INTERACTION OF 9-Bev PROTONS WITH FREE AND QUASIFREE NUCLEONS IN PHOTOGRAPHIC EMULSIONS*

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The problem of the angular and energy characteristics of secondary particles produced in collisions between protons and nucleons is considered.

AN emulsion camera was used to study interactions of 9-Bev protons with nucleons. It consisted of layers of NIKFI type R emulsion and was irradiated with the internal proton beam of the proton synchrotron to the high-energy laboratory of the Joint Institute for Nuclear Research (see also references 2 and 3). Scanning was carried out along the tracks of the primary protons, with 600-fold magnification. All stars and scatterings through angles larger than 5° were detected. In track length of 978 m, 2623 cases of nuclear interaction were found. The mean free path was 37.3 ± 0.3 cm, in agreement with results obtained earlier.[2]

1. In order to segregate proton-proton (p-p) and proton-neutron (p-n) interactions, cases having no more than two slow protons (with ionization $I \geq 1.4\, I_{plateau}$) were chosen. Lack of a recoil nucleus and, in cases with an even number of prongs, lack of a β-electron were also required. The subsequent selection was carried out according to the criteria:

(1) The slow proton should have a track length $l \geq 4$ mm ($E_p \geq 31$ Mev). This makes it possible to exclude cases of proton-nucleus interaction with evaporation of a single proton.

(2) For a given energy of the proton, its angle of emission should not exceed the angle of elastic proton-proton scattering.

(3) For a given multiplicity n the angle of proton emission should not exceed some $\vartheta_{max}(n)$, corresponding to the kinematics of the proton-nucleon (p-N) collision.

(4) The following inequality[4] should be fulfilled:

$$\sum(E_i - p_i \cos\vartheta_i) \leqslant M + E_0 - p_0,$$

where E_i, p_i and ϑ_i are the energy, momentum and angle of emission of the i-th secondary charged particle in the laboratory system (l.s.), M is the proton mass, E_0 and p_0 are the energy and momentum of the incident proton in the l.s. Since no measurements were made of the momenta of the fast particles, in applying this criterion, particles having a blob density $b \leq 1.4\, b_{plateau}$ were considered to be π mesons. The values 196 Mev and 137 Mev/c were employed for these as lower limits of energy and momentum, respectively.

In this way, 170 cases with an even number and 110 with an odd number of prongs were chosen. Cases with an even number of prongs were considered to be interactions with free protons or with quasifree protons in the photoemulsion nuclei. Cases with an odd number of prongs were considered to be interactions with quasifree neutrons. In addition, 20 cases of elastic p-p scattering were found. Criteria of selection of these cases and the efficiency of detecting them were taken from the work of reference 2.

The total cross section for elastic p-p scattering turned out to be $\sigma_{pp}^{el} = (10 \pm 3)$ mb, consistent with values found in other works.[2,5]

2. In selecting cases of inelastic interactions of nucleons with nucleons in the photoemulsions, the question of the purity of selected events arose, since the criteria indicated above are necessary, but not sufficient.

First of all, it is necessary to make sure that the cases discarded by criterion (1) are practically free of p-N interactions. If p-N interactions were contained among cases with one slow proton ($l \leq 4$ mm), one would expect a forward-backward asymmetry for these protons. We present the data on the number of slow protons emitted into the forward and backward hemispheres in the l.s. for the

*Some results of this work were contained in the report of V. I. Veksler to the International Conference on Peaceful Uses of Atomic Energy, Geneva, August 1958.[1]

cases discarded because of criterion (1) only:

	Number of slow protons forwards	Number of slow protons backwards
Cases with an even number of prongs:	26	27
Cases with an odd number of prongs:	28	26
Total:	54	53

From this it can be seen that the same number of slow protons were emitted into the forward and backward hemispheres. This is evidence that the overwhelming proportion of slow protons comes from the evaporation process.

