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*INELASTIC INTERACTION OF PROTONS AND NUCLEONS AT AN ENERGY OF 9 Bev**

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The multiplicity dependence of the angular and energy characteristics of secondary particles in proton-nucleon collisions at 9 Bev is studied. A comparison is made with results of calculations[15,16] based on the single-meson scheme.

THE general properties of proton-nucleon (pN-interactions) at 9 Bev were described in earlier papers[2,3] (see also [4]). Certain important details of the phenomena, however, remained unclear, particularly those concerning the dependence of the angle and energy characteristics on the multiplicity and on the asymmetry of the c.m.s. angular distribution of the secondary protons in pn interactions. The present study was aimed at an investigation of these problems and at better results, which we had hoped to attain by increasing the statistical material and improving the procedure (more stringent selection of events, more accurate ionization measurement, and measurement of the signs of the secondary-particle charges).

We scanned the primary-proton tracks, by the accelerated method (see [5]), in a pellicle stack made up of NIKFI-R emulsions irradiated by 9-Bev protons inside the proton synchrotron of the Joint Institute for Nuclear Research. We scanned a total of 3 km of track and found about 8000 interactions. The mean free path for the interaction was found to be 35.9 ± 0.4 cm.

From among the interactions found we sorted out the cases that satisfied the criteria for collisions between protons and free or quasi-free nucleons.[2,3] A total of about 900 events of this type were found. In order to obtain the cleanest material on the proton-nucleon interaction, particular attention was paid to absence of a cluster in the center of the event, which could be due either to a very slow recoil nucleus or to a slow electron. We therefore chose for the measurement 425 such "clean" cases, of which 251 had an even number of secondary charged particles (pp interactions) and 174 had an odd number of prongs (pn interactions).

The fast secondary particles were identified by measuring the multiple scattering and the ionization density. We used the g/g_0 (relative ionization density) vs. $p\beta$ (for pions and protons) curves calculated by Barkas and Young.[6] These curves are shown in Fig. 1 together with the experimental points.

In addition, we determined the signs of the charges of the secondary particles from the deflection in the magnetic field of the proton synchrotron.* Using the procedure described by Gramenitskii et al,[7] we determined the quantity $\gamma_m = \theta_{meas}/\bar{\theta}_{mult}\sqrt{t}$, where θ_{meas} — actual change in the direction of the particle over the length t, and $\bar{\theta}_{mult}$ — mean square of the multiple-scattering angle at the same length. The length of the track was not less than 6 cm here. To verify the method we measured γ_m on the tracks of positive particles (particles from 2-prong events in pp interactions and particles identified as protons from the measurements of the ionization and scattering). For 14 out of 90 positive particles γ_m was negative, i.e., the sign of the charge, is incorrectly determined in (16 ± 4)% of the cases, owing to the influence of multiple scattering.

We also analyzed three-prong events among the pn interactions. In this case the number of positive particles was twice the number of negative ones. Actually 57 and 28 particles were observed with positive and negative γ_m, respectively, i.e., the ratio of the number of positive to negative particles was 2.0 ± 0.47. It can be concluded from this check that the sign of the charge of a particle with track longer than 6 cm is correctly determined in 80—85 percent of the cases.

The fast particles were measured and identified with tracks having dip angles φ less than or

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*Some results of this investigation were also reported by V. I. Veksler.[1]

*During the time of irradiation the stack was in the 12 000 oe magnetic field of the proton synchrotron.

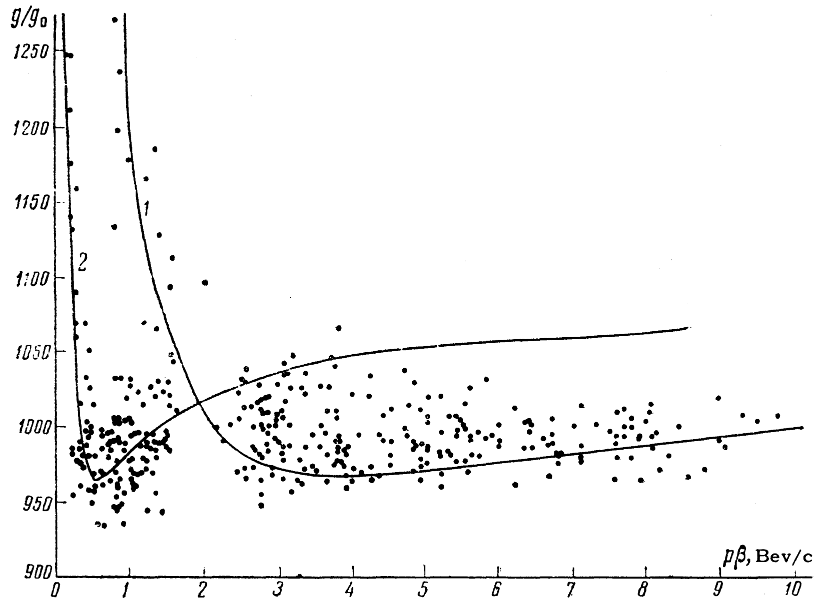

FIG. 1. The dependence of the relative cluster density g/g_0 on $p\beta$: 1 – proton; 2 – pions.

