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19. The quantity M_t was evaluated on the basis of the relation [14]

$$M_t = \sum_i (E_{\pi, i} - p_{\pi, i} \cos \theta_{\pi, i}) \qquad (1)$$

(the sum was done over all π-mesons) or using the formula

$$M_t = M_N - (E_p - p_p \cos \theta_p) \qquad (2)$$

in cases in which a proton was emitted. $E_{\pi, i}$, E_p, $P_{\pi, i}$, P_p are the total energy and momentum of a π-meson and of a proton, respectively. $\theta_{\pi, i}$; θ_p are the angles of emission, and M_N is the mass of a nucleon.
20. The quantity M_t expressed in the mass of a nucleon is equal to the value of energy ε, which a proton gives to π-mesons, i.e. equal to the target mass, with which the π^--meson collides. The maximal and minimal values of M_t were obtained for limiting suppositions about the nature of identified swift positive particles (whether they are $\pi^\pm$-mesons or protons).

ELASTIC AND INELASTIC PROTON-NUCLEON INTERACTIONS AT HIGH ENERGIES

Staff of the Joint Institute for Nuclear Research, Physical Institute of the Academy of Sciences of the USSR, Phys. Technical Institute of the Academy of Sciences of the Uzbek SSR, Physical Institute of the Bulgarian Academy of Sciences.

(presented by V. I. Veksler)

PART I

S. A. Azimov, B. P. Bannik, V. G. Grishin, Do In Seb, L. F. Kirillova, P. K. Markov, V. A. Nikitin, L. G. Popova, I. N. Silin, L. V. Silvestrov, E. N. Tsyganov, M. G. Shafranova, B. A. Shahbazyan, A. A. Yuldashev, A. Zlateva, A. Peieva, L. Khristov and Ch. Chernev.

PROTON-PROTON ELASTIC SCATTERING AT THE ENERGY OF 8.5 AND 2.8 BeV

Preliminary data on proton-proton elastic scattering at 8.5 BeV were published earlier [1]. In this work the accumulation of statistics is continued. To increase the statistics in the region of small angles a photo-emulsion chamber, loaded with water [2] was exposed to 8.2 BeV protons. Because of the small difference in the energies these data were combined. 480 events of elastic scattering were detected on the whole.

Experimental results are given in Table I.

The total cross section of the elastic scattering is equal to 8.74+0.40 mb. The differential cross

Table 1. $p-p$ scattering results at 8.2 BeV

θ in the center of mass system	Scanning efficiency		Differential cross sections		Combined data
	" Dry " chamber	" Wet " chamber	" Dry " chamber	" Wet " chamber	
1.5°–2.5°	0.916 ± 0.030	1.000 ± 0.040	153.6 ± 33	$142\pm^{49}_{41}$	149 ± 27
2.5°–4.5°	0.970 ± 0.007	0.918 ± 0.040	124.0 ± 15	$103\pm^{32}_{26}$	120 ± 13
4.5°–6.5°	0.968 ± 0.009	0.913 ± 0.030	93.0 ± 11	$92\pm^{21}_{15}$	93 ± 9.6
6.5°–8.5°	0.945 ± 0.013	0.868 ± 0.043	63.3 ± 7.7	$51\pm^{13}_{10}$	59 ± 6.3
8.5°–10.5°	0.845 ± 0.013	—	35.9 ± 5.5	—	35.9 ± 5.5
10.5°–12.5°	0.890 ± 0.035	—	13.3 ± 2.9	—	13.3 ± 2.9
12.5°–14.5°	0.700 ± 0.044	—	6.5 ± 2.1	—	6.5 ± 2.1
14.5°–16.5°		—	4.0 ± 1.5	—	4.0 ± 1.5
16.5°–18.5°		—	1.0 ± 0.7	—	1.0 ± 0.7
18.5°–20.5°		—	0.5 ± 0.5	—	0.5 ± 0.5

section obtained (differing from the data published earlier [3]), are in sharp disagreement with the simple theory of proton-proton scattering where the real part of phase shifts and the dependence of the interaction on the spin [4] are neglected. According to this theory:

$$\frac{d\sigma(\theta)}{d\Omega} \leq \left|\frac{\sigma_{tot}}{4\pi\lambda\!\!\!^{-}}\right|^2$$

Taking $\sigma_{tot} = 30$ mb (σ_{inel} is taken from the work of Bogachev et al [5]), we have:

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{nucl} \leq 57\,\text{mb/sr}$$

that is not consistent with our experiment.

Following Bethe's method [6], the interference of nuclear and Coulomb scatterings was calculated for the spinless particles. The real part of the scattering amplitude was taken from our experimental data in the region of angles where the Coulomb scattering is negligible. The form factor was taken in the form:

$$F^2(k\theta) = e^{-\left(\frac{ka\theta}{\sqrt{2}}\right)^2}$$

The radial parameter " a " is related with the mean square radius r_n by the following equation:

$$r_n = \sqrt{3/2}\, a$$

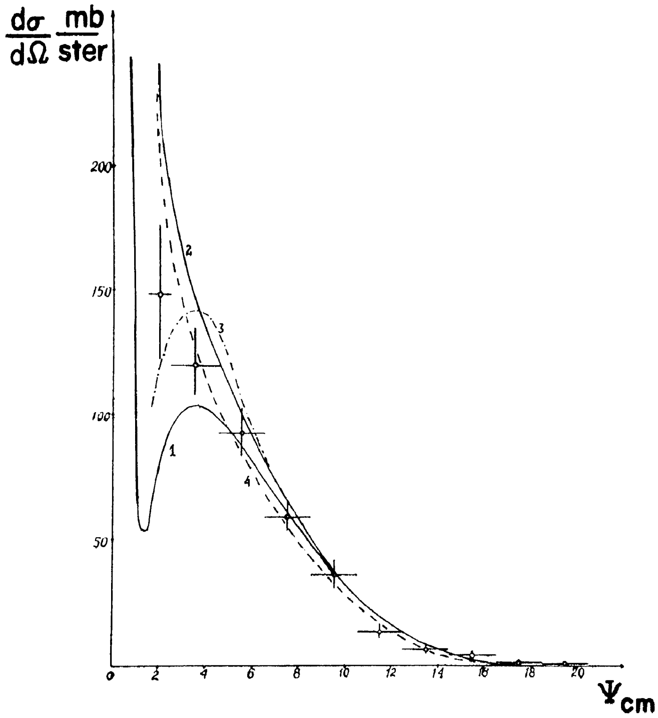

Fig. 1 Experimental data on elastic scattering at the energy 8.5 BeV and the calculated curves under the assumption of the paper by Bethe [6],

Curve 1 $a = 1.0f$ $\text{Re}f(0) = +3.04\times10^{-13}$ cm
$\text{Im}f(0) = 2.38\times10^{-13}$ cm

Curve 2 $a = 1.0f$ $\text{Re}f(0) = -3.04\times10^{-13}$ cm
$\text{Im}f(0) = 2.38\times10^{-13}$ cm

Curve 3 $a = 1.2f$ $\text{Re}f(0) = +4.2\times10^{-13}$ cm
$\text{Im}f(0) = 2.38\times10^{-13}$ cm

Curve 4 $a = 1.0f$ $\text{Re}f(0) = -2.70\times10^{-13}$ cm
$\text{Im}f(0) = 2.38\times10^{-13}$ cm

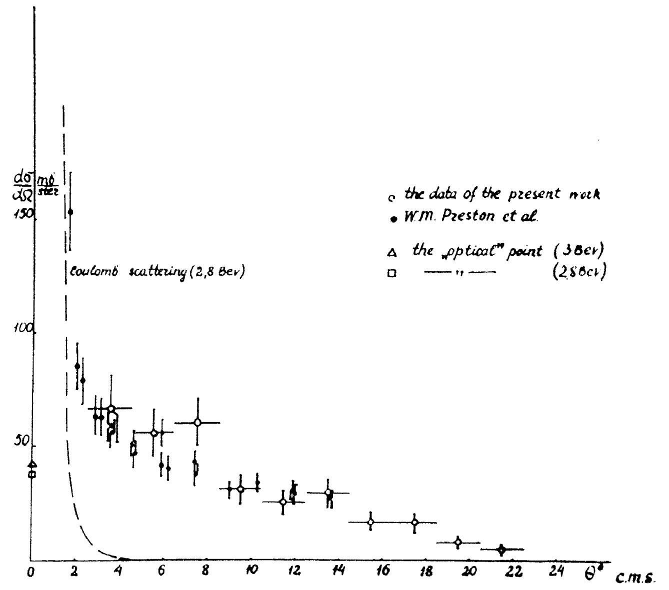

Fig. 2 *(a)* Experimental data on elastic scattering at the energy 2.8 BeV—obtained in present work in comparison with the data of Veksler [7].
Circles are the data of present work.
Squares are the data of Veksler [7].

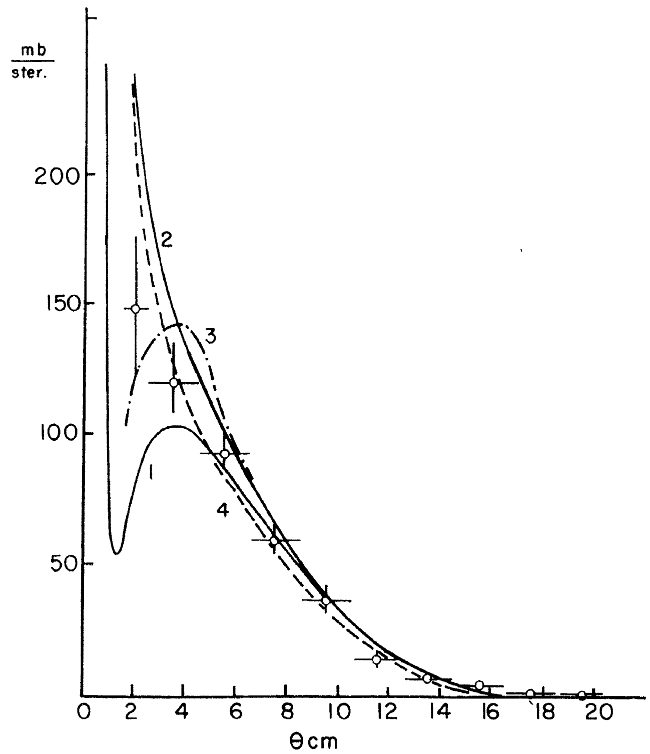

Fig. 2 *(b)* Differential cross section of elastic p—p scattering
- - - - - Coulomb cross section.
— - — - — Model C (see Cork et al [3]).

The experimental data and calculated results are given in Fig. 1. From Fig. 1 the conclusion on the absence of any considerable real part in the scattering amplitude suggests itself. In this case the assumption on the difference of total interaction cross sections in singlet and triplet states is needed to explain the experimental data. It is of interest to note that if the real part of the scattering amplitude is negligible for our energy $\sigma^s_{\text{tot}} = 100$ mb $\sigma^t_{\text{tot}} = 6$ mb. Purely imaginary optical potentials for singlet and triplet interaction which well describe experimental data may be chosen.

