JOINT INSTITUTE FOR NUCLEAR RESEARCH

Laboratory of Nuclear Problems

P-405

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REACTION $pn \to pn\pi^0$ IN THE ENERGY RANGE FROM THE THRESHOLD TO 665 MEV

ЖЭТФ, 1960, т 38, в 3, с 734-746

Dubna 1959

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* The results of this investigation were reported at the IV and VI Sessions of the Scientific Council of JINR (May 1958 and 1959).

Abstract

By a combined investigation of neutral pion production in p-d and p-p collisions the data were obtained on the magnitudes of the total cross sections and angular distributions for the reaction $pn \to pn\pi^0$ in the energy range from the threshold to 665 MeV. The comparison of these cross sections with those from other reactions shows that the requirement which the hypothesis of the isotopic invariance imposes on the relation between the total cross sections for various reactions of pion production is fulfilled in the investigated energy region within the experimental error (up to 10%). The pion production in the state with the isotopic spin $T = 1$ is approximately twice as intensive as in the state with $T = 0$. The angular distribution of neutral pions produced in nucleon-nucleon collisions at an energy of about 650 MeV was found to be close to isotropic in contrast to that of the charged pions which is essentially anisotropic by the data of Neganov and Savchenko. This difference contradicts the hypothesis of the isotopic invariance. The latter conclusion has, however, some objections and is of a preliminary character.

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I. Introduction

The investigation of neutral pion production in p-n collisions is now of a certain interest as it allows to clear up in this way the role of the transitions with the isotopic spin T = 0 in the inelastic nucleon collisions. At the same time the comparison of the magnitudes of the cross sections of the reaction mentioned above with those for the pion production in other reactions studied earlier makes it possible to establish to what extent the hypothesis of the charge independence of nuclear forces is valid.

Of the two reactions for neutral pion production in nucleon-nucleon collisions:

$$p + p \rightarrow \pi^0 + p + p \qquad (1)$$

and

$$p + n \rightarrow \pi^0 + \begin{cases} p + n \\ d \end{cases} \qquad (2)$$

the latter is more intensive, but its investigation is much more difficult than that of reaction (1). Reaction (2) remains so far one of those studied least of all among the processes of the type "nucleon + nucleon → pion". This reaction may be investigated by two methods: by bombarding the hydrogen nuclei by neutrons [1-3] and by comparing experimentally the cross sections of the reaction

$$p + d \rightarrow \pi^0 + \text{nucleons} \qquad (3)$$

with the cross sections of reaction (1) [4-7]. In the first case there arise the difficulties concerning the methods (low intensity of neutron beams etc.), as well as those of a principle character (a large width of the neutron energy spectrum[8]). In the second case the measurements are simpler as for the methods used, but the interpretation of the experimental data becomes considerably difficult because of the nucleon motion in a deuterium nucleus (that is equivalent to the problem of the wide neutron spectrum in the first case) and because of other effects which are due to the nucleon binding and to the presence of an odd nucleon in the final state of reaction (3) if compared with reaction (2).

To study reaction (2) we have chosen the second way from those mentioned above. A combined investigation of reactions (3) and (1) has been made under the same experimental conditions in the wide energy interval. The measurements of the cross sections were made both above and below the threshold for pion production in the collisions of free nucleons (280 MeV) to reconstruct momentum distribution of nucleons in a deuteron, without that the interpretation of the results of the measurements is impossible in the region adjacent to the threshold. The main attention was drawn to the investigation of the neutral pion angular distribution. This characteristic of reaction (2) was little studied: earlier at energies 400 and 590 MeV there were measured the angular distributions for the second channel of the reaction (where a deuteron is produced in the final state); the total angular distribution for both channels of the reaction was determined with a low accuracy at 660 MeV |6|.

2. Experimental Methods

A general set-up and the methods of measurements are analogous to those described in our previous paper |11|. The information on the angular distributions of neutral pions and on the magnitudes of the total cross sections for reaction (2) have been obtained by measuring γ quanta yields from the decay of neutral pions produced in the targets when they are traversed by proton beam . The experiments were performed with the external unpolarized proton beam of the six-meter synchrocyclotron of JINR. A γ telescope having a low energy threshold and consisting of scintillation counters and a Čerenkov counter was used to detect γ quanta. Heavy and ordinary water poured into thin-walled containers as well as light graphite and polyethelene $(CH_2)_n$ plates served as targets. The comparison of γ-quanta yields from these targets allowed to find the magnitudes of the ratios of the differential cross sections for a deuteron and carbon

$$\sigma'_{pd} = (d\sigma^{\gamma}_{pd}/d\Omega)/(d\sigma^{\gamma}_{pc}/d\Omega)$$

and the differential cross sections for the deuteron themselves (the cross sections for carbon were measured earlier |11|). When determining the ratios σ'_{pd} in the low proton energy region the data |11| obtained with the help of the liquid hydrogen target were used.

3. Differential and Total Cross Sections for Reaction p+d → π^0 + nucleons

The angular dependences of the relative cross section σ'_{pd} and the differential cross section of the reaction (3) have been measured in detail at proton energies E = 665, 560 and 485 MeV* (see Table 1).

T a b l e 1. E = 665 MeV.

θ°	16	20	33	45	60
$\langle\sigma'_{pn}\rangle = \sigma'_{pd} - \sigma'_{pp}$, %	20.7 ± 1.0	20.5 ± 1.5	19.4 ± 0.7	20.4 ± 1.5	16.4 ± 0.7
σ'_{pd}, %	35.4 ± 1.2	35.9 ± 1.8	34.5 ± 0.9	34.9 ± 1.7	29.1 ± 0.9
$d\sigma^{\gamma}_{pd}/d\Omega$, 10^{-27} cm²/ster	3.72 ± 0.30	3.41 ± 0.30	2.62 ± 0.16	2.20 ± 0.25	1.34 ± 0.08

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* E is the effective energy of the beam determined with account of the energy loss in the target and of the beam dispersion |12|.

