EMULSION STUDY OF THE INTERACTION BETWEEN 8.7-Bev PROTONS AND QUASI-FREE NUCLEONS

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The angular and momentum distributions of protons and π mesons from stars produced by 8.7-Bev protons in photographic emulsion and containing no more than one gray and one black track are investigated. It is shown that most stars of this type can be regarded as resulting from inelastic interactions between the proton and a free or quasi-free nucleon. Interactions of this type comprise $\sim 25\%$ of the total number of inelastic interactions with nuclei of the emulsion. The angular and momentum distributions of the protons and mesons (in the nucleon-nucleon c.m.s.) are compared with the predictions of the peripheral[12] and central[1,10,11] interaction theories. It is shown that part of the interactions with quasi-free nucleons (about 20%) cannot be ascribed to peripheral interactions, mainly because of the large emission angles and large transverse momenta of the secondary protons. Nevertheless, the characteristics of most of the cases agree with the properties expected for peripheral interactions.

In a previous experiment,[1] we studied the angular distributions of secondary particles in stars produced by the interactions between 8.7-Bev protons and emulsion nuclei. It was shown that an appreciable part of such stars (at least 15%) are characterized by a narrower angular distribution of the particles in comparison with the predictions of the theory of central interactions with one nucleon, and even more so with several nucleons. It was noted that these interactions are apparently peripheral nucleon-nucleon interactions. In the present study, we investigated the energy and angular characteristics of different kinds of particles emitted in interactions of the nucleon-nucleon type.

1. EXPERIMENTAL METHOD

In this work, we used part of an emulsion stack (stack No. 13, NIKFI-BR emulsion) of 10×10 cm pellicles exposed to the 8.7-Bev proton beam at the Joint Institute for Nuclear Research.

The basic problem of the experiment was to study the energy and angular distribution of secondary particles in interactions between the incident nucleon and a free or quasi-free nucleon. By interactions with a quasi-free nucleon we have in mind those in which only a very small part (< 2%) of the primary energy in the laboratory system is transferred to other nucleons of the same nucleus.*

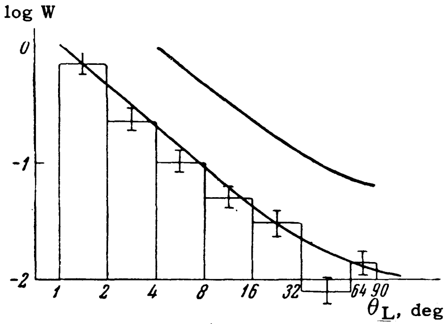

FIG. 1. Probability W of finding tracks with a minimum length L_{min} in one emulsion pellicle (histogram – experimental data; solid lines – calculated results; upper curve represents L_{min} = 2 mm, and lower curve L_{min} = 10 mm). Geometrical correction $k_g = W^{-1}$.

About 2000 stars were found as a result of the scanning of the emulsion pellicles (mainly by scanning along the tracks of the primary proton beam and only partially by area scanning). From these stars, we selected 330 stars of different types which contained tracks flat enough so as to permit accurate measurements of the particle momentum (p) and ionization (I).

*Such a definition practically excludes not only central collisions but also peripheral collisions with other nucleons.

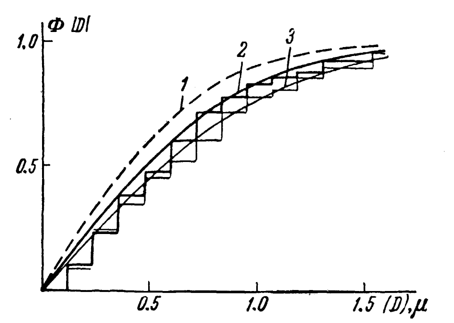

FIG. 2. Integral distribution of second differences of the coordinates from measurements of primary proton beam tracks (2) for a cell length of 2000 μ. Shown for comparison are the corresponding distributions for Coulomb scattering (1) at 9.2 Bev/c and for a group of secondary particles (3) of measured momentum greater than 6 Bev/c.

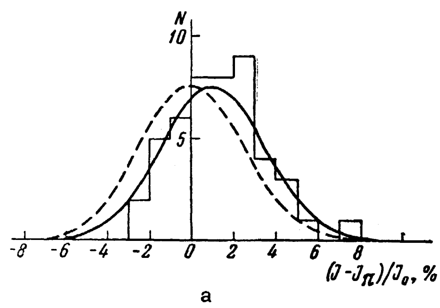

FIG. 3a. Results of measurements of relative ionization for π mesons in the region of the minimum of the ionization vs. momentum curve ($p\beta = 0.4 - 0.8$ Bev/c). Taken as the zero value of the axis of abscissas is the theoretical value of the ionization for π mesons at the position of the minimum.

