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A Cosmic Ray Experiment Using Nuclear Photographic Emulsions

Mercedes Merner

MERNER — COSMIC RAY EXPERIMENT USING NUCLEAR PHOTOGRAPHIC EMULSIONS

A COSMIC RAY EXPERIMENT
USING NUCLEAR PHOTOGRAPHIC EMULSIONS

A Thesis
Presented to
the Faculty of the Department of Physics
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

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by
Mercedes Merner
June 1949

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

France V. Scholes
DEAN

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Thesis committee

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CHAIRMAN

Stephen S. Friedland

Roy Thomas

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CHAPTER I

THE EXPERIMENT

A "camera" containing thirty-six nuclear plates was carried into the upper atmosphere to an altitude of twelve miles by a free balloon flight. These plates were arranged in four groups separated by successively thicker layers of steel so that nuclear events under different amounts of matter could be observed.

After recovery of the equipment these plates were developed and examined under the microscope. Four plates were selected for intensive investigation, and data was collected on the tracks found in the areas examined.

In the first part of this report nuclear plate technique will be discussed in general together with the properties of the particular Ilford C-2 emulsions used in this experiment. In the second part detailed information will be given on the arrangement of the plates in the "camera," the time exposed, and the searching procedure used. In the third part the data collected in the examination of a total area of 4.8 cm^2 will be tabulated and analyzed.

CHAPTER I

THE [illegible]

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CHAPTER II

NUCLEAR EMULSIONS

The photographic plates used in this experiment were 1.7 mm thick glass slides, 1 X 3 inches in size, coated with .2 mm thick Ilford C-2 emulsions, manufactured by Ilford Ltd., London, England. These emulsions have been especially developed to record the tracks of charged particles.

The Photographic Proces.[1]

The photographic emulsion, nuclear or otherwise, consists of a light-sensitive substance, such as silver bromide crystals, embedded in a material which will insure uniform distribution and transparency to light. Because of its suitable properties and availability, gelatin is usually used. This emulsion, after coating on a backing of glass or celluloid, is then ready for use.

As an incoming beam of light passes through the emulsion some of the photons react with the ions of which the silver bromide crystals are built up. The photon supplies enough energy to liberate an electron from a bromine ion thus allowing it to move freely through the crystal lattice of silver and bromine ions. The neutral bromine atom then

1 Charles E. K. Mees, The Theory of the Photographic Process (New York: The Macmillan Company, 1942), 1124 pp.

CHAPTER II

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The photographic plates used [illegible]

1.7 mm thick glass slides. [illegible]

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thus allowing it [illegible]

of silver and bromine [illegible]

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1 [illegible]

Process (New York: [illegible]

diffuses into the gelatin; the electron drifts until it reaches a "sensitivity speck," thought to be silver sulfide particles which are present as a deliberate impurity in the silver bromide. Here the electron is "trapped" by a region of low potential energy. The electrostatic field set up by the trapped electron attracts a silver ion which is neutralized to form an atom of free silver. The free silver acts in the same way as the sulfide, and the process is repeated building up a grain of metallic silver. The presence of conduction electrons during exposure is shown by the photoconductivity of halide crystals; the mobility of silver ions in the crystal lattice has been shown by measurements of conduction under conditions of darkness.

The silver specks formed in this manner throughout the emulsion constitute what is called the "latent image." During the development process they act as nuclei for the reduction of an entire silver bromide crystal to metallic silver. The whole crystal thus acts as a unit during development, magnifying the original free silver content by a factor as high as 10^4.[2] Experiments seem to show that developability of a grain does not depend on the number of silver specks contained in it but on the presence of one of

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2 Herman Yagoda, "Tracks of Densely Ionizing Particles in Nuclear Emulsions," Nucleonics, 2:5, 1948.

diffuses into the [illegible] reaches a "sensitivity speck," [illegible] particles which are present [illegible] silver bromide. Here [illegible] of low potential energy. [illegible] the trapped electron attracts [illegible] to form an atom of [illegible] silver. [illegible] in the same way as the [illegible] building up a grain of [illegible]. The presence of conduction electrons during exposure [illegible] conductivity of silver [illegible] in the crystal lattice [illegible] conduction under conditions of [illegible].

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2 Herman Yagoda, "[illegible] in Nuclear Emulsions," Nucleonics, [illegible]

proper size and location.

It is seen that formation of the latent image is due to the release of electrons, and any other process which produces free electrons in the emulsion would be expected to show a blackening of the film upon development. For instance, the trail of electrons left by an ionizing particle passing through the emulsion should render its track developable. Particles from radioactive substances do indeed blacken an ordinary photographic plate; however, the tracks of alpha particles are distorted and confused by the interlocking halide crystals of ordinary emulsions while the grains forming the tracks of less highly ionizing particles such as protons are so far apart that they are lost in the general background of fog.

Composition of Nuclear Emulsions

Workers in several countries conducted investigations to improve the quality of photographic emulsions for recording the tracks of charged particles.[3] Recently, plates have been developed that record electrons and other particles even near minimum ionization. (see Fig. 1)

This improvement has been achieved by increasing the silver bromide content by a factor of as high as eight while

3 Maurice M. Shapiro, "Tracks of Nuclear Particles in Photographic Emulsions," Reviews of Modern Physics, 13: 58-71. 1941.

proper size and location.

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<u>Comparison of Nuclear Emulsions</u>

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This [illegible] has been [illegible] silver bromide [illegible]

8 Maurice L. Shapiro, "Tracks of Nuclear Particles in Photographic Emulsions," Reviews of Modern Physics, [illegible] 1941.

at the same time decreasing the size of the individual crystals and keeping them isolated in the gelatin.[4] Thus the track of a highly ionizing particle will not spread out into an irresolvable mass, while that of a proton, for instance, will still be easily visible under the microscope. A list of the properties of typical optical and nuclear emulsions is given in Table I.

The response to hydrogen peroxide as shown in Table I is of great interest as it has been shown to be a major factor in the fading of the latent image in nuclear emulsions.[5] In cosmic ray work, for example, where it is often desirable to expose plates for long periods of time in order to secure a greater number of rare events, fading becomes a matter of considerable importance. As indicated above, hydrogen peroxide, even in minute quantities, blackens ordinary coarse-grained emulsions. In nuclear emulsions, on the contrary, it has been used with considerable success in erasing all previous tracks so that they will not be confused with the tracks recorded during the actual experiment. During traversal of the gelatin by the ionizing particle, the water contained in it is decomposed and hydrogen peroxide generated.

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4 J. H. Webb, "Photographic Plates for Use in Nuclear Physics," Physical Review, 74:514, 1948.

5 Yagoda, op. cit., p.5.

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a J. R. [illegible], "[illegible]" Physics, [illegible]

b Yagoda, op. cit., [illegible]

Properties	Optical Type	Nuclear Type (Ilford C-2)
AgBr/Gelatin, by weight	47/53	80/20
AgBr/Gelatin, by volume	15/85	45/55
Grain diameter	1 to 315 microns	0.1 to 0.6 microns
Grain separation	Interlocking	Isolated by gelatin
Emulsion thickness	2 to 3 microns	25 to 200 microns
Emulsion weight	1 to 4 mg per cm^2	5 to 20 mg per cm^2
Sensitivity to light	very high	poor
Sensitivity to H_2O_2 vapor	fogging	latent image eradication
Response to alpha particles	dense blackening	individual tracks
Response to beta particles	moderate blackening	faint fog
Response to gamma radiation	faint blackening	almost none

Table I

Properties of Typical Optical and Nuclear Emulsions[6]

6 Yagoda, op. cit., p. 5.

If development is delayed, this peroxide will have time to diffuse into the halide crystals and act on the silver specks forming the latent image. It has been shown that hydrogen peroxide exerts a solvent effect on colloidally dispersed silver, which could be used to account for its bleaching of the latent image. However, it is difficult to explain why it should act so differently in the two emulsions. This fading may be reduced by lowering the gelatin content, so that each particle will have less opportunity to form H_2O_2, and storing in a cool dry place to lower the water content in the gelatin and hinder diffusion.

Developing Process for Thick Emulsions

As will be shown in the next section, identification of the particle making a certain track is usually impossible unless it reaches the end of its path in the emulsion, and inaccurate unless the total length of the track is long. It is thus evident that it is desirable to use emulsions as thick as possible. The short working distance of a high-power objective limits emulsions to less than 300 microns of thickness, although reflecting microscopes[7] have been successfully used to overcome this difficulty. With these

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7 W.J. Bates and G. P. S. Occhialini, "Applications of the Reflecting Microscope to the Nuclear Plates Technique," Nature, 161:473, 1948.

If development is delayed, [illegible]
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water content in the gelatin and [illegible]

Developing Process for Thick Emulsions

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Nature, 161: [illegible]

instruments tracks in the emulsion may even be examined through the glass backing. In addition, great thickness tends to distort the images of tracks due to scattering of the light in its long path through the inhomogeneous gelatin and silver specks of the film.

There are major difficulties, however, involved in the use of emulsions as thick as 50 to 200 microns, those commonly in use at the present time. Since grain-counting is extremely important in determining the characteristics of the particle responsible for a certain track, uniform development at all depths is essential. Ordinary methods, suitable for optical emulsions a few microns thick, give a much higher grain density at the top of a 200 micron emulsion than at the bottom. This is due to the great amount of time needed for the solutions to diffuse through the emulsion.

