Evidence for the Multiple Production of Mesons in a Single Nucleon-Nucleon Collision*

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Evidence has been obtained for the multiple production of mesons in a single nucleon-nucleon collision in a photographic emulsion exposed to the cosmic radiation at an altitude of 95,000 ft. The nuclear encounter in which the mesons were created was produced by a primary proton of 3×10^{13} ev energy. Directly in line with the incident proton 7 particles of minimum ionization were emitted in a central core with an angular divergence of 0.003 radian. In addition 8 other minimum ionization particles were emitted in a wider diffuse cone of 0.13 radian angular divergence. Only one track had the appearance of a fragment which, however, could have been a proton of 10-Mev energy. Most of the particles in the central core had energies in excess of 250 Bev, while those in the diffuse cone were of much lower energies as determined by small angle scattering measurements. A pair of very small angular divergence was produced in the central core 4800 microns from the point of origin of the nuclear interaction. Assuming that the pair were produced by a gamma-ray from the decay of a neutral meson, a lower limit of 2×10^{-15} second was deduced for its mean life. Both the angular and the energy distribution of the emitted particles is in good agreement with the assumption that in the center-of-mass system the mesons are emitted in two distinct cones of angular width of about 30° forward and backward with reference to the direction of the primary proton. The average multiplicity of 15 agrees with the recent calculation by Fermi, and according to his prediction about one-half of the particles could be made up of nucleon-antinucleon pairs.

I. INTRODUCTION

THUS far no clear-cut evidence has been obtained in which a high energy particle has produced more than one meson in a single nucleon-nucleon collision. In several nuclear interactions observed in photographic plates[1–5] on the order of 25 or 30 minimum ionization tracks were produced which have been shown to be predominantly mesons.[6] In all cases, however, the interactions occurred with silver or bromine nuclei, so that the contribution to the production of mesons by the numerous energetic secondaries could not be estimated. In the case of the star observed by the Rochester group,[5] the impinging particle was not a single nucleon but an alpha-particle of very high energy colliding with the nucleus of a heavy atom of the emulsion, as demonstrated by the many heavy tracks present. Numerous mesons were shown to be produced; however, in spite of the strong case for the multiple production of mesons in a single act, many secondary mesons emitted in successive collisions were distributed over such a wide angle cone that they had to be the result of plural production within the same nucleus.[7]

II. DATA

The event shown in Fig. 1 gives an example of the multiple production of mesons in a single act by an extremely high energy proton. This event was observed in an Ilford G-5 type emulsion 200 microns in thickness which was exposed to the cosmic radiation in the stratosphere. A free balloon[8] supported the plates at an elevation above 90,000 ft. for over 16 hours.

The event occurred about midway between the surfaces of the emulsion, and most of the tracks are very nearly parallel to the surface. Track A of minimum ionization extends over 10,000 microns in the emulsion and is taken to be the incident primary proton producing the nuclear interaction. Track B passes into the glass after a short distance and cannot be identified; however, a proton of about 10 Mev would produce a track of similar appearance. Track C is a 200-Mev proton, as determined from its small angle scattering and grain density.

The other 15 tracks, all of minimum ionization, lie in a narrow cone directly opposite the incident track A. In the upper section of Fig. 1, five of the minimum ionization tracks can easily be seen. The other 10 tracks are so closely spaced that they appear as a single heavy black track. The lower section of Fig. 1 shows these 10 tracks at a distance of 4800 microns from the nuclear interaction where they are more widely separated and all but two of them are easily resolved.

The arrow marked γ on the lower section of Fig. 1 is directed toward a point in the region of the core where a pair of charged particles originate and travel parallel to the other tracks in the core. In the region shown in Fig. 1, the angle between the tracks is so small that they appear as a single track.

