EDWARD GEORGE BILPUCH. Star Production By Heavy Ion Component Of Cosmic Rays. (Under the direction of Dr. A. V. Masket.)

Four stars caused by heavy ions were found in 24 Ilford G-5 plates exposed at about 98,000 feet. The plates were attached to a free balloon and remained aloft for approximately 8 1/2 hours. The four events were analyzed for possible meson production. In each event there is a diffused shower of minimum ionization particles, and an attempt is made to associate these particles to the recent Fermi theory on multiple meson production. In regard to this, histograms are given showing meson distribution in the shower with respect to the polar angle as defined by the direction of the incoming heavy ion.

Analysis has shown that this type event cannot be considered a single nucleon-nucleon interaction as required by Fermi's theory. In general, they are of a more complex nature.

STAR PRODUCTION BY HEAVY ION
COMPONENT OF COSMIC RAYS

By

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CHAPTER I

INTRODUCTION

1. PURPOSE OF THIS WORK

Several high energy, nuclear disintegrations have been found in twenty-four G-5, 300 micron plates. These events have been caused by the heavy ion component of the cosmic radiation colliding with a nucleus of the emulsion. In each event analysed, there is present a diffused shower of minimum ionising particles. Workers, in studying similar events, have shown that the shower of minimum ionising particles are positive and negative pi-mesons and β - particles created in the interaction.

The main purpose of this paper is to investigate some high energy events which contain the characteristic shower of mesons and attempt to associate the shower with a theory of meson production.

2. HISTORICAL REVIEW

Lord, Fainberg and Schein[1] found evidence of multiple production of mesons in a single nucleon-nucleon collision. The event occurred in the Ilford G-5 type emulsion flown at an altitude of 95,000 feet. The incident particle was identified as a proton of $3x10^{13}$ ev energy. In line with the direction of the incident particle was a central core of seven particles of minimum ionisation which had an angular divergence of 0.003 radians. The energies of these particles were in excess of 250 Bev. In addition to the central core, eight other minimum ionising particles were emitted in a diffused cone of 0.13 radians angular divergence. The energy for individual particles in the diffused shower was found by small angle scattering to be much less than that for the particles in the central core. The track lengths of the particles in the core and many of the track lengths in the diffused shower were in excess of 10,000 microns and could be identified as mesons.

Both the angular and the energy distribution of the emitted mesons are in good agreement with the assumption that in the center-of-mass system, the mesons are emitted in two distinct cones of angular width 30° forward and backward with reference to the direction of the primary proton. The complete lack of slow particles around the central core and the fact that only one track could be an ordinary star evaporation nucleon, clearly demonstrated that this event was almost entirely a nucleon-nucleon interaction either with a very light element or possibly with a deuteron or hydrogen nucleus of the emulsion.

In the central core, at 4800 microns from its origin, there was produced a pair of very small angular divergence. It was assumed that this pair was produced by a gamma-ray from the decay of a neutral meson which was created in the interaction. A lower limit of the lifetime of the neutral meson was given to be $2x10^{-15}$ sec.

The Bristol group[2-5] has employed the method of measuring the scattering of charged particles emerging from nuclear explosions produced by cosmic radiation. They have found that at least 90% of the shower particles emerging from nuclear explosions with K.E. less than 150 Mev produced by proton and alpha-particles of great energy are pi-mesons. A shower particle is defined as one with a grain-density less than 1.5 times the minimum grain-density. If mu-mesons are sometimes created, they are present in numbers less than 2% of the pi particles. Also, if electrons or other charged particles of small rest-mass are sometimes emitted from nuclear explosions with an energy less than 150 Mev, they occur with a frequency less than 2% of the pi particles. They postulate that the pi-mesons must be created directly and that they cannot be regarded as the products of decay of mesons of appreciably greater mass and very short lifetime. Their observations prove that more massive parent mesons have lifetimes less than 10^{-13} sec. They conclude that it is reasonable to suppose that the pi-mesons are directly produced in nucleon-nucleon collisions.

Another startling event was found by Bradt, Peters and Kaplan[6,7] in electron sensitive Kodak NTB-3 plates flown at an altitude of 100,000 feet. The event gave rise to 56 singly charged relativistic particles and 18 non-relativistic heavy particles which carried away 23 units of charge. This interaction was produced by a primary alpha-particle of energy 10^{12} to 10^{13}ev colliding with a silver or bromine nucleous of the emulsion. Of the 56 relativistic particles, 23 were in a very narrow core which had a total projected angular spread of 2.5 degrees. The remaining 33 relativistic particles had an angular spread of 60 degrees with the direction of the incident alpha-particle. The core was so dense that the individual tracks were not resolvable in the immediate vicinity of the star. In addition to minimum ionising tracks, pair production was observed in the core which indicated the presence of a large number of high energy gamma-rays. The energy of the gamma-rays was estimated from the angle of divergence of the observed pairs. One electron pair was estimated at 10 Bev and another at 50 Bev. These workers assumed that the gamma-rays resulted from the decay of neutral mesons and could therefore conclude that the lifetime of the mesons was $\lesssim 10^{-13}$ sec. One of the pairs within the core was observed to give rise to another pair. They concluded that at least eight and probably about ten pair were created in the core over an average path length of 0.26 radiation units of glass and emulsion.

It was possible to explain the structure of the shower either by the assumption of multiple meson production in primary, secondary and tertiary encounters in the target nucleus or by the assumption of a considerable degree of anisotropy of meson production in the center-of-mass system of the incident and target nucleons inthe primary encounter. These conclusions were based on the transformation relations connecting the angular distribution of the mesons in the laboratory system with the angular and the energy distributions of the mesons in the center-of-mass system.

In another paper, Bradt and Peters[8] illustrate an event emitting 42 charged fragments of which 10 are minimum ionization collimated in the forward direction. The incident particle was identified to be calcium ($Z=20$) with an energy of the order of at least 100 Bev. The target nucleus was assumed to be silver or bromine. This event also shows a fast, singly charged particle causing a second nuclear event.

Other events initiated by singly charged particles giving rise to a diffused shower of minimum ionizing particles plus evaporation particles are illustrated by Lord and Schein[9].

Recently, a paper by Pickup and Voyvodic[10] gave projection drawings for several nuclear events caused by the heavy component of cosmic radiation. They illustrate an event caused by a carbon nucleus giving rise to 82 charged fragments, of which 35 are approximately minimum ionisation located in a diffused cone in the forward direction. By considering charge conservation, they conclude that at least 28 pi-mesons were created. Another event shows an alpha-particle in a central collision with a silver or bromine nucleus giving a star with 59 charged fragments. Associated with this event is a diffused shower of 28 minimum ionisation particles. The alpha-particle was one centimeter long, and multiple scattering measurements indicated that its energy was greater than 65 Bev. The third event shows a nitrogen nucleus giving rise to 60 charged fragments. An estimate of the energy of the incident particle could not be given. The direction of the incident nucleus was approximately in line with the center of a wide cone of 17 shower particles. This event also shows a heavily ionising particle ejected sideways giving rise to the characteristic "hammer" track together with the disintegration electron. A "hammer" track is caused by the disintegration of a Li^8 or B^8 nucleus into two alpha-particles and an electron.

3. THEORY

During the past few years, there has been much evidence presented for the production of many mesons in a single interaction. It is only proper then that there should appear upon the scene theoretical considerations which would explain this observed phenomenon.

Heitler and Janossy[11]. have presented a theory which explains the general features of these showers in terms of single meson production in successive collisions. This type of meson production is referred to as plural production. Theories dealing with multiple meson production (production of more than one meson in a single interaction) have been presented by Lewis, Oppenheimer and Wouthuysen[12]. and recently by Fermi[13,14]. It is this latter theory of meson production with which this paper is concerned.

Fermi assumes that when two high energy nucleons collide, the energy available in their center-of-mass system is released in a small volume having dimensions of the order of magnitude of the pion (pi-meson) cloud surrounding the nucleons. These pion clouds are considered to have fixed lateral dimensions of $R \sim \frac{\hbar}{\mu c}$ where μ is the pion rest-mass. The energy in such a collision can give rise to states representing a certain number of pions in addition to the original two nucleons. Due to a Lorentz contraction in the direction of motion, the pion fields will tend to behave as flat discs, and a considerable amount of angular momentum will be involved in off-centered collisions.

For high energy collisions, the number of mesons created is a function of the energy and of the impact parameter, r, where r may range from 0 to R. The angular momentum created is assumed to be carried off by the mesons, and this gives rise to a shower of mesons in the backward and forward directions in the center-of-mass system. If a collision is centered, there is no angular momentum, and meson emission is isotropic. If the collision is off-center, angular momentum is present which causes a peaked distribution in the backward and forward hemispheres. When the off-centered collision is converted to the laboratory system, there is a dense core of high energy mesons and a diffused cone containing mesons with lower energy.

For energies $\gtrsim 5\times10^{12}$ev, Fermi suggests that the production of nucleon-antinucleon pairs is possible and may compete favorably with meson creation. The number of all charged particles will be slightly greater than if mesons alone were created. Fermi[14]. gives two formulas for the number of particles created:

1. $1.2(W'/MC^2)^{\frac{1}{4}}$

2. $1.06(W'/MC^2)^{\frac{1}{4}}$

Formula 1 is used on the assumption that nucleon-antinucleon pairs are possible. Formula 2 gives the number of pi-mesons if one assumes that only meson creation is possible. W' refers to the energy of the incident nucleon in the laboratory system, and MC^2 is the rest-mass energy of the nucleon.

Fermi's theory for observed angular distribution may be conveniently treated in the manner as presented by Pickup and Voyvodic[10].

The impact parameter, r, is given by

$$\frac{r}{R} = \frac{3\, f_1(\rho)}{2\, f_2(\rho)}$$

where $$f_1(\rho) = \frac{2}{\rho^3} + \frac{4}{3\rho(1-\rho^2)} - \frac{3+\rho^2}{3\rho^4} \ln\frac{1+\rho}{1-\rho}$$

and $$f_2(\rho) = \frac{1}{\rho}\ln\frac{1+\rho}{1-\rho} + \frac{2}{1-\rho^2}$$

Values of $\frac{r}{R}$ are assumed and the value of ρ can be found.