Developing procedures yielding uniform grain density at all depths have been worked out by a number of investigators. All these involve some method for allowing developing solutions to penetrate the plate throughout before actual reduction of the bromide crystals takes place. This may be done by first soaking the plates in solutions at such a low temperature that development will not occur,[8] or by

8 C. C. Dilworth, G. P. S. Occhialini, and R. M. Payne, "Processing Thick Emulsions for Nuclear Research," <u>Nature</u>, 162:102-103, 1948.

instrument's [illegible] in the emulsion [illegible] through the glass backing. In addition, [illegible] boards to distort the traces [illegible] the light in its long [illegible] and silver grains of the film.

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[1] R. C. Gilbert, [illegible] "Processing [illegible]", Science, 153:153-155, 1941.

chemically prohibiting development until the emulsion is completely permeated.

The method used in developing the plates studied in this experiment is of the latter type and was adapted by Blau and De Felice[9] for use with nuclear emulsions. The plate is first soaked in a solution containing most of the components of an ordinary developer with the exception of alkali. This lack of alkali keeps the rate of development very low. After a sufficient amount of time has been allowed for diffusion, the plates are placed in the second bath which contains the missing alkali and an additional amount of developing agent. Since the emulsion is thoroughly permeated, development can proceed evenly. The details of the procedure are as follows:

Step 1: Soak in water for 10 min.
Step 2: Solution A for 30 min. (slight agitation)
Step 3: Solution B for 30 min. (no agitation)
Step 4: 2% acetic acid 15 min. (agitation)
Step 5: Fix in F-5 at 74° F with constant agitation 6-8 hrs.
Step 6: Wash in running water 2 hrs.

<u>Solution A</u>:

Elon	1.1 gm
Na_2SO_3	24.0 gm
Hydroquinone	4.4 gm
KBr	2.0 gm
H_2O to make	2000 cc

9 M. Blau and F. A. De Felice, "Development of Thick Emulsions by a Two-Bath Method," Physical Review, 74:1198, 1948.

chemically prohibitive, development until the [illegible] is completely permeated.

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Step 1: [illegible]
Step 2: Solution [illegible]
Step 3: [illegible]
Step 4: [illegible]
Step 5: [illegible]
Step 6: [illegible]

Solution A:

Elon	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
H_2O to make	[illegible]

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9. [illegible] Kirk and [illegible] Pallice [illegible] 1949.

Solution B

Stock D-19 developing agent	400 cc
H_2O	1600 cc
Additional Na_2CO_3	16 gm

A constant temperature is maintained throughout the process by keeping the containers of the different solutions immersed in a tank of water. This water is constantly circulated by a pump through refrigerator coils which keep it within the range of 18-21°C by thermostatic control. Regulation of temperature is necessary during development to produce uniform results and during fixing to protect the emulsions from excessive swelling.

The holder supporting the plates in the solutions is attached to a rod which is moved up and down a distance of three centimeters by an electric motor. The rod oscillates at three cycles per minute for "agitation" and at two cycles per minute for "slight agitation."

It should be noticed that a time of six to eight hours is required for the fixing bath to remove the undeveloped silver bromide grains. The removal of this component causes the emulsions to shrink a little over 50 per cent in thickness upon drying. Considerable difficulty has been experienced with the peeling of 200 micron emulsions from their glass backings due to the strain produced by this shrinkage.

Energy Loss, Energy, and Range Relationships

A charged particle moving through matter loses energy by two principle processes: ionization and radiation. The loss due to ionization at first decreases rapidly, levels off in regions of kinetic energy near the particle's rest energy, and finally increases slowly due to the relativistic increase of the effective range of the electric field associated with the moving particle. In Fig. 1 curves of energy loss against energy are shown for several particles. Since grain density in nuclear emulsions is directly dependent on energy loss along the track, study of the relationships between energy loss per unit path, energy, and range of a particle afford a means for the determination of its mass and charge through knowledge of variation of grain-density with residual range.

The energy lost per unit path in radiation by a charged particle of mass M and charge ze due to acceleration in the fields of nuclei of atomic number Z is given by the following expression:[10]

$$-\frac{dE}{dx} = \frac{z^4 Z^2}{M^2} E f\left(\frac{E}{M}\right) \qquad (1)$$

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10 F. K. Richtmyer and E. H. Kennard, Introduction to Modern Physics (New York: McGraw-Hill Book Company, Inc., 1942), p. 683.

Energy Loss, [illegible] and [illegible]

A charged particle [illegible] through [illegible] [illegible] by two principal processes: [illegible] and [illegible]. [illegible] loss due to [illegible] [illegible] [illegible] [illegible] are in regions of electric [illegible] [illegible] the [illegible] energy, and finally increases [illegible] [illegible] increase of the [illegible] [illegible] [illegible] ciated with the moving particle. [illegible] loss against energy [illegible] for [illegible] [illegible]. [illegible] grain density [illegible] energy loss [illegible] [illegible] lower energy [illegible] [illegible] [illegible] [illegible] ticle [illegible] the [illegible] [illegible] change [illegible] [illegible] of [illegible] [illegible] residual range.

The energy loss [illegible] of a charged particle of mass M and charge ze [illegible] in the field of [illegible] [illegible] following expression:

[illegible]

10 [illegible] and [illegible] [illegible] 1951), p. [illegible]

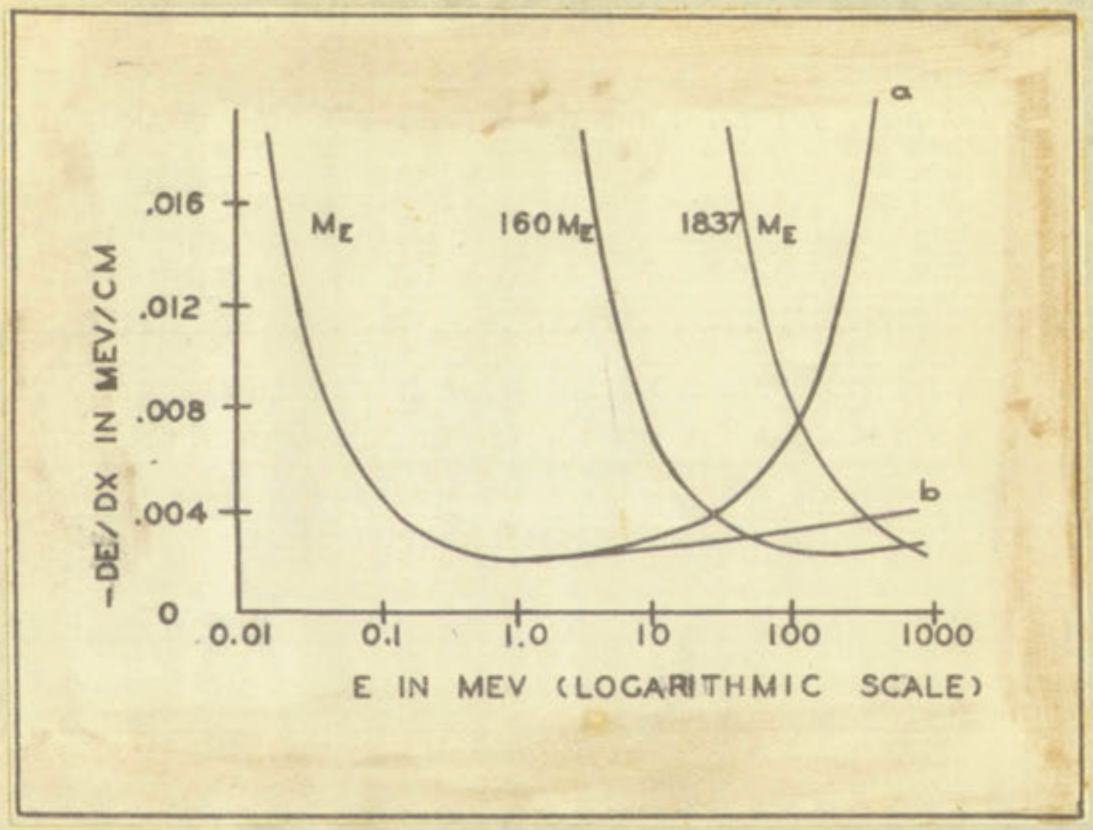

Fig. 1. Energy loss in air plotted against energy for a proton, electron, and particle with mass 160 times that of an electron. Curve a shows the total energy loss for an electron, b the loss due to ionization alone for the same particle. For the proton and meson in the energy ranges shown, loss duo to radiation is negligible.[11]

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11 Richtmyer and Kennard, op. cit., p. 682.

Fig. 1. Energy loss [illegible] for a proton, electron [illegible] that of an electron. [illegible] for an electron, [illegible] such particle. [illegible] shown. [illegible] 11

11 Richtmyer and Kennard, [illegible] p. 171.

where f(E/M) is a function that is the same for all particles and all materials. At high energies f becomes nearly constant. The value of this expression for an electron in air is given by the difference between curves a and b in Fig. 1. The radiation loss would be much higher in lead than in air for the same energies of the electron due to the Z^2 dependence.