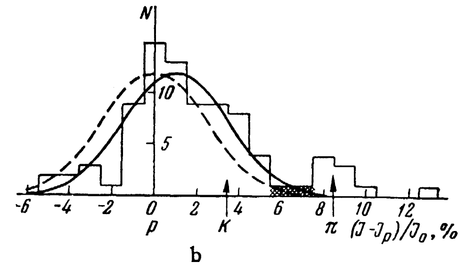

FIG. 3b. Results of measurements of the relative ionization for particles of momenta $p\beta > 2.5$ Bev/c. Taken as the zero value on the abscissa axis is the theoretical value of the ionization for a proton of this momentum (also shown are the positions of the maxima of the corresponding curves for K and π mesons).

We determined (as a function of the laboratory space angle θ_L) the geometrical correction k_g necessary for the analysis of all angular and momentum distributions (see Fig. 1). The corrections for fast and slow particles were different (curves 1 and 2, respectively). It should be mentioned that the very strict selection criteria as regards the dip angle δ of the fast tracks which were to be measured (length $L \geq 1$ cm in one pellicle, which corresponded, on the average, to angles $\delta \leq 1°$) were dictated by the very strong dependence of spurious scattering on the angle δ as was observed by us in some pellicles.

The statistical error of the momentum measurements was, as a rule, 25%; spurious scattering and "noise" were determined from measurements on primary proton tracks (in the same pellicle). The results of such measurements are shown in Fig. 2. In the region of the greatest momentum (≥ 6 Bev/c), where it was difficult to take into account spurious scattering in individual cases, we usually resorted to a statistical treatment of the data for a group of tracks; the mean value of the momentum of such particles was 7.5 Bev/c.

The total error in the measurement of the relative ionization I/I_0 on secondary particle tracks (with respect to primary beam tracks at the same place in the pellicle) was estimated as $\sim 2\%$, which is confirmed by the spread in the values of I/I_0 for π mesons in the region of the ionization curve minimum (Fig. 3a). In all cases the measurements were repeated. The particles were identified with the help of the curves of Barkas.[2]

In the region bordering on the point of intersection of the proton and π-meson curves ($p\beta = 1.5 - 2.5$ Bev/c), where it is not possible to identify the particles with the required accuracy, we made a statistical analysis of the sign of the charge of the particles based on the study of the magnetic deflection in the field of the accelerator.[3] We thus obtained the ratio $N_+ : N_- = 1.50 \pm 0.50$.

As additional information, we used data obtained by electronic methods at the Joint Institute for Nuclear Research* concerning the composition of a beam of positive charged secondary particles for the angle $\theta_L = 1°$, momentum $p = 2.25$ Bev/c, and a copper target, and for $\theta_L = 3°$, $p = 2.9$ Bev/c and a beryllium target; in both cases the ratio of the number of π^+ mesons to the number of protons was $N_{\pi^+} : N_p \approx 0.8 : 1$. If we take into account the values for $N_+ : N_-$ and $N_{\pi^+} : N_p$, we obtain for the ratio of the number of mesons of both signs to the number of protons $N_{\pi\pm} : N_p = 3 : 1$.

Figure 3b shows the distribution of the relative ionization for secondary particles of momentum $p\beta > 2.5$ Bev/c. It is seen that in the great majority of cases, π mesons are well-separated from protons. (In the figure, the "zone of indetermi-

*The authors thank M. F. Likhachev, V. S. Stavinskiĭ, Hsu Yun-Ch'ang and Chan Nai-Sen for permission to use the results of their measurements prior to publication.

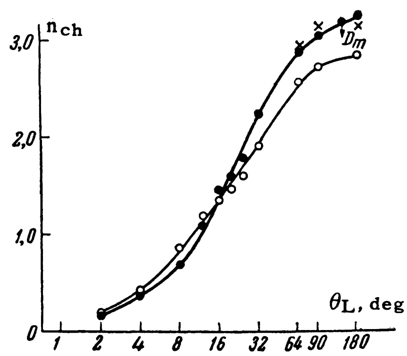

FIG. 4. Angular distribution of relativistic or gray tracks n_{ch} (in lab system) for stars of type $n_b \leq 1$, $n_g \leq 1$ (without elastic scatters): ● – pp interactions (69 stars with even values of $n_s + n_g$), ○ – pn interactions (58 stars with odd values of $n_s + n_g$). Points indicated by crosses were calculated from the requirement of symmetry in the c.m.s. distribution with respect to the angle 90° (for even values of $n_s + n_g$). Here, and in the figures which follow, the arrow indicates the allowable deviation for the 95% confidence level (D_m) according to the Kolmogorov test.

nacy'' in which the probabilities of identifying particles as protons and π mesons differ by a factor less than three, is shown cross-hatched.)

