Emulsion Cloud-Chamber Observations on the Interactions of High Energy Primary Cosmic Radiation*

M. F. KAPLON AND D. M. RITSON
University of Rochester, Rochester, New York

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The initial investigations with the emulsion cloud chamber are surveyed. A study of some "purely electronic" showers is presented and an upper limit on the electron-photon component of the primary radiation is given as ≤ 2 percent of the proton component at energies in excess of $\sim 3\times 10^{11}$ ev. High energy nuclear interactions occurring in brass are discussed, and evidence is presented for the similarity of nucleon-nucleon and nucleon-nucleus interactions at very high energies. A study of the soft radiation produced in these interactions gives a ratio of neutral mesons to charged particles of 0.5. The primary proton spectrum is extended to energies of approximately 5×10^{12} ev, and evidence is presented for the constancy of the α-particle to proton ratio in the primary flux up to these energies.

I. INTRODUCTION

HIGH energy nuclear interactions are characterized by their resultant mixed shower cascades consisting of penetrating (nucleonic and mesonic) and soft (electronic) components. Interactions whose energies are greater than approximately 5×10^{11} ev have been previously studied by a variety of techniques: cloud chambers, counters, and photographic emulsions. Cloud chambers and counter systems have the great advantage of automatic selection (by a suitable triggering mechanism) but suffer from their lack of high resolution; usually only the resultant cascade is observed but not the initiating event. The photographic emulsion is capable of extremely high resolution and allows a detailed study of the primary interaction but suffers the lack of a method of systematic selection of events; previously high energy events have been found in photographic emulsions only in the course of surveys of many cubic centimeters of emulsion. We describe here a technique of observing high energy nuclear interactions which has the advantage of both systematic selection and high resolution.

Sensitive nuclear emulsions are exposed in an emulsion cloud chamber consisting of carefully aligned alternate layers of absorber and emulsion. A high energy particle interacts in the absorber; the emulsions directly below the absorber in which the interaction occurs show mainly the charged component produced in this interaction. Further down in the emulsion-absorber stack the electronic component begins to multiply and form well-marked electronic showers. These electronic showers form the basis for the systematic selection of high energy events.

The experimental procedure to locate high energy events then consists of a systematic survey for electronic showers in one of the emulsions deep in the stack; if the plates are carefully aligned, it is then possible to trace the shower in succeeding and preceding emulsions. As the shower is traced back towards its origin, the electronic component diminishes, and an emulsion is reached in which the shower (now primarily pure penetrating component) first appears; this is usually near the origin of the shower (which occurs in the absorber directly above this emulsion), and the tracks in this emulsion project back to the point of origin. In this fashion all those showers are located which have an energy greater than a given value (the critical energy for selection being determined by the character of the absorber), whose zenith angles are less than some critical angle (dependent upon the geometry of the stack), and which are initiated in the absorbers above the scanned detection emulsion.

As stated above, the energy range for which this technique is applicable depends upon the material of which the stack is constructed. For the experiment described in this paper (brass absorbers) we do not observe the cores of electronic showers above the background of random tracks unless their energies are greater than $\sim 10^{11}$ ev: We find that a shower consisting of 5 or more parallel tracks within a radius of $\sim 100\mu$ can be detected in the emulsions exposed in this experiment; reference to Fig. 3 shows that this corresponds to a shower whose energy is $\gtrsim 10^{11}$ ev. In an arrangement consisting solely of photographic emulsion this limit would be as high as $\sim 5\times 10^{12}$ ev, while for very high Z materials (e.g., lead) this limit would be as low as $\sim 10^{16}$ ev.

When an emulsion cloud chamber is flown at high altitudes, the high energy interactions are produced by the latitude insensitive components of the primary cosmic-ray beam. With an arrangement of this type we obtain direct experimental data on the flux and composition of the high energy primary radiation[1] (Sec. VII), information concerning the nature of the primary interactions[2] (Sec. V) as well as an estimate on the lifetime of the neutral π-meson.[3] Pure electronic showers are observed (events not directly connected to a nuclear

* This work was supported by the AEC.

[1] Kaplon, Ritson, and Woodruff, Phys. Rev. 85, 933 (1952). See reference 16.
[2] M. F. Kaplon and D. M. Ritson, Phys. Rev. 85, 932 (1952). See reference 16.
[3] Kaplon, Peters, and Ritson, Phys. Rev. 85, 900 (1952). See reference 16.

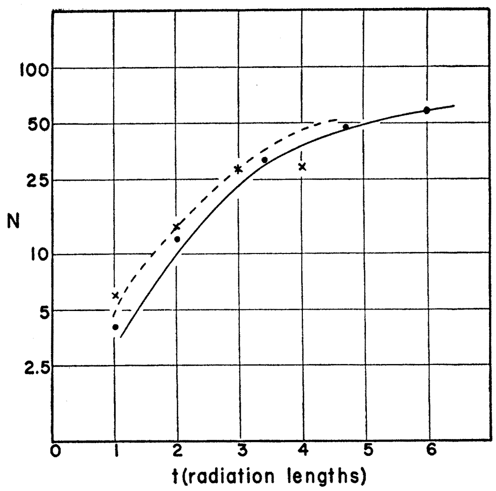

FIG. 1. Observed integral electron spectra for two different electron showers. The ordinate represents the total number of electrons exceeding the cut-off energy (defined by accepting electrons within a circle of 100 μ radius centered on the shower axis); the abscissa represents the distance in radiation lengths from the origin. The curves are the theoretical predictions normalized to the experimental data at their maxima. The dashed curve refers to a shower (×) of estimated energy $\sim 2.5\times10^{11}$ ev and the solid curve (●) to a shower of $\sim 5\times10^{11}$ ev.

interaction in the stack) which apparently arise from an incident electron or γ-ray. We are thus enabled to make a rather detailed study of soft shower development through several radiation lengths. These results are presented in Sec. III.

II. EXPERIMENTAL

We have extended our analysis on the emulsion cloud chamber used previously.[4] It consisted of a carefully aligned stack of 20 4-inch by 6-inch Ilford G-5 100-μ emulsions on 1.3-mm glass backing, separated by 3-mm brass absorbers (see Fig. 3 of reference 4). This arrangement was flow with the emulsion surfaces horizontal for six hours above 90,000 ft by a "Skyhook" balloon at White Sands, New Mexico (the actual flight curve is given in Fig. 2 of reference 4). The emulsions were processed by the usual methods of temperature development and after processing were cut to 3-inch by 2-inch size for microscopic observation.

The vertical spacing between successive emulsions in this experimental arrangement was 5 mm, consisting of 3 mm of brass, 1.3 mm of glass, 0.6 mm of air, and 0.1 mm of emulsion. The effective radiation length (X_0) for this combination of materials is 2.35 cm; thus, for vertical incidence 0.213 radiation lengths are traversed from plate to plate, and the entire stack in the vertical direction was 4.25 radiation lengths. The geometrical mean free path for nucleon interactions $\lambda_N[\sigma_N=\pi(1.45\times10^{-13}A^{\frac{1}{3}})^2]$ for the above combination of materials is 16.6 cm; for vertical incidence 0.03 of a mean free path is traversed from plate to plate, and the entire stack in the vertical direction is 0.6 nuclear mean free paths. For α-particles[4] the entire stack is of the order of one mean free path.

The actual positioning of the plates during flight was determined by tracing G-rays (heavy primaries) through the stack. These particles provided straight marker lines which were used to determine the relative position of two plates. In order to predict with perfect accuracy the position of a track from one plate to the next the following details must be known:

(1) Lateral horizontal displacement of plates.
(2) Relative rotation of the plates.
(3) Spacing of the plates.
(4) Tilt of the plates.
(5) Deviations of the plates from perfect planes.

In principle, all five characteristics can be determined by setting up the equations derived from a series of G-rays passing through the plates; in practice corrections were applied only for errors due to (1). The errors due to causes (2)–(5) were minimized by the design of the stack but were in all cases of the order of the machining tolerances (several mils) involved in the construction of the brass plate assembly. In practice the precision to which the position of a track could be predicted was thus limited to a few hundred microns. This space resolution is not sufficient to completely eliminate confusion with background when tracing single minimum ionizing tracks from one plate to the next, but it is sufficient to enable one to trace unequivocally a group of several minimum ionizing tracks or a single high energy track of more than several times minimum ionization (e.g., α-particles or heavy primaries).