III. DISCUSSION

The angular distribution of the tracks in the core is shown in Fig. 2. It is to be noticed that the curve in Fig. 2 shows the manner in which 7 minimum ionization particles were emitted in an extremely narrow bundle of 0.003-radian half-width (central core) and the other 8 in a considerably larger cone of 0.13-radian half-width (diffuse cone). Since all of the particles in the central

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1 Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. 40, 862 (1949).
2 Schein, Lord, and Elston, Echo Lake Cosmic Ray Symposium, page 66, Office of Naval Research (1949); J. J. Lord and Marcel Schein, Phys. Rev. 77, 19 (1950).
3 J. Hornbostel and E. O. Salant, Phys. Rev. 76, 859 (1949).
4 Leprince-Ringuet, Bousser, Hoang, Jauneau, and Morellet, Comptes Rendus 229, 163 (1949).
5 Kaplon, Peters, and Bradt, Phys. Rev. 76, 1735 (1949).
6 P. H. Fowler, Phil. Mag. 41, 169 (1950).
7 W. Heitler and L. Jánossy, Proc. Phys. Soc. London A62, 669 (1949).

8 The assistance of the Office of Naval Research and the General Mills Company is gratefully acknowledged.

core and some of those in the diffuse cone remain in the emulsion for over 10,000 microns (Table I), it has been possible to measure systematically the relative separation of the tracks, and hence to determine by accurate measurements of the small angle scattering[6] their momentum. Either the measured value or lower limit for the momentum times velocity[9] is given in Table I for each of the tracks. It is to be noted that the energies E, as deduced from the momentum p, of 5 of the tracks in the central core exceed 250 Bev, while the particles of lower energy are found to be in the larger diffuse cone.

The momentum of the two particles forming the pair γ, in Fig. 1, are given in Table I. Assuming that the pair consists of electrons originating from one of the two gamma-rays emitted in the decay of a neutral meson, it is possible to make estimates of the energy of this neutral meson. It can easily be shown that the energy of the neutral meson is given by the following relation:

$$E = Mc^2(1-\beta^2)^{-\frac{1}{2}} = Mc^2[(h\nu'/h\nu)^2 - \sin^2\theta]^{\frac{1}{2}}/(\cos\theta - \beta);$$

Mc^2 = rest energy of proton; θ = angle between gamma-ray and the direction of motion of the neutral meson in the laboratory system of coordinates; $h\nu$ = energy of the gamma-ray in the laboratory system of coordinates; $h\nu'$ = energy of the gamma-ray in the reference frame fixed to the neutral meson (equal to one-half of mass energy of neutral meson;[10] about 75 Mev).

TABLE I. Data on the tracks of the event of Fig. 1.

Track numbered from right to left in Fig. 1	Length of track in emulsion of first plate in microns	$p\beta$ in Bev/c
A	11,000	30,000
B	176	0.01
C	2700	0.36
electron Pr_1	3450	3.6
electron Pr_2	4200	3.0
Diffuse cone		
1	605	*
2	1300	
3	10,600	
4	3040	
5	9630	3.91 } *
6	2310	2.6 }
7	2360	
8	2620	
Central core		
1′	6990	> 50
2′	9400	>250
3′	10,250	>250
4′	11,700	>250
5′	11,700	>250
6′	10,000	>250
7′	9500	86

* On the remaining 6 tracks in the diffuse cone accurate determinations of momentum are in progress, and will be reported at a later date.