From (1) the energy loss by an electron of mass m moving with kinetic energy E_e is

$$-\frac{dE}{dx} = \frac{Z^2}{m^2} E_e f\left(\frac{E_e}{m}\right)$$

The same energy loss for a particle of mass M and electronic charge will occur in general at some other energy E_M and is given by

$$-\frac{dE}{dx} = \frac{Z^2}{M^2} E_M f\left(\frac{E_M}{M}\right)$$

Equating these two quantities and considering f(E/M) constant over the ranges involved the expression

$$\frac{E_e}{m^2} = \frac{E_M}{M^2} \text{ or } E_M = \frac{M^2 E_e}{m^2} \qquad (2)$$

is obtained. From inspection of the curves in Fig. 1 it can be seen that the radiation loss is negligible for an electron of energy smaller than .5 Mev or its rest energy. Therefore from (2) a particle of mass M will experience a negligible loss of energy from radiation if the condition

$$E_M << \frac{M^2}{m^2} \ .5 \text{ MeV} \qquad (3)$$

where $f(Z,v)$ is a function that is the same for all [illegible] and all materials, and [illegible] is [illegible] constant. The value of this expression for [illegible] is given by the difference between [illegible] The radiation loss [illegible] for the same energy of the electron [illegible] reference.

From (1) the energy loss by radiation of a particle moving with kinetic energy [illegible] is

$$-\frac{dE}{dx} = [illegible]$$

The same energy loss for a particle of mass [illegible] electronic charge will occur in general at a new energy [illegible] given by

$$-\frac{dE}{dx} = [illegible]$$

Equating these two quantities and considering [illegible] over the ranges involved the expression

$$\frac{E_1}{M} = [illegible] \text{ or } E_1 = [illegible] \qquad (8)$$

is obtained. From [illegible] it [illegible] be seen that the radiation loss is [illegible] of energy smaller than [illegible]. Therefore, from (8) a particle of mass [illegible] will [illegible] loss of energy from [illegible] if the condition

$$E_1 << \frac{M^2}{\mu^2} \cdot 5 \text{ Mev} \qquad (9)$$

is satisfied.

For protons this critical energy is around 10^6 Mev, for mesons, 10^4 Mev. In emulsions of the type used here, a particle must have an energy loss of at least .012 Mev per centimeter of its path to render the track visible. From Fig. 1 it may be seen that mesons will be recorded to a maximum energy of 5 Mev and protons to a maximum of 50 Mev. Thus the radiation loss need not be taken into account in studying the energy loss and grain-density relationships; the energy loss is almost entirely due to ionization.

The relativistic expression giving the energy loss per unit path, dE/dx, due to the ionization of a particle of charge ez and velocity v is[12]

$$-\frac{dE}{dx} = \frac{-4\pi(ez)^2 e^2 N Z}{mv^2}\left[\ln \frac{2mv^2}{I} - \ln (1-\beta^2) - \beta^2\right] \quad (4)$$

where Z is the atomic number of the stopping material, N is the number of atoms per cubic centimeter of the material, I is its average ionization potential, m is the mass of an electron, and $\beta = v/c$, c being the velocity of light.

This formula is a valid expression of the energy loss for particles much heavier than electrons and for energies above 1 Mev and below those of (3). The curve for a proton

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12 M. S. Livingston and H. Bethe, "Nuclear Physics: Part C. Nuclear Dynamics, Experimental," Reviews of Modern Physics, 9:261-290, 1947.

traveling through air is shown in Fig. 2a.

The total range R of the particle in the material is related to the energy loss curve by the integral:

$$R = \int_0^E \frac{dE}{\frac{dE}{dx}} \tag{5}$$

and may therefore be found from investigation of the area beneath the dE/dx versus energy curve. The range-energy curve for a proton in air is shown in Fig. 2b. From it and the curve of Fig. 2a the plot of energy loss versus range may be drawn.

Knowing the curves for energy loss and range for one particle of certain charge and mass, it is possible to determine these curves for particles of differing z and M. From (4) it can be seen that at the same velocities, dE/dx is independent of the mass and directly proportional to the square of the charge. Therefore

$$\frac{dE}{dx}(v) = \left(\frac{z}{z_o}\right)^2 \frac{dE_o}{dx}(v) \tag{6}$$

where dE_o/dx and dE/dx are the energy losses of the known particle of charge $z_o e$ and a second particle of charge ze, respectively, both particles traveling at the same velocity.

Similar relations between the range-energy curves may be found from the expression for R given in (5). At equal velocities $E = M/m\ E_o$, where m is the mass of a particle of

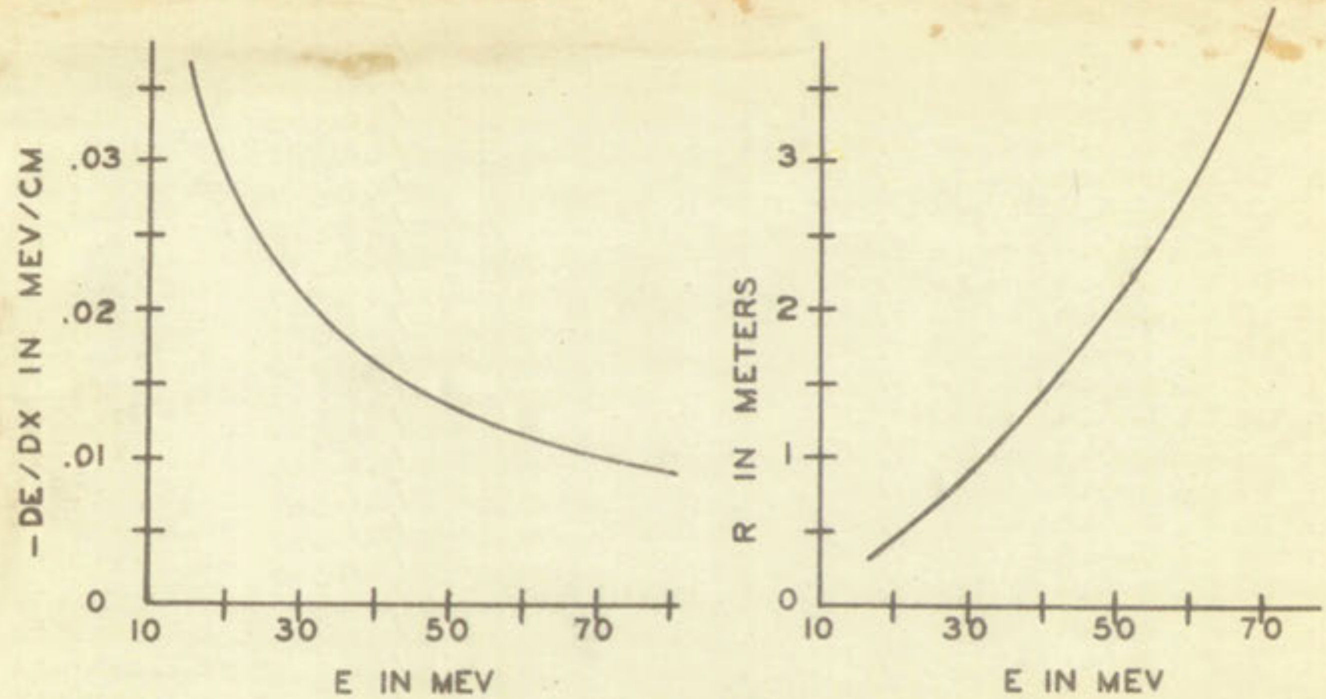

FIG. 2a

FIG. 2b

Fig. 2. Theoretical range, energy, and energy loss relations[13] for a proton in air. (a) Energy loss plotted against energy. (b) Range plotted against energy.

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13 J. H. Smith, "Theoretical Range-Energy Values for Protons in Air and Aluminum," Physical Review, 71:33, 1947.

energy E_o and M is the mass of the second particle of energy E. From this and (5) and (6) may be written

$$R(r) = \int_0^E \frac{dE_o}{\frac{dE}{dx}} = \int_0^{E_o \frac{M}{m}} \frac{dE_o}{\left(\frac{z_o}{z}\right)^2 \frac{dE_o}{dx}} = \frac{M}{m}\left(\frac{z}{z_o}\right)^2 R_o(v)$$

$$\text{or } R(v) = \frac{M}{m}\left(\frac{z}{z_o}\right)^2 R_o(v) \qquad (7)$$

where R is the known and R_o the unknown range.

Again using the relation that at the same velocities $E = M/m\ E_o$, (6) and (7) may be expressed in terms of the energy of the particles as follows:

$$\frac{dE}{dx}(E) = \left(\frac{z}{z_o}\right)^2 \frac{dE_o}{dx}\left(\frac{m}{M}E\right) \qquad (8)$$

$$R(E) = \left(\frac{z_o}{z}\right)^2 \frac{M}{m} R_o\left(\frac{m}{M}E\right) \qquad (9)$$

For an example, from the dE/dx versus range curve given in Fig. 2b for a proton, the rate of loss of energy at 60 Mev is .012 Mev/cm. For a deuteron of the same energy, since the charge is the same, using (8) and (9) and the curves of Fig. 2 gives

$$R_{deuteron}(60\text{ Mev}) = \frac{2}{1}(1)^2 R_{proton}(\tfrac{1}{2}\text{X}60\text{ Mev}) = 2\text{X}7 = 14 \text{ meters}$$

$$\frac{dE}{dx}_{deuteron}(60\text{ Mev}) = (1)^2 \frac{dE}{dx}_{proton}(\tfrac{60}{2}\text{Mev}) = .018\ \frac{\text{Mev}}{\text{cm}}$$

In this way a family of curves for different charges and mass could be drawn. The minimum would have the same value for particles of the same charge and different mass, but

energy E_0 and [illegible]

B. From this and [illegible] and [illegible] [illegible]

$$[illegible]$$

or $N(r) =$ [illegible]

where R is [illegible] and [illegible]

Again using the relation [illegible]

E = [illegible] and [illegible] energy of the particles as follows

$$[illegible]$$

$$N(E) = [illegible]$$ [illegible]

For an example, [illegible] given in Fig. [illegible] at 60 Mev is .015 Mev/cm. [illegible] since the charge is the same. Using [illegible] and [illegible] and the curves of Fig. [illegible] gives

$$[illegible]$$

In this way a family of curves [illegible] could be drawn. [illegible] for particles of the same [illegible]

would be displaced to the right for mass larger than that of a proton and to the left for mass smaller. The value at the minimum in case of particles of larger charge would be increased over that of the proton by a factor equal to the square of the ratio of the second charge to that of the proton.