75	96	120	135	145	160
19.1 ± 1.0	18.9 ± 1.0	16.3 ± 1.3	15.5 ± 1.4	14.1 ± 1.4	16.2 ± 3.5
30.7 ± 1.3	29.7 ± 1.2	26.2 ± 1.4	24.7 ± 1.7	23.5 ± 1.7	26.2 ± 3.7
1.17 ± 0.07	0.89 ± 0.06	0.66 ± 0.05	0.56 ± 0.04	0.52 ± 0.04	0.51 ± 0.07

E = 560 MeV

θ°	16	34	60	90	130	150
$\langle\langle \sigma'_{pn} \rangle\rangle$, %	24.5±1.2	22.1±1.4	16.7±0.9	17.6±0.7	17.1±0.9	19.9±1.0
σ'_{pd}, %	34.4±1.6	31.5±1.6	24.2±1.2	24.4±0.9	23.5±1.3	25.9±1.3
$d\sigma^{\gamma}_{pd}/d\Omega$, 10^{-27} cm²/ster	2.37±0.20	1.56±0.13	0.70±0.06	0.47±0.03	0.31±0.02	0.33±0.03

E = 485 MeV

θ°	16	35	60	90	130	150
$\langle\langle \sigma'_{pn} \rangle\rangle$, %	21.5±1.0	21.1±1.0	16.0±1.0	13.6±0.8	16.5±1.4	19.2±1.7
σ'_{pd}, %	26.6±1.4	26.4±1.1	21.3±1.3	18.1±1.1	20.5±1.6	23.7±1.9
$d\sigma^{\gamma}_{pd}/d\Omega$, 10^{-27} cm²/ster	0.96±0.09	0.79±0.06	0.41±0.04	0.23±0.02	0.19±0.02	0.19±0.02

θ is the angle of γ quanta emergence in the laboratory system (l.s.).

At other proton energies the ratios σ'_{pd} and the differential cross sections for carbon were measured either at the "isotropic" angles (see, e.g. Table 2), or at the angles of about 60 and 120° in the l.s. This allowed to determine the magnitudes of the total cross sections irrespective to the character of the angular distribution of neutral pions [13,11]. The magnitudes of the total cross sections $\sigma^{\pi^0}_{pd}$ found for reaction (3) are given in Table 3. While determining the cross section in the point E = 175 MeV the extrapolated value σ'_{pd} = (10 ± 4)% was used.

T a b l e 2.

$\vartheta = 55^\circ$.

E, MeV	665	645	610	560	485
$\langle\langle \sigma'_{pn} \rangle\rangle$, %	19.4 ± 0.7	21.0 ± 1.4	19.4 ± 1.2	22.1 ± 1.4	21.1 ± 1.0
σ'_{pd}, %	34.5 ± 0.9	35.2 ± 1.5	30.8 ± 1.3	31.5 ± 1.6	26.4 ± 1.1

440	370	330	290	250	215	175 extr.
18.9 ± 1.0	16.5±1.2	15.9±1.2	10.0±1.8	9.4±2.0	13 ± 4	10 ± 4
21.9 ± 1.2	17.5±1.3	16.1±1.2	10.0±1.8	9.4±2.0	13 ± 4	10 ± 4

ϑ - the angle of γ quantum emergence in the center-of-mass system of colliding nucleons (c.m.s.).

Table 3.

E, MeV	665	652	645	630	620
$\sigma_{pd}^{\pi^0}$, 10^{-27} cm^2	7.9 ± 0.4	7.6 ± 0.5	8.0 ± 0.5	7.6 ± 0.4	7.0 ± 0.6
$\sigma_{pd}^{\pi^0}$, rel units.	1.00	0.96 ± 0.06	1.01 ± 0.04	0.96 ± 0.03	0.89 ± 0.06

E, MeV	610	597	590	560	520	508
$\sigma_{pd}^{\pi^0}$, 10^{-27} cm^2	6.8 ± 0.4	6.1 ± 0.5	5.8 ± 0.4	4.45 ± 0.30	3.1 ± 0.2	2.9 ± 0.2
$\sigma_{pd}^{\pi^0}$, rel units.	0.86 ± 0.04	0.77 ± 0.05	0.73 ± 0.03	0.56 ± 0.02	0.39 ± 0.02	0.37 ± 0.02

E, MeV	485	440	437 a)	400	370	340 b)
$\sigma_{pd}^{\pi^0}$, 10^{-27} cm^2	2.37 ± 0.18	1.54 ± 0.12	1.15 ± 0.22	1.0 ± 0.1	0.68 ± 0.08	0.59 ± 0.15
$\sigma_{pd}^{\pi^0}$, rel units.	0.30 ± 0.02	0.19 ± 0.01	-	0.13 ± 0.01	0.086 ± 0.008	-

E, MeV	330	290	250	215	175 extr.
$\sigma_{pd}^{\pi^0}$, 10^{-27} cm^2	0.38 ± 0.06	0.19 ± 0.04	0.08 ± 0.02	0.06 ± 0.02	0.025 ± 0.010
$\sigma_{pd}^{\pi^0}$, rel units.	0.048 ± 0.007	0.024 ± 0.005	0.010 ± 0.002	0.008 ± 0.002	0.003 ± 0.001

a) - by the data of Stallwood et al.[7]

b) - by the data of Hales and Moyer [4] and paper.[11]

In the energy range 580 - 660 MeV the relative cross sections σ'_{pd} obtained in the present investigation are somewhat different from those found earlier[6]. The reason for this divergence is, likely, to be the local overheating of the L D target which conducts the heat badly when radiating it with the internal beam of the accelerator. This introduces a systematical error into the calorimetric method[6] for the determination of the proton beam. With decreasing the working radius of the target its heating rapidly decreases and the above error must disappear. Indeed, at the energies lower than 580 MeV the magnitudes of σ'_{pd} obtained in the present experiment and in[6] coincide within the experimental error (20% in[6]).

