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Observations on Some High Energy Cosmic-Ray Collisions in Photographic Emulsions

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A brief account is given of some high energy disintegrations initiated in photographic emulsions by primary cosmic-ray particles at about 90,000 feet above sea level. In particular, six events which show only relativistic or near relativistic fragments and a typical forward cone of shower particles are described in detail. The angular distribution of the shower particles is, in some of these cases, consistent with them, being due to the multiple production of mesons in a single interaction between an incoming nucleon and a hydrogen nucleus, or a nucleon on the edge of a heavier nucleus, according to the mechanism of Fermi's recent theory. One of these events has thus been interpreted as a collision between an incoming lithium nucleus with an energy of about 2×10^{12} ev per nucleon and a hydrogen nucleus in the emulsion.

I. INTRODUCTION

THE interactions of cosmic-ray particles with nuclei are interpreted in terms of primary collisions between individual nucleons. Owing to the great density of nuclear matter these primary interactions may be followed by secondary collision processes, after which any residual nucleus is left in an excited state and evaporation fragments may be emitted. Electromagnetic radiation could be emitted by bremsstrahlung or other processes, but there is no definite evidence for this in cosmic-ray disintegrations if we exclude the neutral pi-meson decay radiation. It is also known[1] that aggregates of nucleons, too energetic to be explained as evaporation products, are emitted occasionally in cosmic-ray disintegrations, although the mechanism for this is somewhat obscure at present.

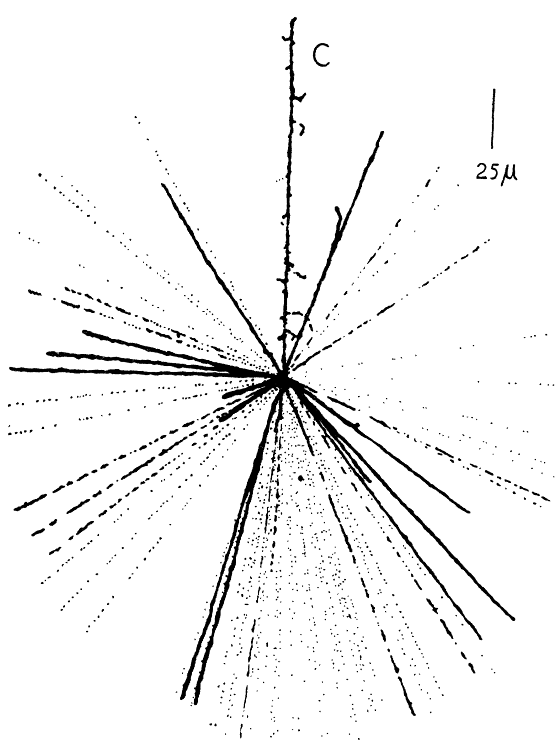

FIG. 1. 82-pronged star with primary carbon nucleus.

In the individual collisions between nucleons, neutral and charged pi-mesons are created depending on the energy available and the closeness of the collision. If the collisions are sufficiently energetic ($\gtrsim$several Bev) considerations following Yukawa's theory[2] indicate the possibility of the production of more than one meson in single interaction (multiple production), and the most complex disintegrations would then contain showers of mesons produced multiply in a series of collisions (pluromultiple production). These plural collisions may be subsequent collisions of the primary and knock-on nucleons, and further interactions of the initially produced mesons themselves with nucleons, with possible multiple meson production here, also. The collision of an incoming nucleon or heavier nucleus with a target nucleus may range from a central to a glancing type of collision, so that the interactions will be quite complex in general.

If the energy involved in a single collision is extremely high the situation may be further complicated by the production of nucleon-antinucleon pairs as recently postulated by Fermi.[3] Furthermore, the possible existence of mesons heavier than pi-mesons is still an outstanding cosmic-ray problem, although if such mesons exist, it would appear from their apparent scarcity, that they are either created rarely compared with pi-mesons or they are extremely short-lived. In the latter case they could play an important part in nuclear interactions, although they could not then be identified with the *V*-particles of cosmic-rays.

One of the more interesting problems is to show if pi-mesons are, in fact, produced multiply in single nucleonic interactions, and, if so, what laws they obey. A direct experiment, using hydrogen as a target nucleus, presents serious difficulties. In a photographic emulsion there is an admixture of hydrogen and heavier nuclei, and, occasionally, one would expect to observe a colli-

[1] S. O. C. Sorensen, Phil. Mag. 42, 188 (1951); see also Fig. 3, present paper.

[2] R. Peierls, Reports on Progress in Physics (London) 6, 78 (1939).

[3] E. Fermi, Prog. Theor. Phys. 5, 570 (1951); referred to as Fermi *I*.

sion between an incoming proton and a hydrogen nucleus or a nucleon on the edge of a heavy nucleus, with the residual nucleus left relatively unexcited, or, conversely, between a nucleon in an incoming heavy nucleus and a hydrogen nucleus in the emulsion or a nucleon on the edge of a heavier nucleus. In the latter case the residue of the incoming nucleus may continue on its original path relatively undisturbed.

The main purpose of this paper is to describe in detail a few events which are believed to be examples of these rarer types of collision processes, and to compare the angular distributions of the minimum ionization tracks produced (assumed to be pi-mesons) with those predicted by Fermi's theory[3,4] of multiple meson production.

