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INVESTIGATION OF A HIGH-ENERGY INTERACTION EVENT IN PHOTOGRAPHIC EMULSION

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A star of the 5 + 21 p type produced by a primary particle of $\sim 10^{12}$ ev was investigated. The measured angular distribution of the secondary shower particles exhibits two maxima. The event was interpreted as a peripheral collision of two nucleons. The ratio of the number of neutral π mesons to the total number of charged shower particles was found to be of the order of 0.4. A secondary interaction of the 0 + 6 p type, which is probably due to a single π-N collision in a peripheral collision of nucleons, was detected.

A star of the 5 + 21 p type has been found in a stack of Ilford G-5 nuclear emulsions, irradiated in Italy at an altitude of 25 — 30 km. The particles of the narrow cone are contained within a half-angle of 0.017 radians, while the half-angle of the wide cone is equal to 0.62 radians.

1. DETERMINATION OF THE PRIMARY PARTICLE ENERGY. ANGULAR DISTRIBUTION OF SHOWER PARTICLES.

The angles were measured using a MBI-8M microscope with total magnification of 1800 ×. Angles smaller than 2° were measured by the coordinate method[1] while a goniometer was used for larger ones. One of the particles, apparently belonging to the shower, was emitted backwards in the laboratory system (very unfortunate geometry). In the following discussion, this particle has not been taken into account.

The energy of the primary particle E_0 was determined, first assuming a nucleon-nucleon, then a tunnel-effect interaction. Under the first assumption, the energy was determined by two methods: 1) the half-angle method[2] and 2) the Castagnoli method.[3] The following results were obtained:

N - N collision

Method 1 $\quad \gamma_c = 20.1; \qquad E_0 = 7.5\times10^{11}$ ev

Method 2 $\quad \gamma_c = 21.0^{+3.8}_{-4.7}; \qquad E_0 = (8.3^{+3.0}_{-3.7})\times10^{11}$ ev

Tunnel-effect collision $\qquad (l = 3.3)$

$$E_0 = (1.8^{+0.6}_{-0.8})\times10^{12} \text{ ev.}$$

In the above, γ_c is the Lorentz factor of the center-of-mass system of the colliding nucleons with respect to the laboratory system (l.s.), and l is the length of the nuclear tunnel (in terms of the number of nucleons).

The histogram of the differential angular distribution in the l.s. is shown in Fig. 1. The figure also shows the Landau curve[4] (curve 1) for a symmetrical distribution in c.m.s., the Heisenberg curves[5] for an isotropic (curve 2) and anisotropic (curve 3) distribution in c.m.s. for a head-on N-N collision, and the Landau curve for a tunnel-effect collision (curve 4). The probability that the shower is symmetric was determined by the χ^2 method. It has been found that $P(\chi^2) = 92\%$. The probability of a good fit between the histogram of the experimental distribution and the Landau distribution amounts to 1%; with a Heisenberg distribution (assuming an anisotropic distribution) it amounts to 2%. From the theories of Landau and Heisenberg,

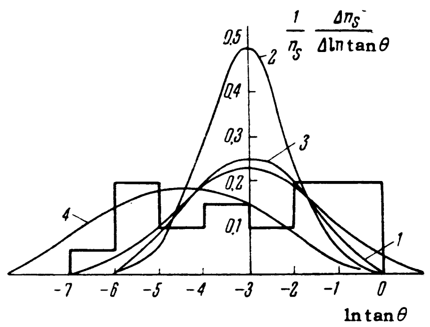

FIG. 1. Histogram of the differential angular distribution in the laboratory system.

one expects the maximum number of particles in the angle range of 1 — 9° in the l.s. for the investigated event. The distribution obtained indicates, however, a marked deficiency of particles in this range, which in c.m.s. corresponds to the vicinity of the angle $\pi/2$.

According to Lindern,[6] in the coordinate system

$$x = \log(\gamma_c \tan\theta), \qquad y = dN / d\log(\gamma_c \tan\theta)$$

(θ represents the angles in l.s.) the differential angular distribution can be approximated by a Gaussian curve with $\sigma = 0.36$ for an isotropic and $\sigma = 0.70$ for an anisotropic Heisenberg distribution. The angular distribution of the event investigated is shown in such coordinates in Fig. 2. The curve represents a Gaussian curve corresponding to the experimental data for $\sigma = 0.9$. As could be expected from the angular distribution in the l.s., the distribution is characterized by the presence of two maxima. A similar angular distribution is expected for a peripheral collision of two nucleons in the case where they are similarly excited[7,8] (a double π-N collision).

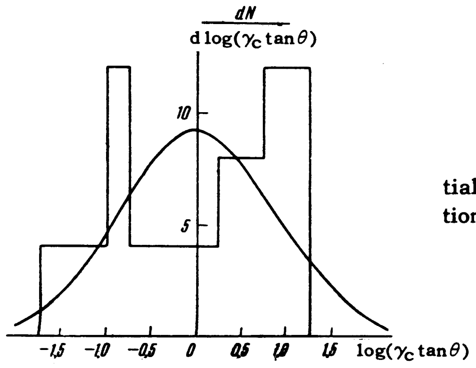

FIG. 2. Differential angular distribution in the c.m.s.