4. Total Cross Sections of Reaction (2)

The comparison of the obtained cross sections for the reaction $p + d \to \pi^0$ with those for the reaction $p + p \to \pi^0$ found earlier[11] allows, in principle, after taking into account the influence of the nucleon binding in a deuteron to determine the cross sections of reaction (2) we are interested in. The nucleon binding changes the magnitudes of the cross sections. As a result the cross section for the deuteron is found not to be equal to the sum of the cross sections for the proton and neutron. In the energy region under consideration which is situated not very far from the meson production threshold the main effect of those due to the nucleon binding is the change of the magnitudes of the cross sections because of the nucleon motion in a deuteron|14|. In the investigations performed earlier|5,6,15| the influence of the binding was taken into account in no way. The cross section for the neutron has been found by a simple subtraction "D - H" that may be regarded only as a first rough approximation. The use of a similar approximation in these experiments was quite justified since they were performed at high energies where the corrections taking into account the influence of the binding were measurable with an inaccuracy in the determination of the cross sections (15-30%). In order to pass to the low energy region as well as to decrease the inaccuracy in the determination of the cross sections at high energies it is necessary to take into account, at least approximately, the influence of nucleon binding. To solve this problem one ought to know the momentum distribution of nucleons in a deuteron.

In the energy region which lies near and below the threshold the energy dependence of the cross sections for the reactions occuring on the deuteron nucleons, in particular reaction (3), are fully determined by the character of the momentum nucleon distribution, mainly by the form of its high momentum "tail". With decreasing the incident proton energy the role of the deuteron nucleons possessing large momenta at the moment of collisions become even more essential. At the same time the contribution from the low energy part of the momentum distribution rapidly disappears. Due to this the investigation of the energy dependence of reaction (3) cross section in the region near the threshold is rather a sensitive method for studying the form of the momentum distribution (and especially its "tail"). The momentum distribution for the deuteron has been found by this method in|14| according to the data of Table 3 of the present paper. It was found to be close to the function calculated by Salpeter and Goldstein|16|. Being aware of the momentum distribution one may reconstract the magnitudes of the reaction (2) cross sections starting from the data on the cross sections of reactions (3) and (1):

$$\sigma_{pn}^{\pi^0} = \sigma_{pd}^{\pi^-} / k g_{pn} - \sigma_{pp}^{\pi^-} g_{pp} / g_{pn} . \qquad (4)$$

The functions g_{pn} and g_{pp} which are characteristic for the change of the magnitudes of the cross sections due to the intranuclear motion, and the coefficient k taking into account all the rest effects due to the presence of the "odd" nucleon were calculated in|14|. Making use of them and of the data of Table 3 we obtain the total cross sections for reaction (2):

T a b l e 4.

E, MeV	665	652	645	630	620
$\sigma_{pn}^{\pi^0}$, $10^{-27}cm^2$	6.3 ± 0.4	6.1 ± 0.5	6.5 ± 0.5	6.1 ± 0.4	5.6 ± 0.5
$\sigma_{pn}^{\pi^0}$, rel. units.	1.00	0.97 ± 0.06	1.03 ± 0.04	0.97 ± 0.03	0.89 ± 0.06
η_m	1.90	1.86	1.84	1.79	1.76

E, MeV	610	597	590	560	520	508
$\sigma_{pn}^{\pi^0}$, $10^{-27}cm^2$	5.5 ± 0.4	4.9 ± 0.4	4.6 ± 0.3	3.41 ± 0.25	2.2 ± 0.2	2.02 ±0.17
$\sigma_{pn}^{\pi^0}$, rel. units.	0.87 ± 0.04	0.79 ± 0.06	0.75 ± 0.03	0.54 ± 0.02	0.35 ± 0.02	0.32 ±0.02
η_m	1.73	1.69	1.66	1.56	1.43	1.38

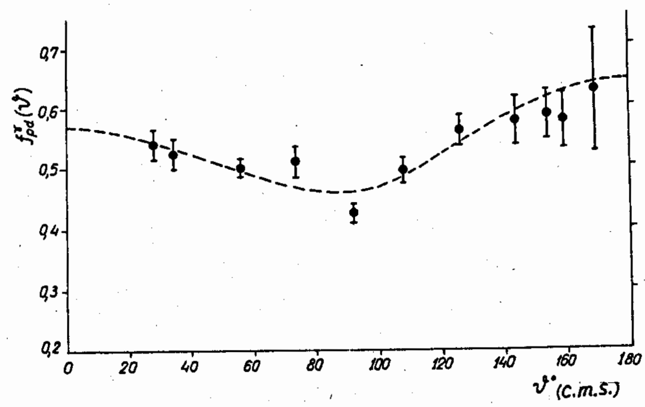
E, MeV	485	440	400	370	330	290
$\sigma_{pn}^{\pi^0}$, $10^{-27}cm^2$	1.57 ± 0.13	0.95 ± 0.10	0.56 ± 0.06	0.34 ± 0.04	0.15 ± 0.03	0.011±0.003
$\sigma_{pn}^{\pi^0}$, rel. units.	0.250 ± 0.015	0.151 ± 0.010	0.089 ± 0.007	0.065 ± 0.007	0.033 ±0.006	0.0020±0.0005
η_m	1.30	1.12	0.95	0.81	0.59	0.25

Here η_m is the maximum momentum of a neutral pion in the c.m.s. in the units of the meson mass m_π c.

