THE pn → pnπ^0 *REACTION IN THE ENERGY RANGE FROM THRESHOLD TO 665 Mev*

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By simultaneous investigation of π^0-meson production in pd and pp collisions, information is obtained on the magnitudes of the total cross sections and angular distributions for the pn → pnπ^0 reaction in the energy region from threshold up to 665 Mev. Comparison of these cross sections with those of other reactions shows that the condition imposed on the relation between the total cross sections of various meson productions by the isotopic invariance hypothesis is fulfilled (to within 10 per cent) in the investigated energy region. Production of π mesons in a state with isotopic spin T = 1 is almost twice as intense as that in states with T = 0. The angular distribution of π^0 mesons produced in nucleon-nucleon collisions at an energy of about 650 Mev was found to be approximately isotropic, in contrast to the distribution of charged π^+ mesons which is essentially anisotropic.[18] This difference contradicts the hypothesis of isotopic invariance.

1. INTRODUCTION

THE investigation of the reaction of production of neutral π mesons in pn collisions is of considerable interest at the present time in connection with the possibility of explaining by this means the role of transitions with isotopic spin T = 0 in processes of inelastic nucleon collisions. In addition, comparison of the magnitudes of the reaction cross sections mentioned with the cross sections of production of π mesons in other previously studied reactions permits one to establish the degree of validity of the hypothesis of charge invariance of nuclear forces.

Although the second of the two reactions for the production of π^0 mesons in nucleon collisions

$$p + p \rightarrow \pi^0 + p + p, \quad (1)$$

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

is the more intense, its investigation has encountered significantly greater difficulties than in the case of reaction (1). The reaction (2) remains at the present time one of the least studied among processes of the type "nucleon + nucleon → π meson." This reaction can be studied by two means: by bombardment of a hydrogen nucleus by neutrons,[1-3] and by experimental comparison of the reaction cross sections of

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

with the cross sections of reaction (1).[4-7] In the first case, difficulties both of a methodological character (low intensity of neutron beams, etc) and in principle (large width of the neutron-energy spectrum[8]) arise. In the second case, the measurements are methodologically simpler but the interpretation of the experimental data is made much more difficult by reason of the motion of the nucleons in the nucleus of deuterium (which is equivalent to the problem of a broad neutron spectrum in the first case) and by reason of other effects brought about by the coupling of nucleons even in the presence of an extra nucleon in the final state of the reaction (3) in comparison with the reactions (2).

For a study of the reaction (2), we chose the second of the two possibilities pointed out above. Joint investigation of reactions (3) and (1) was carried out under identical experimental conditions over a wide range of energies. Measurements of the cross section were carried out both above and below the threshold of production of π mesons in the collision of free nucleons (280 Mev) with the aim of establishing the momentum distribution of the nucleons in the deuteron without which interpretation of the results of measurement in the region adjoining the threshold would be impossible. Chief interest in the work was devoted to the study of the angular distribution of π^0 mesons. This characteristic of reaction (2) was studied less: previously, at energies 400 and 590 Mev, the angular distribution was measured[9,10] for the second reaction channel (where the deuteron is produced in a final

TABLE I

E, Mev	θ°	$\langle\langle\sigma'_{pn}\rangle\rangle=\sigma'_{pd}-\sigma'_{pp}$, %	σ'_{pd}, %	$d\sigma^{\gamma}_{pd}/d\Omega$, 10^{-27} cm²/sr
665	16	20.7±1.0	35.4±1.2	3.72±0.30
	20	20.5±1.5	35.9±1.8	3.41±0.30
	33	19.4±0.7	34.5±0.9	2.62±0.16
	45	20.4±1.5	34.9±1.7	2.20±0.25
	60	16.4±0.7	29.1±0.9	1.34±0.08
	75	19.1±1.0	30.7±1.3	1.17±0.07
	96	18.9±1.0	29.7±1.2	0.89±0.06
	120	16.3±1.3	26.2±1.4	0.66±0.05
	135	15.5±1.4	24.7±1.7	0.56±0.04
	145	14.1±1.4	23.5±1.7	0.52±0.04
	160	16.2±3.5	26.2±3.7	0.51±0.07
560	16	24.5±1.2	34.4±1.6	2.37±0.20
	34	22.1±1.4	31.5±1.6	1.56±0.13
	60	16.7±0.9	24.2±1.2	0.70±0.06
	90	17.6±0.7	24.4±0.9	0.47±0.03
	130	17.1±0.9	23.5±1.3	0.31±0.02
	150	19.9±1.0	25.9±1.3	0.33±0.03
485	16	21.5±1.0	26.6±1.4	0.96±0.09
	35	21.1±1.0	26.4±1.1	0.79±0.06
	60	16.0±1.0	21.3±1.3	0.41±0.04
	90	13.6±0.8	18.1±1.1	0.23±0.02
	130	16.5±1.4	20.5±1.6	0.19±0.02
	150	19.2±1.7	23.7±1.9	0.19±0.02