To use this emulsion-absorber arrangement to obtain information relevant to the high energy flux values, it was necessary to adopt criteria for shower selection to accomplish the following:

(a) Make certain that for each shower selected a primary particle could be found.
(b) Eliminate purely electronic showers.
(c) Work in a region of sufficiently high energy so that the scanning for showers is 100 percent efficient.

In order to meet the above conditions the following criteria were adopted:

(1) The zenith angle of the shower must be greater than some minimum value.
(2) The shower must either:
  (a) start 2 radiation units inside the stack;
  (b) be multicored;
  (c) or contain at least 6 collimated tracks in the first plate in which it is visible.
(3) The shower must either:
  (a) not die out within 3 radiation units;
  (b) or must be seen for at least 2 radiation units and further develop after this.

Criterion (1) is a scanning criterion and was adopted to decrease inefficiency due to increasing background and decreasing visibility of small zenith angle showers.

[4] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. 85, 295 (1952).

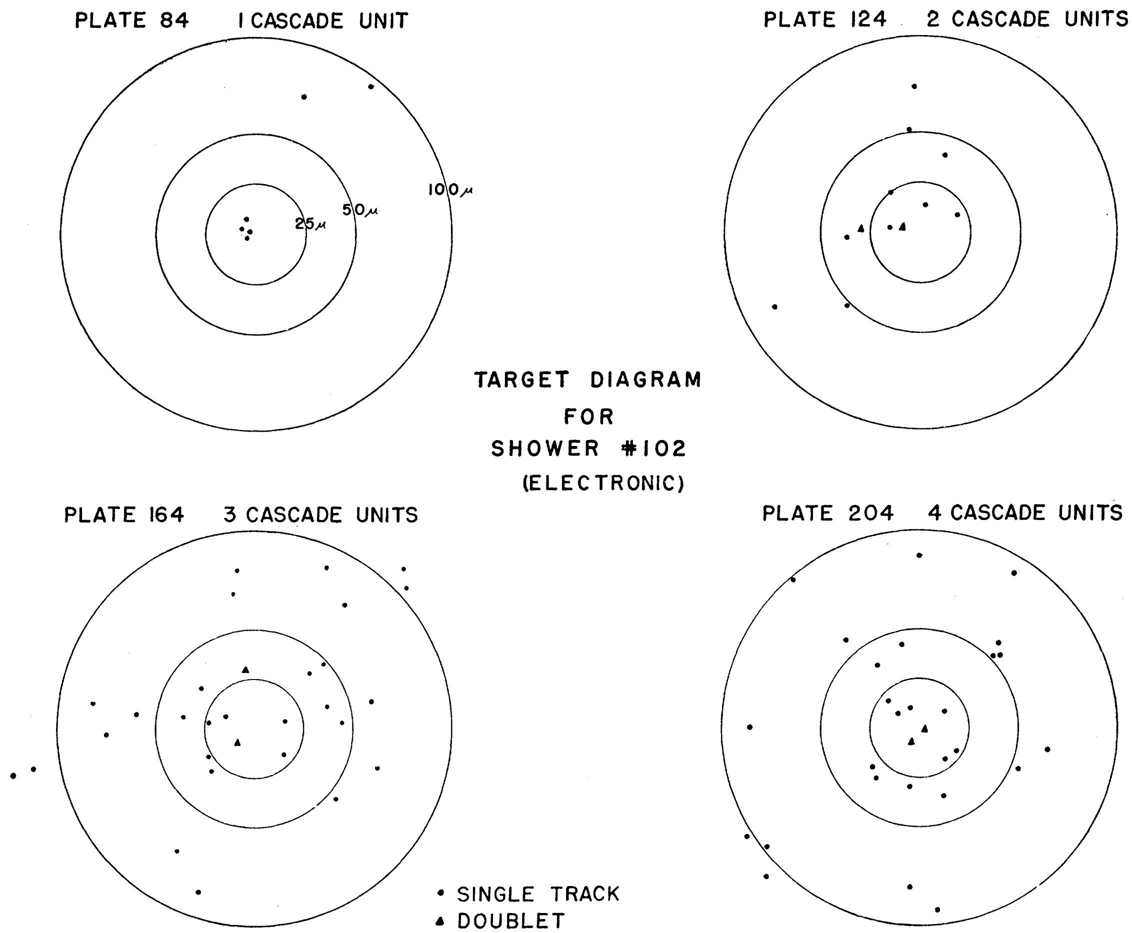

FIG. 2. Target diagrams for a typical electron shower at successive stages of its development. The points represent electron tracks projected onto a plane perpendicular to the shower axis, and the circles centered on the shower axis are of 25, 50, and 100 μ radius, respectively.

The second criterion was applied to eliminate purely electronic showers, and the third criterion was to insure that the energy cutoff is sufficiently high to make shower selection efficient. The criteria given above were adopted for selection of high energy nuclear events to obtain flux values; to obtain further events for studying the characteristics of these interactions certain of the above criteria were relaxed, particularly 2(a) and 2(b).

III. "PURELY ELECTRONIC" SHOWERS

In the introduction it was noted that electron showers were observed which were not associated directly with a nuclear event. These "purely electronic" showers apparently arise from electrons and photons incident from outside the stack. Unlike nuclear showers (see Sec. V) these events are characterized by their low initial multiplicity, in some cases originating from only a pair of minimum ionizing particles. We describe here observations on these events.

In an emulsion an electronic shower several radiation lengths from its origin appears as a highly compressed core of minimum ionizing tracks with a sharply decreasing density outside the core. This development can be described in the following qualitative fashion. The number of electrons with energies in the range $E, E+dE$ at a depth t from the point at which a photon of energy W_0 is incident on the absorber is given by the usual one-dimensional cascade function $\pi(W_0, E, t)$.[5] If in the high energy region (approximation A of reference 5) it is assumed that the lateral distribution of the electronic shower arises solely from the multiple Coulomb scattering,[6] the electrons of energy E will be spread over a circle whose radius is $\sim E_s/E$ radiation

[5] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941).

[6] Though the assumption is commonly made that the lateral distribution of electrons in a cascade shower arises solely from multiple Coulomb scattering, this assumption does not appear completely justified. M. Stearns in Phys. Rev. **76**, 836 (1949) has shown that the angles characterizing the processes of pair formation and bremsstrahlung are $\sim(mc^2/E)\log(E/mc^2)$ radians; this is to be contrasted with the angle mc^2/E radians upon which the justification for neglecting the characteristic angular deviation as compared to multiple Coulomb scattering is usually made. For one radiation length the angle $(mc^2/E)\log(E/mc^2)$ is the same order of magnitude as the root mean square angle due to multiple scattering.

units ($E_s \sim 20$ Mev) and will make angles of $\sim E_s/E$ radians with the shower axis.[5] In this experiment, to eliminate the background of random minimum ionizing tracks, we imposed the restriction that tracks counted make an angle of less than 1° with the shower axis; this is equivalent on the average to $E > 1$ Bev and to most of the observable electrons being confined to within 400 μ of the shower axis for the combination of materials used in this experiment. Thus the imposition of an angular or radial cutoff is equivalent on the average to restricting observations to electrons whose energy exceeds some cut-off value E_{c0}; this value E_{c0} is a very insensitive function of the depth t. If E_{c0} is assumed constant with depth and if the number of electrons whose energy exceeds E_{c0} at a given depth is known, the development of a shower can be calculated without any knowledge of the radial distribution in the shower. Thus,

$$N(W_0, E_{c0}, t) = \int_{E_{c0}}^{\infty} \pi(W_0, E', t)dE'$$

becomes in this approximation a function solely of the ratio W_0/E_{c0} and t; this function is that given by the one dimensional cascade theory.[5] Experimentally we determine the number of electrons N at a given depth t' and can therefore evaluate W_0/E_{c0}, thus enabling the behavior of the shower to be predicted at other depths t. In Fig. 1 is plotted the observed integral electron spectrum for two electronic showers and the integral spectrum derived theoretically.

