JOINT INSTITUTE FOR NUCLEAR RESEARCH

Laboratory of Nuclear Problems

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INVESTIGATION OF THE REACTIONS pp - pp and pn - pn

(Report at the 4-th Session of the Joint Institute Scientific Council, May 1958)

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The purpose of this paper was to complete the systematic investigation /I-4/ of neutral pion production in nucleon-nucleon collisions at 670 MeV and at lower energies. The experiments were devoted mainly to the analysis of the angular distribution of π^o-mesons in the reactions :

$$pp - pp\pi^o \quad (I) \qquad \text{and} \qquad pn - pn\pi^o \quad (2)$$

Data on the angular distributions of π^o mesons were obtained by measuring the angular dependence of the yield of γ rays emitted in π^o meson decay.

Fig.I shows the counter telescope used to detect γ rays. Gamma-rays produced on a target were collimated by means of a lead diaphragm and fall upon a lead converter where they were converted into electron-positron pairs. The pairs were detected by Čerenkov and scintillation counters set in coinsidence. In order that the gamma-telescope might have a low energy threshold and, thus, could effectively detect γ rays with the energy up to IO MeV, special measures were taken (small thickness of the converter/I÷2mm/ and scintillators/2÷3mm/,a "wide geometry" of the telescope). The telescope was not sensitive to neutrons (efficiency of $\approx 10^{-4}$) as well as to charged particles.The latter was achieved due to the application of a scintillation counter placed in front of the converter and set in anticoincidence. In detecting γ rays the counting rate decreased by a factor of 25 when the 2mm converter was removed. This ratio was improved untill 40 with increasing the converter thickness up to 5 mm. The coincidence circuits with the resolving time 10^{-8} sec permitted to use the telescope in conditions of a comperatively large background. The gamma-tlescope efficiency was determined experi-

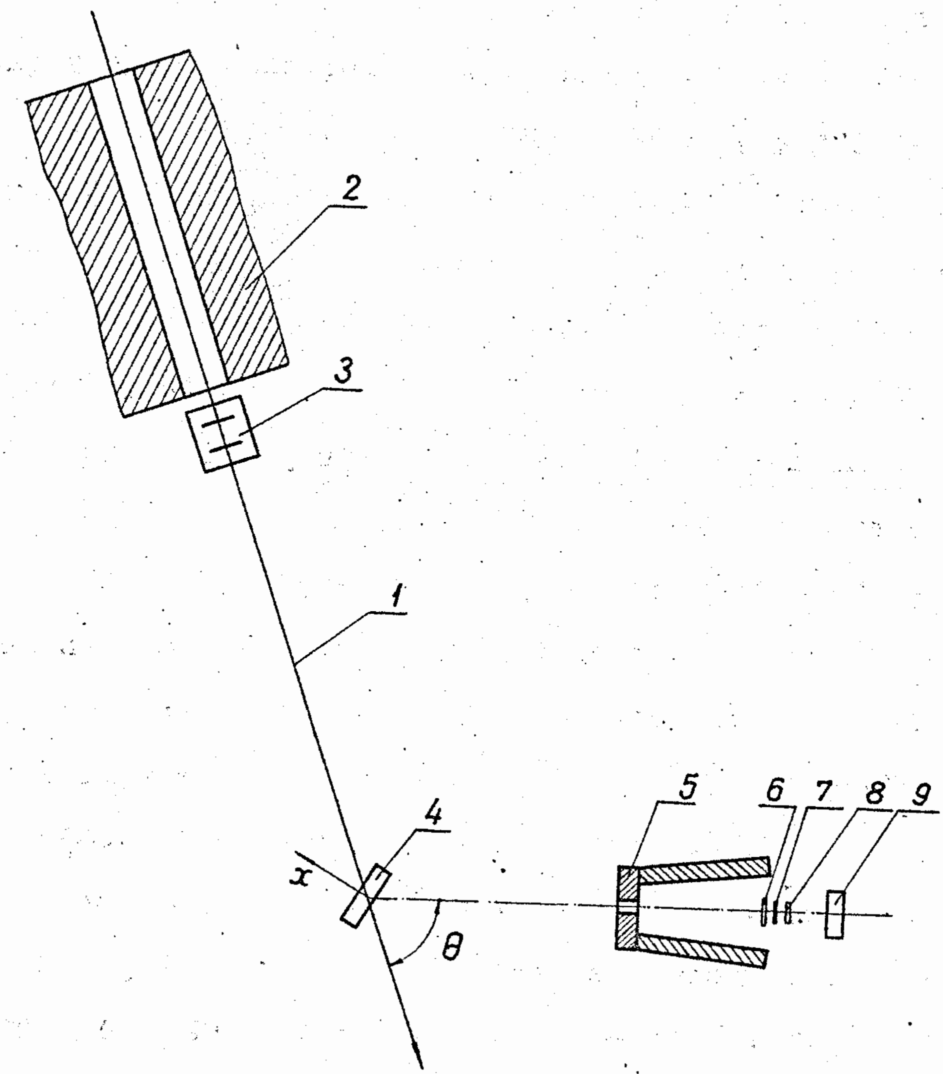

Fig. I.