state) and the total angular distribution for both channels of the reaction was determined with low accuracy at an energy of 660 Mev.[6]

2. METHOD OF MEASUREMENT

The general setup and the method of measurement employed in the current research is similar to that described in our previous article.[11] Information on the angular distributions of π^0 mesons and on the magnitudes of the total cross sections for the reaction (2) were obtained by measurement of the yield of gamma quanta from the decay of π^0 mesons produced in targets upon transmission through them of a beam of protons. The experiments were completed on the external unpolarized proton beam of the sixty meter proton synchrotron of the Joint Institute for Nuclear Research. A γ telescope with a low energy threshold was used for recording the γ quanta; this telescope contained scintillation counters and a Cerenkov counter. As targets, we used heavy and light water, poured in thin-walled containers, and also plates of light graphite and polyethylene $(CH_2)_n$. Determination of the γ-quantum yield from these targets permitted us to find the values of the relation of the differential cross sections for the deuteron and hydrogen:

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

and the differential cross sections for the deuteron (cross sections for hydrogen were measured earlier[11]). For the determination of the values of σ'_{pd} in the region of low proton energies, the data[11] obtained with a liquid hydrogen target were also used.

3. DIFFERENTIAL AND TOTAL CROSS SECTIONS FOR THE REACTION $p + d \rightarrow \pi^0$ + nucleons

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

Here θ is the angle of emission of the γ photons in the laboratory system of coordinates (l.s.). For other proton energies, the ratios σ'_{pd} and the differential cross sections for hydrogen were measured either at the "isotropic" angles (see, for example, Table II), or at angles around 60 and 120° in the l.s., which permitted us to determine the magnitudes of the total cross sections without making assumptions on the character of the angular distribution of the π^0 mesons.[11,13] The values of the total cross sections $\sigma^{\pi^0}_{pd}$ for the reaction (3) thus found are given in Table III. In the determination of the cross section at the point E = 175 Mev, the extrapolated value is σ'_{pd} = (10 ± 4) per cent.

In the energy region 580 — 660 Mev, the relative cross sections σ'_{pd} found in the present work differ somewhat from those found earlier.[6] The reason for this discrepancy is evidently a local heating of the poor heat conducting target of LiD in irradiating it in the external beam of the accelerator, which produces a systematic error in the calorimetric method of determination of proton flux employed in reference 6. Heating of the tar-

*E – effective energy of the beam, determined with account of the energy loss in the target and of the dispersion of the beam.[12]

TABLE II. $\vartheta = 55^0$*

E, Mev	$\langle\langle\sigma'_{pn}\rangle\rangle$, %	σ'_{pd}, %	E, Mev	$\langle\langle\sigma'_{pn}\rangle\rangle$, %	σ'_{pd}, %
665	19.4±0.7	34.5±0.9	370	16.5±1.2	17.5±1.3
645	21.0±1.4	35.2±1.5	330	15.9±1.2	16.1±1.2
610	19.4±1.2	30.8±1.3	290	10.0±1.8	10.0±1.8
560	22.1±1.4	31.5±1.6	250	9.4±2.0	9.4±2.0
485	21.1±1.0	26.4±1.1	215	13±4	13±4
440	18.9±1.0	21.9±1.2	175 (extrap.)	10±4	10±4

*ϑ = angle of flight of γ photons in the center of mass system of the colliding nucleons.