The emulsion-absorber arrangement provided a convenient method for observing the lateral development of electron showers at varying depths t. This was accomplished by obtaining target diagrams (electron distributions projected onto the plane perpendicular to the shower axis) of several showers for different depths t. Figure 2 shows the target diagrams for a typical electron shower. This procedure gives directly the experimental core structure of the shower, that is, the number of electrons whose energy exceeds some cut-off energy E_{c0} contained within a radius R of the shower axis at a depth t. Though no completely satisfactory theory of the lateral development of soft showers has been developed (see also reference 6), the existing theories should give some agreement with the observed results. To this end we have used the theory developed by Fernbach and Eyges[7] in conjunction with the one-dimensional cascade theory[5,8] to calculate the structure function for the lateral structure of soft showers:

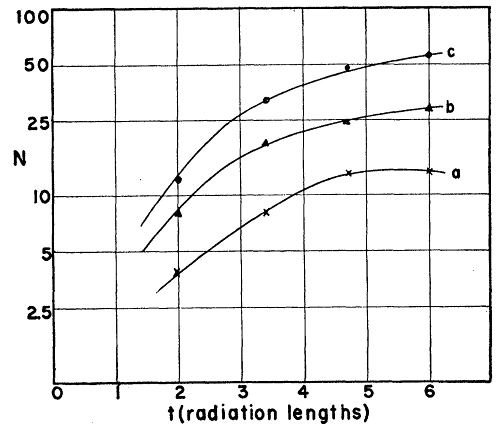

FIG. 4. Observed radial electron distributions for electron showers. The number of electrons contained within circles of radii 25, 50, and 100 μ (curves a, b, c) is plotted against the depth of the shower (radiation lengths). The shower energy is estimated $\sim 2.5\times 10^{11}$ ev.

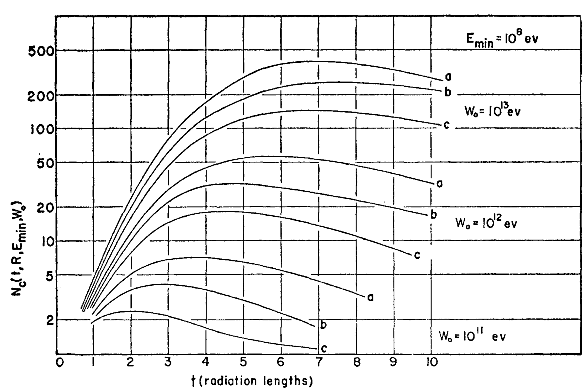

FIG. 3. The radial distribution function for photon initiated showers is plotted as ordinate *vs* radiation length as abscissa for different values of radii and incident photon energy. $N_c(t, R, E_{min}, W_0)$ represents the number of electrons with energy in excess of E_{min} contained within a circle of radius R (centered on the shower axis) at a depth t (radian units) from the point at which a photon of energy W_0 is incident on the absorber. The curves a, b, c refer to radii of 25, 50, and 100 μ, respectively, for an absorber for which the radiation length $X_0 = 2.35$ cm. For other materials of radiation length X_0' cm, $R'(\mu) = (X_0'/2.35)R(\mu)$.

$$N_c(t, R, E_{min}, W_0) = \int_{E_{min}}^{\infty} dE\pi(W_0, E, t) \int_0^{RE/E_s} xP_R(x, s(t))dx.$$

Here $P_R(ER/E_s, s)RdR$ is proportional to the fraction of electrons of energy E in the annular ring R, $R+dR$ at a depth t from the origin of the shower; s is defined by $\log(W_0/E)+\lambda'(s)t=0$.[5] $\pi(W_0, E, t)$ is the differential electron spectrum, and the structure function $N_c(t, R, E_{min}, W_0)$ represents the number of electrons at a depth t and within a circle of radius R. The energy of these electrons is greater than E_{min} and they arise from an initial photon of energy W_0. The function N_c is relatively insensitive to the choice of E_{min}, the major contributions arising from larger E. In Fig. 3 is plotted the structure function *versus* t parameterized for several values of R and W_0, and Figs. 4 and 5 show experimental core structures for several values of R as a

[7] See S. Fernbach, Phys. Rev. **82**, 288 (1951).

[8] L. Janossy and H. Messel, Proc. Roy. Irish Acad. **54**, 31 (1951).

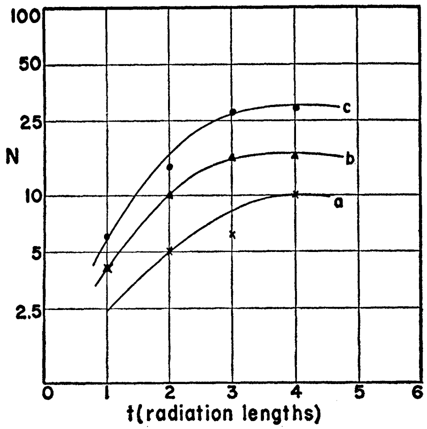

FIG. 5. Observed radial electron distributions for electron showers. The number of electrons contained within circles of radii 24, 50, and 100 μ (curves a, b, c) is plotted against the depth of the shower (radiation lengths). The shower energy is estimated $\sim 5\times 10^{11}$ ev.

function of t. It can be seen that the shape of these curves is similar to the theoretical curves of Fig. 3. This qualitative agreement does not necessarily imply the correctness of the form of P_R given by Fernbach and Eyges; the shape of N_c is relatively insensitive to the choice of P_R.

In order to make a more complete comparison with theory, both the energy and the point of origin of the shower must be known. A suitable event is furnished by the soft shower cascade observed in the "T-Star."[3] This is a double-cored soft shower arising from an energetic nuclear interaction and has been analyzed on the assumption of the two photon decay of a neutral π-meson. From opening angle and energy partition the total energy in the double cored soft shower was estimated as 1.5×10^{12} ev; using the above-mentioned calculation based on the theory of Fernbach and Eyges, we estimated 3×10^{12} ev. This discrepancy most probably arises from the fact that the calculations of radial distributions are rather inaccurate in the regions which make the major contributions to our results (small R and large E). Notwithstanding this numerical discrepancy of the order of two, the qualitative predictions are reasonably well in accord with the observations.

IV. ENERGY DETERMINATION IN NUCLEAR SHOWERS

Showers which originate from a high energy nuclear event (in contrast to "purely electronic" showers) are generally characterized by a multicored soft shower structure in the later stages of their development and by their characteristic appearance (large number of tracks projecting back to a unique origin) in the earliest observable stage.

There are three different methods that are of use in estimating the energy of high energy nuclear events in the photographic emulsion: measurement of multiple Coulomb scattering, kinematical estimate based on opening angles, and determination of the energy carried in the soft component. The applicability of each of these methods depends on the geometry and arrangement of the photographic emulsions during exposure and on the local geometry of the event with respect to the emulsion.

In order to employ fully the scattering method to determine the energies of individual tracks in high energy events extremely long path lengths must be available. With plates exposed in a horizontal geometry with respect to the source of the high energy primary particles, as in this experiment, this condition is never realized. The method of relative scattering[4] over long cell lengths is in principle applicable with our geometry, but from a practical point of view it is difficult to implement owing to the impossibility of successfully identifying the same group of minimum ionizing tracks when they are accompanied by a cascading electronic shower.

The kinematical method is most applicable, and the easiest to use for observations of high energy events in emulsions, being relatively insensitive to the particular geometry employed. Its main disadvantages lie in its inherent statistical nature and the necessity for making assumptions concerning the nature of the interaction in order to derive information relevant to the energy of the event.

The soft component method is most efficiently applicable for events of high enough energy such that the majority of the γ-rays associated with the event give rise to well-marked electronic cores. This method then requires some assumption concerning the characteristics of high energy nuclear events in order to infer their energy from the soft component energy. As the conditions of this experiment do not favor the scattering method we shall discuss only the kinematical and soft component methods.