Mass Determination Methods

If the relation between dE/dx and the grain density of a certain emulsion were accurately known, the family of curves discussed above would provide a method for the determination of the mass and charge of the particle responsible for producing a given track.

In practice, since different batches of emulsion differ in their response to ionization, a set of calibration curves[14] is made up of grain-density against a range of a group of tracks known to be due to a certain particle; in cosmic ray work this would usually be a group of tracks whose characteristics qualitatively identified them as fast protons. The spread in the grain-density versus range curves obtained from this group of particles would give an indication of the amount of fading that had taken place. The

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14 C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, "Processes Involving Charged Mesons," Nature, 159:695, 1947.

would be displaced to the right [illegible] for a proton and to the left for [illegible] particle. [illegible] minimum in case of particles of [illegible] created over that of the [illegible] square of the ratio of the [illegible] tons.

[illegible]

If the relation between [illegible] of a certain emulsion were [illegible] curves discussed above would provide a method for the determination of the mass and charge of the particle [illegible] for producing a given track.

In practice, since different [illegible] differ in their response to [illegible] a set of [illegible] curves[14] is made up of grain-density [illegible] group of tracks known to be due to [illegible] [illegible] characteristic [illegible] The spread is [illegible] obtained from this group [illegible] tion of the [illegible]

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14 C. M. G. Lattes, [illegible] and C. F. Powell, "[illegible]," Nature, 159:[illegible], 194[illegible].

degree of reliability of this type of mass determination would thus be indicated in this particular exposure. From the mean of the curves thus produced, a family of curves could be calculated (by the methods discussed in the previous section) for particles of various charges and mass, allowing for each the expected deviation from the mean due to fading. Comparison of these graphs with that of the grain-density versus range variation of an unknown track would then identify the particle making the track.

It should be noticed that if a track does not end in the emulsion, then two of either mass, charge, or energy must be known approximately before the third can be determined.

An exception to this occurs in the case of a particle at minimum ionization. Then the ratio of its grain-density to that of a proton also at minimum ionization is equal to the square of the ratio of their respective charges. Therefore, if, as in the case of the recently discovered very heavy nuclei in cosmic radiation at great heights,[15] the track at minimum ionization is visible, the charge may be determined if the grain density at minimum ionization of

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15 H. L. Bradt, P. Freier, E. J. Lofgren, E. P. Ney, F. Oppenheimer, and B. Perers, "Evidence for Heavy Nuclei as a Component of Primary Cosmic Radiation," Review of Modern Physics, 21:101-103, 1949.

degree of reliability of [illegible]. If [illegible] of data [illegible] obtained, it would then be indicated for the particular [illegible] range [illegible] the mean of the curves thus produced [illegible] could be calculated (by the method [illegible] in the previous section) for particles of various charges and mass, allowing for each the expected deviation from [illegible]. Comparison of these groups with that of the [illegible] versus range variation [illegible] would then identify the particle making the track.

It should be noticed that [illegible] in the emulsion, that [illegible] of either [illegible] must be known approximately before the [illegible] can be determined.

An extension of this method to the [illegible] at minimum ionization. Since the [illegible] to that of a proton [illegible] at minimum [illegible] the square of the [illegible] form, [illegible] heavy nuclei in cosmic radiation at great [illegible] track at minimum ionization [illegible], the [illegible] determined [illegible].

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10 [illegible]

[illegible] *Physics*, [illegible]

some other particle of known charge in the same emulsion may be found. Once the charge is determined the approximate mass is also known.

The relation of grain density to energy loss is very closely constant so long as the density of the grains rendered developable by the ionizing particle does not approach the density of the total number of silver halide grains in the emulsion.[16] Once this has happened the grain-density cannot become greater even for considerable increases in ionization of the incoming particle. Since this condition is reached toward the end of their path by all particles, a track length of 100 to 200 microns is necessary for positive identification of protons and deuterons, and a much longer one if differentiation between different meson masses is desired.

It is possible to determine the ratios of the masses of two tracks made at the same time by particles having the same charge to a much greater degree of accuracy than the absolute values.[17] From (6) of the preceding section, it is seen that for z/z_0 equal to unity the energy loss and

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16 Webb, op. cit., p. 526.

17 C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, "A Determination of the Ratio of the Masses of π and μ Mesons by the Method of Grain-Counting," Proceedings of the Physical Society, 61:173-183.

some other particle [illegible] the energy [illegible] can be found. [illegible] is also known.

The [illegible] closely [illegible] developable by the [illegible] density of the [illegible] emulsion.[16] [illegible] become [illegible] of the incoming particle. [illegible] toward the end of [illegible] particles, [illegible] of 100 to 800 microns is necessary for [illegible] tion of protons and [illegible] ferentiation between [illegible].

It is [illegible] of two [illegible] same charge [illegible] absolute values.[17] [illegible] seen that [illegible]

16 [illegible], *op. cit.*, [illegible].

17 [illegible] Powell, [illegible] *Proceedings of the Physical Society*, [illegible].

therefore grain density of two particles of different masses but equal velocities is identical. The ranges of the particles at the same velocities are, however, related by the ratio of their masses (7). Therefore if places are found in the two tracks where grain densities are equal, the residual ranges will be related by the ratio of the masses. This method is particularly useful in the case of π-μ meson decay[18] for it eliminates errors due to fading and variability of the emulsion since the tracks are produced within a short range of each other in time and space and these factors should be equal. The assumption must be made, of course, that the charges of the two particles are identical. Once the ratios are known, if the μ meson is identified with those commonly found in cosmic rays at low altitudes then the mass of the π meson may be determined.

Another method[19] sometimes used to determine the mass of a particle is based on its small-angle scattering and is therefore not dependent on evenness of development or degree of fading. A charged particle in passing through a medium

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18 C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, "Observations on the Tracks of Slow Mesons in Photographic Emulsions, Part 1," Nature, 160:453-456, 1947.

19 Y. Goldschmidt-Clermont, D. T. King, H. Muirhead, and D. M. Ritson, "Determination of the Masses of Charged Particles Observed in the Photographic Plate," Proceedings of the Physical Society, 61:183-194, 1948.

suffers frequent small deflections due to elastic collisions with the nuclei of the atoms of which it is composed. The angular deflections due to these collisions are statistically distributed and a function of the energy and therefore of the residual range and mass of the particle. The theoretical form of this function has been worked out, and a family of curves for different particles somewhat similar to those for grain density may be drawn. A comparison of experimental with calculated curves will serve to identify the particle making the track. Since a relatively larger statistical error is involved due to the smaller number of scatterings than grains in a given length of track, grain-counting is an inherently more reliable method for mass determination. With most exposures of reasonable length, fading may be kept at a minimum and proper care and developing processes will insure uniform grain distribution. Recent investigations to develop more accurate procedures for measuring small-angle scattering have not resulted in a great deal of success.[20]

Nevertheless this method is of great importance when long exposure makes fading inevitable. The difference in the scattering characteristics of mesons and protons, for example, is so great that they may often be identified by a quick inspection of the tracks.

20 S. A. Goudsmit, and W. T. Scott, "Proposed Method for Measuring Scattering of Particle Tracks," Physical Review, 74:1538, 1947.

surface pressure small deflection [illegible] is directly [illegible]
with the [illegible] of the [illegible]
angular [illegible]
distribution [illegible]
the [illegible]
form of this [illegible]
curves [illegible]
quite [illegible]
with calculated [illegible]
within [illegible]
may be [illegible]
than [illegible]
inherent [illegible]
With [illegible]
as a [illegible]
linear [illegible]
develop [illegible]
scattering [illegible]

Nevertheless, [illegible]
long [illegible]
the [illegible]
example, [illegible]
quick [illegible]

[illegible]

CHAPTER III

EXPERIMENTAL PROCEDURE

Construction of the Plate Holders

The "camera" in which the plates were carried aloft is shown in Fig. 3. It consists of ten layers of aluminum or steel, each numbered on the side for correct assembly. Each of the four holders (Fig. 3b) contained nine Ilford C-2 plates, making a total of thirty-six. Each plate was numbered in the lower right-hand corner and placed in position with the emulsion up in the manner as shown in Fig. 3b. There was no paper or other packing placed between the layers of plates. After all nine were put in position, they were secured from moving about by a strip of gummed tape across each end. The small gap left at the side after the plates had been pushed as far to the left as possible was filled with a roll of paper. Paper used by the manufacturer to separate the plates in the original packing was used to avoid possible radioactive contamination. The depression left in the bottom of each holder by the thickness of the shoulder supporting the plates was fitted with a piece of 1/32 inch sheet aluminum to bring it flush with the edge of the holder. As the aluminum alloy used has a specific gravity of around 2.7, glass of 2.5, and the emulsion of 3.6, a