TABLE III

E, Mev	$\sigma^{\pi^0}_{pd}$, 10^{-27} cm²	$\sigma^{\pi^0}_{pd}$, rel. units	E, Mev	$\sigma^{\pi^0}_{pd}$, 10^{-27} cm²	$\sigma^{\pi^0}_{pd}$, rel. units
665	7.9±0.4	1.00	485	2.35±0.18	0.30±0.02
652	7.6±0.5	0.96±0.06	440	1.54±0.12	0.19±0.01
645	8.0±0.5	1.01±0.04	437*	1.15±0.22	—
630	7.6±0.4	0.96±0.03	400	1.0±0.1	0.13±0.01
620	7.0±0.6	0.89±0.06	370	0.68±0.08	0.086±0.008
610	6.8±0.4	0.86±0.04	340**	0.59±0.15	—
597	6.1±0.5	0.77±0.05	330	0.38±0.06	0.048±0.007
590	5.8±0.4	0.73±0.03	290	0.19±0.04	0.024±0.005
560	4.45±0.30	0.56±0.02	250	0.08±0.02	0.010±0.002
520	3.1±0.2	0.39±0.02	215	0.06±0.02	0.008±0.002
508	2.9±0.2	0.37±0.02	175 (extrap.)	0.025±0.010	0.003±0.001

*According to the data of Stallwood et al.[7]

**According to the data of Hales and Moyer[4] and reference 11.

get decreases rapidly with decrease in the working radius of the target and the error should then disappear. Actually, at energies below 580 Mev, the values of σ'_{pd} obtained in the present work and in reference 6 agree within the limits of error of measurement (equal to 20 per cent in reference 6).

4. TOTAL CROSS SECTIONS OF THE REACTION (2)

A comparison of the cross sections obtained for the reaction $p + d \rightarrow \pi^0$ with the cross sections of the reaction $p + p \rightarrow \pi^0$ obtained earlier[11] permits us in principle to determine the cross section of the reaction (2) of interest to us, after calculation of the effects of the binding of the nucleons in the deuteron. The binding of the nucleons changes the values of the cross sections, as a result of which the cross section for the deuteron is not equal to the sum of the cross sections for the proton and the neutron. In the energy region under consideration, which is located not far from the threshold of the reaction of meson production, the change in the values of the cross sections because of the motion of the nucleon in the deuteron is fundamental because of the effect brought about by the coupling of the nucleons.[14] In researches previously completed,[5,6,15] the effect of the coupling was not taken into consideration. The cross section for the neutron was found by simple subtraction "D – H," which is valid only at a rough first approximation. Use of a similar approximation in these researches was quite correct, since the experiments were carried out in the high-energy region where the corrections which take into account the effect of binding were commensurate with the errors of determination of the cross section, which amounted to about 15 — 30 per cent in the researches mentioned. In order to make progress in the region of low energies, and also to decrease the crudeness of the determination of the cross section for high energies, it is necessary, if only approximately, to take into account the coupling of the nucleons. For the solution of this problem, it is necessary to know the momentum distribution of the nucleons in the deuteron.

In the energy region around and below threshold, the energy dependence of the cross sections of the reaction which takes place on the nucleons of the deuteron, and in particular the reaction (3), is entirely determined by the character of the momentum distribution of the nucleons, especially by the shape of its high momentum "tail." With decrease in the energy of the emitted proton, a more significant role is played in the reaction by the nucleons of a deuteron possessing high momenta at the moment of collision, while the contribution from the low energy part of the momentum distribution quickly disappears. For this reason, the investigation of the energy dependence of the cross section of reaction (3) in the region around threshold is a sufficiently sensitive method of studying the shape of the momentum distribution (and especially of its "tail"). The momentum distribution for the deuteron was found by this method in reference 14 from the data of Table III of the present work. It was shown to be close to the function calculated by Salpeter and Goldstein.[16] Knowing the momentum distribution, we can establish the magnitudes of the cross sections of reaction (2) by starting out from the data on the cross sections of reactions (3) and (1):[14]

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

The functions g_p and g_{pp}, which characterize the change in the values of the cross sections because of intranuclear motion, and the coefficient k, which takes into account all other effects, are connected with the presence of a "spare" nucleon, computed in reference 14. By making use of these and the data of Table III, we obtain the total cross sections of the reaction (2) (Table IV).