For the kinematical analysis we assume nucleon-nucleon collisions and the existence of a center-of-mass system (c.m.) for discussing the interaction. We denote by ϑ and θ angles referred, respectively, to the c.m. or laboratory (l.) system; $\bar{\beta}$ is the velocity of the c.m., $\bar{\beta}_i$ the velocity of the ith particle in thec.m. system, and $\gamma=2\bar{\gamma}^2-1$[with $\bar{\gamma}^2=1/(1-\bar{\beta}^2)$] is the energy per nucleon of the incident particle. Application of the Lorentz transformation gives

$$\bar{\gamma}\tan\theta_i=\frac{\sin\vartheta_i}{(\bar{\beta}/\bar{\beta}_i+\cos\vartheta_i)}.$$

The reasonable assumption is made that the angular distribution of particles produced in the c.m. is symmetric about a plane transverse to the direction of motion of the incident particle; we find in the small angle approximation for laboratory angles

$$\bar{\gamma}^2\theta_F\theta_{1-F}=\frac{\sin^2\vartheta}{(\bar{\beta}^2/\bar{\beta}_0{}^2-\cos^2\vartheta)},$$

where the subscripts F, $1-F$ refer to the angles containing a fraction F, $1-F$ of the total number of produced particles and $\bar{\beta}_0$ is the particle velocity, assumed equal for the angles ϑ and $\pi-\vartheta$. With the further assumption that $\bar{\beta}/\bar{\beta}_0\approx 1$ we have in sufficient approximation $\gamma=2/(\theta_F\theta_{1-F})$.

Kinematical energy estimates are usually made using the angle $\theta_{\frac{1}{2}}$ which involves the greatest statistical accuracy. Without prior knowledge concerning the angular distribution in the c.m. the use of the angle $\theta_{\frac{1}{2}}$ alone for an energy estimate is inherently bad. A distribution such as $\cos^{2n}\vartheta$, for instance, in the c.m. gives in the l. system an extremely broad plateau in the neighborhood of $\theta_{\frac{1}{2}}$, so that it is possible to make an extremely gross error in energy estimate. Though the use of angles θ_F for $F\neq\frac{1}{2}$ involve greater statistical inaccuracy, one is at least enabled to obtain an internal consistency check on the energy estimate.

In order to obtain this internal check the normalized integral angular distribution in the l. system,

$$F(\theta_F)=\int_0^{\theta_F} N(\theta)d\theta/N,$$

is plotted *versus* $\log\theta_F$ (N refers to the number of charged shower particles). As $\log\bar{\gamma}\theta_F=-\log\bar{\gamma}\theta_{1-F}$, the plot will be symmetric with respect to reflections through the point $F=\frac{1}{2}$, $\log\theta_{\frac{1}{2}}$ as origin. The appearance of this symmetry property in our experimental angular distributions is consistent with the assumptions made concerning the c.m. distribution (but does not uniquely require this).

The method of the soft component is perhaps the most indirect of those available but has some fair degree of accuracy in the case of the highest energy events. In using this method it is assumed that the soft component resulting from high energy nuclear interactions is not directly produced but arises from the decay of some strongly coupled nuclear particle (e.g., π^0 mesons). When the energy carried by the soft component is determined, the energy of the initial event is inferred on the basis of some assumption concerning the equipartition of energy between the various produced particles (see Sec. VI).

There are two methods available to estimate the energy of the soft component. The first is applicable to the lower energy soft component, presumably arising from the decay of the slower π^0 mesons appearing at wide angles in the l. system and consists of determining the separation of relatively isolated doublets situated within a radiation length of the initial event. By assuming an average conversion behavior for the γ-rays the energy of the initiating photon can be estimated from the doublet separation.[9] The energy carried by the high energy soft component can be determined by applying the methods discussed in Sec. III.

[9] Bradt, Kaplon, and Peters, Helv. Phys. Acta **23**, 24 (1950).

It has been found in some special events which are susceptible to a good measurement by both the kinematical and soft component methods that the energy estimates agree within the statistical limits.[3]

V. NUCLEAR SHOWERS

A scan for showers was made in the emulsion under the 12th brass plate; these showers were traced both deeper into the stack and back into the stack towards their point of origin. Qualitatively these showers exhibited one of the following characteristics in tracing back towards a point of origin:

(a) There was a gradual diminution of the number of minimum ionizing tracks from plate to plate until the shower consisted of only a few tracks and could not be followed further or

(b) the shower diminished in size, the multiplicity changing rather markedly from plete to plate until a plate was reached where the shower appeared as a rather compressed bundle of minimum ionizing tracks ($\sim$20 on the average); no shower of even small multiplicity was then found in the predicted region of the preceding plate.

Showers exhibiting characteristic (a) are considered to be of "purely electronic" origin (incident electron or γ-ray), while showers exhibiting characteristic (b) are considered to be of nuclear origin. A shower of nuclear origin containing on the average 5 or more neutral mesons in the central core will give rise to approximately 10 or more high energy γ-rays near the origin and will thus multiply more rapidly than a shower initiated by a single electron or γ-ray. The rapid change of multiplicity (b) is thus consistent with the assumption of the nuclear origin of these showers.

This argument is strengthened by the observation that for those showers selected as being of nuclear origin, many exhibited multicore characteristics, while no shower falling into the "purely electronic" class exhibited this characteristic. For those showers exhibiting nuclear characteristics a detailed search was made in the emulsion preceding its first appearance for a charged primary. Owing to the random background of minimum ionizing tracks, it was impossible to associate with certainty a single minimum ionizing track as being the incident primary for a given interaction; sometimes several tracks of the proper orientation were found within the predicted area (circle of $\sim 700\mu$ diameter). In those cases in which several tracks were found, any of which could possibly have been the minimum ionizing primary, their relative orientation was such that only one of them could be the desired primary; their spatial separation was also inconsistent with the possibility of any two or more of them being associated as a part of the shower. Thus it was possible to say that these showers made a transition from $\sim$20 particles to at most one particle in the preceding emulsion. This is consistent with a neutral or charged strongly interacting particle producing a high energy interaction in the intervening brass absorber. For those showers whose primaries had $Z>1$ it was always possible to uniquely

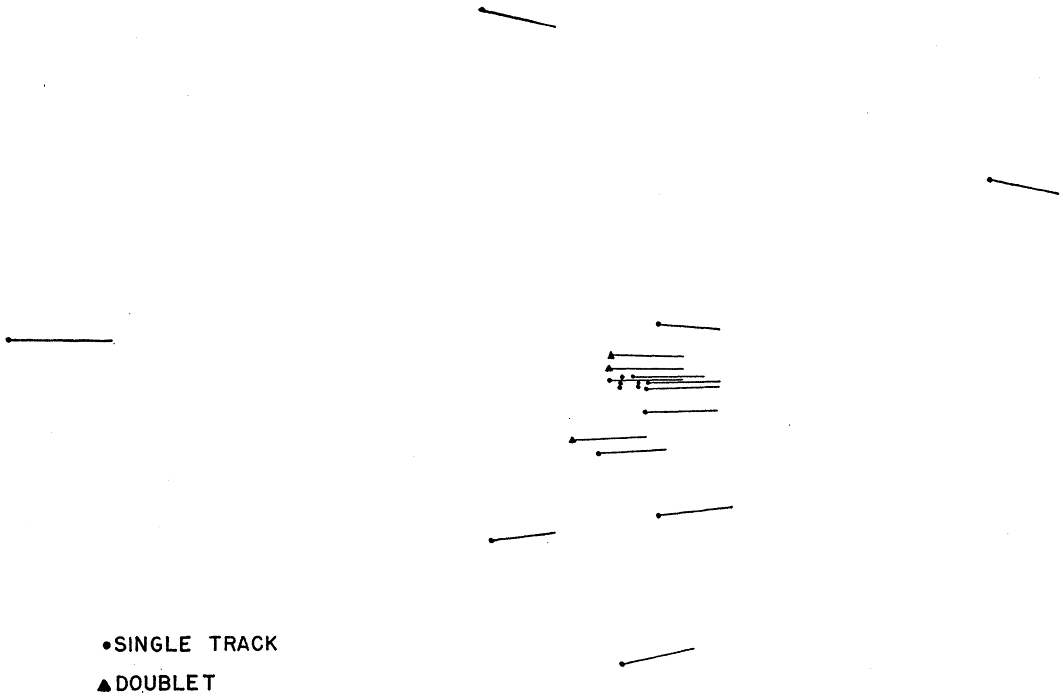

FIG. 6. Target diagram of the charged shower particles produced by an interaction in brass of an energetic cosmic-ray nucleon (shower 59 of Table I). The shower particles are projected onto a plane perpendicular to the shower axis.

locate that primary and trace it back to its point of entrance into the stack.