The equation for N (number of mesons created) can be written in the form

$$\frac{N}{(W'/MC^2)^{\frac{1}{4}}} = C_2\left[\frac{f(\rho)}{f_2(\rho)}\right]^{\frac{3}{4}}$$

where

$$f(\rho) = \frac{1+\rho^2}{\rho^3}\ln\frac{1+\rho}{1-\rho} - \frac{2}{\rho^2}$$

C_2 is a constant, W' is the energy of the colliding nucleon in the laboratory system, and MC^2 is the nucleonic rest-mass energy. On assuming an equal probability for positive, negative and neutral pi-mesons, the number of charged mesons is given by

$$\frac{N}{(W'/MC^2)^{\frac{1}{4}}} = 2.19(3)\left[\frac{f(\rho)}{f_2(\rho)}\right]^{\frac{3}{4}}$$

Therefore, if N is known by observation, and a value assumed for $\frac{N}{N}$, a value for W' can be calculated.

The number of all charged mesons per radian at polar angle in the center-of-mass system can be expressed as

$$\frac{dN}{d\theta} = \frac{N}{f(\rho)}\sin\theta\ f_4(\rho\cos\theta)$$

where

$$f_4(x) = \frac{2}{x^2(1-x^2)} - \frac{1}{x^3}\ln\frac{1+x}{1-x}$$

The corresponding distribution in the laboratory system may be given by the following equations:

$$\left(\frac{dN}{d\theta}\right)' \simeq \bar{\gamma}\frac{dN}{d\theta}\frac{\cos\theta+1}{\cos^2\theta'}$$

$$\text{TAN } \theta' \simeq \frac{1}{\bar{\gamma}} \text{ TAN } \frac{\theta}{2}$$

The primed values refer to the laboratory system.

$$\bar{\gamma} \simeq (W'/2MC^2)^{\frac{1}{4}}$$

θ = polar angle relative to the incident direction in the center-of-mass system.

θ' = polar angle relative to the incident direction in the laboratory system.

$\frac{dN}{d\theta}$ = distribution of mesons per radian in the center-of-mass system.

The above equations are valid only if one assumes relativistic velocities for the created particles.

Thus by observing N and assuming a value for $\frac{r}{R}$, W' can be calculated. From this value of W', one can find $\bar{\gamma}$. Using the value of $\frac{r}{R}$, ρ can be calculated; and therefore, the theoretical distribution in the center-of-mass system can be found. Using the values $\frac{dN}{d\theta}$ and $\bar{\gamma}$ in the above equation, a theoretical distribution can be plotted in the laboratory frame of reference. The observed distribution can be calculated directly from the event, and the two can therefore be compared.

CHAPTER II

EXPERIMENTAL TECHNIQUES

1. HISTORY OF THE EMULSION

The emulsions used in this work have been designated Series 7 for laboratory purposes. They are 300 micron, Ilford G-5 plates. Before the plates were exposed, they were sealed in an air-tight, lucite container which was supported at the edges by thin strips of brass forming a cradle. This was done in order to have the plates covered by as little material as possible.

The plates were exposed in August, 1951, at geomagnetic latitude 55 N. They were attached to one of the balloons associated with the project "Skyhook" in Minnesota. Figure 1 gives the record of the complete flight for these particular plates. The balloon reached a maximum altitude of 98,000 feet and remained approximately at that altitude for 8½ hours. The minimum pressure achieved was 11 mm mercury, which corresponds to approximately 15 gm cm^{-1} residual air pressure.

The Ilford G-5 emulsions are electron sensitive and will record all charged particles at all energies. This is of particular value in this work, since the primary cosmic radiation has energies in the range 10^{12} to 10^{13} ev.

2. DEVELOPMENT OF THE EMULSION

The plates were developed according to the method called "temperature development". This method was presented by Dalworth,

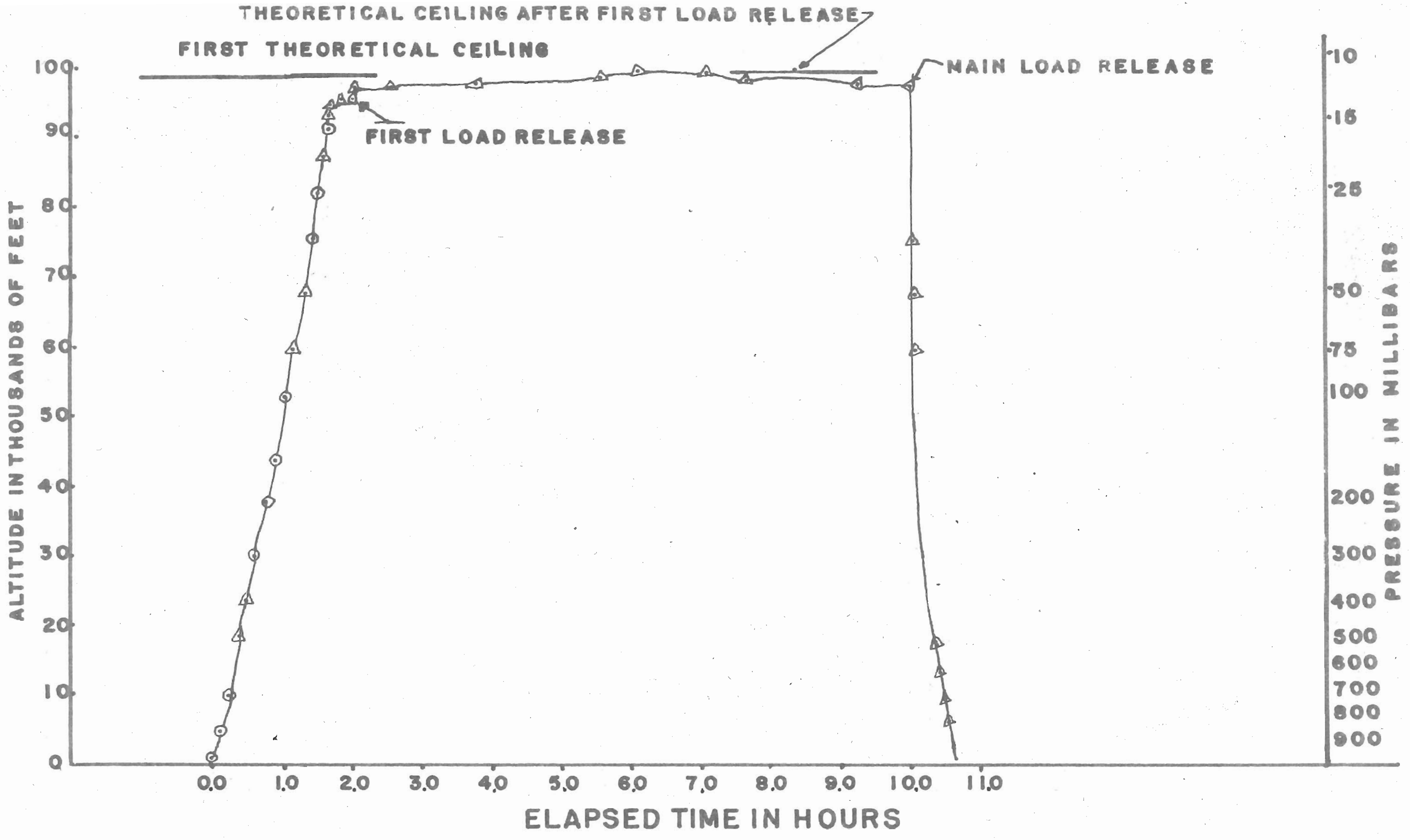
THEORETICAL CEILING AFTER FIRST LOAD RELEASE
FIRST THEORETICAL CEILING
MAIN LOAD RELEASE
FIRST LOAD RELEASE
ALTITUDE IN THOUSANDS OF FEET
100
90
80
70
60
50
40
30
20
10
0
PRESSURE IN MILLIBARS
10
15
25
50
75
100
200
300
400
500
600
700
800
900
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
ELAPSED TIME IN HOURS

FIGURE I

Occhialini and Payne[15]. The first step in the procedure is to saturate the emulsion with developer mixed 1 : 1 at a temperature which keeps the developer inactive. The cold temperature is recommended to be 5° C. The plates are then transferred to a solution of diluted developer mixed 3 parts water to 1 part developer. Development is allowed to proceed at a temperature of approximately 20° C. Since emulsions vary in thickness, one must rely upon the method of trial and error to get the best development for any particular thickness of emulsion. Occasions may arise when one wants the plates overdeveloped or underdeveloped, and one must therefore vary the time of warm development accordingly.

Development can be stopped almost immediately by transferring the plates to a solution of 2% acetic acid at 5° C. The time for which the plates are left in this solution should be of the same order as that required for the cold stage of development to allow thorough penetration of the solution. Strong agitation should accompany the plates in the acid solution. It is at this time that the plates should be carefully and gently wiped with the finger in order to remove any silver grains that may be on the surface of the emulsion.

The plates are then transferred to a 30% sodium thiosulphate solution (hypo) at 5° C. After a suitable time, the hypo solution is raised to a temperature of 20° C. Agitation of this solution should continue until the plates are ready to be washed. The plates should be kept in this solution for 50% longer than the time required for them to clear. The washing process should then commence, and be continued until the washing solution gives no indication of the presence of hypo as judged by the potassium permanganate test.

A recent paper by Dainton, Gattiker and Lock[16] gives experimental results for penetrating time of developers for specific thicknesses of emulsions. Included in this paper are the times for warm development, stop bath, fixing, washing and drying for emulsions of thicknesses 100, 200, 400, 600 and 1000 microns.