Experimental arrangement

I) Proton beam, 2) Shielding, 3) Ionisation chamber, 4) Target;
5) Lead diaphragm, 6) Anticoincidence scintillation counter,
7) Lead converter, 8) Scintillation counter, 9) Čerenkov counter.

mentally by the method described in [2] for each angle and energy with the accuracy $(2 \div 3)$ per cent.

The experiments were carried out on the Joint Institute for Nuclear Research synchrocyclotron external proton beam with the intensity $10^8 p/cm^2 sec$. The proton flux was measured by a calibrated ionization chamber with the accuracy of ≈ 3 per cent. The maximum average energy of a proton beam at the place where the experimental equipment was located amounted to 670 MeV. The energy distribution of the proton beam is well described by the Gaussian function with a dispersion (2.8 ± 0.3) MeV [5]. The proton energy decrease was achieved by slowing down the protons in polyethylene blocks. Here the beam dispersion somewhat increased. The dispersion as well as the energy loss in a target were taken into account when determining the effective energy E_p.

The large background presented one of the main difficulties in measurements. It was reduced by stepped collimating the proton beam and by a special regime of the synchrocyclotron operation.

The cross section for the reaction (I) was found by the subtraction method, exposing a polyethylene and a light graphite targets. The thickness of the targets was taken to be about 3 g/cm^2.

In some experiments a liquid hydrogen target was used. It was desirable that the counting rate "with a target" should be considerably larger than that "without a target". For this purpose the telescope was placed at a small distance from the proton beam. Gamma-radiation coming from different points of a target was registered by a telescope with different efficiency. This was taken into account since the maximum relative correction is equal to I.5 per cent for the targets used, and the measurement accuracy of gamma yield ratios must be less than I per cent. A number of control experiments were performed in which a good agreement between measured and calculated corrections was observed. The main and the most laborious control experiment was carried out at the proton energy E_p = 280 MeV. As this value is below the threshold of π^o meson production in p-p collisions, the measured ratio of hydrogen cross sections to that of carbon must be equal to zero provided the corrections are found correctly. Indeed, the experimental result obtained is close to zero:

$$\left(\sigma_{pp}^{\pi^o} / \sigma_{pc}^{\pi^o} \right)_{measured} = -0.001 \pm 0.006$$

Making use of the measured cross section for neutral pion production on carbon one can obtain the upper limit $\sigma_{pp}^{\pi^o}/275/ < 5.10^{-30} cm^2$. This value characterizes as well the accuracy of the method used.

Reaction pp → ppπ^o

Investigation of the angular distribution of γ rays produced in proton-proton collisions has been made in two stages: the angular distribution of γ rays produced in collisions of protons with carbon nuclei was measured and then using the subtraction method (CH_2-C) the ratio of differential cross sections for hydrogen and carbon was obtained for each angle. Fig. 2 represents the obtained angular distribution of γ rays in the reaction (I) at the proton energy of 665 MeV. It is well described by the polynom

$$f_{pp}^{\gamma}(\theta) \sim 1/3 + (0.07 \pm 0.02) \cos^2\theta$$

This function found by the least square method and accordingly normalized is shown in Fig.2.