To extract information about the nuclear interaction, measurements were made on the shower in the emulsion directly below the absorber in which the interaction occurred. To accomplish this a target diagram of the shower was made; the entrance and exit points into and from the emulsion of those particles satisfying given geometrical criteria were accurately determined using a precision microscope stage. These tracks were then plotted as a target diagram; the plot may be direct (i.e., the shower projected onto the plane of the emulsion), but it is more convenient to project these tracks onto a plane perpendicular to the shower axis. These tracks were extended back along their trajectories and the showers of nuclear characteristics were found to project back to a common origin with the limits of accuracy of our measurements. Figures 6 and 8 are typical target diagrams for nuclear showers; Fig. 6 represents a shower made by singly charged or neutral primary, and Fig. 8 an interaction produced by a primary α-particle.

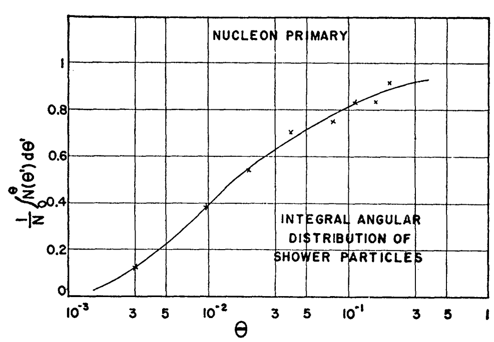

FIG. 7. Normalized integral angular distribution in the laboratory system for the shower of Fig. 6. The ordinate represents the fraction of the charged shower particles contained within the polar angle θ and is plotted *versus* $\log\theta$ as abscissa.

The angular distribution of the shower particles in the laboratory system is obtained from the target diagram. By applying the kinematical methods of Sec. IV to these angular distributions an energy estimate for each shower was obtained. Figures 7 and 9 represent the normalized integral angular distributions in the l. system derived from the target diagrams of Figs. 6 and 8, respectively. The symmetry properties exhibited by these angular distributions are consistent with the assumptions underlying the kinematical method of energy estimate (see Sec. IV).

We have tacitly assumed in the above in deriving the angular distribution that the minimum ionizing tracks appearing in the first emulsion below the interaction are all shower particles emanating from the primary interaction. There are two possible sources of adulteration:

(a) conversion of γ-rays formed directly or indirectly in the primary interaction;
(b) particles produced in secondary nuclear interactions.

The contribution of electron-positron pairs from the conversion of meson "bremsstrahlung" can be neglected (see Sec. VI); those neutral mesons in the central

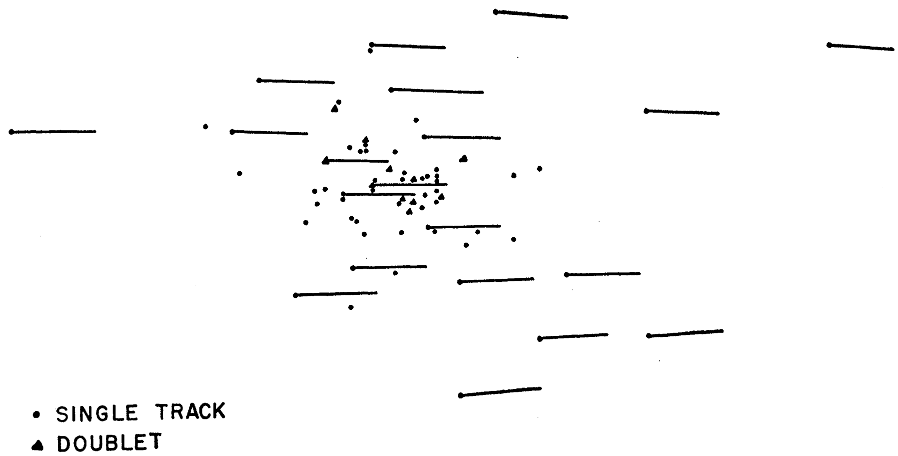

FIG. 8. Target diagram of the charged shower particles produced by an interaction in brass of an energetic cosmic-ray α-particle (shower A of Table I). The shower particles are projected onto a plane perpendicular to the shower axis.

shower core (average energy in the l. system $\sim 2-4 \times 10^{11}$ ev) have such a large Lorentz time dilation factor ($\sim 1-2.5\times 10^{3}$) that their decay into two γ-rays is sufficiently retarded (the π^0 lifetime is taken as $\sim 10^{-14}$ second[3]), so that they cannot contribute appreciably to the appearance of charged particles by pair conversion. If, however, an appreciable fraction of the soft component accompanying penetrating showers should arise from the decay of shorter lived strongly interacting particles, it is possible that the charged multiplicity we observe represents an upper limit to the actual charged multiplicity. The neutral mesons in the more diffuse part of the shower can, however, effectively decay immediately into two γ-rays; with our average conditions ($N_{ch}^{\text{diffuse}} \sim 10$) we have approximately 10 γ-rays traveling on the average 0.1 of a radiation length; since on the average one of these γ-rays may convert to an electron-positron pair, it is possible that two of the shower particles may in reality be electrons. The contribution of secondary interactions to the shower at its first point of observation can be neglected; secondary interactions from the diffuse shower particles are of relatively low energy and will not contribute shower particles of the proper orientation; any contributions from secondary interactions of the shower particles in the core (probability for interaction of all core particles is ~ 0.2) can be eliminated by their inability to project back to a common origin with the rest of the shower particles. We can conclude, therefore, that on the above assumptions as to the nature of the shower particles we observe an essentially unadulterated penetrating shower in the emulsion directly beneath that absorber in which the interaction occurs.

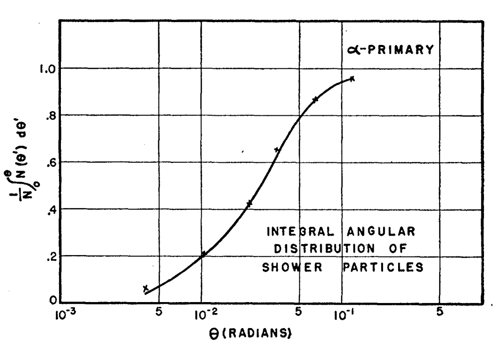

FIG. 9. Normalized integral angular distribution in the laboratory system for the shower of Fig. 8. The ordinate represents the fraction of the charged shower particles contained within the polar angle θ and is plotted *versus* $\log\theta$ as abscissa.

The analysis of the angular distribution in the first emulsion contains information relevant not only to the energy of the shower but also to the degree of anisotropy of the charged particle distribution in the c.m. system (we make here the same assumptions concerning the symmetry properties in the c.m. as in Sec. IV). A convenient parameter for characterizing the departure

TABLE I. Summary of high energy showers.

1 Shower, primary, target nucleus	2 Number of charged particles, N_{ch}	3 $\frac{N_{\pi^0}}{N_{ch}}$[a]	4 $\gamma\times 10^{-3}$	5 X	6 $\frac{r}{R}$	7 N_{ch} (Fermi)[b]
$A(\alpha)$, Cu	21(84)	0.6 ±0.2	3	1.17	0.18	15
178(α), Cu	23(92)	0.72 ±0.15	6	2	0.46	14
$R(\alpha)$,[c] Ag	14(56)	0.75 ±0.25	0.48	2.33	0.57	6.6
77(p), Cu	24	···	4	1.17	0.18	16.5
104(p), Cu	20	0.5 ±0.3	1.3	1.33	0.23	11.7
67(p,n)Cu	9	1.2 ±0.5	4.5	1.33	0.23	16
60(p,n)Cu	26	···	19.5	1.33	0.23	23
91(p,n)Cu	16	0.6 ±0.35	1.3	1.7	0.34	10.8
224(p,n)Cu	24	···	1.8	1.9	0.42	11.6
63K(p,n)Cu	19	···	6.1	2.5	0.62	12
55K(p,n)Cu	18	···	1.29	3.3	0.73	6.1
17(p)Cu	24	1.1 ±0.3	5.1	3.7	0.76	7.9
72K(p,n)Cu	17	···	0.5	4	0.78	4.5
59(p,n)Cu	24	0.5 ±0.3	8.9	4	0.78	8.8
222(p,n)Cu	16	···	1	6	0.85	4.2
66(p,n)Cu	11	0.75 ±0.4	0.64	6.67	0.87	2.7
T(p)Cu	36	0.6 ±0.2	19.4	6.67	0.87	6.3
58K(p,n)Cu	15	···	30	8.7	0.9	8
179(p,n)Cu	24	···	0.8	20	~1	$\lesssim$2
67K(p,n)Cu	15	···	0.8	20	~1	$\lesssim$2
Z(p,n)Cu	15	0.5 ±0.25	50	24	~1	$\lesssim$3.4
184(p,n)Cu	10	···	5	33	~1	$\lesssim$2
45K(p,n)Cu	14	···	7.2	66	~1	$\lesssim$2
S(p)[d] light element	15	···	32	···	~1	$\lesssim$6
G-L(p)[e]Ag	18	···	23	$\geq$9	~1	$\lesssim$6
		Av. 0.71 ±0.1				