2. SEPARATION OF INTERACTIONS WITH QUASI-FREE NUCLEONS

The usual procedure for separating interactions with individual nucleons of the emulsion nuclei (see, for example, reference 4) involves the selection of events in which the nucleus as a whole does not experience any visible excitation (including β decay in the case of pp interactions). Usually, about 10% of all interactions observed in emulsion are selected in this way. An additional, although weak, ''sifting out'' of non-nucleon interactions is made by the application of the modified kinematical criterion of Birger and Smorodin[5] based on the laws of conservation of energy and momentum of all particles before and after the interaction. In individual cases, however, this criterion is a necessary condition, but is far from satisfactory, owing to the scanty information on the energy characteristics of all the interaction products.

On the other hand, whenever we have to do with a statistical analysis of data on a comparatively large number of interactions, it turns out to be possible to limit ourselves to the kinematical criterion, which, under some quite natural assumptions, changes, generally speaking, from a necessary into a necessary and sufficient condition. Actually, we assume that it is possible to find some characteristic, in particular, a small number of black and gray tracks, which distinguishes interactions with a ''target'' mass quite close to the mass of a nucleon. Since there are no targets with a mass smaller than that of a nucleon, one can then also calculate the upper limit of a possible ''contamination'' of interactions of a non-nucleon type in the group of interactions.

The method employed by us to determine the average mass of the ''target'' $\overline{M}_T$ from data on the angular and momentum distribution of the secondary mesons and protons was based on the relation

$$\overline{n_N (E_L - p_L^{\parallel} c)} + k_0 \overline{n_{\pi\pm} (E_L - p_L^{\parallel} c)_{\pi\pm}} = 1.05\, M_N c^2, \quad \text{(1a)}$$

where n_N and $n_{\pi\pm}$ are the numbers of secondary nucleons and charged π mesons having a given value of the quantity $E_L - p_L^{\parallel} c$, which is the difference between the total energy and the longitudinal momentum in the laboratory system; $k_0 = 1.5$* is a coefficient taking into account (on the average) neutral mesons; M_n is the nucleon mass. Here it was assumed that the average energies and the longitudinal momenta of the charged and neutral nucleons (or, correspondingly, mesons) are the same. The quantities $(\overline{E}_L - \overline{p}_L^{\parallel} c)_p$, $(\overline{E}_L - \overline{p}_L^{\parallel} c)_\pi$, and $\overline{n}_{\pi\pm}$ can be determined from an analysis of the angular and energy characteristics of π mesons and protons. In order to obtain more accurate angular distributions, we made use of the data (see Fig. 4) obtained in a previous work[1] for 127 stars of the type $n_b \leq 1$ and $n_g \leq 1$ found without any bias and not including cases which can be regarded as elastic scattering of the primary proton (see below).

As seen in Fig. 4, the character of the angular distribution for 69 stars with an even number of shower (n_s) and gray (n_g) tracks is in agreement with the assumption that the angular and momentum distributions of protons and mesons are symmetric about the angle $\theta_0 = 90°$ in the nucleon-nucleon c.m.s. for pp interactions.† If it is assumed that there is full symmetry of the angular and momentum distributions for both protons and mesons (relative to the angle $\theta_0 = 90°$), then, after summation of symmetric particles by pairs, relation (1a) becomes equivalent to a c.m.s. energy balance:‡

*In particular, the closeness of k_0 to 1.5 is confirmed by the appropriate statistical-theory calculations made by V. M. Maksimenko for the case of central interactions.

†At the same time, for odd values of $n_s + n_g$ (pn interactions) there is a very marked asymmetry evidently connected with the asymmetry in emission of protons.[4]

‡Omitted from relation (2) is that small part of the energy which can be released in a nuclear disintegration in accordance with the foregoing definition of a quasi-free nucleon of the target.

$$\overline{n}_N\overline{E}_{0p} + k_0\overline{n}_{\pi\pm}\overline{\varepsilon}_{0\pi} = 2\gamma_c M_N c^2. \qquad (2)$$

Here $\overline{E}_{0p}$ and $\overline{\epsilon}_{0\pi}$ are the mean c.m.s. energies of the protons and mesons, respectively, which can be determined experimentally by means of the momentum and angular characteristics of the particles in the forward cone. As will be seen from what follows, the value of $\overline{n}_N$ obtained by us with the aid of relation (2) is 2.0 ± 0.2, which corresponds to a possible mixture of collisions with two nucleons ($n_N = 3$) of up to 20%.

Hence the selection of stars on the basis of a small number of black ($n_b \leq 1$) and gray ($n_g \leq 1$) tracks separates interactions characterized by an average "target" mass close to M_N. The total number of such interactions is then ~ 25% of all interactions with emulsion nuclei. On this basis, one can calculate that the ratio of interactions of type pp to pn in these stars should be ~ 1.2. It should be noted that for stars with $n_b = 2.3$ (with $n_g \leq 1$) the average mass of the target already turns out to be significantly greater than M_N, and, at the same time, the departure from symmetry relative to the angle $\theta_0 = 90°$ in the angular distribution is quite marked.