II. EXAMPLES OF COLLISION PROCESSES IN PHOTOGRAPHIC EMULSIONS

Before proceeding to discuss the special events, a few examples are given here of some of the more complex types of disintegrations. They were found in Ilford G5 emulsions exposed to cosmic radiation by means of free balloon flights at about 90,000 feet. More general information on the statistics of events will be given in a subsequent publication. The illustrations are from tracings made in a projection microscope. Different types of cosmic-ray disintegrations have also been discussed by various authors.[5–14] In particular, Bradt, and Peters[14] have shown that heavy primary nuclei are sometimes degraded into component nuclei in collisions, the general direction of motion being maintained.

Figure 1: This shows a central collision of an incoming carbon nucleus identified by delta-ray counting with a silver or bromine nucleus in the emulsion, giving a star with 82 charged fragments. There is a wide angle shower of about 35 particles with approximately minimum ionization, including 4 in the backward hemisphere, and from charge conservation in the collision at least 28 charged particles must have been created. If we assume that these are pi-mesons, then most of the shower particles must be charged pi-mesons. The wide angle shower undoubtedly results in part from plural collisions and the absence of any narrow cone is an indication that the carbon nucleus was not extremely energetic.

Figure 2: An α-particle makes a central collision with a silver or bromine nucleus giving a star with 59 charged fragments, including a fairly wide angle shower of 28, approximately minimum ionization particles. On the assumption that the target nucleus was silver, at least 9 of these were created in the collision (pi-mesons). The α-particle was about one-cm long in the emulsion, and multiple scattering measurements made on it indicate that the energy was greater than 65 Bev.

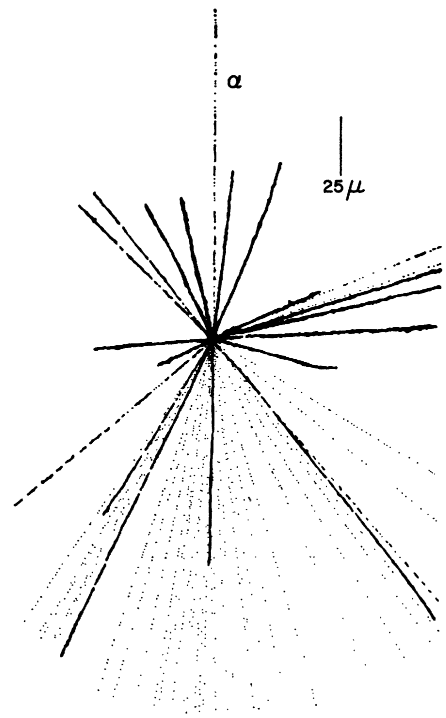

FIG. 2. 59-pronged star with primary α-particle.

Figure 3: A collision between an incident light nucleus and a silver or bromine nucleus gives a star with 60 charged fragments. The charge of the light nucleus, measured by delta-ray counting was 7 ± 1, and is thus probably nitrogen. The incident nucleus was approximately in line with the center of a wide cone of about 17 shower particles. One of the heavily ionizing particles ejected sideways was a Li^8 (or B^8) nucleus with an energy $\simeq$65 Mev, giving the characteristic "hammer" track, together with the disintegration electron. On the assumption that the target nucleus was silver and a nitrogen nucleus was incident, conservation of charge requires that at least 7 charged particles (pi-mesons) were created in the collision. This is probably an event of considerably lower energy than that of Fig. 1.

Figure 4: An incident, singly-charged particle makes a collision in which only two of the usual heavy evaporation tracks are produced, together with a somewhat asymmetric, fairly narrow cone of about 20 shower particles. One of the shower particles produces a fairly energetic secondary star. It is likely that the shower is partly the result of one or two nucleonic collisions with multiple meson production. The collision may be a

[4] E. Fermi, Phys. Rev. **81**, 863 (1951); referred to as Fermi *II*.
[5] LePrince-Ringuet, Bousser, Hoang Tchang Fong, Jauneou, and Morellet, Phys. Rev. **76**, 1278 (1949).
[6] J. J. Lord and M. Schein, Phys. Rev. **77**, 19 (1950).
[7] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).
[8] Camerini, Coor, Davies, Fowler, Lock, Muirhead, and Tobin, Phil. Mag. **40**, 1073 (1949).
[9] Salant, Hornbostel, Fisk, and Smith, Phys. Rev. **79**, 184 (1950).
[10] L. S. Osborne, Phys. Rev. **81**, 239 (1951).
[11] Hoang Tchang Fong, Ann. Phys. **5**, 537 (1950).
[12] P. Freier and E. P. Ney, Phys. Rev. **77**, 337 (1950).
[13] Bradt, Kaplon, and Peters, Helv. Phys. Acta **23**, 24 (1950).
[14] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950); **80**, 943 (1950).