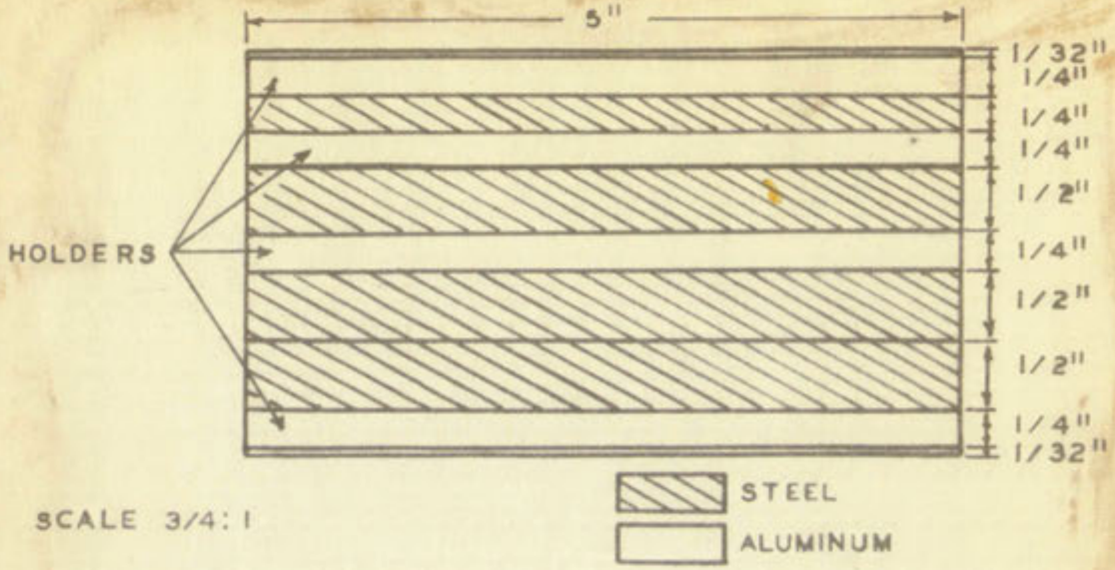

FIG. 3a

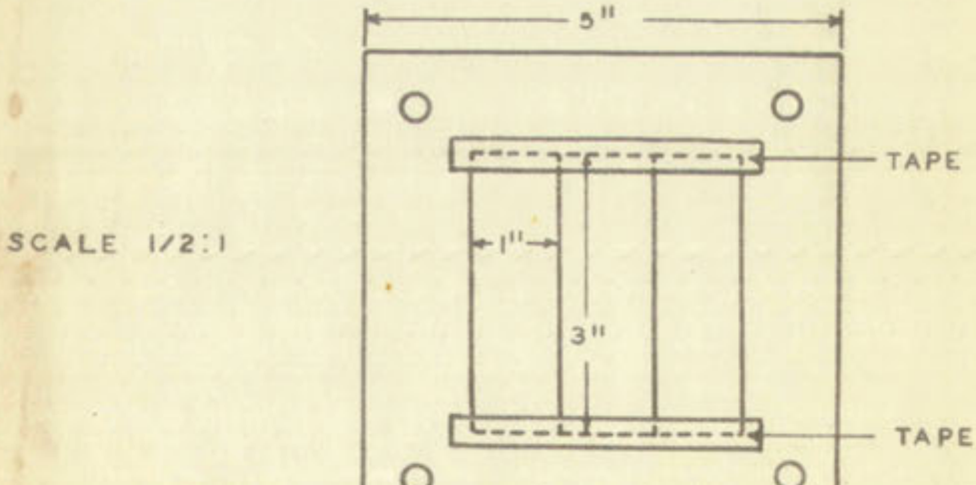

FIG. 3b

Fig. 3. (a) Front view of "Camera" with holders and steel plates.

(b) Holder loaded with photographic plates.

path of relatively uniform density was offered to incoming particles between the denser layers of steel of specific gravity about 7.6.

The holders were carefully constructed so that the relative position of the plates would be known closely enough so that tracks of large penetrating power might be traced through the different layers.

Since the nuclear plates used could be handled only under a Wratten No. 2 Safe-Light, loading the holders took a considerable length of time and was therefore done a few days ahead of time. The plates in their holders were stored in a refrigerator until the actual time of the balloon flight. The rest of the camera was kept at room temperature and assembled with the holders the morning of the flight. The completed assembly was placed in a close-fitting cardboard box, which was then padded and placed in a larger one.

This box after being sealed in the dark room was carried to the launching site and attached to the balloons with cords and a 3 X 15 foot yellow cloth streamer. The streamer permitted easier tracking of the balloons in flight and attracted attention to the equipment after descent, thus improving the chances for its recovery.

The Balloon Flight

The equipment was carried aloft by eight Dewey and

Almy balloons, two large ones (type J-2000) and six smaller ones (type J-350). The balloons were filled with helium and launched March 15, 1949 at 11:24 Mountain Standard Time. The launching site was just north of the University of New Mexico golf course.

Three theodolite stations were prepared to track the balloons. One was located on the roof of the Administration Building of the University of New Mexico in Albuquerque, one on Cedro Peak about 16 miles east and slightly south of Albuquerque, and the third at Otto 35 miles due east of Albuquerque. As expected, once above the influence of ground winds, the prevailing west winds carried the balloons eastward. Due to failure of radio communication and other unfavorable conditions the station at Cedro was unable to sight the balloons. The University station was able to see them at the launching site and tracked them successfully until 12:43 P.M. when they were lost in clouds on the eastern horizon. The station at Otto succeeded in obtaining two observations: at 12:15 and at 12:20 P.M.

The first balloon was seen to break at 12:29 and descent probably began soon after. From the two overlapping observations, fortunately occurring at a time near maximum height, the balloons were computed to be 52,800 feet above the ground. From this the rate of ascent was determined, and the maximum height attained by the equipment is estimated to

disky balloons, two large [illegible] -- [illegible]

weat[illegible] type J-[illegible]. [illegible] filled [illegible]

[illegible] 770, 1949 [illegible]. The launching site was just north of the [illegible] golf course.

Three theodolite stations were prepared to track the balloons. One was located on the roof of the [illegible] building of the University of New Mexico [illegible], one on [illegible] about [illegible] mile [illegible] of the [illegible], and the [illegible] Albuquerque. As expected, [illegible] Manzano Mountains. The prevailing west[illegible] the balloons east-ward. Due to failure of radio communication [illegible] university [illegible] the station [illegible] sight the balloons. [illegible] then at the launching site [illegible] until 12:44 P.M. [illegible] on [illegible]. [illegible] theodolites [illegible].

The first balloons [illegible] went generally [illegible]. [illegible] observations [illegible] height, the balloons were [illegible] the ground. [illegible] the rate of ascent [illegible] the maximum height [illegible]

be approximately 12 miles or 65,000 feet above sea level. Due to the few available observations on which it is based, this value may differ from the correct one by 10,000 feet or more.

The equipment and remains of the balloons were recovered a few days later near Pintado, New Mexico, 108 miles east and a little south of Albuquerque. The fall of the balloons had been observed by the local resident who reported their location, but there was no timepiece available and the estimated time of 1:00 P.M. is very approximate. The plates were therefore aloft for a time of at least 1 hour and 19 minutes by direct observation. The balloon seemed to be descending fairly rapidly when lost on the horizon so the total time of flight was probably no longer than an hour and a half.

The plates were brought back to Albuquerque and stored in a refrigerator. They were then developed in groups of twelve, the maximum allowed by the dark-room equipment, according to the process described on p. 9.

It appeared that a number of plates had been damaged due to their tight fit in the holders (there was considerable variation in the length of the plates). The numbering scheme is shown in Fig. 4a. Those plates too badly damaged to be available for study are shown cross-hatched.

The time involved in searching all the plates for events was so prohibitive that only a relatively small area

be approximately 1½ miles or [illegible]. Due to the few available [illegible] this value [illegible] ours.

The [illegible] a few [illegible] were [illegible] minutes by [illegible] sending [illegible] close of [illegible].

The [illegible] in a [illegible]. [illegible] twelve, the maximum [illegible] cording to the [illegible] for [illegible].

It appeared [illegible] due to the [illegible] mula [illegible] to be available [illegible].

[illegible]