From the energy conservation law, one can determine the Lorentz γ factor of the excited nucleons in the c.m.s.

$$\bar{\gamma} = E_0' / E^*, \tag{1}$$

where E_0' is the nucleon energy in the c.m.s., $E^* = 2\sqrt{\epsilon E_0'}$ is the energy of the excited nucleon in its proper system, and ϵ is the π-meson energy. For an average value $\bar{\epsilon} = 0.5\mu\gamma_c$, we have $\bar{\gamma} = 1.8$. If the excitation energy E^* is known (in our case, it is equal to 11.5 M, where M is the rest mass of the nucleon), one can determine the expected number of shower particles n_s' and the number of particles n_s'' emitted by each of the excited nucleons.[9] It was found that $n_s' = n_s'' = 7$.

To compare the theories with experiment, n_s', n_s'', and $\bar{\gamma}$ have also been determined from an analysis of the experimental data. For a first approximation, the symmetry between the two nucleons in the c.m.s. makes it possible to put $n_s' = n_s''$. However, for a small number of secondary particles, large fluctuations may be expected, and thus the values of n_s' and n_s'' have been estimated by plotting the integral distribution curve in the c.m.s. (see Fig. 3. The quantity F indicated in the figure represents the ratio of the particles with angles smaller than θ to the total number of secondary shower particles.) From this curve, the values $n_s' = 9$ and $n_s'' = 11$ have been obtained.

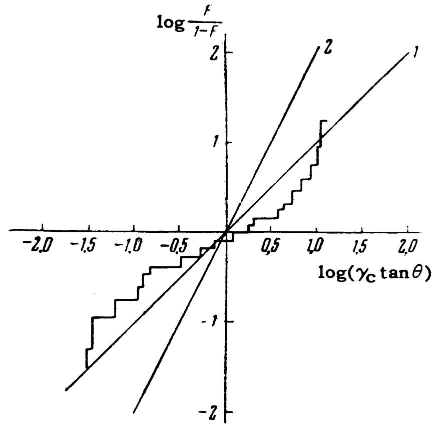

FIG. 3. Integral angular distribution in the c.m.s.

The straight lines 1 and 2 in Fig. 3 correspond to isotropic and anisotropic distributions. It can be seen that the angular distribution in the event investigated cannot be approximated by any straight line, which again indicates a deficiency of particles near the angle $\pi/2$.

For a determination of $\bar{\gamma}$, measurements were made separately for the particles n_s' and n_s''. It was found that

$$\bar{\gamma} = (\gamma_1 + \gamma_2) / 2\sqrt{\gamma_1\gamma_2} = 3.0, \tag{2}$$

where γ_1 and γ_2 are the Lorentz factors in l.s. of the first and second excited nuclei respectively, determined according to reference 3.

The integral angular distribution of shower particles is shown in Fig. 4 separately for each emitting nucleon. The experimental points lie on a

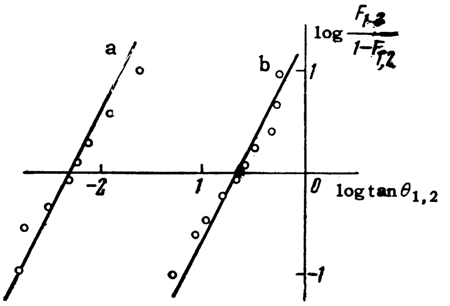

FIG. 4. Integral angular distribution of particles emitted: a – by the first nucleon, b – by the second nucleon.

straight line with slope equal to two, corresponding to an isotropical distribution.

2. THE SOFT COMPONENT

For a study of the soft components accompanying the shower, the cone with an opening angle of 0.06 rad was scanned for about 4 cm from the shower origin. Ten pairs have been detected. The criterion established in reference 10 was used for distinguishing the "associated" and bremsstrahlung pairs. According to this criterion, four "associated" pairs have been detected. The energy of these pairs was determined from the opening angle according to reference 11:

$$\vartheta = \frac{4mc^2}{E}\log\frac{E}{mc^2}, \quad (3)$$

where θ is the pair opening angle and mc^2 is the rest energy of the electron. For two pairs, it was also possible to determine the energy from the relative scattering (see Table).