For different models, in the case of either complex or purely imaginary potential, the mean square radius of the proton-proton interactions is almost the same and equal to (1.2-1.3) f.

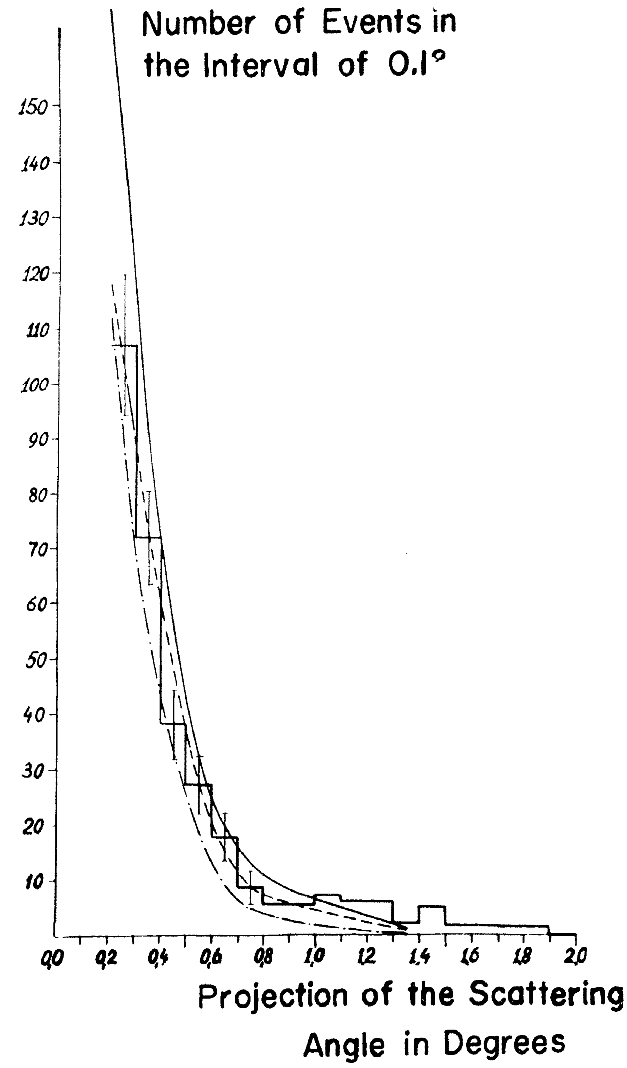

Fig. 3 Elastic scattering of protons at the energy 8.7 BeV at photo-emulsion nuclei.

We think that in the region of small scattering angles the statistics should be increased to obtain more reliable conclusions on the presence or absence of the interference of Coulomb and nuclear scattering. In connection with this, data on elastic scattering of protons on photoemulsion nuclei at 8.7 BeV are of some interest. The obtained angular distribution in the laboratory coordinate system in the projection on the emulsion plane is represented in the form of the histogram in Fig. 3. Theoretical curves are also given here. Calculations were carried out for three values of the real part of the forward nucleon-nucleon scattering amplitude:

$$\mathrm{Re}\, f_{NN}(0)\,.$$

The upper curve corresponds to $\mathrm{Re} f_{NN}(0) = -14.7f$, the center one to $\mathrm{Re} f_{NN}(0) = 14.4f$, the lower one to $\mathrm{Re} f_{NN}(0) = 0$. From Fig. 3 it is seen that $\mathrm{Re} f_{NN}(0) = 14.4f$ does not agree with the experiment. (The estimation by χ^2 method gives the probability of coincidence of the curve with the experiment equal to 0.1 per cent). These results do not contradict the data on $p-p$ scattering.

Due to the disagreement of the data on elastic $p-p$ scattering at 8.5 BeV with the simple non-spin purely absorbing model, we estimated by the method of Lubimov et al[1] the upper limit of the cross section of charge-exchange proton-neutron elastic scattering, which must be small according to this model.

The number of quasielastic $p-p$ scattering events was compared with that of the cases which could be interpreted as charge-exchange elastic scattering on quasifree neutrons. The value of the charge-exchange cross section which we obtained, ($\sigma_{\mathrm{exch}} \leq 0.45 \pm 0.45$ mb), means that the whole nucleon elastic scattering cannot be described as a peripheral interaction with one meson exchange. In this case:

$$\frac{\sigma \text{ charge exchange}}{\sigma \text{ elastic}} = 4$$

2.8 BeV and 6.2 BeV elastic proton-proton scattering was studied in the small angle region by the method analogous to that of Lubimov et al. [1] 252 events of elastic scattering at the energy 2.8 BeV and 83 events at the energy 8.2 BeV were found. In the first report of this result [7] the possibility of a large systematic error in absolute measurements was indicated. The data obtained in this paper are in good agreement with the earlier report [7] in their absolute values. Experimental results are given in Fig. 2. It is seen, from the data, that in the region of 3 BeV, an excess over the point obtained according to the optical theorem for non-spin case also takes place.

PART II

Van Shu-feng, T. Visky, I. M. Gramenitsky, V. G. Grishin, N. Dalkhazav, I. M. Dremin, Z. Corbel, R. M. Lebedev, V. M. Maksimenko, A. A.Nomofilov, M. I. Podgoretsky, L. Rob, V. P. Streltsov, D. Tuvdendorge, M. S. Khvastunov and D. S. Chernavsky.

