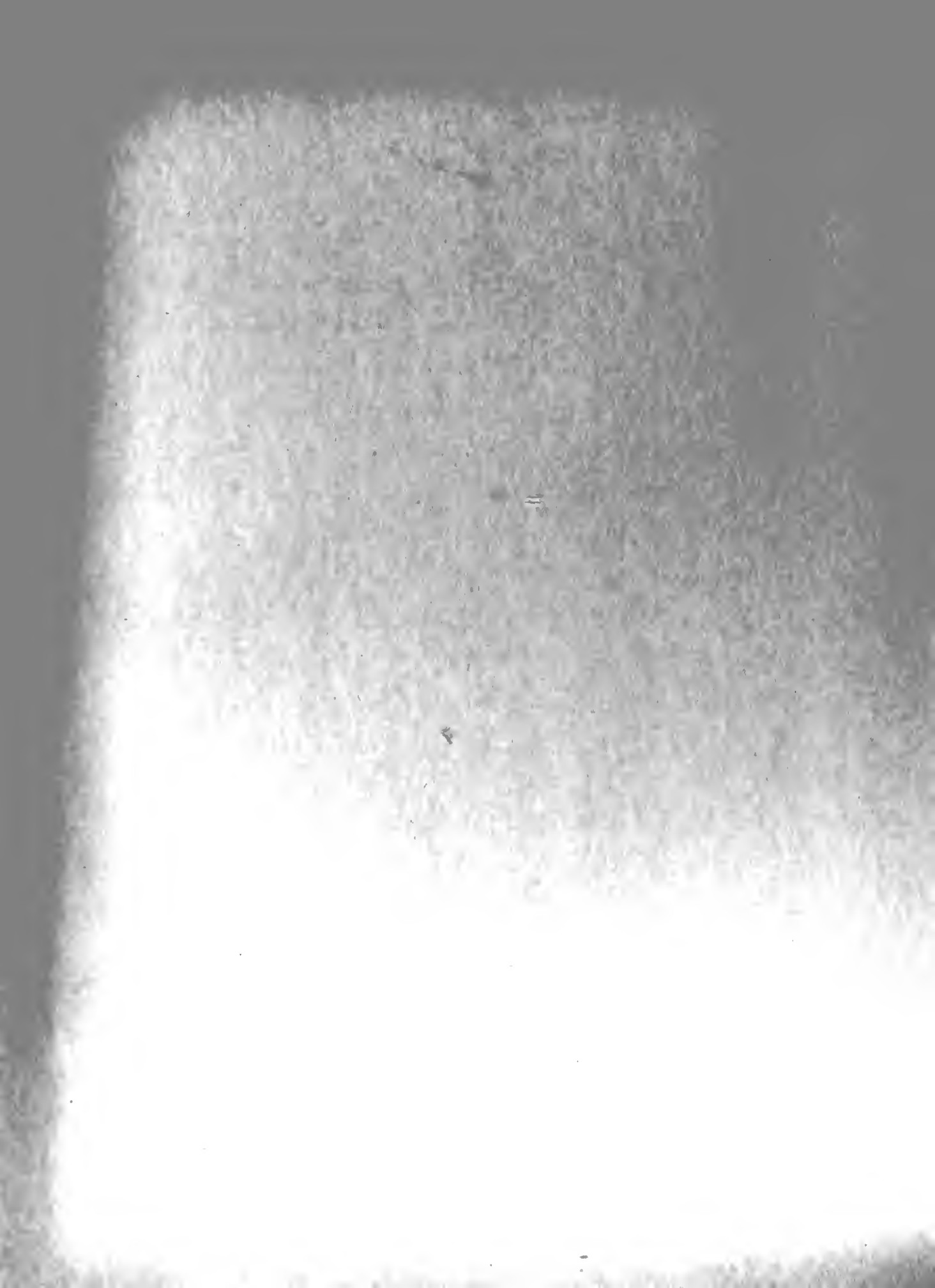
to note that the thickness of the emulsion commonly used has much increased in recent years -- the Ilford Laboratory reports that 1000 and 1200μ emulsion layers are produced regularly and that 2000μ has occasionally been made. Also available are unsupported emulsions, sometimes termed "pellicles", which are very useful for they can be stacked into a large sensitive volume, approximating a solid block of emulsion. The pellicles may be subsequently separated and developed individually. For special applications when it is essential that the experimenter pour his own plates to avoid any preliminary exposure, the manufacturer can supply emulsion in gel form and treated glass.

Nuclear track emulsions combine a fine grain with high intrinsic sensitivity and close packing of the grains. This feature makes them particularly suitable for high resolution work in connection with charged particles. The grain size of the emulsion is of the order of 0.2 - 0.5 microns, depending on the sensitivity of the grains. In the preparation of these concentrated emulsions, care is taken to prevent the background density of fog grains from increasing in proportion to the greater increment of silver halide.

The compositions of the emulsions in terms of the number of grams of each element present per cubic centimeter of completely dry emulsion are given in Table 2-I.
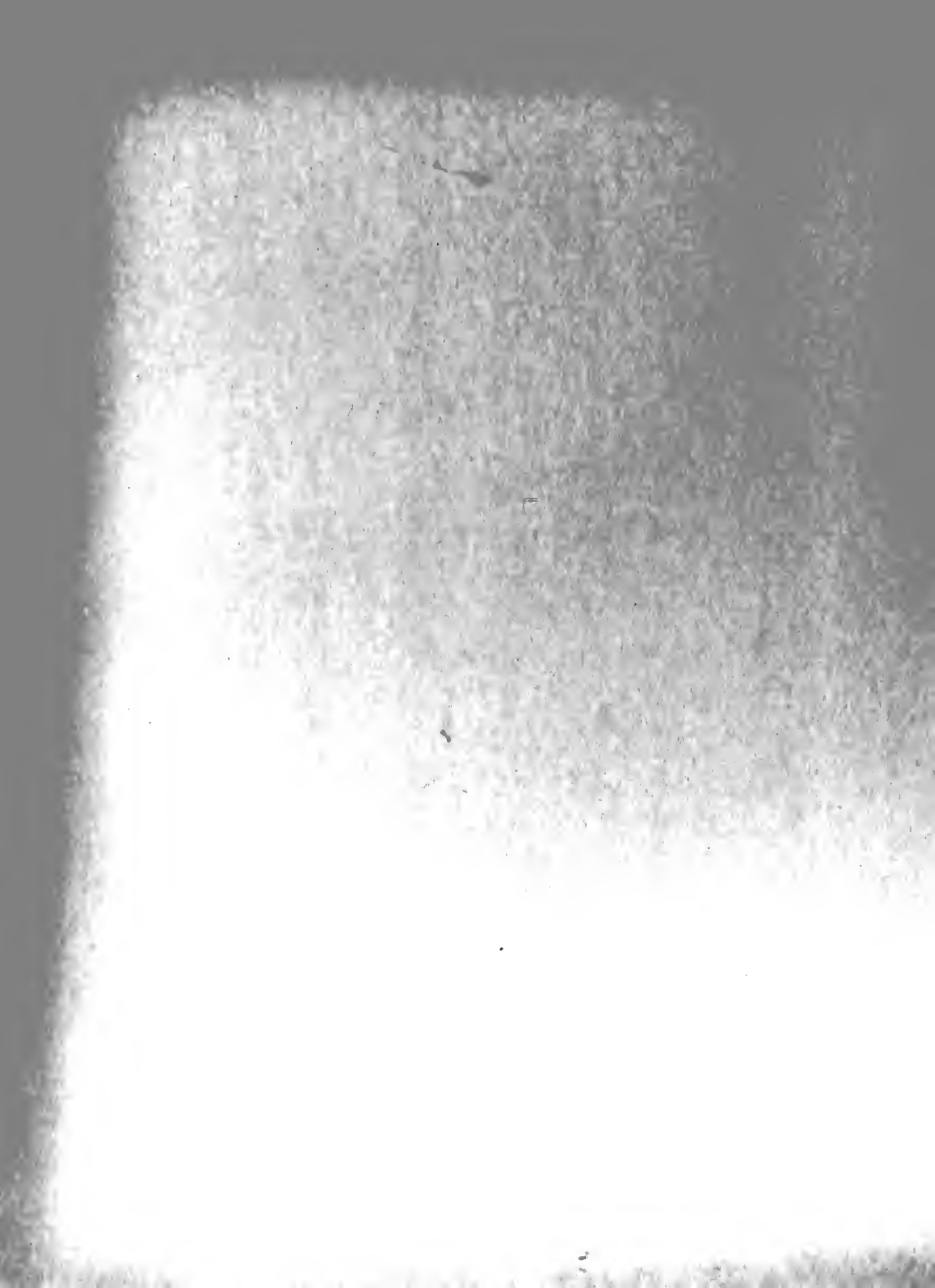
TABLE 2-I

The compositions of dry Ilford, Kodak Ltd., and Eastman
Kodak nuclear emulsions in grams/cubic centimeter*

Element	Ilford	Kodak Ltd.	Eastman Kodak
Silver	2.025	1.97	1.70
Bromine	1.465	1.44	1.22
Iodine	0.057	0.036	0.054
Carbon	0.30	0.27	0.34
Hydrogen	0.049	0.038	0.043
Oxygen	0.20	0.16	0.17
Sulfur	0.011	...	...
Nitrogen	0.073	0.080	0.11

Note: The last five elements comprise the gelatin constituent
of the emulsion.

*Beiser, A., "Nuclear Emulsion Technique," Revs. Mod. Phys.,
24, 274 (October 1952).

For the Ilford G5 emulsions, which are sensitive to tracks of minimum
ionization, the bromine and iodine contents are 1.496 and 0.026 g/cm ^{3}
respectively. The figures for the Eastman Kodak emulsions do not include
the type NTC, which has a much lower silver halide content (65 per cent)
than do their other types (81 per cent).

For certain purposes, it may be desirable for the experimenter to
have access to specific information on minor constituents of the emulsion
which may have a significant bearing on its properties. Workable formulas
for the laboratory preparation of nuclear emulsions are available through
the efforts of Demers (1947) and Halg and Jenny (1948). Their techniques
are recommended to the worker interested in the field.

Gelatin has the property of readily absorbing and retaining moisture;
hence, the emulsion compositions will vary with atmospheric humidity.
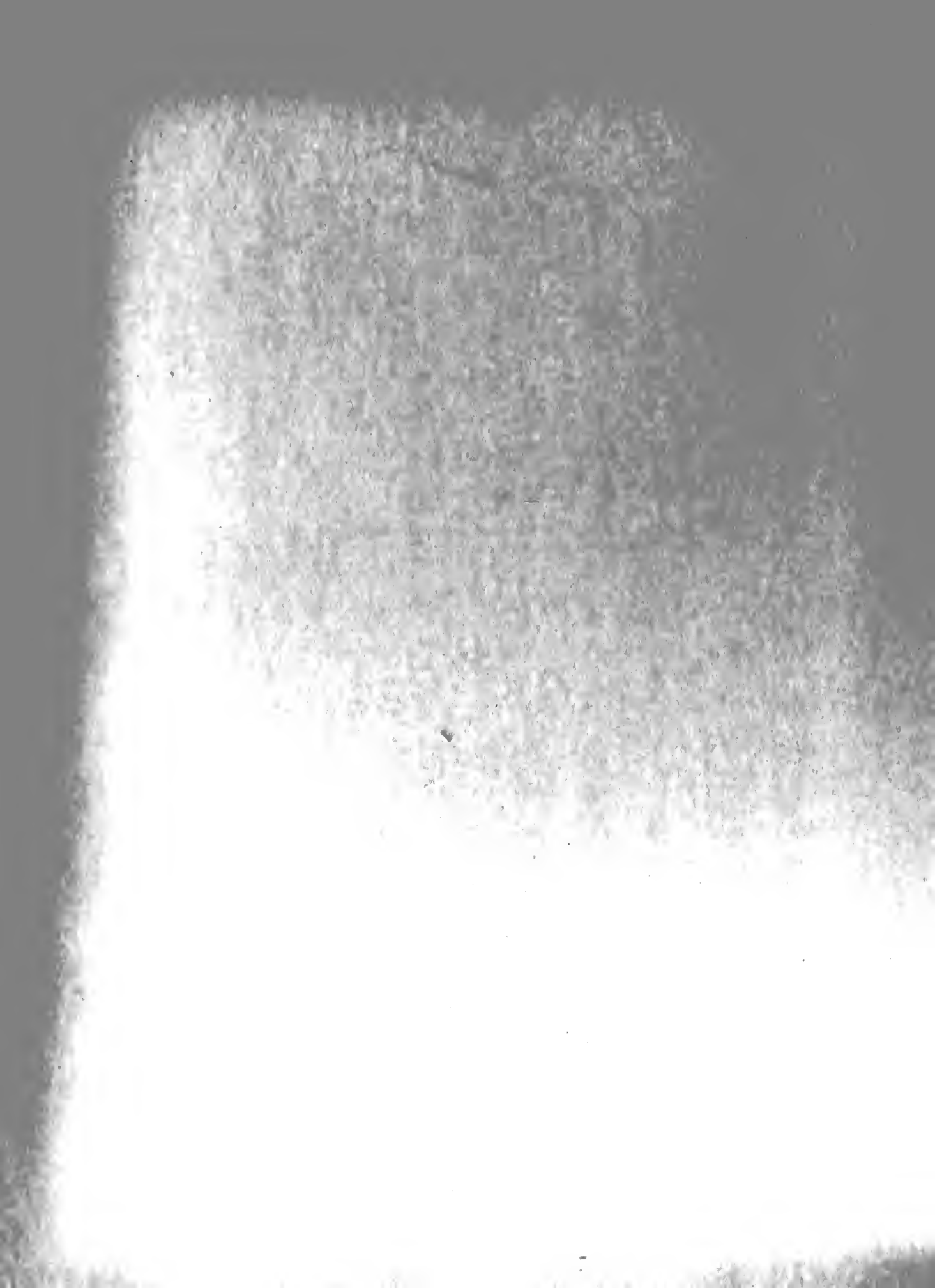
This variation for different relative humidities at a temperature of 20° C. is illustrated by Table 2-II.

TABLE 2-II

The percentage moisture contents by weight of Ilford,
Kodak Ltd., and Eastman Kodak nuclear emulsions
at various relative humidities at 20° C.*

% Relative humidity	Ilford	Kodak Ltd.	Eastman Kodak
0	1.41	...	...
30	2.06	1.3	...
50	2.65	2.6	2.2
60	2.95	...	...
70	3.70	3.5	4.0
85	5.17	...	...

*Beiser, A., "Nuclear Emulsion Technique," Revs. Mod. Phys., 24, 274 (October 1952).

2-2 SENSITIVITIES

Nuclear track emulsions are classified according to sensitivities. It is convenient to indicate these in terms of the energy of various particles capable of producing recognizable tracks. In general, there exists a maximum detectable energy of a particle in the emulsions. This is due to the decrease in energy loss with increasing kinetic energy. The number of developed grains is reduced until they can no longer be distinguished against the background.

With the exception of an emulsion especially designated as having a characteristic composition (see Sec. 2-1), the variation in sensitivities among the varied types of emulsions is primarily due to the addition of different dye sensitizers. The sensitivity of a nuclear emulsion also

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depends directly upon the grain size, the larger grain emulsions having the greater sensitivity and suffering less from fading.

Tables 2-III, 2-IV, and 2-V give the sensitivities of Ilford, Kodak Ltd., and Eastman Kodak emulsions for electrons, mu-mesons, protons, deuterons, and alpha-particles.*

TABLE 2-III

The maximum detectable energies in Mev of various particles in Ilford nuclear emulsions

Particle	D1	E1	C2	B2	G5
Electron	...	...	0.03	0.07	all
mu-Meson	...	2	5.5	0.14	all
Proton	...	20	50	120	all
Deuteron	...	40	100	240	all
Alpha-particle	low	500	1500	all	all

TABLE 2-IV

The maximum detectable energies in Mev of various particles in Kodak Ltd. nuclear emulsions

Particle	NT1a	NT2a	NT4
Electron	...	0.1	all
mu-Meson	2	20	all
Proton	20	200	all
Deuteron	40	400	all
Alpha-particle	500	all	all

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*Beiser, A., "Nuclear Emulsion Technique," Revs. Mod. Phys., 24 275 (October 1952).
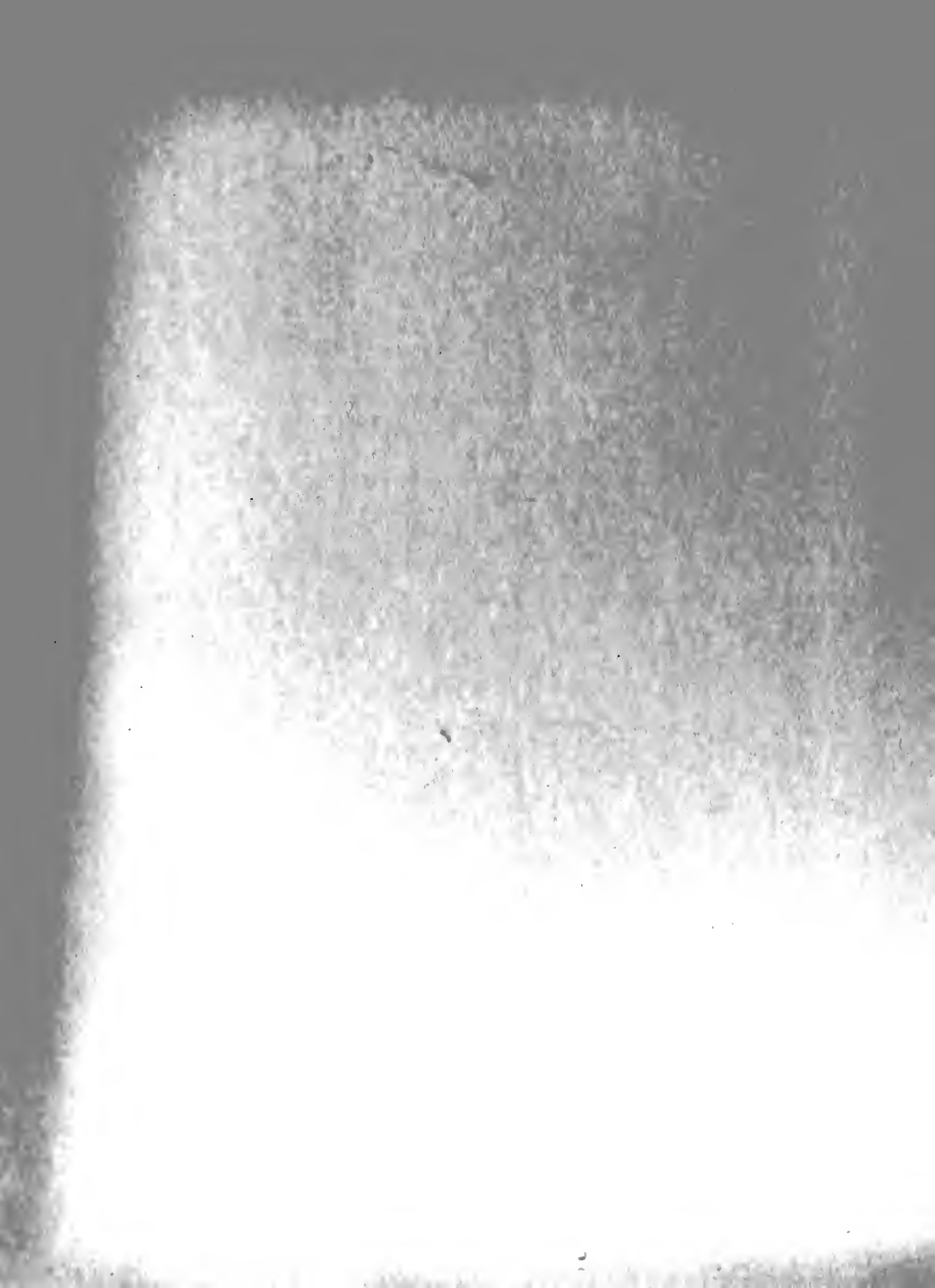
TABLE 2-V

The maximum detectable energies in Mev of various particles
in Eastman Kodak nuclear emulsions

Particle	NTC	NTC3	NTA	NTB	NTB2	NTB3
Electron	...	...	...	0.03	0.2	0.4
mu-Meson	...	1	2	6	40	85
Proton	...	1.5	3	8	50	110
Deuteron	...	20	40	100	750	1500
Alpha-particle	low	100	200	800	all	all

From the data of these sensitivity tables it should be readily
apparent that the different emulsions are associated with the detection
and investigation of specific particles. The NTC plate, since it does
not record proton tracks and records alpha particle trajectories poorly,
is serviceable as a medium for the registration of fission fragment
tracks. The equivalent Ilford plate is the type D1. The Ilford B2
(or Kodak Ltd. NT2a) is an extremely sensitive emulsion and records tracks
of alpha particles and energetic protons. The Ilford C2 is of finer
grain than B2 and is thus suited for more accurate track-length measure-
ments. According to Powell this plate is especially adaptable to auto-
radiography. The equivalent Eastman Kodak plate is type NTB. Either
the NTC3 or NTA emulsion is serviceable for differentiation of alpha
particle and proton tracks for the latter record poorly. Equivalent
plates are the Ilford E1 and the Kodak Ltd. NT1a. For the registering
of high velocity particles of low ionizing power, the Kodak Ltd. NT2a
plate is especially recommended. The NTB3 or NTB2 plates display greater
sensitivity for mesons and are thus particularly fitted for use in cosmic
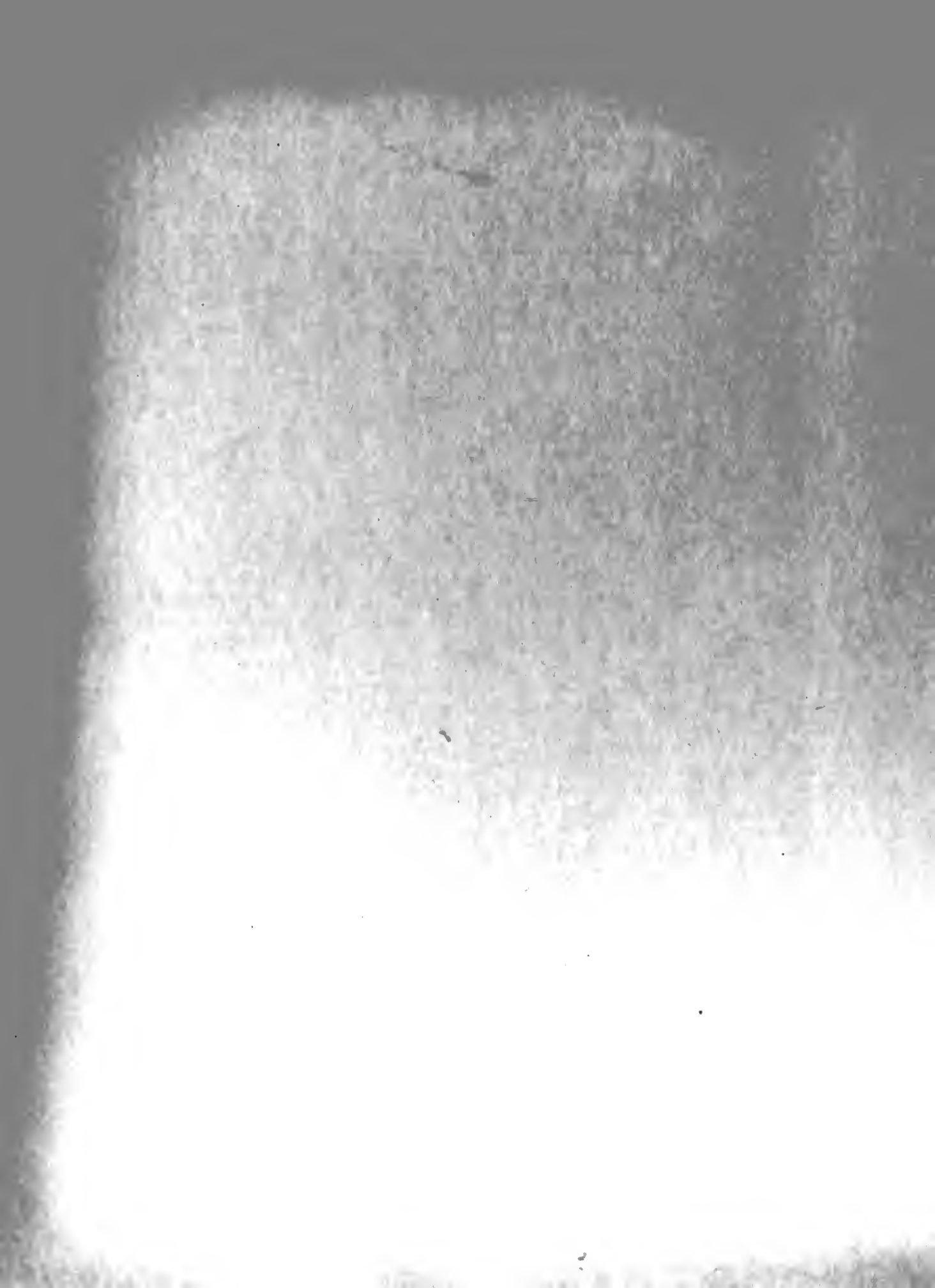
ray research. This feature of fast accumulation of a large cosmic ray background would in itself make them unsuitable for other applications. The Ilford G5 and the Kodak Ltd. NT4 emulsions are sensitive to minimum ionization, i.e., fast electrons.