TABLE IV

E, Mev	$\sigma_{pn}^{\pi^0}$, 10^{-27}cm^2	$\sigma_{pn}^{\pi^0}$, rel. units	η_m*
665	6.3±0.4	1.00	1.90
652	6.1±0.5	0.97±0.06	1.86
645	6.5±0.5	1.03±0.04	1.84
630	6.1±0.4	0.97±0.03	1.79
620	5.6±0.5	0.89±0.06	1.76
610	5.5±0.4	0.87±0.04	1.73
597	4.9±0.4	0.79±0.06	1.69
590	4.6±0.3	0.75±0.03	1.66
560	3.41±0.25	0.54±0.02	1.56
520	2.2±0.2	0.35±0.02	1.43
508	2.02±0.17	0.32±0.02	1.38
485	1.57±0.13	0.250±0.015	1.30
440	0.95±0.10	0.151±0.010	1.12
400	0.56±0.06	0.089±0.007	0.95
370	0.34±0.04	0.065±0.007	0.81
330	0.15±0.03	0.033±0.006	0.59
290	0.011±0.003	0.0020±0.0005	0.25

*Here η_m is the maximum momentum of the π^0 mesons in the center of mass system, in units of the meson mass $m_\pi c$.

5. ANGULAR DISTRIBUTIONS OF γ QUANTA

The angular distributions of γ quanta from decay of π^0 mesons produced in reaction (3) were measured by us in the energy region 400 — 665 Mev. For these energies, the effect of coupling of nucleons in the deuteron on the angular distribution was still small and could be simply taken into account by means of the introduction of an effective center-of-mass system whose velocity in the laboratory coordinates, $\bar{\beta}_c$, differs slightly from the velocity of the center-of-mass system for the case of a collision with a nucleon at rest. The quantity $\bar{\beta}_c$ was determined by integration over $\mathbf{p}_2$ of the velocity of the center of mass of the emerging proton and nucleon, moving in the deuteron with momentum $\mathbf{p}_2$, with account of the Salpeter-Goldstein momentum distribution and the energy dependence of the cross section (these calculations are similar to those carried out in reference 14). The angular distribution of π^0 mesons in the effective center-of-mass system introduced in such fashion practically coincides with the angular distribution (in the center-of-mass system) of π mesons produced by collision of free nucleons.

The measured angular distribution of γ quanta produced in pd collisions at energy 665 Mev is shown in Fig. 1. As is seen from the drawing, the

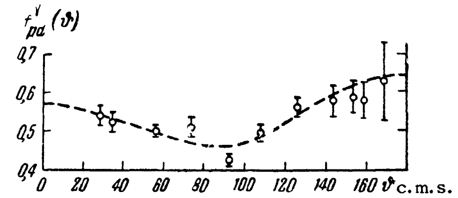

FIG. 1. Angular distribution in the effective center-of-mass system of γ quanta from the decay of π^0 mesons produced in pd collisions at an energy of 665 Mev. The dashed curve was obtained by the method of least squares with account of a small correction for screening.[17]

distribution $f_{pd}^{\gamma}(\vartheta)$ is slightly asymmetric relative to 90°, while the angular distributions for reactions (2) and (1) should be symmetric if the hypothesis of isotopic invariance is valid. The asymmetry arises by virtue of the absorption of the π meson at the emission of a proton. In such a simple and "porous" nucleus as the deuteron, the absorption must be small and the asymmetry of the angular distribution is not large. Actually, the contribution of the term proportional to $\cos\vartheta$ in the distribution $f_{pd}^{\gamma}(\vartheta)$ (Fig. 1) amounts to 5 per cent at most. This small correction can be sufficiently accurately taken into account (in view of its smallness) on the basis of a simpler model of a homogeneous nucleus with account of experimental data on the absorption of π mesons and nucleons in nuclear material. In the case of a complicated nucleus (carbon), where the absorption is large and the contribution of the asymmetric term to the angular distribution amounts to 30 per cent, the dependence of the coefficient k on the angle computed in such a fashion is in poor agreement with experimental data.[11,17]

