NUCLEAR INTERACTIONS OF 8.7-Bev PROTONS IN PHOTOGRAPHIC EMULSIONS

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Inelastic interactions of 8.7-Bev protons with photoemulsion nuclei were studied and, in particular, the interaction cross section, multiple production of particles and their angular distribution. From comparison with calculations based on the statistical theory, some conclusions are drawn concerning the existence of interactions of peripheral (nucleon-nucleon) type, as well as the role of secondary interactions inside the complex nucleus.

THIS work was carried out with a small part of one of the photo-emulsion stacks irradiated with the primary 8.7-Bev proton beam inside the accelerating chamber of the proton synchrotron of the Joint Institute for Nuclear Research.*

Photoemulsion layers of type NIKFI-R and thickness $\sim 450\,\mu$ were exposed without backing, and had a track-density of 27 — 30 grains per $100\,\mu$ for relativistic particles. Scanning along the track of the primary particles was carried out with 630-fold magnification. In all, about 25,000 tracks with total length ~ 300 m were scanned.

1. INELASTIC INTERACTION CROSS SECTION

The method of scanning along the tracks of the proton beam was almost 100% efficient in finding interactions, even in the case where the interaction resulted in the proton being deflected through an angle of 2° and greater without emission of any other charged particles.

The desired mean free path λ for interaction with photoemulsion nuclei was determined in the way usually done when this method is used.

In Table I we give the corresponding λ's for two types of interactions, star production and "pure" scattering (for angles greater than 5° and between 1° and 5°).† In the latter case, corrections were introduced for the efficiency of measuring similar scatterings and were determined by comparing the angular distributions in the plane of the photo-emulsion and in the perpendicular direction.

The value of λ for the totality of interactions

TABLE I

Type of Interaction	λ cm
Star production	35.0±1.3
Scattering through angles $\theta_l > 5°$	1750±500
Scattering through angles $1° \leqslant \theta_l \leqslant 5°$, without correction	750±150
The same, with correction for counting efficiency	500±100

indicated in lines 1 and 2 of Table I do not differ, within the limits of experimental error, from results in the literature,[1,2] nor does the mean free path for star formation differ from results obtained for protons of energy 1 to 6 Bev.[3-5] However, to obtain the mean free path characterizing the inelastic interactions of protons with nuclei as usually defined, one must include all interactions other than elastic.

For protons of a given energy, this task reduces basically to taking account of processes of diffraction scattering by the various nuclei of the photoemulsion, in which a few (not more than three) particles are "boiled off." This can be seen, in particular, from Table II, where we show our distributions with angle θ_l of a single fast particle undergoing two types of interaction:* "pure" scattering without production of visible stars and stars of the type $n_s = 1$, $n_g = 0$, $n_b = 1 - 3$. Table II shows that, within the limits of statistical error,

*The error in energy determination was less than 5%.

†In Table I and the following, θ_l denotes the angle of deflection of a fast particle relative to the direction of the primary beam, the half-width of which constituted ± 0.2°. The analogous angle in the center-of-mass (c.m.) system is denoted by θ_0.

*We employ the following nomenclature for the number of particles with different ionizing powers: n_s corresponds to ionization $J \leqslant 1.5J_{min}$, n_g to $J = (1.5-5)J_{min}$, n_b to $J > 5J_{min}$. The boundary between "grey" and "black" tracks was less definite (tracks were separated visually) and corresponded, on the average, to an energy somewhat larger than the 30 Mev usually employed for protons.

TABLE II. Angular distributions for interactions of type $n_b = n_g = 0$, $n_s = 1$ (scattering) and type $n_s = 1$, $n_g = 0$, $n_b = 1-3$ (stars)*

θ_l, degrees	<1	1–2	2–3	3–4	4–5	5–10	10–30	>30	Total number of cases
$n_g = n_b = 0$	—	13	9	8	1	5	8	2	46
$n_g = 0$, n_b=1–3	2	7	12	13	1	8	10	7	60

*Scatterings with angles <1° were not counted. Cases with angles 2, 3° etc. were included in columns 2–3°, 3–4°, respectively, etc.

the angular distributions for both types of interaction were the same.

Cronin, Cool, and Abashian[6] give theoretical angular distributions for light (C) and heavy (Pb) nuclei for an incident of momentum of 0.95 Bev/c and for various assumptions about the form factors of these nuclei. By extrapolating the data of these authors to momenta ~10 Bev, it is easy to see that the great majority (not less than 95%) of the cases of diffraction scattering by photoemulsion nuclei go through angles θ_l less than 1 — 1.5°. From these considerations, we believe it possible to include as diffraction scattering all interactions satisfying the following two conditions

$$\text{a) } n_s = 1, \quad n_g = 0, \quad n_b \leqslant n_{b_0} = 3;$$
$$\text{b) } \theta_l < \theta_0 = 2°.$$

The resulting value for the mean free path λ for inelastic interactions with photoemulsion nuclei, taking into account errors connected both with statistical fluctuations and with the uncertainty of how to take the diffraction scattering into account, is $\lambda_{inel} = 34 \pm 2$ cm.

In so far as the total geometrical cross section for all photoemulsion nuclei, determined from the relation $\sigma_{geom} = \pi\,(1.38 \times 10^{-13}\,\text{cm})^2 A^{2/3}$, corresponds to a mean free path $\lambda_{geom} \cong 27$ cm, the value for λ_{inel} obtained above means that the so-called transparency of the photoemulsion nuclei is, on the average, 20%.