2-3 FACTORS AFFECTING EMULSION PROPERTIES

The effect of atmospheric humidity on emulsion density has already been discussed (see Sec. 2-1). Humidity also exerts a slight influence on nuclear emulsion sensitivity. The latter, however, varies principally with temperature. The emulsion melting point is somewhere above 45° C., and the plates should, of course, not be exposed to excessive heat. An optimum exposure temperature for maximum sensitivity exists for all emulsions in common use. This temperature is found to be in the vicinity of 20° C., according to Beiser (1952). The maximum sensitivity for the Ilford G5 emulsion has been studied by Lord (1951) and determined to be around 0° C. with slightly decreased sensitivity at higher and lower temperatures. If an emulsion is employed at other than optimum temperature, the reduced sensitivity must be taken into account in interpreting tracks.

There is little danger of interference by pressure effects in present-day emulsions. Manufacturers have added a thin coating of transparent gelatin to the surface of their plates as a protection against abrasion and mechanical shock.

Direct contact with certain metals, such as copper, aluminum, and iron, fogs or even decomposes the emulsion. To prevent accidental union, experiments with nuclear emulsions should not be conducted at too close

proximity to loose metals.

The phenomenon of latent image fading is markedly influenced by time of storage, atmospheric conditions, temperature, and emulsion composition. Beiser (1951) has investigated the change in fading rate with time of delay between exposure and development under a constant set of storage conditions. He has found the fading coefficient* to vary according to the relation

$$F = 1 - \exp(-ct).$$

Fig. 2-1 is a plot of F as a function of t for various values of c, a constant dependent upon the emulsion and the storage conditions.

The part played by the atmospheric humidity on latent image fading is particularly important. Albouy and Faraggi (1949) have investigated the variation in fading with the relative humidity of the atmosphere surrounding the emulsion. Results which they obtained indicate strongly that the rate of fading is an exponential function of the quantity of moisture retained by the gelatin. If the rate of disappearance of the number of grains in a given track length after storage before development for a time t is defined by $-dN/dt$, the fading produced under otherwise fixed conditions has been found to vary according to the exponential relation**

$$-dN/dt = Ce^{-k/T}$$

where T is the absolute temperature of storage and C and k are constants.

Both the pH and the halide grain size affect the susceptibility of

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*Given by $F = (D_o - D_f)$, where D_f is the photographic density after delayed development following exposure and D_o is the density of the control image made immediately before development.

**Confirmed by the experiments of Albouy and Faraggi (1949).
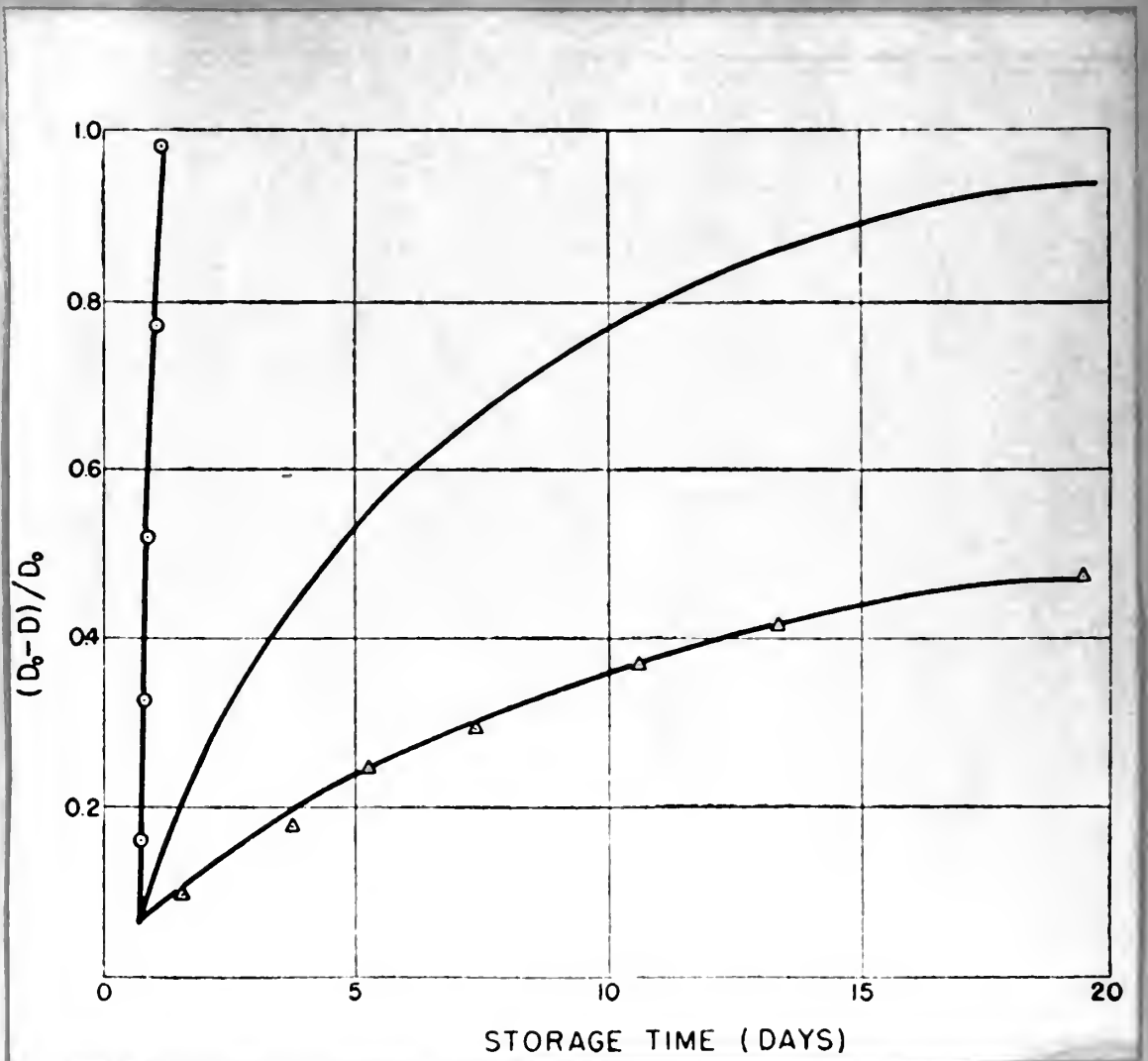
Fig. 2-1. The variation of the fading coefficient with time of storage under various conditions (Beiser, 1951). Experimental points from Yagoda and Kaplan (1948). The upper curve refers to storage at saturation humidity, and the lower curve to normal laboratory conditions. (Beiser, A. 1952. Rev. Mod. Phys. 24, 277).

an emulsion to fading. In general, the lower the pH and the smaller the grains the more rapid the fading (Albouy and Faraggi, 1949).

CHAPTER III

TRACK EVALUATION

3-1 GENERAL

Ionizing particles which happen to enter nuclear emulsions leave behind a number of silver halide crystals which have been so altered that, upon development and subsequent viewing under the microscope, they appear in the form of lines of black grains of colloidal silver (like irregular black beads on an invisible thread) and identify the trajectories of the particles. The more strongly ionizing the particles, the more numerous are these grains; and the greater their initial energies, the larger the resulting tracks. A considerable amount of theoretical and experimental work has been devoted to establishing precise relationships, which connect these quantities. Assuming then that circumstances are favorable and a track beginning and ending in the emulsion is observed the problem is to identify the particle which made the track (mass and charge) and to measure its initial energy. These types of measurements can be supplemented by more elaborate methods, for example, those making use of the multiple small-angle scattering of light particles or by the counting of delta rays which are secondary electrons produced in the ionizing process and of sufficient energies to have observable ranges in an emulsion. Auxiliary techniques, such as those utilizing the deflection of charged particles in an intense magnetic field, are frequently of value in specialized applications.

3-2 SPECIFIC ENERGY LOSS

The grain density of the track produced by a particle traversing
a nuclear emulsion is usually measured in terms of the number of devel-
oped silver grains per unit path length. In general, grain density
depends upon the amount of ionization produced in the halide grains and
upon their sensitivity. If the latter is taken to be constant, the grain
density is a function of the rate of energy loss per unit distance, $-dE/dx$,
which is proportional to the number of ions produced per unit length of
path. This specific energy loss (also called specific ionization) varies
directly with the square of the charge of the incident particle, inversely
as the speed of the latter, and directly with the number of electrons
per cubic centimeter of the stopping material.

A formula which permits the computation of the rate of energy loss
of electrons per unit distance as a function of energy has been given
by Livingston and Bethe (1937) from a theoretical quantum mechanical
derivation as

$$- \frac{dE}{dx} = \frac{4 \, z^2 e^4 N}{mv^2} \left\{ Z \left[\ln \left(\frac{2mv^2}{I} \right) - \ln \left(1 - v^2/c^2 \right) \right] - C_k \right\} \quad (3-1)$$

where ze is the charge of the particle and v its velocity, N the atomic
density, Z the atomic number of the atoms of the stopping material, I
the effective ionization potential, m the mass of the electron, and C_k
a correction term which depends only upon the absorber and the speed of
the incident particle. It must be applied in case v is comparable with
the velocity of the K electron of the stopping material but large com-
pared with those of the other orbital electrons. I is usually treated
as an empirical constant to be fixed by the substitution of known data.

For alpha particles from radionuclides, for example, in standard air the values Z = 7.22 (an effective weighted mean) and I = 80.5 ev give a good fit to observed data (Halliday, 1950). For all except the very highest speeds, the relativistic correction terms involving v^2/c^2 nearly cancel; we can show this by expanding $\ln (1 - v^2/c^2)$ in a power series. According to Halliday (1950), for a 10 Mev alpha-particle in standard air, the first term in the square brackets is 5.1, while the sum of the last two terms is only 4.5×10^{-4}. This means that if the speed is reasonably great ($2mv^2/I > e$, where e is here the base of natural logarithms), the main variation of -dE/dx with v is in the unbracketed term. Thus -dE/dx varies inversely with v^2 under such circumstances, and as a result the grain density of a track will increase in the direction of motion of the particle.

At low energies (<1 Mev for protons and <0.1 Mev for alpha-particles) the ionization density must drop again, going to zero as the particle stops. Equation (3-1) does not show this; the reason is that in deriving the expression, no consideration was given to the random capture and loss of electrons that occurs as the particle slows down. For a more critical discussion of Eq. (3-1) the reader is referred to the paper of Wheeler and Ladenburg (1941).

In Fig. 3-1 specific energy loss curves (according to Eq. (3-1)) in Mev per centimeter of air path for various particles are drawn to the same scale. To convert the curves to energy loss in an emulsion they must be multiplied by the stopping power of the emulsion relative to air (see Sec. 3-4). These theoretical specific ionization curves for each particle are displaced from each other because -dE/dx is plotted
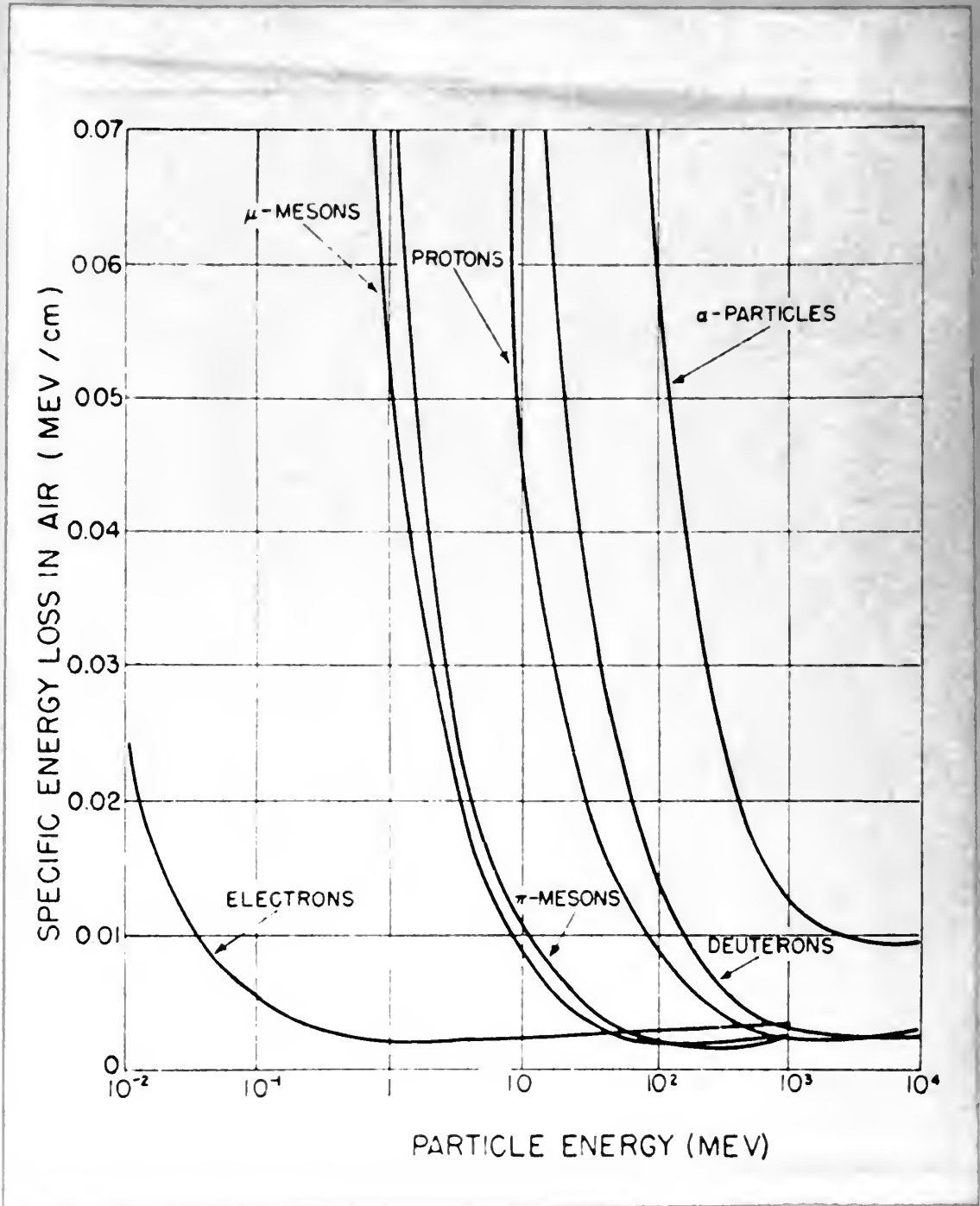
Fig. 3-1. Specific energy loss of various particles in air as a function of energy. (Beiser, A. 1952. Revs. Mod. Phys. 24, 279).

in terms of particle energy, which is a function of mass. Note the broad minimum which occurs at roughly 2 $m_0 c^2$ for any kind of particle, where m_0 is its rest mass. The ionization minimum, for example, occurs near 2000 Mev for protons and 8000 Mev for alpha-particles. Since the minimum specific energy loss for alpha-particles is four times that for singly-charged particles, any track exhibiting less than four times minimum grain density must be due to one of the latter. Tracks with grain densities above four times minimum may, of course, be due to either, other methods of analysis being required for identification of particle charge. After the minimum, the energy loss rises logarithmically with particle energy.

Since the formation of a latent image is based on an ionization process, it should be possible to express grain density as a function of specific energy loss (Blau, 1949). Such a relationship would be of great importance to the nuclear physicist employing the photographic technique for registration of charged particles. Differentiation of nuclear particles by observation of grain spacing along the developed track is possible since all grains are not of equal sensitivity and require different degrees of energy expenditure for latent image formation. Considering the complexity of the photographic process, it is obvious that we cannot expect a linear relationship between the specific energy losses of particles at various points on their trajectories and the corresponding grain densities. Determinations with Ilford G5 emulsions have shown that for low dE/dx values a direct proportionality does exist (Fowler and Perkins, 1951). However, the rate of energy loss of high velocity particles is affected by the polarization of the medium; this means

that for high dE/dx values the proportionality relationship is no longer true. The phenomena of space charge and recombination which are due to the high ion density prevailing during extremely short periods within the affected grains must be taken into account. The rapidity of liberation of electrons by the passage of high-velocity charged particles may lead to inefficiency in the photographic process. Electrons should be freed at such a rate that the ionic movement of the silver ions can keep pace with the electronic process and thus neutralize the electrons as fast as they become trapped.

The conditions here can be compared with those in strongly-ionized electrolytes. Debye and Hückel (1923) solved the latter problem by assuming that the potential of an ion cloud surrounding an isolated ion is proportional to $N^{\frac{1}{2}}$, where N is the number of ions present. Blau (1949) has proposed the following dependence of the grain density on the energy loss

$$dN/dx = c\left\{1 - \exp\left[-b(dE/dx)^{\frac{1}{2}}\right]\right\}, \quad (3\text{-}2)$$

N (x) being the total number of grains over the residual range x (counted from the end of the track) dN/dx the number of grains per unit track length and c and b empirical constants characteristic for a certain type of emulsion and processing conditions. The constant c represents the actual number of grains present per unit length in the undeveloped emulsion and b is a measure of the efficiency with which the liberated electrons due to the incident particle render the halide grains developable. Blau in her confirmation employed a value of $b \cong 2.5$ and $c = 4$ for the Ilford C2 plate.

The measurement of grain density of a track is complicated by grain

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saturation if densities above 200 grains per 100 microns are employed. It is then impossible to evaluate dE/dx for such tracks on the basis of grain counts; other methods are available in certain cases, however, such as the evaluation of the delta-rays produced (Sec. 3-6).

3-3 RANGE-ENERGY RELATIONSHIPS

The main portion of the energy loss suffered by charged particles traversing matter goes into production of ions through the interactions of the bombarding particles with the orbital electrons of the stopping material. Although random collisions and loss of discrete amounts of energy are involved, the process may be considered as continuous when taken over a finite path length. The exact form of the relationship between the energy and range of a given particle in a stopping material must be known in order to interpret range measurements in terms of the initial energies of the particles involved.

In principle, this relationship can be calculated by integrating Eq. (3-1) for energy loss, provided proper values of the average ionization potentials of the atoms are inserted. The range of a particle of initial energy E is given by

$$R(E) = \int_0^E \frac{dE}{(-dE/dx)} \qquad (3-3)$$

Combining Eqs. (3-1) and (3-3) gives

$$R = (M/z^2)f(v) \qquad (3-4)$$

where M is the mass, z the charge, and v the velocity of the particle. If the range-energy relation for one particle is known, the relations for particles of different mass are known. If $R_p(E)$ is the range of a proton

of energy E, then the range of a singly-charged particle of mass M and energy E is equal to M/M_p times the range of the proton of same velocity, i.e., of energy $E \frac{M_p}{M}$

$$R_M(E) = \frac{M}{M_p} R_p \left(E \frac{M_p}{M}\right). \qquad (3-5)$$

Based on the above considerations useful deductions of a general nature can be made. For example, if we consider a proton and a deuteron of the same speed, the energy of the former is half that of the latter. Since the particles carry the same charge $\neq$ e, the loss in energy of the deuteron will be twice that of the proton for a given reduction in speed. It follows that the distance travelled by the deuteron for a given change in speed is twice that of the proton, and the result is true irrespective of the particular values of the speed. The range of a deuteron is thus twice that of a proton of half its energy. Similarly, the range of a triton is three times that of a proton of a third of its energy. A range-energy curve for deuterons and tritons in a given medium can thus be deduced if the corresponding curve for protons is available.

The range of particles of M proton masses and charge z can also be derived from the proton relation after a correction to take into account the capture and loss of electrons which occur when the particle slows down to atomic electron velocities. Thus the range of an alpha-particle of energy E would be, with z = 2,

$$R_\alpha(E) = \frac{1}{4} \frac{M_\alpha}{M_p} R_p \left(E \frac{M_p}{M_\alpha}\right) \neq \delta \qquad (3-6)$$

where δ = 0.20 cm. in air; in the emulsion δ is roughly equivalent to one micron. This correction is relatively less important at higher energies.

Livingston and Bethe (1937) have accurately evaluated the integral

of Eq. (3-3) for protons in air up to energies of 15 Mev. Smith (1946) by using the equation

$$R = R(15) + \int_{15}^{E} dE/(-dE/dx) \qquad (3-7)$$

has extended the computation to 10 Bev. The range-energy curves illustrating these theoretical results are given in Figs. 3-2 and 3-3. By multiplying the range values by the stopping power of emulsion relative to air (Sec. 3-4) these curves may be applied to nuclear emulsions.