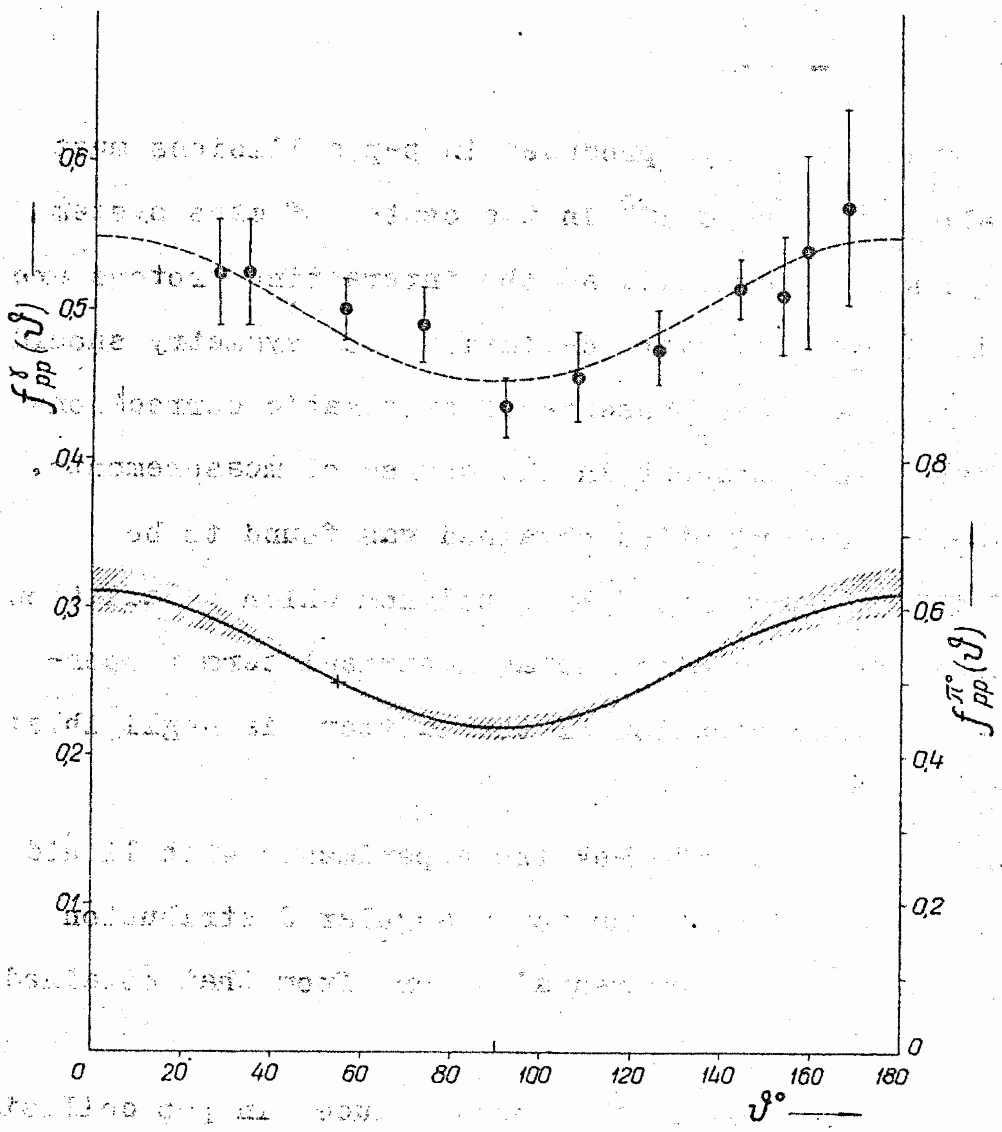

Fig. 2.

Angular distributions of γ rays $f^{\gamma}_{pp}(\Theta)$ and π^{o} mesons $f^{\pi^{o}}_{pp}(\Theta)$ at the proton energy E_p=665 Mev.

ɸ - gamma-ray yield at the angle Θ in c.m.s. in relative units. The dashed line is plotted by the least square method (see the text).

The solid curve represents the angular distribution of π^{o} mesons $f^{\pi^{o}}_{pp}(\Theta)$ (see the text). The edge of shaded area corresponds to the standard deviation. + is the point of normalization.

The distribution of γ rays produced in p-p collisions must be symmetrical about the angle 90° in the center of mass system of the colliding nucleons(c.m.s.), as the interacting protons are indistinguishable. Therefore every deviation from symmetry should be considered to indicate the presence of systematic corrections which were not taken into account in the course of measurements. The gamma-ray angular distribution obtained was found to be symmetrical. If it is approximated by a polynom which in addition to zero and second terms has also the asymmetrical term proportional to Cos θ, the contribution of the latter is negligible: (0.009 ± 0.011) Cos θ.

At the proton energy of 670 MeV the experiments with liquid hydrogen were also carried out. The found angular distribution does not differ within the experimental errors from that obtained by the subtraction method.

The angular distribution of π° mesons produced in p-p collisions at E_p = 665 MeV can be determined from the measured angular distribution of γ rays. It was found to be close to isotropic and is described by the function

$$f_{pp}^{\pi^{\circ}}(\theta) \sim 1/3 + (0.13 \pm 0.04)\,\mathrm{Cos}^2\,\theta$$

which is given in Fig.2. This distribution is close to that calculated by Mandelstam /6/ on the basis of a resonance model:

$$f_{pp}^{\pi^{\circ}}(\theta) \sim 1/3 + 0.04\,\mathrm{Cos}^2\,\theta$$

The similar experiments have been performed also at lower proton energies of 560,510 and 485 MeV. The found angular distributions of neutral pions are approximated by the following polynoms:

E_p=560 MeV – $f_{pp}^{\pi^{\circ}}(\theta) \sim 1/3 + (0.33 \pm 0.17)\,\mathrm{Cos}^2\,\theta$

E_p=510 MeV – $f_{pp}^{\pi^{\circ}}(\theta) \sim 1/3 + (0.15 \pm 0.25)\,\mathrm{Cos}^2\,\theta$