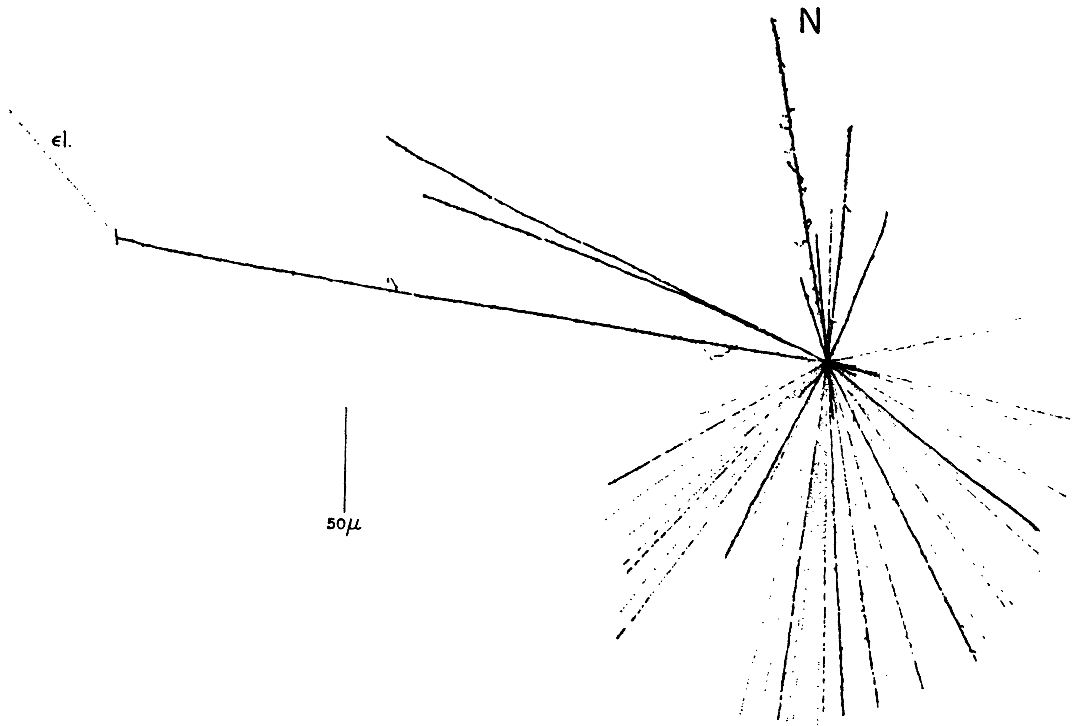

FIG. 3. 60-pronged star with primary nitrogen nucleus.

glancing collision with a heavy nucleus or a fairly complete break-up of a light nucleus in the emulsion with some meson production.

III. THEORY OF MESON PRODUCTION

While Heitler and Janossy[15] have presented a case for explaining most of the general features of meson showers in terms of single meson production in successive collisions (pure plural production), there would seem to be difficulties in attempting to explain the details of some of the showers by this picture. Furthermore, there is theoretical reason to expect multiple meson production if the collisions are sufficiently energetic. Heisenberg,[16] and Lewis, Oppenheimer, and Wouthuyen[17] have put forward different theories of multiple production, but, in their present form, both theories indicate a greater multiplicity than appears to be observed in practice in narrow shower cones.

Recently Fermi[3,4] presented a theory which predicts a lower multiplicity. Nucleons are considered to interact by virtue of surrounding pion (pi-meson) fields of fixed lateral dimensions $R \sim \hbar/\mu c$ (μ = the pion rest mass, and R is independent of energy). In a collision, thermodynamical equilibrium is assumed to be attained very rapidly throughout the colliding volume, and mesons may materialize with a certain energy distribution, the process being considered analogous to the emission of black body radiation in the collision of ultra-relativistic nucleons. Owing 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.

The average number of mesons created in such a very high energy collision is a function of the energy and of the collision impact parameter, r. The mesons are assumed to carry off any angular momentum created, and this gives rise to a preferential emission in backward and forward directions in the c.m. system. In the case of centered collisions, where no angular momentum is involved, the distribution will be isotropic. On converting to the laboratory system the net result for an off-centered collision is, on the average, a peaked forward cone of very high energy mesons, together with a diffuse tail or cone containing an equal number of mesons with lower energy.

If the energy is sufficiently high ($\gtrsim 5\times10^{12}$ ev), Fermi suggests that the production of nucleon-antinucleon pairs may compete favorably with meson creation, and the number of all charged particles will be slightly greater than if mesons alone were created. Also, the creation of any heavy pi-mesons may be important at such energies. However, these possibilities are neglected in describing the events below. In any case they would not change the general conclusions.

For purposes of comparison with observed angular distributions, the theory in Fermi II^4 may conveniently

[15] W. Heitler and L. Janossy, Helv. Phys. Acta **23**, 417 (1950).
[16] W. Heisenberg, Z. Physik **126**, 569 (1949); Nature **164**, 65 (1949).
[17] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

be treated as follows: The number of mesons created is given by $N=C_1f(\rho)$, where

$$f(\rho)=(1+\rho^2)/\rho^3 \ln(1+\rho)/(1-\rho)-2/\rho^2.$$

ρ is a parameter which depends on the angular momentum coefficient and the temperature attained in the equilibrium, but we have used r as the variable in the graphs below, since it has a more direct physical meaning. The impact parameter r is given by

$$r/R=3/2(f_1(\rho)/f(\rho)),$$

where

$$f_1(\rho)=2/\rho^3+(4/3\rho)/(1-\rho^2) -((1+\rho^2/3)/\rho^4) \ln(1+\rho)/(1-\rho)$$

and

$$f_2(\rho)=(1/\rho) \ln((1+\rho)/(1-\rho))+2/(1-\rho^2).$$

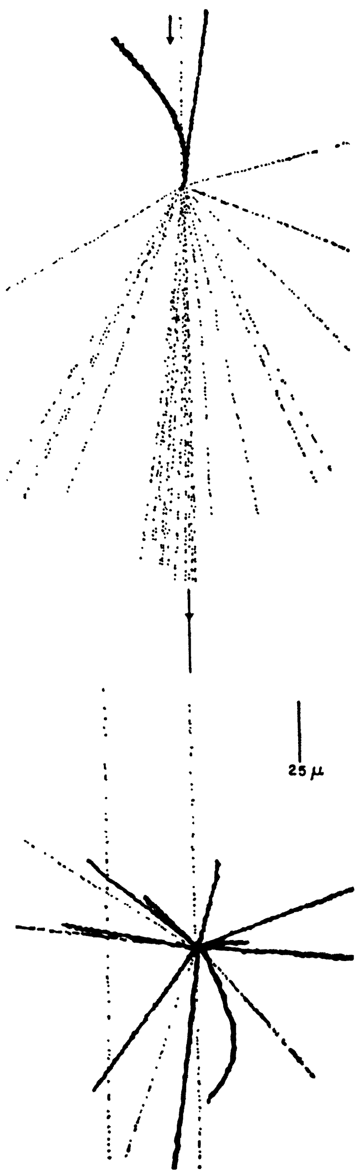

FIG. 4. 27-pronged star with primary proton.