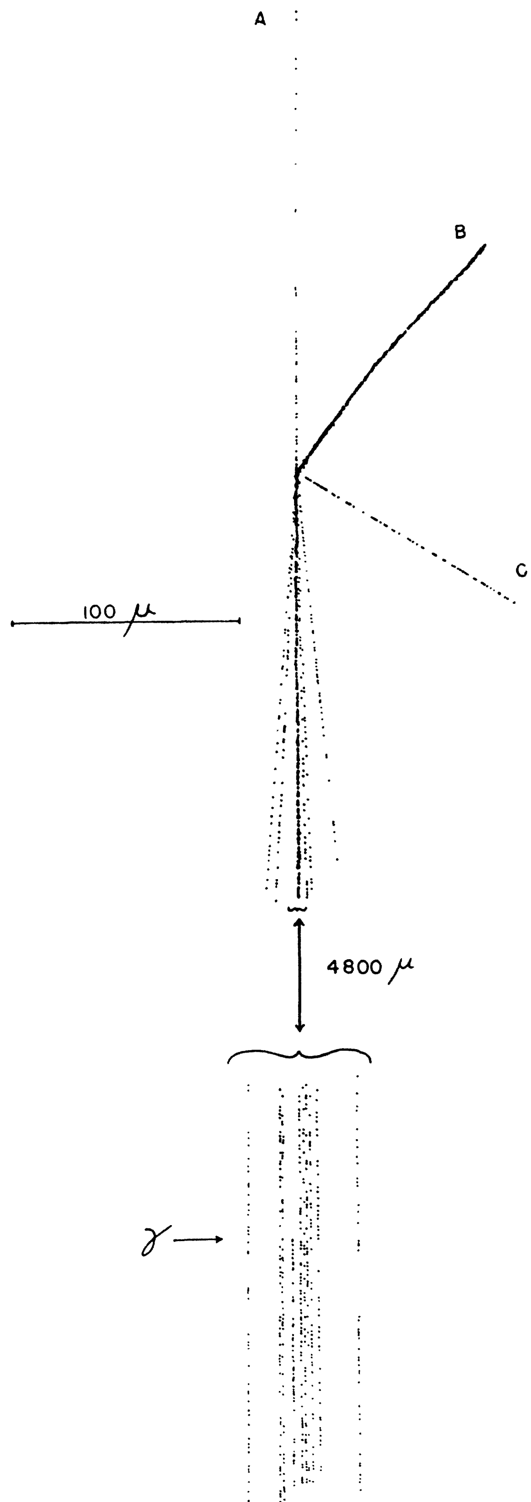

FIG. 1. Microprojection drawing of a high energy star produced by a 3×10^{13}-ev proton.

The pair γ was produced in the central core and the electrons remained in the core over their whole length in the emulsion (4000 microns). Hence the gamma-ray,

[9] At these very high values of momentum $\beta \simeq 1$ and $E \simeq pc$.
[10] Bjorkland, Crandall, Moyer, and York, Phys. Rev. 77, 213 (1950).

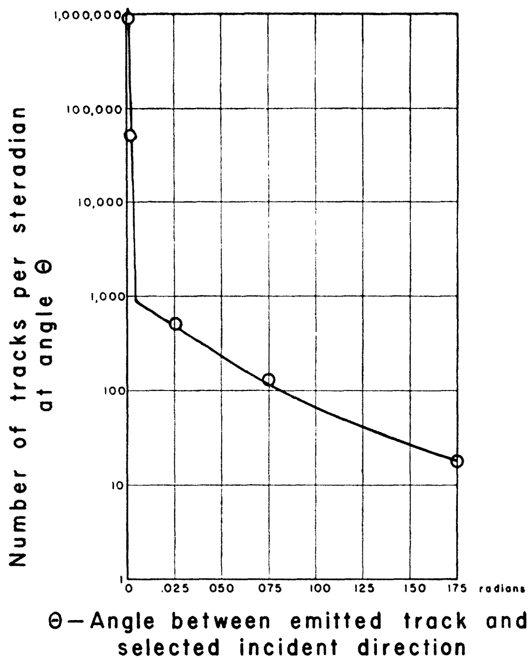

FIG. 2. Angular distribution of the 15 emitted minimum ionization tracks of the star in Fig. 1.

in the laboratory system of coordinates, was emitted at an angle with respect to the direction of motion of the neutral meson of the same order of magnitude as the angle between the tracks in the narrow cone (0.001 radian). These conditions are satisfied in the above equation by either a meson (a) of approximately 1000 Bev or (b) by one of 10-Bev energy. Since 6 of the ionizing particles emitted in the narrow core were shown to have energies greater than 250 Bev, one has to assume that the energy of the neutral meson was that of type (a). Otherwise the assumption would have to be made that meson (b) was emitted almost directly backward in the center-of-mass reference frame (less than 0.003 radian with respect to the incident proton).

