# NUCLEON-NUCLEON AND PION-NUCLEON INTERACTION

Rapporteur V.I. V e k s l e r

Joint Institute of Nuclear Research Dubna (USSR) •

## I n t r o d u c t i o n

My task is to cover the experimental results relating to proton-proton and pion-proton collisions in the high energy region, and a comparison of the available data with the theoretical representations.

The discussion will be limited to an energy region from 1.5-2 to 10 Bev.

The selection of the lower boundary of the range under review is determined by the fact that at high energies inelastic processes begin to play an essential role.

The upper boundary coincides with the maximum energies of particles which can be obtained on the Dubna accelerator.

Extensive use of data on cosmic experiments did not appear to be advisable in connection with a great ambiguity usually associated with the interpretation of these experiments.

Over the whole energy range considered, the de Broglie wavelength is many times as small as the effective dimensions in the interaction region. Therefore pion and nucleon elastic scattering by nucleons may provide information on the structure
3176 of these particles. Experimental facts relating to high

energy elastic collisions are usually compared with the so-called optical model which allows to determine the magnitude of the particle interaction region and certain important phenomenological nucleon characteristics. Up till now, in analyzing inelastic collisions, practically only the statistical multiple production theory developed by Fermi and improved by many theoretists by taking into account hydrodynamics, by introducing isobaric states and by a rigorous computation of phase volumes taking into consideration the relativity of particles and the conservation laws, has been considered as a theoretical scheme.

My difficult task is aggravated by the fact that no detailed discussion of the characteristic features observed in experimental studies of nucleon-nucleon and pion-nucleon collisions in the given energy range took place at the 1957 and 1958 Conferences.

At the same time, the established experimental facts and, in particular, the new data obtained both in Berkley and in Dubna, are apparently very essential for the understanding of the nucleon structure.

A model was suggested a long time ago which represents the nucleon as a dense core with a relatively loose meson cloud surrounding it. Various consequences of such (or similar) a nucleon model for collisions of nucleons and pions with nucleons (Yastrov, Blokhintsev, Barashenkov et al., Ito et al.) have been considered repeatedly. However, it appears that only now, due to the new experimental data which will be discussed later, and to the general approach developed in the papers by Chew and Low, Pomeranchuk and Okun, a rigorous possibility of an efficient singling out of the nucleon 8176 periphery and the analysis of peripheral collisions in the high energy region is arising. Of special importance for the problems studied are ideas suggested by Tamm and successfully developed by Dremin and Chernavsky.

## NUCLEON-NUCLEON COLLISIONS

### a) Elastic p-p and p-n Collisions (Experiment)

I would like to begin the review of experimental data with a paper by Fowler et al. [1] describing a detailed analysis of the results of an extensive series of runs carried out with the aid of diverse methods. These data characterize the energy range from 0.8 Bev to 2.7 Bev. We shall be interested in the quantitative characteristics of the interaction in the range from 1.5 to 2 Bev and higher.

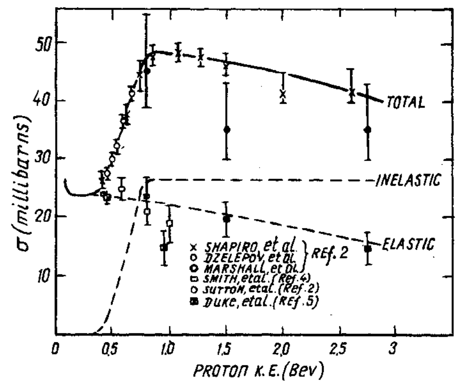


Fig. 1.

Fig. 1 summarizes data relating to the total cross section and the cross sections of inelastic and elastic collisions in the energy rage indicated [38].

Fig. 2 shows elastic scattering histograms. On the x-axis is plotted the cosine of the angle in the C.M.S.; on the y-axis, the number of the events considered. As can be seen from the picture, the total number of events used for determining the elastic cross-section is extremely small.

The next work of interest to us which is dedicated to elastic nucleon scattering was conducted by Cork et al.[2] on Bevatron.

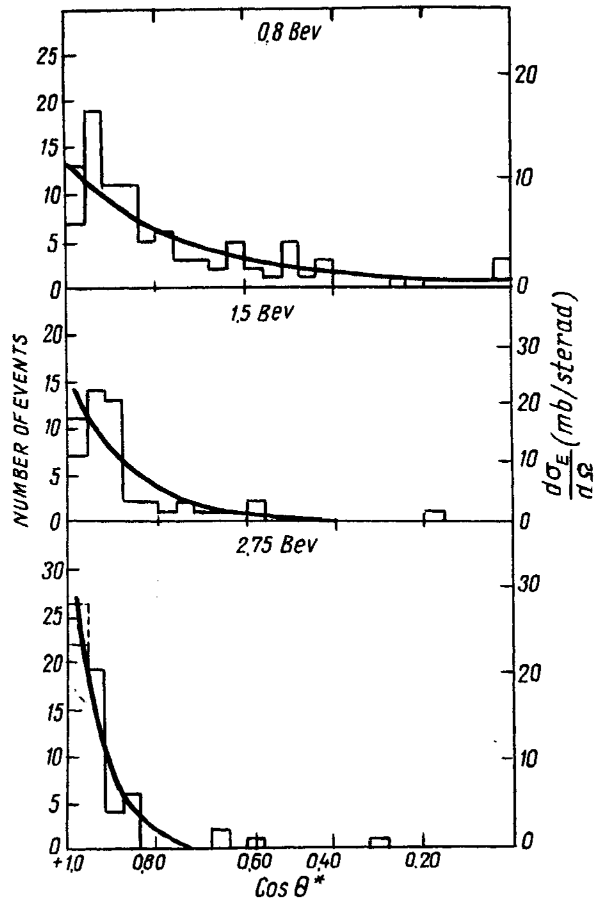


Fig.2.

Elastic scattering in targets placed across a beam of protons moving in a bevatron vacuum chamber was studied by means of electronic apparatus. The differential cross section was investigated at beam energies of 2.24 Bev,4.40 Bev and 6.15 Bev. The data obtained in this work are summarized in Table 1.

To obtain a total elastic scattering cross section, integration was carried out in all angles. The differential cross section at $0^o$ was defined by extrapolation using the optical theorem. As the total cross section $\sigma_t$ is well-known,

Table 1

| T Bev | $\theta_0$ Degree | $\theta_{c.m.}$ degree | $d\sigma/d\Omega$ (mb/sterad) | Standard statistical deviation (%) | Total statistical error (%) |
|---|---|---|---|---|---|
| 2.24 | 5 | 14.75 ± 0.3 | 20.8 | 2.4 | 5.9 |
| | 8 | 23.6 ± 0.3 | 11.0 | 1.8 | 5.4 |
| | 10 | 29.2 ± 0.25 | 6.64 | 2.4 | 9.2 |
| | 15 | 44.0 ± 0.26 | 1.12 | 2.0 | 8.7 |
| | 20 | 57.6 ± 0.33 | 0.428 | 3.1 | 14 |
| | 25 | 70.3 ± 0.4 | 0.255 | 3.0 | 13.4 |
| | 35 | 93.5 ± 0.4 | 0.1455 | 3.3 | 19.1 |
| 4.40 | 3 | 10.6 ± 0.4 | 20.5 | 1.7 | 5.3 |
| | 4 | 14.2 ± 0.4 | 18.3 | 1.2 | 7.8 |
| | 5 | 17.5 ± 0.4 | 12.73 | 1.2 | 7.1 |
| | 6 | 21.3 ± 0.4 | 6.01 | 1.8 | 8.6 |
| | 7 | 24.5 ± 0.4 | 2.96 | 2.1 | 11.0 |
| | 8 | 28.5 ± 0.4 | 1.99 | 6.6 | 11.7 |
| | 10 | 37.4 ± 0.4 | 0.473 | 7.1 | 13.4 |
| | 15 | 53.2 ± 0.4 | 0.100 | 11.1 | 29 |
| | 20 | 69.0 ± 0.4 | 0.0382 | 21 | 41 |
| 6.15 | · 1.9 | 7.6 ± 0.4 | 27.7 | 2.25 | 10.2 |
| | 3 | 11.6 ± 0.4 | 24.6 | 3.1 | 9.0 |
| | 4 | 15.2 ± 0.4 | 10.1 | 3.7 | 13.0 |
| | 5 | 20.0 ± 0.4 | 5.51 | 3.5 | 20 |
| | 5 | 20.8 ± 0.4 | 3.06 | 7.8 | 23 |
| | 6 | 23.6 ± 0.4 | 1.31 | 15.6 | 24 |
| | 7 | 27.6 ± 0.4 | 0.651 | 7.0 | 45 |

the lower boundary of the value of the forward scattering amplitude was defined from the condition.

$$\operatorname{Im} f(0) = \frac{\sigma_t}{4\pi\lambda} .$$

3176

Elastic p-p scattering at 6.2 Bev was investigated in the work of Kalbach et al.[3] published in 1958. A stack of Ilford G-5 emulsions 600 $\mu$ thick was placed in a light container placed under a bevatron beam. The average track density per $cm^2$ amounted to $4.7 \times 10^5$ protons. The isolation of elastic p-p scattering events was done by searching for secondary protons deflected from the beam. By commonly used criteria (two ionizing tracks, coplanarity, kinematics,etc), 31 scattering events were selected out of the total 132 found. 3063 inelastic collisions were found in the same work. The mean free path for inelastic collisions was found to be 36.4cm. A comparison of these data shows that the elastic p-p scattering cross section at 6.2 Bev

$$\sigma_e = (8.8 \pm 2.0)\ mb.$$

Fig. 3 reveals the angular distribution of elastic scattering. On the x-axis are plotted the angles in the C.M.S.

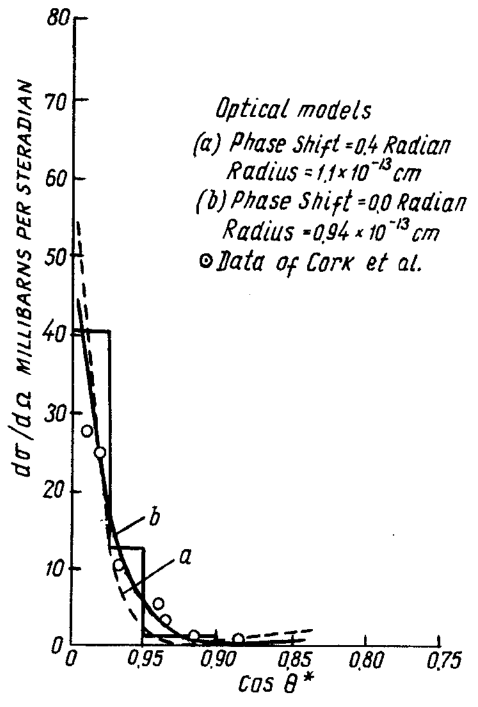


Fig.3.

Smooth curves shown in the picture relate to an optical model with somewhat different parameters. Table 2 lists the respec- 3176 tive differential cross sections in millibarns per steradian (taking into account scanning efficiency).

Table 2

| Range of Cos $\theta^*$ | Uncorrected number of secondaries | Corrected cross section, mb per sterad |
|---|---|---|
| 1.000-0.975 | 17.5 | 40.4 |
| 0.975-0.950 | 8.0 | 12.7 |
| 0.950-0.925 | 2.0 | 1.3 |
| 0.925-0.900 | 2.5 | 1.4 |
| 0.900-0.875 | 1.0 | 0.6 |
| $0 \leq \cos\theta^* \leq 0.875$ | 0.0 | 0.0 |

Important new data concerning proton-proton scattering were obtained by a group of physicists (Markov et al.[4]) on the Dubna proton synchrotron. Elastic scattering of protons with an energy of 8.5 Bev on free photo-emuslion protons was investigated. A new method was used in this work which consisted in exposure photo-plates with a proton beam directed normally to the photo-emulsion plane. One of the essential adventages of this method is the possibility of considerably increasing the exposure density, providing at the same time very efficient conditions for the selection of elastic collisions ( the scanning efficiency is close to 92 per cent). This allows to advance into the range of considerably smaller angles than the limiting angles for which published data have been available so far: up to 0,2$^o$ in the laboratory system, which corresponds to 1$^o$ in C.M.S. A stack of photo-plates consisting of type Nikphi-R emulsion layers 400$\mu$ thick was exposed with a 8.5 Bev internal

3176

proton beam on the Joint Institute proton synchrotron. The possible sources of errors were carefully taken into account, and satisfactory statistics were obtained. Of 799 two-prong stars externally resembling elastic scattering 145 proved to satisfy very strict kinematic criteria. The authors estimate that the contribution of quasi-elastic collisions does not exceed about 1 per cent.

I shall not dwell any more on the details of the new method used by Markov et al.(4) and shall refer those interested to the original paper. A summary of experimental data obtained by Markov et al.[4] is given in Fig.4 and Table 2a.

