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INTERACTION OF A HIGH-ENERGY MULTIPLY CHARGED PARTICLE WITH AN EMULSION NUCLEUS

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A unique event of the 16 + 201Z type produced by an interaction between a multiply charged particle with an energy of 3×10^{11} eV per nucleon and an emulsion nucleus was investigated. Because of the high multiplicity of the interaction and the convenient position of the event in the emulsion, it was possible to obtain sufficiently good statistics for the observation of a correlation between the emission angle and the secondary-particle transverse momentum in the small-angle region ($\theta_i < 4°$). A correlation of 0.81 has been found. The transverse-momentum distribution is consistent with that previously obtained for secondary particles produced in nucleon-nucleon and nucleon-nucleus interactions. The mean transverse momentum was found to be 215 MeV/c. The angular distribution is in good agreement with the hydrodynamic theory.

INTRODUCTION

DESPITE the fact that in recent years a large number of studies of multiple production of particles in high-energy nuclear interactions have been made, cases in which the energy of a considerable part of the secondary particles can be determined are still rare. Hence most of the experimental studies have a statistical character. Moreover, cases in which it is possible to analyze the energy characteristics of the secondary particles produced by multiply charged particles have not been investigated.

We chose for detailed investigation an interaction of the type 16 + 201Z. It was found in a systematic scanning for high-energy interactions in a stack composed of 400-μ NIKFI-R emulsion pellicles exposed in a satellite spaceship in August, 1960.

The small dip angle of the primary particle ($\varphi \sim 1°$ in unprocessed emulsion) and the almost central position of the point of interaction in the pellicle permitted measurement of the emission angles of all secondary particles with good accuracy.

The charge of the primary particle, determined from δ-ray measurements was $Z = 9 \pm 1$. The target nucleus was Ag or Br, which was indicated by the large number of evaporation particles.

The observed multiplicity of the interaction is twice as great as the multiplicity expected from Landau's hydrodynamic theory under the assumption that the mass of the incident nucleus is equal to the mass of the target nucleus.[1]

All secondary particle tracks were followed to the point where they left the emulsion or to secondary interactions. A total of 150 cm of relativistic tracks were followed and two secondary interactions were found (θ_i is the angle between the direction of emission of the particle producing the secondary interaction relative to the direction of the primary track):

Type of interaction:	18+10p	35+5p
θ_i:	1°52′	2°16′
E, GeV:	42	3
$p_\perp$, MeV/c:	1340	117

The energies of the particles producing these reactions were determined from the angular distribution of the particles in these interactions. We note that no claim to great accuracy can be made for the transverse momenta determined from secondary interactions either in the present work or in the work published previously. The energies of 30% of the secondary particles were determined by the direct measurement of multiple scattering of their tracks. The large multiplicity of the interaction ensures sufficient statistics, although the fraction of particles with measured energies is not large.

1. MEASUREMENT OF THE ANGLES AND ANGULAR DISTRIBUTION OF SHOWER PARTICLES

The measurements were made on an MBI-8M microscope with an overall magnification of 2700.

The primary particle range in the emulsion pellicle in which the interaction took place was about 1 cm. This permitted a sufficiently accurate determination of the shower axis.

The measurements and calculations of the space angles θ_i formed by each of the shower particles to the extrapolated direction of flight of the primary particle were carried out in the same way as before.[2] All measurements were made twice. Moreover, small angles were measured at two distances, 2000 and 3000 μ, from the interaction center. Careful measurement along with the convenient position of the interaction ensured a high accuracy in the angle determinations.

There are no particles with $Z \geq 2$ in the narrow cone. Consequently, the number of protons among the shower particles is equal to the primary charge. However, only two particles with $Z = 1$ have emission angles θ_i corresponding to the most probable value of the emission angle of the primary nucleons in a disintegration of a heavy nucleus as calculated from the formula [3]

$$(\bar{\theta}^2)^{1/2} = 0.1\,E^{-1},$$

where E is the primary particle l.s. energy in GeV per nucleon. A considerable gap is observed here in the angular distribution between these two particles and the particles following them. All this indicates that an interaction between a large number of nucleons of the incident nucleus and target nucleus probably occurred.

The energy of the primary particle was determined from the angular distribution of the shower particles with the two central particles excluded. The error introduced by the presence of the remaining protons among the shower particles is not important, owing to the large multiplicity of the produced shower. In the determination of the energy from the angular distribution of the shower particles for a nucleon-nucleon interaction we also assumed additionally that the collision between the nuclei can be considered as a superposition of collisions between individual nucleons. The energy of the primary particles in the c.m.s. in units of the rest mass of the interacting particle was determined from the median angle [4] and by Castagnoli's method.[5] The values obtained are in good agreement with one another. The mean value turned out to be $\bar{\gamma} = 12.7 \pm 2.5$. This value corresponds to a primary particle l.s. energy equal to 3.2×10^{11} eV per nucleon.