The angular distribution $f_{pn+pp}^{\gamma}(\vartheta)$ obtained from the distribution $f_{pd}^{\gamma}(\vartheta)$ after introduction in it of a computed correction to the absorption is well described by the polynomial

$$f^{\gamma}_{pn+pp}(\vartheta) \sim {}^1/_3 + (0.07 \pm 0.02)\cos^2\vartheta.$$

By computing from it the distribution found for the reaction (1) in reference 11, one can obtain the angular distribution of γ quanta in the reaction (2), $f^{\gamma}_{pn}(\vartheta)$, for E = 665 Mev. This distribution is approximated by the polynomial

$$f^{\gamma}_{pn}(\vartheta) \sim {}^1/_3 + (0.08 \pm 0.02)\cos^2\vartheta.$$

The distribution $f^{\gamma}_{pn}(\vartheta)$ was shown to be symmetric relative to 90°. If it is approximated by a polynomial, which in addition to the zero and second order terms also contains an asymmetric term proportional to $\cos\vartheta$, then the latter is shown to be insignificant: $(0.01 \pm 0.01)\cos\vartheta$. The correction to the total cross section is also small and of a much higher power of the cosine than the second. From this it follows (see reference 11) that, in the energy region up to 660 Mev, the distribution of γ quanta in the reaction (2) has the form

$$f^{\gamma}_{pn}(\vartheta) \sim {}^1/_3 + b_{\gamma}\cos^2\vartheta.$$

The quantities b_{γ} obtained for different proton energies are shown in Table V.

TABLE V

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

6. DISCUSSION OF RESULTS

Total cross sections and the hypothesis of isotopic invariance. A well known consequence of the hypothesis of isotopic invariance is the relation connecting the total cross sections of formation of neutral and charged π mesons in nucleon-nucleon collisions:

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

Making use of the values of the total cross sections of the reaction (2) found in the present work and of the cross sections of other reactions studied earlier,[11,18–22] one can verify the feasibility of Eq. (5) in the wide energy range from threshold to 665 Mev. As is seen from Fig. 2, this ratio is actually close to unity in the energy region under discussion.

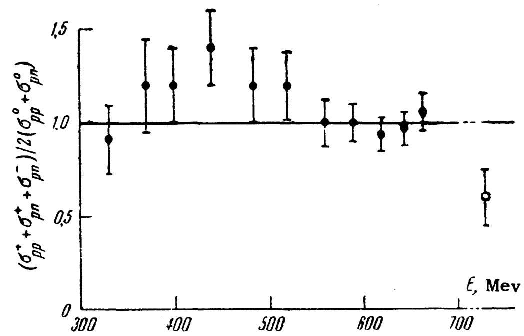

FIG. 2. Ratio of the total cross sections for production of charged and neutral π mesons at different proton energies: ● – according to the data of the present work and references 11, 18–22; □ – according to the data of Batson et al.,[23] E = 970 Mev.

For energies ≈ 600 Mev, where the total cross sec-

TABLE VI

E, Mev	σ_{01}, 10^{-27} cm²	σ_{10}, 10^{-27} cm²	σ_{11}, 10^{-27} cm²	σ_0, 10^{-27} cm²	σ_1, 10^{-27} cm²
660	1.7±1.1	10.9±0.5	3.22±0.17	5.1±3.3	17.1±0.6
645	2.6±1.1	10.2±0.5	2.93±0.17	7.8±3.3	16.0±0.6
630	3.1±0.9	9.1±0.5	2.74±0.16	9.3±2.7	14.5±0.6
620	2.7±1.1	8.5±0.5	2.55±0.17	8.1±3.3	13.5±0.6
610	2.9±0.9	8.1±0.5	2.25±0.14	8.7±2.7	12.5±0.6
597	2.3±0.9	7.5±0.5	1.96±0.14	6.9±2.7	11.5±0.6
590	1.9±0.8 1.9±0.9*	7.3±0.5	1.84±0.12	5.6±2.4	11.0±0.6
560	0.9±0.6	6.0±0.4	1.24±0.08	2.7±1.8	8.4±0.5
520	$0.1^{+0.6}_{-0.1}$	4.5±0.4	0.75±0.06	$0.3^{+1.8}_{-0.3}$	6.1±0.4
485	$0.1^{+0.5}_{-0.1}$	3.4±0.3	0.45±0.03	$0.3^{+1.5}_{-0.3}$	4.2±0.3
440	$0.1^{+0.4}_{-0.1}$	2.3±0.2	0.20±0.02	$0.3^{+1.2}_{-0.3}$	2.7±0.2
400	$0.1^{+0.3}_{-0.1}$ 0.22±0.08*	1.2±0.2	0.09±0.02	$0.3^{+0.9}_{-0.3}$ 0.65±0.25*	1.4±0.2
370	$0.1^{+0.2}_{-0.1}$	0.8±0.2	0.04±0.01	$0.3^{+0.6}_{-0.3}$	0.8±0.2
330	—	0.33±0.04	0.014±0.006	—	0.35±0.04