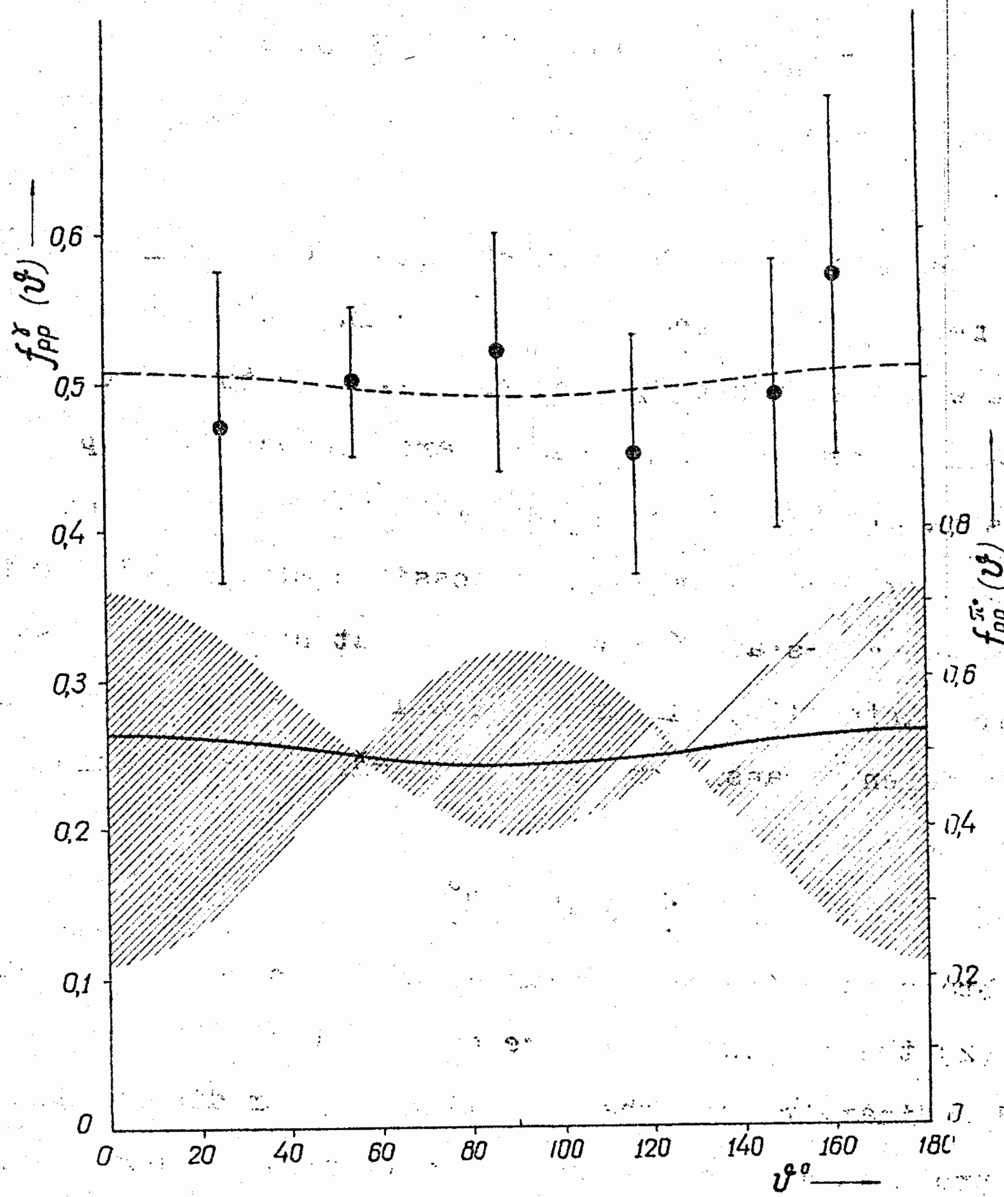

Fig. 3.

The same as in Fig. 2 but E_p = 485 MeV.

E_p=485 MeV $- f_{pp}^{\pi^0}(\theta) \sim 1/3 + (0.03 \pm 0.25)\cos^2\theta$

The latter curve and the angular distribution of γ rays is represented in Fig.3.

As may be seen from the data obtained, the angular distribution of π^0 mesons in the reaction (I) remains isotropic and does not change with decreasing proton energy. From this follows that in the small energy region π^0 mesons are produced in p-p collisions mainly due to transition into "displaced" S-state (we use the term by Mandelstam) with a possible mixture of transition into "displaced" D-state (if we asume, that nonresonant Ss transition has low intensity). In order to solve the problem of the role of different transition one should make investigations in the lower energy region.