In interactions with quasifree nucleons, it is possible for a neutron to be emitted by the residual nucleus. In order to estimate the importance of this, let us consider the p-n interaction. In the emission of a single neutron from a photoemulsion nucleus, one should see a β-electron in more than 75% of the cases. In the selected p-n cases, β-electrons were observed in 43% of the cases. This indicates the possibility of emission of two neutrons by the photoemulsion nucleus, with the residual nucleus being stable. Experimental data[6] on the cross sections for (p, pn) and (p, p2n) reactions do not contradict the above assumption. Apparently the emission of the second neutron is mainly connected with the evaporation process. This is confirmed by comparison of characteristics of the interactions with a β-electron and without a β-electron. The mean multiplicity of these two types of interaction (2.54 ± 0.15 and 2.67 ± 0.22, respectively) and their angular distributions, given in Fig. 1, do not differ.

The ratio of p-p to p-n collisions was 1.55 ± 0.12. The cross section for inelastic p-p interactions turned out to be approximately 21 mb, and the ratio $\sigma_{pp}^{el}/\sigma_{pp}^{inel} \sim 0.5$. In evaluating the cross section for inelastic p-p interactions, it was assumed that the interactions with quasifree protons and quasifree neutrons were equally probable. This is confirmed by the equality of numbers of cases with even and odd numbers of prongs, and having one evaporation proton. The value σ_{pp}^{inel} agrees with the experimental data obtained in references 2 and 7 and with the theoretical estimates.[8,9]

All of the facts mentioned testify to the purity of selected cases. However, it should be emphasized that in work with photoemulsions, some arbitrariness always remains in the choice of inelastic proton-nucleon interactions. In particular, on account of secondary interactions inside the nucleus, p-p collisions can sometimes be taken to be p-n ones, and vice versa.

3. The distributions with number of charged secondary particles are given in Tables I and II for p-p and p-n collisions. In the lower lines of the tables are given results of calculations carried out with the statistical theory, taking the iso-

TABLE I. Distribution of p-p interactions with number of charged particles

Number of interactions, %	2	4	6	8
Experiment	45.3±5.2	44.7±5.1	8.8±2.3	1.2±0.8
Theory	32.8	58.5	8.6	0.1

TABLE II. Distribution of p-n interactions with number of charged particles

Number of interactions, %	1	3	5	7
Experiment	33.6±5.5	52.7±7.9	12.7±3.4	0.9±0.9
Theory	14.5	59.4	25.0	1.1

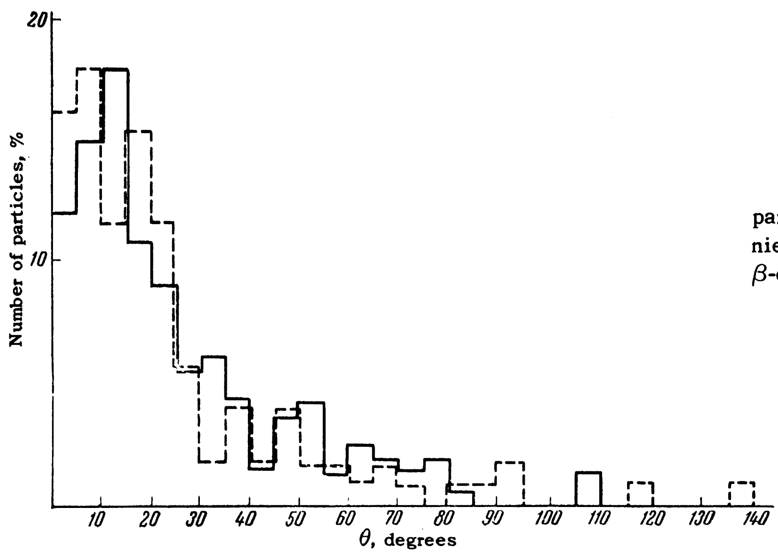

FIG. 1. Angular distributions of the secondary particles in the l.s. for p–n interactions accompanied by a β-electron (dashed line) and without a β-electron (solid line).

baric states into account.* The mean number of charged particles in p-p interactions was equal to 3.22 ± 0.12, and for p-n interactions, to 2.62 ± 0.13. The corresponding theoretical values are 3.53 and 3.25.

