[10] P. Lehmann and K. Miller, Compt. rend. **240**, 1525 (1955).
[11] C. E. Mandeville and M. V. Scherb, Phys. Rev. **73**, 848 (1948).
[12] Biedenharn, Blatt and Rose, Revs. Mod. Phys. **25**, 249 (1952).
[13] Hollander, Perlman and Seaborg, Revs. Mod. Phys. **25**, 469 (1953).
[14] B. S. Dzhelepov and L. K. Peker Схемы распада радиоактивных изотопов (Decay Schemes of Radioactive Isotopes), Academy of Sciences Press, 1957.
[15] C. Perrier and E. Segre, J. Chim. Phys. **5**, 712 (1937).
[16] Iu. B. Gerlit, International conference on peaceful uses of atomic energy, Geneva, 1955; Vol. 7, p. 671.
[17] Sanin, Melioranskii and Lotova, Вестник МГУ (Bulletin, Moscow State University) **12**, 87 (1955).

Translated by M. Hamermesh
9

SOVIET PHYSICS JETP VOLUME 35 (8), NUMBER 1 JANUARY, 1959

MEASUREMENT OF THE TOTAL CHARGED π MESON PRODUCTION CROSS SECTION IN NEUTRON-PROTON COLLISIONS AT 586 Mev NEUTRON ENERGY

Iu. M. KAZARINOV and Iu. N. SIMONOV

Joint Institute for Nuclear Research and Laboratory of Nuclear Problems

Submitted to JETP editor February 27, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 78-84 (July, 1958)

The total yield of charged π mesons, produced in collisions between neutrons of 586 Mev effective energy and protons, was measured at angles in the range from 15 to 120° (in the laboratory system). Assuming charge independence of nuclear forces, the total cross-section for the production of π^+ and π^- mesons, derived from the experimental data, was found to be $\sigma(np \to \pi^+) = \sigma(np \to \pi^-) = (2.0 \pm 0.5) \times 10^{-27}$ cm^2.

THE process of production of charged π mesons in neutron-proton collisions has not, so far, been studied extensively. Comprehensive investigations were carried out only for 409 Mev neutrons. One experiment only was carried out at an energy close to 600 Mev.[2] The spectra and yields of π^+ and π^- mesons, emitted at the angle $\Phi = 90°$ in the laboratory system* (l.s.) from a target containing liquid hydrogen bombarded by neutrons originating in the charge exchange of 670-Mev protons, were measured in that work in relative units, using nuclear emulsions. The relatively small cross section for meson production, the fact that three particles are present in the final stage of the reactions studied, and also the fact that the neutron beam used is not monoenergetic, all contribute to the difficulties of experiments on π^+- and π^--meson production in $n-p$ collisions. On the other hand, a detailed study of $n-p$ collisions at energies considerably larger than the meson production threshold necessitates an investigation of these processes. The study of the process of meson production in $n-p$ collisions is also of interest for understanding the character of the interaction between two nucleons with different isotropic spin ($T = 0$ and $T = 1$).

*The angle Φ was measured with respect to the direction of the incident neutron beam.

THE EXPERIMENT

The measurements were carried out with the synchrocyclotron of the Joint Institute for Nuclear Research. The neutron beam used in the experiments was obtained by charge-exchange scattering of 680-Mev protons on a Be target. The energy distribution of the neutrons in the beam had a maximum at 600 Mev and a half-width of 130 Mev.[3]

To determine the differential cross-section for charged π-meson production in $n-p$ collisions, we measured the ratio of the total number of π^+ and π^- mesons N_π to the number of recoil protons N_p, emitted from the scattering medium at a given angle Φ to the direction of the neutron beam. The differential π-meson production cross-section was then obtained from the determined ratio N_π/N_p and from the differential cross section for elastic n — p scattering, measured earlier by the authors.[4]

To measure the π-meson yield, polyethylene and graphite were used as scattering media and were placed alternately in the neutron beam. The charged particles emitted from the scatterer were recorded by a detector. The difference between the number of particles scattered by polyethyelene and graphite, as recorded by the detector, gives the total flux of charged particles emitted from the scatterer as the result of n — p collisions. Estimates have shown that, for a given neutron energy, this flux is determined essentially by the number of recoil protons and π mesons incident upon the detector. It was found that, in the conditions of the experiment, the number of μ mesons and β particles produced in π-meson decay amounted to less than 10 or 15% of the number of π mesons. This made it possible to neglect the admixture of μ mesons and β particles and to assume, in first approximation, that all particles, other than recoil protons, were π mesons. The necessary corrections were introduced later into the results of the measurements.