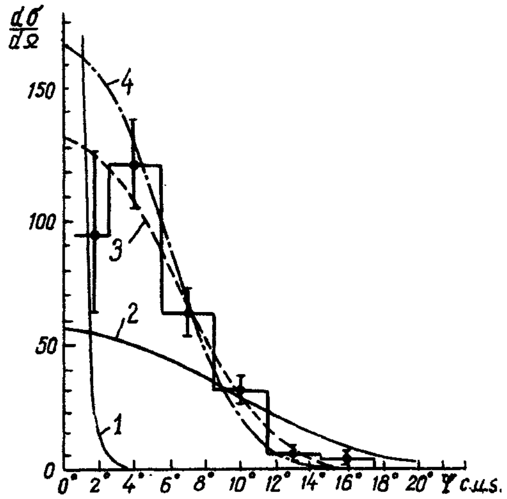


**Fig.4.**

I - differential Coulomb - scattering cross-section; 2 - absolutely black disk R = 0,94f, a = 0,453; 3 - uniform sphere R = I,5f, $K=0,I9I0 \cdot IO^{I3} cm^{-I}$, $K_I=0I546 \cdot IO^{I3} cm^{-I}$, ($\sigma_e$= 8,4mb), U=34,I Mev, V=27,5 Mev; 4 - uniform spere R=I,7f, $K=0,I247 \cdot IO^{I3} cm^{-I}$, $K_I=0,I225 \cdot IO^{I3} cm^{-I}$; ($\sigma_e$=8,4mb), U=22,3 Mev, V=2I,8 Mev.

T a b l e 2a

Differential cross section of elastic p-p scattering at 8.5 Bev

| $\psi^0$ C.M.S. | 1.0-2.5 | 25-5.5 | 5.5-8.5 | 8.5-11.5 | 11.5-14.5 | 14.5-17.5 |
|---|---|---|---|---|---|---|
| $\frac{d\sigma}{d\Omega}$ $\frac{mb}{sterad}$ | 95±33 | 123±18 | 63.2±9.5 | 31.5±5.7 | 5.5±2.2 | 3.6±1.6 |

C.M.S. angles are plotted on the x-axis, the y-axis giving the differential cross section in millibarns per steradian.

3176

Integration leads to the value of the total elastic interaction cross-section

$$\sigma_e = (8.6 \pm 0.8)\ mb$$

which agrees, within the error limits, with the value found by other method in the work of Bogachev et al.[12,.

The smooth curves shown in Fig.4 relate to different optical models.

The investigation of proton-proton elastic scattering in photographic emulsion by means of scanning along the track was carried out in Dubna by Bogachev et al.[5] The total number of elastic scattering events selected for analysis in this work amounts to 27. The data obtained qualitatively agree with those obtained in the previous work, though the statistics are rather scanty (Fig.5).

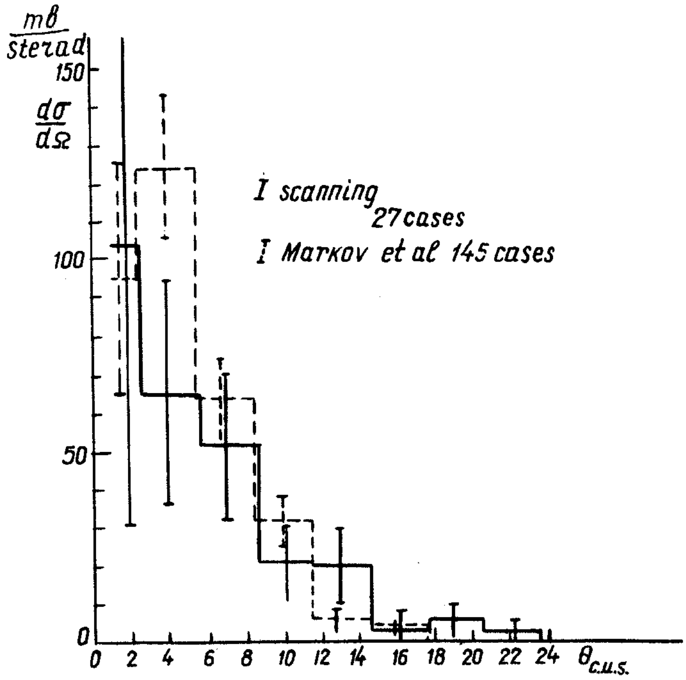


Fig.5.

In his work which was briefly reviewed here Preston [6] studied elastic proton-proton small angle scattering at 3 Bev. In this experiment a liquid-hydrogen target was irradiated with a cosmotron beam, and protons scattered at small angles

3176

were detected with the aid of photo-plates. Mesons from inelastic p - p collisions were isolated by the magnetic field. This method made it possible to measure the differential scattering cross scetion in the very small angle range (0.4-4.5°) in the laboratory system Fig. 6 presents the differential scattering cross section as a function of the angle in the laboratory system. The differential cross-section at 0° was determined by the optical theorem. In the author's

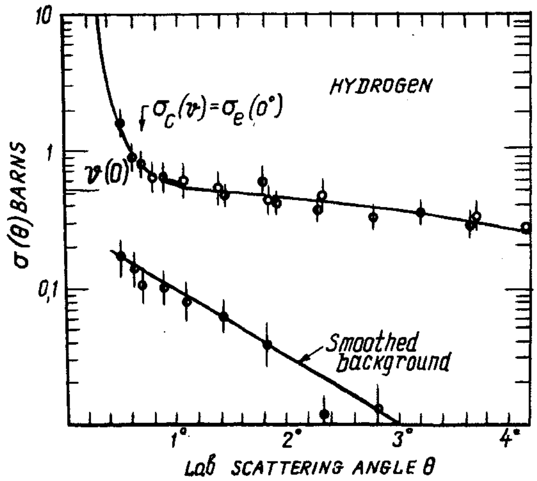


Fig.6.

opinion, the rise of the curve in the small angle region is associated, with Coulomb scattering. The magnitude of the total elastic p - p scattering cross section was not determined in this work.

In concluding this section we present Table 3 summarizing the data on the total elastic and inelastic cross section at various energies [38].

b) Analysis of Elastic Nucleon-Nucleon Collisions

Elastic scattering observed experimentally may include both coherent and incoherent scattering which may, in principle be caused by the flipping of the spins of the colliding particles. Coherent scattering, in turn may be

3176

T a b l e 3

p - p

| $E_p$ Bev | $\lambdabar$ $10^{-14}$ cm | $\sigma_t$ | $\sigma_e$ | $\sigma_i$ |
|---|---|---|---|---|
| 1.49 | 2.35 | $47.2^{+2.6}_{-1.2}$ | 20 ± 2 | 27 ± 3 |
| 2.00 | | $41.4^{+3.2}_{-1.4}$ | | |
| 2.24 | 1.92 | | 16.9 ± 2.5 | |
| 2.60 | | $41.6^{+4.0}_{-1.6}$ | | |
| 2.75 | 1.73 | | 15 ± 2 | 26 ± 3 |
| 3.00 | | | 8.9 ± 1.0 | |
| 4.40 | 1.37 | | 9.0 ± 1.4 | |
| 5.3 | | 32.4 ± 6.0 | 5.6 ± 2.3 | |
| 6.15 | 1.16 | | 6.9 ± 1.0 | |
| 6.2 | | | 8.8 ± 2.0[3] | 22.6 ± 5.3[15] |
| 9.0 | 0.96 | | 8.6 ± 0.8(4) | 21[12] |
| | | p - n | | |
| 1.40 | | 42.2 ± 1.8 | | |
| 1.48 | | $33.6^{+2.0}_{-1.7}$ | | |
| 2.00 | | $34.3^{+2.3}_{-1.5}$ | | |
| 2.60 | | $31.4^{+2.2}_{-1.3}$ | | |
| 4.5 | | 33.6 ± 1.6 | | |

caused by a nucleon potential, by the absorption of the incident wave or by both. In the latter case, interference takes place, and it is impossible to determine the contribution of each of these processes separately.

3176

Two approaches have been used so far for analyzing experiments in the energy region under consideration.

Belenky [7], Grishin et al.[8,9] ,Ito et al.[10] carried out a phase analysis of elastic scattering on the assumption that the scattering amplitude is a purely imaginary value and the spin interaction is absent.

The first assumption which is actually generally accepted was based on the experimental fact of the large pion production cross section $\sigma_{in} \sim$ (20-25 mb) which represents the bulk of the total cross section ($\sigma_t \sim 35$ mb) and should cause a characteristic diffraction scattering. The second assumption stems essentially from the first (complete statisticity of the processes). No <u>direct</u> experimental data as to the presence of the so-called potential scattering $(\mathrm{Re}\, f(\theta) \neq 0)$ or the existence of a spin interaction in this energy region are available so far. Within the framework of the assumptions made, a phase analysis is carried out in a comparatively simple way.

Indeed, in this case the scattering amplitude is a purely imaginary value and the following relation takes place:

$$\bar{\lambda}\,(1-\beta_\ell) = \int_{-1}^{+1} P_\ell(x)\sqrt{\frac{d\sigma}{d\Omega}}\,dx.$$

Here $\beta_\ell = e^{2i\delta_\ell}$, $P_\ell(x)$ Legendre polynomial,

and $\frac{d\sigma}{d\Omega}$ differential elastic scattering, measured experimentally.

Further, using the well-known formula

$$\sigma_{i\ell} = \pi\bar{\lambda}^2(2\ell+1)(1-\beta_\ell^2)$$

we calculated the contributions made by various orbital momenta to the inelastic cross section of the p-p collision. 3176

Table 4 shows the effective values of "$\ell$" for various energies.

Table 4

| E/Bev/ | $\ell$ | $\lambda\cdot 10^{+14}$cm |
|---|---|---|
| 1.5 | 2 - 5 | 2.35 |
| 2.75 | 2 - 7 | 1.73 |
| 6.15 | 2 - 11 | 1.16 |
| 9 | 2 - 14 | 0.96 |

A somewhat modified phase analysis method is suggested in the paper of Barashenkov et al.[36] but this is also based on the results of the analysis with $\mathrm{Re}f(\theta)=0$.

An attempt to take into account the particle similarity on the same assumptions was made by Ito et al. [10].

The essential result obtained in this approach to the elastic collision analysis is the following: it is possible to make a conclusion as to the angular momenta responsible for nucleon collisions and to obtain data on the extension of the interaction region at sufficiently high energies.

A drawback of the method discussed is unjustified discarding of potential scattering or, in a more general form, neglecting the real part of the scattering amplitude. It should be noted that in the angle region considered so far, this assumption did not contradict the experimental data. However, the experience of the Dubna group (Markov et al.[4]) cannot be reconciled with neglecting the real part of the amplitude. Therefore, the carrying out of a phase analysis would require the knowledge of a practically unattainable number of parameters. In this connection it would seem reasonable to use optical models.

In cases where the nucleon wavelength in CMS is considerably smaller than the dimensions of the interaction region, a study of scattering with the aid of the optical model may yield certain important nucleon characteristics. In our energy region this requirement is satisfied well enough. Already at energies of 2.24 Bev the nucleon wavelength in CMS is equal to 1.92 x x $10^{-14}$ cm, and at 9 Bev, 0.96 x $10^{-14}$ cm. Therefore it is expedient to interpret the results from the point of view of the optical model developed by Fernbach et al. In this approach the region of interaction between two particles is characterized by a complex index of refraction whose real and imaginary parts are responsible for the phase shift and the absorption of the incident plane wave. If the index of refraction changes little at a distance of the order of the wavelength, then, as is well-known, the geometrical optics approximation can be used. The incident wave may be regarded as a beam of rays, for each of which the phase shift and absorption in passing through the interaction region depend only on the coordinate. In terms of phase analysis this is equivalent to a statement that a great number of partical waves with different angular momenta take part in the scattering. In this case the elastic scattering amplitude is defined by the relation

$$f(\theta) = ik\int_0^\infty (1 - ae^{i\Phi})\, J_0(k\rho \sin\theta)\rho\, d\rho$$

where $\theta$ scattering angle in C.M.S., $\rho$ - "impact parameter."

The total elastic scattering cross section, as is easy to see, is $\sigma_{e} = 2\pi\int_0^\infty |1 - ae^{i\Phi}|^2 \rho\, d\rho$

the absorption cross-section being defined by the formula

$$\sigma_{in} = 2\pi\int_0^\infty (1 - a^2)\rho\, d\rho$$ 3176

The above expressions relate to spinless particles; the identical nature of the particles is not taken into account either.

For small angles, under the assumptions made, the scattering amplitude and hence the differential elastic cross-section are functions of the parameter, k sin $\theta$.

Fig. 7 gives the data obtained in the work of Cork et al. [2] cited above. On the x-axis is plotted the value k sin $\theta$ where the value k is expressed in terms of $10^{13}$ $cm^{-1}$.

According to the authors, in a very good approximation the radial interaction form-factor appears to be energy independent. This fact is of great interest.