A histogram of the differential angular distribution of the shower particles produced in the interaction is given in Fig. 1. The large number of secondary particles makes it possible to compare with

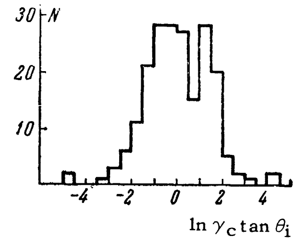

FIG. 1. Differential angular distribution of secondary particles.

good accuracy their angular distribution with the theoretically predicted distributions. The rms deviation determined from the formula*

$$\sigma = \left[\overline{(\lg \operatorname{tg} \theta_i - \overline{\lg \operatorname{tg} \theta_i})^2}\right]^{1/2},$$

for the experimental distribution proved to be $\sigma = 0.59 \pm 0.03$. Hence the observed distribution rather strongly deviates from an isotropic one. The obtained value agrees well with the value found by Lohrmann et al[6] for interactions of multiply charged particles of energy 2.5×10^{11} eV per nucleon and also with the distribution calculated from Landau's theory.[1] Poorer agreement is observed with the calculations of Milekhin,[7] according to which $\sigma = 0.71$.

2. ESTIMATE OF THE SECONDARY PARTICLE ENERGIES

The favorable position of the interaction made it possible to estimate directly the secondary particle energies from measurements of multiple scattering along their tracks.

We used basic cell lengths t = 500 and 250 μ for particles with emission angles θ_i greater and less than 2°, respectively. The measurements were made only on those tracks whose length permitted the necessary number of independent measurements of second differences with an accuracy of up to 70% for the energy measurements. There were 61 such tracks. Recalculation for cell lengths of 500, 1000, and 2000 μ were made by the overlapping-cell technique. For each track, apart from the second differences (D_2) we also calculated the third (D_3) and the fourth (D_4) differences. A check showed that a slight distortion of the second order was present. There was no possibility of measuring the value of spurious scattering with sufficient accuracy. The value of spurious scattering was estimated from the higher-order differences, since the contribution of spurious scattering (D_s) increases with increasing order of the difference for a given cell length. The values of spurious scattering (in microns) obtained for various cell lengths by two methods are shown be-

*lg = log, tg = tan.

low. For the second method we used the multiple-cell technique.

t, μ:	500	1000	2000
D_{2s} from differences above:	0.192	0.250	0.420
D_{2s} from multiple cells:	0.174	0.270	0.500

Quite good agreement was observed between the values obtained by the different methods. As was shown by Chasnikov,[8] the ratios $\rho = D_3/D_2$ and $q = D_4/D_2$ are good indicators of the contribution of Coulomb scattering D_c to the measured second difference D_2. Since the contribution of D_c to the measured value of D_2 increases with the cell length, the values of ρ and q tend to values corresponding to the Coulomb scattering ($\rho_c = 1.22$ and $q_c = 2.0$). Such a change was well manifested in the case of the measured tracks.

The value of D_c for all tracks was estimated on cells with $\rho = 1.6 - 1.3$ from the formula

$$D_c = (1.82D_2^2 - 0.55D_3^2)^{1/2}.$$

The value of D_c was also determined by the multiple cell technique on more than 30 tracks. For the remaining tracks the values of D_c were calculated by the usual method with the use of the foregoing values for D_s.

The particle energy was determined from the formula

$$p\beta c = Kt^{3/2}/\overline{D_c}$$

on two to three cells. The value of the scattering constant K for the corresponding cells was taken from Voyvodic and Pickup.[9] The values of the energies obtained from D_c for different cells estimated by the methods indicated above were in good agreement with one another. For the final value we took their mean. In the case of only two particles we estimated the lower limit of their energy.

The total number of particles N, the number of measured particles N_m, and their mean energy are shown in the table for different angular intervals. Moreover, if we take the energy carried away by each unmeasured particle to be equal to the mean value in the corresponding angular interval, then the lower limit for the primary particle energy is $\sim 2.2 \times 10^{12}$ eV. It was assumed that all particles are pions, that the π^0 mesons carry away an energy equal to half the energy of the charged particles, and that the protons (the two central particles) each carry away an energy equal to 3×10^{11} eV. The value of the primary particle energy obtained in this way is in quite good agreement with the value $\sim 5.7 \times 10^{12}$ eV obtained from the angular distribution.

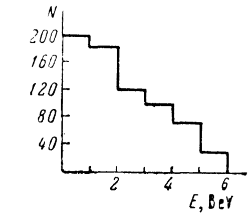

FIG. 2. Integral energy spectrum.