2. DISTRIBUTION ACCORDING TO THE NUMBERS OF FAST AND SLOW PARTICLES

The number of interactions which can be interpreted as pure charge exchange, the incident proton going into a neutron without appreciable loss of energy, is very small; of 520 stars, there were only 17 cases of type $n_s = 0$, corresponding to a cross section of only 3% of the cross section for inelastic interaction with photoemulsion nuclei. In these 17 cases, the charge exchange was, apparently, sometimes accompanied by production of neutral mesons.

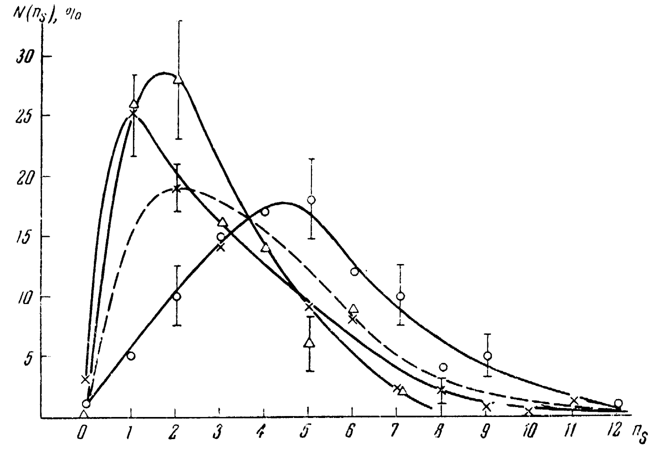

FIG. 1. Distribution of interactions of various types with respect to the number of fast particles n_s: Δ – n_b = 0 to 2, $n_g = 0$, $\bar{n}_s = 3.0 \pm 0.15$; × – n_b = 3 to 8, n_g = 0 or $1 \leqslant n_b + n_g \leqslant 8$, $n_g > 0$, $\bar{n}_s = 3.1 \pm 0.1$; o – $n_b + n_g \geqslant 9$, $\bar{n}_s = 4.8 + 0.15$. The dashed curve is the distribution summed over all stars, $\bar{n}_s = 3.7 \pm 0.05$.

In Figs. 1 — 3 we give the distribution of stars with number of fast particles n_s, and with number of slow particles n_b and n_g for interactions of different types. From these distributions, the presence of a rather noticeable correlation between the values of any two quantities of the three quantities (n_b, n_g, n_s) is evident. Calculation of the corresponding coefficients of pairwise correlation* k leads to the following values

$$k(n_b, n_g) = 0.60; \quad k(n_b, n_s) = 0.42;$$
$$k(n_g, n_s) = 0.35.$$

From consideration of Figs. 1 — 3 it also follows that the character of the distribution with number of particles, selected for a large number of fast ($n_s \geq 7$) or slow ($n_g > 1$ and $n_b > 8$) particles differs essentially from the mean distributions. An analogous conclusion, as will be shown below, follows from consideration of the angular

*The correlation coefficients were determined by the usual formula $k(x, y) = (\overline{xy} - \bar{x}\bar{y})[D(x)D(y)]^{-1/2}$, where D is the dispersion of the quantities x and y.

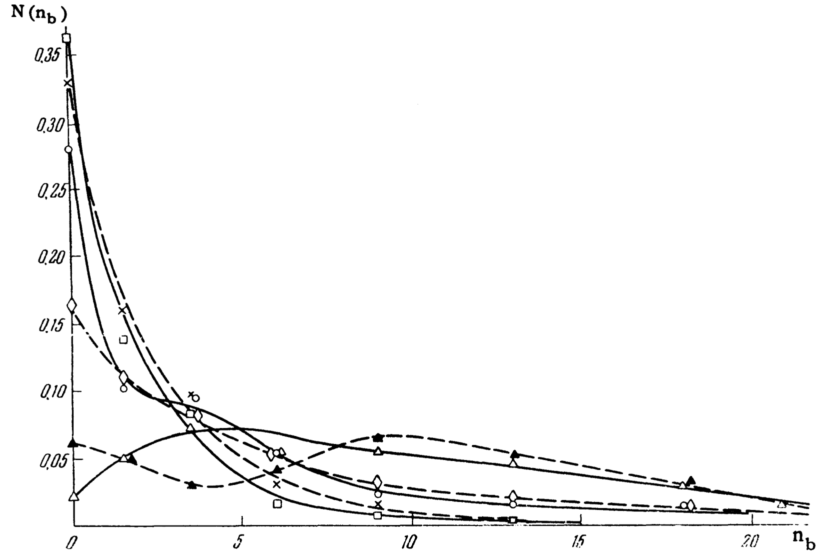

FIG. 2. Distribution of interactions of various types with number of black tracks n_b: □ – $n_g = 0$, ○ – $n_g = 1$, Δ – $n_g > 1$, × – $n_s = 1(0)$, ◇ – $n_s = 2-6$, ▲ – $n_s \geqslant 7$.

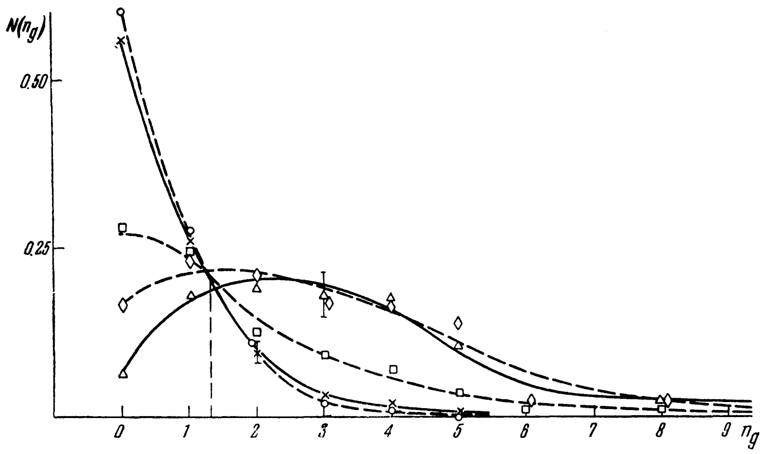

FIG. 3. Distribution of interactions of various types with number of grey tracks n_g: × – $n_b + n_g \leqslant 8$, Δ – $n_b + n_g > 8$, ○ – $n_s = 1(0)$, □ – $n_s = 2–6$, ◇ – $n_s \geqslant 7$.

distributions of fast particles. On the other hand, a large part of the interactions selected by their small number of fast and slow particles, differs in angular distribution but little from nucleon-nucleon ones.