Using an optical model and assuming that the nucleon-nucleon interaction area is a homogeneous sphere with a complex index of refraction, Grishin et al.[11] analysed

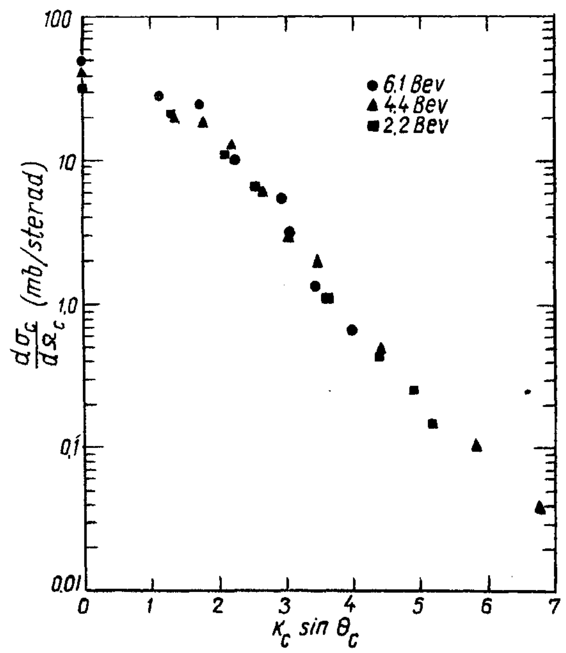


Fig.7.

the experimental data obtained by Cork et al. [2], Fowler et al.[1]. It was shown that the available results could be described with the aid of a sphere with a radius $R = (1.08 \pm 0.07) \times 10^{-13}$ cm. which is energy independent. Contributions to the elastic scattering cross section from the imaginary and real parts of the scattering amplitude, and the absorption coefficients, K, are presented in Table 5

T a b l e 5

| E Bev | K $10^{-13}cm^{-1}$ | $\|Re f(\theta)\|^2 / \|f(\theta)\|^2$ % | | |
|---|---|---|---|---|
| | | $K=1{,}05 \cdot 10^{-13}$ cm | $R=1{,}1 \cdot 10^{-13}$ cm | $R=1{,}15 \cdot 10^{-13}$ cm |
| 1.5 | 0.64 - 2.6 | 6 -21 | 12-27 | 20-35 |
| 2.27 | 0.60 - 2.0 | 5 - 22 | 9-28 | 15-35 |
| 4.40 | 0.53 - 1.3 | 0 - 21 | 0-29 | 5-35 |
| 6.15 | 0.51 - 1.0 | 0 - 16 | 0-23 | 0-30 |

As can be seen from Table 5, the data for high energies can be reconciled with the model of a purely absorbing nucleon. The authors of one experimental works carried out in Dubna draw an essentially different conclusion. Figure 4 indicates that it is impossible to reconcile the obtained histogram with the model of a purely absorbing sphere, no matter what parameters of this sphere are assumed. It is also impossible to satisfy the experimental data by introducing this or that dependence of the absorption coefficient of the sphere on the radius.

With a given magnitude of the inelastic cross section which always remains close to 20 mb in our energy region all models of a purely absorbing proton yield one and the same value of the differential cross section at an angle of $0^{\circ}$ determined only by the optical theorem (of course, here we neglect the dependence of the forces on the spins).

Therefore, at energies of 9 Bev and perhaps at lower energies, one should not neglect the real part of the scattering amplitude and consider the whole scattering to be purely diffractional. Unfortunately, no available experimental data obtained on Bevatron and Cosmotron, except those of Preston,[6] contain sufficiently precise information about small angles.

In the cited work by Cork et al.[2] the differential cross section was found only up to $7.6^{\circ}$. If the data relating to energy of 6.15 Bev and the data **obtained** by Markov et al. [4] at 8.5 Bev were plotted on the graph showing the dependence of $\lambda^2 \frac{d\sigma}{d\Omega}$ on $k \sin\theta$ (Fig.8), it would turn **out that**

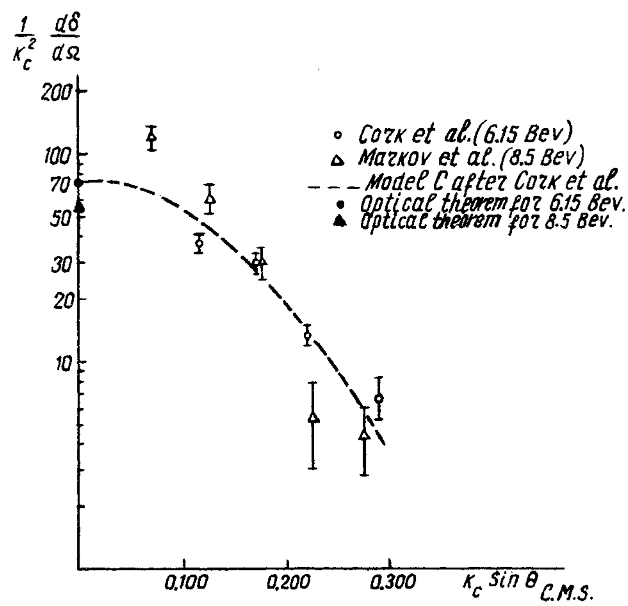


**Fig.8.**

these data agree in the large angle region. As to the optical model used by Cork et al.[2] which conveniently describes their experimental **data**, it cannot be reconciled with the data of Markov et al.[4] in the small angle region (Cork et al.[2] have no experimental data for this region).

Kalbach et al.[3] obtained data on smaller angles than
3176 those investigated by Cork et al.[2] However, the **statistics**

of this group are insignificant (31 cases), and it is impossible to compare it with the data obtained in Dubna.

In an interesting work by Preston [6] performed at 3 Bev, proton-proton scattering was especially investigated in the small angle region. As reported by **Wilson**, who presented this paper, the author arrives at the conclusion that the real part of the scattering amplitude does not exceed 20 per cent of the imaginary part.

The rms interaction radius found by Preston, $\sqrt{\overline{r}^2} = 1.05 \cdot 10^{-13}$ sm is about 1.5 times as large as the electromagnetic proton radius(Hofstadter).

The experiments of Markov et al.[4] can be fitted with the optical homogeneous sphere model which takes into account both absorption and refraction. The agreement of the calculation with the histogram (Fig.4) is obtained with the following model parameters: radius of homogeneous sphere= $R=(1.5-1.7) \times 10^{-13}$ cm., absorption coefficient = $(1.25-1.91) \times 10^{12}$ cm.$^{-1}$), variation of the real part of the wave vector = $(1.25-1.55) \times 10^{12}$ cm.$^{-1}$ The above values of the absorption and refraction coefficients corresponds to an imaginary potential of 22 - 34 Mev and to a real potential of 22 - 28 Mev.

The differential small angle scattering cross section found in the work cited can also be fitted with the model of a purely absorbing proton. In this case, however, one would have to assume that the interaction strongly depends on the spin state. i.e. the cross sections in the singlet and triplet states differ drastically*. To draw an unambiguous

---

*This circumstance was noted by D.I.Blokhintsev.

3176

conclusion as to which of these two possibilities (absorbing and refracting sphere or strong dependence of interaction on the spin state) takes place, data on the nucleon polarization in elastic scattering in the high energy region are required.

It is noteworthy that the optical model discussed above is valid in the case of a proton-proton collision with large relative orbital momenta, $\ell$, i.e. where it is possible to speak of an "impact parameter," $\rho$. Therefore, strictly speaking, the optical consideration cannot yield correct information on so-called central collisions, when $\ell$ is small. However, the contribution of this region does not essentially affect the analysis carried out.

c) Inelastic p-p and p-n Interactions

Inelastic nucleon interaction in the 3 to 10 Bev energy region were studied during the past year on Bevatron and in Dubna. A few groups of authors (Bogachev et al.[12,13], WangShu-fen et al.[14] studied various characteristics of p-p and p-n collisions by the nuclear emulsion technique. Since the above-mentioned works gave similar results, with small exceptions, I shall combine the data obtained by these authors.

An emulsion stack compiled of emulsioh layers ofNIKPHI-R type was irradiated with an internal proton beam on the Joint Institute proton synchrotron. When scanning the primary proton track, all the stars and scattering events at angles exceeding $5^{o}$ were recorded. About 6,000 nuclear interactions were detected on a total length of approximately 2 km. The interaction mean free path proved to be equal to $37.3 \pm 0.3$cm, according to the results of the first work[12] To select proton-proton and proton-neutron free and quasi-free collisions selection criteria were used which were more rigid than usual. Altogether 335 cases were selected which were related to proton- proton interactions, and 204 cases related to proton-neutron collisions.

Using the number of p-p and p-n interactions and the known number of hydrogen atoms contained in the emulsions under investigation, one can estimate the inelastic p-p interaction cross - section. It proved to be equal to about 21 mb.

Table 6 illustrates the distribution of cases of p-p and p-n interactions based on the number of charged particles. The mean number of charged particles for p-p and p-n interactions proved to be equal to 3.27 ± 0.10 and 2.61 ± 0.15.

Table 6

| Multiplicity (pp) | 2 | 4 | 6 | 8 |
|---|---|---|---|---|
| Number of interactions, % | 45.4 ± 5.2 | 46.1 ± 5.3 | 7.9 ± 2.2 | 0.6 ± 0.6 |
| Multiplicity (pn) | 1 | 3 | 5 | 7 |
| Number of interactions, % | 36.2 ± 6.2 | 50.0 ± 7.3 | 10.6 ± 3.4 | 3.2 ± 1.8 |

In the work [14] the identification and determination of the energy of fast particles produced in the interactions were carried out. Besides, all slow particles were identified in every case. Altogether 122 protons and 54 mesons were found

Figure 9 shows the angular distribution of particles from two prong, four-prong and 6-8 prong stars belonging to p-p interactions. A similar distribution for 3-prong and

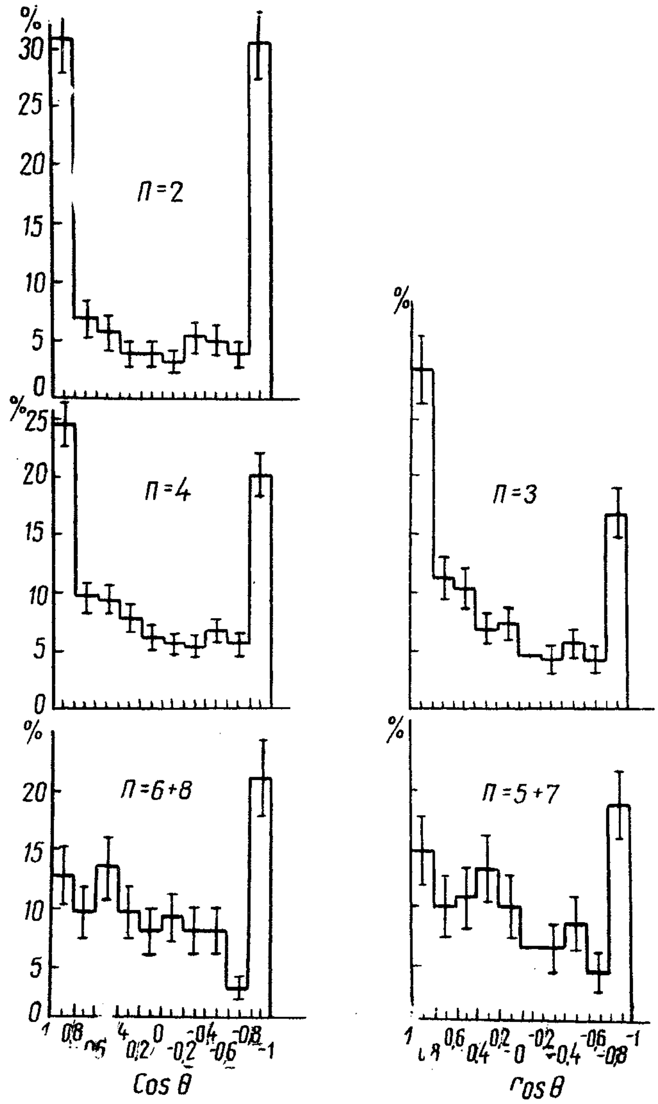


Fig. 9.

7 prong stars for cases of p-n collisions is plotted in the same figure. The cosine of the angle at the centre-of-gravity system is marked off along the abscissa axis, and the number of particles along the ordinate axis. A sharp anisotropy can be observed in the angular distributions of the secondary particles, which smooths down as the multiplicity increase. It is important that the p-n distribution is not only anisotropic, but perceptibly asymmetric as well.

As has been shown in the papers quoted, the anisotropy under consideration is caused mainly by the fact that the protons arising during inelastic collisions conserve the direction of their movement in the centre-of-gravity system. The great majority of protons fly out in the centre-of-gravity system within a cone having an apex angle of not over $35^{\circ}$. The angular distribution of the pions proved to be wider. Among the thirty two identified secondary particles flying out in the centre-of-inertia system at angles under $30^{\circ}$, nine were found to be pions, and the other twenty-three, protons. On the other hand, at an angle greater than $30^{\circ}$, of 38 particles only eleven proved to be protons.

According to the data of a paper by Bogachev et al.[13] the pion distribution also displays a certain, though less considerable, anisotropy. The angluar distribution of pions and protons is shown in Fig.10.

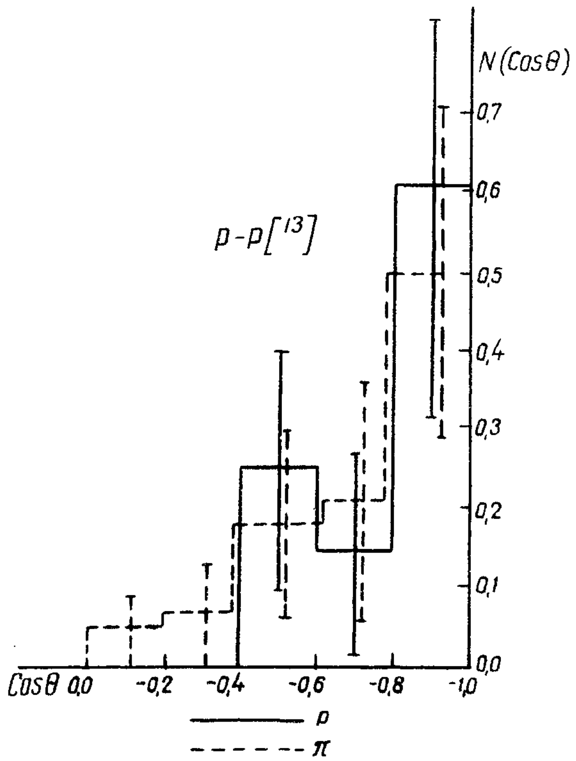


Fig.10.

The average numbers of protons and charged pions per act of inelastic p-p interaction are, respectively, $1.3 \pm 0.3$ and $1.9 \pm 0.3$. The momentum spectra of the protons and charged

3176

$\pi$-mesons from (p-p) interations in the centre-of-gravity system measured in work [13] are given in Fig.11 and 12.