Figure 2 gives the integral energy distribution for all shower particles in the l.s. obtained under the assumption that the energy of the unmeasured particles is distributed in the same way as the measured particles in the corresponding angular intervals.

3. SOFT COMPONENT

A scanning for electron-positron pairs associated with the π^0 mesons produced in the interaction was carried out in two emulsion pellicles: in the pellicle in which the interaction took place and in the neighboring pellicle in the direction of the shower axis. The aim of the scanning for electron-positron pairs was to determine the mean energy of π^0 mesons and to compare them with the mean energy of the charged particles.

It is known that the most accurate method of determining the energy of a pair is based on an estimate of each of its components from multiple scattering measurements of the tracks. We therefore selected such a region in which the multiple scattering measurements could be best carried out. This region proved to lie on one side of the shower axis ($\varphi = 1°48'$) in a plane perpendicular to the emulsion surface. In the plane of the emulsion this region embraced an angle ±5° relative to the shower axis, which corresponded to the

Angular interval, deg	N	N_m	%	$\bar{E}$, GeV	$p_\perp$, MeV/c
0—1	23	10	43.5	4.6	67±7
1—2	34	17	50	4.3	105±5
2—3	20	15	75	3.6	151±7
3—4	19	6	31.6	2.8	173±24
4—27	93	13	14.0	2.0	302±28
>27	12	0	0	—	—
Total	201	61	30.5	—	158±15

maximum projected angle of emission of the particle $\theta_i < \theta_{1/2}$. The search for pairs was carried out over a distance up to one radiation length in emulsion (2.9 cm).

It should be mentioned that the search for the pairs was not made by the usual method involving the complete scanning of a chosen volume of emulsion. We used the following method to scan for pairs. The center of the interaction was placed at the center of rotation of the MBI-8M microscope stage and the shower axis was set parallel to the x direction. Then the search was made over curvilinear arc-strips each 1000 μ from the center of the interaction with the table rotated by $\pm 5°$ relative to the initial position. In these strips we looked for two tracks close to one another ($r \leq 15\,\mu$, i.e., $E \geq 0.5$ GeV) or tracks of double ionization, and when such tracks were observed they were followed to their point of production. To determine the efficiency of this method, in the region close to the interaction, where the probability of missing tracks is the greatest (up to 7000 μ) a second scanning was made every 500 μ, which did not yield any additional events. Owing to the use of this method, the scanning speed was increased by a factor of 10.

In the selected region we found 21 associated pairs. The bremsstrahlung pairs were separated by criteria suggested by Brisbout et al.[10] The energy of the electron and positron were estimated from multiple scattering measurements on their tracks by the methods indicated in Sec. 2. As the basic cell length we took $t = 250\,\mu$. In the determination of the energy we took note of the possibility of radiative energy losses. For ten pairs it proved to be possible to estimate the energy of both the electron and positron and for five pairs we obtained only the value of the energy of one component. The energy of the other component, as well as the remaining six pairs, was not estimated, owing to the small range suitable for measurement. The mean energy of the π^0 mesons in the ten measured pairs was 4.8 ± 1.4 GeV, while if we take into account the incompletely measured five pairs the value is 5.8 GeV. This value of the π^0 energy should be considered as an upper limit, since it was assumed that we always measured the low-energy component of the pair and that the unmeasured component had an energy 1.6 times as great. This was done on the basis of the fact that the mean value of the ratio of the component energies for the ten measured pairs was 1.6.

The mean energy of the π^0 mesons can be compared with the mean energies of the charged particles emitted in the selected volume. Of a total of 37 particles the energies of 32 were determined. The mean energy for the charged particles proved to be 4.2 ± 1.0 GeV. As is seen, good agreement was observed between the mean energies for charged and neutral pions.

Starting from the number of electron-positron pairs observed in the selected region at two different distances from the center and also from the law of "radioactive decay," we calculated the expected number of π^0 mesons. The mean value of the ratio of the number of neutral mesons to charged particles turned out to be

$$N_{\pi^0}/N_{\rm ch} = 0.48 \pm 0.03.$$

The obtained value indicates that the nature of the secondary particles does not differ from that in nucleon-nucleon interactions which is quite understandable.

We followed ~60 cm of electron track and found one true trident.

4. TRANSVERSE MOMENTA OF SECONDARY PARTICLES

The transverse momenta of the secondary particles are of importance for the study of the interaction process at high energies. The value of the transverse momentum is not sensitive to transitions to other coordinate systems. Moreover, experiments have confirmed that the transverse-momentum distribution for the secondary particles remains constant over a wide interval of primary energies, observed multiplicities, and target masses.