tions were measured with the least error, Eq. (5) is satisfied with an accuracy to within 8 — 10 per cent. Of the quantities entering into this equation, the least studied is the cross section $\sigma_{pn}^{\pi\pm}$, experimental information on which has been obtained only at two energies (400 (reference 20) and 590 Mev[21]). For other values of the energy, the values of $\sigma_{pn}^{\pi\pm}$ used in Fig. 2 were found by means of an approximation[22] of the energy dependence of the cross section $\sigma_{pn}^{\pi\pm}$ by the power function $\eta_m^{4-4.5}$. The errors connected with the use of a similar approximation cannot be large, since the contribution of the cross section $\sigma_{pn}^{\pi\pm}$ to Eq. (5) is comparatively small in the energy region under consideration. In the region of higher energies, the ratio (5) was recently measured at E = 970 Mev.[23] The cross section $\sigma_{pn}^{\pi 0}$ at this energy was shown to be unexpectedly large, which led to a value of the ratio (5) differing somewhat from unity (Fig. 2).

Making use of the cross section obtained for the reaction (2), it is possible to determine the value of the partial cross section[22] σ_{01} (which corresponds to the transition $T_N = 0 \rightarrow T_N = 1$; T_N is the isotopic spin of the nucleons)

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

at different energies (Table VI). The cross section σ_{01} can also be obtained from the relation

$$\sigma_{01} = 2\sigma_{pn}^{\pi\pm} - \sigma_{pp}^{\pi^0}. \tag{7}$$

The values of σ_{01} marked in the table by an asterisk were found by the latter method. Along with the partial cross sections, values of the cross sections of production of π mesons in nucleon-nucleon collisions are given in Table VI for total isotopic spin T = 1 and 0: $\sigma_1 = \sigma_{pp}^{\pi^+} + \sigma_{pp}^{\pi 0}$ and $\sigma_0 = 3\sigma_{01}$.

Comparison of the magnitudes of the cross sections given in Table VI shows that in the energy region from threshold up to 665 Mev, σ_1 is approximately double σ_0 (Fig. 3). Better agreement with experimental data is obtained if, following Rosenfeld,[22] we assume that σ_{01} changes with the energy as η_m^4:

$$\sigma_{01} = 0.3\,\eta_m^4 \cdot 10^{-27}\ \text{cm}^2. \tag{8}$$

The total cross sections of the reaction (2) found in the present work are close to the cross sections computed on the basis of the resonance phenomenological theory of Mandelstam[24] (Fig. 4). At energies E > 660 Mev, the increase of this cross section slowed down, in agreement with the theory of Mandelstam.

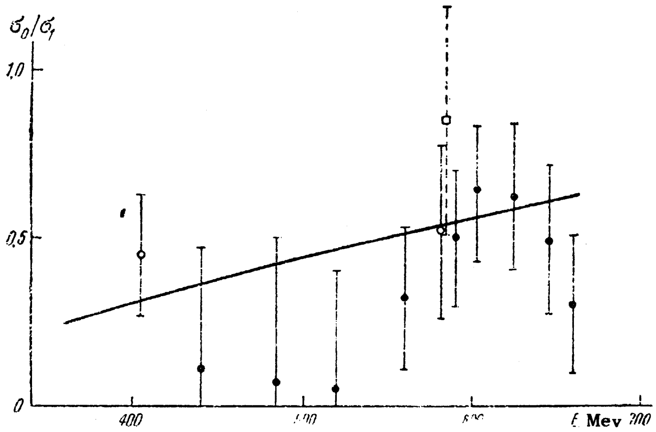

FIG. 3. Ratio of the cross section of production of π mesons by nucleons in states with isotopic spin T = 0 and T = 1: ● – obtained from the relation (6) from the data of the present work and references 11, 18, 19, and 22; ○ – obtained from the relation (7) from the data of references 11, 20, and 21; □ – obtained by starting out from the total cross sections.[21] The curve corresponds to the dependence (8).