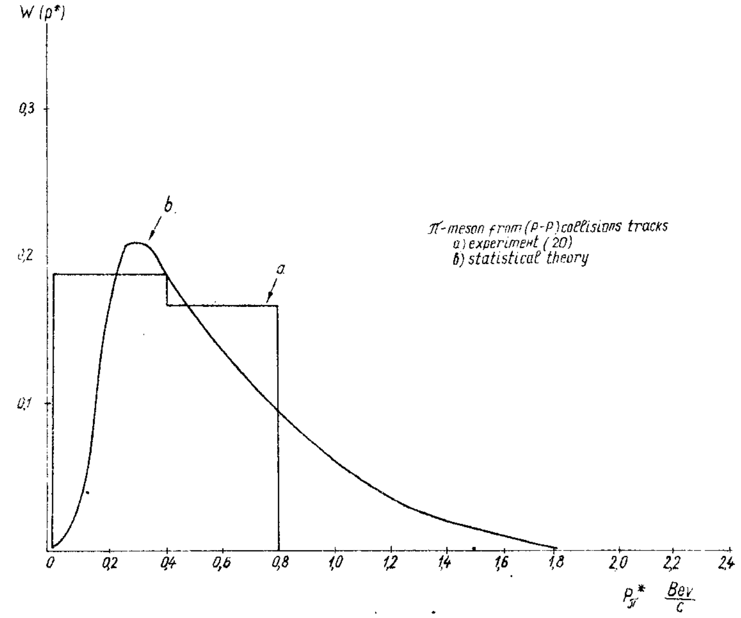


Fig.11

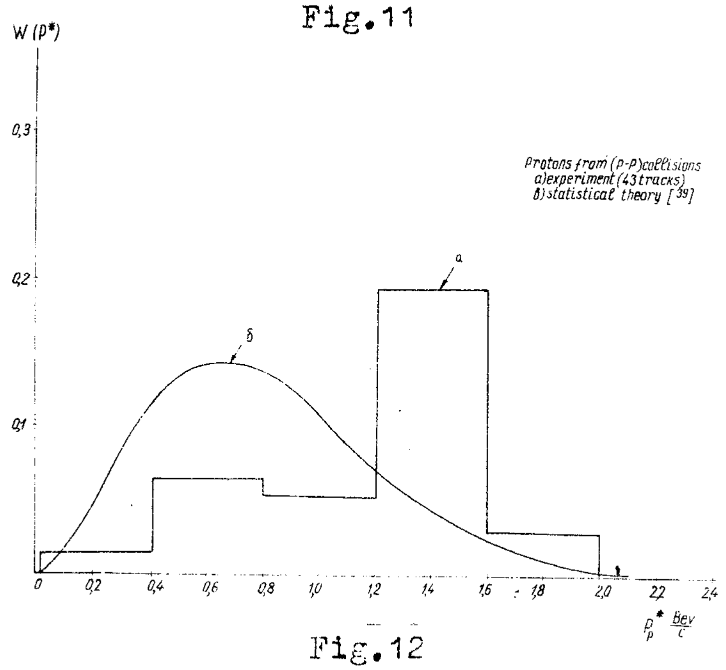


Fig.12

The energy losses of the primary proton in proton - proton interactions can be determined by means of both slow and fast secondary protons. The average value of the momentum of protons flying out backwards in the centre-of-gravity system is 1400 Mev/c, while the average momentum of forward moving protons in the same system is $\geqslant$ 1100 Mev/c.

It follows from this data that the average energy losses of protons in inelastic collisions is 30 to 35 per cent. The
3176 average energy of the mesons in the centre-of-gravity system

proves to be close to 300 or 400 Mev. Analysis of all the material obtained has enabled the authors to draw the following conclusions:

1. The angular distribution of nucleons in p-p interactions is sharply anisotropic in the centre-of-gravity system. The angular distribution of all secondary particles, anisotropic at low multiplicity, approaches isotropy as the multiplicity increases.

2. The asymmetry observed in the angular distribution of secondary particles in pn interactions is due to the fact that in the centre-of-gravity system protons fly mainly in the forward hemisphere, while neutrons fly mainly in the back one.

3. The proportion of energy of the primary proton transferred to the $\pi$-mesons in the laboratory system is about 30 to 35 per cent, which corresponds to an inelasticity coefficient of about 0.50 in the centre-of-gravity system.

Studies of inelastic collisions at 6.2 Bev have been made by the Kalbach group of American physicists [15] as well as by the Daniel group of Indian physicists[16]. Both these investigations were also carried out by the photographic emulsion method. Stacks of Ilfor G - 5 600 micron emulsions, placed in a thin container were exposed by the internal beam of Bevatron.
The total beam density in the paper of Kalbach et al. was $10^5$ tracks per sq. cm. The method of searching for elastic processes in the work of Kalbach et al. differs considerably from that usually used. In this work 315 events of pp collisions were selected for analysis. Particles were identified by means of grain count and multiple scattering.

Figure 13 presents the angular distributions of protons emitted in 2-prong, 4-prong and 6-prong stars.

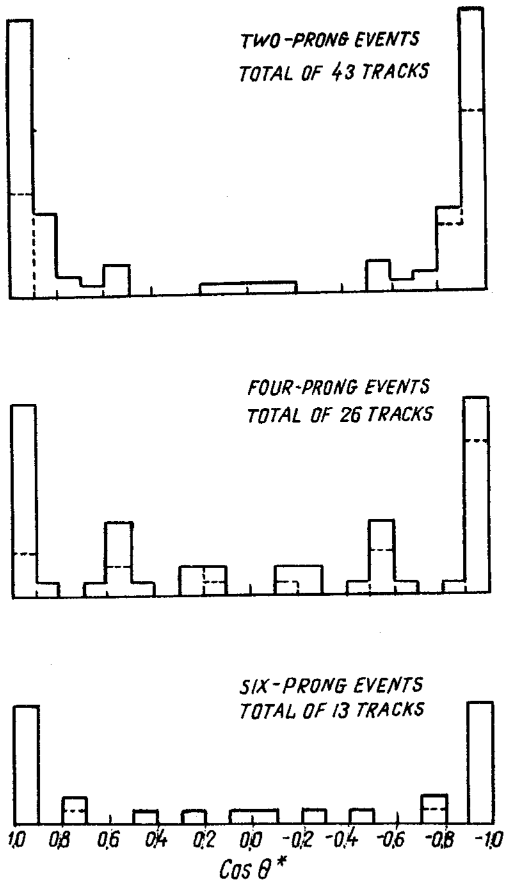


Fig.13.

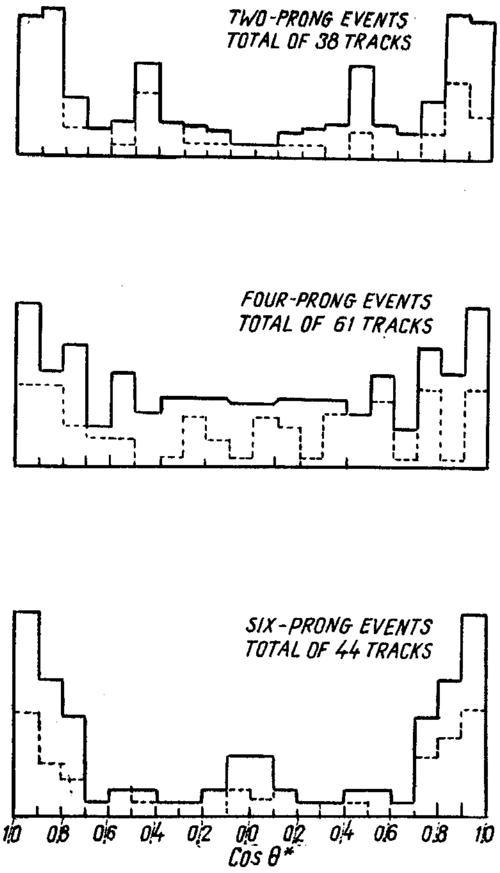


Fig.14.

Figure 14 shows the angular distribution of mesons in 2-, 4- and 6-prong stars.

The subsequent figures (Fig.15 and 16) show the momentum distributions of $\pi$-mesons and protons from stars of various multiplicity in the centre-of-mass sytem (solid curve is statistic theory. The total cross section of pp-interaction at 6.2 Bev determined by Kalbach et al. is $\sigma_t$ =31 mb.

Practically analogical results were obtained in the above quoted work of Daniel et al.[16] in which inelastic pp-interactions were sought by scanning along the track. 197 pp-collision events, which the authors regarded both as free and quasi-free protons, were used for the analysis. Of them 73 satisfy the stricter criteria. Fig.17 shows the angular proton distribution in 2-,4- and 6-prong stars. Figure 18 shows the angular distribution of $\pi$-mesons in these inelastic collisions.

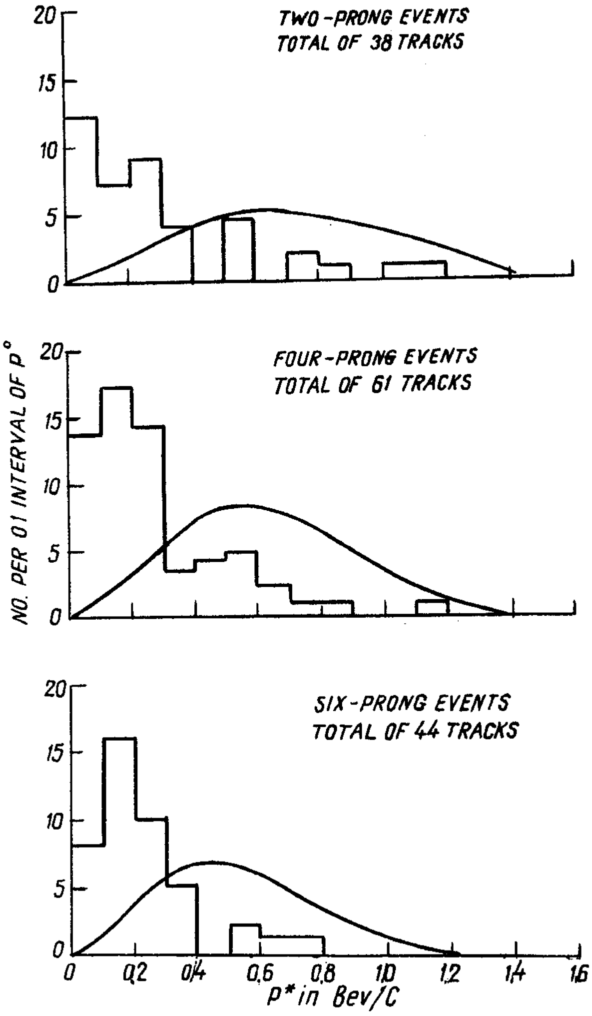


Fig.15.

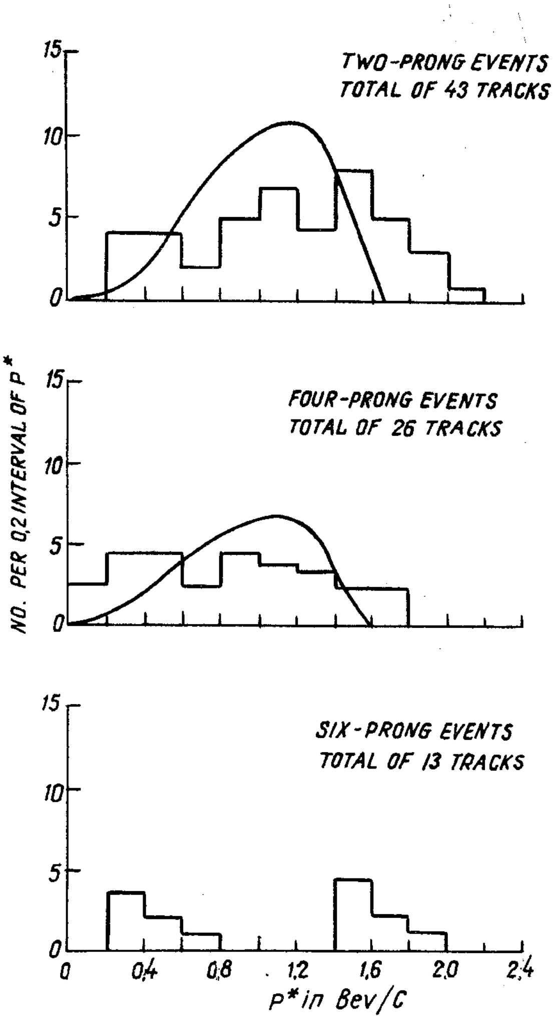


Fig.16.

According to the data of these investigations all the protons are concentrated in the laboratory coordinate system inside a narrow cone with an apex angle of approximately 10$^{o}$. The $\pi$-mesons are distributed more isotropically though some anisotropy can be observed among them also. There is an average of 0.5 proton for each inelastic interaction.

The inelasticity coefficient in the centre-of-mass system approximates 0.5. The total inelastic collision cross-section is 25 mb.