5. Angular Distributions of γ Quanta

Angular distributions of γ quanta from the decay of neutral pions produced in reaction (3) have been measured in the energy region 400-665 MeV. At these energies the influence of the nucleon binding in a deuteron upon the angular distribution is not great and may be simply taken into account by introducing the effective c.m.s. system, the velocity of which in the l.s. $\bar{\beta}_c$ is only slightly different from that of the c.m.s. for the case of the collision with the nucleon at rest. The quantity $\bar{\beta}_c$ has been determined by integrating the velocity of the c.m.s. of an incident proton and nucleon moving in a deuteron with the momentum $\vec{p}_2$ over $\vec{p}_2$, with account of the Salpeter-Goldstein momentum distribution and of the energy dependence of the cross section (these calculations are analogous to those given in [14]). The angular distribution of neutral pions in the effective c.m.s. thus introduced practically coincides with the angular distribution (in the c.m.s.) of pions produced in the collision of unbound nucleons.

The measured angular distribution of γ quanta produced in p-d collisions at 665 MeV is plotted in Fig.1.



F i g. 1.

Angular distribution of γ quanta from the decay of neutral pions produced in p-d collisions at 665 MeV (in the effective c.m.s.). The dashed curve is drawn by the least square method with account of a small correction for screining.[17].

As is seen from this Figure the distribution $f^{r}_{pd}(\vartheta)$ is somewhat asymmetrical with respect to 90^{0} while the angular distributions for reactions (2) and (1) must be symmetrical if the hypothesis of the isotopic invariance is valid. The asymmetry appears due to the absorption of a pion and an incident proton. In such a simple and "spread" nucleus as a deuteron the absorption must be small and the asymmetry of the angular distribution is not large. Indeed, the contribution of the term proportional to $\cos\vartheta$ to the distribution $f^{r}_{pd}(\vartheta)$ (Fig.1) is only 5%. This small correction may be calculated sufficiently accurately (due to its smallness) on the basis of the simplified model of a homogeneous nucleus with account of the experimental data on the pion and nucleon absorption in the nuclear matter. In case of a complex nucleus (carbon) where the absorption is great and the contribution of the asymmetrical term to the angular distribution amounts to 30% the dependence of the coefficient k upon the angle thus calculated agree rather well with the experimental data[17,11].

The angular distribution $f^{r}_{pn+pp}(\vartheta)$ obtained from the distribution $f^{r}_{pd}(\vartheta)$ after introducing the correction for absorption into it is well described by the polynomial

$$f^{r}_{pn+pp}(\vartheta) \sim 1/3 + (0.07 \pm 0.02)\cos^{2}\vartheta .$$

If one subtracts the distribution found for reaction (1)[11] from the above distribution one may get the angular distribution of γ quanta in reaction (2) $f^{\gamma}_{pn}(\vartheta)$ at E = 665MeV. This distribution in approximated by the polynomial:

$$f^{\gamma}_{pn}(\vartheta) \sim 1/3 + (0.08 \pm 0.02) \cos^2\vartheta .$$

The distribution $f^{\gamma}_{pn}(\vartheta)$ is found to be symmetrical with respect to 90°. If we approximate it by a polynomial which besides zero and the second term contains an asymmetrical term as well proportional to $\cos\vartheta$, then the latter is found to be insignificant: $(0.01 \pm 0.01) \cos\vartheta$. Small is also the contribution to the total cross section from higher than the second powers of cosine. It follows from here[11] that in the energy region to 660 MeV the distribution of γ quanta in reaction (2) is of the form

$$f^{\gamma}_{pn}(\vartheta) \sim 1/3 + b_{\gamma} \cos^2\vartheta .$$

The magnitudes of b_{γ} obtained at various proton energies are presented in Table 5.

T a b l e 5.

E,MeV	665	630	590	560	520	508	485	440	400
b_{γ}	0.08±0.02	0.11±0.05	0.10±0.04	0.18±0.05	0.14±0.05	0.16±0.06	0.18±0.05	0.13±0.05	0.12±0.06

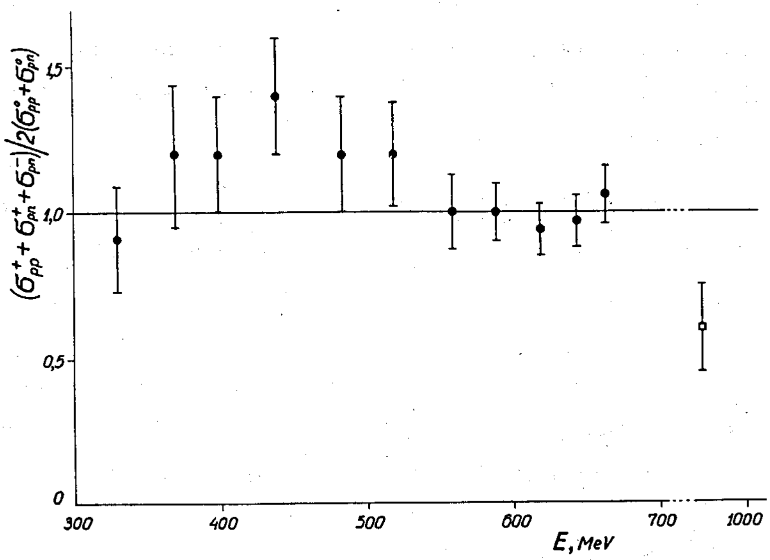
6. Discussion

Total Cross Sections and the Hypothesis of Isotopic Invariance

A well-known consequence of the hypotehsis of the isotopic invariance is the relationship connecting the total cross sections for the neutral and charged pion production in nucleon-nucleon collisions:

$$(\sigma^{\pi^+}_{pp} + \sigma^{\pi^+}_{pn} + \sigma^{\pi^-}_{pn}) / 2(\sigma^{\pi^0}_{pp} + \sigma^{\pi^0}_{pn}) = 1 . \qquad (5)$$