equal to 5°. Therefore to obtain the angle and momentum distributions and the mean values of the various quantities we introduced geometrical corrections[7] for the number of particles which have an angle φ greater than 5° for a given direction angle θ. In the calculation of the statistical errors under these conditions we used the previously obtained results.[8]

As noted earlier,[3] particles with $p\beta$ ranging from 1.5 to 2.5 Bev/c (region where the pion and proton curves intersect in Fig. 1) cannot be identified in practice by their ionization and scattering. The same reference cites some indirect arguments in favor of assuming the greater part of the particles entering into this region being pions. In addition to the foregoing, we can also advance the following arguments. It is natural to assume the ratio of the total number of pions to the number of charged particles in the pp interactions to be close to 1.5. This ratio, calculated from the inelasticity coefficient under the assumption that all the particles in the intersection region are protons, was found to be 2.41 ± 0.35. Thus, the assumption that all the particles in the "intersection region" are protons must be excluded.

Table I*

Multiplicity	Protons		Pions	
	p_c	$p_\perp$	p_c	$p_\perp$
2	1280±60	368±36	662±78	414±72
4	1010±50	439±37	393±30	260±28
6–8	920±70	549±71	442±43	355±45

*Momenta given in Mev/c units.

To estimate the percentage of protons in those particles we can use the result of indirect identification of the secondary positively-charged particles in the momentum interval 2.3–2.9 Bev/c, obtained with the aid of electronic circuitry in a study of the interaction between 9-Bev protons and beryllium nuclei. It was shown that in the secondary particles emitted with this momentum at 0–2° the number of protons is almost equal to the number of positive pions.*

If we assume that this is true in the entire "intersection region," then we obtain for pp interactions the ratio $n(\pi^{\pm 0})/n(\pi^{\pm}) = 1.40 \pm 0.23$.† It must be noted that many other characteristics of pp interaction, particularly the natural requirement of symmetry of the angular distribution of the pions and protons in the c.m.s., likewise do not contradict the foregoing assumption, which we have subsequently used in the reduction of all the experimental results.

In the analysis of the pp interactions, great interest is attached to the comparison of various characteristics of the secondary particles at different multiplicities. Table I lists the mean values of the c.m.s. momentum (p_c) and the transverse momentum of the secondary protons and pions from the pp interactions.

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†In the calculation we assumed all the negative particles from the "intersection region" to be negative pions, and each positive particle was assumed equally likely to be a proton or a positive pion.

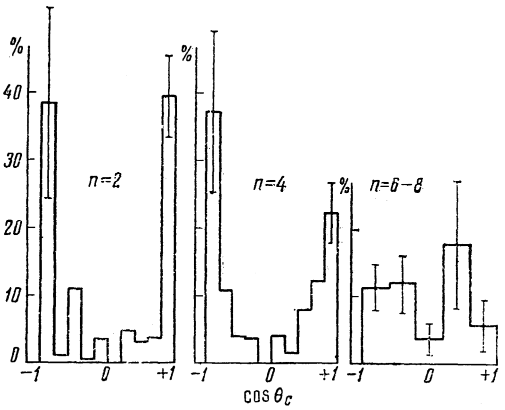

FIG. 2. Angular distribution of protons in the c.m.s. for different multiplicities in pp interactions. The ordinates represent the percentage of events.

From the data of Table I we can conclude that the average characteristics depend relatively little on the number of charged particles.*

The angular distribution of the protons in the c.m.s. for pp-interactions (Fig. 2) is highly isotropic at low multiplicity, and becomes close to isotropic on going to n = 6—8.