In the analysis of stars with a small number of particles, both slow and fast ($n_s + n_g$), a certain role can, generally speaking, be played by a mixture of cases of elastic scattering, whose cross section[6] is ~ 85% of the cross section for inelastic interactions of protons with light and heavy emulsion nuclei. However, only a small part of the cases of elastic scattering (< 2%) involves a deflection of the proton by an angle $\theta_L \geq 1.5°$ with respect to the primary particle, and therefore the discarding of all cases in which the proton is deflected by an angle $\theta_L \leq 1.5°$ ensures a practically complete elimination of cases of elastic scattering.

As regards weak excitation of the residual nucleus associated with the presence of one black track, and sometimes even a recoil nucleus, this can evidently be made to agree with the obtained target mass M_N (on the average) if one takes into account the presence of internal (Fermi) motion of the quasi-free nucleons involved in the interactions with the primary particles. Indeed, as a result of the interaction, the residual nucleus should acquire a recoil momentum equal in magnitude, but of opposite sign, to the momentum of the nucleon leaving the target. For light nuclei, the rms value of this momentum is ~ 350 Mev/c.

We compared the estimate obtained above for the fraction of collisions with quasi-free nucleons in emulsion nuclei (~ 25%) with existing information on the character of the proton distribution in nuclei.[8] To do this, we assumed that the distributions of neutrons and protons coincide. Furthermore, instead of the optical model usually employed for the calculation of the transparency of nuclei, we used the rougher model of successive collisions with nucleons encountered along a chord of length determined by the collision parameter (with a subsequent averaging over the collision parameters).

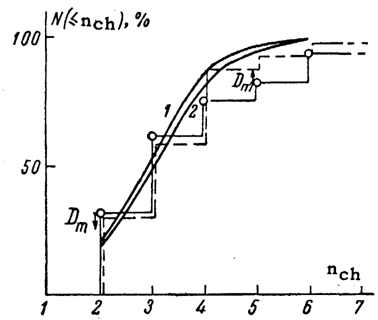

FIG. 5. Integral distributions of the number of charged products per star ($n_{ch} = n_s + n_g$). The solid-line histogram represents the experimental results of the present work; the dashed-line histogram represents the results obtained in reference 14. Curves 1 and 2 are the theoretical results for peripheral[12] and central[1,11,12] interactions, respectively.

On the basis of a similar model, we calculated the cross sections for inelastic interactions and the total cross sections for emulsion nuclei with the aid of the corresponding cross sections for the elementary processes: $\sigma_{inel} = 25$ and $\sigma_{tot} = 33$ mb.* The results of the calculations agree with good accuracy (5 — 7%) with the corresponding results of Barashenkov[9] obtained with the optical model of the nucleus.

Using the same model for the calculation of the number of collisions with one nucleon, we obtained estimates of 45 and 42%, respectively, of the cross sections σ_{inel} and σ_{tot} (interactions with two nucleons constitute ~ 20%). If we impose the additional condition that the secondary particles produced in the first interaction do not encounter any nucleons in their paths, we then estimate that 30% of the interactions take place with one nucleon.

3. ANGULAR AND MOMENTUM DISTRIBUTIONS OF PARTICLES IN INTERACTIONS WITH QUASI-FREE NUCLEONS

For the selected stars of type $n_b \leq 1$, $n_g \leq 1$ in which we identified and measured ~ 80 particles and which could be considered mainly as nucleon-

*Later measurements recently made at CERN (private communication) indicate that it is more correct to take the value $\sigma_{inel} = 30$ mb and $\sigma_{tot} = 38$ mb.

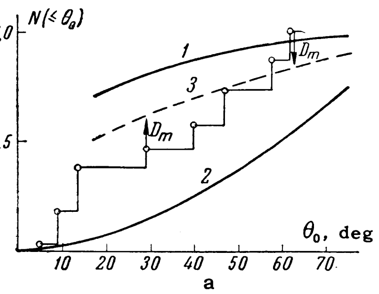

FIG. 6a. Integral c.m.s. angular distribution for protons. Curves 1 and 2 are the theoretical distributions for peripheral[12] and central[1,11,12] (isotropy) interactions; curve 3 is the distribution for a mixture of interactions of both types (70% N_{periph} + 30% N_{centr}).