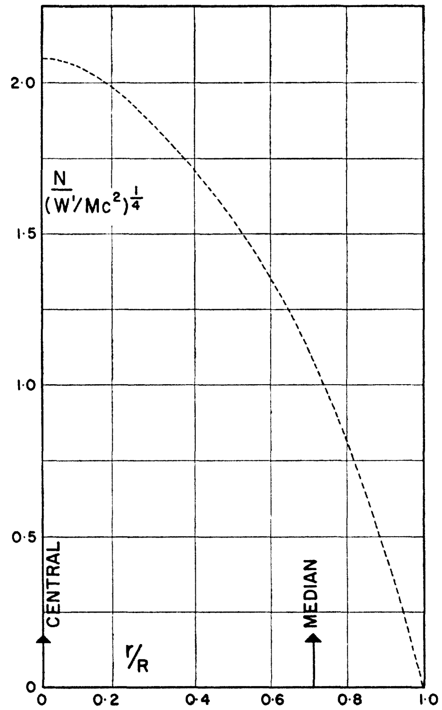

FIG. 5. Curve showing the variation of $N/(W'/Mc^2)^{\frac{1}{4}}$ with impact parameter r. N = number of mesons; W' = total energy in laboratory system.

The equation for N can also be written in the form $N/(W'/Mc^2)^{\frac{1}{4}}=C_2f(\rho)/(f_2(\rho))^{\frac{3}{4}}$, where 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. If there is only one kind of meson possible we calculate that $C_2=2.50$. If three kinds of mesons are possible, i.e., negative, positive, and neutral pi-mesons, C_2 will be increased by a statistical weighting factor $3^{\frac{1}{4}}$, and in this case $C_2=3.29$. Assuming equal probability for the three kinds of pi-mesons, the number of charged pi-mesons will then be given by

$$N/(W'/Mc^2)^{\frac{1}{4}}=2.19(3)(f(\rho)/(f_2(\rho)))^{\frac{3}{4}}.$$[18]

Figure 5 shows a plot of $N/(W'/Mc^2)^{\frac{1}{4}}$ *versus* r/R for this latter formula.

The number of all charged mesons per radian at polar angle θ in the c.m. system can be expressed as

$$dN/d\theta=C_1 \sin\theta f_4(\rho \cos\theta)=(N/f(\rho)) \sin\theta f_4(\rho \cos\theta),$$

where $f_4(x)=2/(x^2(1-x^2))-(1/x^3) \ln(1+x)/(1-x)$. In Fig. 6 $(1/N)(dN/d\theta)$ is plotted against θ for several values of r/R.

Thus if N is known by observation and a valued assumed for r/R, Fig. 1 gives W' and Fig. 6 gives the

[18] For a median collision ($\rho\simeq0.96$; $r\simeq0.71$), $N=1.10(W'/Mc^2)^{\frac{1}{4}}$. When $\rho=0$, $N/(W'/Mc^2)^{\frac{1}{4}}=2.19(3)\times0.943=2.07$ which is the same as the formula for the case with no angular momentum deducible, from Fermi I,[3] paragraph 6. With the angular momentum correction 0.51 this gives $N/(W'/Mc^2)^{\frac{1}{4}}\simeq1.06$, which is the formula given by Fermi for charged pi-mesons when no nucleon-antinucleon pairs are possible.

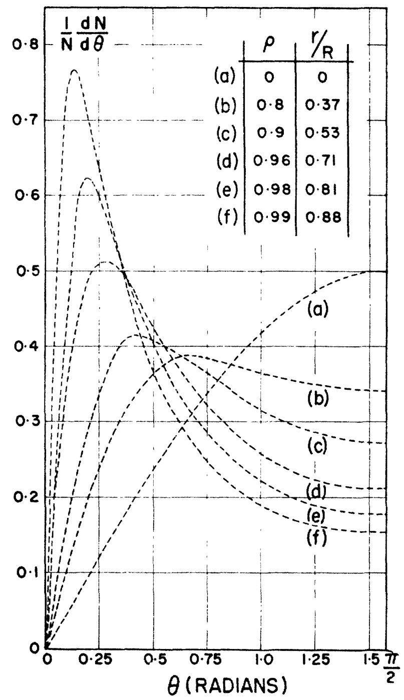

FIG. 6. Curves showing the angular distribution of mesons in the c.m. system for several values of impact parameter r. The distribution from 0 to π is symmetrical about $\pi/2$.

angular distribution $dN/d\theta$ in the c.m. system. The corresponding distribution in the laboratory system may be obtained by means of the following relativistic transformations, where the primed variables refer to the laboratory system:

$$\left(\frac{dN}{d\theta}\right)^1=\bar{\gamma}\frac{dN/d\theta(\cos\theta+v'/v)^2}{\cos^2\theta'[1+(v'/v)\cos\theta]}\simeq\bar{\gamma}dN/d\theta\frac{(\cos\theta+1)}{\cos^2\theta'},$$

$$\tan\theta^1=\sin\theta/\bar{\gamma}(\cos\theta+v'/v)\simeq 1/\bar{\gamma}(\tan\theta/2),$$

($\bar{\gamma}$ = energy in rest mass units of one nucleon in the c.m. system, v = meson velocity and θ = polar angle relative to incident direction), $\bar{\gamma}^2=(\gamma+1)/2$ or $\bar{\gamma}\simeq(\gamma/2)^{\frac{1}{2}}$, where $\gamma=1/[1-(v'/c)^2]^{\frac{1}{2}}\simeq W'/Mc^2$.

