High Energy Collisions with the Production of Meson Showers

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Eighteen events of meson showers produced in high energy collisions have been analyzed to study the mechanism of the production of mesons. The angles ψ of the mesons have been measured relative to the primary direction or relative to the shower axis for neutron induced showers. The mean value of $\cos\psi$, $\langle\cos\psi\rangle_{Av}$, has been plotted against the number N of the mesons produced. It is found that the observed points can be divided into three regions corresponding to single, double, and triple collisions inside the nucleus. The points representing single collisions lie considerably below the theoretical curve of Heisenberg for completely inelastic collisions and it is concluded that in these collisions only a fraction $(1/K)$ of the incident energy goes to the meson production. For these events the values of K and primary energy E_p have been estimated by applying Heisenberg's theory to partially inelastic collisions. For double and triple collision events the number of mesons produced in successive collisions inside the nucleus has been estimated from the angular dispersions of the single collision events.

I. INTRODUCTION

OUT of a total of 1000 stars obtained in 400 μ Ilford G.5 nuclear plates exposed to cosmic rays at 80,000 feet, 18 high energy stars have been selected for the study of meson shower production. Stars in which the minimum charge, carried by all the evaporation particles, is greater than 8 are ascribed to heavy nuclei and those with less than 8 to light nuclei. Tracks of grain density <1.5 minimum are taken as shower tracks and are assumed to be mesons but occasional slow mesons are also identified and included in the shower. Tracks having grain densities from 1.5 to $5\times$minimum are classified as medium and are almost exclusively protons. The evaporation particles have grain densities greater than $5\times$minimum. In these events the initiating particles are protons or neutrons. In the case of proton reactions the angle ψ of each shower track is measured relative to the primary direction, taking into account the shrinkage of the emulsions after processing. For neutron reactions, following Osborne,[1] the shower axis, defined as the "center of gravity" of the meson shower tracks is taken as the primary direction and the angles ψ of the mesons are measured relative to this. The difference in the methods for obtaining ψ for proton and neutron stars does not affect the majority of the events and is discussed later.

II. EXPERIMENTAL OBSERVATIONS AND RESULTS

The mean values of $\cos\psi$, $\langle\cos\psi\rangle_{Av}$, and of ψ, $(\bar{\psi})$ are given in Table I as well as the value of ψ_m, the angle of the meson at the greatest angle from the primary direction. In column 2 of Table I the first number refers to the number of shower tracks (grain density, $g<16/50\mu$), the second to medium tracks $(16<g<50/50\mu)$ and the third number of evaporation particles $(g>50/50\mu)$. In Fig. 1 the number of shower particles N is plotted against $\langle\cos\psi\rangle_{Av}$. Curve $1A$ represents the corresponding relation for a completely inelastic nucleon-nucleon collision as given by Heisenberg,[2]

$$\langle\cos\psi\rangle_{Av}\simeq 1-8/n^2, \tag{1}$$

where n = total number of mesons $=\frac{3}{2}$ times the observed number N of charged mesons from symmetrical theory.

Peyrou *et al.*[3] have pointed out that the maximum angle of the shower particle ψ_m is directly related to the primary energy assuming an isotropic distribution in the c.m. system. When values of ψ_m are plotted against N (Fig. 2) these form a similar pattern to the $\langle\cos\psi\rangle_{Av}$, N plot of Fig. 1.

From Fig. 1 the following are seen:

(1) One set of points lies about the curve 1 which is significantly below the theoretical curve $1A$. These events include most of the light nuclei and some of the heavy ones and may be interpreted reasonably as the result of single nucleon-nucleon collisions where only a fraction $1/K$ of the incident energy is used for meson production. This agrees with the conclusion obtained by LePrince-Ringuet *et al.*[4] for a high energy star. The high energy $p-p$ collision denoted by star $L1$ and described previously[5] indicated that about 1/10 of the incident energy of 1000 Bev was used for meson production. If in these events a few fast proton tracks were included in the shower tracks, curve 1 would be displaced further from the theoretical curve indicating higher values of K.

(2) A number of events lie well above the theoretical curve $1A$. These events may be reasonably interpreted as because of successive meson producing collisions inside the nucleus. This process of pluro-multiple production of mesons (LePrince-Ringuet *et al.*,[4] Osborne,[1] Kaplon *et al.*[6]) appears to be more probable when only a fraction of the energy of the primary particle is used

[1] L. S. Osborne, Phys. Rev. 81, 239 (1951).

[2] W. Heisenberg, Nature 164, 65 (1949); Z. Physik 126, 569 (1949).

[3] Peyrou, d'Espagnat, and LePrince-Ringuet, Compt. rend. 228, 1777 (1949).

[4] LePrince-Ringuet, Bousser, Fong, Jauneau, and Morellet, Compt. rend. 229, 163 (1949).

[5] Hopper, Biswas, and Darby, Phys. Rev. 84, 457 (1951).

[6] Kaplon, Peters, and Bradt, Phys. Rev. 76, 1735 (1949).