[a] Uncorrected for secondary effects; see Sec. VI.
[b] See reference 11.
[c] See reference 9.
[d] See reference 13.
[e] See reference 14.

from isotropy in the c.m. system is given by the quantity

$$X=\frac{(\theta_{3/4}/\theta_{1/4})}{(\theta_{3/4}/\theta_{1/4})_{\text{Isotropic}}},$$

that is, X is the ratio of the $\frac{3}{4}$ to the $\frac{1}{4}$ widths in the l. system for a given shower to the $\frac{3}{4}$ to $\frac{1}{4}$ widths in the l. system for a hypothetical shower isotropic in the c.m. system. Thus $X\sim 1$ indicates a shower isotropic in the c.m. system and $X\ll 1$ indicates a shower anisotropic in the c.m. system.

Table I summarizes the results of the shower analysis. Column 1 identifies in order our designation for the shower, its primary appearing inside the parentheses, and the target nucleus; Column 2 the total number of observed charged shower particles; Column 3 the uncorrected ratio of neutral mesons to charged shower particles (see Sec. VI); Column 4 the energy per nucleon (γ) in the l. system in units of the nucleon rest mass of the initiating particle; Column 5 gives the parameter X measuring the departure of the angular distribution from isotropy in the c.m. system; Column 6 gives the impact parameter calculated from the Fermi theory[10] to give an X corresponding to that observed; and Column 7 gives the charged π-meson multiplicity calculated on the basis of Fermi's theory[11] using the energy (Column 4) and the impact parameter r/R (Column 6) as the two independent parameters.

Table I exhibits the following striking features:

(1) The similarities between high energy stars occurring in nucleon-nucleon collisions,[12,13] Ag,[13,14] and brass.

(2) The sidely varying degrees of anisotropy of those showers produced by single nucleons as compared to the isotropy of the α-particle showers.

(3) The relatively constant multiplicity of the α-particle showers.

In addition to these we have the symmetry property exhibited by the angular distribution in the l. system. These features can be rather well accounted for by adapting the statistical view presented by the Fermi theory.[10]

The similarities between the nucleon induced showers occurring in target nuclei of widely varying A indicate that subsequent collisions inside the nucleus do not contribute appreciably to the final multiplicity. The symmetry property exhibited by the angular distributions supports the view that the charged particles are produced in a single c.m. system and that their angular distribution in this system is symmetric about a plane transverse to the direction of motion of the c.m. system. These features can be explained on the assumption that most of the particles produced in an interaction inside a nucleus are sufficiently collimated in a high energy collision to interact simultaneously in the next collision inside the nucleus. On the Fermi theory[10,15] the collision of such an ensemble of particles might be expected to lead to very similar results to that of a single energetic particle interacting with a nucleon. Thus a nucleon-nucleus collision at sufficiently high energies can be effectively treated as a nucleon-nucleon collision, the only difference being in the relation of the velocity of the c.m. system to the velocity of the original primary nucleon. In the extreme case when all the particles emitted in the first interaction simultaneously collide with the next nucleon, the c.m. system for this second collision characterized by $\bar{\gamma}_2$ is related to the incident nucleon energy by $\gamma\approx 4\bar{\gamma}_2^2$; when this situation occurs n successive times the relation $\gamma\approx 2n\bar{\gamma}_n^2$ holds.[15a] These relations suggest that the primary energies listed in Column 4 of Table I, which are obtained from the relation $\gamma=2\bar{\gamma}^2$, may represent a lower limit to the actual primary energy (e.g., in brass n may reasonably be 3 or 4 and the true energies could be as high as 3 or 4 times those listed in Table I).[16] However, a definitive relation between the experimentally determined $\bar{\gamma}$ and the primary nucleon energy would depend on the fine details of each individual interaction, and thus we have adopted the relation $\gamma=2\bar{\gamma}^2$ to characterize the primary energy. (The estimate of our median acceptance energy for nuclear showers based on energy estimates for electron showers, Sec. VII, is in qualitative agreement with the median energy obtained for nuclear showers using the relation $\gamma=2\bar{\gamma}^2$.)

The features (2) and (3) lend further support to the view that at sufficiently high energies a nucleon-nucleus interaction can be effectively considered as a nucleon-nucleon interaction. On this basis the occurrence of

[10] E. Fermi, Phys. Rev. **81**, 683 (1951).

[11] The charged particle multiplicity is calculated on the basis of Fermi's theory assuming only π-mesons are produced. If one also allows for the production of nucleon-antinucleon pairs, the calculated charge multiplicity given is changed by the same factor (0.985) for each shower, independent of the impact parameter. In this case then according to the Fermi theory 40 percent of the charged particles are π^+ and π^- mesons and 60 percent of the charged particles are proton-antiproton pairs.

[12] Lord, Fainberg, and Schein, Phys. Rev. **80**, 970 (1950). The S-star is the first example observed of a star induced by a high energy proton and appears to have been formed in a glancing collision (single nucleon-nucleon) with a light nucleus of the emulsion.

[13] Two very high energy proton induced interactions occurring in emulsion have been recently observed at this laboratory; one occurs in a Ag nucleus, and the other has no black or gray prongs. Both exhibit similar characteristics to those described in the text.

[14] A. Gerosa and P. Levi-Setti, Nuovo cimento **8**, 601 (1951).

[15] U. Haber-Schaim, Phys. Rev. **84**, 1199 (1951).

[15a] Consider a collection of particles with energies and momenta E_i and P_i in the l. system and $\bar{E}_i$ and $\bar{P}_i$ in the c.m. system. Making a Lorentz transformation along the Z direction from the l. system to the c.m. with velocity $\bar{\beta}$ with respect to the l. system, we have $(\bar{\gamma}^2=1/(1-\bar{\beta}^2))\ \Sigma_i\bar{P}_{i,z}=\bar{\gamma}(\Sigma_iP_{i,z}-\bar{\beta}\Sigma_iE_i)$. As the c.m. system is defined by $\Sigma_i\bar{P}_{i,z}=\Sigma_i\bar{P}_{i,y}=\Sigma_i\bar{P}_{i,x}=0$, we find $\bar{\beta}=P_{i,z}/\Sigma_iE_i$. For the specific case cited in the text for the nth collision with a nucleon $\Sigma_iE_i=E+nM$, where $E=\gamma M$ is the energy of the original incident nucleon and P its momentum, we find $\bar{\beta}_n=[P/(E+nM)]=(\gamma^2-1)^{\frac{1}{2}}/(\gamma+n)$ and $\bar{\gamma}_n^2=(\gamma+n)^2/(2n\gamma+n^2-1)$. For $\gamma\gg n$ we have $\gamma\approx 2n\bar{\gamma}_n^2$.

[16] These considerations apply to results previously reported, references 1, 2, and 3; in particular footnote 5 of reference 2 is in error, and the exponent in the integral primary proton flux will have larger limits of error.

widely varying degrees of anisotropy for nucleon induced showers is to be expected; if, however, the shower was produced in a series of collisions the angular distribution should tend to show a more "average" behavior. This "average" behavior is in fact observed for the α-particle induced showers in which we observe the sum behavior of 4 independently interacting nucleons. It is difficult to see any explanation of the above features on the basis of the plural theory[17] or any variant thereof.[18]

It is also of interest to consider the variation of multiplicity of shower particles as a function of the incident primary energy. We have analyzed the data of Pickup and Voyvodic[19] on lower energy emulsion showers by the kinematical methods of Sec. IV. Utilizing also the data of Perkins[20] in this lower energy region and considering the average behavior of the shower multiplicity in these different energy regions (we use $N_{\mathrm{ch}}\approx 20$ at 4.5×10^{12}), we find that the shower multiplicity varies approximately as the $\frac{1}{4}$ power of the incident energy per nucleon ($\gamma^{\frac{1}{4}}$) in the l. system. For this variation of multiplicity with energy we find $N_{\mathrm{ch}}\approx 2.5\gamma^{\frac{1}{4}}$ in agreement with the prediction of the Fermi theory of multiple meson production for 0 impact parameter; Fermi gives $N_{\mathrm{ch}}=2.3\gamma^{\frac{1}{4}}$. Furthermore, we do not observe any appreciable variation of multiplicity with impact parameter; the predictions of the Fermi theory in this respect probably result from the detailed assumptions made about the form of the equilibrium volume, and these assumptions do not represent a fundamental feature of the theory.