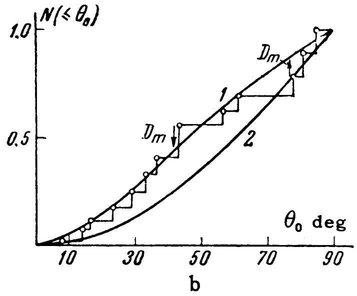

FIG. 6b. Integral c.m.s. angular distribution for π mesons. The notation is the same as in Fig. 6a.

nucleon interactions, the following characteristics were studied: 1) the distribution of the number of shower and gray tracks ($n_{ch} = n_s + n_g$) per star; 2) the c.m.s. angular distribution of protons and mesons; 3) c.m.s. total and transverse momentum and energy distributions for protons and mesons; 4) dependence of the mean momentum of the particles on the c.m.s. angle of emission. The greater part of these characteristics were compared with theoretical calculations based on two extreme assumptions as regards the interaction mechanism: a) central interaction of nucleons with the formation of a single excited system with zero angular momentum;[1,10,11] b) interaction of the peripheral type characterized by the exchange of one meson between the colliding nucleons.[12]

1. The integral distribution of the number of relativistic and gray tracks n_{ch} for $n_{ch} \geq 2$ is shown in Fig. 5.* As seen from the figure, the n_{ch} distribution is not a sufficiently sensitive characteristic for separating central and peripheral interactions. Along with the agreement of the experimental data ($\bar{n}_{ch} = 3.1 \pm 0.2$) with the mean multiplicity expected in the case of central and peripheral interactions (3.4 and 3.2, respectively), it should be noted that a considerable part of the stars with $n_{ch} > 6$ (constituting 5% of all cases) can in no way be explained by single collisions, and they should probably be ascribed chiefly to double inelastic interactions of nucleons in the nucleus. Moreover, the ratio of the number of stars with even n_{ch} to the number with odd n_{ch} 69 : 58 is in good agreement with the estimate given above for the relative numbers of pp and pn interactions.

2. The proton and meson angular c.m.s. distributions (in the forward hemisphere) are given in Figs. 6a and 6b, respectively. In the case of the former, the (π, p) particles, not identifiable directly, were not included because the angle θ_0 was not determined for them with sufficient accuracy.

It is seen from Fig. 6a that there is a considerable excess of protons in the small-angle region as compared to an isotropic distribution. If it is assumed that the observed interactions are a mixture of peripheral and central collisions with an isotropic distribution, then we can obtain satisfactory agreement with experiment for a "mixture" in which 50 to 70% are peripheral processes, where the "allowable" level of statistical fluctuations is estimated on the basis of the Kolmogorov test.* The meson angular distribution (Fig. 6b) agrees with the view of a purely peripheral character of all interactions, although the difference between peripheral and central collisions in this case is very weak. At the same time, the anisotropy in the proton angular distribution in this case proves to be distinctly less than in the case of the interactions studied (by other selection criteria for nucleon-nucleon interactions) in the experiment by the group at the Joint Institute for Nuclear Research.[14]

It should also be noted that under selection criteria permitting interactions with two and more black tracks in a star, which is a less strict condition than the criteria used by us, the extent to which the protons and mesons tend to be emitted forward (in the nucleon-nucleon system) again increases, despite the appreciably greater mass of the target as compared with the mass of a nucleon.

3. The integral c.m.s. momentum distributions for protons and π mesons (in the forward cone)

*The restriction $n_{ch} \geq 2$ is connected with the fact that a certain part of the stars with $n_{ch} = 1$ can be related to the process of diffraction production of π mesons.[13] However, in the determination of the mean value of n_{ch}, we also included cases with $n_{ch} = 1$.

*Formulas obtained by Gnedenko and Korolyuk[15] show that this test enhances the role of statistical fluctuations if the number of observed events is not sufficiently large.

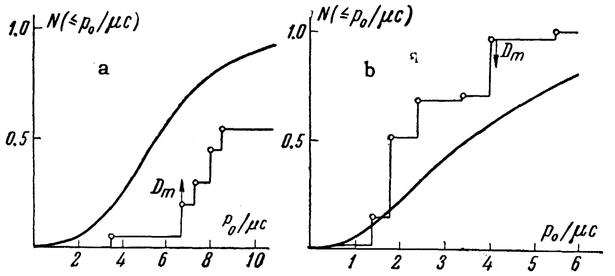

FIG. 7. Integral c.m.s. momentum distributions for protons (a) and π mesons (b) (in units of μc, where μ is the π-meson mass). Solid curve – theoretical distributions[11] for central interactions [the (π, p) particles are not included in case a].

are shown in Figs. 7a and 7b, respectively. Also shown there are the results of the statistical theory of central collisions. From a comparison of experiment with theory, one can conclude that, among the observed interactions, no more than 30 – 40% are central. The mean proton momentum is 1150 ± 110 Mev/c, which is practically no different from the data reported by Wang Shu-Fen et al;[14] the meson momentum (340 ± 55 Mev) proved to be approximately 25% lower. It should be borne in mind that the data of Wang Shu-Fen et al.[14] are based primarily on measurements of particles in the backward cone.