A satisfactory procedure for the Series 7 plates is as follows:

Soak in D-19 developer mixed 1:1 at 5° C	45 min.
In diluted developer mixed 3:1 at 20° C	40 min.
Stop bath of 2% acetic acid at 5° C with strong agitation	45 min.
Fixing bath of 30% hypo at 5° C	30 min.
Fixing bath of 30% hypo at 20° C with strong agitation	6 hrs.
Wash in water at 15° C	2 hrs.
Dry at 20° C, preferably where there is circulating air	

It should be mentioned that the emulsions, while in the washing stage, have a tendency to reticulate, and therefore should be watched carefully. Reticulation of the emulsion has a tendency to occur more frequently if the temperature of the water is allowed to rise. This is particularly true for temperatures above 20° C. It is therefore recommended that the washing process take place at a temperature between 12° C and 18° C. At a lower temperature, the washing requires more time, but the danger of reticulation is eliminated.

The procedure given above for 300 micron, Ilford G-5 plates has proved satisfactory. The emulsion shows a uniformity of development except for the first few microns at the top; and there is very little distortion except at the edges. The shrinkage factor was calculated to be 2.37.

Curve B in Figure 2 gives the calibration curve for the Series 7 plates, while Curve A is another calibration for a set of plates developed at an earlier date. It is necessary to plot a calibration curve for each set of plates, since the degree of development may vary somewhat. In addition, manufacturing techniques may also vary within certain limits.

Points for the curve were found by observing π-μ decays, decay electrons from the μ-mesons, and long π-meson tracks. Measurements were made in the manner described by Heck[17].

3. METHOD OF FINDING EVENTS

The original purpose of scanning the plates 7-1 through 7-24 was to find all heavy ions with track lengths in excess of a certain minimum value. The minimum value was set at 6,000 microns. With this length of track in one emulsion, a heavy ion could be identified without following it from emulsion to emulsion.

The plates were scanned by hand using the Leitz Ortholux microscope. The 24:1 objective was used in conjunction with the 6x periplan eyepiece. This arrangement gives an overall magnification of 150, and the diameter of the field of view is 540 microns.

The plane of the emulsions was flown in a vertical position with the long edge of the emulsion in the horizontal position. It was found that if the zenith were defined as a line perpendicular to the

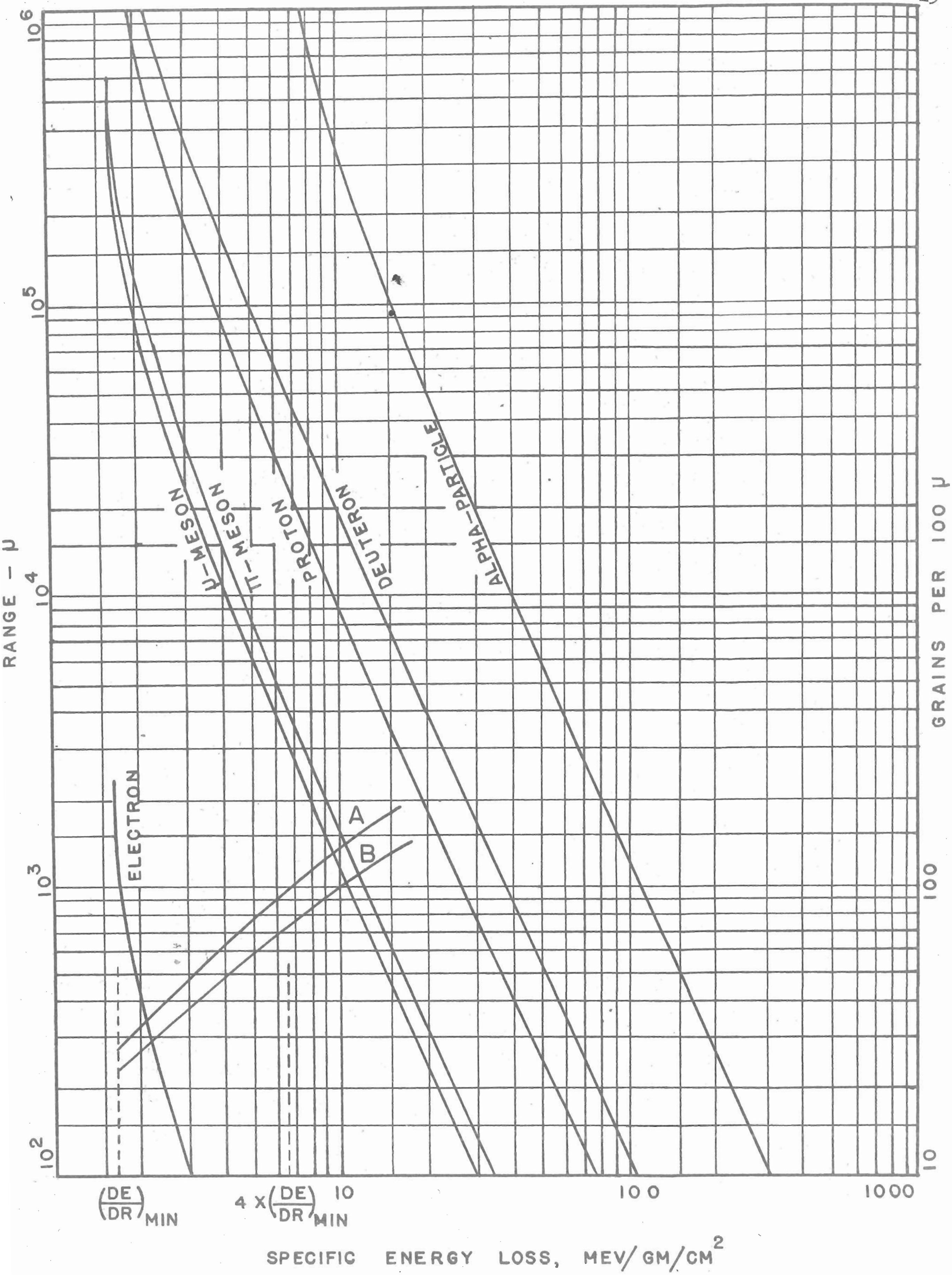
RANGE - μ
10^6
10^5
10^4
10^3
10^2
GRAINS PER 100 μ
100
10
μ-MESON
π-MESON
PROTON
DEUTERON
ALPHA-PARTICLE
ELECTRON
A
B
(DE/DR)MIN
4 X (DE/DR)MIN
10
100
1000
SPECIFIC ENERGY LOSS, MEV/GM/CM²

FIGURE 2

long edge and parallel to the emulsion, that nearly all the heavy ions entered the emulsion with zenith angle from 0° to 40°. Hence, any heavy ion having a track length greater than the minimum value would travel more than three fields of view in the vertical direction. This made it possible to scan along the edge, then skip a field of view and scan back. The entire plate was scanned in this manner. Several plates were picked at random, and the entire emulsion scanned with no noticeable difference in the number of acceptable heavy ions recorded by the two methods.

The heavy ion interactions recorded in this paper were found by following all heavy ions observed in the emulsions. The method of skipping a field of the emulsion is dangerous, in that some of the heavy ion interactions may have been overlooked. If the event occurred in one field of view, the ion would necessarily come in at a large angle with the emulsion and hence would be very short. Also, the emitted particles in the forward direction would leave the emulsion immediately. A star of this type would be difficult to analyze; and identification of particles would be hopeless, unless the plates were originally stacked, making it possible to follow a track from one emulsion to another. Unfortunately, the present plates were not aligned before exposure. Also to be considered is the fact that a heavy ion may enter the emulsion almost parallel and interact immediately. This type event may have been missed, but it is reasonable to assume that it does not occur frequently.

A total of five events caused by the heavy component of cosmic radiation have been found, of which four have been analyzed. The fifth is an interaction of a heavy ion in which a few evaporation particles are emitted. The ion continues in the same direction without apparent loss of charge. This event is very similar to one recorded by Bradt and Peters[8].

4. IDENTIFICATION OF HEAVY IONS

The silver halide grains in the emulsions are made developable by the ionization produced by a charged particle. Since the same process is responsible for the energy loss of the particle in its passage through matter, the grain density will increase with increasing charge and decreasing velocity of the particles, and will be independent of mass. For heavy ions, the track will be a solid column of developed silver whose thickness can be many times larger than the diameter of the grains in the emulsion. The width of these tracks is far too large to be accounted for by the increased range of the electric field of multiply charged nuclei. The width of such tracks is due to secondary electrons with energy enough to render a few grains developable in the neighborhood of the trajectory. From the number of these secondary electrons (delta-rays) ejected from a heavy track, it is possible to determine the charge of the particle.

The most common method[8] used for determining the charge of heavy ions is based on the measurement of:

(a) the frequency of occurence of delta-rays per unit length of track and

(b) the ranges of the particles in the assembly of glass and emulsion constituting the photographic plates.

For particles of low energy which occur frequently in the primary radiation at geomagnetic latitudes greater than 45°, the above method suffers from the fact that the charge and energy can be accurately determined only if the particle happens to reach the end of its range in one of the emulsions. Even for higher energies, the above method was impossible to use because the present set of plates was not aligned before exposure, making it impossible to follow an ion through glass and emulsion.

However, a recent paper by Dainton, Fowler and Kent[18] eliminates this difficulty. They determine the charge and energy of the heavy ions in cosmic radiation from the frequency of the accompanying delta-rays and the multiple scattering in its path through the emulsion. They illustrate this method by the charge spectrum of 226 tracks in emulsions exposed at 95,000 feet. Figure 3 represents the theoretical values for Ilford G-5 plates of number of delta-rays per 100 microns (N_δ) versus the average angular deviation per 100 microns ($\bar{\alpha}$) for ions of various charges. The solid lines represent lines of constant charge, while the dashed lines are lines of constant range. Also, an energy scale is introduced at the top of the figure.