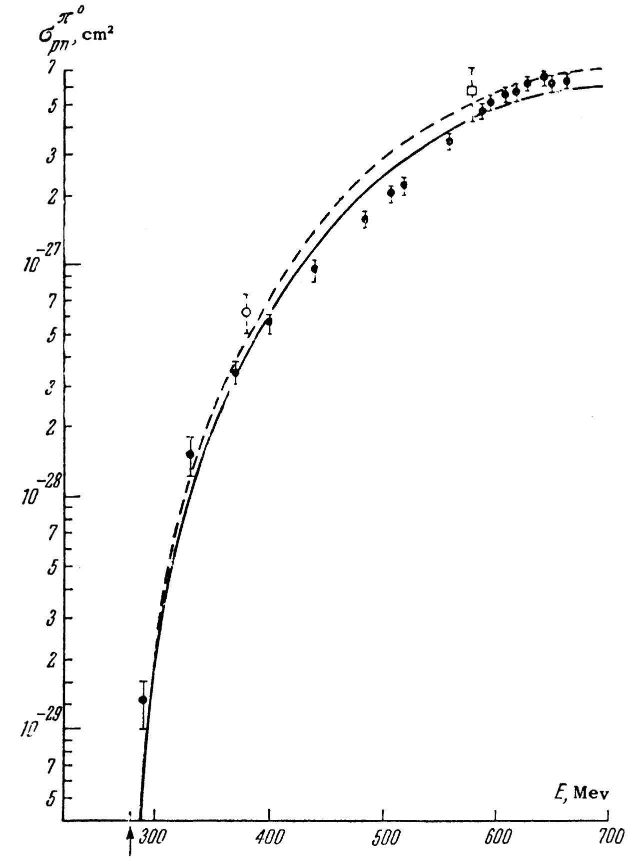

FIG. 4. Total cross sections of the reaction pn → pnπ^0: ● – data of the present work; ○ – data of reference 2; □ – data of reference 3. The solid curve was computed on the basis of the resonant theory of Mandelstam, the dashed curve takes into account the non-resonant transition (8) in the state with T = 0. The arrow indicates the reaction threshold.

The angular distributions of π mesons and the hypothesis of isotopic invariance. The angular distributions of π^0 mesons in the reaction (2), $f_{pn}^{\pi 0}(\vartheta)$, can be established according to the measured angular distributions of the γ quanta.[11] In the energy region from threshold up to 665 Mev, the function $f_{pn}^{\pi^0}(\vartheta)$ as also the function $f_{pn}^{\gamma}(\vartheta)$ has the form

$$f_{pn}^{\pi^0}(\vartheta) \sim {}^1/_3 + b_{\pi^0}\cos^2\vartheta.$$

The values obtained for b_π are given in Table VII.

As is seen from this table, the isotropy of the angular distribution of the π^0 mesons in reaction (2) increases along with increase in the energy of the emitted proton. This result agrees qualitatively (Fig. 5) with the predictions of the Mandelstam theory (private communication). The agreement with the theory is complete if, in addition to resonant transitions, we also take into account the non-resonant transition (8) from the state with T = 0, for which the isotropic angular distribution is characteristic.[11,21]

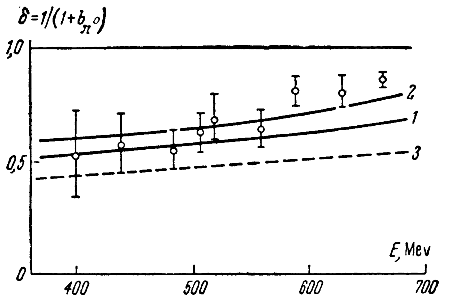

FIG. 5. Angular distributions of π^0 mesons produced from pn collisions. The quantity δ is the fraction of π^0 mesons distributed isotropically. The curve 1 was computed by Mandelstam on the basis of his resonance theory; curves 2 and 3 were computed with account of the non-resonant transition (8) under the assumption of an isotropic and $\sim\cos^2\vartheta$ distribution, respectively.