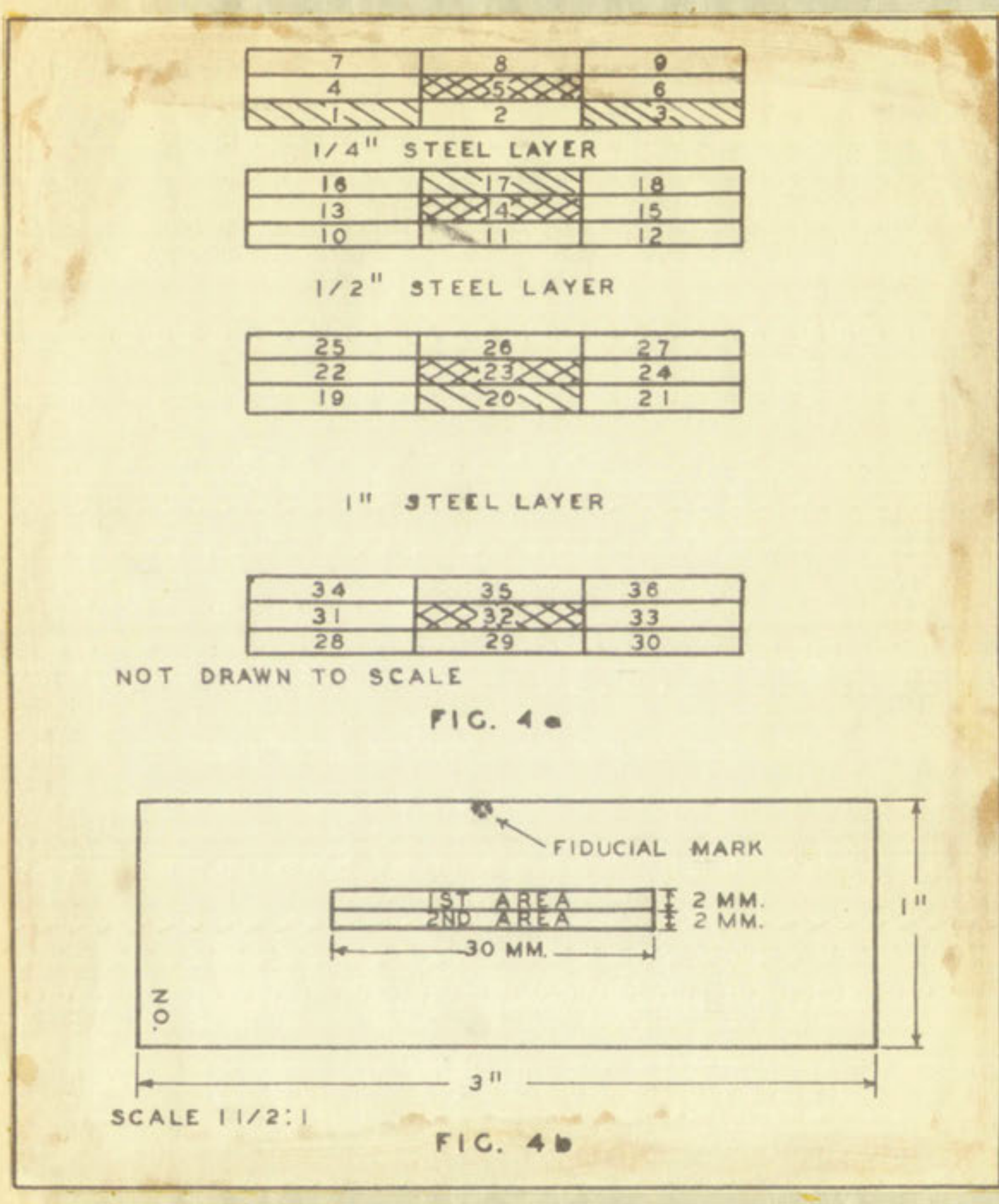

Fig. 4. (a) Numbering of plates. Those too badly damaged for use are diagonally ruled. The four selected for study are shown crosshatched. (b) Location of areas scanned on each plate.

was examined. The plates in the central column were selected because of their symmetry in regard to the amount of matter on each side. Of these the four shown in black in Fig. 4a constitute the only set for which a plate in the corresponding position in each of the four groups was in good enough condition to study.

Searching Procedure

A Spencer microscope with binocular, inclined body and mechanical stage was used for searching the plates. The three objectives available were 16 mm (10X) dry, 4 mm(44X) dry, and 1.8 mm(97X) oil immersion. The eyepieces used had a magnification of ten. Thus a maximum magnification of approximately 1000 was available. The 16 mm low power objective proved not to afford enough magnification to see the tracks of 10 to 60 microns length most commonly found. The 4 mm objective with its field of view of 350 microns rendered tracks of this size easily visible. Because of its small field of view the 1.8 mm oil immersion objective was used only to examine occasional events of unusual interest, while the 4 mm objective was used for routine scanning.

The eyepiece micrometer was calibrated for the 44X objective and 10X eyepieces. The smallest divisions were 1.6 microns apart while the twenty larger ones, each containing five of the smallest divisions, were at a distance of 8.0

was examined. The plates in the [illegible] were selected because of their [illegible] in regard to [illegible] on each disc. Of these the four [illegible] constitute the only set for which a plate [illegible] the correspond-ing position in each [illegible] in good enough condition to study.

Scanning Procedure

A Spencer microscope with binocular, inclined body and mechanical stage was used for scanning the plates. The three objectives available were 16 mm (10X) dry, 4 mm (44X) dry, and 1.8 mm (97X) oil immersion. The eyepieces used had a magnification of ten, thus a maximum magnification of approximately 1000 was available. The 16 mm low power objective proved useful in allowing [illegible] magnification [illegible] tracks of 10 to 50 microns [illegible]. The 4 mm objective with its field of view of [illegible] tracks of [illegible] field of view [illegible] only [illegible] why the 4 mm objective was used for [illegible].

The [illegible] objective and [illegible]. The [illegible] 1.6 microns [illegible] ing five of the [illegible]

microns.

A reference point was formed on the edge of each plate studied by the place of intersection of two scratches made with a razor blade on a drop of India ink. The plate was then placed in the mechanical stage and the coordinates of this fiducial point recorded to the nearest 5/100 mm. The stage is graduated in millimeters and may be read with the vernier to 1/10 mm or 100 microns and estimated to the nearest 50 microns. As the field of view of the 4 mm objective is 350 microns, an event recorded with this degree of accuracy may be relocated without too much trouble. Upon replacement of the plate in the stage, events may be located by computing their position relative to the fiducial point. The plate usually moved so little upon replacement that events would be found within one-half the smallest division of the mechanical stage.

An area roughly in the center of the four plates studied (those numbered 5, 14, 23, and 32 in Fig. 4a) was selected for scanning. The shape and location are shown in Fig. 4b. A 2 X 30 mm^2 area was covered in six horizontal strips. With a field of view of diameter 350 microns this afforded enough overlapping so that events occurring at the top of one field of view and at the bottom of another would not be missed. As the plate was moved across the field of view the finite depth of focus of the objective made it

[illegible].

A reference point was formed on [illegible] at this place shaded by the plane of [illegible] with a rated plate [illegible] Fig. [illegible] then placed in the [illegible] this fiducial point [illegible] stage is graduated in [illegible] vernier to 1/10 mm [illegible] of 20 microns [illegible] is 500 microns [illegible] ency may be [illegible] placement of the [illegible] by comparing the [illegible] The plate [illegible] events would be [illegible] of the [illegible].

In order to [illegible] fied (those [illegible] Fig. 22, and [illegible] selected for [illegible]. The [illegible] Fig. 21. [illegible] stage. [illegible] allowed [illegible] top of the field [illegible] not be [illegible] view the [illegible]

necessary to continually turn the vertical fine-adjustment screw.

First an area of .6 cm^2 (labeled "1st" in Fig. 4b) was scanned on each of the four plates. The numbers of proton and heavier tracks were recorded, and "stars" of one and more prongs were drawn to scale and located by coordinates. To increase the total number of events a second area of equal size adjacent to the first was scanned. This time proton counting was omitted and the stars were merely sketched for identification. Otherwise the same information was recorded for each of the two areas.

necessary to continually [illegible] the vertical [illegible] acres.

First an area of [illegible] [illegible] [illegible] was sampled on each of the four dates. The whole [illegible] and heavier tracks were recorded [illegible] the same grounds were [illegible] to reach [illegible] [illegible]. To increase the total number of [illegible] an area of equal size adjacent to the first was sampled. [illegible] ton counting was omitted and the [illegible] were [illegible] for identification. Therefore the [illegible] was recorded for each of the two areas.

CHAPTER IV

ANALYSIS OF DATA

The data collected from the scanning of the four plates is shown in Tables II, III, and IV. Before discussing the significance of this material, the nature of the different categories and the terminology used will be described.

Recording of Data

Six of the categories listed in the tables are types of "stars." A nuclear disintegration or evaporation can be recognized by the tracks left by the charged particles coming from a single point. In the case of two-pronged stars, it is necessary to check by increase of grain-density to verify that it represents two particles coming out from a common point and not one particle which has suffered wide-angle scattering. A one-pronged star is an isolated track which begins and ends in the emulsion.

"Stars under emulsion" are those groups of three or more tracks which seem to come from the same point in the glass just underneath the emulsion. It is possible that this orientation in some cases is accidental, but most of them probably represent nuclear disintegrations occurring just beneath the emulsion.

The group labeled "protons" consists of single tracks

over fifty microns in length whose grain-density and scattering characterize them as probably protons. High energy alpha particles and deuterons would be included in this group but their numbers should be small compared to the total. Tracks under fifty microns were not recorded in this category because protons, alpha particles, and deuterons of this range look much alike.

Under the category of "alpha-type tracks" were counted tracks definitely heavier than protons not seeming to originate in nuclear disintegrations. They are divided into two groups. "emulsion-surface" contains those tracks ending (or beginning) in the emulsion and crossing its surface. Those tracks coming from the glass below and ending in the emulsion are listed as "emulsion-glass." It will be seen that tracks from "stars under emulsion" may also be considered under the "emulsion-glass" category. However the number of tracks involved in these stars is small compared with the total.

The entries called "heavy tracks" include tracks which pass completely through the emulsion and show a high enough grain-density throughout to insure that they are due to particles at least as heavy as alphas. There were a number of tracks of this type ending in the emulsion. Their coordinates were recorded so that they could be further studied, but they were not included in the tables as with particles

over fifty microns in length from [illegible] and were having characteristics [illegible] alpha particles and [illegible] group out [illegible] would [illegible] total. [illegible] fifty microns [illegible] category because [illegible] particles [illegible] this range look much alike.

Under the category of [illegible] tracks definitely [illegible] in nuclear disintegrations [illegible] two groups. "[illegible]" [illegible] (or [illegible]) in the [illegible]. Those tracks [illegible] are listed as "[illegible]." [illegible] broken [illegible] under the "[illegible]" category. However the number of tracks involved [illegible] total.