For particles moving at relativistic velocities, N_δ varies as Z^2, and is independent of the precise value of the energy. Figure 3 shows that as the energy increases, N_δ becomes constant. This occurs when the energy per nucleon is greater than 1.5 Bev. The charge can therefore be deduced from the observed value of N_δ without an exact knowledge of the range. It must be remembered that this is only true where the energy per nucleon of the heavy ion is high enough to produce

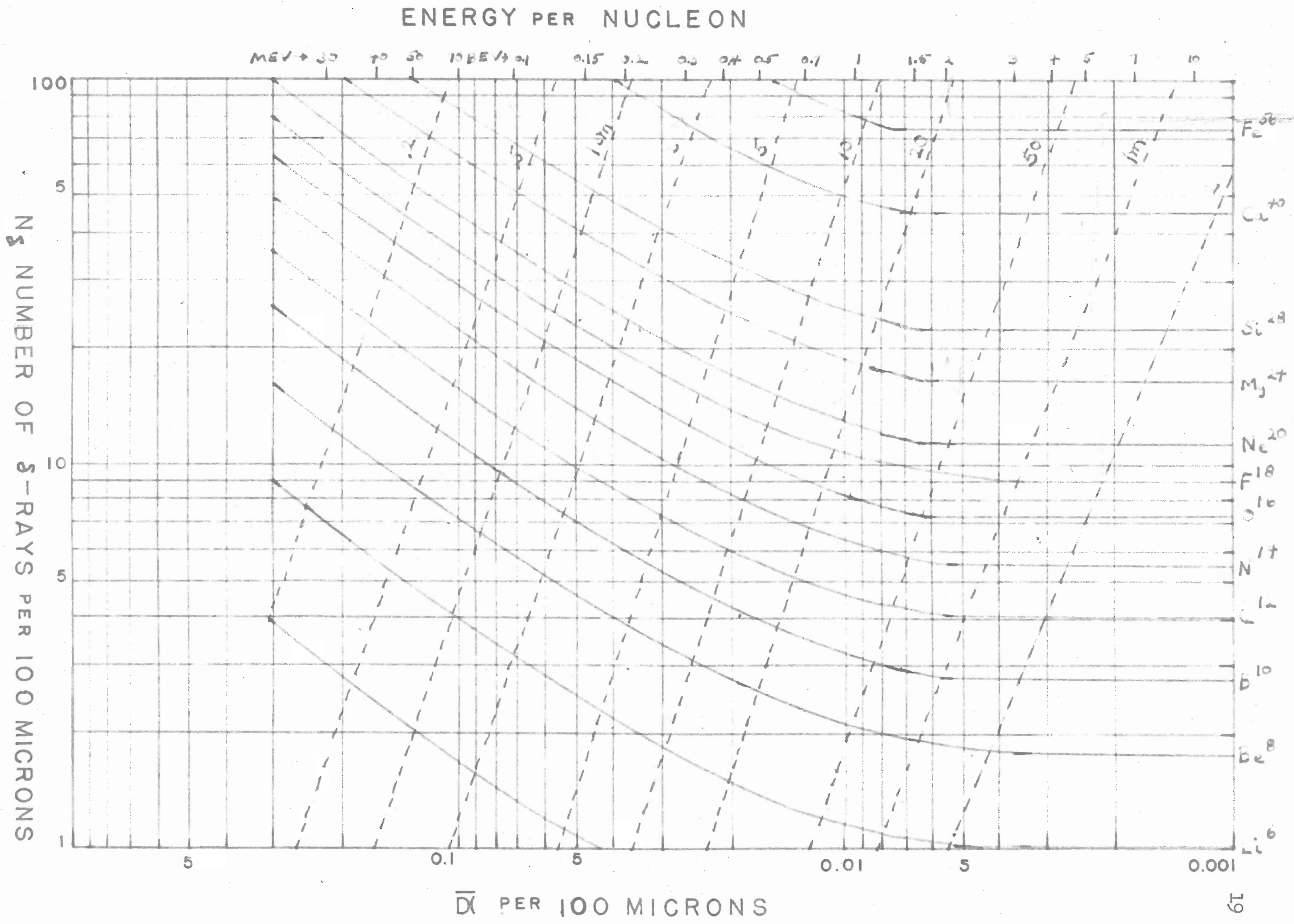
ENERGY PER NUCLEON
MEV + 30
40
50
10 BEV/N 0.1
0.15
0.2
0.3
0.4
0.5
0.7
1
1.5
2
3
4
5
7
10
100
5
10
5
1
N_δ NUMBER OF δ-RAYS PER 100 MICRONS
5
0.1
5
0.01
5
0.001
$\overline{D\alpha}$ PER 100 MICRONS
Fe^{56}
Ca^{40}
Si^{28}
Mg^{24}
Ne^{20}
F^{18}
O^{16}
N^{14}
C^{12}
B^{10}
Be^{8}
Li^{6}
.2
.5
1
2
5
10
20
50
100

FIGURE 3

a constant number of delta-rays per unit length over a long range. There are several methods one can employ to determine whether the energy of the ion is high enough to determine its charge by counting N_δ alone.

1. If the ion track is of great length ($\sim$10,000 microns) and N_δ is constant over this entire range, or
2. If the ion interacts with a nucleus of the emulsion and produces results which show it to be a high energy interaction.

In both of the above cases, we can identify the particle by comparing the observed value of N_δ with the anticipated value of N_δ for various charges from Figure 3, and we can also set a lower limit to the energy of the particle.

Two long ion tracks were chosen for identification by counting N_δ and measuring the multiple scattering. The tracks were 23,000 and 15,000 microns in length, but did not end in the emulsion. The method of measuring scattering was the same used as described by Heck[16], except that readings were taken in the microscope itself rather than on a projected field. The Leitz Ortholux microscope was used and the lens system consisted of the 100:1 oil emersion objective with the 10x compensated eyepieces. With this lens system, 100 divisions on the eyepiece scale were equal to 50 microns. The plate was rotated on the stage until the track being studied was parallel to one of the axes. Hence, one could move along the entire length of track by changing only one coordinate.

Several calculations were made for $\bar{\alpha}$ and N_δ at intervals of 5,000 microns for each track. $\bar{\alpha}$ and N_δ represent the average values per 100 microns over a track length of 1,000 microns. The observed values for the two tracks are shown in Table I. Several values were calculated in order to show whether or not the track was caused by a high energy or a low energy ion. Table I shows that for each track, the number of delta-rays and the angular deviation stays relatively constant. Looking at Figure 3, we see immediately that Track I was caused by a particle of $Z = 8 \pm 1$. This corresponds to an oxygen nucleus. Track 2 with $N_\delta = 5.7$ delta-rays/100 microns and $\bar{\alpha} = 0.001873$ rad./100 microns corresponds to $Z = 7 \pm 1$. Therefore, Track 2 was caused by a nitrogen nucleus.

Since N_δ remained constant, we could have identified the particle just as readily as in the above case by counting delta-rays alone.

The value of $\bar{\alpha}$ is helpful in the above cases, in that it allows us to place a lower limit on the energy of the heavy ion. In the case of Track 1, $\bar{\alpha} = 0.002085$ rad./100 microns, which corresponds to an energy of 6 Bev per nucleon (Figure 3). In the case of Track 2, $\bar{\alpha} = 0.001873$ rad./100 microns, which corresponds to an energy of approximately 8 Bev per nucleon.

5. METHOD OF FINDING POLAR ANGLE DEPENDENCE

The polar angle is defined by the direction of the incoming ion, and all shower particles are found with respect to this direction. A particle was considered a shower particle if its ionization was less than 1.5 times minimum ionization. For the series 7 plates, minimum ionization was found to be 23 ± 1 grains/100 microns. Therefore, any particle whose grain count was less than or equal to 36 grains/100

TABLE I

TRACK 1 Plate 7 - 10

coordinates $y = 0.2$ $x = 52.5$ x(micrometer) = 5.0

Length of Track in Emulsion: 23,750 microns

Range in Emulsion μ	N_δ δ-rays/100 μ	$\bar{\alpha}$ rad./100 μ
19,500	6.80	0.00195
14,500	7.0	0.00222
9,500	7.4	0.00195
4,500	7.1	0.00222

Ave. $N_\delta = 7.1 \pm 1$ Ave. $\bar{\alpha} = 0.002085 \pm 0.000137$

TRACK 2 Plae 7 - 2

coordinates $y = 25.76$ $x = 52.9$ x(micrometer) = 5.0

Length of Track in Emulsion: 15,680 microns

15,000	6.1	0.001617
10,000	6.0	0.002912
5,000	5.73	0.001912
500	5.0	0.002050

Ave. $N_\delta = 5.7 \pm 1$ Ave. $\bar{\alpha} = 0.001873 \pm 0.000256$

microns was considered a shower particle.

The same optical system was used here as for the identification of heavy ions.

The shower particles were assumed to be mesons, and hence, for the analysis of the event, it was necessary to know the polar angle (θ) dependence. The angle θ was found in the following manner.

A point on the eyepiece scale was placed at the center of the star, and this was defined as the origin of a coordinate system in the emulsion. Once the eyepiece is set, it must not be moved until all measurements are complete. Moving the eyepiece will change the origin of the coordinate, and consequently all values of θ will not be with respect to the same origin. The micrometer screws can be read to within 5 microns and the depth of focus to within 1 micron.

The values of x_0, y_0, and z_0 are read directly from the micrometer stage of the microscope. Then the micrometer screws are moved, placing a point of the track caused by the heavy ion directly under the point on the eyepiece scale defined as the origin. Again, the coordinates (x_1, y_1, z_1) are read directly from the micrometer stage. These two points define a vector, and by taking the difference properly, the vector can be made to point in the direction defined by the heavy ion.

$$x_1' = x_0 - x_1$$
$$y_1' = y_0 - y_1$$
$$z_1' = z_0 - z_1$$

It must be remembered that z_1' is not the actual depth that the ion has traveled. The emulsions were originally 300 microns, and after development, they are only a fraction of this value. The shrinkage factor for these emulsions is 2.37, and the value of z_1' must be multiplied by this value. The same is true for any measurement made on the z coordinate.