TABLE I. Summary of data from 18 high energy stars showing the multiplicity classification obtained for the meson showers and the estimated values of K, the ratio of the incident energy to the energy of the shower for single collisions.

Star	Class	Incoming particle	No. of shower particles N	$\langle\cos\psi\rangle_{Av}$	$\bar{\psi}$ deg	ψ_m deg	Multiplicity classification	$N[\langle\cos\psi\rangle_{Av}]_N$	$\Sigma N_1[\langle\cos\psi\rangle_{Av}]_{N_1}$	$\Delta\psi$ deg	Calc. K	E_p (Bev)
$L1$	7+0+0	p	6	0.992	5.2	15.9	6			1.3	(10)	(1000)[a]
$L2$	1+3+3	p	2[b]	0.568	71.9	79.6	2			20.5	1.8	4.7
$L3$	3+1+7	n	3	0.803	35.0	51.0	3				2.0	10
$L4$	4+1+3	p	3	0.884	26.8	37.0	3			8.0	3.2	16
$L5$	6+0+6	p	5	0.800	28.9	80.5	3, 2	4.0	3.6	11.5		
$L6$	5+0+4	p	4	0.959	13.9	22.0	4			5.0	5.9	52
$H1$	8+3+13	n	8	0.875	26.7	45.3	5,3	7.0	7.4			
$H2$	12+6+13	p	12[c]	0.754	30.1	94.9	5, 4, 3	9.1	11.1	19.3		
$H3$	10+1+9	n	10	0.924	19.9	40.0	6, 4	9.2	9.7			
$H4$	11+8+13	p	10	0.577	51.8	90.7	3, 3, 2, 2	5.8	7.1	36.2		
$H5$	4+1+11	n	4	0.165	81.5	90.0	2, 2	2.0	2.0			
$H6$	9+4+15	p	8	0.738	34.9	110.0	3, 2, 2	5.9	6.1	16.1		
$H7$	4+1+20	n	4	0.953	21.0	27.2	4				5.0	44
$H8$	14+4+12	n	14	0.818	27.6	84.5	6, 5, 3	11.4	13.3			
$H9$	6+10+14	p	5	0.875	25.4	46.6	?			5.0		
$H10$	3+1+17	n	3	0.834	31.6	48.0	3				2.3	11.5
$H11$	3+1+14	n	3	0.546	49.0	80.0	3				1.0	5.0
$H12$	5+3+8	n	5	0.963	20.6	28.0	5				4.4	59

[a] Star $L1$ refers to a p–p collision (reference 5).
[b] Two of the medium prongs are mesons.
[c] One medium prong is a slow π^- meson.

in a collision. The points may be roughly divided into two regions about the dotted curves 2 and 3. Those around curve 2 may be interpreted as the result of two meson producing collisions inside the nucleus and those around curve 3 to 3 collisions. One isolated point ($H4$) possibly represents a 4-collision process. From the values of ψ_m and $\langle\cos\psi\rangle_{Av}$, it is possible to indicate the type of collision taking place. The total number of mesons N can be subdivided into $N_1+N_2+\cdots$ for successive collisions by using the ψ_m, N curve (Fig. 2) for a single collision and from a study of the number of mesons occurring within a certain angle. In this way the multiplicities N are subdivided for the successive collisions as given in column 8 of Table I. These subdivisions can be checked from the $\langle\cos\psi\rangle_{Av}$ values as follows: If $[\langle\cos\psi\rangle_{Av}]_N$ corresponds to total multiplicity N and $[\langle\cos\psi\rangle_{Av}]_{N_1}$, $[\langle\cos\psi\rangle_{Av}]_{N_2}$, $\cdots$ to numbers N_1, $N_2\cdots$ for single collisions, then

$$N[\langle\cos\psi\rangle_{Av}]_N \simeq N_1[\langle\cos\psi\rangle_{Av}]_{N_1}+N_2[\langle\cos\psi\rangle_{Av}]_{N_2}+\cdots, \quad (2)$$

where $N=N_1+N_2+\cdots$. The numerical values of the two sides of Eq. (2) are given in columns (9) and (10) of the table, which show general agreement, the difference being somewhat large for three events of high plurality. The relation (2) is valid when the nucleons taking part in the successive meson producing collisions inside the nucleus move nearly in the same direction as the primary particle. This is unlikely when a number of successive meson producing collisions occur inside the nucleus. This can be seen from a comparison of the values of $\Delta\psi$, the difference between the direction of the primary and the shower axis, given in column 11 where large values of $\Delta\psi$ occur for 3- and 4-fold collisions. For these events if the angles ψ are measured relative to the shower axis of the star instead of the primary proton direction, the values of $N[\langle\cos\psi\rangle_{Av}]_N$ are closer to the value of $\sum N_1[\langle\cos\psi\rangle_{Av}]_{N_1}$. (For example in events $H2$ and $H5$, the $N[\langle\cos\psi\rangle_{Av}]_N$ values are 10.1 and 7.5, respectively, when the angles ψ are meas-