Reaction pn-pnπ^0

To obtain data on the angular distribution of mesons in the reaction (2) the measurements were carried out with targets of heavy and ordinary water. The resulting angular distribution of γ rays produced in proton-deuteron collisions at 665 MeV is given in Fig.4. Here one can find information on the angular distribution of γ rays in the reaction (2) as a deuteron contains both a proton and a neutron, and the angular distribution for the reaction (I) was already measured. However, one cannot limit oneself to the mere subtraction of cross sections: deuteron minus hydrogen. We shall discuss this problem in more detail. The deuteron cross section differs from the sum of hydrogen and neutron cross sections due to two factors: a) changing of cross sections because of nucleon motion inside a nucleus (in the energy region under consideration this cause the increase of the cross section) and b) screening of a nucleon by a nucleon from the bombarding proton. The latter leads to decrease of the cross

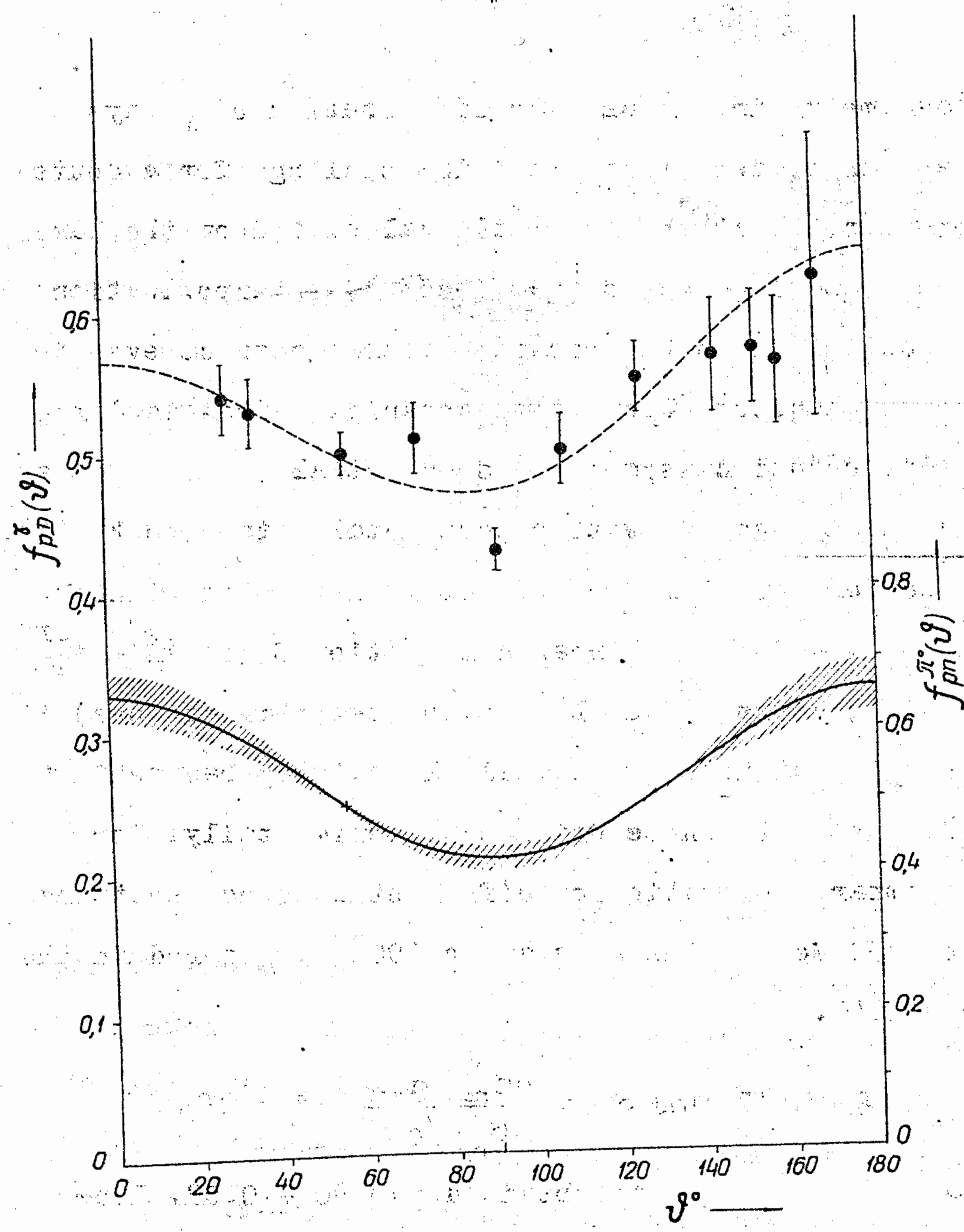

Fig. 4.

The angular distribution of γ rays $f^{\gamma}_{pD}(\Theta)$ and π^0 mesons $f^{\pi^0}_{pn}(\Theta)$ at E_p=665 MeV (see ref. to Fig. 2).

section and to asymmetry in the angular distribution of γ rays. This asymmetry as can be seen from Fig.4 is not large for a deuteron and therefore can be rather accurately calculated on the basis of a simple nuclear model (e.g., optical model). The application of the optical model for this purpose is reasonable since even in a case of the carbon nucleus (where the screening effect is large and the angular distribution asymmetry is essential) the calculated curve is in a good agreement with experimental data (see Fig.5).