Extensive experiments have established the range-energy relations for protons, alpha-particles, and deuterons. The early results of Lattes, Fowler, and Cüer (1947) were improved upon by several investigators and extended to higher energies by Bradner et al. (1950). The former authors employed Ilford B1 emulsions and the latter C2 emulsions in their work. No appreciable change is found between different batches of emulsion of the same type, but the stopping powers of type Ilford E1, Ilford G5, and Kodak Ltd. NT2a are respectively 0.3 per cent lower, 1 per cent higher, and 1.8 per cent higher than that of Ilford C2 (Bradner et al., 1950, Rotblat, 1950). Plates in equilibrium with the atmosphere at average pressure and humidity exhibit ranges increased by three to four per cent. This effect is due to the absorption of moisture by the gelatin of the emulsion.

The measurements of Lattes et al. (1947a), made using particles produced in nuclear transmutations, are given in Table 3-I for protons and alpha-particles up to 13 Mev. According to Beiser (1952), the accuracy of these figures is ± two per cent above 2 Mev. Included is an extrapolation of the results to 35 Mev, with a believed accuracy of ± eight per cent. Table 3-II gives the experimental values of Bradner et al.
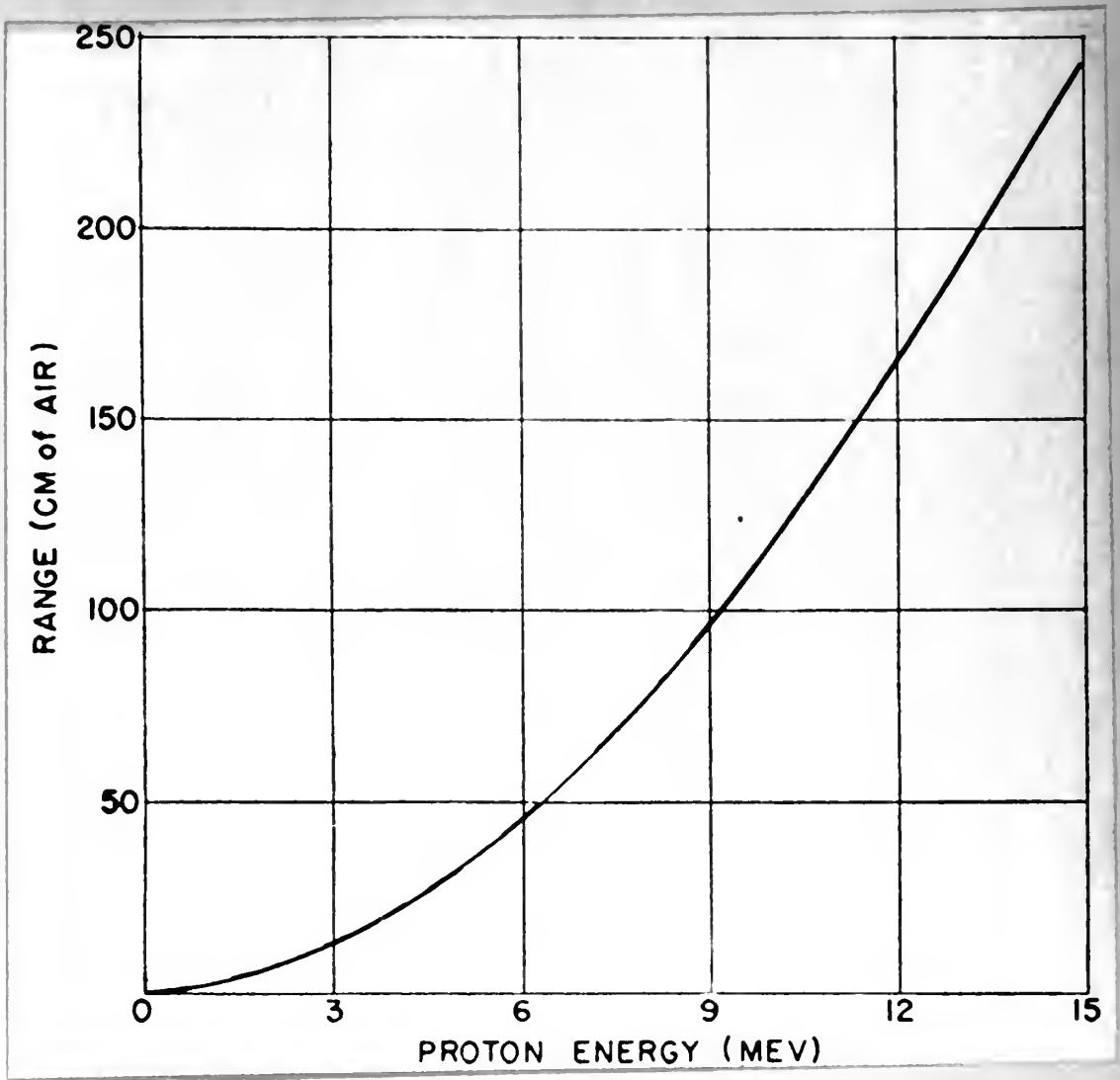
Fig. 3-2. Theoretical range-energy curve for pro-
tons in air to energies of 15 Mev - data from Livingston
and Bethe, 1937. (Beiser, A. 1952. <u>Rev</u>. <u>Mod</u>. <u>Phys</u>. 2<u>l</u>,
281).
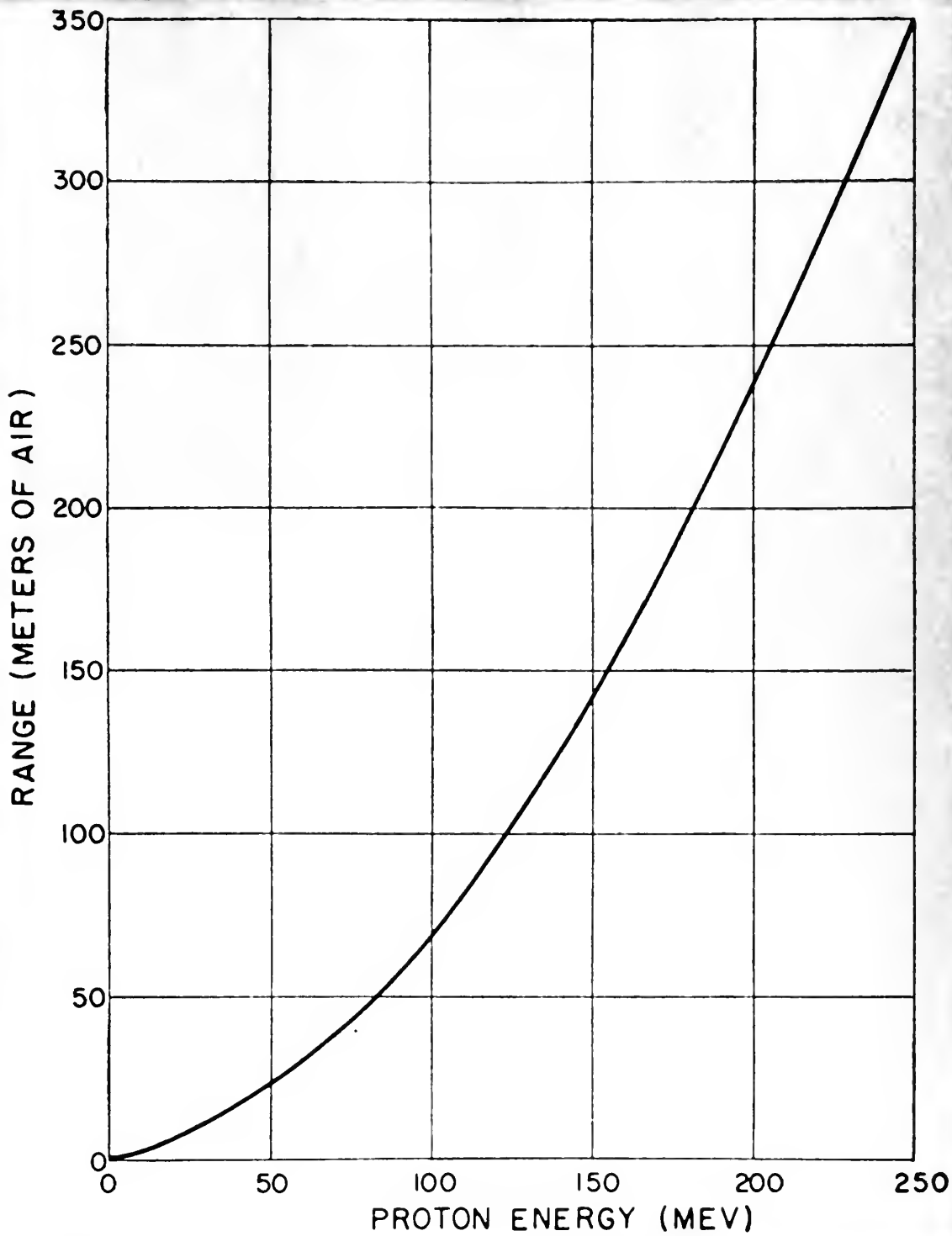
Fig. 3-3. Theoretical range-energy curve for protons in air to energies of 250 Mev - data from Smith, 1946. (Beiser, A. 1952. Revs. Mod. Phys. 24, 281).

(1950) for protons between 7.8 and 39.5 Mev obtained from the Berkeley
cyclotron. The probably reliability of the extrapolated values of Table
3-I is indicated by the close agreement with the experimental values of
Table 3-II. The range-energy relations for alpha-particles and deuterons
in the Kodak NTB emulsion obtained by Gailar et al. (1952) are presented
in Table 3-III and Table 3-IV, respectively. Natural alpha-emitters
and particles accelerated in the Purdue University cyclotron were used
in the determinations. It is of interest to note that the ranges in the
NTB emulsion are practically identical with those reported in the Ilford
B1 and C2 emulsions. There is also substantial agreement with the results
of Steigert et al. for the Kodak NTA emulsion (Table 3-V). Natural
alpha-particles from polonium and thorium-active deposit sources and the
two long-range alpha-groups in the Al^{27} (d,α) Mg^{25} reactions, observed
at various angles under conditions of good geometry, were used for
determination of the experimental values of Table 3-V.

TABLE 3-I

Range-energy relationship for protons and alpha-particles in Ilford B1
emulsions (measured to 13.0 Mev by Lattes et al., 1947a, and
extrapolated by Camerini and Lattes, 1947)*

Energy Mev	Proton range microns	Alpha-particle range microns
0.5	5.5	2.1
1.0	14.5	3.52
1.5	26.0	4.96
2.0	40.0	6.54
2.5	56.5	8.34
3.0	75.0	10.38
3.5	97.0	12.60
4.0	120.5	15.0
4.5	146.0	17.65
5.0	173.0	20.5
5.5	202.0	23.6
6.0	234.0	26.7
6.5	269.0	30.0
7.0	306.0	33.6
7.5	345.0	37.5
8.0	385.0	41.4
8.5	426.0	45.3
9.0	469.0	49.5
9.5	515.0	53.7
10.0	564.0	58.0
10.5	614.0	62.6
11.0	666.0	67.7
11.5	720.0	72.7
12.0	776.0	77.8
12.5	834.0	83.4
13.0	895.0	...
15.0	1135	117
20.0	1870	201
25.0	2750	315
30.0	3760	464
35.0	4925	653

*Beiser, A., "Nuclear Emulsion Technique," Revs. Mod. Phys., 24, 282 (October 1952).

TABLE 3-II

Experimental values of the range-energy relationship for protons
in dry Ilford C2 emulsions (Bradner et al., 1950)*

Energy Mev	Range microns
7.8	389
16.4	1358
17.6	1465
22.3	2244
25.6	2849
28.2	3369
33.5	4597
39.5	6123

*Beiser, A., "Nuclear Emulsion Technique," Revs. Mod. Phys., 24,
282 (October 1952).

TABLE 3-III

Range-energy relation for alpha-particles
in the Kodak NTB emulsion *

Energy Mev	Range microns
2.87	10.3
5.30	21.5
5.42[a]	23.0
5.68[a]	25.5
6.04[a]	28.8
6.28[a]	29.6
6.77[a]	33.6
8.78[a]	48.2
8.78[b]	46.9
8.78[c]	48.0
12.66	85.2
15.73	117.0
17.76	141.0

a. soaked plate
b. vacuum-exposed
c. Ilford C2 emulsion

*Gailar, O. et al., "Range-Energy Relations for Alpha-Particles and
Deuterons in the Kodak NTB Emulsion," Rev. Sci. Instr., 24, 126 (1953).
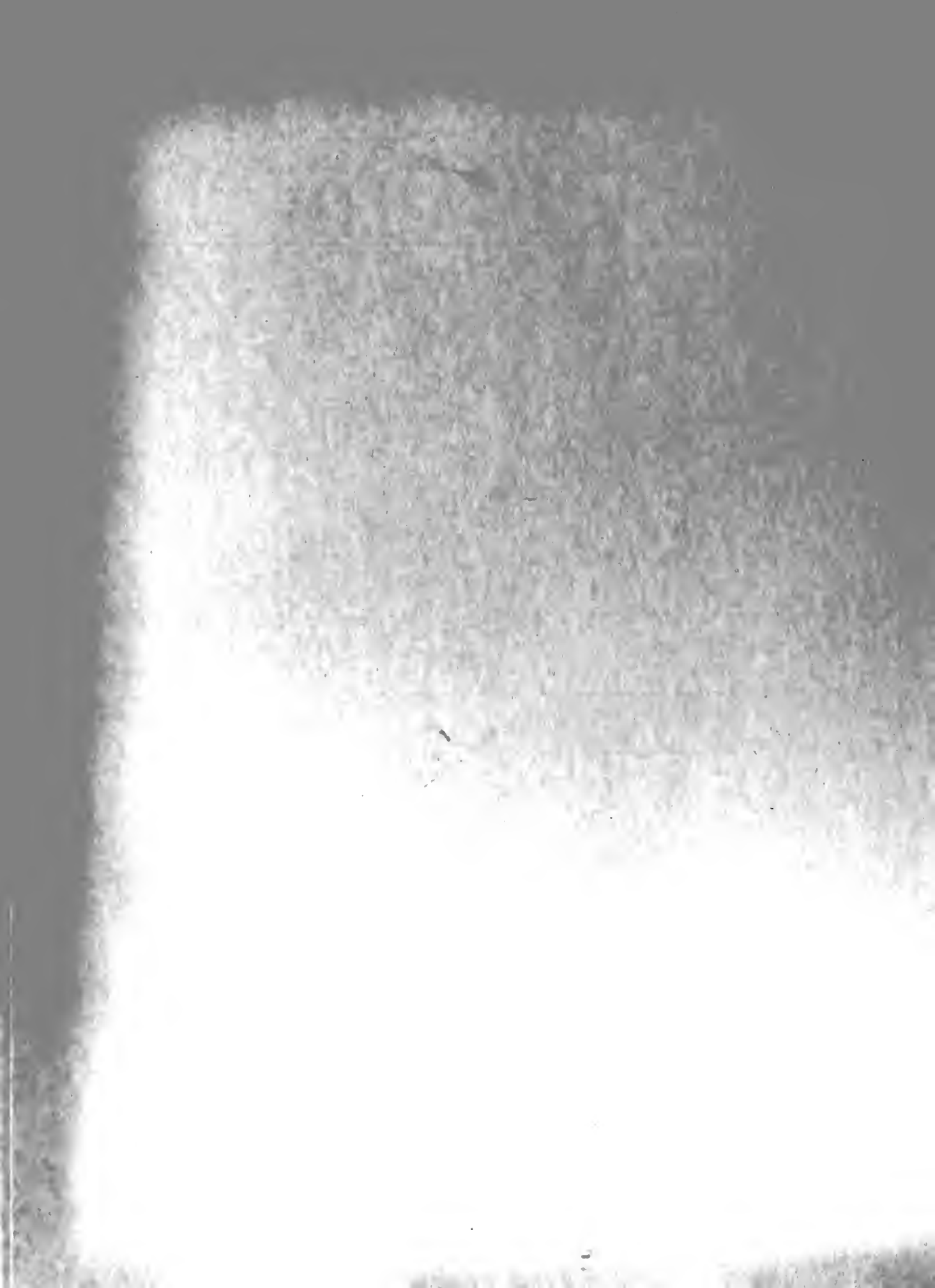
TABLE 3-IV

Range-energy relation for deuterons in the
Kodak NTB emulsion *

Energy Mev	Range microns
1.99	27.2
3.56	62.4
5.74	139.8
7.46	215.0
9.06	294.9

*Gailar, O. et al., "Range-Energy Relations for Alpha-Particles and
Deuterons in the Kodak NTB Emulsion," Rev. Sci. Instr., 24, 127 (1953).

TABLE 3-V

Range-energy relation for alpha-particles
in the Kodak NTA emulsion *

Energy Mev	Range microns
5.30	21.2
6.06	26.8
8.78	47.1
13.77	91.3
13.83	96.6
13.87	97.4
14.34	101.6
14.36	103.9
14.38	103.0
14.87	109.9

*Steigert, F. E. et al., "Alpha-Particle Range-Energy Curve for
Kodak NTA Emulsions," Phys. Rev., 83, 474 (1951).

At high velocities, when plotted on logarithmic scales, the range-energy curves are very nearly straight lines (Fig. 3-4). From such a set of curves it is possible to calculate directly the range-energy relationship for particles of any mass and charge. For example, Vigneron (1953) gives a semi-empirical treatment of the range-energy relation in excellent agreement with experiment. After a brief review of previous methods of computing the range-energy relationship, a general method is described in detail. For particles of less than one Mev the range-energy calculation is based on experimental energy-loss data. For energies greater than one Mev it is shown that the rate of energy loss can be expressed as a function of two parameters which can be calculated in the range 13 Mev $>$ E $>$1 Mev and which are constant for E $>$13 Mev. The range-energy relationship is obtained by the integration of these theoretical energy-loss curves; only three experimental points are required to provide values of the requisite constants. The range-energy relationship for protons in the Ilford C2 emulsion has been calculated for E = 0.1 Mev to E = 220 Mev and is in excellent agreement with published values. Formulae are given for obtaining the range-energy relationship for alpha-particles, tritons, and deuterons from the data for protons. Such a simple approximate formula, with an accuracy of the order of two per cent, for protons between 14 and 30 Mev has been presented by Bradner et al. (1950) as

$$E_{Mev} = 0.251 R_\mu^{0.581} \qquad (3-8)$$

which, as checked indirectly by Gottstein et al. (1951), can probably be safely extrapolated to energies as high as 200 Mev.

It can be concluded that a precise measurement of range yields an
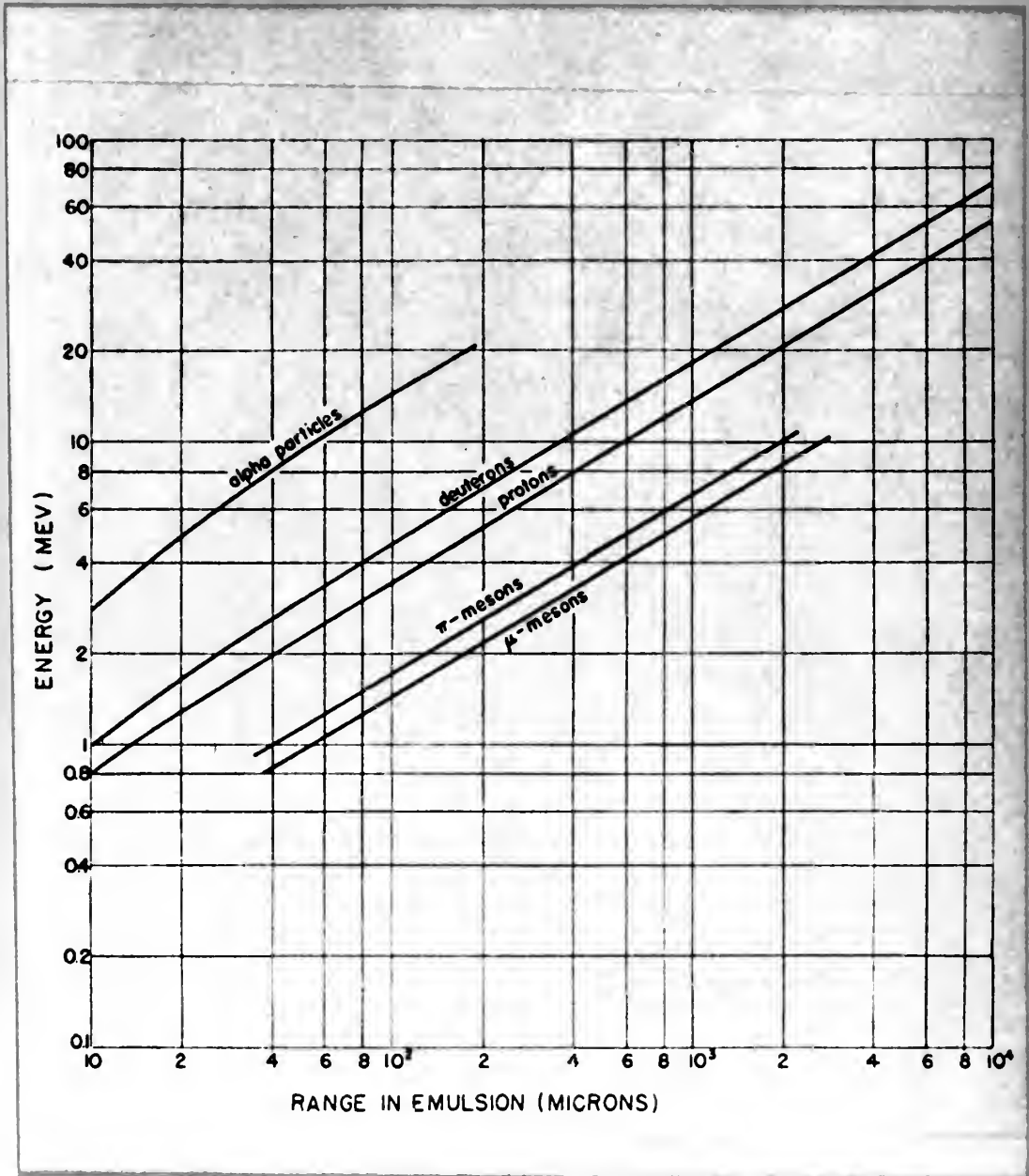
Fig. 3-4. Range-energy relationship in nuclear emulsions for various particles. (Beiser, A. 1952. Revs. Mod. Phys. 24, 283).

accurate determination of particle energies. This holds true for the
mean range of a group of monokinetic identical particles if it is assumed
that any uncertainties present are the result of experimental errors.
However, for an individual track, a slight uncertainty is attributable
to straggling, which, while of the order of only one per cent in air,
becomes of greater importance in the emulsion. Statistical fluctuations
in the slowing down process due to the heterogenous distribution of halide
grains in the emulsion, leading to regions of lower than average grain
concentration, and the finite size and relatively small number of grains
making up a track cause the straggling uncertainty in the precise value
of the range. According to Goldschmidt-Clermont (1954), straggling amounts
to ten per cent for 1 Mev protons with a decrease to two per cent for 5
Mev protons. At high energies, straggling can usually be neglected being
no greater than the uncertainty of the range-energy relation itself.