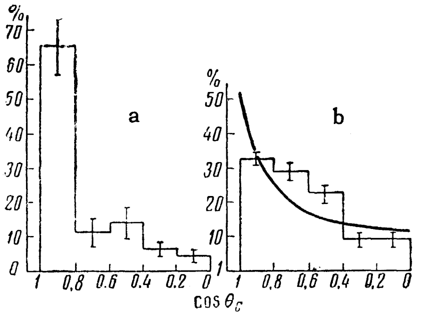

FIG. 3. Angular distribution of secondary protons (a) and pions (b) in the c.m.s., obtained in pp interactions; the smooth curve is calculated by the single-meson scheme.

Figure 3 shows the summary c.m.s. angular distributions of the protons and ions for all pp interactions. It is seen from the plot that the angular distribution of the pions is much closer to isotropic.

From the data of Table I we can readily calculate the total number of mesons as a function of the multiplicity. Table II lists the results of such a calculation together with data on the number of protons per interaction. It can be seen that the total number of mesons increases somewhat with increasing number of charged particles. In the case of large multiplicity (n = 6—8) there are practically no neutral mesons.

Table II

Multiplicity	Total number of mesons	Number of charged mesons	Number of neutral mesons	Number of protons
2	2.0±0.26	0.96±0.16	1.04±0.30	1.04±0.16
4	4.16±0.34	2.72±0.18	1.44±0.38	1.28±0.18
6–8	4.12±0.44	5.04±0.26	—	1.32±0.26

For all the pp interactions taken together, the average number of protons, charged pions, and neutral pions is respectively 1.18 ± 0.10, 2.24 ± 0.14, and 0.90 ± 0.30. An analogous analysis was made for pn interactions.

Table III*

Multiplicity	Protons		Pions	
	p_c	$p_\perp$	p_c	$p_\perp$
3	1010±40	355±43	428±39	252±33
5	918±70	441±45	437±41	291±39
7–9	813±80	543±75	420±90	228±25

*Momenta given in Mev/c units.

Table III lists the mean values of the c.m.s. momentum and of the transverse momentum for different multiplicities.

As in the case of pp interactions, the dependence of the average secondary-particle characteristics on the multiplicity is relatively weak. The mean number of protons, charged pions, and neutral pions per pn interaction is respectively 1.11 ± 0.10, 2.82 ± 0.21 and 1.61 ± 0.49.*

The c.m.s. angular distribution of the protons shown in Fig. 4 is asymmetric, in accord with the results of the earlier investigations[2-4] (see also [10,11]).

As was shown in [12], the c.m.s. angular distribution of the charged pions should be symmetrical for pn interactions. The observed angular distribution of the pions (see Fig. 4) does not contradict this statement, for the difference in the number of pions emitted in the forward and backward hemispheres is 73 ± 50.

The analysis shows that the pN interactions have the following characteristic features:

1) A relatively small fraction of the primary energy of the proton (~ 40%) goes in the mean into pion production.

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*The coefficient of inelasticity and the fraction of the energy lost by the proton (in the laboratory system) to the formation of pions were 0.56 ± 0.08 and 0.40 ± 0.05, respectively, for all pp interactions. These data agree, within the limits of errors, with the earlier results (see[3]).

*It must be noted that the values given pertain only to pn interactions with n > 1 secondary prongs. The average number of protons per event for all pn interactions should be unity (see[9]). With our sampling, the average number of protons should be somewhat greater than unity.

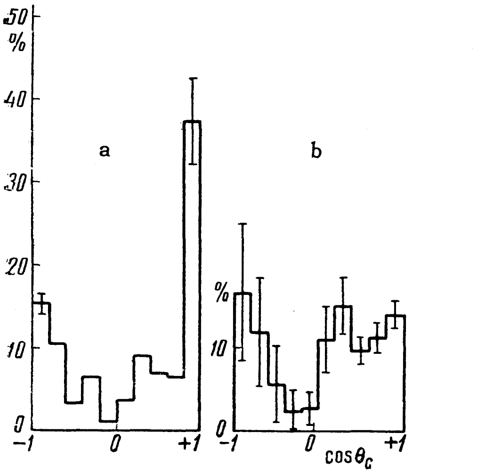

FIG. 4. Angular distribution of protons (a) and pions (b) in the c.m.s. for pn interactions.

2) The angular distribution of the protons in pp interactions is sharply anisotropic in the c.m s., and the degree of anisotropy decreases with increasing multiplicity.

3) The c.m.s. angular distribution of the pions is much closer to isotropic than that of the protons.

4) The average characteristics of the secondary particles ($\bar{p}_c$, $\bar{p}_\perp$, $\bar{n}_p$, $\bar{n}_\pi$) change relatively little with changing multiplicity.

5) A noticeable asymmetry is observed in the angular proton distribution for pn interactions.