The cross section for π^o meson production in p-D collisions can be represented in a form of linear combination $\sigma_{pD}^{\pi^o}=k_1\sigma_{pp}^{\pi^o}+k_2\sigma_{pn}^{\pi^o}$. In considering only factors a) and b) (which are the main ones) it is natural to assume that $k_I=k_2=k$. To calculate the parameter "k" is rather difficult but it can be obtained experimentally. For this one should compare the ratios of differential cross sections for the energy of 590 MeV at the same angle (90^o), measured in the present work and in[7]:

$$\alpha_p = \frac{d\sigma_{pD}^{\gamma}/d\Omega}{d\sigma_{pp}^{\gamma}/d\Omega} = 2.85 \pm 0.17 \quad \text{and} \quad \alpha_n = \frac{d\sigma_{nD}^{\gamma}/d\Omega}{d\sigma_{np}^{\gamma}/d\Omega} = 1.30 \pm 0.04$$

As $I/k=I/\alpha_p+ I/\alpha_n$, from the data obtained k=0,90 $\pm$ 0.03. Proximity of this value to unity indicates that the effects a) and b) are partly compensated. Thus, in determining the cross section for the reaction (2) one can consider that the deuteron cross section is approximately equal to the sum of those for a proton and a neutron. Here a small correction must be introduced, as $K \neq I$.

The angular distribution for the reaction (2) at 665 MeV obtained in this way is well described by a polynom

$$f_{pn}^{\gamma}(\theta) \sim 1/3 + (0.09 \pm 0.02)\cos^2\theta$$

If the hypothesis of charge independence is valid, the angular distribution of γ rays produced in p-n collisions must be symmetri-

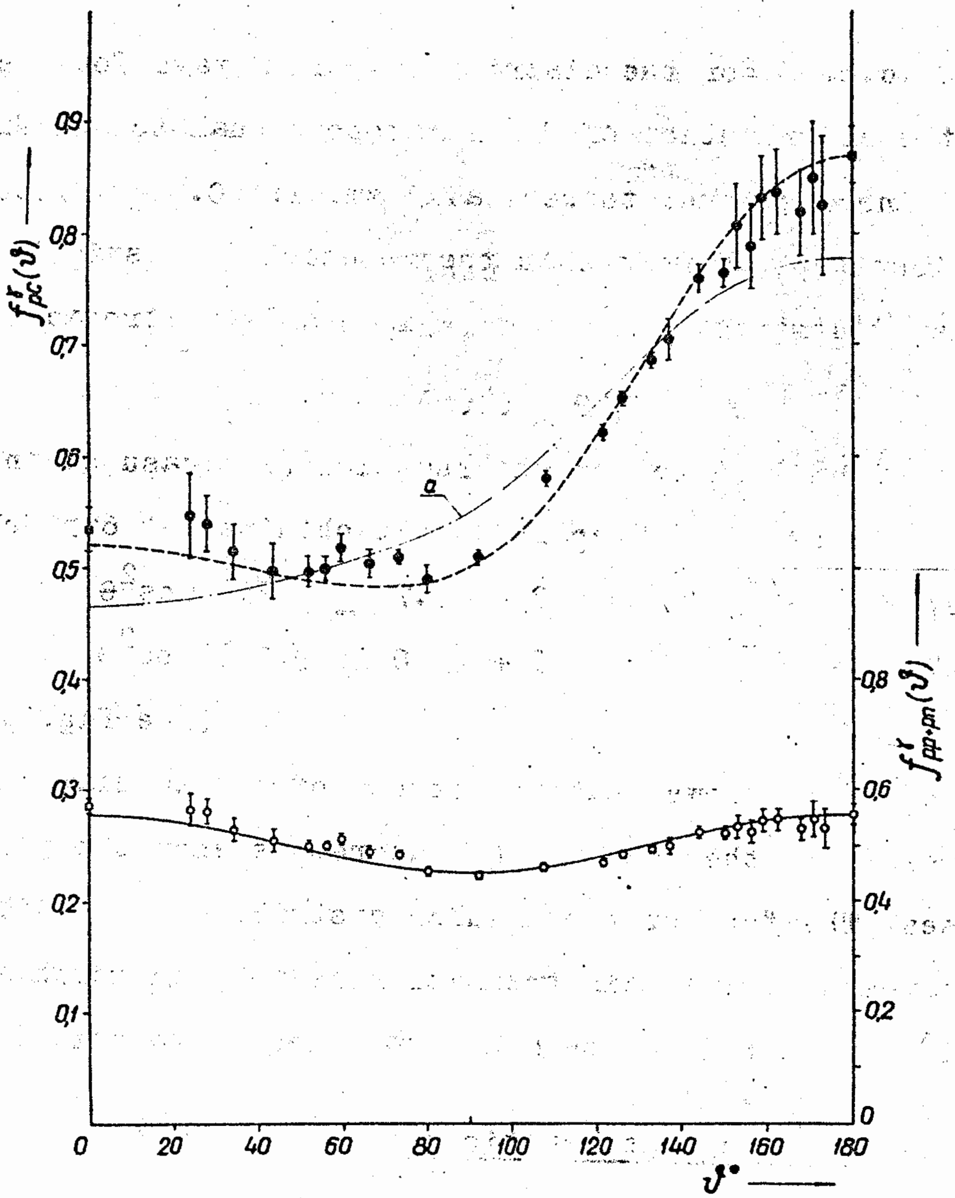

Fig. 5.