INELASTIC PROTON-NUCLEON INTERACTIONS AT 9 BeV

A study of inelastic nucleon-nucleon interactions at high energies may give some information concerning the nucleon structure. The results obtained in a paper by Bogachev et al[5] indicate a strong anisotropy of the angular distribution of the secondary nucleons in the center-of-mass system and give the lower limit of energy in π-mesons. The identification of particles and measurements of their energies was, however, carried out only for slow particles. It was, therefore, useful to continue the study of $(p-p)$ and $(p-n)$ interactions in such conditions in which the measurements of the multiple scattering and the determination of the sign of fast particles is possible.

1. In a stack of NIKFI" R " emulsion pellicles, irradiated in the 9 BeV proton beam of the synchro-

phasotron of the Joint Institute for Nuclear Research, an along-the-track scanning of primary protons was done according to two conventions: First, a conventional method, and secondly, a fast scanning method were used. 411 events of $(p-p)$ interactions and 218 events of $(p-n)$ interactions were selected. The selection of inelastic $(p-p)$ and $(p-n)$ interactions was carried out in accordance with the criteria described in a paper by Bogachev et al [5]. Some of the results presented here are based only on a part of the selected material and must be considered as preliminary.

Prong distributions are given in Table II. The mean number of charged secondaries in $(p-p)$ and $(p-n)$ interactions is: $3.26+0.10$ and 2.58 ± 0.14, respectively.

Table II. Theoretical and experimental mean values of the prong distributions for $p-p$ and $n-p$ interactions. The experimental data refer here to such cases in which the recoil proton had $p_\perp \leqslant 2, 5\mu$; theoretical calculation in the second variation is given taking these circumstances into account.

$p-p$	Variation I		Variation II	
	Calculation	Experiment	Calculation	Experiment
Fraction of 2-prong stars in %	35	46 ± 5.4	35	35 ± 14
Fraction of 4-prong stars in %	58.9	44.7 ± 5.3	63.4	59 ± 18
Fraction of 6-prong stars in %	6	8.1 ± 2.2	1.6	6 ± 3
Fraction of 8-prong stars in %	0.1	0.62 ± 0.62	—	—
Mean multiplicity . .	3.46	3.25 ± 0.10	3.4	3.42

$p-n$	Calculation	Experiment
Fraction of 1-prong stars in %	18.4	35.1 ± 6.1
Fraction of 3-prong stars in %	65.2	53.2 ± 7.5
Fraction of 5-prong stars in %	15.7	9.5 ± 3.2
Fraction of 7-prong stars in %	0.7	2.1 ± 1.5
Mean multiplicity.	2.96	2.6 ± 0.114

2. For the identification of fast particles the measurements of multiple scattering and of blob density on secondary tracks, having dip angle $\phi \leq 5°$ were carried out. In addition, a determination of the sign of the charged particles was made by measuring the curvature in the magnetic field of the accelerator.

It should be noted that the usual identification of positive particles in the interval $p\beta$ from 1.5 BeV/c to 2.5 BeV/c is impossible. Some indirect considerations show, however, that the majority of these particles are π-mesons.

3. The angular distribution in c.m.s. for the secondary protons from $(p-p)$ interaction was done; it shows strong anisotropy (Fig. 4). The angular distribution of π-mesons shown in Fig. 5 is also anisotropic, but it is considerably broader than that of protons. The momentum distribution of protons emitted backward in the c.m.s. is shown in Fig. 6. The mean value of proton energy in the c.m.s. and the mean value of the transverse momentum are $\overline{E}_{pc} = (1520\pm45)$ MeV, $P_\perp = (372\pm25)$ MeV/c. The coefficient of inelasticity K and fraction of energy transmitted into π-mesons in the lab system are

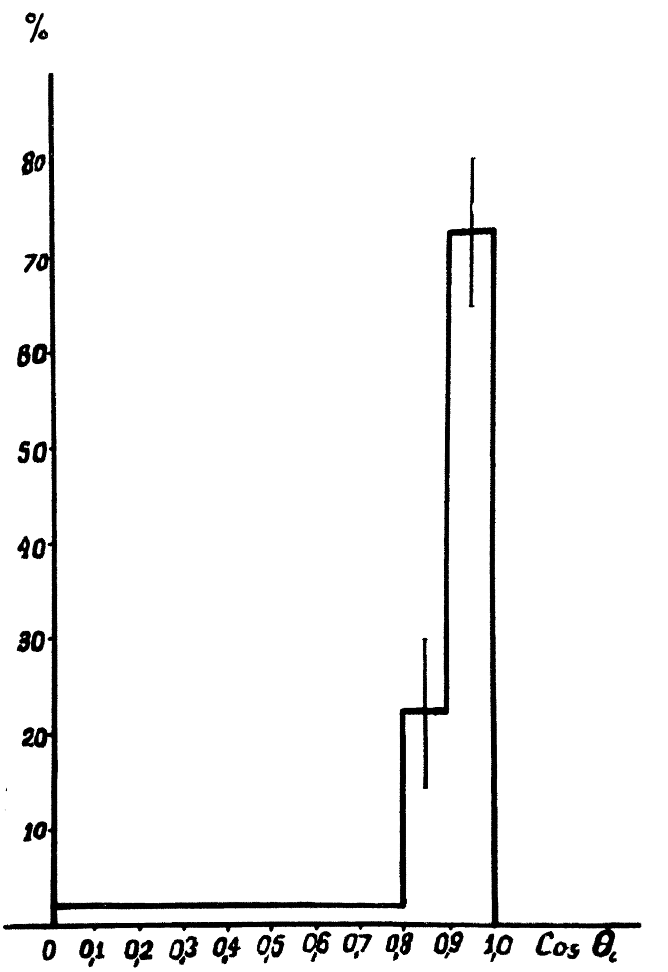

Fig. 4 Angular distribution of protons in c.m.s. for $(p-p)$ interactions.