VI. RATIO OF NEUTRAL MESONS TO CHARGED PARTICLES

Observations made on the number of minimum ionizing tracks present in a shower immediately after interaction and after passage through a further small amount of absorber (some fraction of a radiation length) show that an appreciable multiplication has occurred. This multiplication arises from

(a) γ-rays converting to pairs with some subsequent cascade development;[21] these γ-rays can arise from neutral meson decay or from "bremsstrahlung" associated with the nuclear interaction. (We observe in fact that an appreciable fraction of the multiplication is in the form of pairs.)

(b) Mesons and nucleons created in a subsequent interaction by one of the penetrating shower particles.

To deduce from observations made on the increase in multiplicity the ratio of neutral mesons to charged particles we must therefore take into account the effect of the "bremsstrahlung" in (a) and the effect of the secondary multiplication in (b). The typical experimental conditions under which our observations were made were as follows: We scanned an area corresponding approximately to that defined by the median opening angle of the shower and observed the increase in multiplicity over $\sim\frac{1}{3}$ of a radiation length.

To determine the contribution of "bremsstrahlung" γ-rays to this increase, we note that only tracks lying within $\sim 2°$ of the shower axis were observed. The average opening angle of an electron pair of energy E is $\sim(mc^2/E)\log(E/mc^2)$ radians,[6] and thus we observe pairs for which $E\gtrsim 50$ Mev. The fraction of energy radiated as "bremsstrahlung" in the c.m. system by a spin 0 meson of energy $\bar{E}_\mu$ (in the c.m.) is given by Schiff[22] as (α is the fine structure constant)

$$(\alpha/\pi)[\log(2\bar{E}_\mu/\mu c^2)-\tfrac{3}{2}].$$

We assume a normal "bremsstrahlung" spectrum in the l. system $dn_\gamma=Kdw/w$, where w is the photon energy, the constant K is given by the expression above, and thus the number of γ-rays in the l. system with energies exceeding ~ 50 Mev arising from a single meson of energy $\bar{E}_\mu$ in the c.m. is given by

$$n_\gamma=(\alpha/\pi)[\log(2\bar{E}_\mu/\mu c^2)-\tfrac{3}{2}]\log(E_\mu/50\text{ Mev}),$$

where E_μ is the meson energy in the l. system. For our average shower the charged multiplicity (N_{ch}) was ~ 20, $\bar{\gamma}\sim 50$, $\bar{E}_\mu\sim 3.3Mc^2$ (we assume a total multiplicity of $N\sim 30$) and $E_\mu\sim 270Mc^2$ (the assumption is made that ~ 0.8 of the total shower energy appears in the central core) for those mesons in the forward core. With these values $n_\gamma\sim 0.045$ and if two γ-rays are considered to originate from one neutral meson, the spurious neutral to charged ratio arising from meson "bremsstrahlung" is $0.045/2\approx 0.02$.

The background due to secondary interactions is appreciably more important than that estimated above for "bremsstrahlung." To a good approximation (see Sec. IV) the fraction of shower particles falling in a given target area is proportional to $\frac{1}{2}+k\log(\theta/\theta_{\frac{1}{2}})$ (we are assuming that the behavior of the angular distribution in the logarithmic plot can be approximated as

[17] W. Heitler and L. Janossy, Proc. Phys. Soc. (London) **A62**, 669 (1949).

[18] Messel, Potts, and McCusker (to be published).

[19] E. Pickup and L. Voyvodic, Phys. Rev. **82**, 265 (1951). Their data indicate a median charged multiplicity of ≈ 8 at energies of $\sim 10^{11}$ ev. (These refer to showers with $N_H=0$.)

[20] D. H. Perkins, private communication. Perkins gives a median charged multiplicity of ≈ 13 at a median energy of $\sim 7\times 10^{11}$ ev. (These refer to showers with $N_H\leq 5$.)

[21] To properly assess the cascade development for small radiation lengths ($t\leq 1$) we have performed a Monte Carlo calculation (in Approximation A of reference 5) in units of 1/20 of a radiation length up to one radiation length for photon induced showers. The process of electron-positron pair production by electrons (triplet process) was included in this calculation, the probability for this process being taken as 0.11 of that for pair production by a γ-ray (H. J. Bhabha, Proc. Roy. Soc. (London) **A152**, 559 (1935)). The distribution of the virtual photons responsible for this process was assumed to follow a bremsstrahlung distribution, the above cross section being calculated on this basis for all virtual photons whose energy is in excess of 10^{-4} of the incident photon energy. Energy partition in pair production by a γ-ray was taken into account using the curves on page 199 of Heitler's *Quantum Theory of Radiation* and all secondaries with energies $\geq 10^{-4}$ incident photon energy were accepted in the cascade. We find on the average 0.6 electron after $\frac{1}{3}$ a radiation length, 1.25 electrons after $\frac{1}{2}$ a radiation length, and 1.8 electrons after $\frac{3}{4}$ of a radiation length. It was found that the inclusion of the triplet process contributed negligibly.

[22] L. Schiff, Phys. Rev. **76**, 89 (1949).

a straight line in the neighborhood $\theta_{\frac{1}{2}}$) where the area subtends an angle θ and the constant k is a function of the anisotropy of the shower. If $\langle\log(\theta/\theta_{\frac{1}{2}})\rangle$ is determined, we can then estimate the average number of particles from secondary interactions falling in the target area. For our average conditions ($N_{\mathrm{ch}}\sim 20$) there are approximately 10 charged secondaries near the shower axis whose average energy is of the order of $\frac{1}{18}$ of the primary energy. Thus the characteristic angle for the secondary interaction, taking into account the fact that mesons are now the primary particles, is $\theta_{\frac{1}{2}}{}^{S}\sim 4\theta_{\frac{1}{2}}{}^{P}$. Under the average geometry of our experiment, the angle subtended by the observation area at the point of secondary interaction is $\theta^{S}\sim 3\theta_{\frac{1}{2}}{}^{P}$; thus $\langle\log\theta^{S}/\theta_{\frac{1}{2}}{}^{S})\rangle\approx -0.3$ and $K\sim 0.6$ so that $\sim\frac{1}{3}$ of the secondary particles will fall in the shower area. The probability of a collision in the $\frac{1}{3}$ of a radiation unit is 0.05 per particle (geometrical cross section assumed), and the number of particles produced in the secondary interaction is $N_{\mathrm{ch}}{}^{S}\approx 20/18^{\frac{1}{4}}=10$ (see Sec. V). Therefore, one charged shower particle will produce on the average in $\frac{1}{3}$ of a radiation length (0.17) charged secondaries in the observation area. As one γ-ray in $\frac{1}{3}$ of a radiation length produces on the average 0.6 secondaries,[21] the average number of spurious γ-rays is 0.28 or the spurious neutral to charged ratio from this source is 0.14.

The actual determinations of the neutral to charged ratio (Column 3 of Table I) for the showers observed were made without the above corrections but allowing for soft cascade multiplication.[21] The average figure of 0.71 ± 0.1 must now be corrected by subtracting the total correction of 0.16 due to causes (a) and (b) given above and the contribution due to background. It is difficult properly to assess the contribution of background due to the acceptance criteria being in a certain measure subjective in application; a conservative estimate of this contribution indicates that the error introduced in the neutral to charged ratio is less than 15 percent. The final value for the ratio of neutral mesons to charged particles is thus 0.49 ± 0.1 (calculated assuming a 10 percent background). In arriving at this figure we have not, however, taken into account any secondary nuclear multiplication by strongly interacting neutral particles (e.g., neutrons). It seems probable that this source does not contribute appreciably to secondary multiplication.[23,24] This source would, however, tend to lower the neutral to charged ratio. On the other hand, as the charged particle group probably contains some protons (in approximately equal numbers as neutrons) the ratio of neutral mesons to charged mesons should be equal to or greater than the neutral meson to charged ratio.