Angular distribution of γ rays produced on Carbon at E_p = 665 MeV (see ref.to Fig. 2)
a^p is the function $\varphi(\theta)$ calculated in /3/ on the basis of the optical model. The quantities f were obtained by dividing the measured γ ray yields by $\varphi(\theta)$. The dashed curve was derived by multiplying the lower curve by $\varphi(\theta$

cal about 90° in c.m.s. For the distribution of γ rays found experimentally, the contribution of a term proportional to the first power of the cosine was found to be really small: $(0.01 \pm 0.01) \cos\theta$.

The distribution of π° mesons in the reaction (2) estimated from the angular distribution of γ rays is nearly isotropic

$$f_{pn}^{\pi^{\circ}}(\theta) \sim 1/3 + (0.19 \pm 0.05) \cos^2\theta$$

The angular distribution for the reaction (2) measured in the same way at lower energies differ from that obtained at 665 MeV:

$$E_p = 560 \text{ MeV} \quad - \quad f_{pn}^{\pi^{\circ}}(\theta) \sim 1/3 + (0.74 \pm 0.25) \cos^2\theta$$

$$E_p = 485 \text{ MeV} \quad - \quad f_{pn}^{\pi^{\circ}}(\theta) \sim 1/3 + (1.0 \pm 0.3) \cos^2\theta$$

(see Fig.6)

Comparison of the data shows that anisotropy of the angular distribution of π° mesons in the reaction (2) decreases when the proton energy increases. The form of the angular distribution at small energies indicates that the main transition is that in which at final state the angular π° meson momentum is equal to unity.

Absolute cross sections

The measurement of the absolute differential cross section for γ ray production on hydrogen were made at the effective proton energy of 660 MeV for the angle 33° in the laboratory system:

$$d\sigma_{pc}^{\gamma}/d\Omega_{\circ} = (7.9 \pm 0.4) \times 10^{-27} \text{cm}^2/\text{sterad.}$$

This is in a good agreement with the cross section measured on the internal proton beam [2]: $(8.1 \pm 0.4) \times 10^{-27}$ cm². Later on, in determining the total absolute cross sections we shall use the average value :

$$d\sigma_{pc}^{\gamma}/d\Omega = (8.0 \pm 0.3) \times 10^{-27} \text{cm}^2/\text{sterad.}$$

Taking into account the obtained angular distributions of γ rays we determine the total cross sections for the reactions