The π mesons and recoil protons were identified either by their range or velocity. The range method was used in the region of angles of π-meson emission $\Phi \geq 60°$. For angles $60° < \Phi < 15°$, π mesons were separated, using the velocity method, by means of a Cerenkov detector.

Two types of detectors were used in connection with the two methods of π-meson separation (Table I). A telescope consisting of three scintillation counters, connected in coincidence, was used at large angles, $\Phi \geq 60°$. Estimates based on the results of reference 2 have shown that if the threshold of such a detector is raised, by means of a suitable absorber, to the level of the maximum energy of recoil protons at a given angle Φ, then, in the range $\Phi \geq 60°$, the majority of π mesons is detected.

Velocity selection was used in measurements of the yield of charged mesons at angles $\Phi < 60°$. For this purpose, the middle counter of the telescope was replaced by a Cerenkov detector (Fig. 1), while the other two scintillation counters remained in place. For the determination of the total yield of charged particles, it was necessary to replace again the exchanged scintillation detector. To preserve counter geometry in the exchange, and to effect the exchange quickly, both types of detectors used the same photomultiplier FEU-19M and the scintillator was placed in front of the photocathode directly behind the radiator of the Cerenkov detector. At the angle $\Phi = 15°$, recoil protons could be detected by the Cerenkov detector. A correction was applied for that case to the results, to account for the fraction of protons recorded. The angular definition of the detector, determined by its geometry, was 3°. Energy thresholds of the detector at different angles are given in Table I.

TABLE I

Emission angle of π mesons (l.s.)	Energy threshold of the detector for π mesons (Mev)	Detector
15° 30°	78.0 78.0	Cerenkov counter (water) and two scintillation counters (coincidence)
45°	78.5	Cerenkov counter (plexiglass) and two scintallation counters (coincidence)
60° 90° 120°	65 37 37	Three scintillation counters (coincidence)

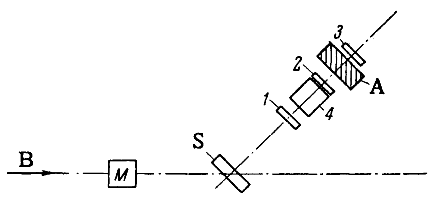

FIG. 1. Schematic diagram of the experiment. n — neutron beam, M — monitor (ionization chamber), 1, 2, 3 — scintillation counters, 4 — radiator of the Cerenkov counter, A — absorber, S — scattering medium.

Polyethyelene and graphite disks of equal stopping power were used as scatterers. The polyethelene disc was 0.9 g/cm^2 thick for angles $\Phi \geq 45°$ and 3.2 g/cm^2 for $\Phi < 45°$. Copper and tungsten plates were used as absorbers.

The measurements were carried out as follows: First, the total flux charged particles incident upon the detector as the result of n — p collisions was determined, for a given beam intensity, under the conditions of the measurement of the differential cross sections for elastic n — p scattering.[4] The usual $CH_2 - C$ difference experiment was carried out for that purpose. The detector was then set to record recoil protons and the total yield of π mesons was measured. This was

TABLE II

Angle Φ	15°	30°	45°	60°	90°	120°
Correction for admixture of μ mesons and electrons	0.9	0.9	0.9	0.92	0.90	0.88
Correction for admixture of protons	0.15					
Correction for π mesons with energy below detector threshold					1.25	1.95
Correction for detection efficiency	1.21	1.21	1.20			
Correction for $\pi-\mu$ decay	1.03	1.03	1.03	1.04	1.06	1.10
N_π/N_p %	8.6±3.5	19±2.3	13.7±2.7	9.7±0.5	4. *±1.3	4.3 ±0.9

*The π meson yield is expressed in terms of the yield of recoil protons at $\Phi = 60°$.