It should be noted that the result for very high energies is essentially independent of the meson energy spectrum, and will only be in serious error for a few mesons projected almost vertically backwards in the c.m. system. Also, in the above and in what follows, the nucleon-nucleon collisions are assumed to be essentially inelastic.

TABLE I. Details of the observed events.

Event	N	Polar angle, θ' (degrees)						
A	6	2.5	3.5	8.3	31	55 ($\gtrsim m$)	70 ($>m$)	
B	7	1.4	3.0	3.8	7.0	35	47 ($>m$)	126
C	12	1.7	1.7	2.0	2.4	2.8	4.7	5.3
		5.5	6.4	8.6	38 (1.5m)	41		
D	13	0.6	2.0	4.8	7.7	8.7	1.0	12.8
		20	21 ($>m$)	24	32	85	148 ($>m$)	
E	8	0.24	0.28	0.80	0.83	6.3	7.0	9.8
		29.2	(α: $\simeq 0$)					
F	3	3.8	4.1	6.0	(α's;	$\simeq 0$	1.8	2.3)

IV. COMPARISON OF SPECIAL EVENTS WITH THEORY

Lord, Fainberg, and Schein[19] have described an event for which Fermi's theory gives a ready explanation in terms of multiple meson production in a median collision between an incoming proton ($W'=3\times10^{13}$ ev) and a nucleon on the edge of a nucleus in the emulsion. They were able to make some energy measurements by multiple scattering, which seem to support the general validity of the above picture. Camerini *et al.*[8] have also shown a photograph of an event which may be of this general type.

It should be noted here that many of the minimum ionization particles with which we are concerned are so energetic that, while in suitable cases it will be possible to measure their energy or set lower limits, it is impossible by present techniques to distinguish between protons and mesons. Consequently, in what follows we have assumed that all incoming particles of minimum ionization are protons, and that the forward shower particles are comprised mainly of pi-mesons.[20] The latter assumption was supported in the case of Lord, Fainberg, and Schein by the observation that pairs of minimum ionization particles (presumably electrons, and resulting from neutral pi-meson decay radiation) originated inside the inner shower cone. In our events below the numbers of tracks involved, and their lengths in the emulsion were such that, assuming approximately equal numbers of neutral, positive, and negative pi-mesons, we would have expected to observe about one electron pair for all the events, so the fact that we did not observe any is not statistically meaningful.

Unfortunately, because of limited track lengths in the emulsion and to distortion in some cases, we have not been able to make many useful energy measurements, and comparison with theory is made on the basis of numbers of shower particles and their angular distributions.

Details of the events are given in Table I. Events A, B, C, and D[21] were formed in a flight at about 85,000 feet in G5 emulsion of 250 microns thickness. Events E and F were formed in flights at over 90,000 feet in G5 emulsions of thicknesses 400 and 600 microns respectively.

Events A, B, C, and D: The events are illustrated in Figs. 7 and 8. In each of these four cases, the incoming particle has minimum ionization, and one or two of the oblique shower particles have ionization greater than

[19] Lord, Fainberg, and Schein, Phys. Rev. **80**, 970 (1951).

[20] The work of Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950), has indicated that the majority of shower particles with energies $\gtrsim$1 Bev are pi-mesons. These authors have also shown that fast pi-mesons may cause stars. However, since such mesons themselves must be produced in disintegrations in the upper atmosphere, it seems reasonable to ascribe incident singly charged particles, in the more energetic events, as protons.

[21] These events were found in 46 cc of emulsion containing $\sim$450 stars with $\geqslant$5 shower particles. However, much of this emulsion was searched under conditions in which the special events may have been missed, and thus the four out of 450 stars probably represents a minimum for the frequency of these events.

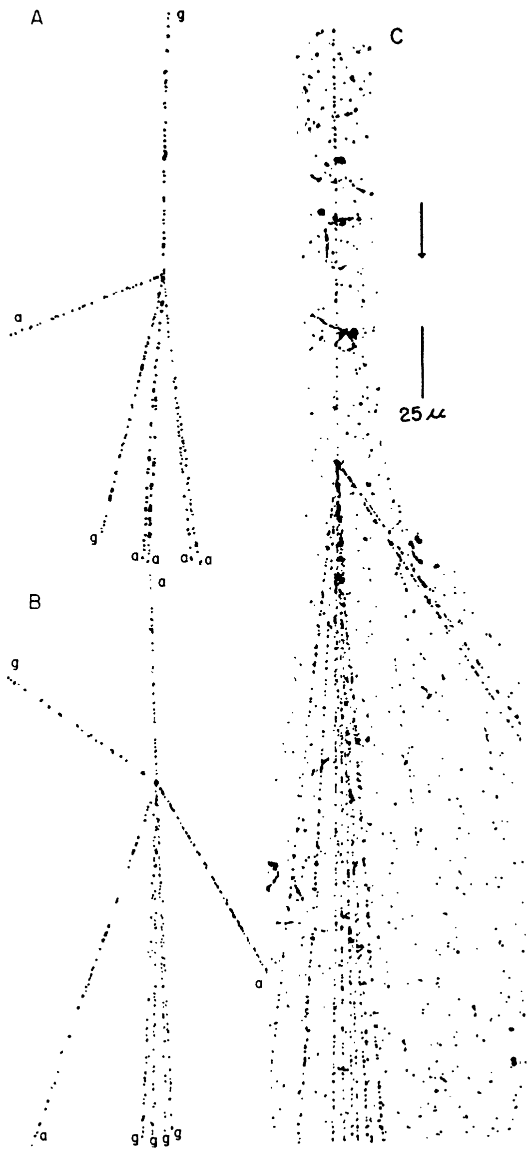

FIG. 7. Microprojections of events A, B, and C.