3-4 STOPPING POWER

Beiser (1952) defines the stopping powers of nuclear emulsions as the
ratios of the ranges of given particles in air at STP to their ranges in
emulsion for specific energy intervals. Provided the stopping power
of the recording medium relative to air is known as a function of the
velocity, the abundant experimental and theoretical data on range-energy
relations for ionizing particles in air can be utilized in evaluating the
energy of particles from track length measurements.

A theoretical expression for the relative atomic stopping power of
an element of atomic number Z is given by

$$s = \frac{B}{B_{air}} \cong \frac{Z}{Z_{air}} \frac{\ln(2mv^2/I)}{\ln(2mv^2/I_{air})}. \qquad (3-9)$$

In order to calculate the stopping power of a photographic emulsion, s for the constituent atoms of the emulsion must be known. A method of computation of stopping power for chemical compounds has been presented by Webb (1948) and is here reviewed. The relative atomic stopping power of one substance, as compared with that of another taken as standard, may be defined by the relation

$$R_o/R = (N/N_o)s/s_o \qquad (3\text{-}10)$$

where R_o is the range in air for a particle and R the range in the test substance, N_o is the effective number of atoms per cubic centimeter at STP based upon mean atomic weight, and N is the number of atoms per cubic centimeter of the test substance. The quantity s/s_o is the atomic stopping power of the substance relative to that of air. Since in experimental work relative differential ranges for small energy increments are usually measured, i.e., $\Delta R_o/\Delta R$, and since s_o for air is taken as unity, we shall change Eq. (3-10) to the form

$$\Delta R_o/\Delta R = (N/N_o)s. \qquad (3\text{-}11)$$

The quantity N may be replaced by its equivalent value expressed in terms of density and atomic weight, i.e.,

$$N = kd/A; \qquad (3\text{-}12)$$

whence

$$\Delta R_o/\Delta R = n\sum_i N_i s_i/N_o . \qquad (3\text{-}13)$$

Here N_i is the number of atoms of the ith kind in each molecule with a stopping power of s_i, and n is the number of molecules of the compound per cubic centimeter, i.e.,

$$n = d/\sum_i N_i A_i . \qquad (3\text{-}14)$$

Since

$$N_o = kd_o /A_o, \qquad\qquad (3\text{-}15)$$

Eq. (3-13) can be more conveniently written in the form

$$\Delta R_o /\Delta R = (A_o d/d_o)\left(\sum_i n_i s_i /\sum_i N_i A_i\right), \qquad (3\text{-}16)$$

for purposes of calculation. Finally this relationship may be abbreviated to read

$$\Delta R_o /\Delta R = (A_o d/d_o)\sum_i p_i s_i /A_i, \qquad (3\text{-}17)$$

where $p_i = N_i A_i /\sum_j N_j A_j$ represents the fractional weight of each element contained in the compound.

Strictly speaking, the photographic emulsion is not a chemical compound but is actually a highly dispersed mixture of two compounds, gelatin and silver bromide. However, if we assume that such a mixture can be treated as a smoothed-over compound of the various constituents atoms, the relative stopping power of an emulsion may be calculated from Eq. (3-17), providing we know the atomic composition of the emulsion and the atomic stopping powers of the constituents involved. Livingston and Bethe (1937) have evaluated the atomic stopping powers of the elements hydrogen, carbon, and silver as a function of energy for alpha-particles and protons. These figures along with the values obtained therefrom by interpolation for the atomic stopping powers of bromine, nitrogen, oxygen, and air (Webb, 1948) are set down in Table 3-VI for various alpha-particle and proton energies.

TABLE 3-VI

Atomic stopping powers for various velocities and
particle energies (Livingston and Bethe, 1937)*

Alpha-particles (Mev)	Energy Protons (Mev)	Stopping Power s						
		Ag	Br	C	H	N	O	Air
2.07	0.52	2.25	2.07	0.940	0.260	1.02	1.10	1.0
4.66	1.17	3.08	2.68	0.932	0.224	1.02	1.10	1.0
8.30	2.09	3.43	2.94	0.921	0.209	1.01	1.10	1.0
12.95	3.26	3.64	3.10	0.914	0.200	1.01	1.09	1.0
18.60	4.70	3.76	3.19	0.908	0.194	1.00	1.09	1.0
33.21	8.36	3.93	3.30	0.899	0.186	1.00	1.08	1.0
51.90	13.06	4.04	3.38	0.892	0.181	0.99	1.08	1.0

*Webb, J. H., "Photographic Plates for Use in Nuclear Physics,"
Phys. Rev., 74, 522 (1948).

Inserting the values of s_i from Table 3-VI into Eq. (3-17) for a specific

emulsion enables the evaluation of $\triangle R_o /\triangle R$ at the various energies.

Such procedure has led to the values of relative stopping power of emul-

sion given in Table 3-VII.

TABLE 3-VII

Stopping power of emulsion*

Energy Mev Alpha-particles	Protons	$\triangle R_o /\triangle R$
2.07	0.52	1511
4.66	1.17	1764
8.30	2.09	1868
12.95	3.26	1930
18.60	4.70	1964
33.20	8.36	2009
51.90	13.06	2040
Extrapolated		
80	20	2065

*Webb, J. H., "Photographic Plates for Use in Nuclear Physics,"
Phys. Rev., 74, 523 (1948).

In Fig. 3-5 the integral stopping power R_o/R for both protons and alpha-particles is plotted as a function of energy in Mev (Webb, 1948). The values for plotting these curves were obtained as follows: Differential-range values in air ΔR_o over small energy intervals (2 Mev) were divided by the stopping-power values in Table 3-VII to obtain the equivalent differential ranges ΔR in emulsion. These latter values were then summed over discrete energy steps to obtain integral emulsion ranges R. The quotients of the integral-range values in air and in the emulsion give the integral stopping powers. The curves of Fig. 3-5, drawn for an emulsion containing 82 per cent silver bromide, might be expected to be similar to most commercial emulsions.

3-5 MASS DETERMINATIONS

A useful concept has been employed by Lattes et al. (1947b) for determining from grain density the relative masses of two types of particles of the same charge value in tracks ending in the emulsion. For singly charged particles, the grain density depends only on velocity, i.e.,
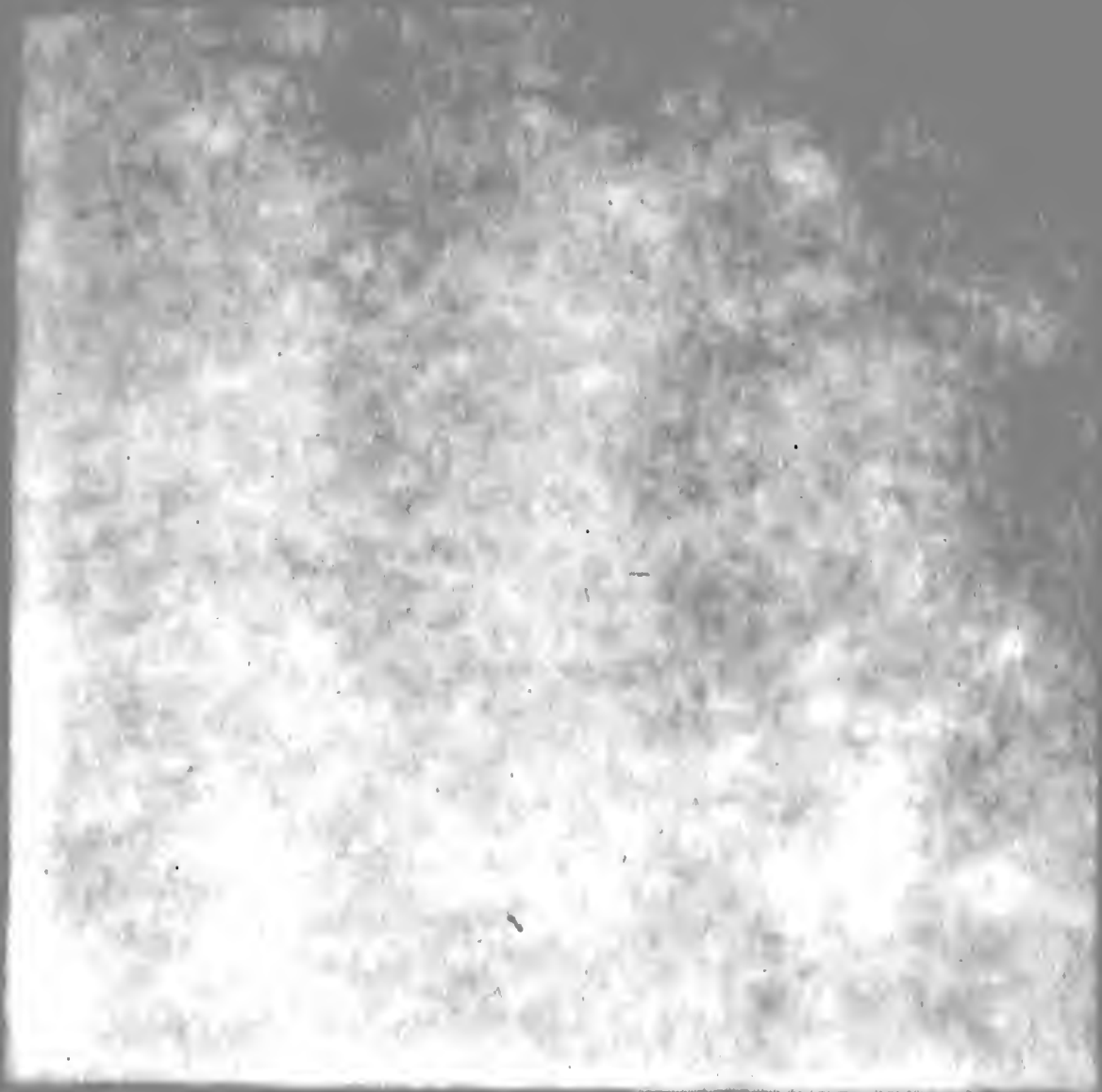
$$\frac{dN}{dR} = f(v). \qquad (3\text{-}18)$$

Now according to Eq. (3-4), the grain density may also be written as a function of residual range divided by M,

$$\frac{dN}{dR} = f(R/M). \qquad (3\text{-}19)$$

Integrating, we find that

$$\frac{N}{M} = f'(R/M) \qquad (3\text{-}20)$$

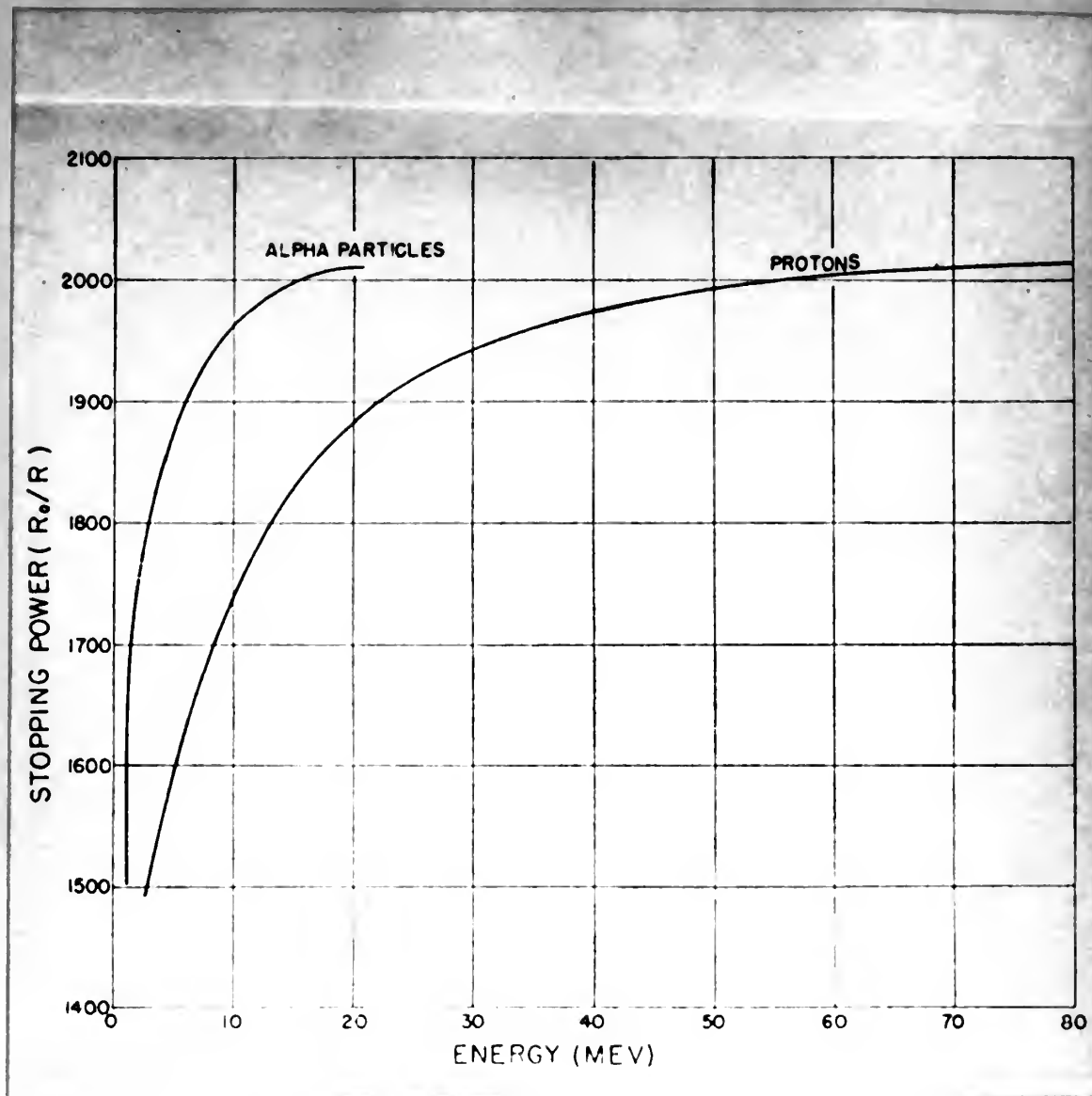Thus, for two different particles having different masses the total numbers

Fig. 3-5. Integral stopping powers of nuclear
emulsions as a function of particle energy. (Webb,
J. H. 1948. Phys. Rev. 7L, 522).

of grains N_a and N_b in the residual paths R_a and R_b will be in the ratio of the masses M_a and M_b, i.e.,

$$R_a/R_b = N_a/N_b = M_a/M_b \qquad (3-21)$$

The procedure is to find points along the two trajectories for which the grain densities are equal. Then the relative masses of the two particles will be in the ratio of the two residual paths, or, alternatively, in the ratio of the total numbers of grains in the two residual paths.

On a logarithmic plot of N versus R, Eq. (3-21) implies that a 45° line will cut the curves of the two particles in the region of the same grain density. If a particular emulsion has been calibrated in this way, singly charged particles can be identified on the basis of plots such as those in Fig. 3-6, taken from the data of Lattes et al. (1947b).

In determining masses by this method it is necessary that the N - R curves for the particles be obtained under the same conditions. The tracks being compared should be of the same age and subject to the same amount of fading. One should make sure that the development is uniform in depth, especially in the case of thick emulsion. If these precautions are observed so that inaccuracies in the use of this technique are minimized, comparative mass measurements of a good degree of precision are possible.

Beiser (1952) describes another method for use with tracks not terminating within the emulsion. The technique makes use of the variation in grain density to provide an estimate of the mass of the particle that produced the track. To identify a given path segment, the grain densities at two points as far apart in the emulsion (calibrated to give the appropriate conversion between grain density and specific
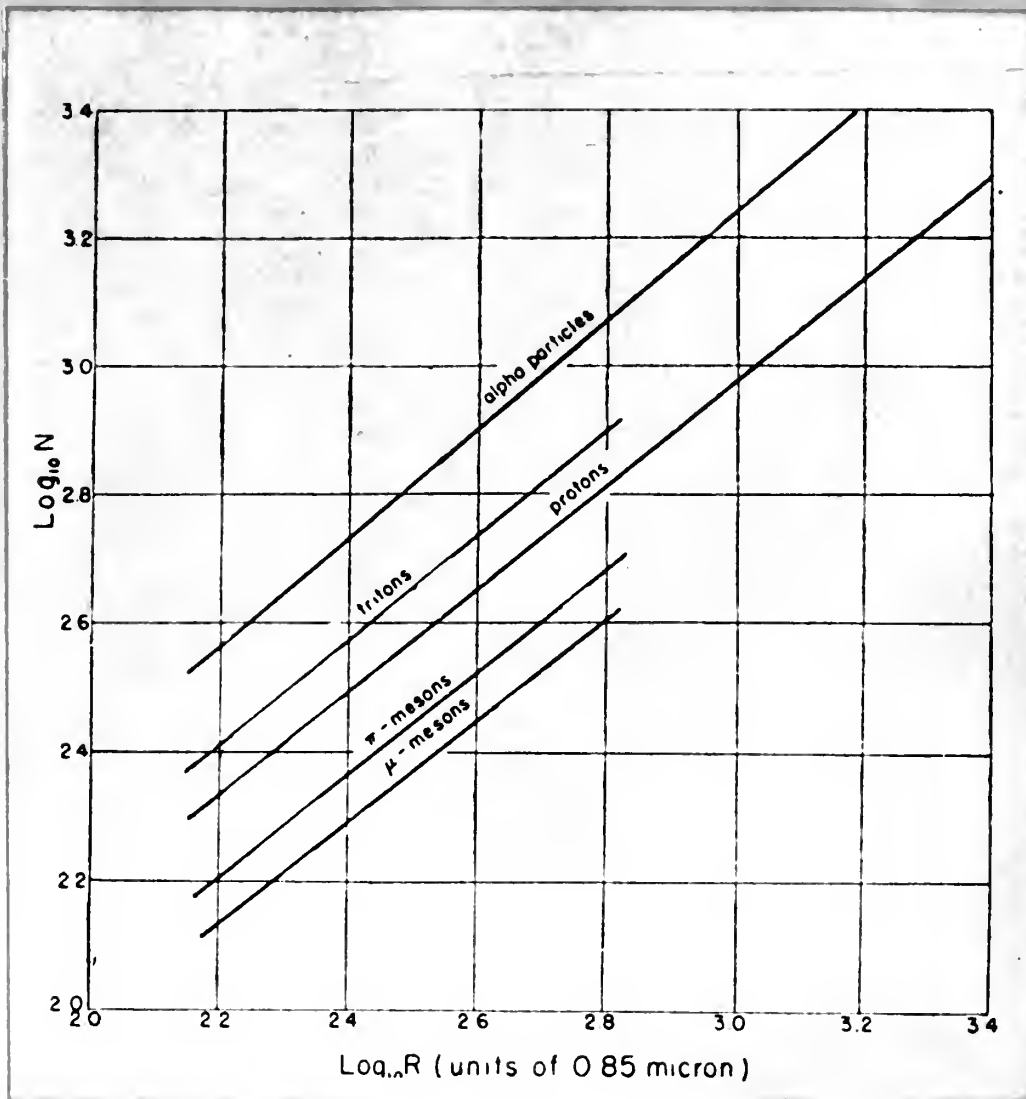
Fig. 3-6. The variation of the total number
of grains N with residual range R for tracks of various
particles in Ilford C2 boron-loaded emulsions.
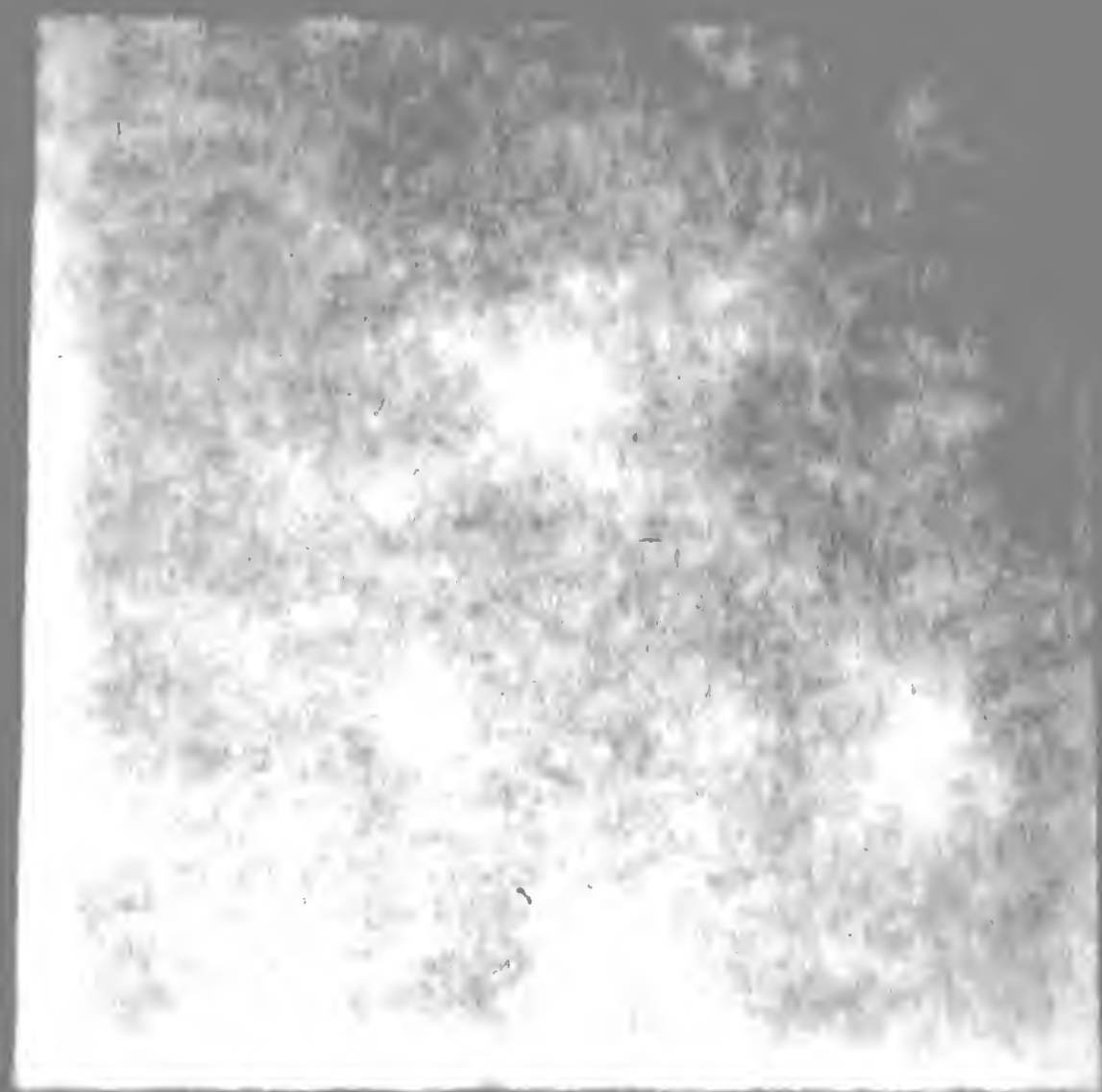(Beiser, A. 1952. Revs. Mod. Phys. 24, 287).

energy loss) as possible are determined. Then the smaller density, corresponding to the higher energy of the particle at that point, is used in conjunction with Fig. 3-7 to find the expected residual ranges of the various possible particles for that rate of energy loss. The various curves are followed down the appropriate distance corresponding to the track length between the two experimental points to obtain the expected specific energy loss for the higher observed grain density. The particle can then be identified; its energy can be obtained from range-energy curves (Fig. 3-4) by making use of the value of the expected residual range.