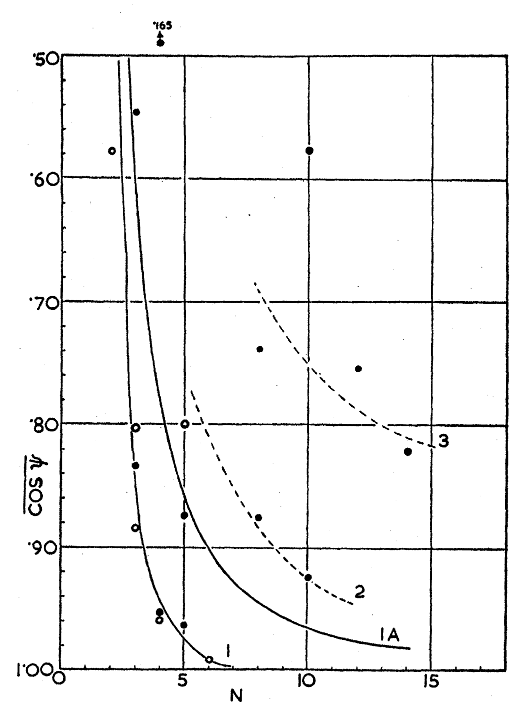

FIG. 1. Number of shower particles N, plotted against $\langle\cos\psi\rangle_{Av}$ for eighteen high energy stars. Blank circles and black circles correspond to light and heavy nuclei, respectively. Curves 1, 2 and 3 represent single, double and triple meson producing collisions in the nucleus. Curve 1A represents relation for completely inelastic single collision according to Heisenberg (see reference 2).

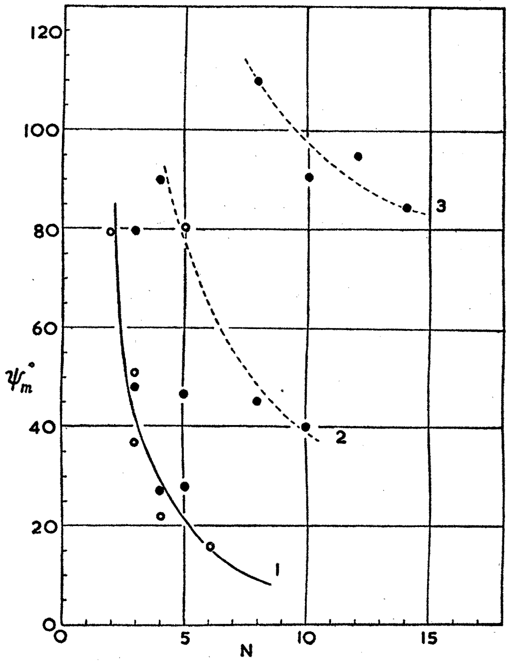

FIG. 2. Number of shower particles N, plotted against $\psi_m{}^0$, the maximum angle of a meson relative to the primary direction or shower axis. Blank circles correspond to light nuclei and black circles to heavy ones. Curves 1, 2, and 3 represent single, double, and triple meson producing collisions.

ured relative to the shower axis.) For single collisions however, it seems better to measure angles ψ relative to the primary proton direction instead of shower axis.

If we apply Heisenberg's theory[2] to partially inelastic collisions the fraction, $1/K$, of the incident energy used for meson production for single collision events can be obtained. For a given number of mesons N, the energy E, available for meson production in the L system, is

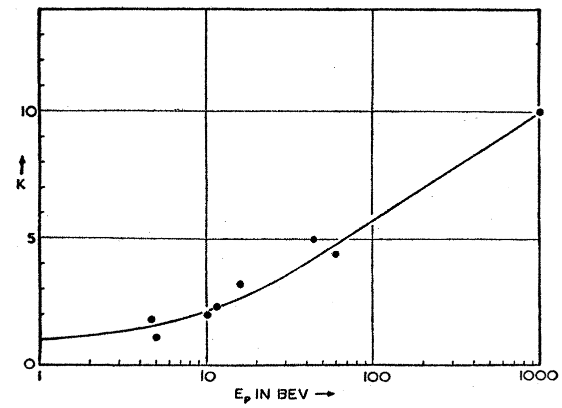

FIG. 3. Energy of the incident particle E_p, plotted against K, the ratio of the energy of the incident particle to the energy of the meson shower for single collisions.

obtained from the N, E curve drawn from the relations

$$N=\tfrac{2}{3}(\epsilon/m)/\ln(\epsilon/m), \quad \epsilon=[2M(M+E)]^{\frac{1}{2}}-2M, \quad (3)$$

where ϵ is the energy available in the c.m. system, m the meson mass, and M the proton mass. The observed value of N and the theoretical value for a completely inelastic collision, are obtained from the value of $\langle\cos\psi\rangle_{\text{Av}}$ for any event using curves 1 and 1A of Fig. 1. From the (N, E) curve of relation (3), the corresponding values of E are determined. The ratio of the theoretical to observed E, represents the factor K. The values of K and estimated primary energies E_p are given in Table I. A plot of K vs E_p shown in Fig. 3 indicates a general increase of K with increasing energy.

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