D) Analysis of Inelastic (p - p and p-n ) Interactions

The above data show that the inelastic p-p cross-section changes gradually within the energy range 2.5 to 3176

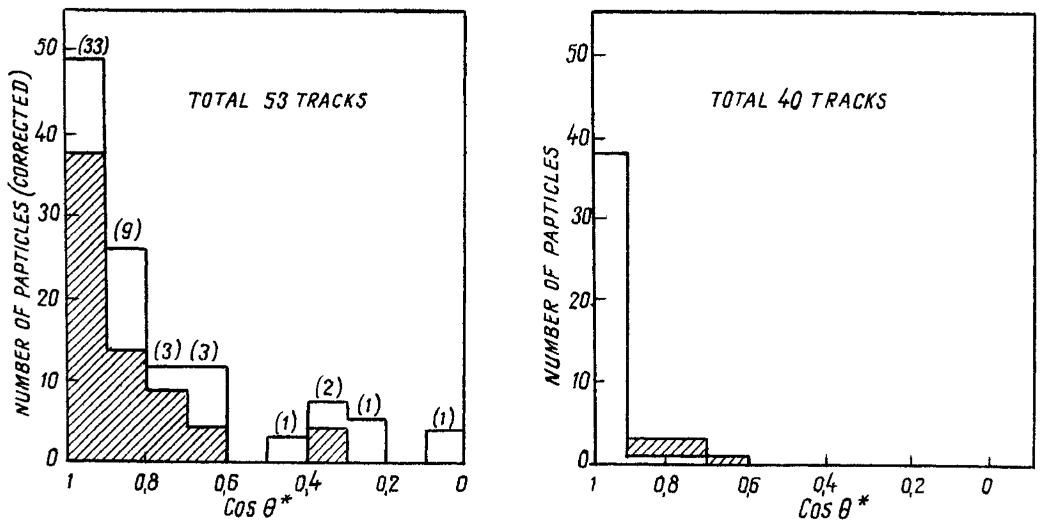


Fig.17.

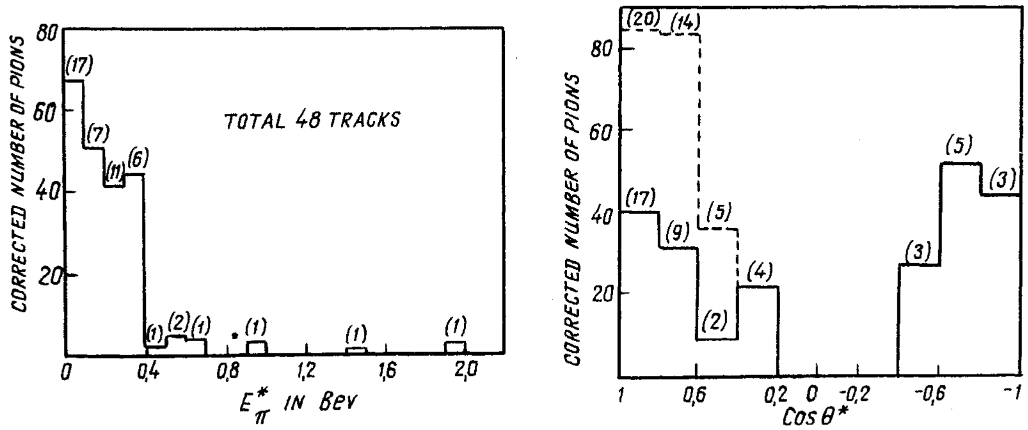


Fig.18.

10 Bev. For example, it equals 27 mb at 2.2 Bev, (22-23) mb at 6 Bev and approximately 21 mb at 9 Bev.

Inelastic interaction usually used to be compared with the Fermi statistical theory. A number of theoreticians in the Soviet Union and elsewhere, including Bilenky, Lepore et al.,Zastavenko, Rosental et al., Lindenbaum et al.,Fialho, Maksimenkoet al. introduced various refinements into the statistical theory of multiple production in an attempt to strictly calculate the phase space volume with allowance for the conservation laws, the relativistic effects, isobaric states, etc. Landau pointed out the necessity of taking into account the hydrodynamic stage of particle divergence.

Apparently, this effect plays no part in the energy range under consideration. The numerous comparisons of the results of investigations of inelastic nucleon-nucleon collisions with statistical theory are rather in agreement with experiment regarding multiplicity; however, in many respects they qualitatively contradict the predictions of this theory.

The curve in Fig. 19 and Table 7 containing data on nultiple production in proton - proton collisions illustrate the first statement. The curve and table has been taken from the papers.

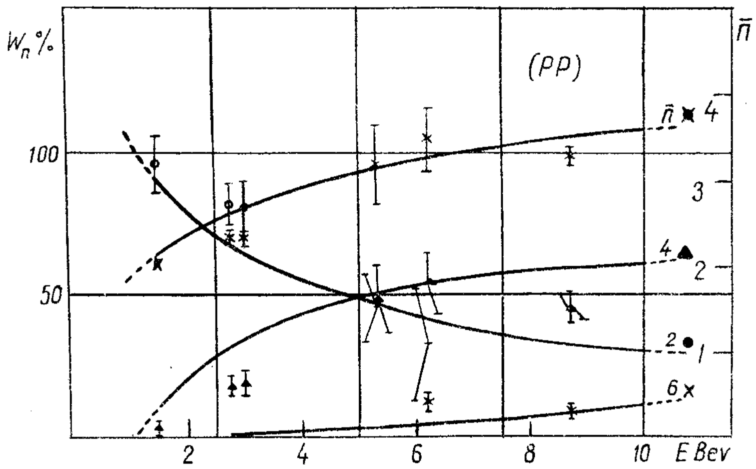


Fig.19.

Barashenkov et al.[17]and Maksimenkoet al.[18,19]It can be seen that alongside the general agreement there are some sufficiently distinct contradictions. On the other hand, according to the data of many authors, whose materials are included in the report the following important contradictions exist between experimental data and statistical theory.

1. The angular nucleon distributions differ sharply from those of pions. Protons and neutrons tend to conserve the direction of their movements in the centre-of-gravity system. 3176

Table 7

Distribution of Stars produced in N-N collisions vs. number of charged particles("prongs")
(The table gives the percentage of stars with given $m$, $E_K$ is
the kinetic energy of an incident nucleon in the laboratory system)

| | Experiment | | | | | Theory* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | p-p collisions | | | | | | | | |
| $E_k$ Bev \ M | 2 | 4 | 6 | 8 | 10 | 2 | 4 | 6 | 8 |
| 1,5 | 96,7 | 3,3 | | | | 913 | 8,7 | | |
| 2,75 | 83,5 | 16,5 | | | | 66,7 | 32,7 | 0,6 | |
| 3,0* | 81,3 | 18,7 | | | | 65,4 | 34,0 | 0,6 | |
| 5,3 | 43,8 | 50,0 | 6,2 | | | 46,1 | 50,0 | 3,2 | |
| 6,2 | 32,5 ± 0,3 | 53,8 ± 10,6 | 11,8 ± 2,7 | 1,3 ± 1,3 | 0,6 ± 0,6 | 41,2 | 54,3 | 4,5 | 0,02 |
| 8,7 | 49±5 | 44 ± 5 | 5 ± 2 | 1 ± 0,8 | | 32,8 | 58,5 | 8,6 | 0,1 |
| | p - n collisions | | | | | | | | |
| | 1 | 3 | 5 | 7 | 9 | 1 | 3 | 5 | 7 |
| 8,7 | 34 ± 5 | 52 ± 8 | 13 ± 3 | 0,9 ± 0,9 | | 14,5 | 59,4 | 25,0 | 11 |

* Photographic emulsion studies. N-N collisions are distinguished by means of not quite unambiguous criteria.

Mesons are distributed much more isotropically. This fact seems unreconcilable with the statistical theory. In this connection it should be noted that the paper of Maximenko et al. [19]. has shown that within the framework of the statistical theory no information at all can be obtained concerning some of the features of angular distributions.

2. Momentum distributions of nucleons and mesons differ sharply, as a rule, from the distributions predicted by the statistical theory; particularly, the statistical theory predicts a considerably harder pion spectrum than that observed experimentally. On the contrary, the nucleon momenta are shifted toward high values, compared to the predictions of the statistical theory.

The average energy loss of fast nucleons in nucleon-nucleon collisions is close to 30-35%, and apparently depends little on the energy of the primary particle. This agrees with the data obtained by Grigorov et al. [20] in a cosmic ray study.

Analysis of the results obtained in investigating inelastic collisions within the energy range under consideration (2 Bev, 6 Bev, 9 Bev ) suggests that peripheral collisions exist and play a substantial part in inelastic interactions. It should be noted that a number of earlier cosmic ray works already asserted the existance of peripheral collisions.

It seems quite plausible to regard as peripheral, collisions in which a comparatively low energy transfer occurs and where the nucleons change the direction of their movement insignificantly. It seems especially important that the peripheral interaction distinguished in conformance with this criteria can apparently be related, owing to Tamm's idea, to 3176 conceptions of single meson exchange. Tamm pointed out that analysis of peripheral nucleon-nucleon collisions was possible on the basis of the idea of single-meson exchange of nucleons as a result of which one or two isobars are produced. The corresponding Feynmann diagrams are presented in Figure 20.

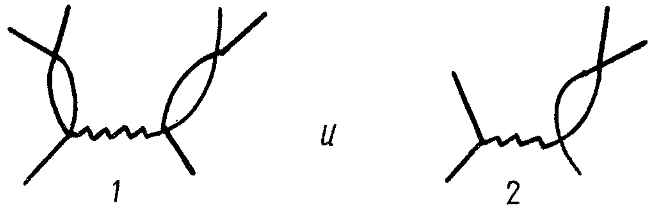


Fig.20.

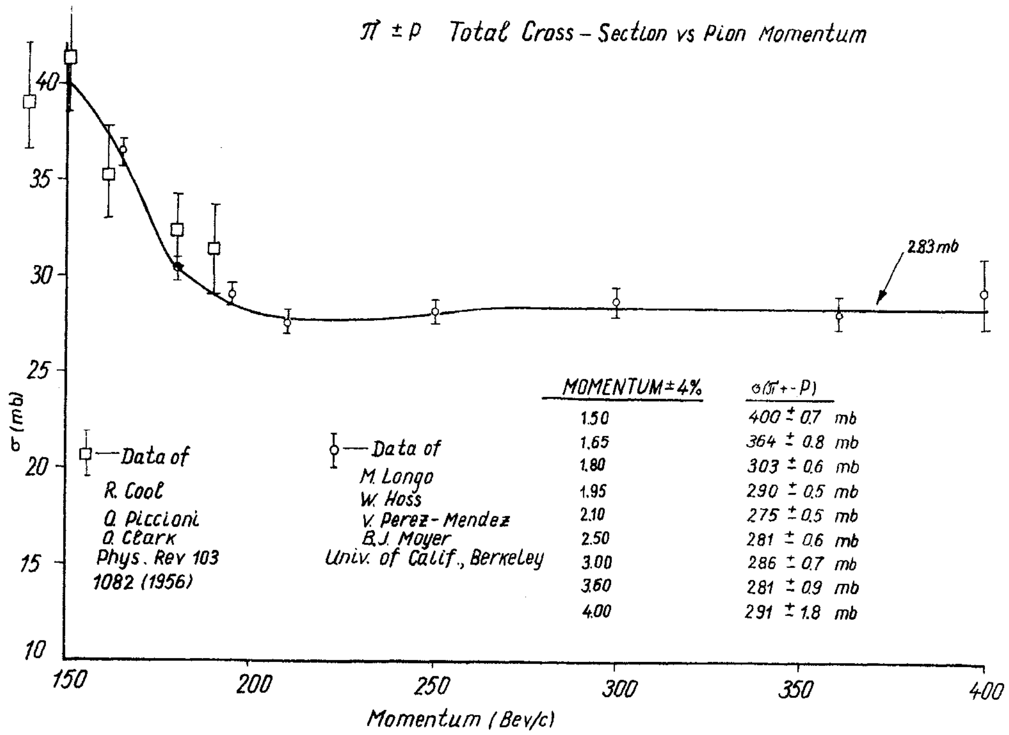


Fig.20a.

In the first case one isobar is formed, and one nucleon remains unexcited. In the second case both nucleons are excited simultaneously.

The formation and subsequent decay of isobars on collision of nucleons has been examined at different times by a number of theoreticians (Peeslee etc.). An important fact noticed by Tamm is that under the assumption of single-meson exchange

3176

a quantitative relationship can be obtained quite unambiguously between the probabilities of various isotopic channels of reactions. On the basis of this hypothesis a numerical estimate of the asymmetry can be obtained, which should be observed in p-n collisions.

Asymmetry in the angular distribution of secondary protons in n-p interactions was observed a long time ago by Fowler et al. Their study was carried out with the aid of a diffusion hydrogen chamber exposed by a neutron beam with an average energy of 1.7 Bev. To account for these and some other similar phenomena the authors assumed that the $\pi$-mesons are generated by the formation of isobars which then decay into a nucleon and a $\pi$-meson. The shortcoming of Fowler's et al. treatment is that they had to assume more or less arbitrarily that isobars form only in states with isotopic spin projections of +3/2 and -3/2.

In this connection it should be emphasied that the idea suggested by Tamm is a substantial step forward inasmuch as it considers a quite definite mechanism of isobar generation, according to which the latter results from the single meson interaction of nucleons. This assumption results in a quite unambiguous relationship between the different isotopic channels of reaction, the truth of which can be checked experimentally. It should be noted that if this idea is correct the interaction will result in an isobar, the energy of which in the laboratory system will exceed its rest mass several-fold. Under these conditions, owing to relativistic time transformation the isobar will fly out of the interaction zone before it decays, i.e. will behave in this respect as a doubly-charged particle.

3176

The Tamm model explains in a very natural manner the observed angular distribution of nucleons, and possibly $\pi$-mesons, gives the correct order of asymmetry in p-n collisions and of the energy losses of fast protons. In order to make a comparison with experimental material Wang Shu-fen et al. [14] specially selected from all available inelastic scattering events those, which do not contradict the assumption of peripheral collision in accordance with the Tamm model. Altogether 23 inelastic collisions were selected for analysis.