The grain counting methods described above are suitable for values of grain density below a certain ionization threshold, above which saturation effects become important and the subjective difficulties of counting make the results unreliable. Measurements of high ionization by grain counting can be successfully made over a limited range, selected by choosing less sensitive or under-developed emulsions. With emulsions of low sensitivity, however, we may expect a non-linear variation of grain density with energy loss so that careful calibration is necessary.

3-6 ALTERNATIVE METHODS OF IONIZATION MEASUREMENT

If the particle is heavy or comparatively slow, the track no longer consists of a linear array of silver grains but appears as solid filaments of developed silver whose thickness can be many times larger than the diameter of the grains in the emulsion. This width is due to a great number of secondary electrons ejected from the atoms of the emulsion
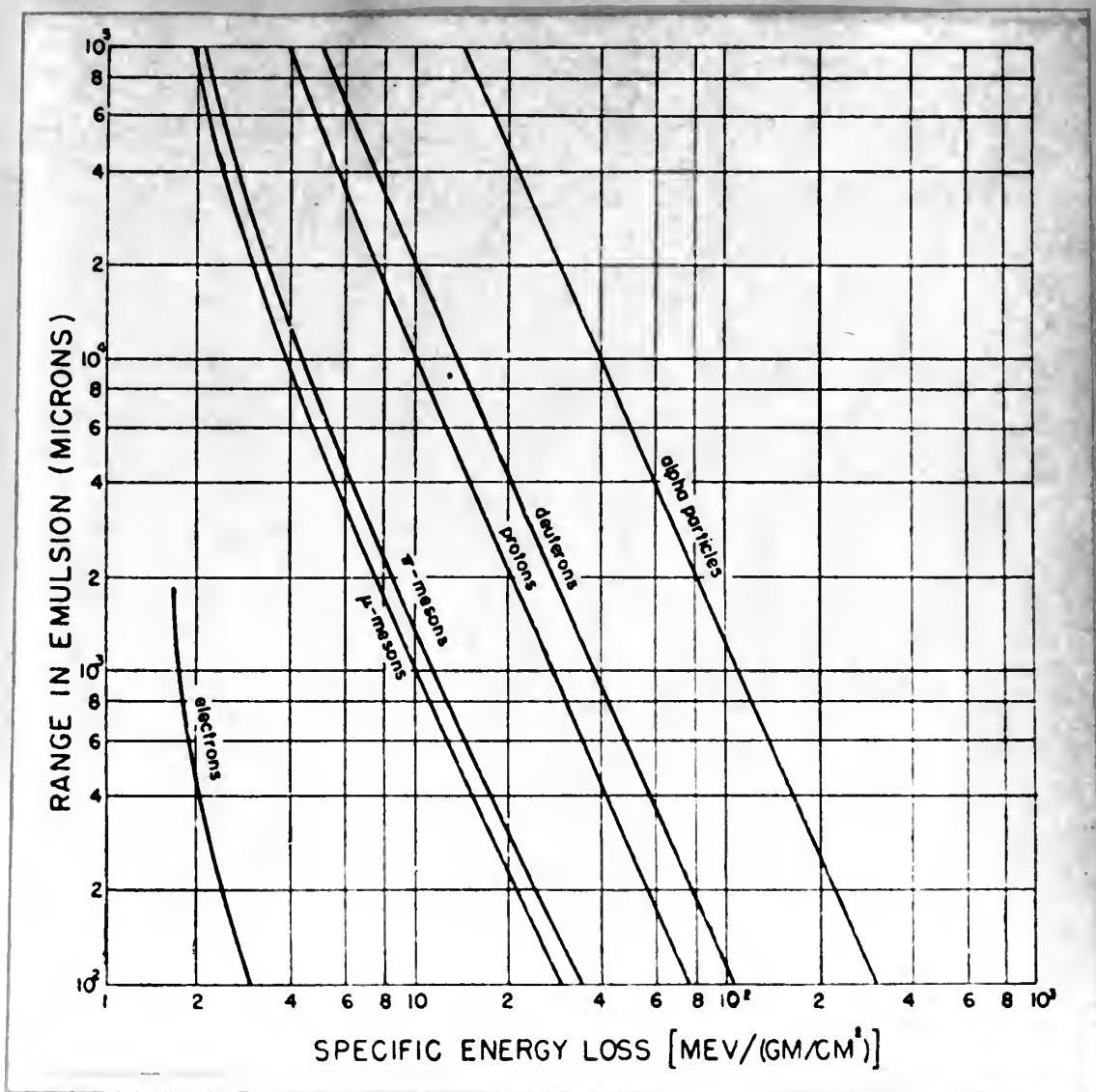
Fig. 3-7. The specific energy loss of various
particles in nuclear emulsions as a function of their
residual ranges, where 10^4 microns of emulsions = 4.0
g/cm^2 - data from Bradt et al., 1950. (Beiser, A.
1952. Revs. Mod. Phys. 24, 287).

with energy high enough to make them appear as independent tracks of several microns length and usually at an angle of about ninety degrees. The number of such electrons or delta-rays per unit length (delta-ray density) in conjunction with range determinations can be used to evaluate charges and energies of the particles.

Bradt & Peters (1948) give a theoretical expression[*] for the frequency of delta-rays of energies less than 30 Kev,

$$n = 2\pi N \left(\frac{e^2}{mc^2}\right) \frac{z^2}{\beta^2} \left(\frac{mc^2}{E_1} - \frac{mc^2}{E_2}\right) \qquad (3-22)$$

where n is the number of delta-rays per unit length of track, N is the density of electrons (of mass m) in the stopping material, and ze and $\beta = v/c$ are the particle charge and speed parameter (c being the speed of light). E_1 and E_2 are, respectively, the lowest and highest electron energies that will produce observable tracks. The maximum delta-ray energy for a given β is $2mc^2\beta^2$ in the nonrelativistic approximation; this will be the value of E_2 for slow particles. The upper energy limit is given by the sensitivity of the emulsion used and the lower limit by the criterion employed for electron track recognition (Bradt & Peters, 1948, use four grains in a row as their minimum for distinguishing short delta-ray tracks from random background grains.) Regardless of the conventions utilized in identifying delta-rays, a constant fraction of the theoretical delta-ray density should be obtained, and for a given set of criteria this density depends on the square of the charge and on the particle velocity in an emulsion of given sensitivity.

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[*]The atomic velocities of the electrons of the medium are neglected in the development.

In order to obtain the charge of an unknown ion, the delta-ray density of an alpha-particle track n_α with known residual range R_α is compared with the density n of the unknown particle at a given residual range R. Now

$$n/n_\alpha = (z^2/z_\alpha^2)(\beta_\alpha^2/\beta^2), \qquad (3-23)$$

and since β^2 is a known function of $Rz^2/M \approx Rz/2$ given by

$$\beta^2 = \psi(Rz/2), \qquad (3-24)$$

the equation

$$n = \frac{z^2}{4} n_\alpha \frac{\psi(R_\alpha)}{\psi(Rz/2)} \qquad (3-25)$$

follows. In Fig. 3-8 Bradt and Peters have plotted log n versus log R for different values of z as calculated using Eq. (3-25).

From such a set of curves, z can be determined very accurately if the track ends in the emulsion; however, if this is not the case, and n varies significantly, it is necessary to guess a value for z and then, by trial and error, successively approximate the actual value.

The ionization along tracks of multiply charged particles show a characteristic taper at the end of their range corresponding to a gradual loss of charge by electron capture (Freier, et al., 1948). The taper length L may be used to calculate an approximate value for the atomic number z of the particle involved if it is assumed the electron capture first occurs when its velocity is equal to that of the electrons which should occupy its K shell. The K electron velocities are proportional to z, and thus the taper length should be a function of z as well. An equation of the form

$$L = az^\alpha \qquad (3-26)$$

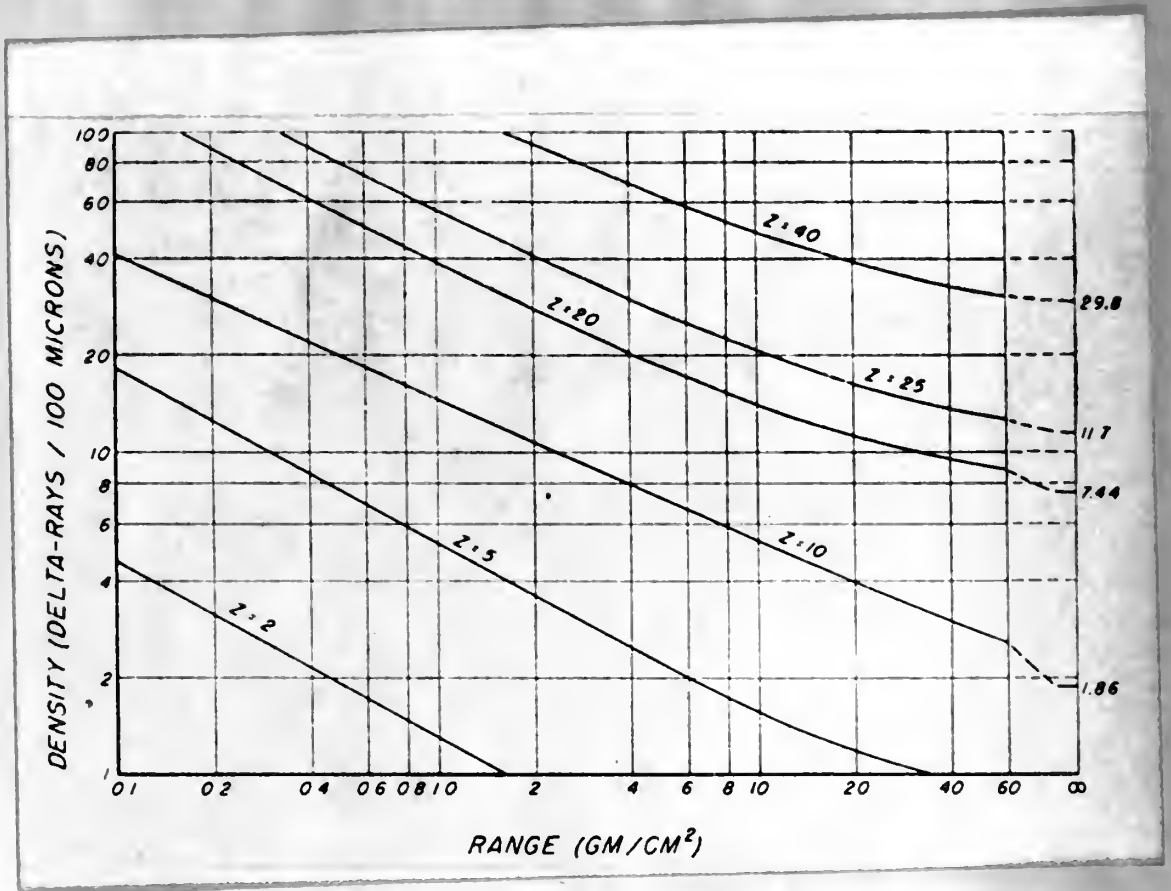results from an analysis of the ionization and electron capture phenomena.

Fig. 3-8. Variation of delta-ray density with
range in emulsion for various values of Z - data from
Bradt and Peters, 1948. (Beiser, A. 1952. Rev. Mod.
Phys. 24, 290).

Experimental determinations by Hoang (1951) indicate that a • 0.7 and α is of the order of unity.

Techniques based upon the evaluation of the multiple scattering in the tracks of particles passing through nuclear emulsions are of considerable usefulness in the determination of the mass and energy of the particle involved, especially in cases where fading of the latent image has changed the grain density or the grains cannot be counted because of overdevelopment and agglomeration. The theory of the measurement of scattering comprises three somewhat distinct problems: The differential cross section for individual single scatterings, the deflection probability function, and the analysis of a sample in terms of the multiple scattering distribution function and of the experimental errors of measurements. According to Bleuler and Goldsmith (1952), the individual scattering angles add up statistically, approximating a Gaussian distribution, and in number are proportional to the square of the charge and to the inverse square of the energy of the particle. If we designate the thickness of traversed material by t, the mean scattering angle $|\overline{\alpha}|$ for a particle of mass m is, as a first approximation, proportional to $\frac{z}{E}\sqrt{t}$. A theoretical relation is given by

$$|\overline{\alpha}| = \frac{2z}{mv^2}\sqrt{t}\ f(v,t). \qquad (3\text{-}27)$$

The function f(v,t), which is termed the scattering constant, varies slowly with the thickness and to a lesser degree with the velocity; it thus remains relatively constant for a given emulsion.

One method in common use for determining the multiple scattering of tracks in nuclear emulsions consists in measuring the angles between successive tangents to the tracks at regular intervals. Most of the

deflections are caused by multiple scattering; however, occasionally large changes of direction are due to single scattering. It is advantageous to exclude the latter and to define $|\bar{\alpha}|$ as the average of all deflections smaller than a critical value, for which four times the mean is chosen. Experimental values for the scattering constant or multiples thereof are available from many sources. Gottstein et al. (1951) supply curves of scattering constant versus a parameter which is a measure of the mean number of collisions experienced by the particle in the distance x, and Bleuler and Goldsmith (1952) give values of the function versus thickness of stopping material for various emulsions. Use of Eq. (3-27) together with the experimental value of scattering angle gives the particle energy E. Then comparison of the latter with the range-energy curves for various particles with tracks ending in the emulsion (Sec. 3-3) will give the particle mass. For track segments a method similar to that given in Sec. 3-5 is used for the mass determinations.

The curvature induced in a track by a strong magnetic field makes possible measurements of charge and mass of the particle. This technique, usually employed in the cloud chamber, is not directly applicable to nuclear emulsions because of the extremely high fields required to produce measurable curvatures in view of the short ranges of particles in the emulsion coupled with the scattering they exhibit. One experiment utilizing the deflection occurring in an air space between two plates and a more reasonable field strength to determine the momenta of particles passing through both plates and the intervening gap is described by Beiser (1952).

CHAPTER IV

OBSERVATION OF TRACKS

In order to employ successively the relatively large numbers of emulsions required in even the simplest investigations, one is forced to spend many hours tediously and systematically microscopically searching the emulsion plates for tracks registered therein by the particular nuclear particles under study. Two search techniques are possible manual and electromechanical; these shall be discussed in this chapter.

The manual method uses only a research-type microscope coupled with the human eye as a searching tool. The long periods of observation required to recognize events and to perform measurements are frequently found too taxing and may be the main reason for the photographic technique not having a still more extensive use. As of the present most of the microscopes available commercially for photographic emulsion work are of the biological-type with varied degrees of mechanical perfection; such improvements, however, only make them adaptable for the simplest operations, such as, scanning and location of events. Microscope manufacturers have only just begun to explore the domain of emulsion technique with a view to the designing of specific microscopes; models have been made or announced by Bausch & Lomb in the United States and Leitz in Germany. Cooke, Troughton, & Simms in England have placed a special microscope in production which is particularly adapted for emulsion work; its widespread use is limited, however, by its high price. Another design especially suited for the measurement of multiple scattering is being manufactured by Koristka in Italy. Physicists in

the nuclear emulsion field have themselves built several convenient accessories in laboratory workshops.

One such device, designed by Barbour (1949), has been found useful in the microscopic analysis of cosmic-ray phenomena. A tilting stage is provided for viewing tracks which dip into the emulsion. Suitable adjustment screws and working distances allow a maximum tilt angle of about 11° with optimum illumination. This means that tracks which pass through the plates at angles of up to 26° with the emulsion surface can be brought into the focal plane of the lens, provided that allowance is made for shrinking of emulsion on development. Accurate measurements of the "dip" angle facilitate matching track segments due to the same particle in different plates. A pantograph attached to the moving stage of the microscope traces its motion with a magnification of about 20. Thus a permanent plot of the location of events on the plate is obtained.

Juric and Smokovic (1952) modified a microscope so that its body could be tilted to a maximum deflection of 13°. The tube is placed perpendicular to the direction of the track, permitting direct measurement of the actual range of the particle providing, of course, that suitable steps are taken to prevent emulsion shrinkage after fixation.

A special superstage has been devised by Putnam and Miller (1952) to facilitate precision range measurements, particularly of long tracks that extend over several fields. A micrometer screw feed drives a separately moving stage attached to the existing microscope stage. The plate is first scanned using the coarse stage screw; when the track to be measured comes into view, its projected length in microns can be

read directly on the drum of the precision screw driving the superstage. This procedure permits the quick and accurate measurement of tracks which are longer than the field of view and the sorting out of a particular track among many in the field.

If these devices, and perhaps others, could be perfected and made readily available to the users of emulsion technique, there is little doubt that they would soon find a relatively broad market (Goldschmidt-Clermont, 1954).

As pertains the optical system itself, objectives with medium or high magnification, flat field, large numerical aperature, and large working distances (distance between the object plane and the front lens) are desirable for observation and measurements of selected events. For systematic scanning an objective with low magnification and high numerical aperature using oil immersion is essential. Several objectives meeting these requirements were successfully developed in recent years, e.g., the Leitz (X 53, n.a. 0.95, w.d. 1mm.) and the Leitz (X 22, n.2. 0.65, w.d. 2.3 mm.) for the high and low magnification work, respectively. A variable iris diaphragm in the tube of the objective for convenient adjustment of the illumination and depth of field should be provided.

Several attempts have been made to make the microscope somewhat automatic, and successful instruments have been built for limited purposes. Most of these devices were designed with a view toward minimizing manual operations and personal error while at the same time increasing speed and ease of measuring. However, it must be emphasized that these mechanisms in their present state of development cannot in any way replace the judgment of the skilled observer in the final analysis of nuclear
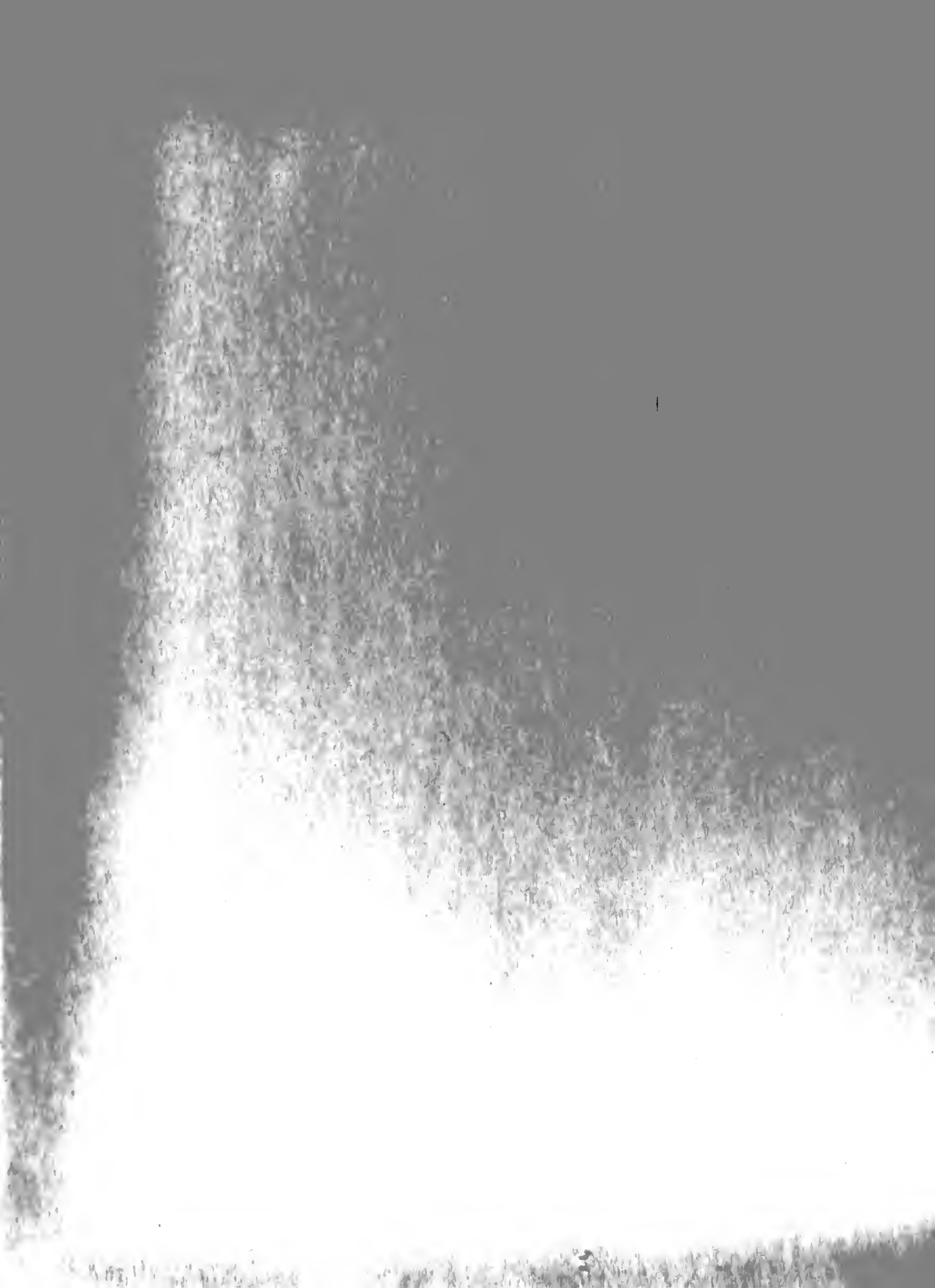
tracks. The field is still open for much progress.

To facilitate scanning Masket and Williams (1950) developed a mechanism incorporating a means for continuously driving a microscope in the horizontal plane at variable speed and automatic reversal of direction with a variable range coupled to the focusing drive that would span concurrently through the emulsion twice for each field of view passing the objective. It further incorporated a means of projection of the field of view enabling observance of scanning without undue eye fatigue.

A somewhat different principle is utilized in a nuclear plate scanner designed and constructed at Battelle Memorial Institute in Columbus, Ohio for analyzing intensity and energy distribution of neutron sources (Nucleonics, 7, 81, 1950). A nuclear plate, mounted on a rotating disk, passes under an oil-immersion objective once each second. The microscope mount turns slowly, moving the lens more or less radially across the disk. The image of any proton recoil track, caused by fast neutron bombardment of the plate, is detected by a photomultiplier located on top of the microscope tube. The resultant signal is amplified and used to activate a recorder which shows the position of the track.

A large and most complex instrument has been developed to make automatic measurements of range, grain density, multiple scattering, delta-ray density, and geometrical orientation of tracks (Blau et al., 1950). The basic element of the apparatus is a microscope with a motor-drive stage. The operator controls the direction and speed of motion by a steering wheel and an accelerator pedal and drives the track

to be analyzed through a target.