Having used the magnitudes of the total cross sections of reaction (2) found in the present investigation and the cross sections of other reactions studied earlier[11,18-22] it is possible to check the validity of equality (5) in the wide energy region from the threshold to 665 MeV. As is seen from Fig. 2



F i g. 2.

Ratio of the total cross sections for charged and neutral pion production at various proton energies. • -by the data of the present paper and [11,18-22], ▫ -by the data of Batson et al.[23]

this relationship in the above-mentioned energy region is really close to unity. At energies near 600 MeV, where the total cross sections are measured with the least inaccuracy, equality (5) is fulfilled with an accuracy 8-10%. Out of the quantities entering into this equality the cross section $\sigma_{pn}^{\pi\pm}$ is the least known. The experimental data on this cross section has been obtained only at two energies (400[20] and 590 MeV[21]). At other energies the quantities $\sigma_{pn}^{\pi\pm}$ used in Fig. 2 have been found by approximating the energy dependence of the cross section $\sigma_{pn}^{\pi\pm}$ by the power function $\gamma_m^{4-4,5}$ [22]. The inaccuracy due to the use of similar approximation cannot be large since in the energy region under consideration the contribution of the cross section $\sigma_{pn}^{\pi\pm}$ to the equality (5) is comparatively small. In the region of higher energies relation (5) has been recently measured at E = 970 [23]. The cross section at this energy is found to be unexpectedly large, that led to the magnitude of the relation (5) somewhat different from unity (Fig.2).

Using the obtained cross sections of reaction (2) it is possible to determine the magnitude of the partial cross section σ_{01} |22| (corresponding to the transition $T_N = 0 \rightarrow T_N = 1$; T_N is nucleon isotopic spin)

$$\sigma_{01} = 2\sigma_{pn}^{\pi^0} + \sigma_{pp}^{\pi^0} - \sigma_{pp}^{\pi^+} \qquad (6)$$

at various energies (Table 6). The cross section σ_{01} may be also obtained from the relation

$$\sigma_{01} = 2\sigma_{pn}^{\pi^+} - \sigma_{pp}^{\pi^+} . \qquad (7)$$

The magnitudes of σ_{01} found in this way are denoted in Table 6 by an asterisk. Besides the partial cross sections in Table 6 are plotted the magnitudes of the cross sections for pion production in nucleon-nucleon collisions with the total isotopic spin T equal to 1 and 0:

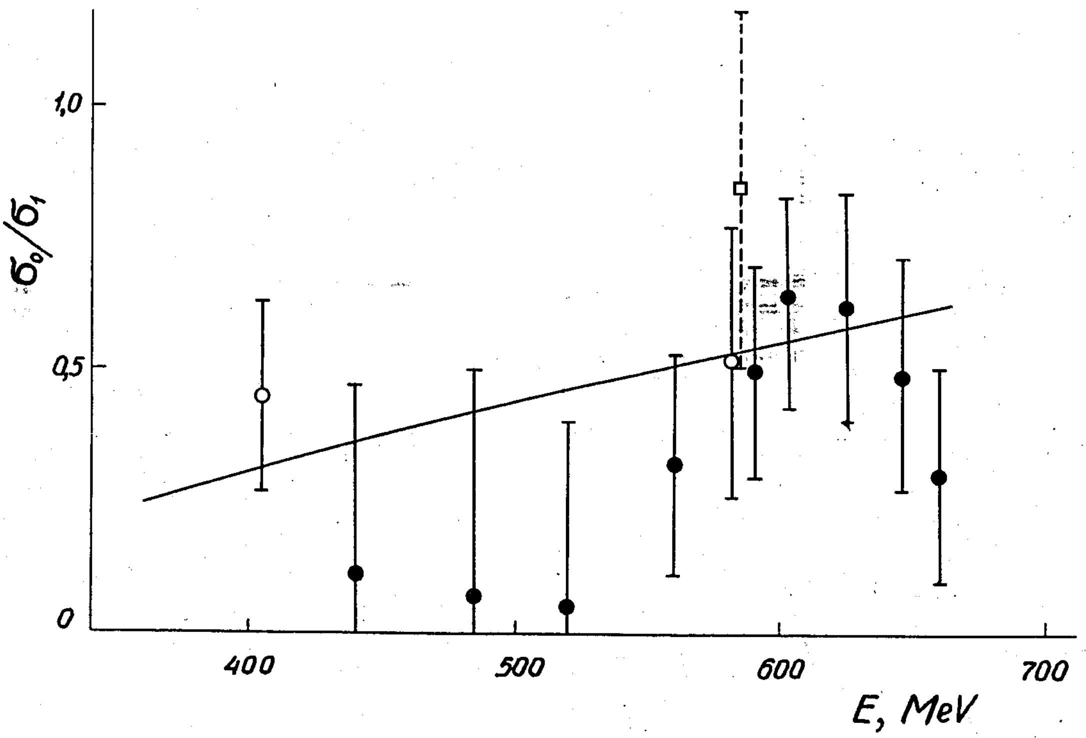
$$\sigma_1 = \sigma_{pp}^{\pi^+} + \sigma_{pp}^{\pi^0} \quad \text{and} \quad \sigma_0 = 3\sigma_{01} .$$

T a b l e 6.