The next step is to record the coordinates of a point on each of the minimum ionization tracks. Those points are called x_2, y_2 and z_2. The differences between these points and the origin defines a vector in the direction of motion of the particle.

$$x_2' = x_2 - x_0$$

$$y_2' = y_2 - y_0$$

$$z_2' = z_2 - z_0$$

Once these vectors are found, it is only a matter of calculation to find the polar angle for each shower particle. If θ' is the angle between the two vectors, then it is given by:

$$\cos\theta' = \frac{X_1'X_2' + Y_1'Y_2' + Z_1'Z_2'}{\sqrt{X_1'^2 + Y_1'^2 + Z_1'^2}\sqrt{X_2'^2 + Y_2'^2 + Z_2'^2}}$$

No consideration has been given the azimuthal angle (φ), since Fermi's theory assumes meson production independent of φ.

A typical calculation is given in Table II and Table III. All primed values are in microns. Since the micrometer screws can be read to within 5 microns, the values of θ' can be in error ± 1°.

These tables show the calculations for the event illustrated in Figure 8, while Figure 9 shows the values plotted as a function of the polar angle.

TABLE II

Plate 7 - 12 coordinates: $y = 20.00$ $x = 52.7$

$x(\text{micrometer}) = 5.0$

Origin $x_0 = 5.002$ $y_0 = 19.982$ $z_0 = 51$

Coord. of heavy ion $x_1 = 4.988$ $y_1 = 19.740$ $z_1 = 49$

Zenith Vector: $x_1' = x_0 - x_1 = 20$ $y_1' = y_0 - y_1 = 250$

$z_1' = z_0 - z_1 = 2(2.37)$

TRACK 1	$x_2 = 4.902$	$y_2 = 20.100$	$z_2 = 47$
gr.count/100 = 22	$x_2' = -100$	$y_2' = 118$	$z_2' = -5(2.37)$
TRACK 2	$x_2 = 4.928$	$y_2 = 20.095$	$z_2 = 69$
gr.count/100 = 32	$x_2' = -74$	$y_2' = 113$	$z_2' = 18(2.37)$
TRACK 3	$x_2 = 4.982$	$y_2 = 20.025$	$z_2 = 62$
gr.count/100 = 30	$x_2' = -20$	$y_2' = 43$	$z_2' = 11(2.37)$
TRACK 4	$x_2 = 4.985$	$y_2 = 20.078$	$z_2 = 45$
gr.count/100 = 26	$x_2' = -17$	$y_2' = 96$	$z_2' = -6(2.37)$
TRACK 5	$x_2 = 4.988$	$y_2 = 20.082$	$z_2 = 62$
gr.count/100 = 24	$x_2' = -14$	$y_2' = 100$	$z_2' = 11(2.37)$
TRACK 6	$x_2 = 4.985$	$y_2 = 20.170$	$z_2 = 49$
gr.count/100 = 24	$x_2' = -17$	$y_2' = 188$	$z_2' = -2(2.37)$
TRACK 7	$x_2 = 4.992$	$y_2 = 20.199$	$z_2 = 58$
gr.count/100 = 22	$x_2' = -10$	$y_2' = 217$	$z_2' = 7(2.37)$
TRACK 8	$x_2 = 5.002$	$y_2 = 20.142$	$z_2 = 44$
gr.count/100 = 28	$x_2' = 0$	$y_2' = 160$	$z_2' = -7(2.37)$
TRACK 9	$x_2 = 5.012$	$y_2 = 20.152$	$z_2 = 60$
gr.count/100 = 24	$x_2' = 10$	$y_2' = 170$	$z_2' = 9(2.37)$
TRACK 10	$x_2 = 5.002$	$y_2 = 20.030$	$z_2 = 45$
gr.count/100 = 24	$x_2' = 0$	$y_2' = 48$	$z_2' = -6(2.37)$
TRACK 11	$x_2 = 5.075$	$y_2 = 20.112$	$z_2 = 51$
gr.count/100 = 35	$x_2' = 77$	$y_2' = 130$	$z_2' = 0$

All primed values are in microns.

TABLE III

Using: $$\cos\theta' = \frac{X_1'X_2' + Y_1'Y_2' + Z_1'Z_2'}{\sqrt{X_1'^2 + Y_1'^2 + Z_1'^2}\sqrt{X_2'^2 + Y_2'^2 + Z_2'^2}}$$

TRACK NO.	COS θ'	θ'
1	.7055	45° 8'
2	.75938	40° 35'
3	.77316	39° 22'
4	.95607	17° 3'
5	.95056	18° 6'
6	.98784	8° 58'
7	.99126	7° 35'
8	.98996	8° 8'
9	.99504	5° 43'
10	.95167	17° 53'
11	.8982	26° 5'

CHAPTER III

ANALYSIS OF EVENTS

All coordinates in the following pages refer to the Leitz Ortholux microscope. All events illustrated are projection drawings made by projecting the events by a system of mirrors upon a plane.

The event illustrated in Figure 4 was found in plate 7-3. The coordinates are:

y = 7.85
x (course) = 73.0
x (micrometer) = 5.0

The heavy ion was assumed to have sufficient energy to allow it to be identified by counting delta-rays alone. The total length of the track is 510 microns and N_δ over this range is equal to 22 delta-rays/100 microns. The element traveling with relativistic velocity and having this delta-ray count is silicon ($Z = 14$; $N = 28$). Due to the difficulty in counting this number of delta-rays/100 microns, the delta-ray count could easily be in error by 2 delta-rays/100 microns. Therefore, a more accurate statement of the atomic number would be $Z = 14 \pm 1$.

The total number of particles emitted from the event is 54. There are in the forward direction 30 minimum or near-minimum ionizing particles which are assumed to be pi-mesons. The total charge emitted, counting relativistic and non-relativistic particles, is 71.

On the assumption that the silicon nucleus collided with a nucleus of the most abundant element in the emulsion, silver, there is a total charge of 61 involved. Therefore, by charge conservation, there

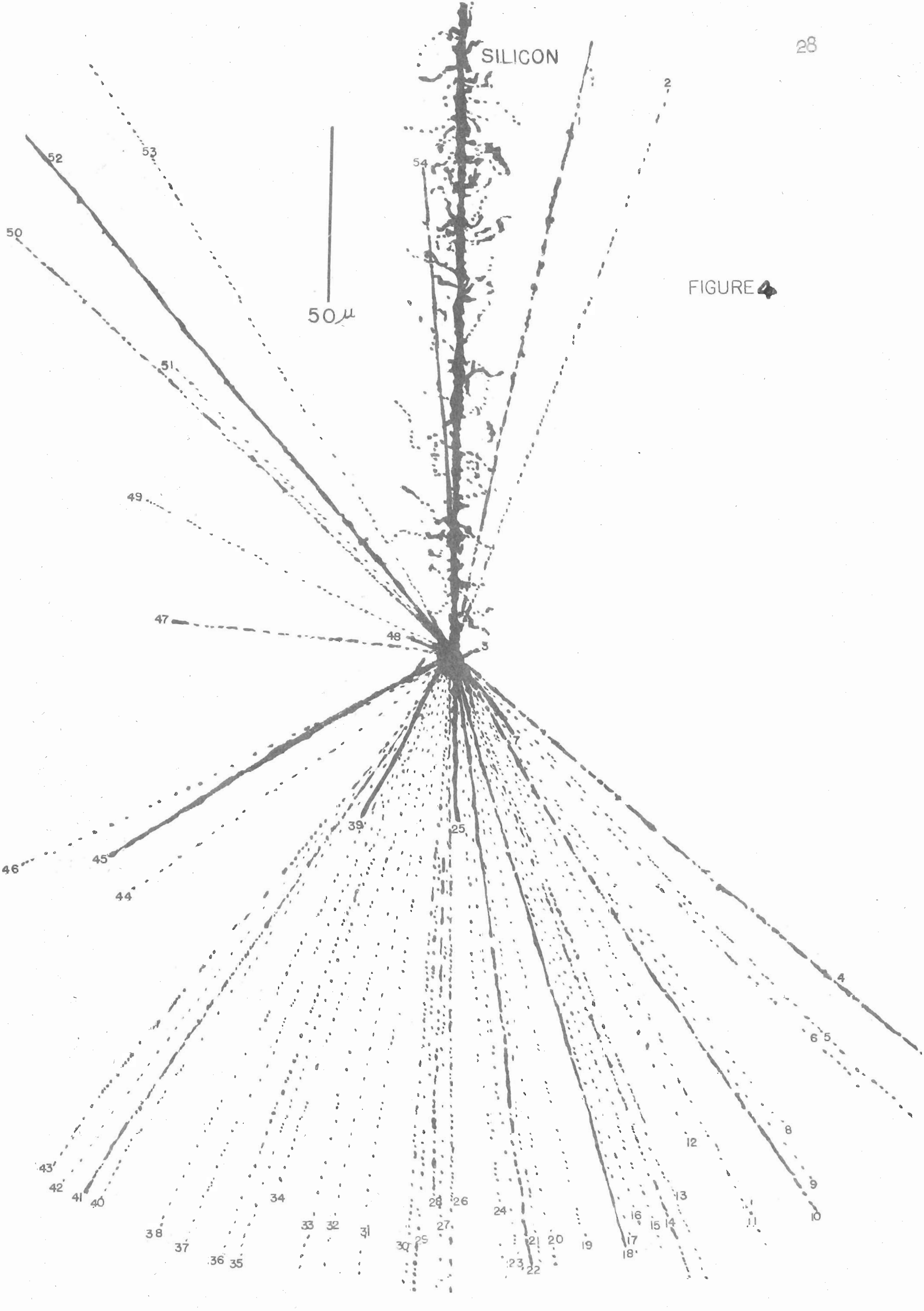
SILICON
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FIGURE 4