minimum (~1.5 to 2 times; see Table I). B and C have a short spur at the origin (~one micron long), which could be a recoil track resulting from a residual nucleus. Owing to the fairly large grain size in our emulsion, and the possibility of chance coincidence of several grains, it is difficult to be sure of these spurs, especially in case A, where the spur is shorter.

The numbers of tracks after collision were 6, 7, 12, and 13, respectively, so that, as we have pointed out previously,[22] from considerations of charge conservation (and assuming that the colliding particles remain as entities with enough kinetic energy, if charged, to give a visible track after the collision) the target nucleon in B and D could not have been a hydrogen nucleus, but must have been a nucleon in a heavier nucleus in the emulsion. On this basis also the events of Lord, Fainberg, and Schein and of Camerini *et al.* must have been collisions with nuclei heavier than hydrogen. Furthermore, although A and C can be p-hydrogen collisions according to the charge argument, we have noted that C has a possible, very short, nuclear recoil. The fact that most of these few cases cannot be simple hydrogen collisions (assuming the incoming particle to be a proton) may be reasonable on considerations of purely geometrical cross sections.

On the assumption that these events do represent multiple meson production in nucleonic interactions, we have plotted the angular distributions in the laboratory system and compared these with angular distributions calculated from Fermi's theory, assuming in each case a median or central type of nucleon-nucleon collision, and a given number of mesons, thus fixing both angular distribution and W'. Using the results of Fig. 6 relativistic transformations from the c.m. to the laboratory

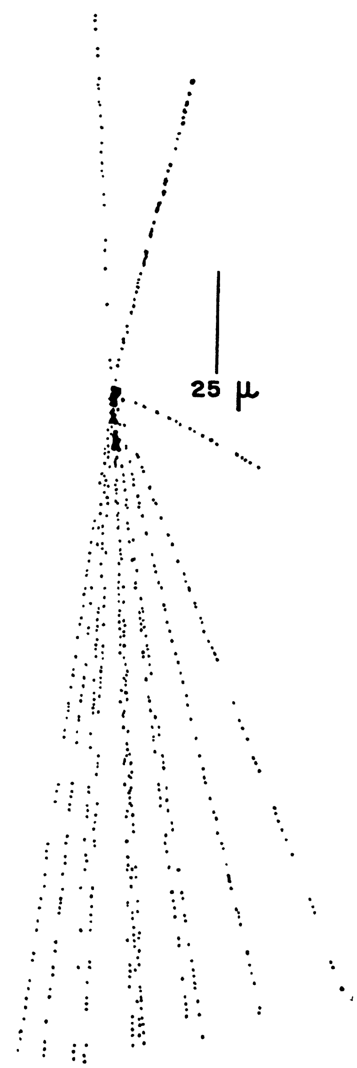

FIG. 8. Microprojections of event D.

[22] E. Pickup and L. Voyvodic, Phys. Rev. 82, 265 (1951).

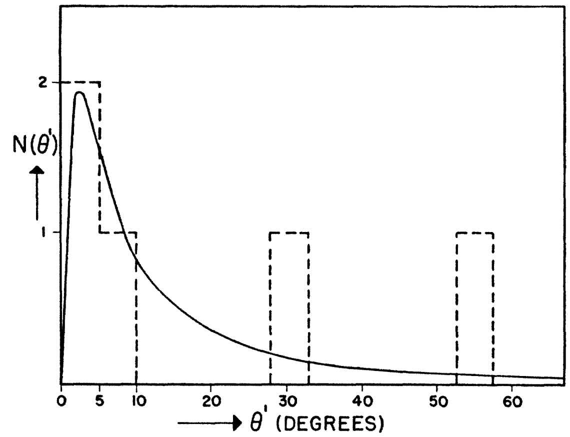

FIG. 9. Histogram shows experimental angular distribution for event *A*. Full curve is theoretical distribution in laboratory system for $N=5$, $r/R=0.37$, $W'\simeq 80$ Bev. $N(\theta')$ = number of mesons per degree.

system were made. The distributions are shown in Figs. 9, 10, 11, and 12 for *A*, *B*, *C*, and *D*, respectively. The largest angle tracks are not shown in the histograms. It will be seen that *A* and *B* are fairly well-represented by median-central collisions with $W'\simeq 80$ Bev and 145 Bev respectively, and $N=5$ and *C* by a central collision with $W'\simeq 600$ Bev and $N=10$ (excluding the two wide angle tracks here). *D* presents more difficulties, on account of the relatively wide angular distribution and the large number of tracks, and it would seem unlikely that it can be fitted to any single distribution, even though the theoretical distributions shown are only average ones. Thus we are led to conclude that this may be a more complicated event involving several collision processes, probably in a light nucleus (C, N, O) in the emulsion. We have noted previously[22] the difficulty, on account of the small number of visible tracks, of attempting to explain *A* and *B* in terms of the complete breakup of carbon, the next lightest element to hydrogen in the emulsion.