E, MeV	660	645	630	620	610	597	590
σ_{01}, 10^{-27}cm^2	1.7 ± 1.1	2.6 ± 1.1	3.1 ± 0.9	2.7 ± 1.1	2.9 ± 0.9	2.3 ± 0.9	1.9 ± 0.8 1.9 ± 0.9*
σ_{10}, 10^{-27}cm^2	10.9±0.5	10.2±0.5	9.1 ± 0.5	8.5 ± 0.5	8.1 ± 0.5	7.5 ± 0.5	7.3 ± 0.5
σ_{11}, 10^{-27}cm^2	3.22±0.17	2.93±0.17	2.74±0.16	2.55±0.17	2.25±0.14	1.96±0.14	1.84±0.12
σ_0, 10^{-27}cm^2	5.1±3.3	7.8±3.3	9.3±2.7	8.1±3.3	8.7±2.7	6.9±2.7	5.6±2.4
σ_1, 10^{-27}cm^2	17.1±0.6	16.0±0.6	14.5±0.6	13.5±0.6	12.5±0.6	11.5±0.6	11.0±0.6

E, MeV	560	520	485	440	400	370	330
σ_{01}, 10^{-27}cm^2	0.9 ± 0.6	$0.1^{+0.6}_{-0.1}$	$0.1^{+0.5}_{-0.1}$	$0.1^{+0.4}_{-0.1}$	$0.1^{+0.3}_{-0.1}$ 0.22±0.08*	$0.1^{+0.2}_{-0.1}$	-
σ_{10}, 10^{-27}cm^2	6.0 ± 0.4	4.5 ± 0.4	3.4 ± 0.3	2.3 ± 0.2	1.2 ± 0.2	0.8 ± 0.2	0.33 ± 0.04
σ_{11}, 10^{-27}cm^2	1.24 ± 0.08	0.75 ± 0.06	0.45 ± 0.003	0.20 ± 0.02	0.09 ± 0.02	0.04 ± 0.01	0.014±0.00
σ_0, 10^{-27}cm^2	2.7 ± 1.8	$0.3^{+1.8}_{-0.3}$	$0.3^{+1.5}_{-0.3}$	$0.3^{+1.2}_{-0.3}$	$0.3^{+0.4}_{-0.3}$ 0.65±0.25*	$0.3^{+0.6}_{-0.3}$	-
σ_1, 10^{-27}cm^2	8.4 ± 0.5	6.1 ± 0.4	4.2 ± 0.3	2.7 ± 0.2	1.4 ± 0.2	0.8 ± 0.2	0.35 ± 0.04

The comparison of the magnitudes of the cross sections given in Table 6 shows that in the energy region from the threshold to 665 MeV σ_1 exceeds σ_0 approximately two times. (Fig.3).



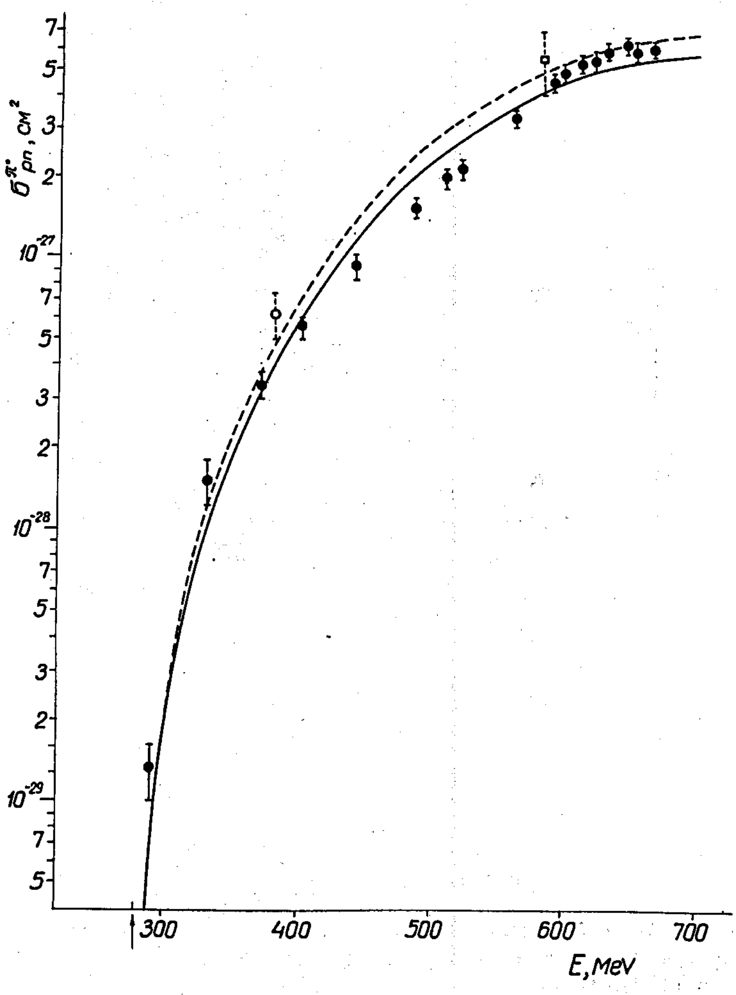
F i g. 3.