3. ANGULAR DISTRIBUTION OF FAST AND SLOW PARTICLES

Determination of the spatial angles θ_l for relativistic particles and grey tracks was carried out, as a rule, from two angles θ_1 and θ_2, projections of the angle θ_l on the plane of the photoemulsion and on the plane perpendicular to it, going through the track of the primary proton. The angles were determined accurate to 1 – 2°.

In Figs. 4 – 6 the integrated angular distributions of relativistic particles are given for stars, divided into groups in dependence on the numbers n_s (Fig. 4), n_b (Fig. 5) or n_g (Fig. 6). To construct the curve for the case $n_s = 1$ in Fig. 4, corrections for the case of diffraction scattering of primary protons on nuclei were introduced.

We calculated the theoretically expected angular distribution of relativistic particles (given in Figs. 4 – 6) in nucleon-nucleon interactions for isotropic emission of charged particles in the c.m. system of the two colliding nucleons and for the momentum distribution predicted by the statistical theory (see Figs. 7a and 7b). In addition to this, analogous angular distributions were obtained under the assumption of collisions in a "tube" of nuclear matter consisting of two and four nucleons.*

As can be seen from Fig. 4, and especially from Figs. 5 and 6, there is a rather large group of interactions for which the angular distribution of fast particles is, apparently, somewhat broader than in the case of "pure" interaction with the maximum (with respect to length) possible "tube" of nuclear matter in the photoemulsion. In these same interactions, a very large number of slow particles are emitted on the average. This number is signifi-

*Angular distributions for the case of a tube of two nucleons are not given on Figs. 4-6 because of lack of space.

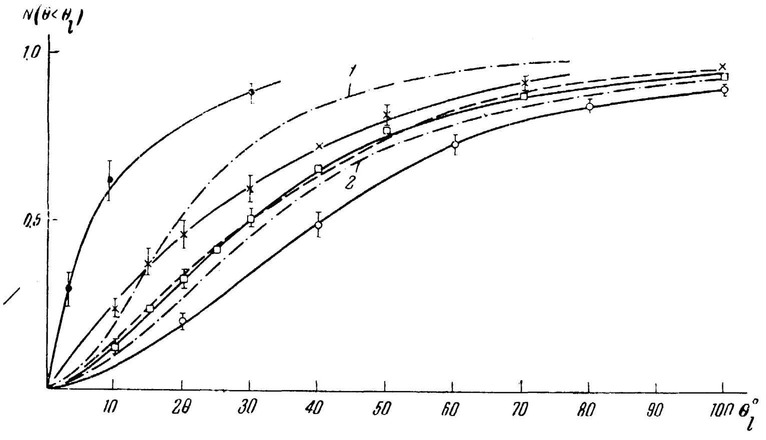

FIG. 4. Integral angular distributions of relativistic particles in stars with various numbers n_s (W is the proportion of stars of given n_s among the total number of stars): ●–$n_s = 1$ (W ≈ 20%), ×–n_s = 2,3 (W = 32%), □–n_s = 4–6 (W = 34%), ○–$n_s \geqslant 7$ (W = 11%). The dashed curve shows the summed distribution. The dashed-dotted curves give the angular distributions calculated from the statistical theory for the interaction of the primary proton with one (1) and four (2) nucleons of the nucleus, simultaneously.

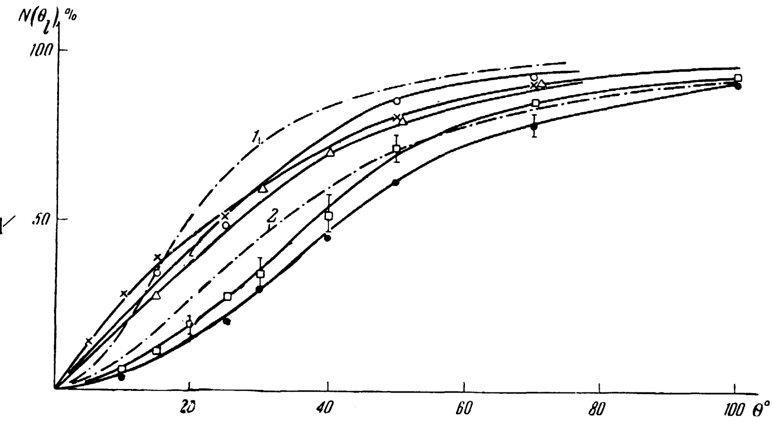

FIG. 5. Integral angular distributions of relativistic particles in stars with various numbers n_b (W is the proportion of stars with given n_b): ○–n_b = 0 (W = 11%) ×–n_b = 1–3 (W = 35%), Δ–n_b = 4–8 (W = 30%), □–n_b = 9–12 (W = 12%), ●–$n_b \geqslant 13$ (W = 12%). The dashed dotted curves are calculated for cases of interaction with one (1) or four (2) nucleons.