Some of the variance between experimental and theoretical data may be connected with a possible discrimination in selection of cases of interaction with quasifree nucleons for high multiplicities.

4. Identification of particles and measurement of their energy was carried out for only the slow particles ($b \geq 1.4\, b_{\text{plateau}}$). For particles coming to rest, the energies were determined from the range-energy curve. Ionization measurements were carried out on the tracks of particles not stopping in the camera. In this case the ionization was determined from the density of blobs[10] for particles with $b \leq 2b_{\text{plateau}}$, and according to the method outlined in reference 11 for particles with $b > 2b_{\text{plateau}}$. In this way the energies of 53 protons and 9 π mesons in p-p interactions and 22 protons and 5 π mesons in p-n interactions were determined.†

From these data it is possible to obtain some information about the angular distribution of secondary protons in the center-of-mass system (c.m.s.) and about the energy losses of the primary protons in production of π mesons. In the case of p-p interactions, 53 protons came off in the angular interval between 155 and 180° in the c.m.s. If the protons are assumed to have an isotropic angular distribution in the c.m.s., then we can expect

$$53 \Big/ \frac{1}{2} \int_{155^\circ}^{180^\circ} \sin\vartheta d\vartheta = 53 \Big/ 0.047 = 1230 \text{ protons}$$

in the 170 interactions.

This estimate shows that the angular distribution of protons is strongly anisotropic in the c.m.s. If one assumes that in each interaction, one or two secondary protons are produced, the half-angles for protons emitted into the backwards or forwards hemispheres are equal to ~ 20° or ~ 30°, respectively. The mean momentum in the c.m.s. of the selected protons in p-p and p-n interactions was equal to

$$(p_c)_{pp} = (1380 \pm 40)\ \text{Mev/c} \quad \text{and} \quad (p_c)_{pn} = (1250 \pm 50)\ \text{Mev/c}.$$

Knowing the energy of the protons emitted between 155 and 180° in the c.m.s. and assuming symmetrical emission of nucleons, it is possible to evaluate a lower limit for the energy loss. The energy transferred to π mesons is, in the l.s.,

$$E_{\pi l} = 2\gamma_c (E_{0c} - \bar{E}_{pc}),$$

where E_{0c} is the energy of the protons in the c.m.s. before the interaction, $\bar{E}_{pc}$ is the mean energy of the protons after interaction, $\gamma_c = (1 - \beta_c^2)^{-1/2}$, where β_c is the velocity in the c.m.s. The proportion of energy transferred to π mesons in p-p interactions was $E_{\pi l}/E_0 \approx 30\%$.

If it is assumed that, on the average, there is one secondary proton in each interaction,* then $^2/_3$ of all protons emitted into the backwards hemisphere were identified. Assuming that in the remaining cases the protons give up all of their kinetic energy in the c.m.s. into production of π mesons, it is possible to find an upper limit for the energy loss, which turned out to be 45%. However, this value is much too high for the actual loss. In fact, within the interval 155 — 180° in the c.m.s. the mean momentum does not change rapidly with changing angle (see Table III) and, consequently, it might be supposed that at angles less than 155° the momentum will not differ much from the values given above. Therefore the mean loss is apparently equal to 30%.

TABLE III

Angular interval, degrees	p_c, Mev/c
180—169	1380±60
169—155	1380±60

This corresponds to a mean energy for the π mesons (under the assumption that in each interaction there is one secondary proton) of $\bar{E}_{\pi l} \sim 800$ Mev in the l.s. and $\bar{E}_{\pi c} \sim 340$ Mev in the c.m.s.

5. In order to obtain the angular distributions of secondary particles in the c.m.s., it is necessary to know the momenta of all particles. The momenta of the fast particles were not measured, and it was assumed that their velocity in the c.m.s. β_{ic} was equal to the velocity of the c.m.s. β_c. For the particles whose momenta were measured, the transformation of emission angle was carried out

*The authors are grateful to V. S. Barashenkov and V. M. Maksimenko for acquainting them with the results of their calculations.