Ratio of the cross sections for pion production by nucleon in the states with the isotopic spin T = 0 and T = 1. ● - obtained from (6) by the data of the present experiment and |11,18,19,22|. ○ - obtained from (7) by the data of |11,20,21|. □ - obtained from the total cross sections |21|. The curve corresponds to dependence (8).

A better agreement with the experimental data is obtained if following Rosenfeld [22] we assume that σ_{01} changes with energy like η_m^4 :

$$\sigma_{01} = 0.3\ \eta_m^4\ 10^{-27}\ cm^2. \qquad (8)$$

The total cross sections of reaction (2) found in present experiment are close to the cross sections calculated on the basis of the resonance phenomenological theory of Mandelstam [24] (Fig.4). In the region of low energies the cross section $\sigma_{pn}^{\pi^0}$ increases like η_m^3. At energies E > 600 MeV the increase of this cross section become slower in agreement with the Mandelstam's theory.



F i g. 4.

Total cross sections for the reaction pn – pnπ^0 . ● – present investigation; ◻ – from [2]; ○ – from [3]. Solid curve is calculated on the basis of the Mandelstam's resonsnce theory. Dashed curve takes into account nonreshnant transition (8) in the state with T = 0 as well. The arrow indicates the reaction threshold.

Angular Distributions of Pions and the Hypothesis of Isotopic Invariance

Angular distributions of neutral pions in reaction (2) $f_{pn}^{\pi^0}(\vartheta)$ may be reconstructed from the measured angular distributions of γ quanta |11|. In the energy region from the threshold to 665 MeV the function $f_{pn}^{\pi^0}(\vartheta)$ as well as $f_{pn}^{\gamma}(\vartheta)$ has the form:

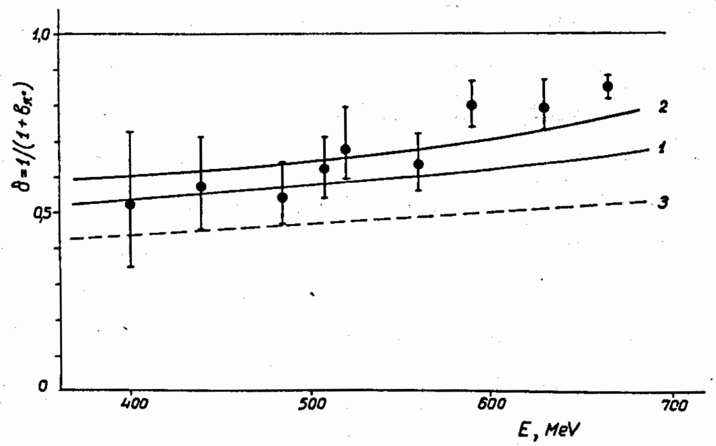
$$f_{pn}^{\pi^0}(\vartheta) \sim 1/3 + b_{\pi^0} \cos^2 \vartheta .$$

The found magnitudes of b_{π^0} are given in Table 7.

T a b l e 7.

E,MeV	665	630	590	560	520	508	485	440	400
b_{π^0}	0.17 ± 0.04	0.26 ± 0.12	0.25 ± 0.10	0.60 ± 0.20	0.48 ± 0.22	0.61 ± 0.23	0.85 ± 0.30	$0.74^{+0.48}_{-0.34}$	$0.9^{+1.3}_{-0.5}$

As is seen from this Table, the isotropy of the angular distribution of neutral pions in reaction (2) increases with increasing the incident proton energy. This result is in a qualitative agreement (Fig. 5) with the predictions of the Mandelstam's theory (private communication). The agreement with the theory become complete if together with the resonance transitions the nonresonant one (8) from the state with T = 0 is also taken into account for which the isotropic angular distribution is characteristic |11,21|



F i g. 5.

Angular distributions of neutral pions produced in p-n collisions. The quantity δ represents a share of neutral pions distributed isotropically. Curve 1 is computed by Mandelstam on the basis of his resonance theory. 2 and 3 are calculated with account of nonresonant transition (8) assuming the isotropic and $\sim \cos^2 \vartheta$ distributions, respectively.

If the hypothesis of the isotopic invariance is valid, the summed angular distributions of neutral and charged pions produced in nucleon-nucleon collisions must be identical (i.e. $f^{\pi^0}_{pp+pn}(\vartheta) = f^{\pi^\pm}_{pp+pn}(\vartheta)$). As at E ≤ 650 MeV the angular distributions $f^{\pi}(\vartheta)$ are described well by the polynomial of type $1/3 + b_\pi \cos^2\vartheta$ then the last statement is equivalent to the equality

$$b_{\pi^0} = b_{\pi^\pm} \qquad (9)$$

Here b_{π^0} and $b_{\pi^\pm}$ are the sums of the coefficients b_π in the angular distributions of neutral and charged pions normalized to the cross sections. The angular distribution of neutral pions at ≈ 650 MeV is close to an isotropic one: $b_\pi = 0.16 \pm 0.04$ at E = 665 MeV by the data of this investigation and [11]. So isotropic at these energies is the distribution of charged pions produced in p-n collisions[21] also. In contrast to this the charged pions produced in p-p collisions[21] are distributed essentially anisotropically: $b_{\pi^+} = 0.61 \pm 0.09$ by the data of Neganov and Savchenko[18]. The difference between the magnitude of the ratio $b_{\pi^0}/b_{\pi^\pm}$ and the unity which characterizes the degree of the violation of the isotopic invariance appears to be considerable:

$$b_{\pi^0}/b_{\pi^\pm} = 0.38 \pm 0.11 \ .$$

The above-mentioned difference of the angular distributions of neutral and charged pions is, perhaps, at present the only violation of the hypothesis of the isotopic invariance[25]. At should be noted, however, that this difference is not finally experimentally established yet. The above magnitude of the ratio $b_{\pi^0}/b_{\pi^\pm}$ should be considered preliminary. On the one hand, the angular distribution of positive pions may turn out to be more isotropic as, e.g. in recent experiments performed by Meshkovski, Shalamov and Shebanov[26].