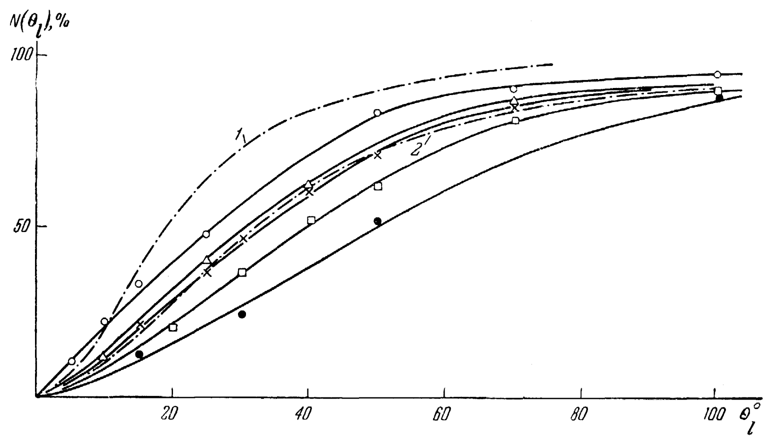

FIG. 6. Integral angular distribution of relativistic particles in stars with various numbers n_g (W is the proportion of stars with given n_g): ○–n_g = 0 (W=46%), Δ–n_g = 1 (W = 24%), ×–n_g = 2, 3 (W = 20%), □–n_g = 4–6 (W = 8%), ●–$n_g \geqslant 7$ (W = 2%). Curves 1 and 2 are calculated for the cases of one and four nucleons, respectively.

cantly larger than in stars of higher energy ($\geq 10^{12}$ ev).

The angular distribution of grey tracks is given on Fig. 8. It can be seen from this figure that the distribution is almost the same in stars of different types and is practically independent of the energy of the particle. In addition, it practically coincides with the angular distributions of strongly ionizing particles from interactions of 1.5-Bev π mesons[7] with photoemulsion nuclei.

Calculations show that if the first interaction of the incident nucleon is with "tubes" of nuclear matter of various dimensions, the total number of grey tracks should be, on the average, significantly less (at most, two), and their angular distribution essentially narrower, than observed in the experiment. This discrepancy, in our view, can be explained only by taking into account the secondary interactions inside the nucleus of the π mesons produced. In addition, a special kinematical analysis demonstrated that even in the cases where there was only one grey track, the corresponding slow proton could not, as a rule, be considered as a recoil from a primary nucleon-

TABLE III. Dependence of the width of the angular distributions on the number of particles n_s produced

	n_s	1	2,3	4—6	7—9	≥10
Experiment	$\theta_{1/2}$	~7°*	23°	30°	39°	47°
	$\cot\theta_{1/2}$	~8*	2.35	1.73	1.23	0.93
Calculation	$\cot\theta_{1/2}$	3.0	2.15	1.67	1.4	1.15
	l	1	2	3	4	6

*The values of $\theta_{1/2}$ and cot $\theta_{1/2}$ are those obtained after introducing corrections for diffraction scattering.

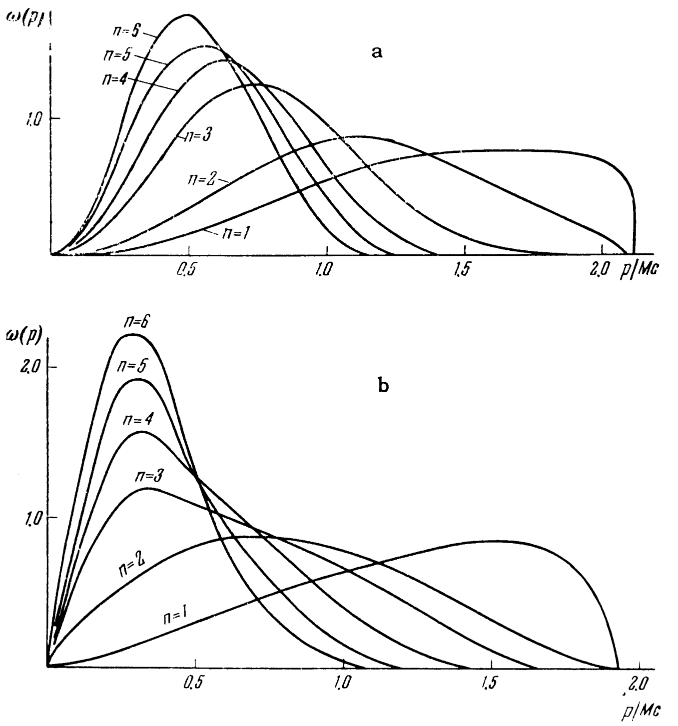

FIG. 7. Momentum spectra of particles in 8.5-Bev nucleon-nucleon interactions according to the statistical theory: a – nucleons, b – π mesons; n is the multiplicity of meson production; M is the nucleon mass; $\omega(p)\,dp$ gives the number of particles with momentum in the interval p, p+dp (normalized to unity).

nucleon interaction.*

The coincidence of the angular distribution of grey tracks with the analogous distribution for meson stars, which we noted above, appears to indicate that the observed particles are mainly recoil protons from π mesons having energies not exceeding 1.5 Bev. The assumption about the presence of secondary interactions of π mesons inside the nucleus allows us to give a qualitative explanation for the breadth of the angular distribution of fast particles in the group of interactions with a large number of fast and slow particles, and also the broader distribution of grey particles and

*The corresponding quantitative criteria were kindly communicated to us by N. G. Birger and Yu. A. Smorodin. They were employed in their paper.[8]

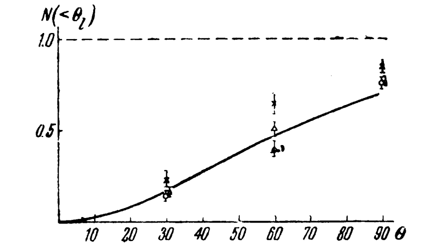

FIG. 8. Integral angular distributions of grey particles: x – J = 1.4 – 2.0 J_{min}; o – J > 2 J_{min}; $\overline{\cot\theta_l \geq 3}$; Δ – J > 2 J_{min}, $\overline{\cot\theta_l} < 3$; The continuous curve gives the distribution of strongly ionizing particles in stars from 1.5-Bev π mesons according to the data of reference 7.

simultaneous increase in the number of grey and black tracks.