If we now consider the value 0.49 ± 0.1 representing the neutral meson to charged particle ratio[24a] and if the reasonable assumption is made that at sufficiently high energies π^0, π^+, and π^- mesons are produced with equal probability (such as predicted by the Fermi theory) we can conclude that particles other than π-mesons are inefficiently produced in this energy region; if 15 percent of the charged shower particles are protons[22] and an equal number of neutrons we predict that under our experimental conditions $N(\pi^6)/N_{\mathrm{ch}}\approx 0.47$. If, however, the true value is 0.39 (probability of $\sim\frac{1}{3}$) then 22 percent of the charged particles can be other than π-mesons.[24]

VII. THE FLUX OF THE HIGH ENERGY RADIATION

In order to obtain data relevant to the high energy flux of the primary radiation, we have applied the selection criteria of Sec. II to an area of 70 cm² in the middle of the emulsion-absorber stack. This area is so located that it presents an approximately spherical geometry in the upper hemisphere to the primary radiation as well as allowing for an efficient selection of showers. Detailed examination of the showers falling in this area showed that 8 were of nuclear origin with a nucleon primary ($Z\leq 1$, see Secs. II and V) and 6 were "purely electronic" showers.

The energy of these showers has been estimated by the methods outlined previously (Sec. IV), and we find from kinematic considerations a median energy of $\sim 4.5\times 10^{12}$ ev. Using an absorption mean free path for nucleons in air of 100 g/cm² and geometrical interaction mean free path in the emulsion-absorber stack and with the further assumption of an isotropic flux over the upper hemisphere, the integral primary flux of nucleons at the top of the atmosphere with energies in excess of $\sim 4.5\times 10^{12}$ ev is 0.04 ± 0.015 nucleons per meter² per steradian per second. Assuming a power law for the integral primary spectrum and using the known values at low energies,[25] we find the integral exponent to be 1.45. Taking into account the fluctuations in the median

[23] Camerini, Davies, Fowler, Franzinetti, Muirhead, Lock, Perkins, and Yekutiel, Phil. Mag. 42, 1241 (1951).

[24] This would indicate that at least within the context of the Fermi theory the production of nucleon-antinucleon pairs is unlikely; the Fermi theory predicts (see reference 11) that if the equilibrium state is reached 60 percent of the charged particles are proton-antiproton pairs. However, the Fermi theory predicts also in this case a rather copious production of neutron-antineutron pairs; these could contribute to the apparent charged multiplication by their secondary interactions. If we assume that that our average shower of 20 charged particles consists of $8\pi^+$ and π^- mesons and 12 charged nucleons, the Fermi theory in this form would predict a neutral to charged ratio of 0.2. If we then take into account the contribution of the 12 neutral nucleons to secondary interactions, we find that our observed neutral to charged ratio could be as low as 0.40 ± 0.1. Though we cannot therefore conclusively rule out the equilibrium production of nucleon-antinucleon pairs, it would appear that it is unlikely.

[24a] We have, in the analysis of this section, profited by a discussion with Professor B. Peters. The value of the neutral to charged ratio is relatively sensitive to both the results of cascade theory at small radiation lengths and the lifetime of the neutral π-meson. If an attempt is made to account for the finite lifetime of the π^0 meson by an analysis similar to that given in reference 9 (taking into account at the same time the results of the Monte Carlo calculation for the soft cascade), the ratio obtained above corresponds to a π^0 lifetime of less than 0.5×10^{-14} sec. A lifetime of 10^{-14} sec could give a ratio as high as 0.6 ± 0.1 on this type of analysis, and longer lifetimes would lead to still higher values.

[25] Winckler, Stix, Dwight, and Sabin, Phys. Rev. 79, 656 (1950).

energy we find that the exponent could possibly be as low as 1.2 and as high as 1.65.[16]

In a survey including an additional 70 cm^2 at the same level in the stack, we find two α-particle induced showers with energies per nucleon in the same range as the nucleon induced showers. Though the statistics are low and the inclusion of the additional area makes the geometry less susceptible to a clean analysis, we believe that the existence of these two high energy α-particle showers is significant and indicates that the relative flux of α-particles to protons at this energy is approximately 10 percent. This figure is in agreement with the ratio of α-particles to protons in the latitude sensitive region and is compatible with results reported previously, which indicate a similar velocity spectrum for all components of the primary beam.[4] If this feature is maintained over the entire spectrum of particles making up the primary beam for all energies, it would indicate that the index in the power spectrum must have an extremely weak dependence on the density and path length traversed through matter in the acceleration region; e.g., in Fermi's theory of the origin of cosmic rays[26] the integral exponent γ in the power spectrum depends on the density in such a way that $\gamma_P/\gamma_\alpha = \lambda_\alpha/\lambda_P$, where λ is the absorption mean free path. As $\lambda_\alpha \sim \frac{1}{2}\lambda_P$ we find that the ratio of protons to α-particles, $N_P/N_\alpha \sim 8\times 10^5$ at the energies of this experiment; the differentiation with respect to heavier nuclei would be even more extreme.

It is further possible to obtain an upper limit to the incident soft radiation for a higher energy range than heretofore reported.[27] We found that approximately $\frac{1}{2}$ of the showers observed efficiently were of a "purely electronic" nature. By using a minimum for shower density acceptance in the control area of 70 cm^2 to assure 100 percent detection efficiency, we estimated that all electronic showers whose energy is in excess of $\sim 3\times 10^{11}$ ev were detected efficiently. This estimate is in qualitative agreement with the energy estimated for the nuclear showers; we inferred a median energy of $\sim 3\times 10^{12}$ ev for nuclear showers which contained at least one electronic core in excess of $\sim 3\times 10^{11}$ ev; i.e., we estimated our average electron shower energy as being $\sim 1/10$ of the average energy of the nuclear showers. Our area of 70 cm^2 contained 6 "purely electronic" showers with energies in excess of $\sim 3\times 10^{11}$ ev. As the conversion efficiency of the stack is 100 percent at this depth for electrons or photons, this corresponds to an incident flux at the flight altitude (18 g/cm^2 residual atmosphere) of 1.3×10^{-2} electrons and photons per $meter^2$ per second per steradian. If this is extrapolated to the top of the atmosphere, assuming an exponential absorption with a mean free path of 40 g/cm^2, we find that the flux of soft radiation incident at the top of the atmosphere is 2.5×10^{-2} particle per $meter^2$ per second per steradian. This figure represents in reality an upper limit, for if the soft component is in actuality incident in the form of some energy spectrum, the absorption mean free path would be longer than the interaction mean free path which is the figure used above; for an incident power spectrum of integral exponent 1.8 the absorption mean free path would be ~ 75 g/cm^2.[28] As the incident proton flux at this energy is 2.2 ± 0.9 particles per $meter^2$ per second per steradian, the incident primary flux of electrons and photons whose energy exceeds $\sim 3\times 10^{11}$ ev is ≤ 2 percent of the primary proton flux at this energy. It is not necessary, however, to assume an incident primary soft component to explain the observed electron showers; it can be accounted for in terms of the two-photon decay of π^0 mesons formed in nuclear interactions in the residual atmosphere above the flight altitude. The atmosphere above the stack in the vertical direction is equivalent in producing nuclear interactions to ≈ 70 percent of the matter in the stack. Thus for each interaction detected in the stack containing on the average two electronic cores, we expect 1.5 soft particles incident from the atmosphere into the stack.

We wish to thank Professor B. Peters, who was associated with this work in its early stages for his many valuable and constructive suggestions. We have enjoyed the opportunity of discussing this work with Professor E. P. George and Professor R. E. Marshak and wish to express our thanks for their comments and suggestions. We are indebted to Mrs. Edythe Woodruff for her assistance, especially in obtaining the data relevant to the high energy flux values; and for their invaluable assistance in scanning the plates we thank Mrs. Katherine Reynolds, Miss Barbara Hull, and Miss Katherine Merry.

[26] E. Fermi, Phys. Rev. **75**, 1169 (1949).
[27] Critchfield, Ney, and Oleska, Phys. Rev. **85**, 461 (1952).
[28] W. Heisenberg, *Cosmic Radiation* (Dover Publications, New York, 1946), p. 18.