Table 8 gives the relation between the number of 2-,3- and 4-prong stars found by experiment and calculated theoretically.

Table 8

Comparison of experimental data with the 2-isobar model

| $N_2/N_4$ | | $N_3/N_2$ | | $N_3/N_2+N_4$ | |
|---|---|---|---|---|---|
| Theory | Experiment | Theory | Experiment | Theory | Experiment |
| 0.89 | 1.60± 0.64 | 0.62 | 0.72±0.33 | 0.29 | 0.44±0.19 |

It can be seen from this table that the experimental results agree with the predictions of the Tamm model. The agreement of experimental data with this scheme improves if (as shown by Maksimenko [37]) one takes into account the existence of the second maximum in $\pi$-p interaction.

Taking advantage of this experimental material the authors estimated the cross-section value which should be ascribed to peripheral collisions. The cross-section proved to be 4-5 mb; this may be compared with the results of Dremin and Chernavsky's [24] theoretical calculations. In a very interesting paper these authors found a method of calculating the total cross-section of various peripheral processes. The cross-sections found by Dremin and Chernavsky for peripheral processes in which 2 isobars are formed are apparently in good agreement with the data of Wang Shu-fen et al.[14].

Some information on the substantial role of peripheral nucleon-nucleon collisions above $10^{10}$ ev can be obtained by studying the nuclear interactions of cosmic ray particles. It has been noted in a number of studies that the angular distribution of secondary particles in the c.m. system is sharply anisotropic for some of the events. The degree of anisotropy is much higher than that predicted by the hydrodynamic theory of multiple production. Besides, the proportion of the energy transferred to $\pi$-meson production is small: the inelasticity factor is far below unity.

Such interactions can be described by means of the "two centre" model. It is assumed that excited systems form in the c.m. system, and then fly out in opposite directions and emit particles.

It must, however, be pointed out that analysis of data on interactions in cosmic rays involves a major uncertainty both in the estimates of the primary particle energy and in accounting the role of the interaction of secondary particles with the nucleons of the target-nucleous.

Obviously, the peripheral collisions occuring according to the Tamm model do not exhaust all the types of inelastic collisions. In this connection it is especially interesting to examine the influence of pion-pion interactions and of the effects of exchange of several mesons in high energy peripheral collisions.

Possibly, collisions of high multiplicity are connected more or less with statistical conceptions. It is also possible that all the processes studied involving $\pi$-meson production will find explanation withing the framework of the present - day meson theory.

## Experimental Data on Pion-Proton Interactions

### a) Total Cross-section

There is a great number of investigations at present devoted to pion-proton interactions. Most of them have already been quoted at previous conferences. Therefore, we shall give here only a short summary of the experimental material referring mainly to energies above 2 Bev.

At 2.76 Bev measurements of the total cross-section of $\pi^+$-meson interaction with hydrogen were made by Likhachev et al.[25] with the proton synchrotron at Dubna. In these measurements a beam of positive pions was extracted by the magnetic field of the accelerator into the annulus of the proton synchrotron. The total cross-section of the $\pi^+p$ was measured by the difference method $(CH_2-C)$ using Cherenkov total inner reflection counters. An estimate was made of the errors due to contamination of the beam with $\mu$-mesons and electrons ( the impurity content was found to be equal to about 3.5%). The possible role of scattering of secondary particles, etc. was determined by means of measurements in two solid angles covered by the last counter.

The total $\pi^-p$ cross-section in the momentum range from 1.5 to 4.0 Bev/c [26] compiled from the data of Moyer's work performed with the aid of electronic instruments ( see figure 20a). The details of the experimental procedure are not known.

The comparison of these data with the results of measurement of $\pi^-p$ interactions shows that the $\pi^-p$ and $\pi$ p cross sections practically coincide in the energy range discussed.

3176

In their work carried out in Dubna Wang Gan -chang et al.[31] measured the total cross section of $\pi^-$p-interaction at 6.8 Bev which proved to be equal to $\sigma_t$ =30 ± 5 mb.

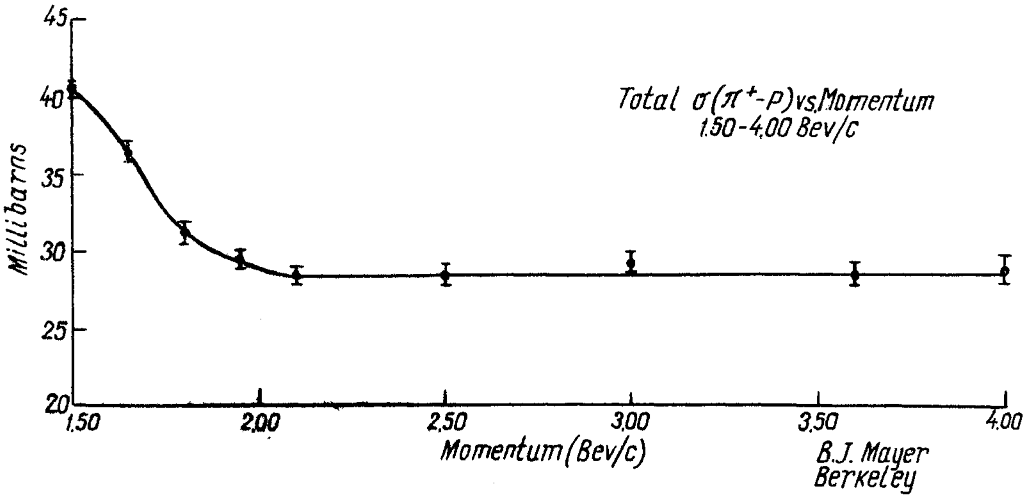


Fig.21.

b) Elastic Scattering

Interactions of $\pi^-$ pions with protons at 5 Bev were studied by Maenchen et al.[27]. The pion beam passed from the bevotron into a diffusion chamber with a magnetic field of 21500 oersted intensity filled with hydrogen at 35 atmospheres. The average momentum of pions in one group of experiments was 4.49 Bev/c and for another group, 4.99 Bev/c. 15500 photographs were examined. The curvature radius, inclines, azimuth angle, ionization density and other parametres were carefully measured. In all, 27 elastic scattering events were observed. Their angular distribution is shown in figure 21. The total elastic cross section was estimated by the authors to be 4.7 mb, though the accuracy of this determination was, of course, not high.

Data have been obtained in Walker's study [28] by means of photographic emulsions, on the interactions of $\pi^-$-mesons with protons at 4.5 Bev. A stack of Ilford G -5 plates 600 microns thick was placed in a beam of $\pi^-$-mesons coming from the bevatron. About 1000 meters of pion tracks were examined and

128 collisions were found; besides, 67 events were observed which could be considered $\pi$-n collisions. The selection criteria were similar to those usually employed in photographic emulsion work (absence of evaporative traces, kinematics etc.). A rough estimate of the corresponding cross section (7.5 mb) was obtained on the basis of the number of elastic interactions on free protons found.

The most detailed study of elastic collision of $\pi^-$-mesons on protons at 1.44 Bev was made in the work of Chretien et al. [29] published in 1958. From the Cosmotron the pion beam passed through a magnetic system with two consecutive deflections, a system of collimators and a double shielding, and entered a propane-liquid bubble chamber. Owing to good collimation the energy spread of the pions did not exceed $\pm 1$ per cent. The propane chamber was 6 1/8" in diameter and 4" deep and contained 0.78 $g/cm^3$ of hydrogen. The chamber was operated without a magnetic field. Altogether 14300 stereoscopic photographs were made. Each photograph was examined twice.

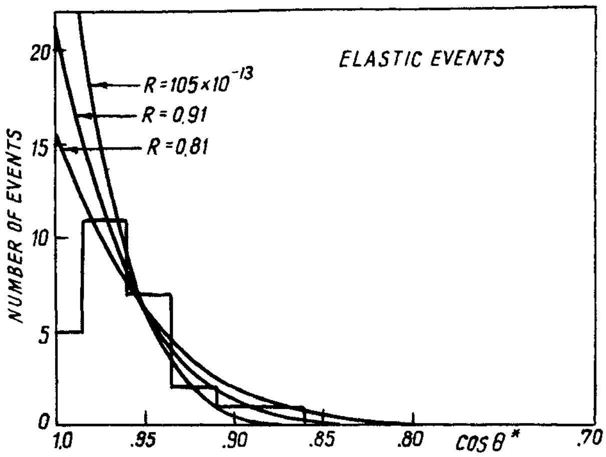


Fig.22.

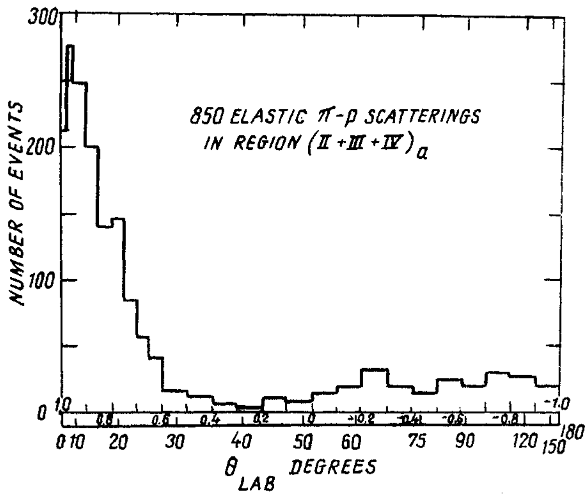


Fig.23.

Elastic $\pi$-p collision events were selected on the basis of strict kinematic criteria. 3000 two-prong stars were measure
3176 and analyzed, and 1027 of them satisfied all the criteria

accepted for selection. An estimate was made of $\pi$p- collision events on quasi-free protons of the carbon nucleons. The percentage of such events was not more than 4 per cent, actually probably still less. The effective volume of the chamber was determined by careful measurements. Fig.22 shows the experimentally determined angular distribution of elastic $\pi$-p scatterings in the centre-of-mass system.

The imaginary part of the scattering amplitude at $0^{o}$ was established with the help of an optical theorem in which the total cross-section in accordance with Cool s et al. [30] data was presumed to be $30 \pm 3$ mb. The real part of the scattering amplitude was determined by dispersion relations. The cross-section at $0^{o}$ was found to be 8.2 mb/ sterad. Integration of the differential cross-section with respect to the angle, taking into account the established value of the forward scattering cross section, gives the value $\sigma_{el} = 10.1 \pm 0.8$ mb. for the total cross-section of $\pi^{-}$-meson scattering by protons.

As can be seen from the above figure, the distribution angle has a sharp forward maximum, dropping to low values at about $40^{o}$ and rising again to an approximately constant value of 0.3 mb/ sterad. between $90^{o}$ and $180^{o}$.

The authors point out that the forward maximum is related principally to the diffraction scattering in accordance with the large absorption cross-section ($\sigma_{in}$ =20 mb.). However, backward scattering is too strong to be due to the same reason. Here the difficulty of interpretation is accounted for by the fact that though the phenomena causing forward and backward scattering are evidently different in nature, their amplitudes can nevertheless interfere. If we ignore this interference and attempt to calculate the expected diffraction scattering we get a curve which agrees very well with experimental data for angles of $30^{\circ}$ and less.

Evidently, elastic high-energy pion collisions have been most thoroughly studied by Wang Gan-chang et al.[31] in his experiments carried out on the proton synchrotron at Dubna. The Dubna group worked with a beam of negative pions having a momentum of 6.8 Bev/ c. To investigate elastic collisions a 24-litre protane bubble chamber was used, which was placed in a magnetic field of 13700 oersted. The pion beam was deflected twice magnetically and was collimated. The mean momentum value was $6.8 \pm 0.6$ Bev/c. Altogether about 3500 stereoscopic photographs were scanned. Each photograph was scanned twice by two scanners. Of all the two-prong stars 550 events resembling elastic collision were selected. Measurement results were treated by an electronic computer putting out the coordinates of traces, recoil proton range ( at stoppages), pion scattering angle, recoil proton angle and the corresponding azimuthal angles. The elastic pion interactions were identified by the strict criteria accepted for such cases.

Thus, 218 events recognized elastic collisions were finally selected. The value of the effective region of the chamber where 213 events out of 218 were found to occur was investigated separately. The muon contamination was estimated and found to be $5 \pm 2$ per cent. The total length of pion traces employed to determine the cross-section was $1.15 \times 10^{6}$ cm. The elastic scattering cross section at angles over $8^{\circ}$ in the centre of mass system was found to be $3.55 \pm 0.25$ mb.

In Fig.23 shows the differential cross section of elastic scattering as a function of the angle in C.M.S.