4. ANALYSIS OF THE ANGULAR DISTRIBUTIONS

1. From the analysis of the distributions shown in Fig. 4, it follows first that there is a close relation between the width of the angular distribution and the number of particles produced. If we characterize the width of the distribution by the median angle $\theta_{1/2}$ and the corresponding value $\gamma_c' = \cot\theta_{1/2}$, then we obtain the pattern displayed in Table III.

In the same table we give the calculated values of $\cot\theta_{1/2} = \gamma_c\beta_c/\overline{\beta}_0$ (γ_c is the Lorentz factor of the c.m. system) for the cases of interaction of the incident nucleon with several nucleons of the nucleus (l is the number of nucleons participating in the interaction) under the assumption that the secondary particles are emitted symmetrically (in the c.m. system) with mean* velocity $\overline{\beta}_0 = 0.7\,c$; β_c is the velocity of the c.m. system.

In comparing Table III and Fig. 4, it should be kept in mind that the small difference between experimental and calculated values of $\cot\theta_{1/2}$ in Table III is somewhat accidental. It can be seen by comparing the calculated curve (1 on Fig. 4) with the experimental curve for $n_s = 2$ and 3,

*As established in the calculations referred to above, roughly these velocities were obtained from the statistical theory for the cases $l = 1$ and $l = 4$ after averaging over the velocities of all nucleons and mesons.

TABLE IV. Connection between the angular characteristic of stars and their distribution with number of black tracks

n_s	$\bar{\theta}_l$ deg	Relative number of cases, in per cent				Total number of cases
		$n_b = 0,1$	$n_b = 2$—5	$n_b = 6$—10	$n_b \geq 11$	
$n_s = 2,3$	<14	72%	15%	13%	—	39
	14—24	41%	39%	16%	5%	44
	>24	20%	40%	22%	19%	86
$n_s = 4$—6	<14	~50%	50%	—	—	4
	14—24	37%	47%	13%	3	30
	>24	14%	26%	26%	34%	139

taking into account the non-monochromatic nature of the spectra of particles produced, that the agreement between calculations and experiment is not satisfactory. In addition, because of the inevitable fluctuations in the number of particles n_s produced in a given type of nuclear interaction, the cases, chosen only by the quantity n_s, should certainly represent a mixture of interactions of the incident nucleon with various numbers of nucleons in the nucleus. This directs attention to the correspondence between the angle $\theta_{1/2}$ for stars with small n_s ($n_s = 2$ and 3) and the calculated value of the angle $\theta_{1/2}$ for nucleon-nucleon interactions, as well as the large (by comparison with the predictions of the statistical theory of a given nucleon-nucleon collision) number of collisions with production of only a few particles.* Both of these facts indicate that, together with collisions with several nucleons of the nucleus and with the lowering of the value of γ_c, collisions can also take place with little inelasticity and larger value of γ_c (i.e., γ_c larger than that γ_{cn} which should obtain for the nucleon-nucleon interaction). The latter can, apparently, be ascribed either to peripheral interaction[9] of the incident nucleon with one of the nucleons of the stationary nucleus, or to peripheral interaction with the nucleus as a whole as a consequence of diffraction phenomena.[10] In the former case, values of γ_c either less than, equal to, or greater than γ_{cn} are possible; in the second case, $\gamma_c > \gamma_{cn}$ only. The presence of interactions with increased values of γ_c follows also from the analysis of stars with $n_s = 1$ (see Fig. 4).

2. It is clear that the number of slow particles in the star, $n_h = n_b + n_g$, is not a very suitable quantity to use in separating different types of nuclear interaction in the photoemulsion. In fact, we calculated the correlation coefficients $k(n_h, \xi)$ and $k(n_s, \xi)$ between the quantities n_h (or n_s) and the angular characteristics of individual interactions ξ. As angular characteristic, we employed in one calculation the mean cotangent of emission of fast particles ($\xi_2 = \overline{\cot\theta_l}$) and, in another calculation, the quantity l obtained by selecting stars by three angular characteristics — the mean cotangent of emission of fast particles, the mean and half value of the same angle. It turned out that in all cases the correlation coefficient lay between 0.30 and 0.45, i.e., the degree of correlation between the number of slow particles n_h and the angular characteristics of the star ξ did not exceed that for the number of fast particles n_s, and this was not greater than the degree of correlation between the quantities n_h and n_s.

3. It seems to us that in the case of the given primary energy, the angular characteristics of the stars (ξ) are a more definite indicator of the type of interaction than the number of slow particles n_h emitted from the nucleus, i.e., the degree of excitation of the nucleus, in so far as n_h mainly characterizes the secondary processes, and ξ more the primary ones.

Table IV illustrates the differing character of the interaction for stars with differing angular characteristics $\xi_1 = \bar{\theta}_l$. It can be seen that for low values of n_s, the distribution of the stars with angular characteristics is far from being invalidated by fluctuations, and has a definite physical meaning in the clarification of the mechanism of nuclear interaction.*

In the following analysis, the quantity ξ_2 is, in our view, a more convenient angular characteristic for the stars than ξ_1, especially for interactions with large values of γ_c. In fact, with an isotropic distribution of particles in the c.m.s., after transforming in the well-known way to angles in the laboratory system (l.s.),

$$\cot\theta_l = \frac{\gamma_c}{\sin\theta_0}\left(\frac{\beta_c}{\beta_0} + \cos\theta_0\right), \quad (1)$$

*This will be discussed in detail below.