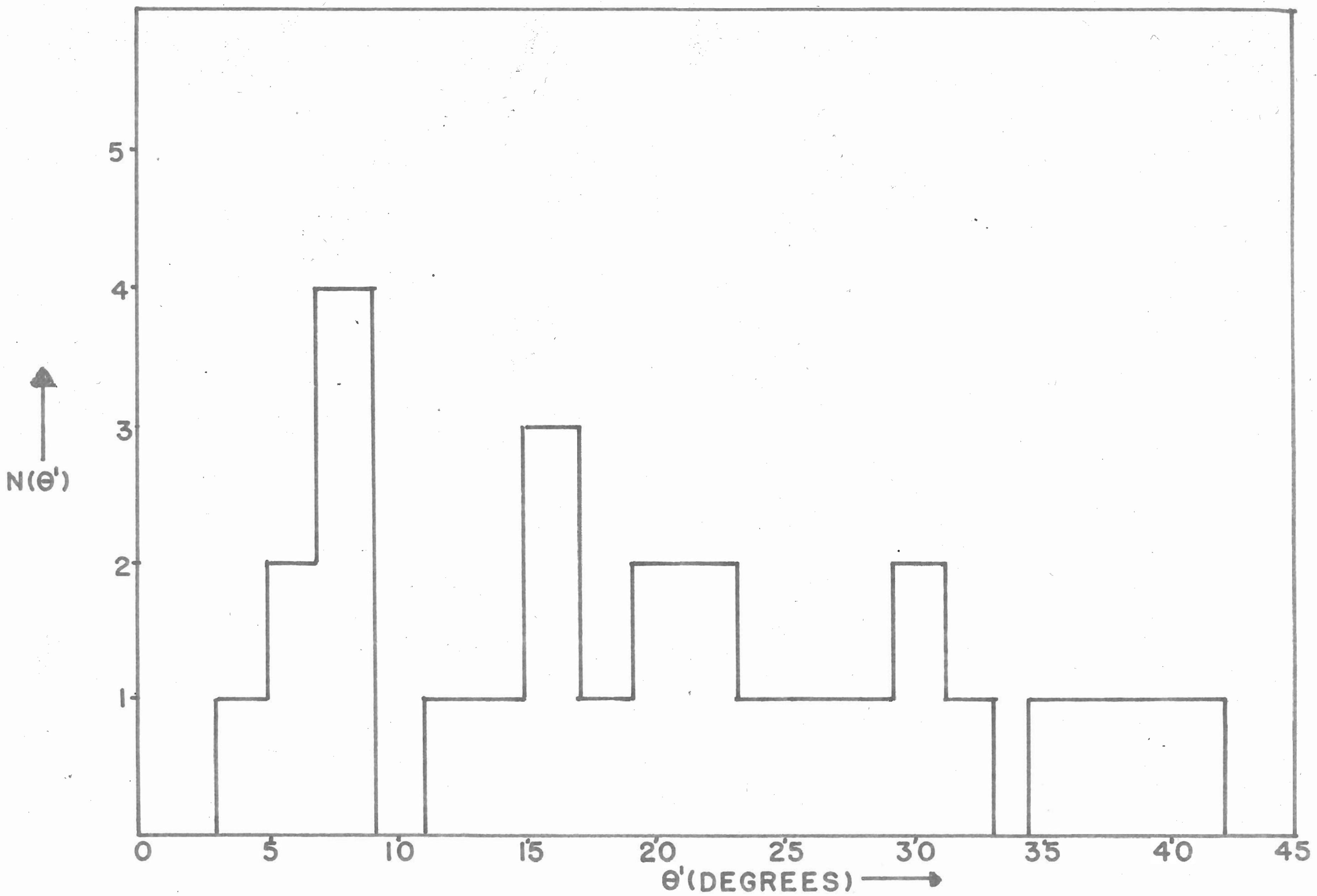


FIGURE 5

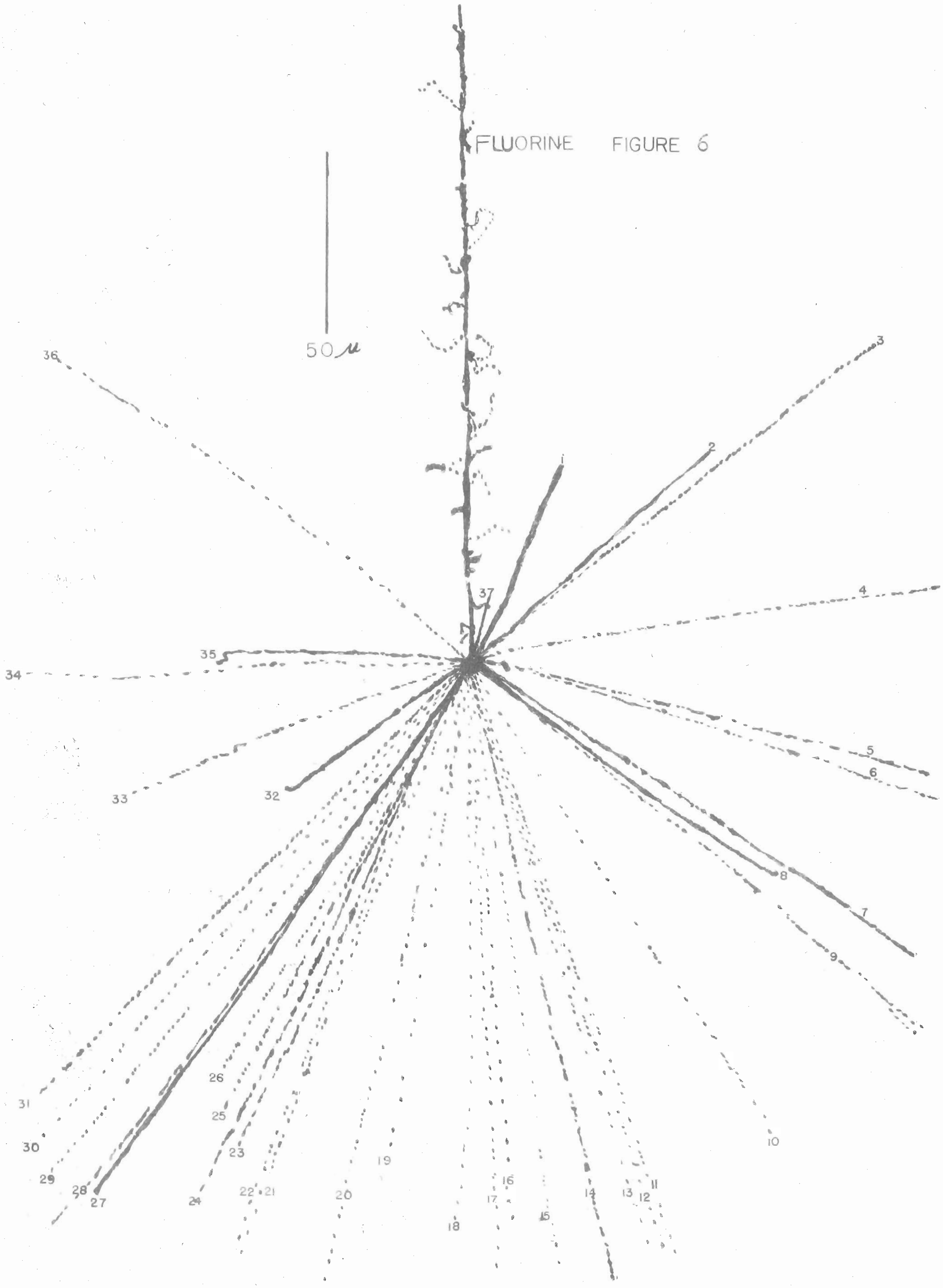
were 10 charges created. The next abundant element in the emulsion is bromine, which has a charge of 35. A collision between silicon and bromine would involve a total charge of 49, and thus 22 charges would be created. The event illustrated in Figure 4 is most likely to be of this latter type, since the diffused shower contains 30 minimum ionizing particles.

Figure 5 gives the angular distribution for the diffused shower of mesons for the event in Figure 4. The polar angle is defined by the direction of the incoming ion. N (θ') gives the number of mesons per degree where θ' refers to the polar angle.

From the theory as presented by Fermi, a theoretical curve could not be found to fit the experimental data. This theory predicts a maximum very close to zero polar angle. Therefore, this event cannot be considered a nucleon-nucleon interaction. It is very likely that this event is of a more complex nature. Possibly, it is an interaction where two or more nucleons of the incident ion interact with two or more nucleons of the target nucleus (pluro-multiple production). In addition, produced mesons may interact with nucleons with possible multiple meson production. Also, the interaction may range from a central collision to a glancing type which all adds to the complexity of the problem.

Figure 6 shows the projection drawing of an event found in plate 7-8. The coordinates are:

y = 14.55
x (course) = 39.4
x (micrometer) = 5.0



FLUORINE FIGURE 6

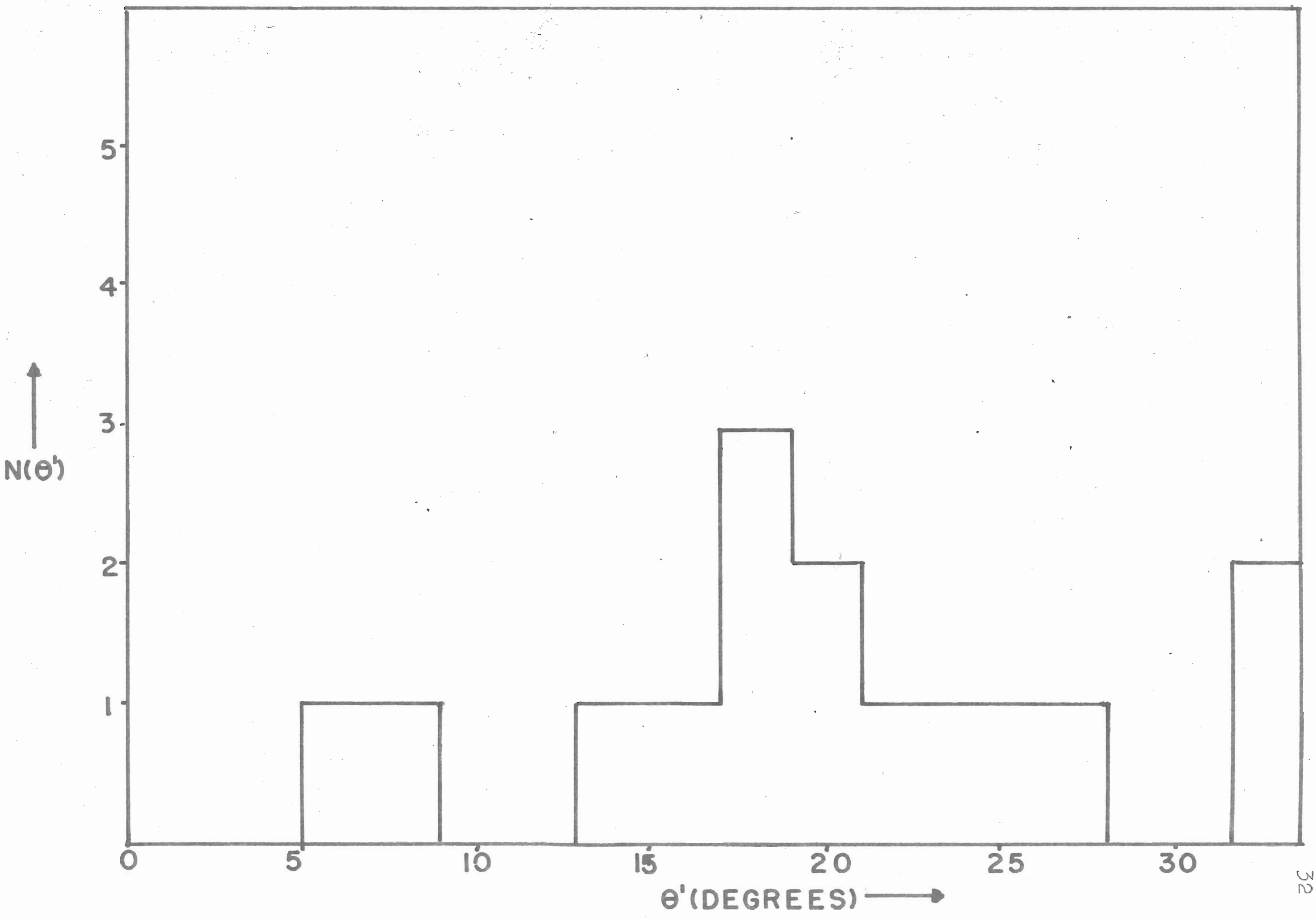


FIGURE 7

The total length of the ion in the emulsion is 1,020 microns. The average delta-ray count over this entire length was found to be 8.8 ± 1 delta-rays/100μ. This corresponds to the element with Z = 9 ± 1 which is flourine.

In the interaction, there are 37 charged particles emitted, of which 15 are at minimum ionization located in the diffused shower in the forward direction. The emitted particles carry away a total charge of 43. Therefore, if we consider that 14 charges were created, and since the incident ion had a charge of 9, the target nucleus must have a charge of approximately Z = 20. This element is not listed as part of the emulsion by the manufacturer, but could easily be an impurity. Figure 7 gives the histogram of the 15 minimum ionization tracks in the diffused cone. Again, a theoretical curve could not be fitted to the observed distribution. We can conclude with certainty that this is not an interaction of the Fermi type, and that it is definitely of a more complex nature.

Figure 8 illustrates another event of the foregoing type. This event was found in plate 7-12 and can be located by the following coordinates:

y = 20.00
x (course) = 52.7
x (micrometer) = 5.0

The ion was 7,150 microns in length. The delta-ray count/100 microns over this entire range was found to be constant at N_δ = 4.1 ± 1. The ion was identified to be carbon. In addition, measurements of small angle scattering were made and $\bar{\alpha}$ was found to be 0.00223 rad./100μ.

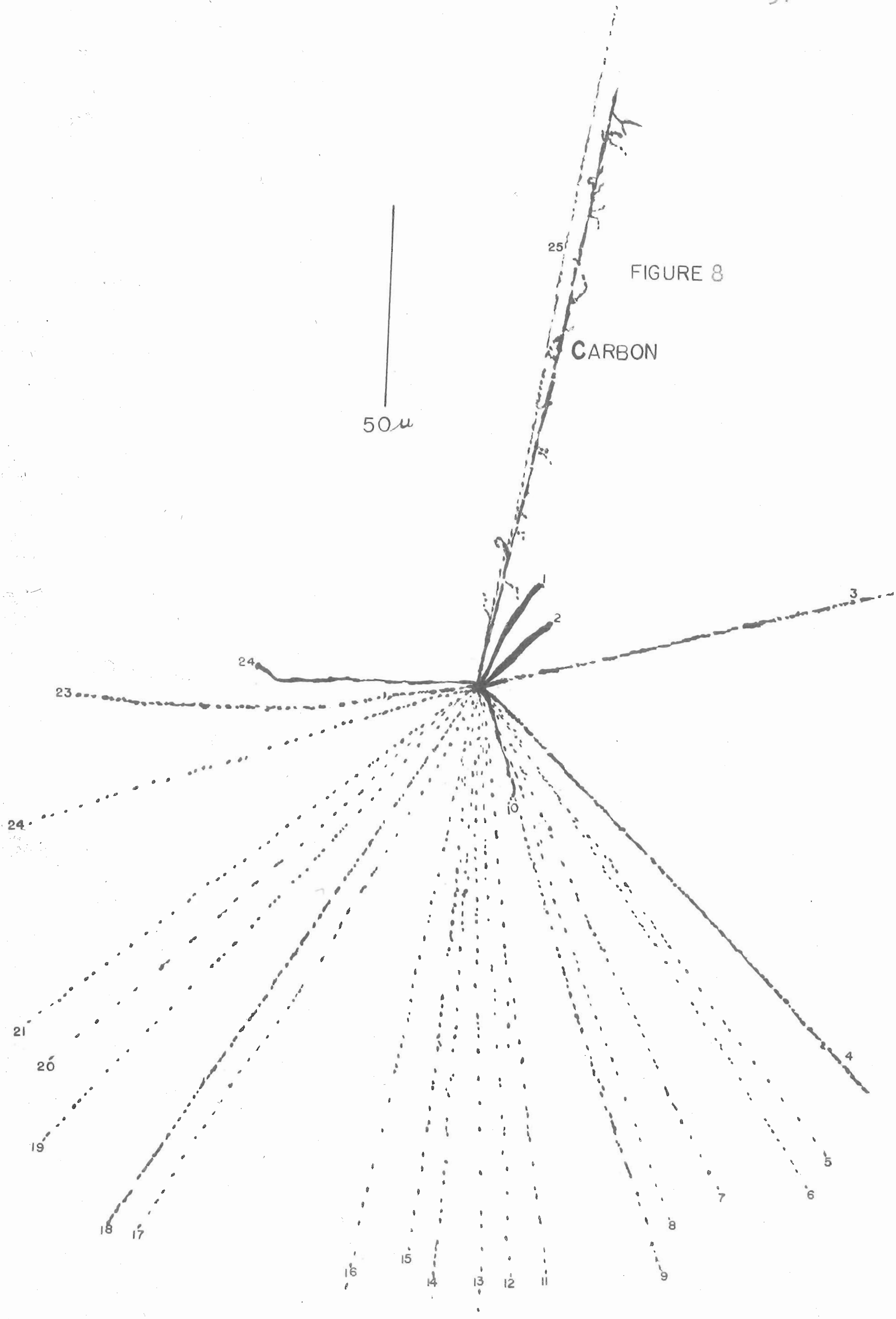


FIGURE 8

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CARBON
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This enables one to set a lower limit to the energy of the incident ion from the energy scale included at the top of Figure 3. The lower limit was found to be 5.5 Bev/nucleon.

There are 25 charged particles emitted, of which 11 are at minimum ionization located in a diffused cone in the forward direction. The emitted particles in this event carry away a total charge of 32; and if we assume the target nucleus to be that of sulpher, we may conclude that 10 charges were created.

Figure 9 gives the observed distribution of the 11 minimum ionizing particles in the diffused shower. As before, they are plotted with respect to the direction of the incoming ion. Attempts to fit a theoretical distribution to the observed distribution proved fruitless. Therefore, this is not a nucleon-nucleon interaction but, again, one of a more complex nature.

The event illustrated in Figure 10 was caused by an ion identified as silicon. The total track length of the ion is 1,500 microns, and has a constant delta-ray count of 21.8 ± 2 delta-rays/100 microns.