Finally, Figs. 8a and 8b give the integral distributions of the proton and meson c.m.s. transverse momentum $p_\perp$. Also given are the theoretical distributions obtained from the theory of central[1,10,11] and peripheral[12] interactions.* From a comparison of experiment with theory for the percentage of central collisions from the proton data, one obtains a lower limit of ~40% and from the π meson data one obtains an upper limit of ~40%. It should be borne in mind, however, that in this case the meson distribution provides a more sensitive criterion for estimating the percentage of central collisions, for the latter differs from peripheral collisions both in the larger momenta and larger angles of emission of the mesons, while for protons the higher momentum values can be offset by the narrower angular distribution of the particles in the case of peripheral interactions.

The latter characteristic of the proton distributions provides an additional possibility of estimating independently the percentage of peripheral interactions. In fact, according to the calculations of Chernavskii,[12] 70% of the recoil protons emitted backward in the c.m.s. should be gray tracks, while such tracks should be practically absent in the case of central interactions. Experiment shows that stars with $n_b \leq 1$, $n_g \leq 1$ have gray tracks at an angle $\theta_L \leq 90°$ in (25 ± 2.5) % of the cases; the overwhelming majority of these are proton tracks. If it is assumed that the number of slow recoil neutrons and protons is the same, one can then readily calculate an upper limit of ~ 80% for the frequency of peripheral interactions, while the lower limit is 60 – 65%.

4. The connection between the mean momentum of the particles p_0 and their c.m.s. angle of emission θ_0 has the following form:*

	θ_0	$\bar{p}_0/\mu c$	θ_0	$p_0/\mu c$
Protons†	0—20°	9.8 ± 1.8	30—90°	7.2 ± 0.7
π mesons	0—20°	3.9 ± 0.5	20—90°	2.1 ± 0.2

As seen from the data, there is a dependence of the momentum p_0 on the angle θ_0, which indicates that the degree of anisotropy of the c.m.s. angular distribution increases, especially for mesons, with an increase in the momentum. It turns out that for mesons such a dependence is more marked in the case of low multiplicity where $n_{ch} \leq 4$.‡

The mean values of the quantities considered above, with an estimate of their accuracy, and comparison with the corresponding theoretical results are given in the table.

The above-mentioned dependence of the momentum p_0 on the angle of emission of the particle θ_0, and, consequently, on θ_L is comparatively weak; for the other investigated quantities $p_\perp$ and θ_0 the dependence on θ_L is considerably stronger, especially for protons. This leads to a situation in which it is very important to introduce geometrical corrections in the distributions of $p_\perp$ and θ_0 and also in the calculation of the corresponding mean values and the errors involved in their determination, while for the distribution of p_0 the geometrical factor has no special significance.**

*It is assumed here that the angular distribution is isotropic for central interactions.

*We note that, for particles with c.m.s. velocities $\theta_0 \geq 0.8$, the same dependence will occur, to a good approximation, in the laboratory system.

†Without (π, p) particles.

‡A similar picture was observed[16] for secondary π mesons in a study of 7-Bev π-meson interactions with nucleons; the anisotropic part of the c.m.s. angular distribution was due almost entirely to the fastest mesons (c.m.s. energy ≳ 0.5 Bev); this group of particles was quite distinct mainly in stars with a small number of prongs.

**The influence of the geometrical corrections on the accuracy of the determination of the mean values was considered quantitatively by M. I. Podgoretskiĭ, to whom the authors express their gratitude for acquainting them with the appropriate formulas.

	Protons			π Mesons		
		theoretical			theoretical	
	exptl.	periph.	centr.	exptl.	periph.	centr.
Mean c.m.s. emission angle $\overline{\theta}_0$, deg	24 ± 5	–	57?	51 ± 11	46	57?
Mean c.m.s. momentum $\overline{p}_0/\mu c$	8.2 ± 0.8	–	5.6	2.4 ± 0.4	–	4.0
Mean total c.m.s. energy $\overline{\varepsilon}_0/\mu c$	10.8 ± 10%	–	–	2.6 ± 15%	–	–
Mean transverse momentum $\overline{p}_\perp/\mu c$	4.1 ± 0.6	2.3	5.3	1.5 ± 0.2	–	3.15

In the analysis of the experimental data for the mean values of momentum and energy shown in the table, it is necessary to bear in mind the following. First, if one carries out an averaging of the values of p_0 without recourse to the introduction of geometrical corrections in the limits of sufficiently wide angular intervals (θ_L = 0 – 4, 4.5 – 11, and 11.5 – 24°), then the mean values of the meson and proton energies and momenta increase by only 2 and 1%, respectively, but the estimates of the statistical errors decrease to $^2/_3 - ^1/_2$ of their corrected value. Second, the same quantities can be averaged under the assumption (as was done in reference 15) that all (π, p) particles not identified directly are π mesons; in this case, the mean energy of the π mesons and protons increases by another 1.5 – 2%. Finally, if we also take into account the mean number of π mesons per interaction, namely 2.8, and use the energy balance (2), we can determine the mean number of secondary nucleons per star, and thus obtain the mean mass of the target $\overline{M}_T$ and the possible percentage of interactions with two nucleons inside a nucleus. One must only keep in mind the fact that relation (2) does not take into account the energy carried off by K mesons, which constitutes, according to rough estimates, about 10 – 15% of the energy of the π mesons.