*In essence, Table IV gives only a more detailed confirmation of the fact that the correlation coefficient between the quantities n_h and ξ differs from zero. An analogous picture is found in the analysis of stars according to the number of grey tracks n_g and with the choice of the quantity $\xi_2 = \overline{\cot\theta_l}$ as angular characteristic.

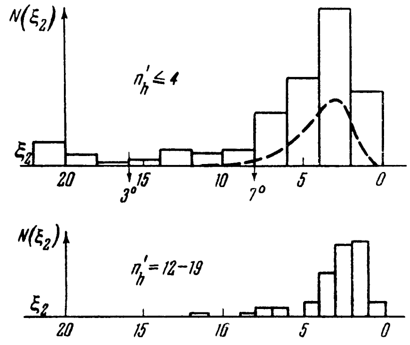

FIG. 9. Distribution of stars with angular characteristic $\xi_2 = \overline{\cot \theta_l}$ for various values of the sum $n'_h = n_b + 3n_g$.

we obtain rather simple features for the function describing the distribution of particles with the quantity $\cot \theta_l$. In particular a) the "half value" $(\cot \theta_l)$, i.e., the value for which the integral distribution S ($< \cot \theta_l$) is 50%, is equal to $\gamma_c\beta_c\,(\overline{1/\beta_0})$, and, is determined, thus, not solely by the quantity γ_c, but by some effective value of the particle velocity in the c.m. system; b) the mean value $\xi_2 = \overline{\cot \theta_l}$ differs from $(\cot \theta_l)_{1/2}$ by the factor $\overline{1/\sin \theta_0} = \pi/2$; c) the spread in angular characteristic relative to $(\overline{\cot \theta_l})_{1/2}$ is approximately proportional to γ_c.

In Fig. 9 we show the distributions with angular characteristic $\xi_2 = \overline{\cot \theta_l}$ for stars with $n_s \geq 2$, plotted in groups depending on the number of slow particles emitted — more precisely, on the quantity $n'_h = n_b + 3n_g$. There the calculated (dashed) curve for fluctuations in the quantity ξ_2 is also plotted, giving somewhat of an overestimate of the role of these fluctuations. As can be seen from Fig. 9, for stars with a small number of slow particles ($n'_h \leq 4$) there is a rather noticeable group of cases for which the angular distribution is essentially different from that proposed by the statistical theory. As n'_h is increased, such anomalous cases disappear, and the center of mass of the distribution of stars is displaced towards smaller values of ξ_2.

4. Starting from the model in which the initial proton interacts with a "tube" of nuclear matter of mass l (in units of the nucleon mass) we tried to carry out a qualitative breakdown of all observed stars with 4 groups. These groups are characterized by values of l of 1, 2, 4, and also $l < 1$; the final value denotes the part of the interactions giving an angular distribution narrower than the nucleon-nucleon one.* As clarified by the following analysis, the quantity γ_c, which can formally be taken to describe the angular distribution of particles in this group, is equal to about 5, which corresponds roughly to the center of mass of the incident nucleon together with one of the virtual π mesons of the stationary nucleon.

The task of breaking down the observed distributions into groups, each of which possesses a given angular distribution and, consequently, a given (aside from fluctuations) value of the quantity ξ_2, was carried out in the following way. First of all, mean values of ξ_2 for each of the groups ($l = 1$, $l = 2$ and $l = 4$) and fluctuations of the quantity ξ_2 about its mean values were calculated, using in this results of the statistical theory. After this, several intervals of values of ξ_2 were chosen, namely,

$$\Delta_1(\xi_2) = 6 \text{ to } 3; \quad \Delta_2(\xi_2) = 3 \text{ to } 1.5; \quad \Delta_3(\xi_2) < 1.5.$$

and the probability of each of the group falling into one or the other of intervals was determined, taking the corresponding fluctuations into account.* Assuming that none of these intervals contained interactions of the type $l < 1$, we have the following three equations for three unknowns:

$$\begin{aligned} W_{11}N_1 + W_{12}N_2 + W_{11}N_4 &= A, \\ W_{21}N_1 + W_{22}N_2 + W_{24}N_4 &= B, \\ W_{31}N_1 + W_{32}N_2 + W_{31}N_4 &= C. \end{aligned} \qquad (2)$$

The quantities on the right-hand side are the number of stars known from experiments for which the value of ξ_2 falls in the interval Δ_1, Δ_2, or Δ_3. On the left-hand side are the calculated values W_{ik} of the probability of stars of the k-th group ($l = k$) falling into the i-th interval of values of ξ_2. Solution of the system (2) leads to the following values of the number of interactions in each of the groups:†

$$N_1 \approx N_2 \approx N_4 \approx 25\%\, N_0,$$

where N_0 is the total number of stars. Here the accuracy of the evaluations of each of the quantities (N_1, N_2, N_4) was 20 – 25%.

The same calculations showed that of the fluctuations from the remaining 25% of the stars falling into the "zeroth" interval of values of ξ_2 ($\xi_2 > 6$), no more than $1/5$ could belong to interactions of the type $l = 1$, and, consequently, $4/5 \cdot 0.25 = 20\%$ belonged to the interactions of the type $l < 1$.

In order to check the degree of agreement between our breakdown of interactions into groups

*Here and in the following, in all cases with $l \geqslant 1$, it will be assumed that all particles are distributed isotropically in the c.m. system.