$K = 0.55 \pm 0.03$ and $E_\pi / E^0 = 0.39 \pm 0.02$. The average number of protons per interaction is $\bar{n}_p = 1.24 \pm \pm 0.28$ and the average number of charged π-mesons is 2.01 ± 0.3. Assuming the number of neutral π-mesons to be half the number of charged ones it is possible to estimate the average number of π-mesons per interaction: $\bar{n}_p = 1.5(\bar{n}_\pi)_{ch} = 3.02 \pm 0.46$. From these data it is easy to obtain the mean energy of one π-meson in the c.m.s.: $\bar{E}_{\pi c} = (475 \pm 78)$ MeV. The mean energy of a π-meson in the c.m.s. obtained from direct measurements is (460 ± 30) MeV. The transverse momentum of π-mesons is (240 ± 20) MeV/c.

The angular distribution of protons in c.m.s. for $(p-n)$ interactions is shown in Fig. 7. The number of protons emitted forward is apparently greater than the number of protons emitted backward; the corresponding difference per interaction is $\Delta_{pn} = 0.62 \pm \pm 0.1$.

The mean proton energy in c.m.s. for $(p-n)$ interactions is (1480 ± 100) MeV and it does not differ from the mean proton energy from $(p-p)$ interactions.

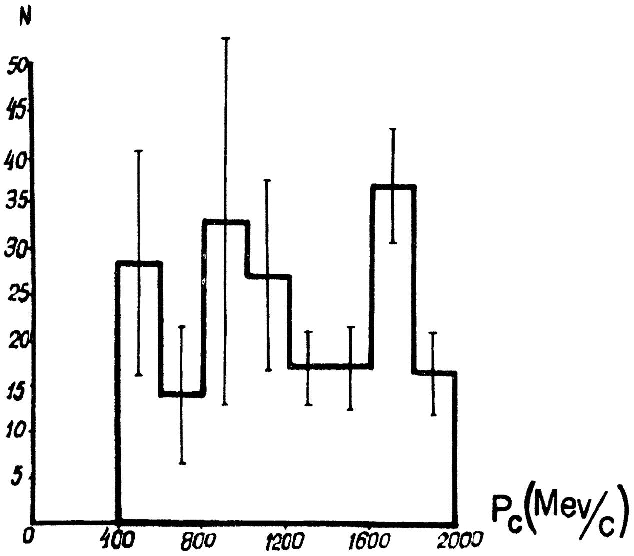

Fig. 6 Momentum distribution of the proton in c.m.s. for $(p-p)$ interactions.

4. An important problem is the dependence of angular and energy distributions of nucleons on multiplicity. Considering two kinds of collisions —peripheral and central—one should expect a broader angular distribution for high multiplicity [8]. Further, to increase the statistics one will consider jointly data from $(p-p)$ and $(p-n)$ interactions as the angular and energy distributions of nucleons in these interactions do not seem to differ.

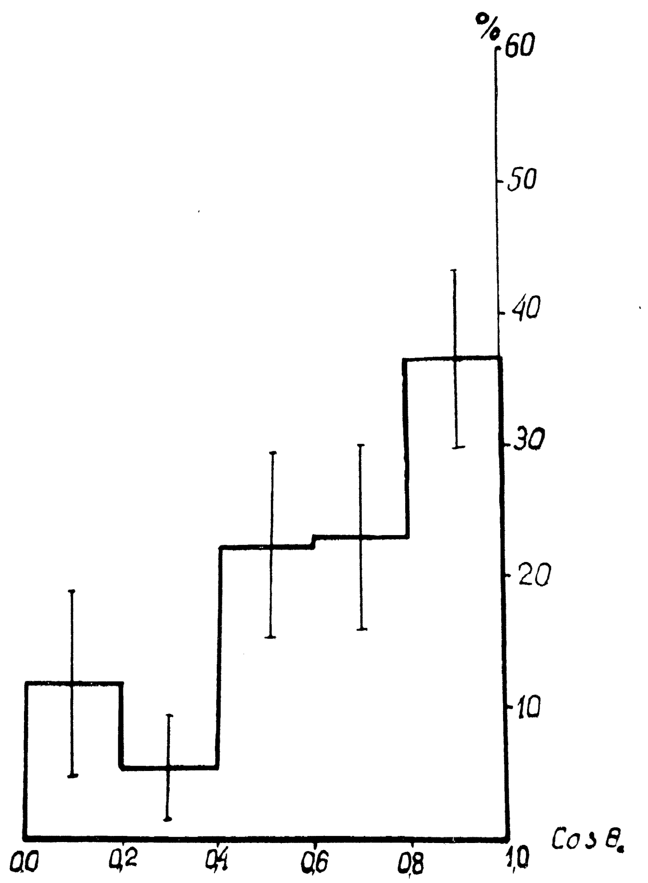

Fig. 5 Angular distribution of π-mesons in c.m.s. for $(p-p)$ interactions.