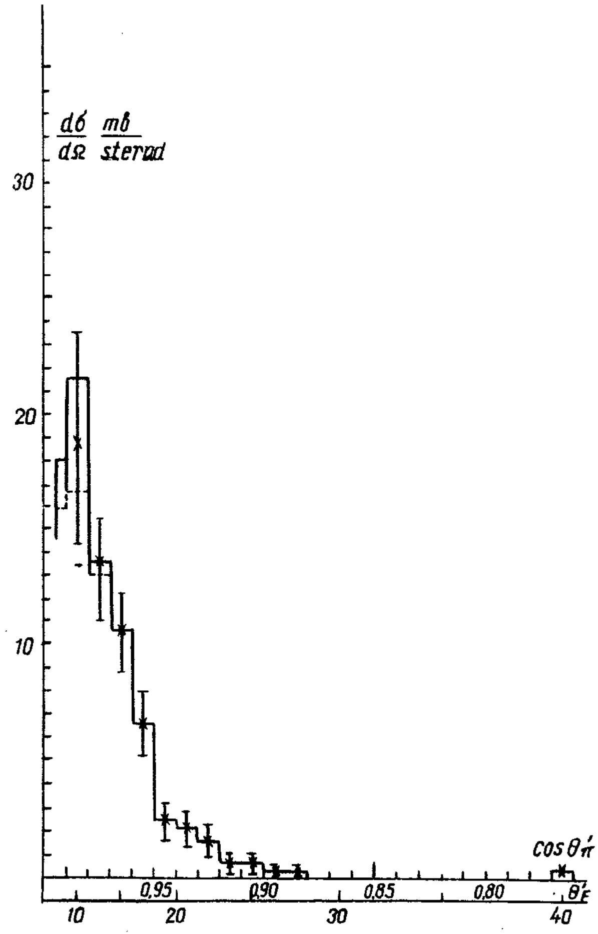


Fig.24.

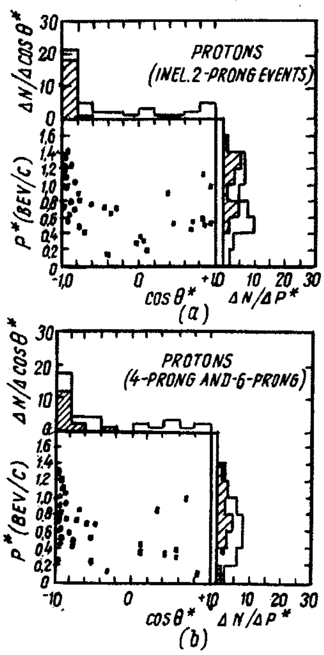


Fig.25.

## c) Inelastic Collisions

The above-mentioned Maenchen experiment [27] performed with the help of a high-pressure hydrogen diffusion chamber revealed 110 inelastic $\pi$-p interactions with an energy of 5 Bev. The authors point out that in the centre of mass system the secondary protons mainly fly backwards ( see Fig.24). Fig.25 shows that the negative pions fly forward more often than backwards in two-prong interactions, while in four-prong and six-prong interactions their angular distribution is isotropic.

The authors found that the above-mentioned peculiarities of proton and pion angular distributions do not agree with the statistical theory. Having thoroughly examined both 3176 angular and energetic correlations between pairs of various particles they found no definite indications of the existence of intermediate isobaric states.

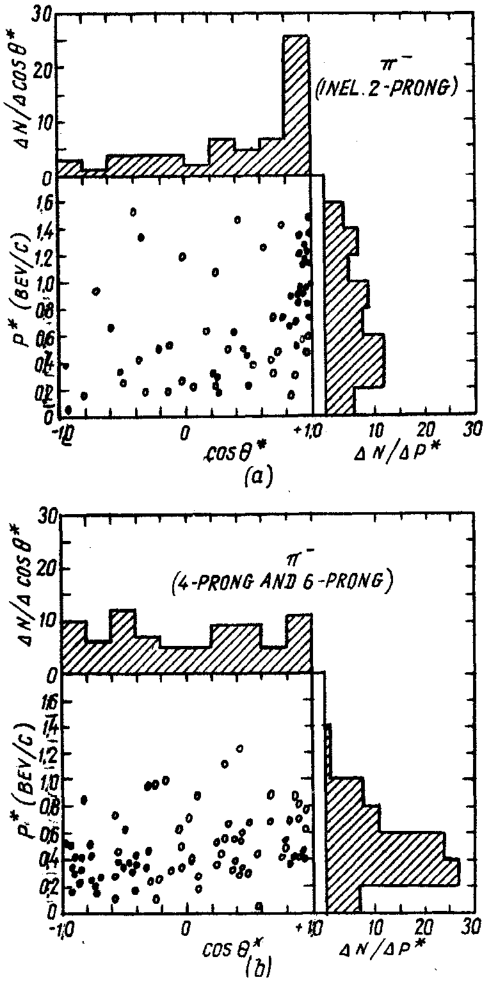


Fig.26.

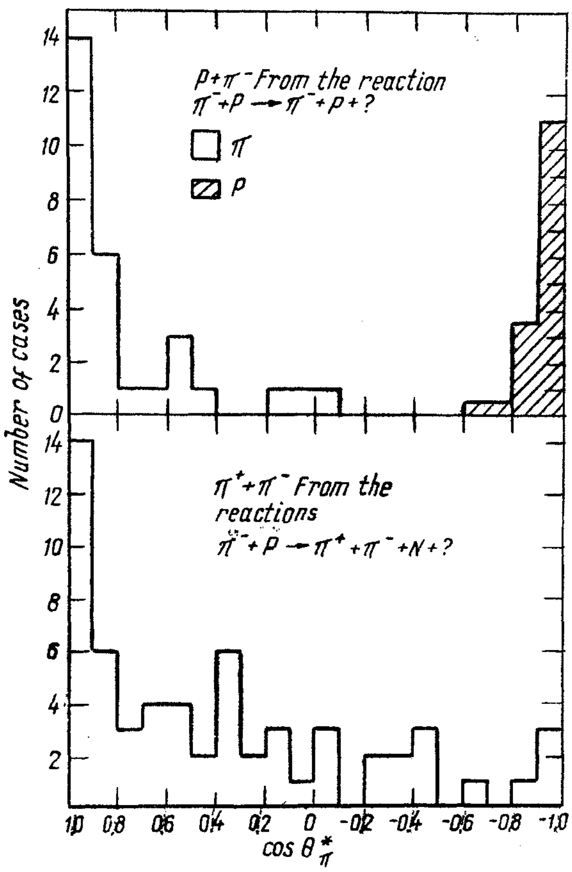


Fig.27.

In Walker's experiment [28] inelastic pion nucleon interactions were investigated by photographic-emulsion methods at 4.5 Bev.

About 1000 meters of tracks were examined and 128 events of p-p interactions were found.

Figure 26 gives the angular distribution of pions and protons in 2-prong interactions in the centre-of-mass system. As can be seen in the figure the protons produced in the reaction are emitted backwards in the centre-of-mass system and are concentrated within a very samll soldi angle. On the
3176 other hand, the negative pions produced in inelastic processes

are concentrated mainly in the forward direction. The distribution of positive pions is more isotropic.

The next figure ( Fig.27) shows the momentum distribution of protons in the centre-of-mass system for 2-prong stars. The data of Maenchen et al.[27] are plotted on the same figure for the sake of comparison. The maximum possible momentum of protons in the centre-of-mass system corresponds to 1.4 Bev/c. It follows from figure 27 that almost half the protons in these reactions possess a momentum exceeding 1000 Mev/c.

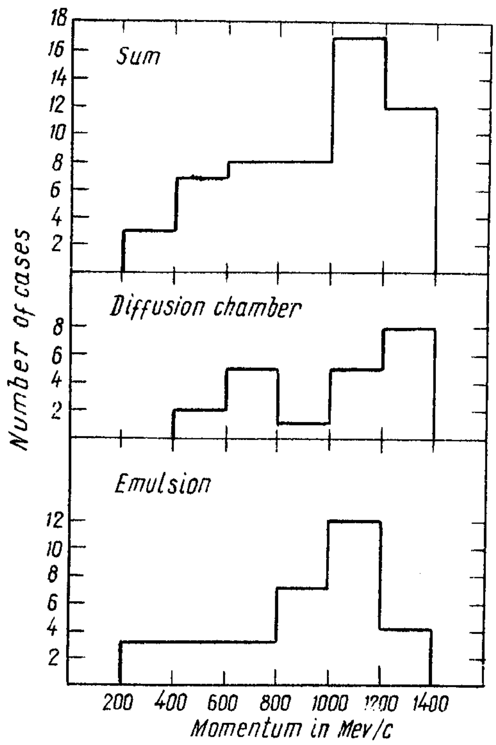


Fig.28.

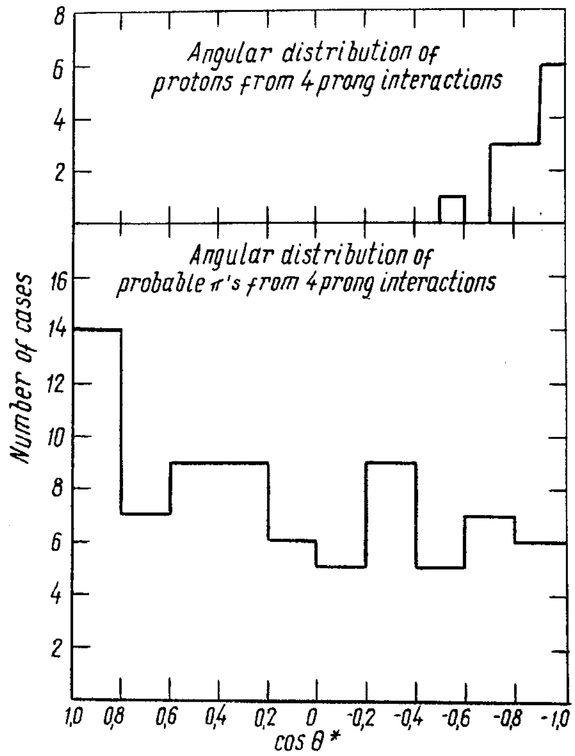


Fig.29.

Figure 28 illustrates the angular distribution of protons and pions from stars containing 4 ionizing particles. In this case we also see that all the protons are concentrated in the direction of their initial movement in centre-of-mass system. On the contrary, pions are distributed much more isotropically.

3176

The distribution of proton momenta in stars of such a type is somewhat broader than in 2-prong stars and the maximum is displaced towards momenta of the order of 800 Mev/c.

The authors point out that the characteristics observed by them for inelastic collision processes do not agree with the requirements of the statistical models. The sharpest contradiction concerns the angular distribution of nucleons.

The simplest picture of generation processes of a single additional pion, which agrees with the results obtained by Walker, consists, as he indicates, in that the primary pion interacts with a peripheral pion of a nucleon field and knocks it out like a delta electron from an atom.

Walker estimates the cross section of processes of such a type at approximately 7 mb.

As is well known, a similar model was suggested at one time by Dyson and Takeda to explain the maximum in the $\pi^-$p-interaction cross section at 1 Bev.

In multiple-pion production the angular distribution of the pions from 5-and 6-prong stars seems almost isotropic in the centre-of-mass system. The common feature of these interactions is that the nucleons move, as before, in the direction of the back hemisphere, though their angular distribution is broader than that of protons produced in 2-prong stars.

The fact of asymmetry in proton emission shows that multiple pion production is also difficult to understand from the piont of view of the statistical model.

Thus, the chief conclusions that may be drawn from this study are as follows:

1. In the centre-of-mass system nucleons move mainly backwards.

2. High energy pions move in the reverse direction.

3. Low energy pions are distributed more or less isotropically.

These results cannot be reconciled with any model of an isobar type, while the $\pi$-$\pi$ collision model seems more satisfactory.

It must, however, be noted that the isotropic angular pion distribution observed in multiple production requires the use of an additional mechanism for its explanation.

Preliminary data on a study of the inelastic interactions of $\pi^-$-mesons with protons and neutrons at 6.8 Bev carried out at Dubna are given in a paper by Belyakov at al. [35]. The study involved the use of an emulsion chamber consisting of a NIKPHI-R-type photographic emulsion 450 microns thick. In distinguishing interactions with free and peripheral nucleons of the photographic emulsion the usual criteria employed in these cases were used. In this manner altogether 44 $\pi$-p interactions and 30 $\pi$-n interactions were found. The average number of secondary relativistic particles equalled $3.0 \pm 0.4$ in the first case and $3.0 \pm 0.5$ in the second.

The authors relate these phenomena to the posible influence of peripheral interactions, particularly, interactions. Such an interpretation agrees qualitatively with the dependence of the average pion momentum on multiplicity. The corresponding data are given in Table. 9.



176

T a b l e 9

| Number of prongs | 2 | 3 | 4 | 5,6,7 |
|---|---|---|---|---|
| $(\bar{pc})_{\pi}$ | 720±240 | 450±110 | 330±110 | 370±80 |

Fig. 29 shows the angular distribution of protons (for all $\pi$ -p and $\pi$-n interactions) and pions for interactions with two and three prongs. In transformation to C.M.S. it was assumed that all the non-dentified particles were protons.

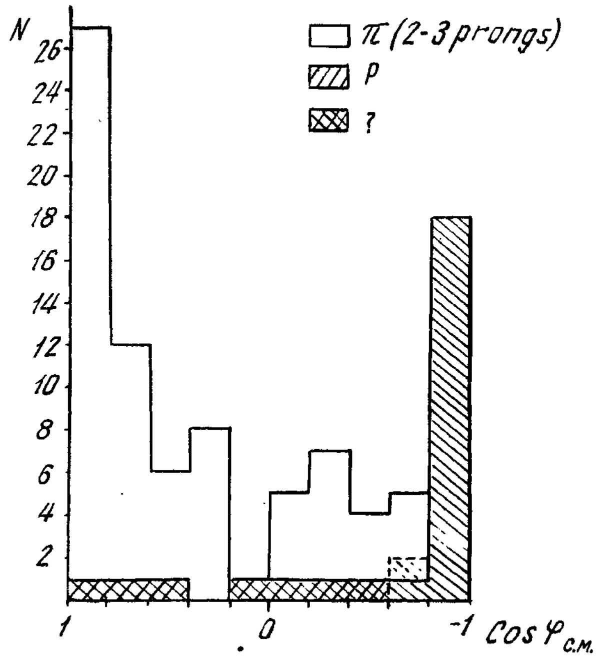


Fig. 30. illustrates the angular distribution of pions for collisions with a greater number of prongs. Fig. 31 depicts the dependence of the angular distribution on the momentum of secondary pions. It can be seen from the presented data that:

1. In C.M.S. protons chiefly fly backward.

2. Fast pions chiefly fly forward.

3. The angular distribution of slow pions is practically isotropic.

D.Analysis of $\pi$ - p interactions

The experimental data reviewed above contain the following characteristic features.