A very promising recent development is the replacement of the eye by a photometric device for evaluation of dense ionization (Ceccarelli and Zorn, 1952). An image of the track is focussed in the plane of a narrow slit of which the long axis is parallel to the track. The light passing through the slit falls on the cathode of a photo-multiplier tube, and the resulting anode-current is measured by a galvanometer. Readings are taken alternately on the track and on the background, and a measure of the total obscuration produced by the track is obtained from their comparison. The blackening distribution is found to be proportional to the distance from the center of the track and independent of the ionization produced by the particle provided that it has an energy loss greater than 200 Mev/g/cm^2. The photometric method appears to be suitable for emulsion of thicknesses up to 200 microns, but owing to the scattering of light, difficulties are met in experiments with thicker emulsions. The photometric technique is particularly well adapted to identification of particles by measurements of multiple scattering and delta-ray density.

Experiments have been performed by use of a wholly different means of obtaining resolution and amplification (Roberts and Young, 1951 and 1952). The method involved is to use the lens system of a conventional microscope the other way around and to scan the resulting image with a television system thereby translating the field of view into a succession of electrical impulses. A cathode ray tube providing a television raster of high brillance and short-time constant is placed in front of the eyepiece of a microscope. The objective produces a minute spot

of light that scans the emulsion. The amount of light transmitted is determined by the density of the plate and is picked up by a multiplier photocell. The output of the latter is used to modulate a projection type of cathode ray tube raster, the rate of which is locked to the scanning raster. The output of the photo-multiplier is also fed via amplitude and time-discriminating circuits to a high-speed counter. Pictures superior to those of a normal optical microscope in size, brightness, contrast, and resolution are obtained. Also, particles are automatically counted and sized. A further development of the device to provide greater counting accuracy makes use of a two-spot scanning system. The instrument seems to solve the scanning problem, but even the most inexperienced eye can detect at a glance whether or not some of the grains among the many scattered over the field of view are aligned over the straight or slightly curved line of a track, which information is, of course, necessary for proper analysis. Goldschmidt-Clermont (1954) sums up the present state of development by saying that the computer required to solve this same problem or a slightly more complicated event, such as recognition of meson decay, can no doubt be realized; however, it will take much progress and research before electro-mechanical scanning robots will contribute to advances in nuclear physics.

CHAPTER V

EXAMPLES OF NUCLEAR TRACKS IN THE PHOTOGRAPHIC EMULSION

As examples of tracks produced by fast charged particles in passing through nuclear research emulsions, Plates I - XIX are shown.*

Plates I - IV illustrate simple experiments in radioactivity, the alpha-particle tracks obtained being clearly visible with an ordinary microscope using a X 40 dry objective (4 mm.) and a X 6 eyepiece with adequate sub-stage illumination in good adjustment. For resolving the detailed structure of the tracks, however, oil immersion objectives of high numerical aperature are usually employed (Chap. IV).

Plates V - VIII show the tracks of fast protons and deuterons in the emulsion. Since these particles are singly charged they are less effective in ionizing the atoms through which they pass than is an alpha-particle of the same speed. Consequently, their specific energy loss is less, and, for a given velocity, protons and deuterons will travel farther before being brought to rest in the emulsion (Fig. 3-4). Particular tracks have been chosen for reproduction which show the effects of the elastic collision of the particles with the nuclei of some of the atoms of the stopping material. Because of their smaller mass, protons suffer more frequent scattering than alpha-particles of the same speed. This feature permits us to differentiate the two particles.

The arrows indicate the directions in which the particles, as a nearly parallel beam and at a small glancing angle to the surface, were

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*Reproduced from photographs in Powell, C. F., and G. P. S. Occhialini. Nuclear Physics in Photographs. London: Oxford University Press, 1947, by permission of the publishers.

made to enter the emulsion.

Plate IX illustrates an event whereby a fast particle enters the nucleus of an element and transmutes it. The transmutations arising from the bombardment of a lithium target by fast deuterons can be represented by the equations:
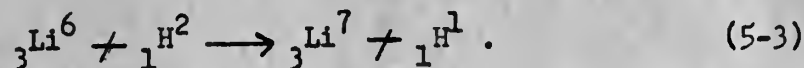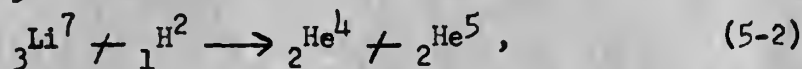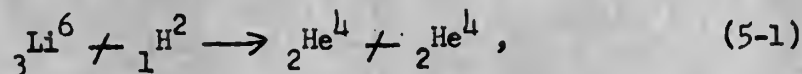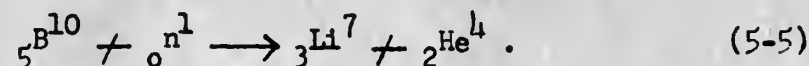
$$_3\text{Li}^6 + {}_1\text{H}^2 \longrightarrow {}_2\text{He}^4 + {}_2\text{He}^4 , \qquad (5\text{-}1)$$

$$_3\text{Li}^7 + {}_1\text{H}^2 \longrightarrow {}_2\text{He}^4 + {}_2\text{He}^5 , \qquad (5\text{-}2)$$

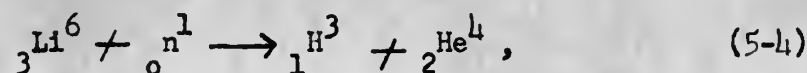$$_3\text{Li}^6 + {}_1\text{H}^2 \longrightarrow {}_3\text{Li}^7 + {}_1\text{H}^1 . \qquad (5\text{-}3)$$

Plate X shows the tracks produced by thermal neutrons entering the nuclei of the light elements lithium and boron. The following reactions occur:

$$_3\text{Li}^6 + {}_0\text{n}^1 \longrightarrow {}_1\text{H}^3 + {}_2\text{He}^4 , \qquad (5\text{-}4)$$

$$_5\text{B}^{10} + {}_0\text{n}^1 \longrightarrow {}_3\text{Li}^7 + {}_2\text{He}^4 . \qquad (5\text{-}5)$$

If fast neutrons pass through plates loaded with boron, a three particle disintegration is produced in accordance with the equation

$$_5\text{B}^{10} + {}_0\text{n}^1 \longrightarrow {}_2\text{He}^4 + {}_2\text{He}^4 + {}_1\text{H}^3 . \qquad (5\text{-}6)$$
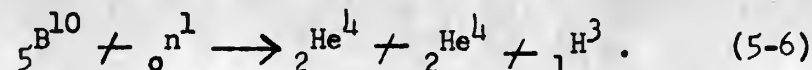
The total mass of the three product nuclei is less than that of the two original particles, and energy is therefore released in the reaction. By applying the principle of the conservation of momentum, it is possible to deduce the direction of motion of the original neutron. Plate XI shows two examples of the reaction represented by Eq. (5-6).

Plate XII illustrates the paths of fission fragments from a U^{235} nucleus which suffers division into two nearly equal parts as a result of the entry of the slow neutron. The kinetic energy of the fragments

is very great -- of the order of 200 Mev -- but the high charge carried by each is manifested by the relatively short range of the tracks.

With primary particles of relatively low energy not more than three or four particles are emitted as the result of the disintegration of a single nucleus, and some of these may be neutrons which will not leave tracks in the emulsion. For charged particles and photons with energies greater than 100 Mev disintegrations with the emission of eight or ten particles can be produced. The microphotographs of Plates XIII and XIV illustrate disintegrations produced by the particles generated by the 184 in. synchro-cyclotron of the University of California. Some of the tracks cannot be distinguished because of the effect of very low specific ionization which is due to the great energies of the particles.

For studying the nuclear disintegrations produced by particles of even greater energies than those we can generate, it is necessary to turn to natural sources -- cosmic radiations. The events of Plates XV and XVI resulted from the emulsions being exposed for six weeks on the Pic du Midi, Hautes Pyrénées, at 2800 meters.

In plates which have been exposed to cosmic radiation at high altitudes can be found, in addition to numerous "stars" and isolated tracks due to protons and alpha-particles, a relatively small number of meson tracks of which the photographs of Plates XVII and XVIII show examples.

Plate XIX illustrates the event whereby a pi-meson enters the emulsion and after traveling a certain distance decays spontaneously into a mu-meson with the latter coming to rest in the emulsion.

PLATE I

$\longleftarrow - - - - 100\,\mu - - - - \longrightarrow$
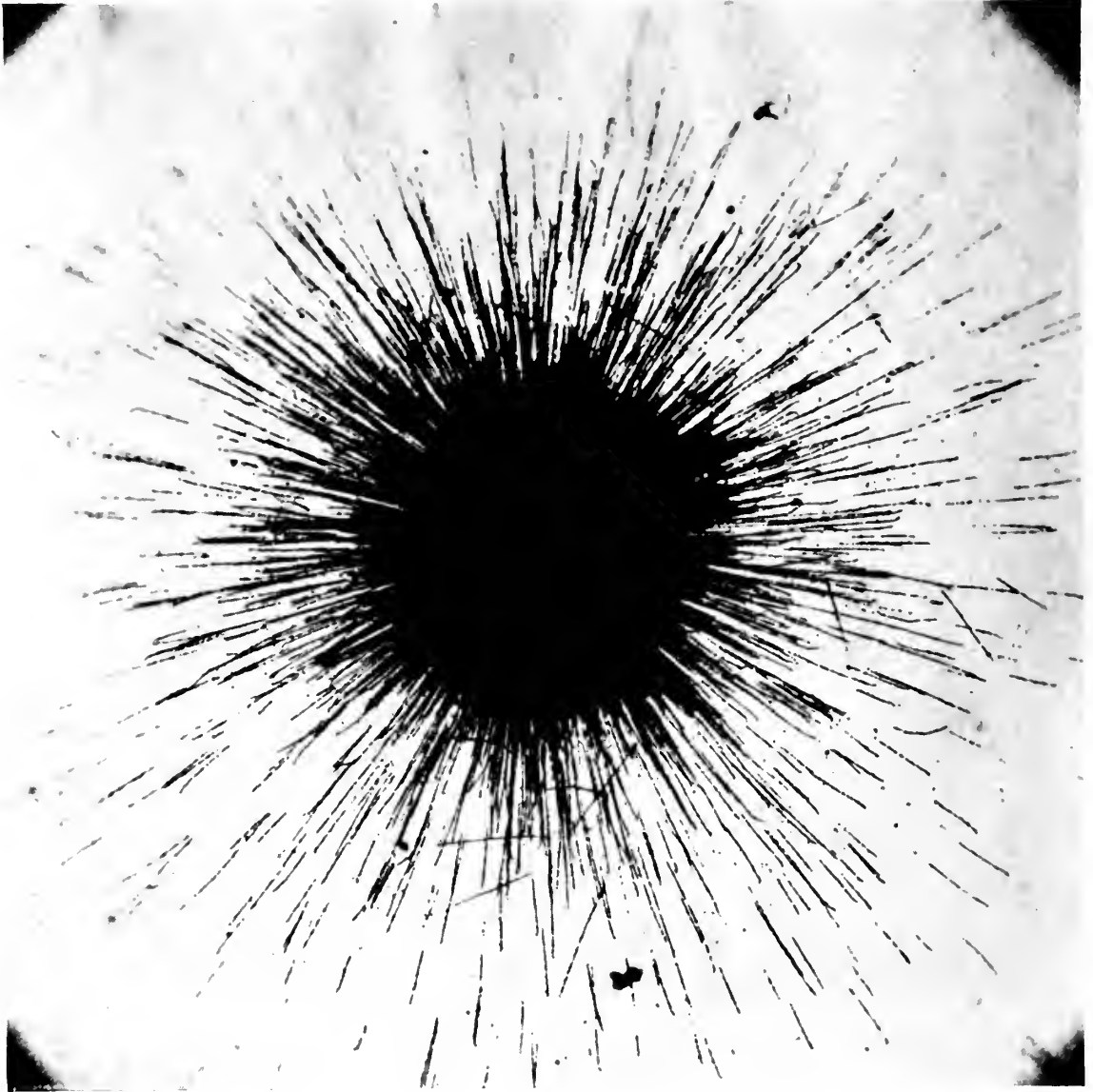
Tracks of α-particles from a speck of radium

This photograph was obtained by shaking a needle, on which a small quantity of radium had been deposited, over a photographic plate. Specks of radio-active material, in many cases too small to be seen under the microscope, were thus detached from the needle and settled on the plate. After a few days the plate was developed and then, under microscopic examination, it was found to be covered with many 'stars' of which this is one example. The photograph shows the tracks of α-particles radiating from a single area of small extent in the centre of the star. It illustrates the great number of particles emitted from a quantity of radium too small to be visible under the microscope. Since only one in a hundred thousand of the radium nuclei will have decayed during the exposure, the photograph gives an impression of the enormous numbers of atoms even in minute quantities of matter.

PLATE II

$\longleftarrow - - - - - - -\ 100\ \mu\ - - - - - - - \longrightarrow$

'Radiothorium stars'

The stars in this photograph have been photographed with a reflection micro-
scope constructed by C. R. Burch. With the size of silver bromide grains
employed in the present emulsions, normal microscope objectives of high
aperture allow us to distinguish most of the details in the tracks of charged
particles, the refinement of the method being limited by the coarseness of the
grains and not by the 'resolving power' of the microscope. With the develop-
ment of emulsions of finer grain, however, we shall require optical instruments
of greater power. The reflection microscope offers the advantage that it can
be used to take photographs with ultra-violet light, thus giving higher resolu-
tion. It also has the advantage of offering a much longer 'working distance'
than is provided with instruments of conventional design, so that it will be
possible to employ it for the examination of emulsions of much greater thick-
ness than 300 μ. The long track in the star in the lower centre of the photo-
graph is from ThC″—range in normal air 8·6 cm.

PLATE III

$$\longleftarrow - - - - - 50\,\mu - - - \cdot - \longrightarrow$$
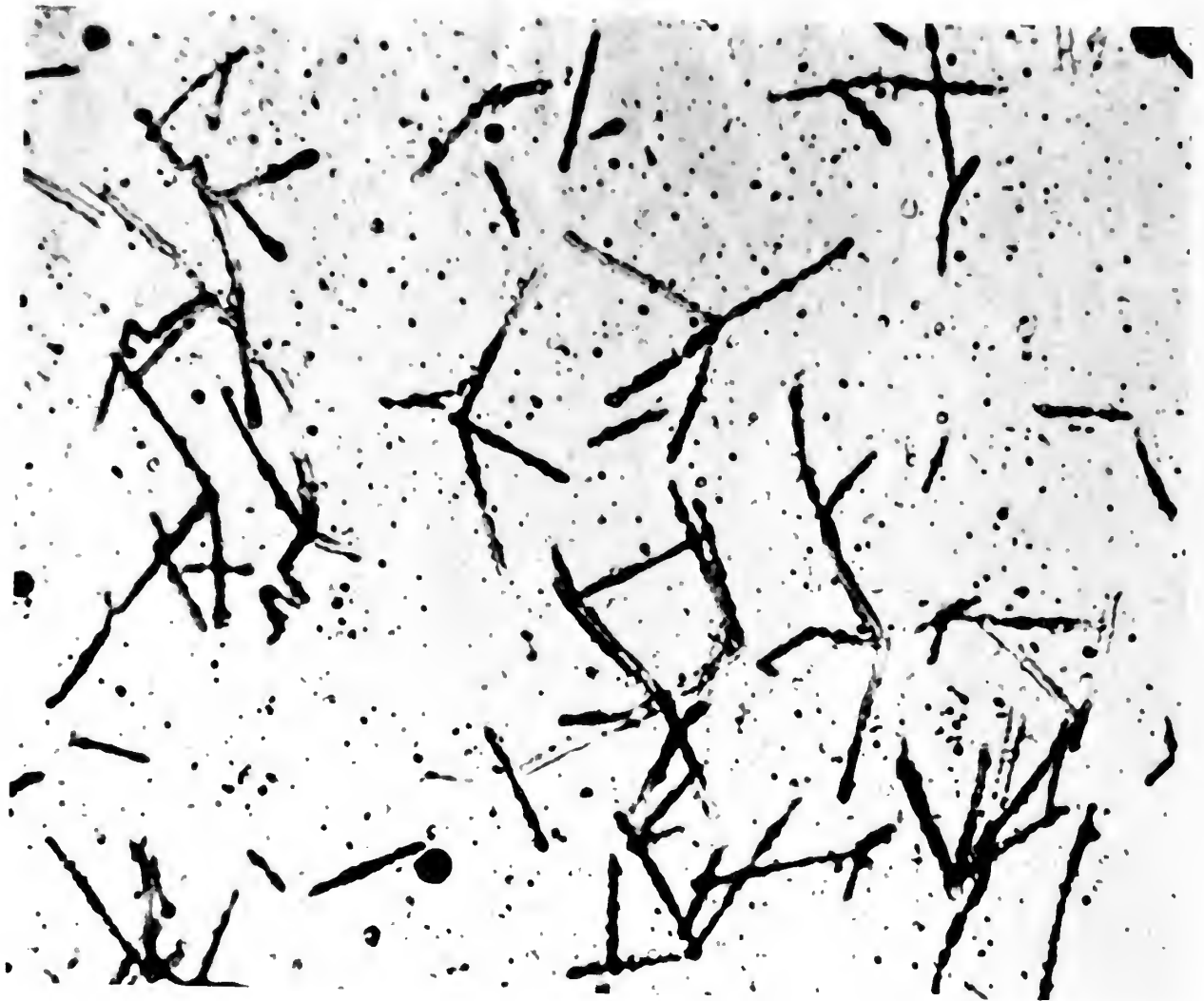
'Radium stars'

This photograph was obtained by bathing a plate in a solution of radium bromide at a concentration of a hundredth of a microgram per litre. The depth of focus of objectives of high aperture is restricted so that only a few of the tracks are in focus along the whole length of the track. The long thin track is due to a proton. It was produced when one of the α-particles entered the nucleus of one of the atoms in the emulsion and transmuted it. Disintegrations of this type were first observed by Rutherford in 1919, using the scintillation method to detect the particles, and represented the first successful attempts to transmute matter artificially.

PLATE IV

← – – – – – – – 100 μ – – – – – – – →

Radiothorium stars after intensification

In taking ordinary photographs it sometimes happens that the exposure is too short, so that the negative is weak and there is insufficient blackening at the points corresponding to the high lights in the subject. In these cases the blackening may be increased by immersing the negative in suitable solutions, which deposit other metals round the developed silver grains in the emulsion, so that the degree of blackening is increased. A similar method may be employed to 'intensify' the tracks formed by charged particles and to render them more clearly visible. The photo-micrograph above shows the kind of effect thus obtained, the intensification in this case being due to a salt of uranium. This process may be useful in cases where it is only necessary to count tracks. It will be seen, however, that the tracks, whilst more distinct, are much coarser than in the untreated plate, so that detailed features are likely to be lost.

PLATE V
↓

$\longleftarrow - - - - - - -\ 100\,\mu\ - - - - - - \longrightarrow$

Tracks of protons and α-particles

A mixed stream of protons and α-particles has entered the emulsion. One of the protons has been deflected through a large angle by collision with the nucleus of an atom in the emulsion. The short tracks at the top of the photograph are due to α-particles. It will be seen that the grains are more closely packed in these tracks, corresponding to the greater ionization along the trajectory, than in the case of the proton. Tracks of some α-particles also show deviations due to collisions with nuclei.

PLATE VI

↓

Double scattering of a proton

A rare event in which a proton is scattered twice during its passage
through the emulsion.

# PLATE VII
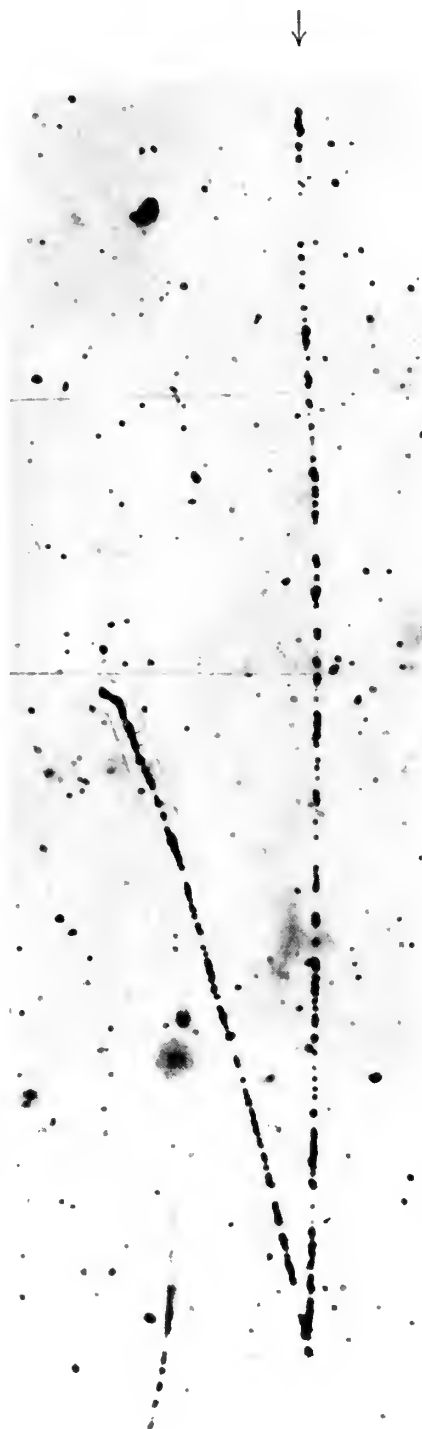
Large-angle scattering of a proton

A very rare event in which a proton has been scattered through an angle of 160°, probably in collision with the nucleus of a silver or bromine atom. The increased frequency of the scattering towards the end of the range can be seen. This, and the increased density of grains in the track towards the end of the range, allows us to distinguish the direction of motion of the particle.
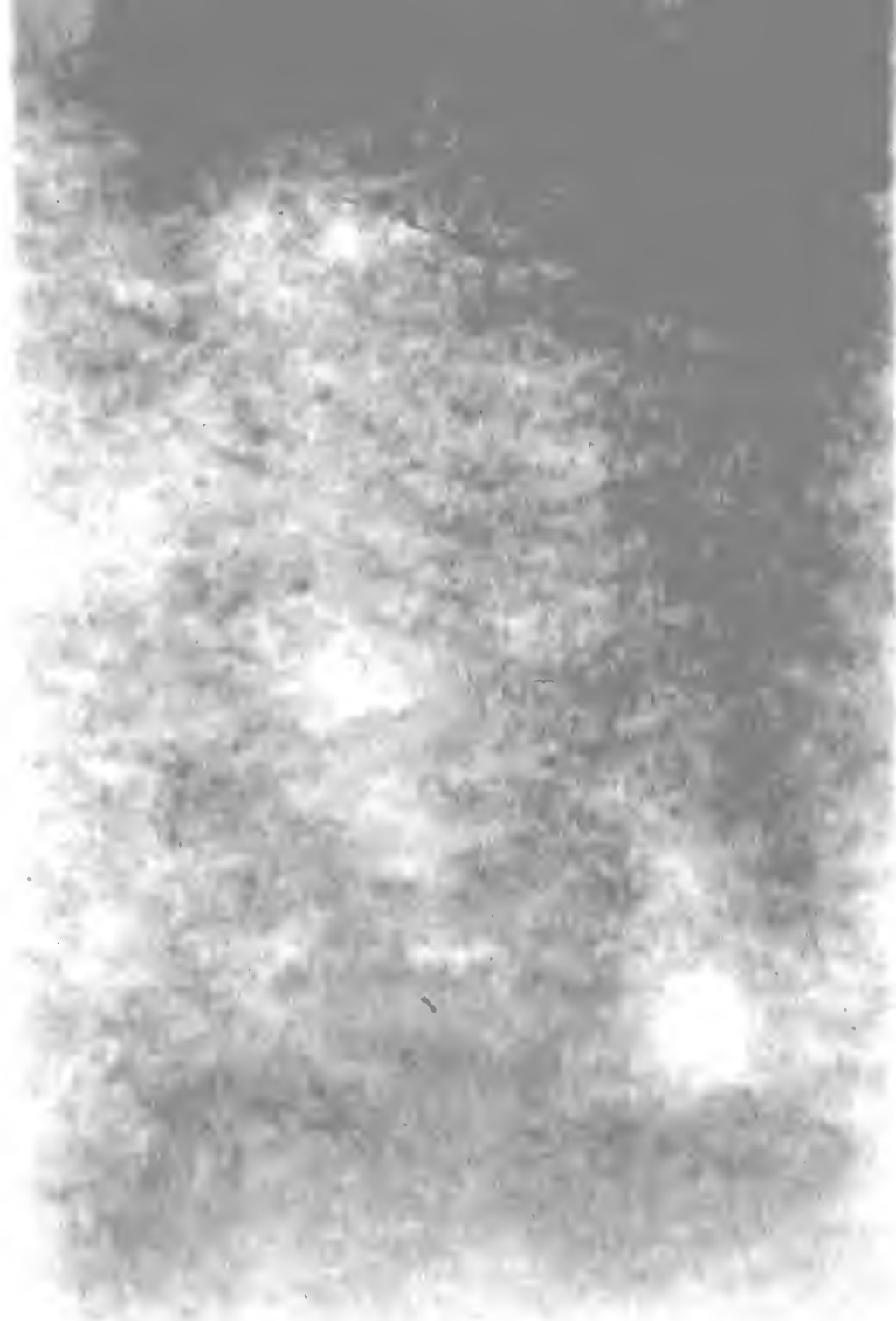
PLATE VIII