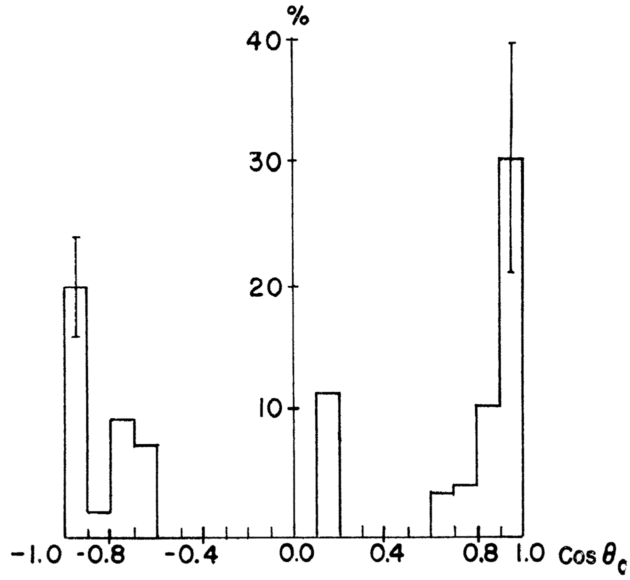

Fig. 7 Angular distribution of protons in c.m.s. for $(p-n)$ interactions.

Table III. Momenta and angles of emission

	p_c(MeV/c)		p (MeV/c)		$\overline{\theta^\circ}_c$	
Multiplicity .	2-3-4	5-6-7	2-3-4	5-6-7	2-3-4	5-6-7
Protons . . .	1240 ± 50	928 ± 65	358 ± 16	421 ± 36	20 ± 2	31 ± 6
Mesons . . .	329 ± 30	370 ± 50	244 ± 18	175 ± 20	39 ± 2	46 ± 5

Table III shows the mean value of momentum, of transverse momentum, and of the angle of emission in c.m.s. for protons and π-mesons for small ($n =$ $= 2$-3-4) and high ($n = 5$-6-7) multiplicities.

For a final conclusion a significant increase of statistics will be needed in order to determine all the characteristics discussed for each value of multiplicity separately. This work is being carried out.

The quantity $\alpha = \sqrt{\frac{p_\perp^2}{2}}$ characterizes the transverse dimensions of the region of the interaction. In Table IV are given the value for protons and π mesons for different multiplicities.

Table IV. The parameter α for protons and mesons

	α MeV/c	
Multiplicity . . .	2-3-4	5-6-7
Protons	296	257
π-mesons	198	140

As it can be seen from Table IV the value of α depends weakly on multiplicity. It is interesting to note that secondary protons in the c.m.s. are emitted within small angles with respect to the primary protons for low as well as for high multiplicities.

In particular for 4- and more-prong interactions nearly all protons are emitted within an angle less than 60°, while for an isotropic angular distribution half of the cases should have angles more than 60°. It is then reasonable to assume, that with the increase of multiplicity one does not have significant changes in the general features of the interactions.

Considering two kinds of interactions, central and peripheral, one must conclude that the major part of the experimental material belongs to one of those kinds.

One may, for example, consider that in central collisions the angular distribution of protons should be nearly isotropic. In this case one may estimate the upper limit of the dimensions of a so-called "kern" which does not exceed 0.2—0.3 of the nuclear radius.

It might be of interest to compare available experimental data with theoretical calculations concerning peripheral nucleon-nucleon interactions. The theoretical calculations were done in the pole approximation.

As is well known in such calculation, one makes the following assumptions:

(1) One neglects the interference of the one-meson graph with multi-meson ones. One may, however, show that the interference terms in such a case are small, as the probability of the coincidence of all the quantum numbers (isospin, its projection, spin, its projection and so on) of the excited nucleus produced in one meson and multi-meson graphs, is small.

(2) In the propagation function one keeps only the pole term. The second term $\int\limits_{(3\mu)^2}^{\infty} \frac{\rho(\kappa)d\kappa}{k^2+\kappa^2}$ is neglected.

(3) The interaction cross section of a virtual π-meson with the nucleon $\sigma(k^2)$ is considered to be weakly dependent on the degree of virtuality of the π-meson, i.e. on the value of k (where k^2 is the momentum four-vector of the intermediate meson). In carrying out the calculation the data on the value of the cross section of $\pi - N$ interactions at corresponding energies were used.

It could be expected from the very beginning that such a calculation was correct if $k^2 < (3\mu)^2$. Considering the theoretical approximation for large value of k^2 one may, however, get some information about the validity of pole approximation in the region $k^2 > (3\mu)^2$ from the experimental data.

There were two variations of the calculation:

Variation I—the calculation without additional restrictions for the value of k^2. The upper limit of k^2 was determined by the conservation laws. In this case the characteristic value of k^2 was $(7\mu)^2$.

Variation II—the calculation with additional restrictions.

Total cross sections of one-meson interaction in the two variations are 18 mb and 4 mb, respectively. Hence it follows that the one-meson graph without additional restrictions may be used to describe the main part of the experimental material. Variation II describes only a part of the one-meson interactions. Therefore, it can be compared only with a small part of the specially selected experimental material. The condition $(p_\perp)_r \leq 2.5\mu$ was chosen as a criterion of such selection, where $(p_\perp)_r$ is the transverse momentum of the recoil proton.

This was done because in the theoretically calculated distribution of $(p_\perp)_r$ (in accordance with variation II) beyond the limit of $p_\perp > 2\mu$ one has a small number of such events (see Fig. 9).