In addition to these four events, we have observed others similar, but with just one or two of the usual low energy evaporation fragments emitted in the disintegration. It seems likely that some of these could also be due to single nucleonic collisions with low energy fragments evaporated from an excited residual nucleus.

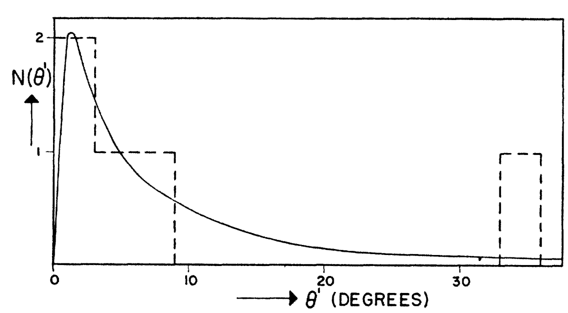

FIG. 10. Histogram shows experimental angular distribution for event *B*. Full curve is theoretical distribution in laboratory system for $N=5$, $r/R=0.53$, $W'\simeq 145$ Bev. $N(\theta')$ = number of mesons per degree.

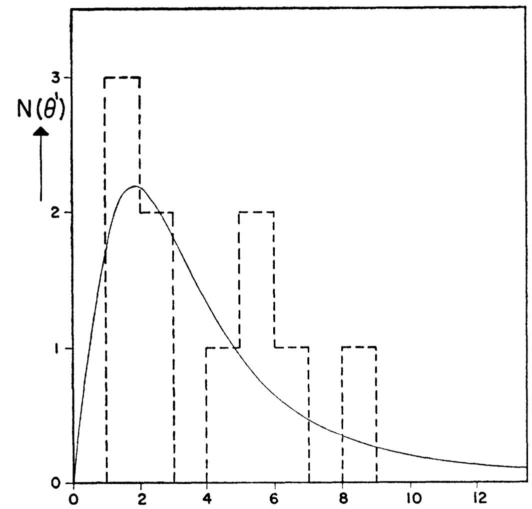

FIG. 11. Histogram shows experimental angular distribution for event *C*. Full curve is theoretical distribution in laboratory system for $N=10$, $r/R=0$, $W'\simeq 600$ Bev. $N(\theta')$ = number of mesons per degree.

Event E: This has been interpreted as the collision of a primary lithium nucleus with a hydrogen nucleus in the emulsion with multiple meson production in a nucleon-nucleon encounter in the collision, the remainder of the lithium nucleus going on, with no measurable deflection, as a helium nucleus. The collision, illustrated in Fig. 13, shows eight minimum ionization particles, four of which lie in a very narrow cone, together with the helium nucleus, at 180 degrees to the lithium track. The other four minimum ionization particles are at wider angles. The polar angles, relative to the lithium direction, are given in Table I. All the tracks were about four mm long in the emulsion.

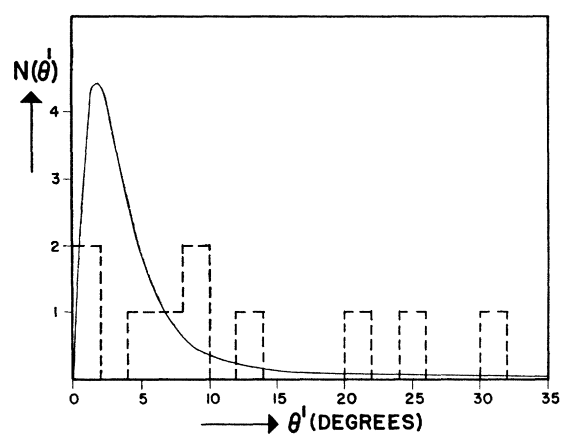

FIG. 12. Histogram shows experimental angular distribution for event *D*. Full curve is theoretical distribution in laboratory system for $N=10$, $r/R=0$, $W'\simeq 600$ Bev. $N(\theta')$ = number of mesons per two degrees.

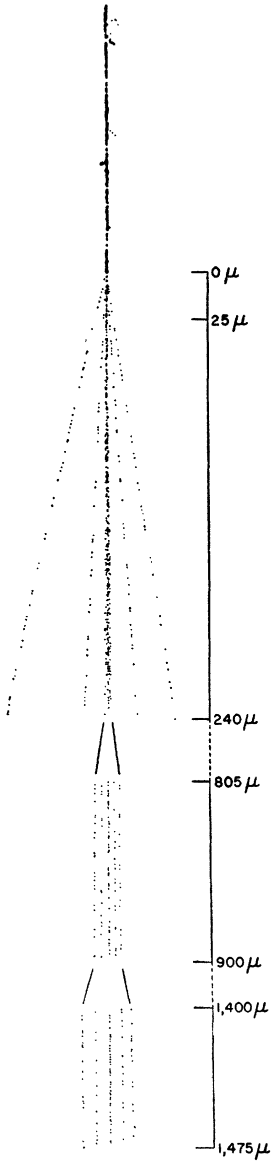

FIG. 13. Microprojection of event E (collision of lithium nucleus).

The grain density for the track identified as due to helium was 74±3 grains per 100 microns, while grain density for the minimum ionization tracks was 19±2 grains per 100 microns (being low in this particular batch of emulsion). This gives an ionization of almost four times minimum for the helium nucleus. Also the absolute number of delta-rays along this track (∼0.9 δ-rays per 100 microns) was approximately as expected for a relativistic helium nucleus. Delta-ray counting was made along the primary track. The mean ratio of delta-rays for this track compared with the helium track was 2.5±0.5, whereas that expected for a primary relativistic nucleus with three units of charge is 2.25. Thus the incoming nucleus was identified as lithium.