*These fluctuations were calculated assuming isotropic and independent distributions of particles: protons (p) and mesons (π), where for $l = 1, 2, 4$, stars containing, respectively, $1p + 2\pi$, $1p + 3\pi$ and $1p + 4\pi$ were chosen as typical.

†Estimates carried out by us showed that these relative probabilities agree satisfactorily with the existing data on the spatial distribution of the density of nucleons in the nucleus.

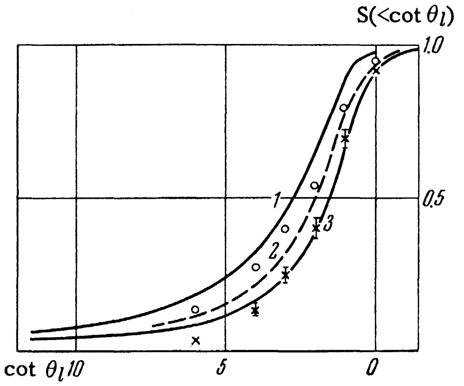

FIG. 10. Angular distributions of fast particles in interactions of various types. Experimental values: × – stars with $\overline{\cot \theta_l}$ = 1.5 to 3.0; ○ – stars with $\overline{\cot \theta_l}$ = 2.5 to 4.5. Theoretical curves: 1 – for interactions with $l = 1$, 2 – for $l = 2$, and 3 – for $l = 4$.

and predictions of the statistical theory, we carried out a supplementary analysis of the angular distributions of fast particles S ($< \cot \theta_l$) and the multiplicity of production n_s. In Fig. 10 we show the experimental data on the angular distributions of particles in stars for two intervals of $\xi_2 : \xi_2 = 4.5$ to 2.5 and $\xi_2 = 3.0$ to 1.5. Also shown are the calculated distributions for interactions of type $l = 1$, $l = 2$ and $l = 4$. Comparison of calculation and experiment shows that in the first interval of ξ_2, as one would expect, there is mainly a mixture of interactions of type $l = 1$ and $l = 2$. However, in the second interval, one finds a distribution which is somewhat broader (in angle) than one would expect for an interaction of type $l = 4$.

5. In a somewhat different aspect, the same question can be elucidated by analyzing the mean values of the quantity $\xi_3 = \Sigma (\sin \theta_l)^{-1}$ for various groups of stars, separated by a simpler criterion — according to the number of slow particles. Here the quantity ξ_3 is convenient in that it is connected in a simple way with some effective value of the transverse momentum of the particle $(p_\perp)_{\text{eff}}$, namely

$$K \sum_{i=1}^{n_s} p_\perp / \sin \theta_l = K (p_\perp)_{\text{eff}} \xi_3 = E_0 - \Delta E, \qquad (3)$$

where K is the mean ratio of the total number of fast particles in the star to the number of charged particles, E is the energy of the primary proton and ΔE is the excitation energy of the nucleus, or, more precisely, the energy taken up by the nonrelativistic particles.

In Table V are given the experimental and calculated values of $\overline{\xi}_3$ and the corresponding values of $(p_\perp)_{\text{eff}}$ for stars of various types, where we have taken $K = 3/2$ and $\Delta E = 1$ Bev.[1] From consideration of the lower-left half of Table V, it can be seen how regularly the values of $(p_\perp)_{\text{eff}}$ decrease with increasing n_s; this is connected, apparently, with the fact that, for given l, an increase in the number of particles n_s produced leads to a decrease in the mean momentum of each of them. However, the value of $(p_\perp)_{\text{eff}}$ averaged over all n_s turns out to be higher than the theoretical one; and this difference cannot be explained only by an admixture of interactions with small l. It is considerably more likely that the transverse momenta of the highest energy particles increase because of the secondary interactions inside the nucleus.

In so far as the upper left-hand part of the table is concerned, we see there that, on the contrary, the value of $(p_\perp)_{\text{eff}}$ is low (compared with the theoretical one) and does not even depend on the multiplicity n_s. It would appear that this fact can be only partially explained by an admixture of interactions with $l > 1$, but mainly by an admixture of interactions having the anomalously narrow angular distribution ($l < 1$).

We tried to check the assumption that the high value of $(p_\perp)_{\text{eff}}$ in the former case could be explained by cascade processes inside the nucleus in "pure" form. With this in mind, we carried out a

TABLE V: Comparison of experimental and calculated values of the quantity $\overline{\xi}_3$ and corresponding values $(p_\perp)_{\text{eff}}$

Experiment*				Theory			
	n_s	$\overline{\xi}_3$	$(p_\perp)_{\text{eff}}/\mu c$		Type of particle	$\overline{\xi}_3$	$(p_\perp)_{\text{eff}}/\mu c$
$n_g \leq 1,\ n_h \leq 4$	2—3	24.5	1.5	$l = 1$	p	5	2.4
	4—6	22	1.6		π	10	
	≥ 7	24	1.5		$p + \pi$	15	
	$(n_g + n_h) < 11$						
$n_g + n_h > 8$	2—3	7.1	5.1	$l = 4$	p	7	1.5
	4—6	13	2.8		π	16	
	≥ 7	19.5	1.8		$p + \pi$	23	
	$\overline{n}_s = 5$	13.5	2.7				

*The accuracy in the experimental data is 15% in the upper half of the table and 5% in the lower.

very approximate calculation of this process according to the following scheme. We assumed that in the subsequent interactions of the primary proton with each of the l nucleons in the nucleus, only one fast nucleon remained, carrying off 70% of the initial energy, and that the remaining 30% of the energy was distributed among the mesons, the number of which was determined by the value of γ_c, according to the statistical theory.[11] We assumed also that in the process of interaction with other nucleons in the nucleus, all mesons of energy up to 550 Mev (total energy $5\mu c^2$) are absorbed and that only mesons of energy greater than 550 Mev are scattered. It is easy to show that this way of considering the process can lead to a value for the multiplicity* for given l which is significantly higher. None the less, in the case of $l = 4$, for example, calculation with this scheme gives $n_s = 5.5$, i.e., a value larger than observed in experiment. For a conclusive decision on the applicability of the model of cascades inside the nucleus in "pure" form, it would be necessary to carry out more rigorous calculations using accurate experimental data on the characteristics of nucleon and π-meson interactions at the various energies.