†In cases in which the particle did not stop in the camera and its momentum was not determined by multiple scattering, it was taken to be a proton with velocity calculated from the ionization. The possible admixture of π mesons and deuterons in these cases was probably small, since in the 22 particles identified (by scattering and ionization) only one turned out to be a π meson, and no deuterons were observed.

*This follows, for example, from the statistical theory. In any case, the mean number of protons in the interaction is less then 1.7 (see the later footnote † on page 875.

according to

$$\tan \vartheta_{ic} = \frac{1}{\gamma_c} \frac{\sin \vartheta_{il}}{\cos \vartheta_{il} - \beta_c / \beta_{il}}.$$

The angular distributions of secondary particles in p-p interactions are given in Fig. 2. The distributions obtained were roughly symmetrical. As a measure of asymmetry, one can employ $\Delta = \Sigma(n_f - n_b)/N$, where n_f and n_b are the number of particles going forwards and backwards, respectively, in the c.m.s. in a given interaction, and N is the total number of interactions. For all p-p interactions, $\Delta_{pp} = 0.16 \pm 0.13$, i.e., was practically zero. This indicates that the assumption $\beta_{ic} = \beta_c$ in our case is a sufficiently good approximation. In Fig. 2 it can be seen that for small multiplicities (n = 2) the angular distribution is sharply anisotropic. With increasing multiplicity the degree of anisotropy decreases, and for n = 6 — 8 the distribution is practically isotropic. It can be shown that the observed anisotropy cannot be produced by an erroneous transformation to the c.m.s. if the initial distribution in the true c.m.s. is isotropic.

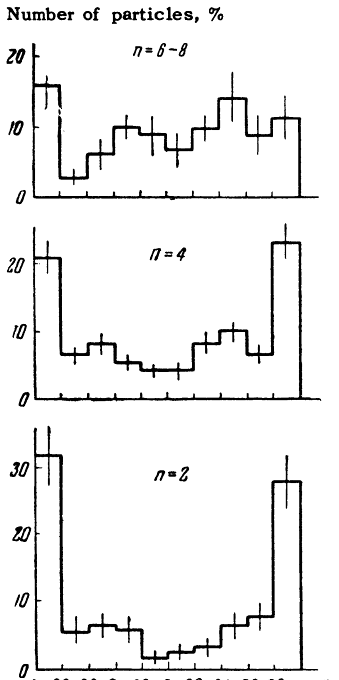

FIG. 2. Angular distributions of secondary particles in p—p collisions in the c.m.s. for various multiplicities n.

It has been shown earlier that the protons have a strongly anisotropic distribution. It seems natural to relate the anisotropy obtained for all secondary particles to them. Then the π mesons should have a substantially broader distribution than the protons. This is confirmed by the following considerations. Within the angular interval 155 — 180° in the c.m.s. there are 53 protons. In the asymmetrical interval 0 — 25° there should be, on the average, the same number of protons; in fact, 72 particles were observed. The remainder, equal to 72 − 53 = 19 ± 11, is an upper limit to the number of π mesons in the interval 0 — 25°.*

In addition, in those cases in a p-N collision with a slow proton, it is possible to evaluate a limiting angle in the l.s. by kinematical considerations[4] inside which a second nucleon can be emitted.† All particles emitted outside this angle are π mesons. Since the calculated limiting angles in the l.s. were roughly equal to 15 — 20°, it is possible to construct the angular distribution of π mesons emitted into the backwards hemisphere in the c.m.s. Angular distributions are given in Table IV for two assumptions about β_{ic}.

TABLE IV

$\cos\vartheta_c$	0—0.5	−0.5—−1.0
	Number of particles	
$\beta_{ic}=\beta_c$	18	32
$\beta_{ic}=1$	24	20

Thus, it is possible to conclude that the distribution of π mesons in the c.m.s. is broader than that of the protons. The data obtained also are not in contradiction with an isotropic distribution of π mesons in the c.m.s.

6. The angular distributions of secondary particles in the c.m.s. for p-n collisions, constructed in the same way as for p-p interactions, are given in Fig. 3. In the case of p-n collisions, a noticeable forwards-backwards asymmetry was observed.‡ The value of Δ_{pn} for all p-n interactions was $\Delta_{pn} = 0.60 \pm 0.15$.