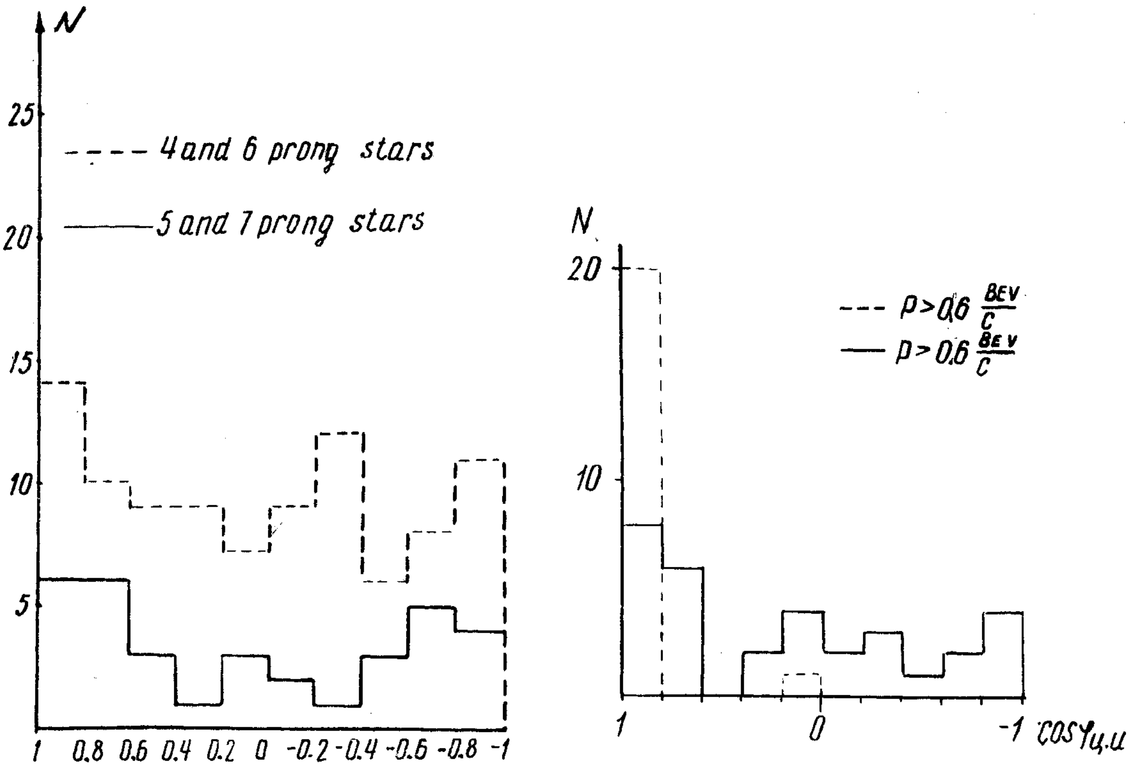


Fig.31. Analysis of $\pi$ -p interactions

Nucleons produced in $\pi$-p collisions fly towards the back hemisphere in the centre-of-mass system. The angular distribution of nucleons in stars with a large number of prongs ( 4 or more) also reveal this characteristic asymmetry, though in their case it is less distinct.

The angular distribution of pions generated in 2 -prong stars is elongated towards the front hemisphere: for stars with larger numbers of prongs the angular distribution is close to the isotopic, though this tendency remains to some extent.

In stars with a small number of prongs the nucleon momenta in the centre-of-mass system are close to their maximum limiting values.

The momentum distribution of protons arising in stars with larger numbers of prongs is broader, though it also has a maximum displaced towards larger momentum values. 3176

In the energy regions under consideration the conceptions of the formation of an isobar contradict experiment, though it should be noted that for low energies this contradiction is not so distinct. The aggregate of experimental facts is in contradiction with the statistical theory both at high and at low energies.

Evidently, the only model that does not contradict the aggregate of facts is that in which the high-energy pion in peripheral interaction forms a delta meson knocked out of the meson cloud of a nucleon collisions with smaller impact parameters lead to multiple pion production

All the above enumerated characteristic features agree with this model, especially in the high energy range.

Individual aspects of the mechanism of inelastic collisions between pions and nucleons are considered in the papers of a number of theoreticians(Ito et al.[34],Barashenkov[17], Blokhintsev et al.[33]).

In these papers an estimate of the effective cross-section of $\pi$-$\pi$ interaction is made on the basis of various assumptions as to nucleon structure, and an explanation is given of some of the characteristic features observed in these processes

Apparently, no sufficiently complete theory of this phenomena exists at the present moment.

It may be hoped that development of the ideas of peripheral collisions will be able to throw some light on this sphere of problems.

Phase shift analysis of elastic $\pi$-p scattering was conducted under the assumption that the spin interactions are unessential and that the scattering amplitude is purely imaginary, i.e., $Re f(\theta)=0$

Particularly it was shown by means of dispersion relations in Bilenky's paper that at high energies

$$\mathrm{Im}\, f(\theta) \gg \mathrm{Re}\, f(\theta)$$

Practically this inequality is true already at $E_{\pi} \sim$ 2 Bev when $\frac{\mathrm{Re}\, f(\theta)}{\mathrm{Im}\, f(\theta)} \approx 0{,}25$

In this respect the mechanism of $\pi$-p scattering possibly differs essentially from that of p-p scattering for which as has been shown above, the scattering amplitude at 9 Bev has a considerable real part.

Bilenky [7], Blokhintsev et al.[33] and Ito et al.[10] made a phase analysis of $\pi$-p scatterings under the above assumptions in the 1.4 - 5 Bev range. An estimate was made of the radius of $\pi$-p interaction, and it was found that $\sqrt{\bar{r^2}} \approx 8 \cdot 10^{-14}$ cm which is in good agreement with the results obtained from the experiments of electron scattering by protons. The absorption coefficient of pions by nucleons depending on the distance at which the collision took place was calculated in quasi-classical approximation. It was found that the coefficient has a tendency to increase greatly on approaching the centre of the nucleon.

An analysis from the point of view of the optical model gave the same results. Special note should be made of the fact that, as in the case of p-p scattering the coupling between the values $\lambda\!\!\!^{-2} \frac{d\sigma}{d\Omega}$ and $k \sin\theta$ constitutes from 1.4 to 6.8 Bev of the same curve for various energies (Fig.32).

Obviously, the physical sense of this result consists in the constancy of the average value of transverse momentum
transferred in the elastic scattering. On the other hand, 3176
according to all available data the average value of the

transverse momentum of secondary particles is observed to be constant also in the case of inelastic collisions over a wide range of energies. Thus it may be considered that within the

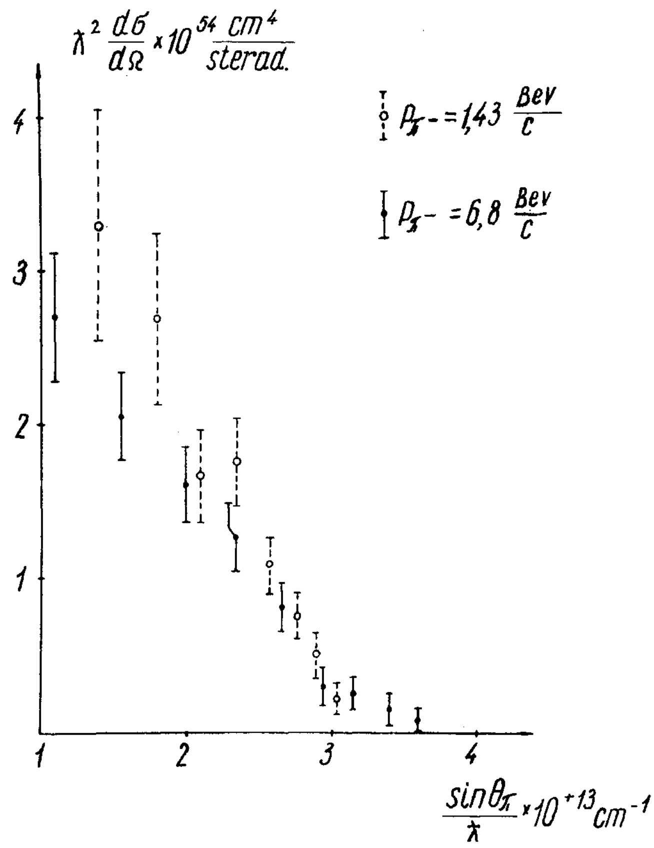


Fig.32.

energy range in question the effective impact parameter determining the value of the cross-section of nucleon-nucleon and nucleon-pion interactions does not depend on the energy. It would be important to relate this characteristic feature to the meson theory.

The author is greatly indebted to D.I.Blokhintsev, N.P. Bogachev, I.M. Gramenitsky, V.G. Grishin, P.K. Markov, M.I. Podgoretsky, I.L.Rosental, I.E. Tamm, E.N. Tsiganov, D.S. Chernavsky and a number of others for their fruitful discussions and valuable suggestions made in connection with the compilation of this report.

The author is especially grateful to N.P. Bogachev, V.G. Grishin, M.I. Podgoretsky and V.A. Shustin for their kind help in the writing of this report. I should also like to express my gratitude to all physicists who sumbitted the materials which have been used in this report.

R e f e r e n c e s

1. W.Fowler, R.Shutt, A.Thorndike, W.Whittemore. P.R., 103, 1489 (1956).

2. B.Cork, A. Wenzel, W.Causey. P.R., 107 859 (1957).

3. R.Kalbach, J.Lord, C.Tsao. R.P., 113, 325 (1959).

4. P.Markov, E.Tsiganov, M.Shafranova, B.Shahbadzyan*.

5. N.Bogachev, S.Bunyatov, Yu. Merekov, V.Sidorov, V Yarba*.

6. W.Preston*.

7. S.Bilenky. JETP, 30, 983 (1956).

8. V.Grishin, I.Saitov. JETP, 33, 1051 (1957).

9. V.Grishin. JETP, 35, 501 (1958).

10. D.Ito, S.Minami, H.Tanaka. N.C.,8, 135 (1958).

11. V.Grishin, I.Saitov, I.Chuvilo. JETP, 34, 1231 (1958).

12. N.Bogachev, S.Bunyatov, I.Gramenitsky, V.Lyubimov, Yu.Merekov, M.Podgoretsky, V.Sidorov, D.Tuvdendordz JETP (in press).

3. N.Bogachev, S.Bunyatov, Yu.Merekov, V.Sidorov, V.Yarba*.

4. WangShu-fen, T.Vishki, I.Gramenitsky, V.Grishin, N.Dalchadzav, R.Lebedev, A.Nomophilov, M.Podgoretsky, V.Streltsov*.

15. R.Kalbach, J.Lord, C.Tsao. R.P., 113, 330 (1959).

16. R.Daniel, N.Kamesware Rao, P.Malhotra, Y.Tsuzuki*.

17. V.Barashenkov*.

18. V.Maksimenko, JETP.

19. V.Maksimenko, A.Nikishov, I.Rosental*.

20. N.Grigorov, V.Murzin. Iyv.Ak.,Nauk, Ser. Phys. 17, 21(1953).

---

*Submitted to IX Conference on High Energy Physics in Kiev.

21. I.Tamm[*].

22. D. Peaslee. P.R.,95,1580 (1954).

23. Fowler, R.Shutt, A.Thorndike, W.Whittemore. P.R., 95, 1026 (1954).

24. J.Dremin, D.Chernavsky[*].

25. M.Likhachev, A.Lyubimov, W.Stavinsky, Chyan Naj-sen[*].

26. B.Moyer[*].

27. G.Maenchen, W.Fowler, W.Powell, R.W.Wright, R.P.,108, 850, (1957).

28. W.Walker. P.R.,108, 872 (1957).

29. M.Chretien, J.Leitner, N.Samies, M.Schwarty, J.Steinberger. P.R., 108, 383, (1957).

30. Cool, Piccioni, Clark. P.R., 103, 1082 (1956).

31. Wang Gan-chang, Wan Tsu-tsien, Din Da tsao, V.Ivanov, Yu. Katyshev, E.Kladnitskaya, L.Kulyukina, Nguen Din Ty, A.Nikitin, S.Otvinovsky, M.Solovyev, R.Sosnovsky, M.Shafranov.

32. S.Bilenky. JETP, 33, 1248 (1957).

33. D. Blokhintsev, V.Barashenkov, V.Grishin. JETP, 35, 311, (1958).

34. D.Ito, S.Minami, H.Tanaka. N.C.,9, 208 (1958).

35. Belyakov, Wang Shu-fen , V.Glagolev, N.Dalkhashav, L.Kirillova, R.Lebedev, N.Melnikova, V.Nikitin, V.Sviridov, M.Sook, K.D. Tolstov.

36. V.Barashenkov, Huan Nyan-nin . JETP, 36, 832 (1959).

37. V. Maksimenko[*].

38. W.Hess. Rev. Mod. Phys. 30, 368 (1958).

39. V.Barashenkov, V.Belyakov, E.Bubelev, Wang Shu-fen , M.Maltsev, Ten Gyn, K.Tolstov. Nuclear Physics, 9, 74(1958).



[*] Submitted to IX Conference on High Energy Physics in Kiev.