6. We turn now to a determination of the number of fast and slow particles (n_s, n_b and n_g) in interactions with different values of the quantity l.

TABLE VI. Proportion of stars (percent) with different l for given n_s

n_s	$l < 1$	$l = 1$	$l = 2$	$l \geqslant 3$ ($l = 4$)
1	$\geqslant 50$	~ 25	~ 15	~ 5
2–3	$\geqslant 25$	~ 30	~ 20	~ 20
4–6	$\leqslant 10$	~ 25	~ 30	~ 40
$\geqslant 7$	—	< 10	~ 20	~ 80

TABLE VII. Distribution of the number of stars with n_s for given l

	l	$n_s = 1$	$n_s = 2–3$	$n_s = 4–6$	$n_s \geqslant 7$	$\bar{n}_s$
Experiment	<1	55(±15)%	35(±12)%	≤10%	—	1.5–2.0
Experiment	1	20(±10)%	40(±10)%	40(±10)%	<10%	3.3±0.3
Theory		≈7%	≈46%	≈46%	0.6%	≈3.3
Experiment	2	10(±4)%	30(±7)%	50(±15)%	10(±5)%	4.0±0.4
Theory		~0.5%	≈14%	≈65%	≈20%	≈4.8
Experiment	$\geqslant 3$	4(±2)%	25(±7)%	40(±15)%	30(±10)%	5.0±0.5
Theory		—	≈5%	≈40%	≈55%	≈6.75

TABLE VIII. Proportion of stars with various l for given n_b and n_g

	$l < 1$	$l = 1$	$l = 2$	$l > 3$		$l < 1$	$l = 1$	$l = 2$	$l \geqslant 3$
$n_b \leqslant 3$	35%	35%	20%	10%	$n_g = 0$	≥30%	~30%	~20%	~15%
$n_b = 4–8$	≥15%	~25%	~30%	~30%	$n_g = 1$	≥15%	~25%	~30%	~30%
$n_b = 9–15$	—	~15%	~25%	~60%	$n_g = 2,3$	~10%	~20%	~30%	~40%
$n_b \geqslant 16$	—	≤10%	~15%	~80%	$n_g \geqslant 4$	—	~10%	~20%	~70%
$\bar{n}_b(l)$	2–3	4–5	6–8	10–12	$\bar{n}_g(l)$	≤0.5	≈0.8	≈1.25	≈2

Grouping all observed stars of given n_s, n_b or n_g first according to the angular characteristics of the fast particles (ξ_2), and then carrying out a regrouping according to l by solving the system of equations (2), we obtained the results given in Tables VI – VIII. From Table VI it follows that interactions with a large number of fast particles correspond mainly to interaction of the incident nucleon with several nucleons of the nucleus. If we assume that the excitation energy ΔE of the nucleus is proportional to either the quantity n_b or n_g, which, in turn, turn out to be proportional to each other (for given l), then it follows from Table VIII that the excitation energy increases with increasing l, but somewhat more slowly than l. The data in Table VII shows that the model of interaction of the incident nucleon with a "tube" of nuclear matter leads to a high value for the multiplicity n_s. Starting from an analysis of the distribution of stars with n_s it thus follows that the interaction of nucleons in a complex nucleus has a character intermediate between that of the pure "tube" and pure cascade models.

In order to answer the question about the simul-

*This is connected, first of all, with the fact that, according to the statistical theory, appreciably less than 70% of the initial energy should be kept, on the average, by one fast nucleon.

taneous or successive character of the interaction of the incident nucleon with the nucleons in the nucleus, it would be necessary to study the corresponding energy characteristics for mesons and nucleons.

CONCLUSIONS

1. The mean free path for inelastic interaction of 8.7-Bev protons with photoemulsion nuclei is equal to 34 ± 2 cm.

2. In the interactions discussed, in a significant part of the cases ($\geq 15\%$) stars are formed which can apparently be related to processes of peripheral nucleon-nucleon interactions. These stars are characterized by a small number of fast particles ($n_s = 1 - 2$) which emerge at small angles (of the order of 5° on the average) relative to the direction of the incident proton.

3. Processes of "pure" charge exchange, i.e., processes in which fast charge particles are not formed, account for about 3% of all interactions in photoemulsions.

4. A significant part (about 25%) of the interactions with photoemulsion nuclei hardly differ, in angular distribution and mean multiplicity of fast particle production, from interactions of the nucleon-nucleon type, calculated with the usual statistical theory.

5. The angular distribution of grey tracks depends only very weakly on the angular distribution of fast particles and differs little from the distributions found in interactions of 1.5-Bev π mesons with photoemulsion nuclei. It can be assumed that the origin of grey particles in this case is connected to a significant degree with secondary interactions of π mesons of energy ~ 1 Bev.

6. The monotonic broadening of the angular distributions with increasing multiplicity of fast particle production corresponds to the picture of interactions intermediate between the representations of successive and simultaneous interactions of the primary nucleon with nucleons of the complex nucleus.

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