First of all, one must make sure that the observed asymmetry cannot arise from an erroneous transformation to the c.m.s. The distribution of charged π mesons in the c.m.s. should be symmetrical, because of the symmetry of the initial state with respect to isotopic spin (just as many

*As noted earlier, the transformation to the c.m.s. is carried out under the assumption $\beta_{ic} = \beta_c$ in the case of fast particles. However, for particles emitted at small angles in the c.m.s. the true value of β_{ic} hardly affects the transition from l.s. to c.m.s. The effects of throwing slow particles into the interval considered from the backwards cone by an incorrect transformation would be quite small.

†This makes it possible to evaluate an upper limit to the mean number of protons in p—p interactions. In 36 out of 53 interactions with a slow proton, at least one fast charged particle – which might be a proton – is emitted within this limit. Thus $\bar{n}_p \leqslant (53 + 36)/53 \sim 1.7$

‡For cases with n = 1 there was a substantial discrimination, since only scatterings through angles greater than 5° were considered. Therefore, the angular distribution in the c.m.s. was strongly distorted in the small-angle region.

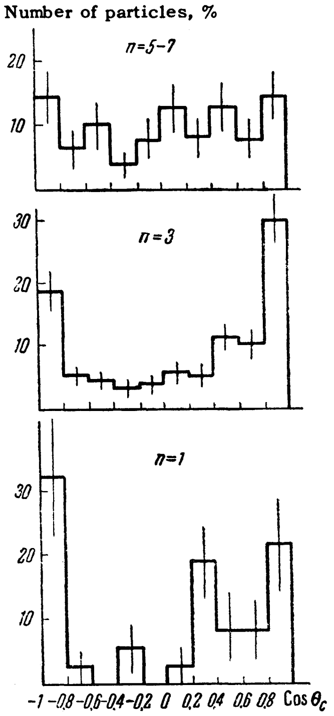

FIG. 3. Angular distributions of secondary particles in p–n collisions in the c.m.s. for various multiplicities n.

π^- mesons should go into the back hemisphere as π^+ mesons into the front and vice versa). The asymmetry of the π mesons may be due to the fact that their velocity $\beta_{\pi c}$ in the c.m.s. is much less than β_c, whereas in the transformation it has been assumed that $\beta_{\pi c} = \beta_c$. This would show up as a marked difference between the energy spectra of secondary particles for p-p and p-n interactions. It has been shown above that the mean value of the momentum in the c.m.s. (calculated from the slow protons in the l.s.) and, consequently, the lower limit of the energy loss, is approximately equal in the cases of p-p and p-n interactions. Therefore, it is difficult to assume that the energy spectra of secondary particles are different in these interactions. The most marked asymmetry shows up in p-n interactions with three secondary particles ($\Delta_3 = 0.83 \pm 0.23$). It is useful to compare the angular distribution of three-pronged events with the summed angular distributions of two- and four-pronged events ($\Delta_{2;4} = 0.12 \pm 0.14$), since the energetic characteristics of these groups do not appear to differ. The angular distributions for $n = 2 - 4$ for all particles and, consequently, for π mesons, is symmetrical. Therefore, the angular distribution of π mesons for $n = 3$ should be symmetrical. The observed asymmetry can come only from the protons. However, the mean energy of secondary nucleons in p-p and p-n interactions in the c.m.s. is the same. Therefore, it follows that the asymmetry in p-n interactions arises because protons go mainly forwards in the c.m.s. and neutrons, backwards.

7. Thus, the analysis of p-p and p-n interactions makes it possible to draw the following conclusions.

(a) The angular distribution of nucleons in p-p interactions is strongly anisotropic in the c.m.s. The angular distribution of all particles in p-p interactions is anisotropic for small multiplicities and becomes approximately isotropic with increasing multiplicity.

(b) The proportion of the energy of the initial proton which is transferred to π mesons is $\sim 30\%$ in the l.s.