An upper limit of the mean life of the neutral meson (b) can be obtained by assuming that the materialization of the gamma-rays occurred at the maximum distance of 4800 microns from the origin of the star. This yields a mean life for the meson (b) which must be less than 2×10^{-15} sec.

An estimate of the energy of the incident proton causing this high energy interaction, Fig. 1, can be obtained by considering the collision in the center-of-mass reference system determined by the incident proton and the target nucleon. The unusually sharp break in the angular distribution curve, Fig. 2, for the emitted particles and their very much higher energy in the central core than in the diffuse cone make it necessary to assume that the 7 tracks in the central core were due to particles emitted in the forward direction (A in Fig. 3) in the center-of-mass system. The 8 tracks of lower energies in the diffuse cone are thus the particles emitted in the backward direction (B in Fig. 3). Accordingly, the energy of the incident proton which is responsible for the production of this star is given by:

$$E = Mc^2\gamma \simeq 2Mc^2\gamma_c^2 \simeq 2Mc^2 \tan^2\tfrac{1}{2}\theta'/\tan^2\theta,$$

where $\gamma=(1-\beta^2)^{-\frac{1}{2}}$ in the laboratory system; $\gamma_c=(1-\beta_c^2)^{-\frac{1}{2}}$ with β_c the velocity of the center-of-mass reference frame; θ = half-width of the central core in the laboratory system of coordinates (0.003 radian); and θ' = half-width of the central core in the center-of-mass system.

The estimated energy is not strongly dependent upon the value of θ'. However, $\theta'=40°$ as approximately given by Fermi's new formulation of the interaction of high energy particles gives $E=3\times10^{13}$ ev or about 48 ergs. The energy of the primary proton was also calculated from the half-width of the diffuse cone and was found to be in good agreement with the above-mentioned value. This is undoubtedly the highest energy of a single proton which has thus far been directly observed in nature.

The complete lack of slow particles around the central core (Fig. 2) and the fact that only one track could be an ordinary star evaporation nucleon clearly demonstrate that we are dealing here almost entirely with a nucleon-nucleon interaction either in a very light element or possibly in a deuteron or hydrogen nucleus present in the emulsion. It is of particular interest to see that even for energies as high as 3×10^{13} ev the number of charged particles of minimum ionization produced in a single act is as low as 15. The pair of particles produced in the core 4800 microns from the point of interaction is most probably an electron pair formed by a gamma-ray from the decay of a neutral meson. Since this distance represents only about 0.2 radiation units, it seems probable that additional neutral mesons were produced in this very high energy nuclear encounter.

The new calculation by Fermi[11] predicts that in the

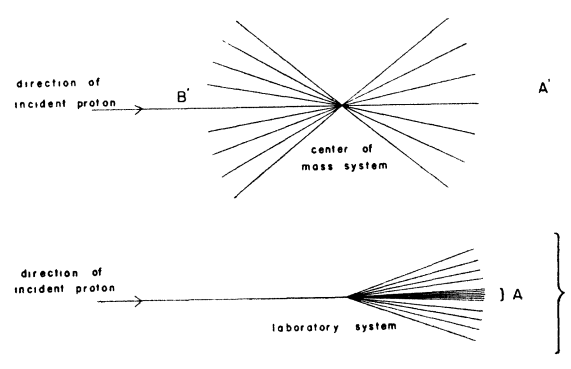

FIG. 3. Diagrammatic drawing of the nucleon-nucleon interaction in Fig. 1 in both the center-of-mass system and the laboratory reference system.