$\uparrow$
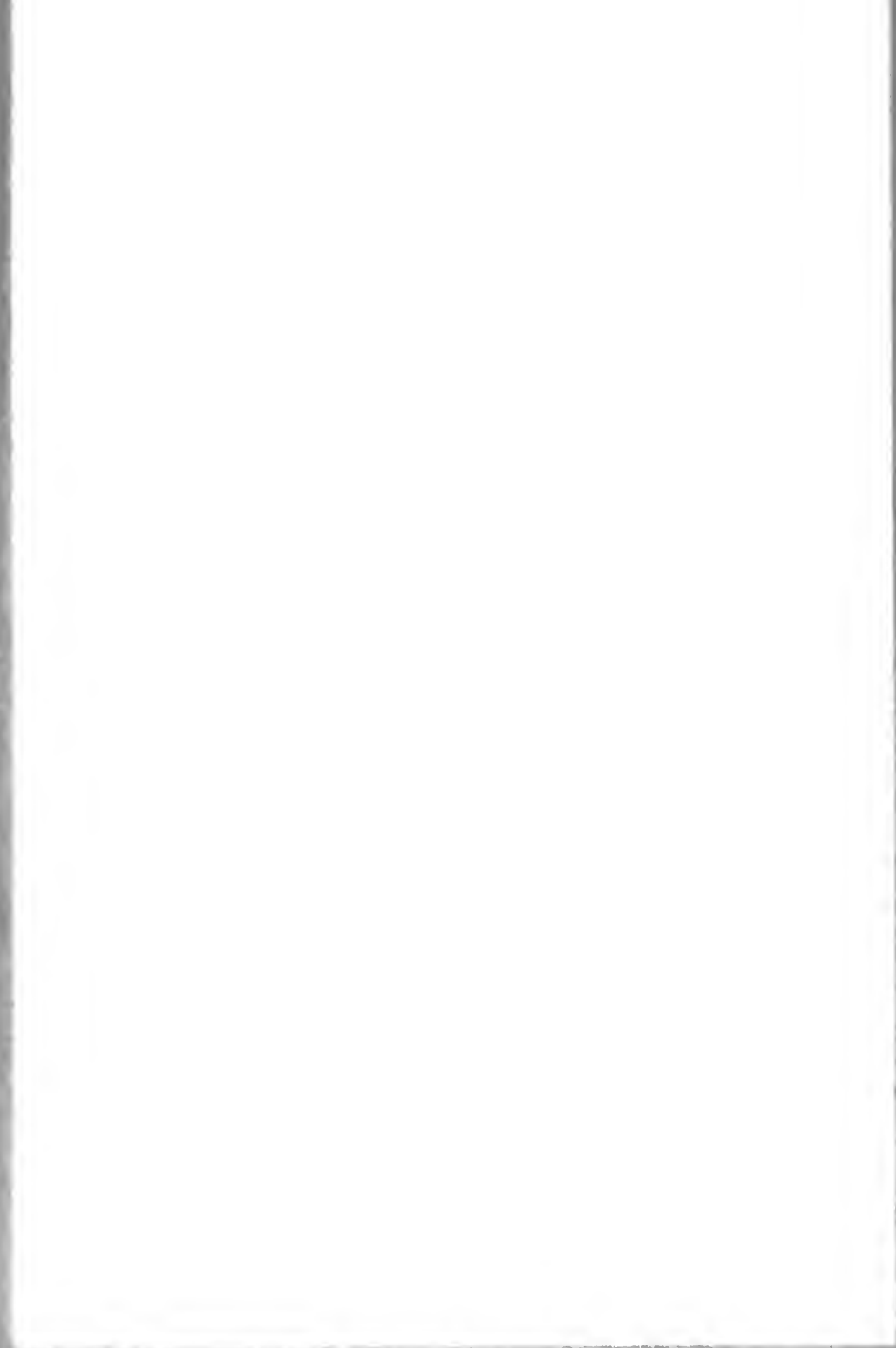
$\longleftarrow - - - - - - - - - - 100\,\mu - - - - - - - - - - \longrightarrow$

Scattering of a deuteron by a proton

Tracks of deuterons in a photographic emulsion. One of the
deuterons has collided with a proton and projected it. To
obtain the tracks in focus along their entire length it has
been necessary to take two photographs.

PLATE IX

100μ

x-Particles and protons from the disintegration of lithium by deuterons

Mosaic of 24 photo-micrographs of a plate showing the tracks of x-particles and protons arising from the bombardment of a lithium target by 900 keV. deuterons. The x-particle tracks are in the form of nearly continuous lines of silver grains. In this emulsion the proton tracks are much more tenuous and can be distinguished from those of x-particles. The lines running obliquely across the plate are due to pressure-marks or scratches and result from friction. They can be readily distinguished from the tracks of particles by the fact that they are confined to the surface grains of the emulsion.

Tracks from the disintegration of lithium and boron by slow neutrons

Tracks produced by the passage of slow neutrons through a photographic emulsion containing lithium borate, incorporated in the emulsion during manufacture. The tracks are due to the two reactions represented on page 57, those of short range arising from boron, and the two of long range from lithium. In the particular emulsion employed, the two separate components of each of the tracks cannot be distinguished. The two nuclei arising from each transmutation fly off in opposite directions, for the original momentum of the neutron is nearly zero on a nuclear scale. In contrast with charged particles, every one of which leaves its own track in passing through the emulsion, thousands of neutrons must be made to stream through the plate in order to produce one disintegration.

PLATE XI
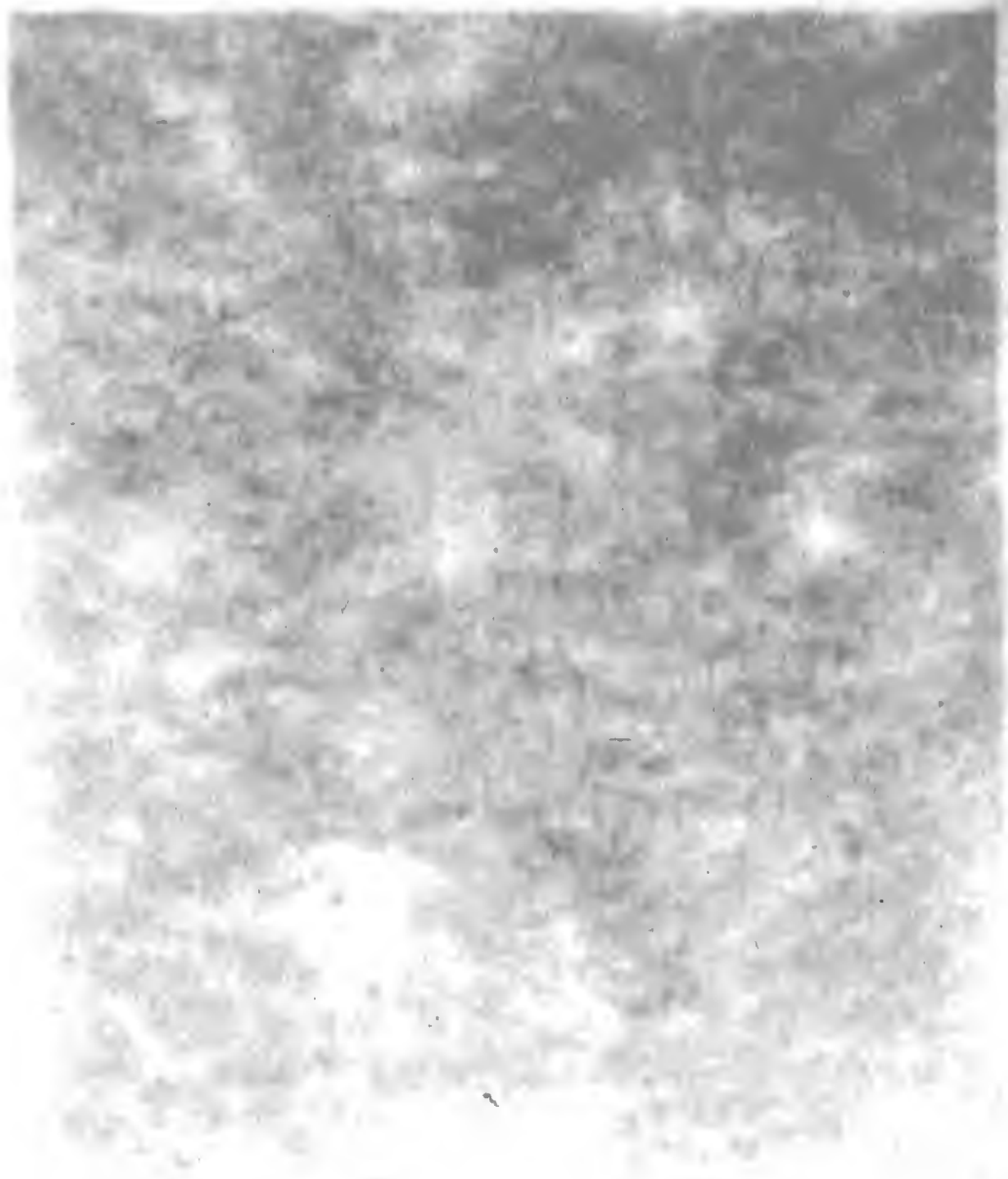
Two examples of the disintegration of $_5\text{B}^{10}$ into two α-particles and a triton. The tritons are in each case moving towards the top of the photograph. The disintegration of lower energy was produced by a 13-MeV. neutron from a high-tension apparatus, and the other by a neutron of estimated energy 35 MeV., present as a component in the cosmic rays.

$\longleftarrow$ – – – – – – – 100 μ – – – – – – – $\longrightarrow$

Disintegration of boron by fast neutrons

PLATE XII

$25\,\mu$

Fission tracks

Examples of tracks produced by the fission of U^{235} by slow neutrons. The uranium was introduced into the plate by a bathing technique, using a solution of uranium citrate. It is not possible, in general, to decide the point along the track at which the fission occurred and thus to determine the ranges of the individual fragments. It will be seen that in a number of cases one of the fission fragments has collided with a nucleus in the emulsion so that a forked track has been produced. In case (d) the two tracks arising from such a collision are nearly at right angles. This probably corresponds to a collision with a silver nucleus, mass number 109, some of the fission fragments having mass numbers nearly equal to this value.

PLATE XIII
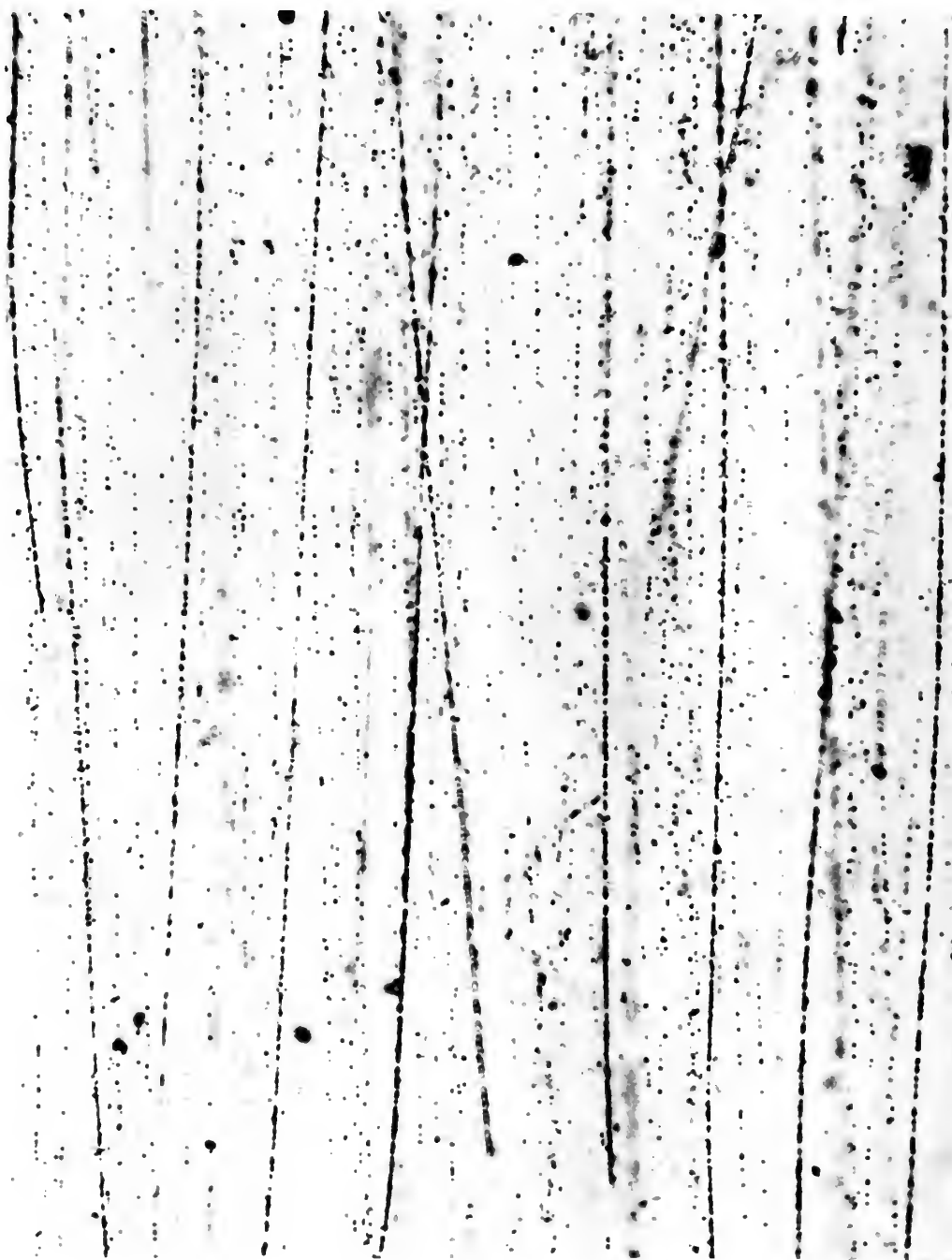
$100\,\mu$

Tracks of particles of great energy

Tracks of α-particles and deuterons from the 184-in. cyclotron entering an emulsion at a small glancing angle. The two types of particles have the same speed on entering the emulsion and the difference in ionization is well displayed, the α-tracks being prominent and those of the deuterons very tenuous. The initial energies of the two types of particle were about 200 MeV. for α-particles and 100 MeV. for deuterons. Two or three α-particles come to the end of their range in the field of view.

PLATE XIV

$- - - - - - - - 100\,\mu - - - - - - - \rightarrow$

Disintegration by particles of great energy

Disintegrations produced by particles generated by the 184-in. synchro-cyclotron of the University of California. In the right-hand photograph the track of the particle producing the disintegration cannot be distinguished, but it was probably a deuteron of energy about 160 MeV. The parallel tracks of other particles, probably α-particles of energy 320 MeV., can be seen. In the photograph on the left, the track of the primary particle is marked *d* and can be more clearly seen by inclining the page to bring the grains in the track into the line of sight.

PLATE XV
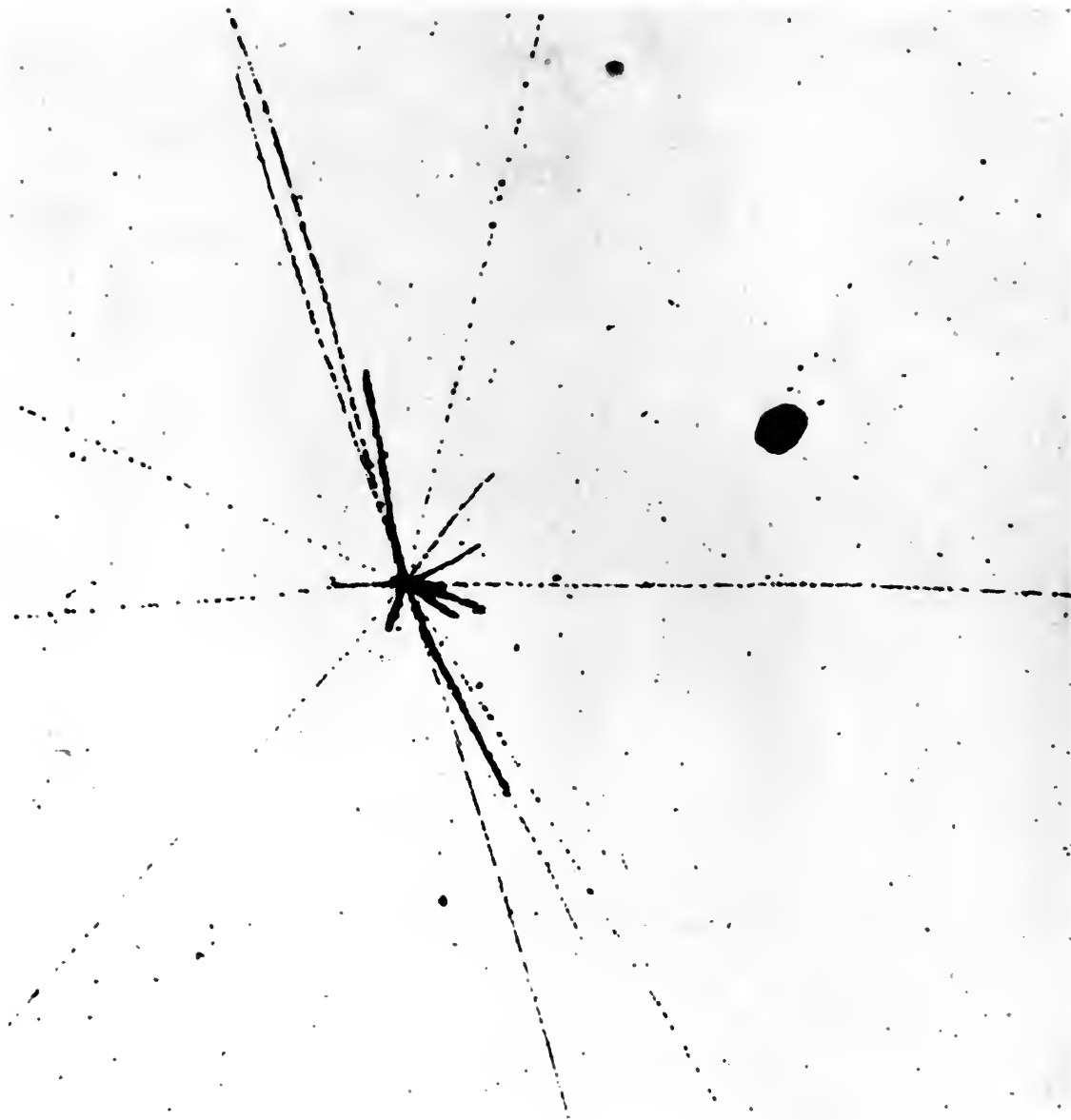
$\leftarrow - - - - - 100\,\mu - - - - - \rightarrow$

'Explosive' disintegration of a nucleus

Disintegration of a nucleus, probably of silver, by a cosmic ray particle. The energy of the particle producing the disintegration must have been about 1,000 MeV. The tracks of seven protons, five α-particles, and a number of heavier nuclear fragments can be distinguished. Most of the particles pass out of the emulsion, into the glass or out of the surface, so that their range, and hence their energy, cannot be determined accurately.

PLATE XVI

Cosmic-ray 'star'

‒ ‒ ‒ 100µ ‒ ‒ ‒→

Disintegration of a heavy nucleus in which an α-particle of long range (energy 32 MeV.) remains in the emulsion. In ordinary air, an α-particle of this energy would have a range of about one metre.

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PLATE XVII

$100\,\mu$

Meson Track

Mosaic of photo-micrographs of the track of a meson which enters the emulsion at the top of the figure and ends in the emulsion at the bottom. Note the frequent changes in direction, giving the appearance of a general curvature, and the 'thinness' of the track along most of the trajectory. The increase of ionization at the end of the range is clearly visible.