The event was found in plate 7-21, and can be located by using the following coordinates:

y = 11.15
x (course) = 76.4
x (micrometer) = 5.0

There is a total of 31 particles emitted. The most interesting feature of this event is that the incident nucleus continues in the same direction, but deminished in charge. This can be interpreted as

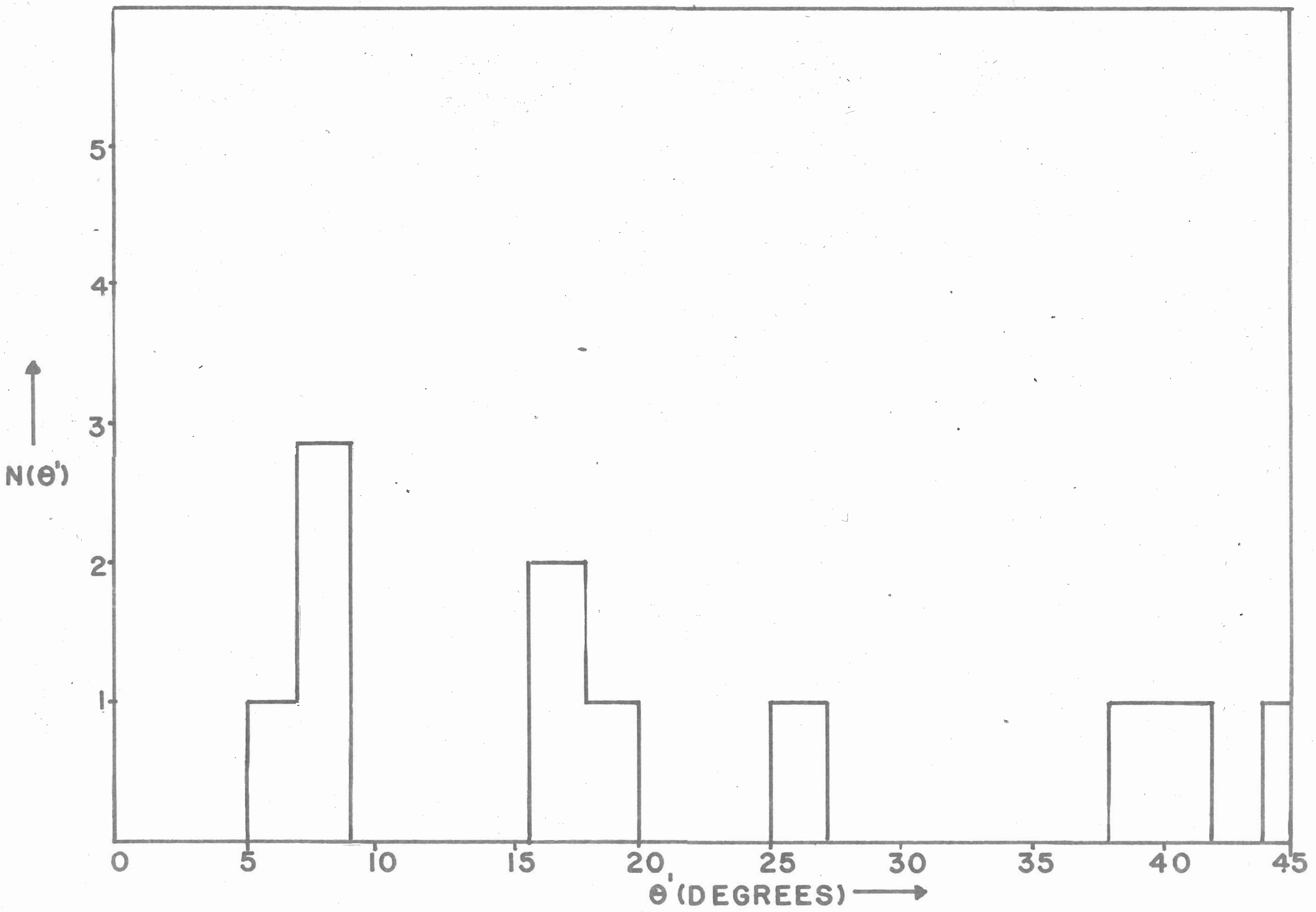
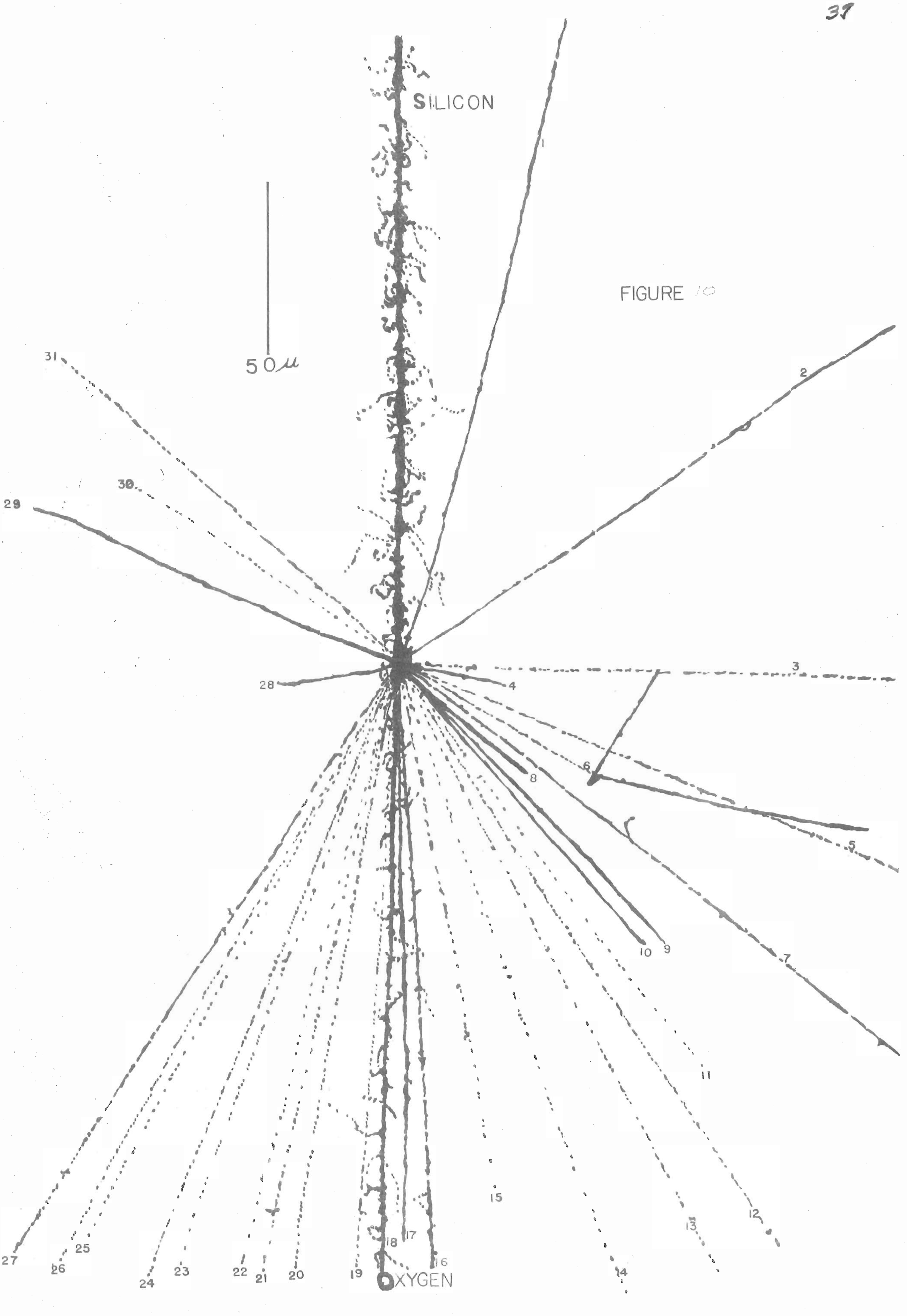


FIGURE 9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OXYGEN

FIGURE 10

a glancing collision with a nucleus of the emulsion when only a few nucleons of the incident ion interact with the target nucleus. By considering charge conservation, the target nucleus was probably that of bromine.

The ion, after collision, had a track length of 540 microns. The delta-ray count over this entire length of track was 7 ± 1 delta-rays/100 microns, which corresponds to an oxygen nucleus. This constant delta-ray count seems to indicate that the primary ion lost but little of its energy per nucleon in the interaction.

There are approximately 6 minimum ionization particles, but they are spread over a wide angle and could not possibly be connected with a nucleon-nucleon interaction.

Another interesting feature of this event is that one of the emitted particles causes a low energy secondary event. The recoil nucleus can also be observed.

CHAPTER IV

CONCLUSION

As this paper has showed, the interactions of the heavy ion component of the primary cosmic radiation cannot be considered as a single nucleon-nucleon interaction. Therefore, Fermi's theory of multiple meson production cannot be applied to such events. The possibility that the nucleon may have been scattered before it interacted in meson production has been considered and found fruitless. If this possibility were true, and the interaction were one of the

Fermi type, we should observe a narrow core of minimum ionising particles in a different direction than that defined by the polar angle. It must be remembered that the histograms given in this paper are independent of the azimuthal angle and maximum points with respect to the direction defined by the incident ion are not necessarily maximums, if the polar angle is shifted to a new position.

In general, the interactions presented in this paper are of a complex nature. They may be interactions of the following types:

1. Pluro-multiple production
2. Plural production
3. Meson production by knock-on nucleons
4. Further interactions of initially produced mesons with nucleons

Meson production may also result from a combination of any of the above types of meson production.

In addition, the collision of the incoming nucleus with the target nucleus may range from a central collision to a glancing collision, which all adds to the complexity of the problem.

It seems that meson production as described by Fermi happens rarely in photographic emulsions. When it does occur, it is most likely to be an interaction between a primary proton and one of the light elements of the emulsion. It also seems likely that this type of production could be the result of two nucleons interacting which were located on the circumferences of the nuclei, providing it were a glancing type collision and not a centered collision. This is what this paper has attempted to prove. From the results of this paper, it seems very unlikely that only a nucleon-nucleon interaction would result when a heavy ion collides with a nucleus of the emulsion.

APPENDIX I

Contents of D-19 Developer

Water, about 125° F (50° C)	500 cc
Elon	2.2 grams
Sodium sulfite, desiccated	96.0 grams
Hydroquinone	8.8 grams
Sodium carbonate, monohydrated	56.0 grams
Potassium bromide	5.0 grams
Cold water to make	1.0 liter

Dissolve chemicals in the order given.

APPENDIX II

Potassium Permanganate Test

Stock solution:

Water (distilled)	8 oz. = 236.8 cc
Potassium permanganate	4 gr. = .260 grams
Sodium hydroxide	8 gr. = .520 grams

Use 15 drops of above solution to 8 oz. (237cc) of distilled water. Then pour ½ oz.(14.8cc) of this solution in small graduate. Now allow water to drip from plates into this solution, and the presence of hypo will be indicated in that the violet solution will turn to an orange color. If more hypo is present, the solution will change to a greenish yellow color.

As certain impurities in water will cause similar discolorations of the solution, a number of drops of tap water should be dropped into the ½oz.(14.8cc) of violet colored solution. If no change takes place, any change in color that will take place from the water drained from the plates will be due to the presence of hypo.

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