[11] E. Fermi, private communication (1950).

above-described star, there would be about 16 high energy charged particles produced by the 3×10^{13}-ev proton. This is in excellent agreement with the total of 15 sharply collimated minimum ionization tracks which were observed. In addition, Fermi postulates that if nucleon-antinucleon pairs should be produced in addition to mesons, at the extremely high energy of the primary (3×10^{13} ev), the number of emitted particles would then be nearly equally divided between meson and nucleon-antinucleon pairs.

The multiplicity observed here is considerably lower than that calculated by other authors.[12,13] Lewis, Oppenheimer, and Wouthuysen estimate the production of a few hundred mesons by a proton of 3×10^{13}-ev energy and Heisenberg predicts a similar number at this same primary energy.**

This report gives only the results of a preliminary investigation carried out in the emulsion in which the star originates. The emitted tracks pass into a second emulsion in which each of them travels about 20,000 microns. The analysis in the second emulsion will be published later.

We wish to thank Professor Fermi for very illuminating discussions of this nuclear interaction in relation to his new theory, and for his valuable suggestions concerning the small angle scattering of the emitted particles.

[12] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[13] W. Heisenberg, Nature **164**, 65 (1949).

** Professor J. R. Oppenheimer pointed out to one of us (Marcel Schein) that his recent calculations in which he assumes a smaller multiplicity of meson production around 10^{10}-ev energy are in agreement with the experimental observations presented in this paper.

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Scattering of Mesons by Nuclear Particles*

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Cross sections for the scattering of mesons by nuclear particles are obtained quantum-mechanically on the basis of the Heitler-Peng version of the perturbation theory. The integral equation taking account of radiation damping in the quantum theory is solved in the classical approximation ($\hbar\rightarrow0$). A comparison of these cross sections with those obtained classically reveals certain discrepancies. It is found that though the cross sections calculated classically and those calculated quantum-mechanically in the classical approximation ($\hbar\rightarrow0$) broadly agree in most cases, usually one finds that some higher order terms which occur in the purely classical treatment are absent in the quantum-mechanical one. The discrepancy is further accentuated in the case of g_2-scattering where the differential cross sections have generally very different angular dependences and differ from each other in numerical coefficients also. These differences are, in general, such that they cannot be accounted for by postulating quantized orientations of the spin. The correspondence obtained between the classical methods and quantum mechanics by tending $\hbar$ to zero in the results obtained from the latter thus provides a test of the correctness of our theories, and, in the present case it suggests, assuming the classical theory as given by Dirac and Bhabha to be correct, the lines along which a new theory of radiation damping may be developed.

I. INTRODUCTION

We find in the case of g_1-scattering of neutral mesons that the expressions (1), (7), and (9), on the one hand, and the corresponding expressions (2), (8), and (10), respectively, on the other, differ from each other in the classical values of the cross sections having some more terms than are present in the quantum-mechanical expressions. The same thing happens in the case of charged mesons as a comparison of the cross sections (20) and (21) reveals. Apart from these terms there is a fair agreement in the broad features of the results in the two cases. In case of g_2-scattering, however, the situation is worse. This is at once evident by a glance at the expressions (5) and (6) or (12) and (13). First, one notices again the absence of a number of terms from the quantum-mechanical expressions; second, one remarks that even when these "higher order" terms are neglected the two expressions still differ from each other in having different numerical coefficients of the various terms, not to speak of the angular dependence which in case of differential cross sections is entirely different. While the cross sections without damping being taken into account differ by a factor 3, the coefficients of the damping terms differ by multiples of 2. This shows that the reason for the difference in the cross sections might not entirely lie in the different modes of averaging over the directions of the spin vector in the classical and the quantum theories (Bhabha[1]). In the case of charged mesons, it is

* Revised copy of manuscript received July 24, 1950.

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[1] H. J. Bhabha, Proc. Ind. Acad. Sci. **A13**, 249 (1941).