The event is therefore tentatively described as follows:

$$Li_3^{7(6)}+H_1^1=He_2^{4(6)}+2p_1^1(n_0')+\sum \text{(pi-mesons)}.$$

Conservation of mass units and charge, and the fact that there were eight minimum ionization tracks fix the number of charged mesons, N, on this picture as $6\leqslant N\leqslant 8$. While, on the basis of charge, we cannot definitely rule out the possibility that this event is really due to a collision with a carbon nucleus resulting in the complete break-up of carbon, rather than a hydrogen collision, the completely relativistic nature of the event and the small number of tracks appear to make this possibility unlikely.

Assuming the multiple production of seven charged mesons and a median nucleon-hydrogen collision ($r\simeq 0.71R$), Fermi's theory gives $W'\simeq 2\times 10^{12}$ ev. The observed angular distribution is compared graphically in Fig. 14 with that calculated for the above energy for a median collision. It will be seen that the agreement is quite reasonable considering the small number of tracks involved, and thus we conclude that the incoming nucleus is lithium with an energy of about 2×10^{12} ev per nucleon. For purposes of comparison the theoretical curve for seven charged mesons for a centered collision ($r=0$; $W'\simeq 150$ Bev) is also shown in Fig. 14.[23] Scattering measurements made on the two innermost minimum ionization tracks, relative to the α-particle, indicate that their energy was greater than 10 Bev. The tracks were not sufficiently long for more precise measurements.

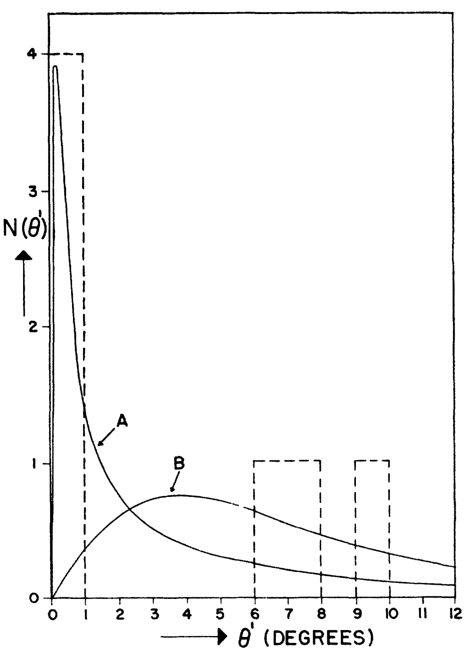

FIG. 14. Histogram shows experimental angular distribution for event E. Full curve A is theoretical distribution in laboratory system for $N=7$, $r/R=0.71$, $W'\simeq 2\times 10^{12}$ ev. For comparison curve B shows theoretical distribution for $N=7$, $r/R=0$, $W'\simeq 150$ Bev. $N(\theta')$ = number of mesons per degree.

[23] It may be noted that an isotropic distribution (regardless of theory) fitting the main forward cone of this event would give a much smaller probability for the more diffuse tracks than would Fermi's theory for an off-centered collision.

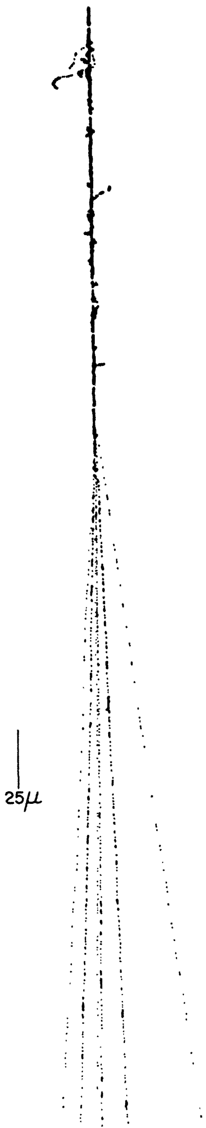

FIG. 15. Microprojection showing event F (collision of oxygen nucleus).

Event F: This is shown in Fig. 15. There are three relativistic particles, each with two units of charge (≃four times minimum ionization) and three minimum ionization particles. The primary was identified as of charge 7.5±1 by delta-ray counting (using the delta-ray count on the α-particles as a criterion). The simplest explanation would be that an incoming oxygen nucleus with an energy of several Bev per nucleon has collided with a hydrogen nucleus in the emulsion, one α-particle of oxygen being split up into nucleons with the possible production of one or two mesons, and the residue of the oxygen nucleus splitting up into three α-particles.

Freier and Ney[12] have discussed an event, which they interpret in terms of the collision of a carbon nucleus with hydrogen in an emulsion, with a boron nucleus going on, and the multiple production of about 10 charged mesons. The spread of their experimental angular distribution, even though the picture is only an average one, makes it seem unlikely that the event can be explained by the present picture on the basis of a single nucleonic interaction, although two interactions could possibly explain it.

V. CONCLUSIONS

An attempt has been made to explain several special high energy interactions in terms of Fermi's recent theory of multiple meson production, and it has been shown that the angular distributions for some of these events fit reasonably well with those given by the theory. Those which do not fit so well could be explained by assuming more complicated collision processes. Our interpretation of the events must, however, be regarded as somewhat tentative at this stage. The special collisions are comparatively rare, and it is hoped that further work with thicker emulsions will yield events which are susceptible to accurate energy, as well as angular distribution, measurements.

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