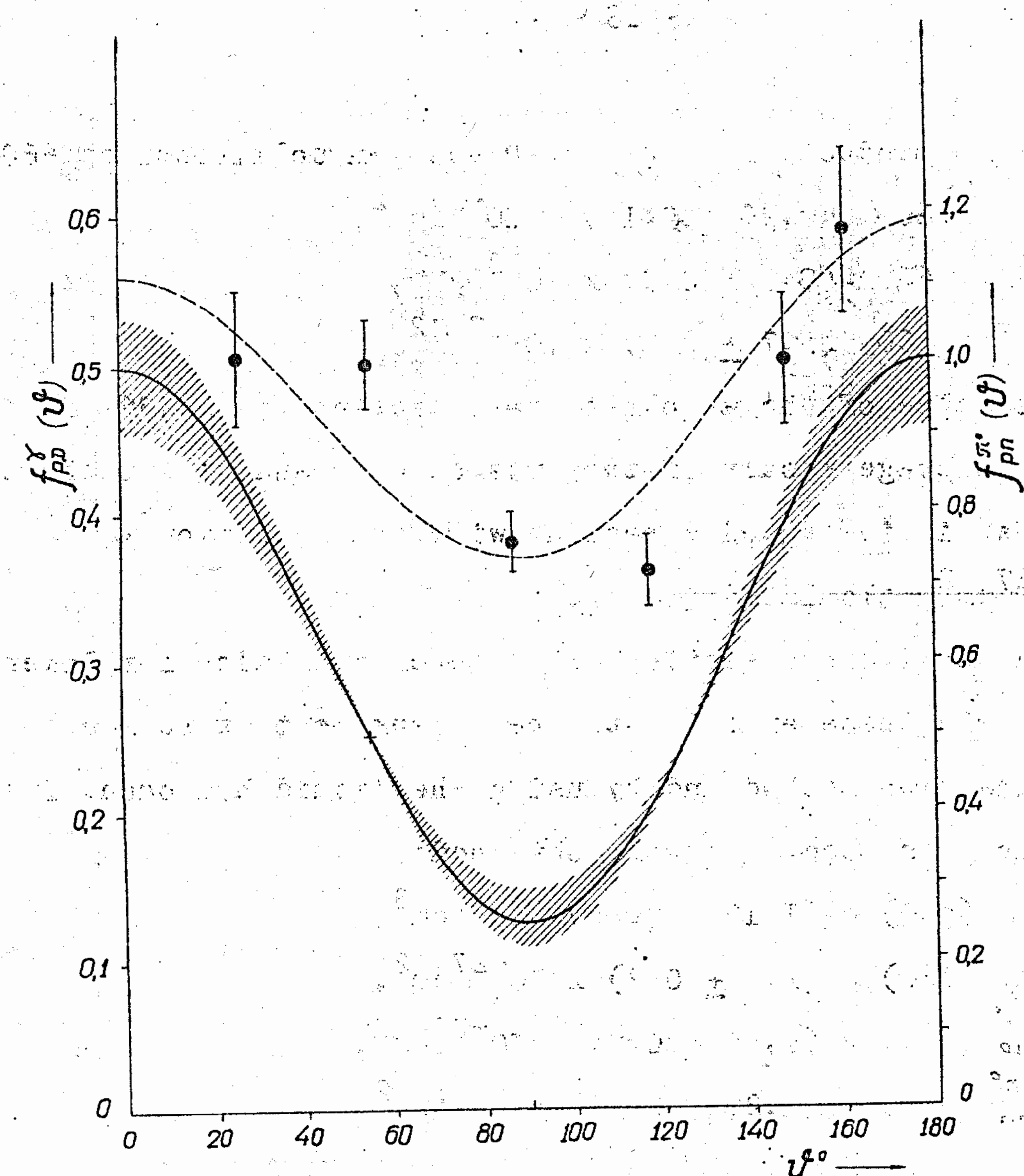

Fig. 6.

The same as in Fig. 4, but E_p = 485 MeV.

of π^0 meson production in p-p, p-D and p-n collisions at 660 Mev:

$$\sigma_{pp}^{\pi^0}(660)=(3.20 \pm 0.17) \times 10^{-27} cm^2,$$
$$\sigma_{pD}^{\pi^0}(660)=(8.0 \pm 0.3) \times 10^{-27} cm^2,$$
$$\sigma_{pn}^{\pi^0}(660)=(5.7 \pm 0.2) \times 10^{-27} cm^2.$$

The value of the absolute cross section $\sigma_{pp}^{\pi^0}=(3.36 \pm 0.14)\times 10^{-27}$ cm^2 (the average result of the present work and /2/) at the energy of 660 MeV is in a good agreement with cross section $\sigma_{pp}^{\pi^0}$ = 3.2×10^{-27}cm^2 calculated in /6/.

The total cross sections were determined also for lower energies. In these experiments the measurements were made by both the subtraction method and by using the liquid hydrogen. The following cross sections were obtained:

$$\sigma_{pp}^{\pi^0}(560) = (1.18 \pm 0.08)\times 10^{-27} cm^2,$$
$$\sigma_{pn}^{\pi^0}(560) = (3.7 \pm 0.2) \times 10^{-27} cm^2,$$
$$\sigma_{pp}^{\pi^0}(485) = (0.45 \pm 0.04) \times 10^{-27} cm^2,$$
$$\sigma_{pn}^{\pi^0}(485) = (2.20 \pm 0.15) \times 10^{-27} cm^2.$$

The comparison of the experimental results on the total cross sections of neutral and positive /8,9/ pion production at 660 Mev give the ratio:

$$\sigma_{pp}^{\pi^+}/\sigma_{pp}^{\pi^0} = 3,25 \pm 0.20$$

(Here $\sigma_{pp}^{\pi^+}$ is the cross section of the reaction $p+p \to p+n+\pi^+$). This ratio differs from the result of Peaslee /10/ (5) and is closer to that calculated by Mandelstam /6/ (3,9) (the latter took into account the interference effects and difference in meson masses).

From the cross sections found at 660 Mev it is possible to determine the cross sections of π-meson production by nucleons in the states T = 1 and T = 0:

$$\sigma_1^{\pi}(660)=(17.1 \pm 0.6)\times 10^{-27} cm^2, \quad \sigma_0^{\pi}(660)=(3 \pm 2)\times 10^{-27} cm^2.$$

This shows that π mesons are produced at the energy of 660 Mev mainly in the state T = I. This is observed at lower energies too:

$\sigma_1^{\pi}(560)=(9.0\pm04) \times 10^{-27}cm^2$, $\sigma_o^{\pi}(560) = (I,8 \pm I.7) \times 10^{-27}cm^2$

$\sigma_1^{\pi}(485)=(4.8\pm0.5) \times 10^{-27}cm^2$, $\sigma_o^{\pi}(485) = (I.5 \pm I.5) \times 10^{-27}cm^2$

It should be noted that the cross section σ_o^{π} is determined as the difference between nearly equal values. Therefore the cross sections σ_o^{π} obtained in the present work as well as in the similar investigations can be essencially changed in future, when the values of absolute cross sections of pion production will be defined more exactly.

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