PLATE XVIII

m

<----------- 50 μ ----------->
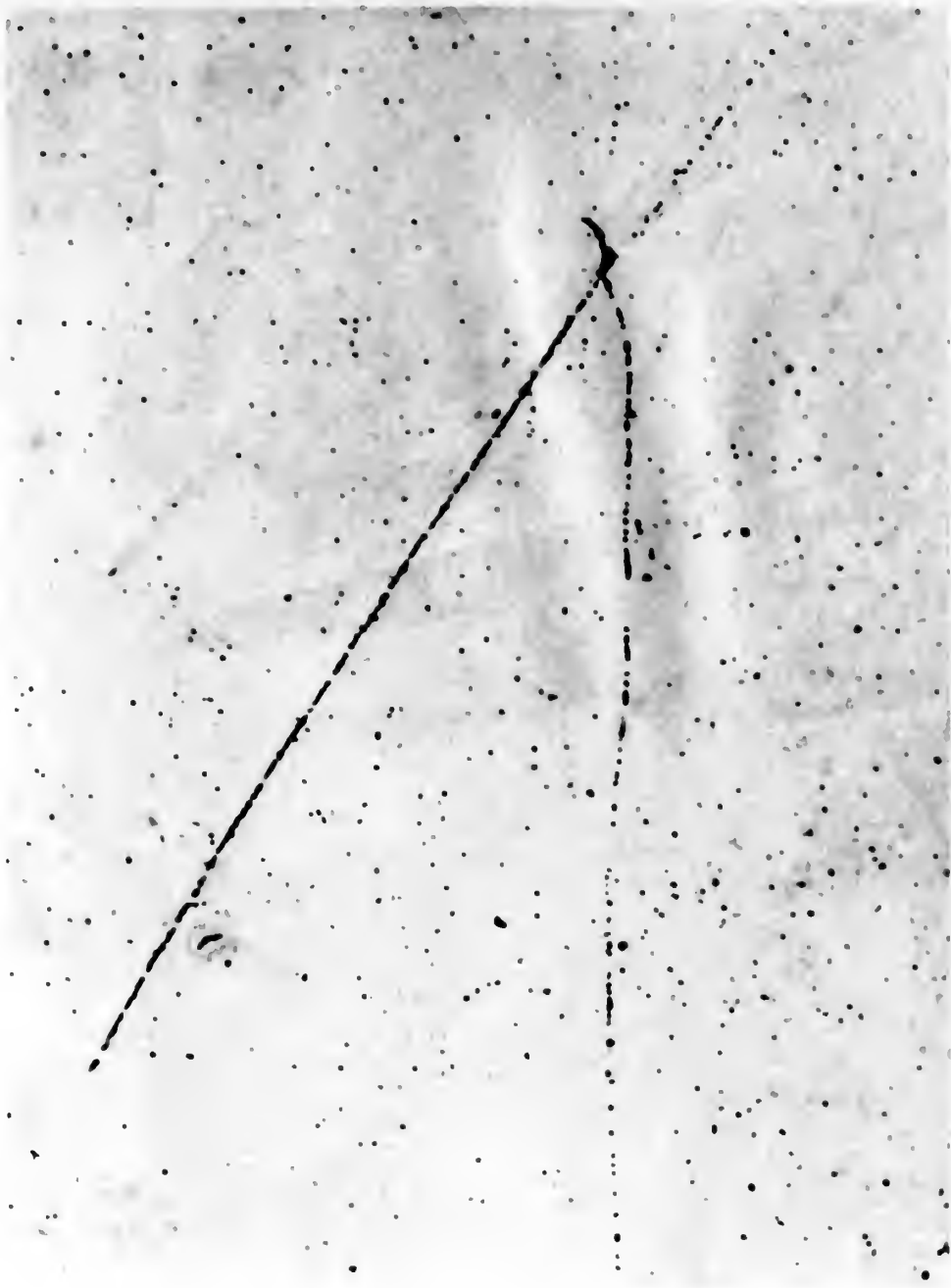
Meson disintegration

Mosaic of photo-micrographs of a disintegration produced by a meson which leads to the emission of a proton and an α-particle. The two tracks of short range are due either to α-particles or, possibly, to heavier nuclear fragments. In all such disintegrations it is likely that neutrons are also emitted which escape detection.

PLATE XIX

$$\longleftarrow \text{ - - - - - - } 200\,\mu \text{ - - - - - - } \longrightarrow$$
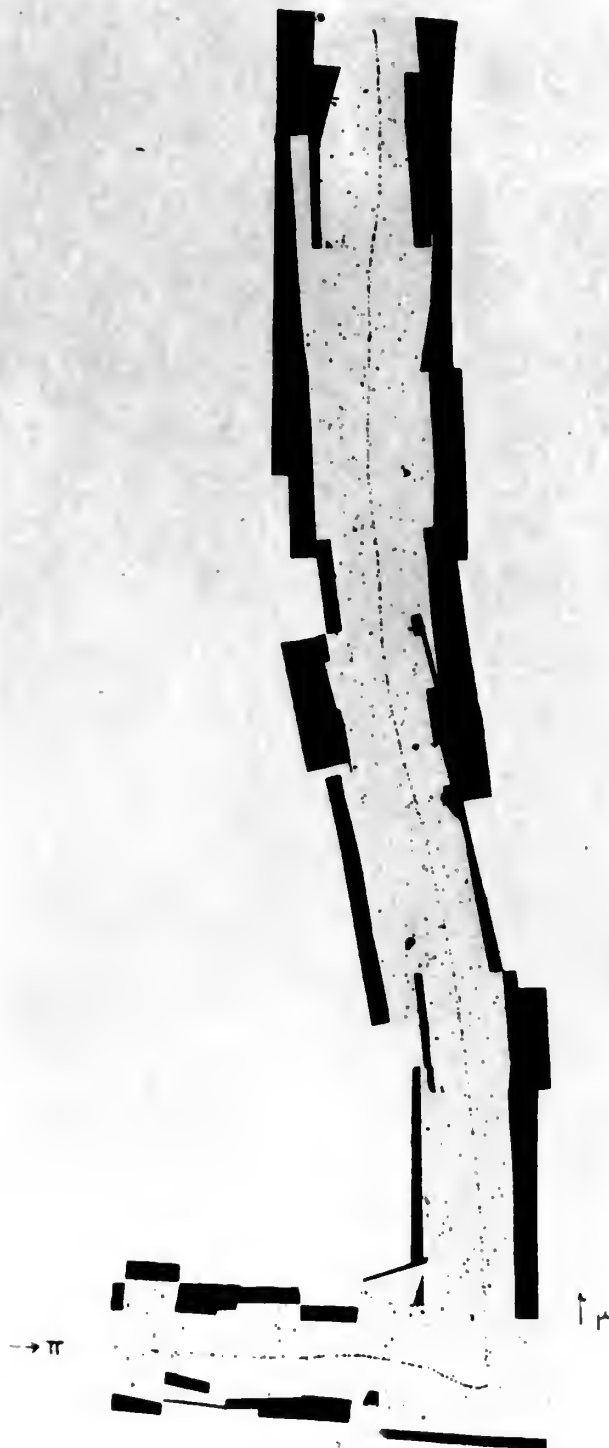
Primary and Secondary Mesons

Primary meson track, π, with secondary light particle, μ. The primary track is too short to allow an accurate determination of the mass to be made by grain counts. The track of the secondary meson ends in the emulsion and grain counts indicate that the initial energy of the particle was about 4 MeV.

SUMMARY

This paper has been intended primarily to serve as a general guide
to the use of emulsions in radioactive measurements, and sufficient
theoretical material has been incorporated to permit the comprehension
of the basic mechanisms underlying the working methods. The theories
of such phenomena as grain density variation, specific energy loss,
stopping power, taper length, delta-ray density, and multiple scattering
have been examined. Combined with quantitative measurements, they are
the bases of the photographic technique, enabling us to determine over
certain ranges the charge, mass, and energy of the incident particles.
The various characteristics of the commercially available nuclear re-
search emulsions have been discussed, and an attempt has been made to
show that by selection of the proper emulsion, the photographic tech-
nique is applicable to the investigation of almost any nuclear event.
Several microphotographs have been included to furnish evidence of its
versatility. The continuing progress of the method has been noted by
the fact that with the advent of minimum ionization sensitive emulsions
physicists were able to gain an insight into the behavior of the many
high-energy tracks occurring, for instance, in cosmic-ray stars and that
a large fraction of our present knowledge of meson physics has been based
on measurements in such emulsions. A discussion of processing techniques
and connected operations, such as prevention of emulsion shrinkage, which,
of course, are most important to insure successful results, is consider-
ed by the writer as not being within the scope of this paper. The
reader is referred to a most interesting and complete treatise of this

subject by Beiser (1952). The adaptability of the photographic technique
to experiments involving special equipment, such as particle accelerators,
has been discussed. Finally, some of the more recent developments
designed to assist the observer of particles tracks in nuclear emulsions
have been cited.

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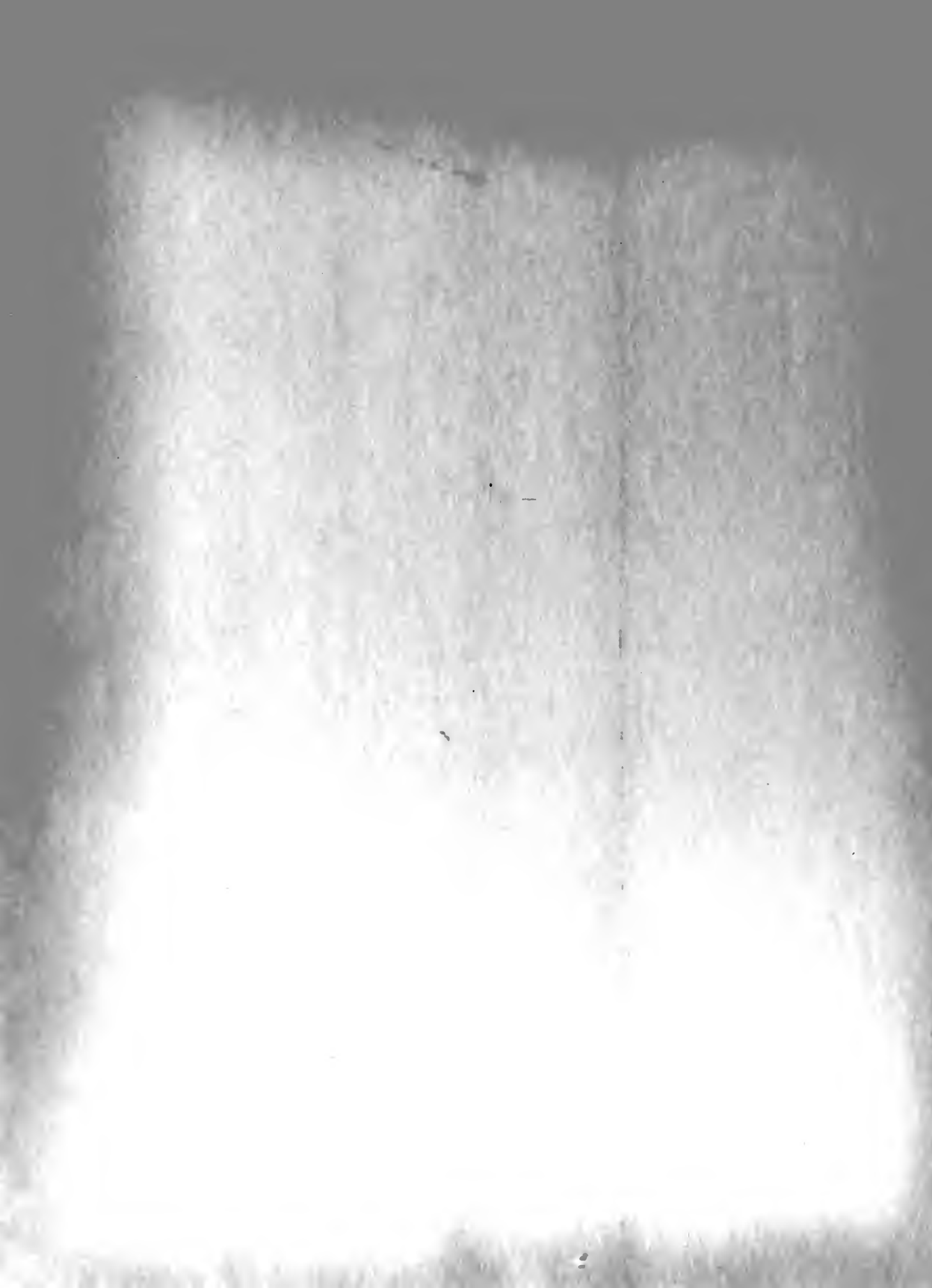
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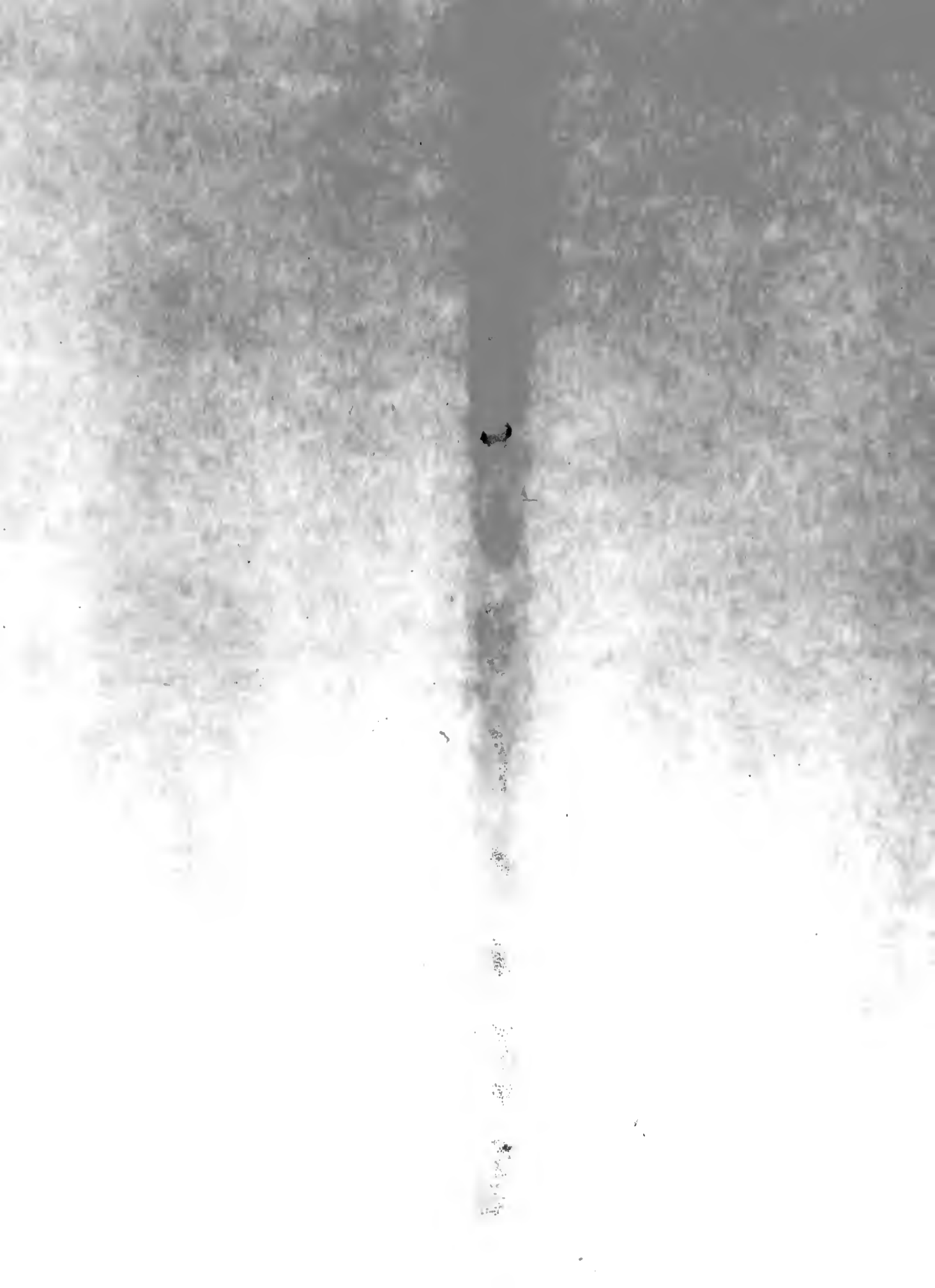Livingston, M. S., and H. A. Bethe. "Nuclear Dynamics, Experimental." Reviews of Modern Physics, 9, 245-390 (1937).
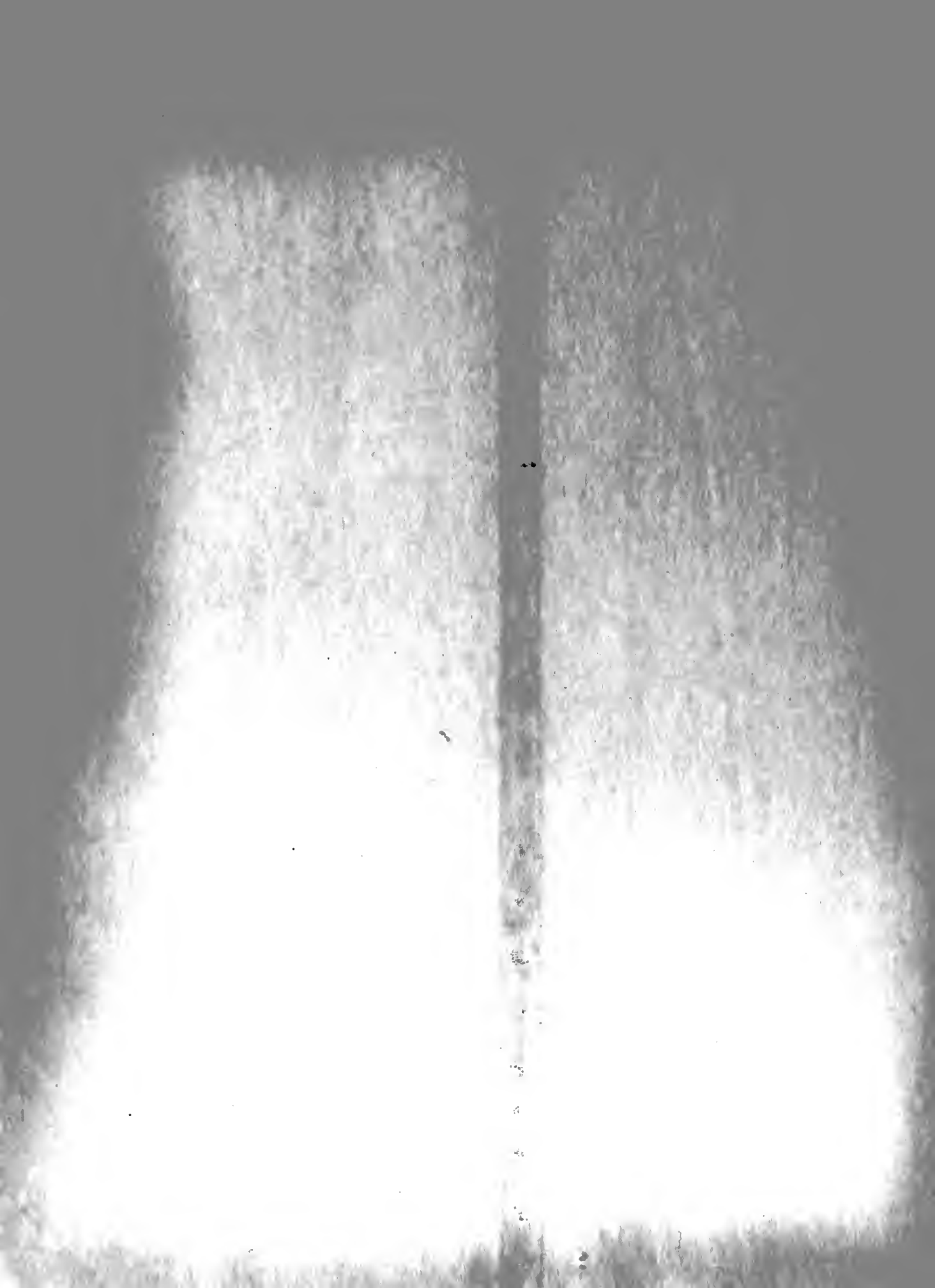
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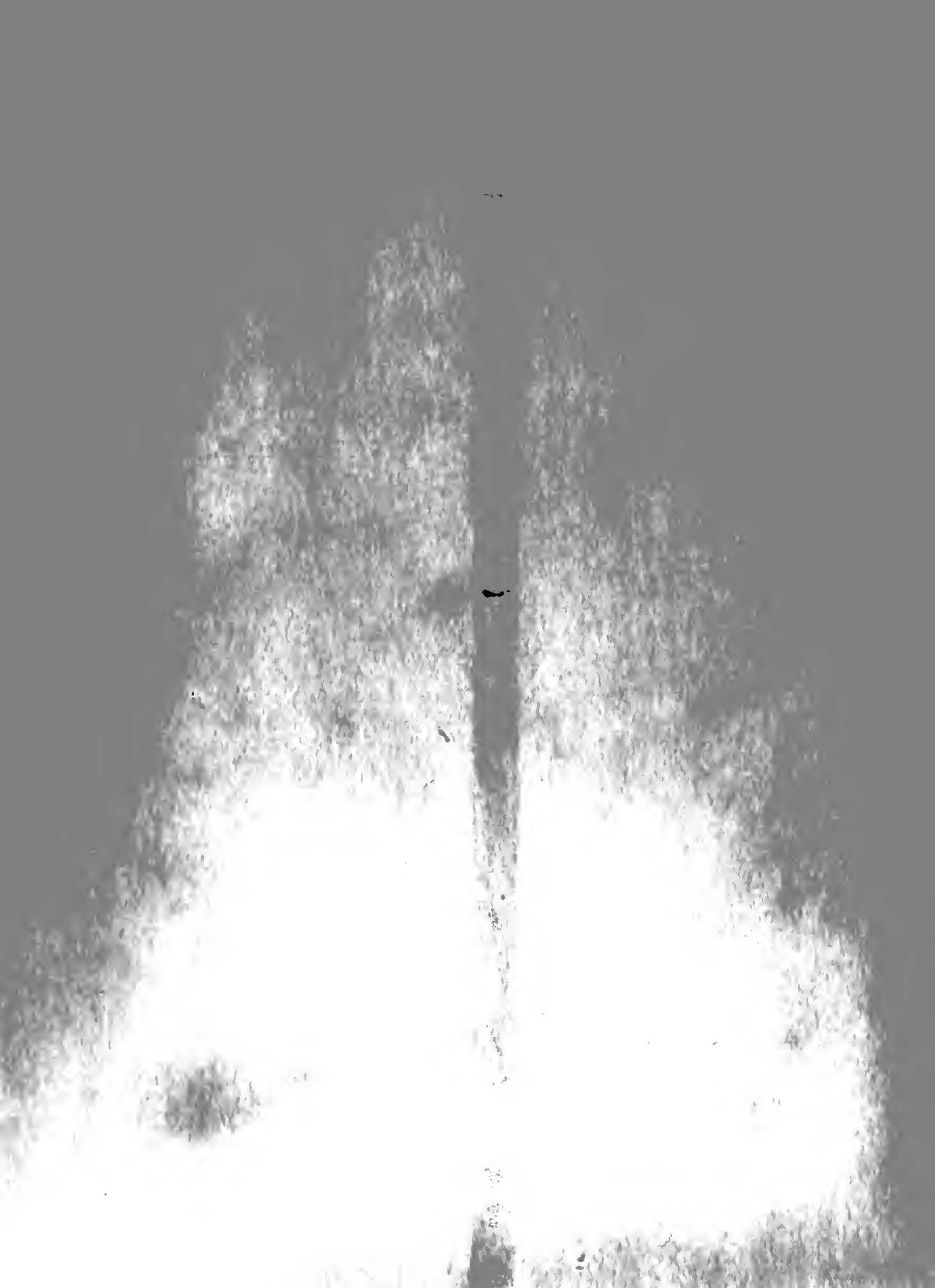
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