On the other hand, the angular distribution of neutral pions in reaction (2) may be somewhat different from that obtained in the present work since the interference between the nucleon states in a deuteron is possible which lead to the change of neutral pion distribution if compared with that which takes place in the proton collision with free nucleons. In connection with this it is necessary both to make the experimental data on the angular distributions of charged pions more accurate and to investigate the angular distribution of neutral pions produced in free p-n collisions.

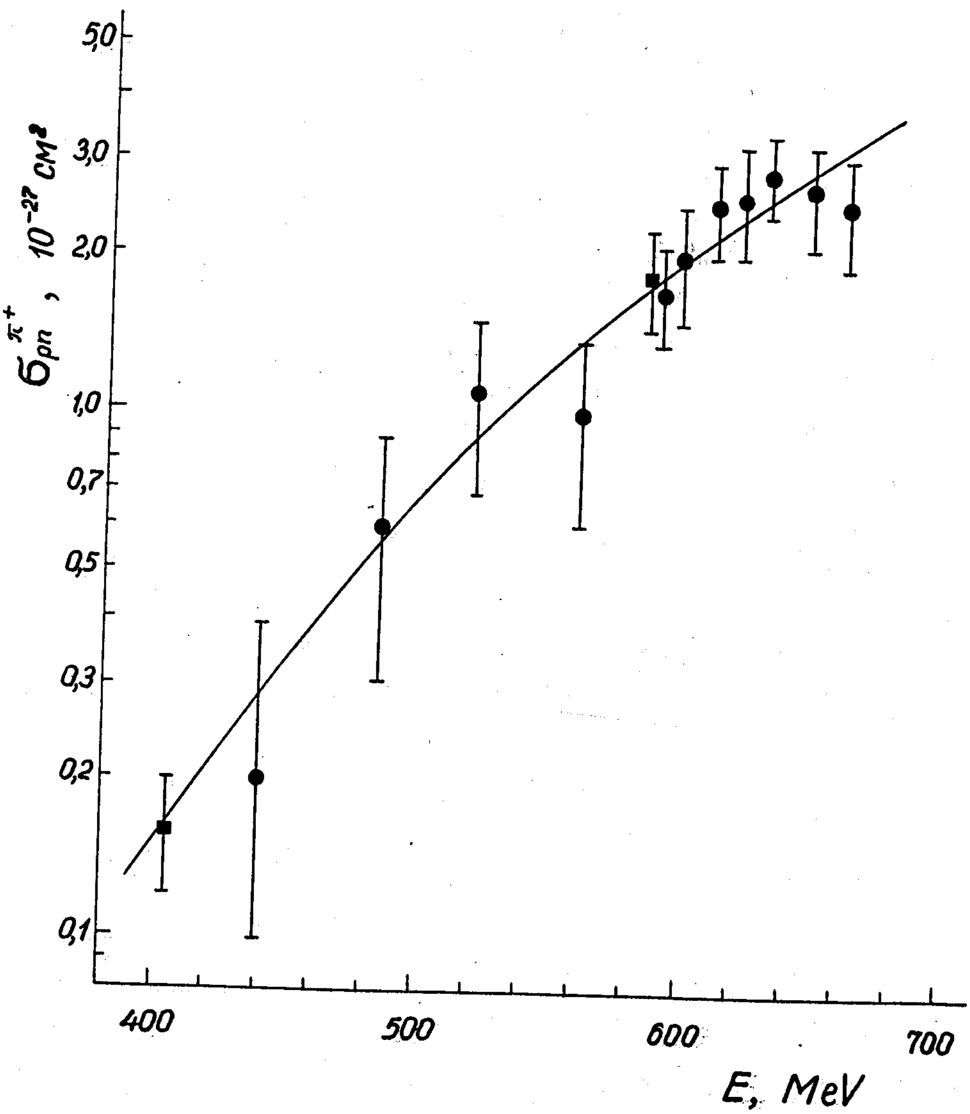
On the Reaction pn → $\pi^\pm$+ Nucleons

Making use of the magnitudes of the cross sections for reaction (2) obtained in present research and the cross sections for pion production in p-p collisions[11,18,19,22] it is possible to determine the cross sections of the reaction pn → $\pi^\pm$ in the wide energy range. This is of a certain interest since the direct investigations of the reaction pn → $\pi^\pm$

are very difficult from an experimental point of view. The found magnitudes of the total cross sections $\sigma_{pn}^{\pi^+}$ (or, what is the same $\sigma_{pn}^{\pi^-}$) are given in Fig. 6 .

As is seen from this Figure the energy dependence of the cross section $\sigma_{pn}^{\pi^+}$ is well described by the function

$$\sigma_{pn}^{\pi^+} = (1.7\pm0.4)\ \eta_m^{4.6\pm0.4} . \qquad (10)$$



F i g. 6.

Total cross sections for the reaction pn → $nn\pi^+$, the hypothesis of the isotopic invariance is assumed to be valid. ● - by the data of the present research and |11,18, 19,22|. ■ - the results of direct measurements |20,21|. The curve corresponds to dependence(10).

The authors are grateful to Dr. S. Mandelstam who kindly sent the results of his calculations unpublished yet. We also wish to thank B.S. Neganov for the discussion of the results and I.V. Tzymbulov for helping to carry out the measurements.

Received by Publishing Department
on September 15, 1959.

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