(c) The observed asymmetry in the angular distribution of secondary particles in p-n interactions comes from the fact that in the c.m.s. the protons are emitted preferentially into the forward hemisphere, and the neutrons into the backward one.

Experimental data on p-p interactions at lower energies[12] also show the nucleons to be anisotropic in the c.m.s. Some proton asymmetry in n-p interactions was observed at 1.7 Bev.[13] In recent papers[14,15] on p-p interactions at 6.2 Bev, the authors came to conclusions, confirmed by our results.

The totality of data seems to indicate that periphery nucleon-nucleon collisions play an important role.* One of many possible theoretical models of such collisions is the scheme considered by Tamm,† in which it is assumed that the interaction goes by way of exchange of one π meson, with formation of two isobars. Such a model makes it possible to explain qualitatively both the anisotropy of the nucleons in p-p collisions and the asymmetry of protons in p-n collisions in the c.m.s. A more detailed analysis of experimental data and comparison with the theory would only be possible with a substantial increase in statistics.

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[1] Proc. Second Internat. Conf. on Peaceful Uses of Atomic Energy, Reports of Soviet Scientists

*This was emphasized by V. I. Veksler in discussion of the results of the present work. Analogous considerations were presented in references 16 and 17.

†We are very grateful to I. E. Tamm for detailed information about calculations connected with various models of periphery collisions.

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Errata

Volume	No.	Author	page	col.	line	Reads	Should read
10	5	Bogachev et al.	872	1	21	± 0.3 cm	± 0.7 cm
11	6	Gol'danskii et al.	1229	r	Eq. (13)	$\frac{1}{4\pi^2}\ \frac{h}{Mc}$	$\frac{1}{4\pi^2}\ \frac{h}{Mc}$
			1331	r	4	$\ldots + \frac{1}{4} + \frac{\gamma_a}{2}$	$\ldots + \frac{1}{4}\cos\ \ + \frac{\lambda}{2}$
12	2	Moroz and Fedorov	210	1	Eq. (7)	$\ldots \frac{\sin k_0 x_0}{k_0} e^{i\mathbf{kx}} d^3k,$	$\ldots \frac{ik_0\delta(k^2)}{\lvert k_0\rvert} e^{ikx}\, d^4k.$
			212	1	Eq. (39)	$\ldots = 4\pi\hbar c \ldots$	$\ldots = -4\pi\hbar c \ldots$
			212-3	r-1	Eqs. (44) and (39)	$\ldots + \frac{1}{2} iel\, \nabla_k \psi_4(x) \ldots$	$\ldots + \frac{1}{2} iel \nabla_k \psi''_4(x) \ldots$
			213	r	Eq. (51), line 2	$\ldots \frac{iel}{2} \int \nabla_m \psi_4(x) \ldots$	$\ldots \frac{iel}{2} \int \nabla_m \psi''_4(x) \ldots$
			213	r	Eq. (53)	$\ldots e^{-ik_0 \lvert x_0 - x'_0 \rvert} e^{i\mathbf{k}(\mathbf{x}-\mathbf{x}')} \frac{d^3k}{k_0}.$	$\ldots e^{ik(x-x')} \frac{d^4k}{2\pi i (k^2 - i\varepsilon)}$
12	3	Nikishov	530	1	Eq. (10)	—	$\mu^{(2)} = \frac{1}{2\beta_2\zeta} \ln\left[\frac{y_1 - 1}{y_1 + 1} \cdot \frac{-y_2 - 1}{-y_2 + 1}\right]$
			533	r	Fig. 4	The dashed curve of Fig. 4 has been incorrectly calculated (corrections to μ^+ scattering on electrons). Its value ranges from − 6 to − 8.	
12	1	Anisovich	72, 75		Eqs. (4a), (4b), (11)	$\sigma(\pi^+ + p \to n + \pi^+ + \pi^+)$	$2\sigma(\pi^+ + p \to n + \pi^+ + \pi^+)$
	5	”	948		Eq. (6)	$\sigma(\pi^- + p \to n + \pi^0 + \pi^0)$	$2\sigma(\pi^- + p \to n + \pi^0 + \pi^0).$