The [illegible] pass completely through the [illegible] [illegible] tracks of [illegible] were recorded so that [illegible] but they were [illegible]

TABLE II

Data for first area scanned (see Fig. 4b).
Figures on each plate are for an area of .6 cm^2.

Events		Plate			
		5	14	23	32
Proton tracks		122	97	89	78
α - type tracks	emulsion-glass	157	154	138	137
	emulsion-surface	64	44	49	45
Heavy tracks		7	5	4	0
Stars under emulsion		8	8	8	10
Stars	1 - prong	12	8	15	18
	2 - prong	11	9	6	8
	3 - prong	11	10	9	17
	4 - prong	3	7	5	9
	5 or more prong	1	3	3	4

TABLE III

Data for second area scanned (see Fig. 4b). Figures on each plate are for an area of .6 cm^2.

Events		Plate			
		5	14	23	32
Proton tracks		not recorded for these areas			
α - type tracks	emulsion-glass	146	172	146	128
	emulsion-surface	48	48	39	40
Heavy tracks		4	6	4	0
Stars under emulsion		16	18	16	12
Stars	1 - prong	19	24	20	12
	2 - prong	10	5	2	6
	3 - prong	7	12	6	14
	4 - prong	7	5	4	6
	5 or more prong	2	0	2	0

TABLE IV

Data for total area scanned. Figures on each plate are for an area of 1.2 cm^2.

Events		Plate 5	Plate 14	Plate 23	Plate 32
Proton tracks (for area of .6 cm^2)		122	97	89	78
α - type tracks	emulsion-glass	303	326	284	265
	emulsion-air	112	92	88	85
Heavy tracks		11	11	8	0
Stars under emulsion		24	26	24	22
Stars	1 - prong	31	32	35	30
	2 - prong	21	14	8	14
	3 - prong	18	22	15	31
	4 - prong	10	12	9	15
	5 or more prong	3	3	5	4

of short range it is difficult to distinguish tracks made by different particles.

A few tracks suspected of being produced by mesons and one apparent π-μ decay were found. Further investigation by means of grain-counting is necessary to verify these identifications and accordingly they were not listed in the tables.

Absence of Meson Tracks

In the examination of a 4.8 cm^2 area, no events were found in which an incoming meson reached the end of its path in the emulsion and formed a star. In plates carried by balloon to 100,000 feet Salant, Hornbostel, and Dollman[21] reported that the ratio of star-forming or negative π mesons to stars of five or more prongs was 1:50 calculated from a total of 211 many-pronged stars. On 10,000 foot mountain exposures,[22] this ratio was found to be 1:10. In airplane flight exposures at 12,000 to 15,000 feet a ratio of 3:100 was found,[23] calculated from 600 stars with five or more prongs. Since the altitude of the last two experiments was

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21 E. O. Salant, J. Hornbostel, and E. M. Dollman, "Tracks in Emulsions at 100,000 Feet," Physical Review, 74:694, 1948.

22 Eric Pickup and Adair Morrison, "Emissions of Mesons in Cosmic Stars in Photographic Emulsions," Physical Review, 75:686, 1949

23 Loc. cit.

of short range it is difficult to distinguish tracks made by different particles.

A few tracks suspected of being produced by mesons and one apparent π-μ decay were found. Further investigation by means of grain-counting is necessary to verify these identifications and accordingly they were not listed in the tables.

Absence of Meson Tracks

In the examination of a 4.8 cm^2 area, no events were found in which an incoming meson reached the end of its path in the emulsion and formed a star. In plates carried by balloons to 100,000 feet Salant, Hornbostel, and Dollman[21] reported that the ratio of star-forming or negative π mesons to stars of five or more prongs was 1:50 calculated from a total of 211 many-pronged stars. On 10,000 foot mountain exposures,[22] this ratio was found to be 1:10. In airplane flight exposures at 12,000 to 15,000 feet a ratio of 3:100 was found,[25] calculated from 600 stars with five or more prongs. Since the altitude of the last two experiments was

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21 E. O. Salant, J. Hornbostel, and E. M. Dollman, "Tracks in Emulsions at 100,000 Feet," Physical Review, 74:694, 1948.

22 Erik Pickup and [illegible], "Relations of Mesons in Cosmic Stars to Photographic Emulsion," Physical Review, 75:[illegible], 1949

25 Loc. cit.

approximately the same, the discrepancy between the percentages of star-forming mesons was ascribed tentatively to the greater amount of nearby matter in the mountain-top exposures. If confirmed by more observations this would be a further strong indication that all such mesons are formed locally. It might be expected that the total of over 2 inches of steel or 3.4 cm of lead in our experiment through which primary rays might pass would lead to a considerable production of such mesons. However since only 1 to 10 star-forming mesons could be expected with every 100 five or more pronged stars, it is not surprising that with only 15 (Table V) none were found.

On the Ilford C-2 emulsions used, mesons form tracks of such low grain density that single tracks could easily be lost in the rather heavy background of grains that was found to be present. Therefore the absence of tracks of this type does not indicate that a large flux of mesons could not be passing through the emulsion.

Distribution of Frequencies of Stars According to Number of Prongs

In Table VI is shown the relation between the number of prongs and frequency of stars found in material exposed at 100,000 feet and 7700 feet as compared with that found by us at approximately 65,000 feet.

TABLE V

Density of Events

Events	Plates				Totals			
	5	14	23	32	Area	Vol.	no/cm^2	no/cm^3
Protons	122	97	89	78	2.4 cm^2	.48 cm^3	161	8010
Stars of 3 or more prongs	31	37	29	50	4.8 cm^2	.96 cm^3	30.6	1800
Stars of 5 or more prongs	3	3	5	4	4.8 cm^2	.96 cm^3	3.13	156

TABLE VI

Distribution of Stars According to Prongs

Elevation	Frequency of stars with given no. of prongs													Total no. of stars
	4	5	6	7	8	9	10	11	12	13	14	15	19	
7700 ft.	35	17	5	4	4	2	0	1	1	0	1	0	0	70
65,000 ft.	46	9	2	1	2	0	1	0	0	0	0	0	0	61
100,000 ft.	39	35	36	45	26	17	13	11	6	11	4	5	2	250

The values for 100,000 feet are given from the same study by Salant, Hornbostel, and Dollman[24] mentioned in the preceding section. They compared their data with that collected by Wambacher at 7700 feet and concluded that the frequency of stars with a very great number of prongs increases rapidly with height.

At 65,000 feet the frequencies should lie somewhere between the two extremes. An examination of Table VI shows that this does not occur. In fact the ratio of four-pronged to stars of many prongs is even larger than in the mountain-top exposures. A large number of four-pronged stars may be found in old emulsions due to the successive decay products of the thorium atoms found as impurities in the gelatin. Since the tracks of these stars range from 20 to 46 microns[25] they are easily visible and in the three-months' old plates used might well affect the results. A brief examination of a plate of the same age developed at the same time but not sent up in the balloon flight has not shown any of these stars, however the systematic scanning of a larger area is necessary before any positive statement can be made.

That higher pronged stars do exist in our plates is shown by the fact that, before systematic scanning was begun, twenty minutes of random examination located one ten-pronged

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25 Webb, op. cit., p. 517.

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[illegible]

and one twelve-pronged star. As these were not in the area later selected for systematic work, they do not appear in the tables.

Rate of Production of Nuclear Disintegrations at High Altitudes

In only two cases so far brought to my attention have estimates in the production rate of stars been made. These are necessarily very approximate since stars are rare events and the times of the exposures are usually not precisely known.

One of these rates was computed by Schein and Lord[26] from data obtained from Ilford C-2 plates exposed at an altitude greater than 60,000 feet for eight hours. They give a value of 6000 stars of more than four prongs per cubic centimeter per day. Although exact figures could not be obtained, this value is much higher than the corresponding one for mountain altitudes. This is amply shown by the very long exposure times of six weeks or more used in the lower altitudes[27] as against those of a few hours for those

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26 Marcel Schein and Jere J. Lord, "On the Production of Mesotrons in Cosmic-Ray Stars in the Stratosphere," Physical Review, 73:189, 1948.

27 G. P. S. Occhialini and C. F. Powell, "Nuclear Disintegrations Produced by Slow Charged Particles of Small Mass," Nature, 159:188, 1947.

and one twelve-page [illegible] later selected [illegible] in [illegible] the tables.

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Is only [illegible] [illegible] indicate [illegible] production [illegible]. These are [illegible] and the [illegible] known.

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26 [illegible] of [illegible] in [illegible] sional Papers, [illegible]

27 [illegible] Dialectical [illegible] Nature, [illegible]

carried by balloons. In spite of the difference in exposures nuclear disintegrations are more commonly found in the latter case.

In the previously mentioned 100,000 foot flight studied by Salant, Hornbostel, and Dollman[28] a value of 2000 stars of more than four prongs formed per cubic centimeter per day is given. Due to lack of knowledge of the movements of the balloons this value is given merely as a definite upper limit. Using an exposure time of an hour and a half and the data from Table V a corresponding value of 2500 stars per cubic centimeter per day is found. This can not be taken as representative since it was computed from a very small number of stars. However since the maximum height attained was 65,000 feet and the average was therefore much lower it still seems unexpectedly large. These three values are suggestive of large fluctuations in star-forming radiation; however this would need to be confirmed or disproved by further investigation.