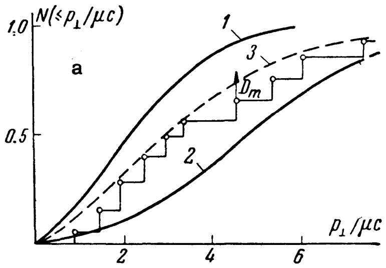

FIG. 8a. Integral distribution of proton transverse momentum. Curves 1 and 2 are the theoretical distributions for peripheral[12] and central[1,10,11] interactions; curve 3 is the distribution for a mixture of interactions of both (60% N_{periph} + 40% N_{centr}).

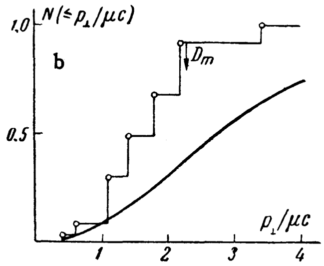

FIG. 8b. Integral distribution for π mesons. The curve represents the theoretical distribution for central interactions.[1,10,11]

In the end, it turns out that the experimental data agree with a relative target mass of unity ($\overline{M}_t = M_N$), but the experimental error permits a value up to 1.2 M_N, which corresponds to a mixture in which 20% of the interactions involve two nucleons in a nucleus. Use of the earlier data on the number of stars of large multiplicity ($n_{ch} \geq 7$) gives approximately the same estimate of the upper limit for the number of inelastic interactions with two nucleons. However, both these estimates apparently give too high a value, since the mean multiplicity of the stars in which the secondary proton has a large transverse momentum ($p_\perp \geq 4\mu c$) does not differ by more than 15% from the multiplicity of the remaining stars.

Besides the value of $\overline{p}_0$ for nucleons and mesons, three quantities closely connected with it are of interest: the inelasticity of the interaction in the c.m.s. (K_0) and in the laboratory system (K_L), and the mean fraction of the initial energy carried away by one fast nucleon ($\overline{\alpha}$). For the stars of type $n_b \leq 1$, $n_g \leq 1$ studied by us $K_0 = 0.43 \pm 0.06$, $K_L = 0.31 \pm 0.04$,* $\overline{\alpha} = 0.55 \pm 0.05$.

The last quantity can be compared with the mean free path for the absorption of nucleons Λ_N, known

*In the determination of K_0 and K_L we took into account only the energy carried off by π mesons.

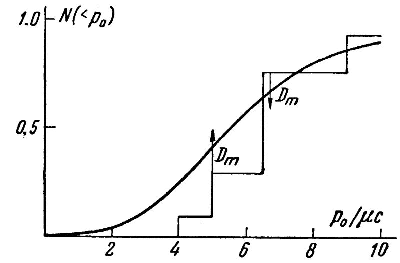

FIG. 9. Integral c.m.s. momentum distribution for protons with angles of emission $\theta_0 = 30 - 150°$. Solid line – theoretical distribution for central interactions.[11]

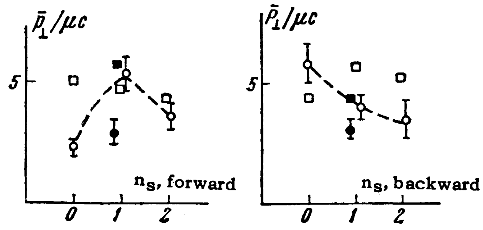

FIG. 10. Dependence of the mean transverse momentum of protons on the number n_s of other charged particles emitted in the forward and backward hemispheres in the c.m.s. (the circles indicate the experimental data and the squares, the theoretical data). Shown separately for $n_s = 1$ are cases with angles of emission $\theta_0 \leq 20°$ (● – experiment, ■ – theory) and angles of emission $\theta_0 > 20°$ (○ – experiment, □ – theory).

for light nuclei from cosmic-ray experiments,[17] namely $(\Lambda_N)_{air} = 125$ g/cm^2. If it is considered that for a nucleon energy spectrum of the form $E^{-\gamma}$ it is the values of α^γ and not the values of α that are averaged, while the mean free path for the interaction is $\Lambda_{air} = \Lambda_N(1 - \overline{\alpha^\gamma}) = 80$ g/cm^2. and also that approximately 35% of the collisions with light nuclei can have the character of two successive collisions with one nucleon, then the agreement between the value $(\Lambda_N)_{air}$ and the value we obtained for $\bar{\alpha}$ proves to be quite satisfactory.*

4. ANALYSIS OF SOME CORRELATIONS AND THE POSSIBILITY OF SEPARATING PERIPHERAL AND CENTRAL INTERACTIONS

For the separation of nucleon-nucleon interactions selected by one or another method into interactions of different types, it may prove highly advantageous to study various types of correlations.