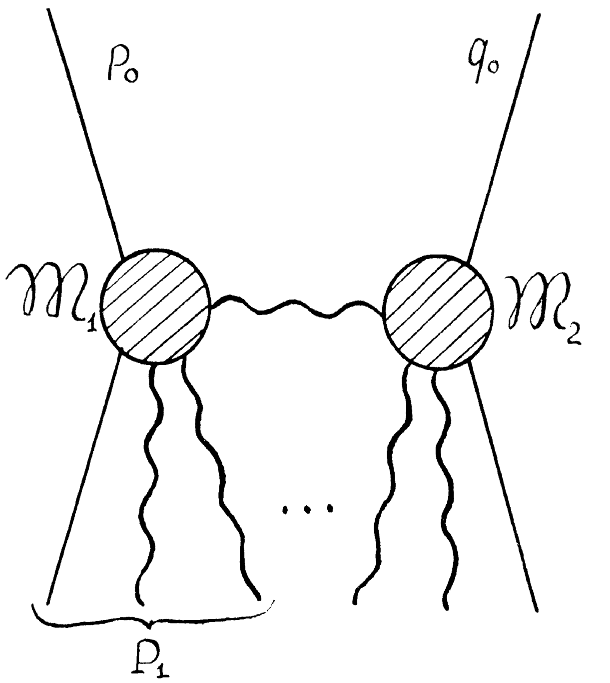

Fig. 8 One-meson graph of nucleon-nucleon interactions.

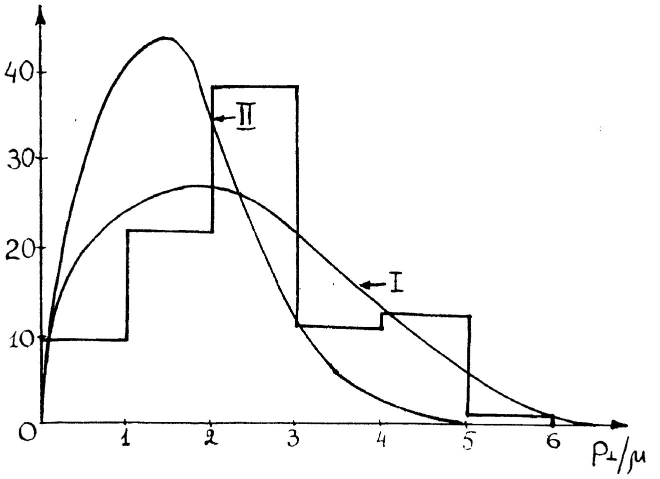

Fig. 9 Distribution of transverse momenta of nucleons. I and II are theoretical curves for variations I and II respectively; the histogram represents the experimental data.

With the first variation the following have been calculated: the distribution of $p_\perp$ for nucleons, the energy distribution of recoil nucleons in the laboratory system and the angular distribution of π-mesons in c.m.s. These results, as well as experimental ones, are presented in Figures 9, 10, 11, respectively. These plots indicate satisfactory agreement.

In Table II are given the theoretical and experimental mean values of the prong distributions for $(p-p)$ and $(p-n)$ interactions. The comparison of these data shows that the theoretical calculations are not in contradiction with the experimental observations.

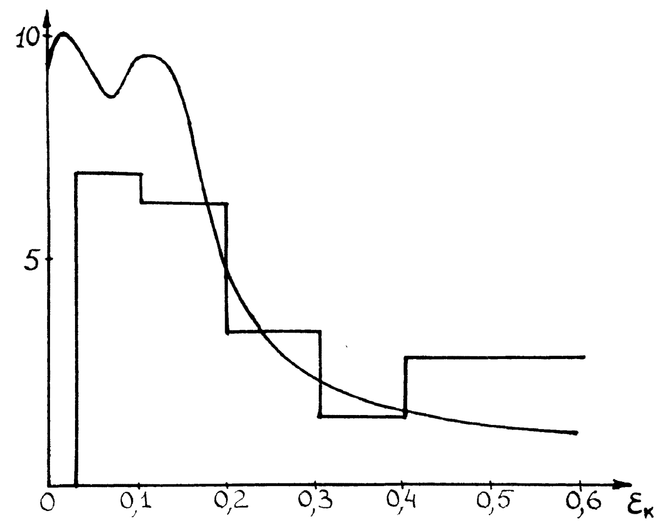

Fig. 10 Energy distribution of recoil nucleons in lab. syst. (variation I).