At present there exists no consistent theory capable of describing the entire pN interaction picture. The statistical theory of multiple particle production describes well only certain characteristics of the interaction, for example the distribution by multiplicities (see [13,14]). On the other hand, the angular distributions of the secondary particles cannot be explained within the framework of the statistical theory. It is important that the statistical theory does not consider in principle the structure of the interacting particles, whereas even the crudest model representations are capable of yielding rather interesting results. If, for example, we assume that the nucleon consists of a "meson cloud" surrounding a central "core,"[15] then we can expect two types of collisions to be present, "central" and "peripheral." This division is, of course, arbitrary.

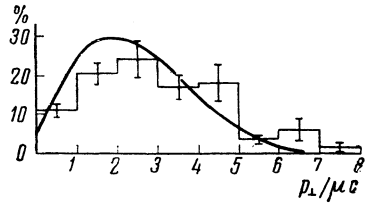

FIG. 5. Distribution of transverse momenta of protons in pp interactions. Smooth curve – result of calculation by the single-meson scheme.

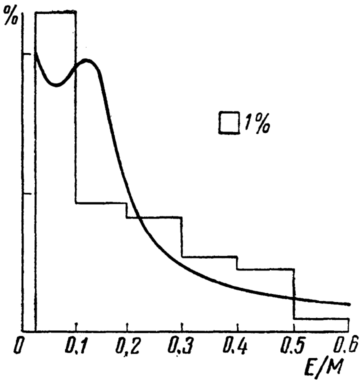

FIG. 6. Energy distribution of the recoil nucleons in pp interactions. Smooth curve – result of calculation by the single-meson scheme. Area under each column of the histogram corresponds to the number of cases in percent. The square on the figure indicates the scale.

On going from small to large multiplicities it is natural to expect the relative role of the "central" collisions to increase. This agrees with the experimental data, which indicate certain changes in the momentum and angular characteristics of the secondary nucleons (see Tables I and III and Fig. 2). On the other hand it is known that the number of charged secondary particles is not a sufficiently sensitive parameter capable of separating the "central" collisions from the "peripheral" ones (see [16]). One might think that the energy loss would be a more suitable criterion. If we assume arbitrarily that the "purely central" collisions are characterized by greater energy losses, we must conclude that the number of such collisions is small, for only in about 6% of all the pN interactions with two secondary protons were both protons emitted in the same c.m.s. direction.

It is apparently natural to classify as "peripheral" collisions in which the recoil nucleon acquires little energy. We can attempt to describe such collisions by using the single-meson scheme in the pole approximation.[16,17] Calculation shows that the cross section of the inelastic pN interaction should amount to about 18 mb, i.e., an appre-

Table IV

pp interactions			pn interactions		
n	number of events, %		n	number of events, %	
	exp	theor		exp	theor
2	44.8±4.2	35	1	29.9±4.2	18.4
4	42.2±4.1	58	3	46.0±5.1	65.2
6	10.6±2.1	6.0	5	16.1±3.1	15.7
8	2.4±0.6	0.1	7	7.5±2.1	0.7
$\bar{n}_{pp}$	3.42±0.10	3.46	9	0.6±0.6	—
			$\bar{n}_{pn}$	3.06±0.14	2.96

ciable portion of the corresponding experimental value, which is approximately 30 mb.[1,18]

It is therefore interesting to compare the experimental and calculated data pertaining to the entire statistical material. Figure 5 shows the experimental and theoretical distributions of the transverse momenta of the proton for pp interactions, while Figs. 3 and 6 show the angular distribution of the pions in the c.m.s. and the energy distribution of the recoil nucleons in the l.s. Table IV lists the theoretical and experimental distributions by number of charged particles for pp and pn interactions.

For pn interactions we have calculated the quantity

$$\Delta = (n_{\text{forw.}} - n_{\text{backw.}})/N$$

(N — total number of interactions) which characterizes the degree of asymmetry of the angular distribution in the c.m.s. We give below values of Δ for different multiplicites

n	1	3	5	7 − 9
$\Delta_{\text{exp.}}$	—	+0,55±0.09	0.0±0.21	−0,64±0,64
$\Delta_{\text{theor.}}$	+0,43	+0.61	−0.03	−0,68

We do not give the experimental value of Δ for cases with n = 1, for which only cases with $\theta_1 \geq 5°$ were considered.

A comparison of the experimental data with the calculations based on the one-meson scheme indicates that they are in qualitative agreement. It is hardly expected to obtain quantitative agreement because, in addition to single-meson interactions, an appreciable role can be played also by processes that follow more complicated schemes.

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189