First of all, from the statistical theory of central interactions it necessarily follows that there is a rather high probability that a momentum close to the value of the initial momentum of each of the colliding nucleons is transferred to the secondary particles. Such a transfer could lead to a situation in which one of the nucleons changes its direction of motion by more than 90° (in the c.m.s.) as a result of the collision and both appear in the same hemisphere. It should be kept in mind that the transfer of a large longitudinal momentum to one of the stationary nucleons of the nucleus cannot, generally speaking, take place in the case of two successive collisions of the peripheral type. Therefore the observation of two high-energy nucleons in one star can be an indication of the existence of central interactions even when there is no doubt as to the single-nucleon character of the collision. Among 140 stars of the type $n_s \leq 4$, $n_g \leq 1$ studied by us, we observed ten cases of simultaneous emission of two fast identified particles at angles $\theta_0 < 90°$ in the nucleon-nucleon c.m.s; in three of the cases, both particles were nucleons and in seven cases one of the particles was a nucleon and the other a π meson or (π, p) particle. Since K mesons constitute only ~10% of the number of π mesons, it is unlikely that in all three cases at least one of the particles considered to be a nucleon was a K meson.

Comparison of various correlations with the theoretical expectations can be carried out rather conveniently if the theoretical results are represented in the form of "artificial stars," i.e., a set of randomly selected characteristics of stars satisfying all the required conservation laws.[11] We studied one such correlation by analyzing the momentum distribution of protons emitted at angles $\theta_0 = 30 - 150°$, since in the case of peripheral collisions most of the nucleons (> 80%) are emitted at angles $\theta_0 \leq 30°$ (or $\theta_0 \geq 150°$); it can then be expected that, in the chosen angular interval, the momentum distribution will be determined only by central collisions. The experimental data (see Fig. 9) agrees with what is expected, although the large statistical fluctuations do not permit reliable conclusions on the relative number of central collisions.

On the other hand, one can consider the transverse momentum distribution for protons for eight stars with one gray track (with $n_b \leq 1$) among which there should be practically no central interactions. It turns out that only in one case does the value of $p_\perp$ exceed 2.5 μc, although among all the stars with $n_b \leq 1$, protons with $p_\perp > 2.5$ μc are encountered in 60% of the cases.

Furthermore, we considered the correlation between the proton transverse momentum $\bar{p}_\perp$ and

*In his calculations, Grigorov[17] took $\Lambda_{air} = 60$ g/cm^2, which, under additional assumptions on the character of the distribution of the quantity α, led to the value $\bar{\alpha} = 0.7$ for the interaction of a nucleon with an air nucleus.

the number (and also angles of emission) of other charged particles emitted either in the same hemisphere as the proton (in the c.m.s.) or in the opposite hemisphere (see Fig. 10). As seen from the analysis of Fig. 10, the correlation between $\bar{p}_{\perp}$ and the number of particles in one hemisphere proves to be considerably stronger than that obtained from the statistical theory of central collisions.

A visible correlation between the transverse or total momentum of the proton and the number of other charged particles (in a given angular interval) has a direct bearing on the asymmetric shower effect considered by Dobrotin et al.[18] for nuclear-active particles with a mean energy of the order of 300 Bev. Indeed, small values of the target masses for one of the colliding nucleons should inevitably be accompanied by a small momentum transfer to this nucleon, while the other nucleon, producing the basic part of the shower, can then considerably change its initial momentum, both longitudinal and transverse.

An asymmetry in the angular distribution of the produced particles was also observed in the emulsion stars studied by us: thus, for example, among 22 stars with $n_{ch} \geq 5$, there were six cases which were quite distinctly characterized by an asymmetric angular distribution of particles (no more than one particle was emitted at angles $\theta_L \leq 23°$ or $\theta_L > 23°$), while for artificial stars with six charged particles, such an asymmetry occurred only in two out of 21 cases, and in both cases the c.m.s. velocities of all charged particles were small.

Most of the correlations described above can be explained in a natural way within the framework of the concept of the peripheral character of the interactions. At the same time, some characteristics of the interactions, especially the presence of secondary protons with c.m.s. angles of emission $\theta_0 < 90°$ can be regarded as an indication of the existence of a certain percentage of collisions of a central type. For the final settlement of the question concerning the percentage of central collisions, it is necessary to conduct further experiments under cleaner conditions (for example, with a hydrogen bubble chamber).

Hence, as a whole, our data indicate that among interactions with emulsion nuclei a) a considerable portion of the events (~25%) have characteristics close to those of an interaction process involving the incident nucleon and only one (quasi-free) nucleon of the nucleus; b) interactions with quasi-free nucleons are mainly of a peripheral character, but there are indications of the existence of a small number of central collisions (about 20%).

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