The presently available experimental data on the transverse momentum are based on the study of nucleon-nucleon or nucleon-nucleus interactions. It seemed of interest to check this universal property of the transverse-momentum distribution for an interaction of a multiply charged particle with an emulsion nucleus and a multiplicity several times that of the interactions investigated thus far.

As has already been indicated, owing to the good geometrical conditions of the investigated case, we are able to estimate the energy of 61 secondary particles. This made it possible to determine directly the transverse momenta from the formula

$$p_\perp = p_i \sin\theta_i,$$

where p_i is the l.s. momentum of the i-th particle. The experimentally obtained transverse-momentum distribution is shown in Fig. 3 by the dashed-line histogram. A direct comparison of this distribution with the theoretical distributions and the experimental distributions obtained earlier would be unjustified, owing to the clear correlation obtained in

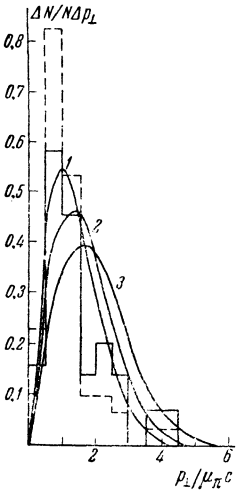

FIG. 3. Transverse momentum distribution. The curves are taken from Kobzev et al[11] (curves 1, 2, and 3 correspond to the mean transverse momenta 196, 224, and 255 MeV/c).

our work between the emission angle and the transverse momentum of the secondary particles in the small-angle region and the different fraction of particles with measured momenta in the different angular intervals (see table).

Owing to the comparatively large statistics in the small-angle region, we were able to determine the mean transverse momenta in intervals of 1° in the 0 – 4° angular region. The correlation coefficient between $p_\perp$ and the angle θ_i proved to be 0.81, i.e., there is almost a linear dependence in this angular region between the transverse momentum and the emission angle. We cannot say anything about the value of the correlation of the transverse momentum for angles >4°, owing to the small number of measured momenta in this region. The correlation between the transverse momentum and the emission angle is shown in Fig. 4. The arrows attached to the points at the edge of the figure indicate that they refer to larger values of θ_i.

In experiments at the Nuclear Physics Institute, Academy of Sciences, Kazakh S.S.R.[11,12] attempts were made to observe a correlation between the transverse momentum of the secondary particles (protons and pions) produced by 9-GeV protons. However, the correlation coefficient was found to be rather small ($r_p = r_\pi \leq 0.3$). In all probability this was due to the fact that, in the small-angle region, in which a tendency for the transverse momentum to increase with the angle θ is expected, there is only one averaged point in those experiments. It is of interest to note that the mean value of the transverse momentum obtained by us for the angular interval 0—6° proved to 136 MeV/c, which is in good agreement with the corresponding value in [12].

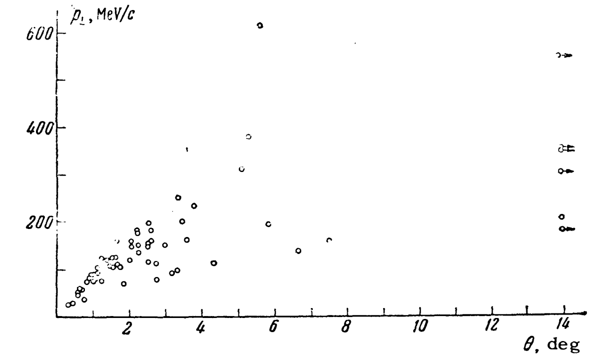

FIG. 4. Correlation between the transverse momentum and the emission angle of the particle.

The solid line in Fig. 3 represents the histogram for the transverse momentum distribution with allowance for the fraction of particles with unmeasured momentum in the different angular intervals. It was assumed that the transverse momentum distribution of the unmeasured particles in the given angular interval is identical with the distribution of the measured particles. The curves in the figure represent the functions

$$\Delta N / N \Delta p = c p_\perp \exp(-p_\perp^2 / b^2),$$

determined in [12] as a satisfactory approximation of the experimental transverse-momentum distribution in nucleon-nucleon and nucleon-nucleus distributions for primary particles of energy 10^{10} – 10^{11} eV. As can be seen, the obtained distribution agrees well with curve 1 calculated under the assumption that $\bar{p}_\perp$ = 196 MeV/c. The mean value of the transverse momentum with allowance for the different fraction of measured particles in the various angular intervals was found to be $\bar{p}_\perp$ = 215 MeV/c. Values greater than 610 MeV/c were not observed.

In conclusion, the authors take this opportunity to express their gratitude to Professor N. L. Grigorov and I. A. Savenko for kindly providing the exposed emulsion stack for the experiment and for discussion of the obtained results and also to F. A. Avetyan for performing part of the measurements.

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