Nuclear Disintegrations Beneath the Emulsion

The large number of "stars under emulsion" is a puzzling feature of the plates examined. As previously

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28 Salant, et. al., op. cit., p. 694.

described these consist of three or more single tracks which seem to come from a single point beneath the emulsion. Since sets of tracks separated by more than 15 microns were recorded as single tracks, these particles radiating from a common center must originate from ordinary stars in a very shallow layer in the glass, from deeper stars with a large number of prongs, or from deeper stars whose prongs have a decided asymmetry in the upward direction.

If all the stars are considered to be formed in a ten micron layer of glass, their density would be in a ratio of 13:1 that of three or more pronged stars in the emulsion, assuming that every star in the glass had three or more prongs in the right direction within a small enough solid angle so that it would be recorded as a "star under emulsion." Glass has a specific gravity of about 2.6 and is made up of 53.3% oxygen and 46.7% silicon by weight. Traces of metallic impurities are usually present. The nuclear emulsion used consists of about 85% silver bromide and 15% gelatin by weight. It has a specific gravity of 3.64. Although the density of the emulsion is about 1.4 times that of the glass, its stopping power is only 1.08 times as large.[29] On this basis the number of stars formed in each would be expected to be about equal.

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29 Webb, op. cit., p. 514.

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to be about equal.

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Furthermore, if for some reason the glass were characterized by a disproportionately large number of disintegrations a large number of "stars above emulsion" should have been seen since each emulsion had the glass backing of another plate directly above it. However, none of these events were present. In fact only one case was found of several emulsion-surface tracks being in the same field of view, and these did not appear to radiate from a common point. The presence of a varying layer of air due to the roughness of the surfaces of the two plates would allow the tracks of a "star above emulsion" to become widely enough separated so that they would not be recognizable as coming from the same point. However, the few microns of air would not be enough to materially absorb the particles from these stars, and the total number of emulsion-glass and emulsion-surface tracks would be expected to be approximately equal. That this is far from being the case may be seen by inspection of Table VII. The tracks from beneath are consistently in a ratio of at least three to one track from above.

If the emulsions are fastened to the glass with a binder containing a great deal of radioactive contamination it would account for the situation described above. The gelatin used in the manufacture of these emulsions is carefully selected and tested to keep the radioactive contamination as low and uniform as possible. It therefore seems

Furthermore, if for some reason, the [illegible] stars characterized have disproportionately a large number of [illegible] tions a large number of "giants" have [illegible] should have been seen since each emulsion [illegible] or another [illegible] directly above [illegible]. However, none of these events were primary. [illegible] than the [illegible] of several emulsion-mounted [illegible] stars, and these do not appear to radiate from a common point. The presence of a [illegible] layer of [illegible] on the surface of the two stacks would [illegible] "star above emulsion" to appear [illegible] separated so that they could not be [illegible] to a common point. However, [illegible] would [illegible] to materially affect the [illegible] and the total number of [illegible] would be expected to be [illegible]. [illegible] far from being [illegible] Plate VII. The [illegible] are [illegible] at least three to one [illegible].

If the emulsions are [illegible] binder containing a [illegible] it would [illegible] above. The gelatin [illegible] fully [illegible] tion [illegible].

TABLE VII

Relative Frequency of Stars Under Emulsion and Other Events

Events	Plate 5	14	23	32
Stars under emulsion	24	26	24	22
Stars of 3 or more prongs	31	37	29	50
Protons	122	97	89	78
Emulsion-glass	303	326	284	265
Emulsion-air	112	92	88	85

TABLE VIII

Distribution of Heavy Tracks

Plate 5		14		23		32	
1st Area	2nd Area	1st Area	2nd Area	1st Area	2nd Area	1st Area	2nd Area
7	4	5	6	4	4	0	0

unlikely that a cementing material thirteen times or more as radioactive as the gelatin would be used.

The final possibility is that the stars are asymmetric in direction of prongs. Since the emulsion side of the plate was up, this would represent an average momentum directed upward. The "evaporation" concept of nuclear disintegration does not involve a momentum transfer from the primary particle to those forming the star. Moreover if a momentum transfer did occur it shows that these stars are not produced by primary radiation since they would have an average momentum directed downward. The fast proton absorption (Table VII) in the different layers of steel as shown by the proton frequency in the four plates indicates that the number directed downward is much greater than those directed upward. If an equal number were directed upward the number of proton tracks in the bottom plate should equal those of the top plate since a similar amount of absorbing material is outside both of them. The data show that this is not the case; that the downward component is much larger than the upward is shown by the fact that plate 23 with 3/4 inches of steel below and 1 inch above shows a number of proton tracks at least as large as those of plate 32 which had 1 3/4 inches of steel above but only 1/16 inches of aluminum below. This is consistent with the view of the protons as primary radiation.

unlikely that a [illegible] is
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The final possibility is that [illegible]
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plate since a similar amount of [illegible] material is out-
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is shown by the fact that plate [illegible]
below and 1 inch above [illegible] at
least as large as those of plate [illegible]
of steel above but only [illegible] below. This
is consistent with the [illegible] of the [illegible] multi-
tion.

No striking asymmetry in the tracks of stars in the emulsion was noticed during scanning, but it would seem that a reexamination of them in this respect might be warranted.

Heavy Particles

With the recent discovery of the presence of heavy nuclei in cosmic radiation in the upper atmosphere it was hoped that a number of these might be found in this experiment. The tracks listed in the data as "heavy particles" seem to be heavier than alpha particles but apparently do not approach the size of those found by the Minnesota and Rochester workers.[30] From the published micro-photographs the diameters of the tracks shown was measured according to the scale shown on each. This was found to be 3.5 and 4 microns in two tracks identified as having been produced by a particle with a charge of approximately 40 electron charges or $Z \backsim 40$. One identified as of $Z \backsim$ 10-15 showed a diameter of 2 microns tapering to 1 micron as the track ended in the emulsion. With the smaller magnification available the diameter of our tracks cannot be measured with much accuracy but a lower limit of .5 micron and upper limit of 2 may be regarded with confidence. They would thus correspond to a Z

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30 P. Freier, E. M. Lofgren, E. P. Ney, F. Oppenheimer, M. L. Bradt, and B. Peters, "Evidence for Heavy Nuclei in the Primary Cosmic Radiation," Physical Review, 74:213-217, 1948.

of perhaps 4-12.

The number of heavy particles found on each plate is shown in Table VII. In spite of the small number of tracks, their total absence from the lowest plate suggests that they have come from above and that they were abosrbed before reaching the lowest stack of plates.

If these tracks are made by primary particles, then it should be possible to trace their tracks through the plates above. A search was made of a 3 X 3 mm^2 area on the plate directly above one of the heavier tracks and no track with a roughly similar direction was found. Considering the small angle made with the vertical by the track which was being traced, and the degree of dislocation above it, the corresponding track should have been found in the area searched. A similar study of the thirty other tracks might yield different results, but time was not available to carry this out. The angle made by these tracks with the vertical is small in most cases, but here the apparent increase of grain-density due to foreshortening may have favored the detection of tracks with these small angles. Aside from foreshortening, shrinkage alone would double the grain-density of near-vertical tracks.

The Minnesota group mentioned above found about one very heavy track per square centimeter for a 3-4 hour exposure at 94,000 feet. In a flight of one hour at 60,000 to

of perhaps 4-13.

The number of heavy [illegible] in each [illegible] is shown in Table VIII. [illegible] small number of [illegible] their total charge from [illegible] plate [illegible] have [illegible] reaching the [illegible].

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70,000 feet, three tracks (one per cm^2) of penetrating particles with ionization only slightly more than that of alpha particles are reported. This was interpreted as confirmation that the very heavy particles found at 94,000 feet are very rapidly absorbed. In the higher flight no very heavy particles were found in plates shielded by one inch of lead. If the heavy tracks found in our emulsions correspond to the lighter component of this heavy primary radiation which are the only ones of range great enough to penetrate this deep in the atmosphere, then our 30 particles for 4.8 cm^2 represent a flux perhaps fifteen times larger than that found in the previous study.

With the small number of tracks of this type found a considerable fluctuation would be expected upon scanning a second area. However the number in the two areas on each plate is surprisingly uniform. This makes it difficult to see how the total lack of these particles on the last plate could be entirely due to chance which would have to be the case if they were produced by nuclear splinters from locally formed stars. On the other hand, it is possible that the knowledge of the number of these tracks found in the previously scanned area might have a large influence on the person recording the tracks.

This, together with the intensification of grain-density of vertical tracks described above, make it quite

70,000 feet, three tracks (one per cm² of penetrating particles with ionization only slightly more than that of alpha particles are reported. This was interpreted as confirmation that the very heavy particles found at 94,000 feet are very rapidly absorbed. In the higher flight no very heavy particles were found in plates shielded by one inch of lead. If the heavy tracks found in our emulsions correspond to the lighter component of this heavy primary radiation which are the only ones of range great enough to penetrate this deep in the atmosphere, then our 80 particles for 4.5 cm^2 represent a flux perhaps fifteen times larger than that found in the previous study.

With the small number of tracks of this type found a considerable fluctuation would be expected upon scanning a second area. However the number in the two areas on each plate is surprisingly uniform. This makes it difficult to see how the total lack of these particles in the lead plate could be entirely due to chance which would have to be the case if they were produced by nuclear splinters from locally formed stars. On the other hand, it is possible that the knowledge of the number of these tracks found in the previously scanned area might have a large influence on the person recording the tracks.

This, together with the identification of a min-density of vertical tracks described above, make it quite

possible that these heavy tracks may be due to locally formed high-energy alpha particles or heavier nuclear splinters.

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