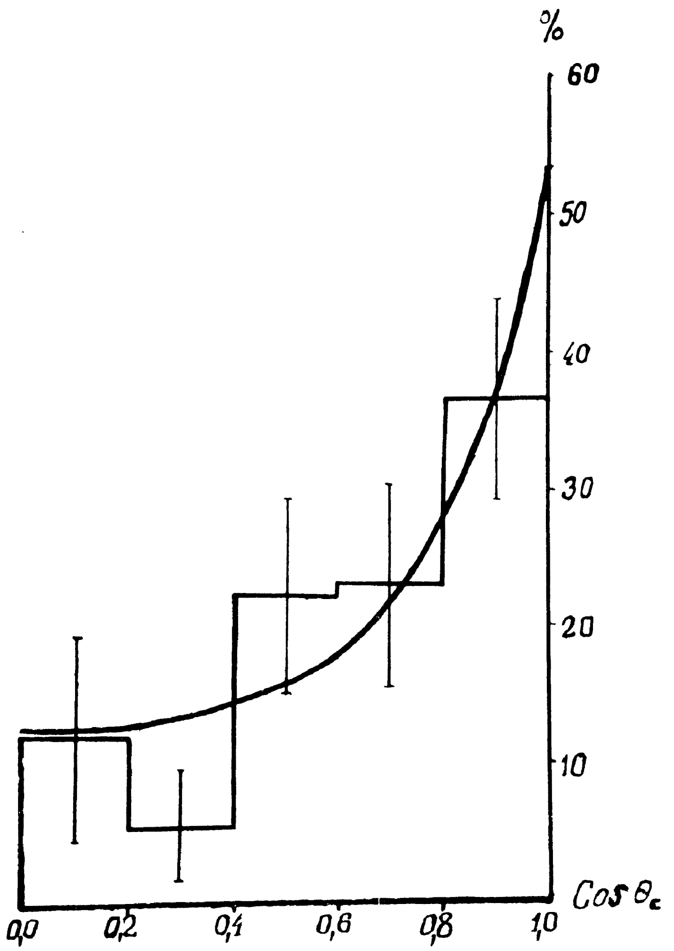

Fig. 11 Angular distribution of recoil nucleons in lab. syst. (variation II).

It is interesting to note that the multiplicity calculated from the one-meson graph approximately agrees with the results of statistical theory. Hence it follows that the multiplicity cannot be considered to be a good criterion to separate peripheral and central collisions. For $(p-n)$ interactions the asymmetry of charged particles in c.m.s. was calculated and was found equal to 0.47, which agreed satisfactorily with the experiment.

In the second variation the energy distribution of recoil nucleons (shown in Fig. 12) and the distribution of multiplicities (given in Table II) were calculated. At the same time in that calculation one assumed that in the back hemisphere there was necessarily a proton. The experimental data are selected in accordance with the criterion $(p_\perp)_r \leq 2.5\mu$ (plotted in Fig. 12); they agree with the theoretical calculation.

The comparison carried out shows that peripheral interaction calculated by means of pole approximation satisfactorily describes the main part of the experiment and, consequently, the pole approximation can be used up to $k^2 \lesssim (7\mu)^2$. This fact indicates: (1) that the non-pole term in the propagation function is small in the region $k^2 \lesssim (7\mu)^2$, (2) the cross section as a function of k^2 is a smooth, slowly changing function up to $k^2 \lesssim (7\mu)^2$.

Thus, the experiments carried out and their further statistical improvement may, it seems to us, give some information (although indirect) about such quantities as the functions $\phi(\kappa)$ and $\sigma(k^2)$ which are very important for modern theoretical physics. This may be of interest since we have no other experimental sources of such information.

That fact that the results of calculations according to the second variation, $k^2 \leq (3\mu)^2$, agree well with part of the experimental results (selected in accordance with criterion $p_\perp \leq 2.5\mu$) is important only as an additional confirmation; there is no new information here.

The comparison of the absolute values of cross sections shows that the contribution of the interactions of another kind (such as multi-meson, K-meson, central) may be 20-30% of the total cross section. However, to separate them out of all the events in our experiment is impossible, as it is difficult to give a criterion for such separation. (High multiplicity in the star, as it was pointed out above cannot be such a criterion.)

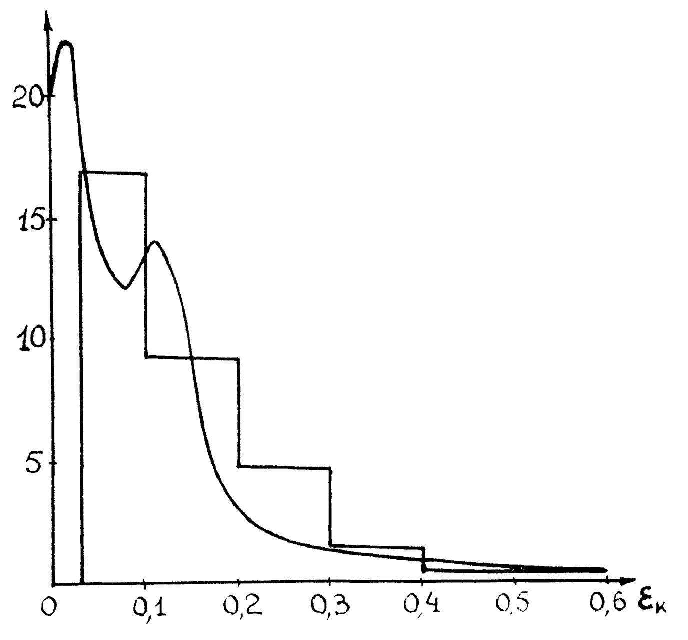

Fig. 12 Energy distribution of recoil nucleon.

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DISCUSSION

SANDWEISS: Referring to your elastic scattering cross section, of 8.7 mb, did that refer to 3 BeV protons?

VEKSLER: 8.2 BeV.

RECENT WORK ON NUCLEON-NUCLEON SCATTERING AT HARWELL

B. Rose

Atomic Energy Research Establishment, Harwell, Didcot, England

I. POLARIZATION IN *n—p* SCATTERING (20-120 MeV) (Huxtable, Langsford, Scanlon, and Thresher)

In comparison with that on the $p-p$ scattering process, the data on $n-p$ scattering in the energy range above 20 MeV is very scarce. We are attempting at Harwell to remedy this in such a manner that, in some respect, the $n-p$ data will be more abundant, even though of less accuracy, than the *pp* data in the energy range up to 100 MeV.

At last year's conference, preliminary data were presented of the $n-p$ differential scattering cross section as a function of energy in the range 37.5-125 MeV. I had hoped that the final values of the cross section would be available to present today, but they are not. However, I offer instead a set of preliminary values for the polarization in $n-p$ scat-