If the hypothesis of isotopic invariance is valid, then the total angular distributions of neutral and charged π mesons produced in nucleonic collisions must be the same [i.e., $f_{pp+pn}^{\pi^0}(\vartheta) = f_{pp+pn}^{\pi^\pm}(\vartheta)$]. Since these angular distributions are accurately described for energies $\approx$ 650 Mev by a polynomial of the type $\frac{1}{3} + b_\pi\cos^2\vartheta$, then the latter confirmation is equivalent to the equation

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

Here b_{π^0} and $b_{\pi^\pm}$ are the sums of the coefficient b_π normalized over the cross sections in angular distributions of neutral and charged π mesons.

The angular distribution of the π^0 mesons for energies $\approx$ 650 Mev are close to isotropic: $b_{\pi^0} = 0.16 \pm 0.04$ for E = 665 Mev according to the data of the present research and reference 11. At these energies, the distribution of charged π mesons produced in pn collisions is quite isotropic.[21] In contrast, the charged π-meson distribution produced in pp collisions is quite anisotropic: $b_{\pi^+} = 0.61 \pm 0.09$ according to the data of Neganov and Savchenko.[18] The difference between the value of the ratio $b_{\pi^0}/b_{\pi^\pm}$ and the units characterizing the degree of violation of isotopic invariance is shown to be significant here:

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

The difference shown between the angular distribution of neutral and charged π mesons is today perhaps the only violation of the hypothesis of isotopic invariance.[25] However, it should be noted that this difference is still not conclusively established experimentally. One must regard the value of the ratio $b_{\pi^0}/b_{\pi^\pm}$ given above as a tentative one. On the other hand, the angular distribution of π^+ mesons can be shown to be more isotropic, as was observed in the recent experiments of Meshkovskiĭ, Shalamov, and Shebanov.[26] However, the angular distribution of neutral π mesons in the reaction (2) can differ somewhat from that given in the present research, inasmuch as interference is possible between the nucleonic state in the deuteron which leads to a change in the distribution of π^0 mesons in comparison to that which is the case for collisions of a proton with free nucleons. In this connection, accurate experimental data on the angular distributions of charged π mesons and the completion of researches on the angular distribution of π^0 mesons formed in free pn collisions are both necessary.

The reaction pn → $\pi^\pm$ + nucleons. Making use of the values of the cross sections of reaction (2) obtained in the present research and the cross sections of production of π mesons in pp collisions,[11,18,19,22] one can determine the cross sections of the reaction pn → $\pi^\pm$ over a wide energy range on the basis of Eq. (5). This is of considerable interest, inasmuch as direct studies of the reaction pn → $\pi^\pm$ entail great experimental difficulties. The values found for the total cross sec-

TABLE VII

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

tions $\sigma_{pn}^{\pi^+}$ (or, what amounts to the same thing, $\sigma_{pn}^{\pi^-}$) are given in Fig. 6. As is seen from the drawing, the energy dependence of the cross section $\sigma_{pn}^{\pi^+}$ is well described by the function

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

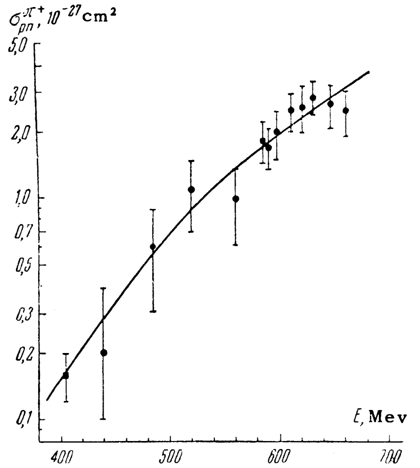

FIG. 6. Total cross sections of the reaction pn → nnπ^+ found under the assumption of the validity of the hypothesis of isotopic invariance: ● – according to the data of the present work and references 11, 18, 19, 22; ■ – are the results of direct measurement.[20,21] The curve corresponds to the dependence (10).

In conclusion, we take this opportunity to thank S. Mandelstam, who kindly sent us the results of his unpublished researches, B. Pontecorvo and B. S. Neganov for discussion of results of the present research, and I. V. Tsymbulov for help given in carrying out the measurements.

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