Distance from the star X, μ	Pair energy from the opening angle E_ϑ, Bev	Pair energy from the relative scattering E_α, Bev	E_{π^0} from E_ϑ, Bev	E_{π^0} from E_α Bev
319	$2.2^{+2.1}_{-0.8}$	—	$4.3^{+4.2}_{-1.5}$	—
5803	$2.2^{+3.2}_{-1.1}$	5.8 ± 0.7	$5.6^{+6.4}_{-2.8}$	11.6 ± 1.5
5929	$1.1^{+1.4}_{-0.6}$	1.5 ± 0.3	$2.8^{+2.8}_{-1.3}$	2.9 ± 0.6
38203	$8.3^{+6.7}_{-3.5}$	—	$16.6^{+13.4}_{-7.1}$	—

For a known number of electron-positron pairs, one can determine the expected numbers of π^0 mesons.[10] (For π^0 mesons in the energy under consideration, the decay mean free path is $\rho = 33\,\mu$.) The value $N(\pi^0) = 3$ (for the narrow cone) has been obtained, which yields a value of the order of 0.4 for the ratio of the number of neutral π mesons to the total number of charged particles in the narrow cone.

The resulting mean energy of π^0 mesons of the narrow cone is

$\bar{E}_{\pi^0} = \left(7.3\ ^{+6.7}_{-3.0}\right)$ Bev- by the opening-angle method

$\bar{E}_{\pi^0} = (7.3 \pm 1.0)$ Bev-by the relative scattering method.

The energies of six particles in the narrow cone were also determined by the relative-scattering method. The average was ~ 4 Bev. This value is of the same order of magnitude as the π^0-meson energy. However, for the transverse momentum, $p_\perp$, one obtains a considerably lower value as compared with the one generally accepted. The disagreement is possibly due to errors in the measurement of secondary-particle energy in connection with the unfortunate geometry.

3. THE SECONDARY INTERACTION

In the scanning, a secondary interaction of the type $0 + 6\,p$ was found at a distance of 3.5 cm from the first star. This interaction was produced by one of the particles of the narrow cone. The event is characterized by a narrow particle jet with a half-angle of two degrees. Strong collimation of the jet particles and their small number indicates the possibility of interpreting this case as a peripheral collision of two nucleons, in which only the incident nucleon was excited (a single π-N collision).[8]

Since, in such a collision, the shower-particle distribution will be symmetrical not in c.m.s. but in the system of the excited nucleons, the angular distribution in the l.s. yields not γ_c but γ', which is the Lorentz factor of the excited nucleons in the l.s. We have found that

$$\gamma' = 19.7\ ^{+9.0}_{-6.1} \text{ by the Castagnoli method}$$

In order to determine the energy of the primary nucleon in the l.s., it is necessary to find E*, the excitation energy of the nucleon in its own system. E* can be determined from curves presented in reference 9 for a known number of shower particles emitted by the excited nucleon. The excitation energy determined in such a way is equal to $E^* = 8\,M$. The energy in the l.s. is

$$E_0 = \gamma' E^* = \left(1.7\ ^{+0.8}_{-0.5}\right)\cdot 10^{11}\ \text{ev}.$$

To strengthen the validity of the above interpretation, the event was tested for a possible N-N collision. For this purpose, assuming the $p_\perp$ of the particle that produced the secondary star to be equal to the generally accepted average value of 0.5 Bev/c, its energy in the l.s. was estimated, and it was found that $E_0 \sim 10^{11}$ ev. This energy value leads to $\gamma_c \sim 7$. This is in sharp disagreement with the value $\gamma_c \sim 20$ determined from the angular distribution of shower particles in the l.s., which should not occur in a head-on N-N collision.

4. DISCUSSION OF EXPERIMENTAL RESULTS

The investigated event has been analyzed assuming a head-on collision of two nucleons and a collision of a nucleon with a tunnel of nuclear matter. However, the angular distribution obtained strongly contradicts the predictions of the theories of Landau and Heisenberg for such collisions. A similar angular distribution with two maxima can be expected in a peripheral collision of two nucleons where both nucleons are excited. In addition, since the probability of a symmetrical distribution for the investigated shower $P(\chi^2) = 92\%$, one should assume that they have an equal degree of excitation. An estimate of the energy of the primary particle by methods presented in references 2 and 3 remains valid, as these methods are correct for all symmetrical stars.

The angular distribution constructed separately for the particles emitted by each excited nucleon is almost isotropic, which, in the energy range under consideration, does not contradict the data presented in the literature[12-14] or the analysis carried out above.

The large number of heavily ionizing tracks N_h can be explained by a mechanism similar to that described in reference 15, namely by an excitation of a nucleus in the interaction of any π meson of the incident nucleon with the nuclear matter in the tunnel (which is possible for $b \sim \hbar/\mu c$). To this assumed interaction, one can also ascribe the 2 – 3 particles having the largest angles in the l.s. The symmetry of the shower then becomes more complete.

The experimental values n_g' and n_g'', within the limits of possible fluctuations, do not contradict the theoretical predictions, nor are the latter contradicted by the experimental value of $\overline{\gamma}$.

Thus, the investigated event can be interpreted as a peripheral collision of a nucleon with a peripheric nucleon of the emulsion nucleus.

The secondary interaction in all probability represents a single π-N collision in a peripheral collision of two nucleons.

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