done, as mentioned above, either by increasing the telescope threshold up to the maximum energy of recoil protons (for angles $\Phi > 60°$), or by exchanging one of the scintillation counters for the Cerenkov detector. Special attention was given to the measurements of the background in determination of the π-meson yield at the angles Φ = 15, 30, and 45°. In this case it was found necessary to measure, apart from the usual chance and true coincidence rate, also the background due to the fact that the detector recorded a considerable fraction of recoil proton incident directly upon the photocathode of the photomultiplier tube in the Cerenkov detector. The total background amounted to less than 5% at 60°, and increased to 20% of the number of mesons incident upon the detector from the polyethyelene scatterer at 15°.

The stability of the neutron beam intensity during the measurements was measured by means of an ionization chamber placed in the beam and connected to an integrating circuit.

RESULTS AND REDUCTION OF DATA

Determination of the Total Cross Section. The following corrections had to be applied to the results before the latter could be used for the determination of the total cross section for π-meson production.

1. Correction for the admixture of μ mesons and electrons. As mentioned above, a small amount of μ mesons and electrons was present, besides protons and π mesons, among the particles incident upon the detector. The number of electrons detected was calculated according to the data of reference 5, assuming that the angular distribution of π^0 mesons in the c.m.s. is given by the expression $0.2 + \cos^2\vartheta$. It was also taken into account that ~1.5% of the π^0 mesons decay according to another scheme. The fraction of the μ mesons was calculated from the known yield of π mesons and the calculated angular distribution of μ mesons.

2. Correction for the admixture of protons. This correction was applied only for the 15° angle, where a considerable fraction of recoil protons could be detected by the Cerenkov detector. The correction was determined from the known neutron spectrum, and the measured dependence of the Cerenkov detector efficiency on the particle velocity (Fig. 2).

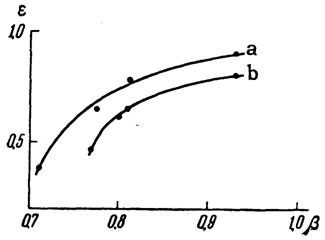

FIG. 2. Dependence of the Cerenkov-counter efficiency ε on the velocity of detected particles β. a – plexiglass, b – water.

3. Corrections for the presence of particles with energy below the detector threshold in the π-meson spectrum. These corrections were found from the π-meson spectrum calculated according to the data of reference 2 under the assumption the π-meson spectrum in c.m.s. is independent of the angle of emission. The calculated correction factors are given in the third column of Table II. These coefficients were also recalculated under the assumption that the π-meson spectra of the reactions $p + p \to \pi^+ + n + p$, $n + p \to \pi^+ + 2n$, $n + p \to \pi^- + 2p$ are identical.*

The values obtained were practically identical with those given in Table II.

4. Corrections for detector efficiency. These were necessary because of the different absorption of π mesons and protons in the detector absorbers and the properties of the Cerenkov detector. The corrections were determined experimentally on

*Evidently, this is the case at energies much higher than the threshold of meson productions. (cf., e.g., reference 6).

π-meson and proton beams of corresponding average energy.

5. Corrections for the $\pi-\mu$ decay. Correction factors were calculated from the known half-life of π mesons, accounting for the π meson spectrum cutoff (cf. point 3).

Strictly speaking, in reducing the data it would be necessary to account for the error due to the fact that the absorption of π^+ and π^- mesons in media is slightly different. An estimate based on the results of reference 7 indicates, however, that the error involved is small in the conditions of the experiment and can be neglected.

The corrected results yield, after integrating over the angles, the following value for the total production cross section of π^+ and π^- mesons in n—p collisions, under the assumption of charge independence of nuclear forces:

$$\sigma(np \to \pi^+) = \sigma(np \to \pi^-) = (2.0 \pm 0.5)\cdot 10^{-27}\ \text{cm}^2.$$

The total cross sections for the studied reactions can be also determined from the π-meson yield found for the so-called "isotropic angle," i.e. the angle, for which the following relation holds between the differential cross-section $\sigma_\pi(\vartheta)$ and the total cross-section:

$$\sigma_\pi(\vartheta_i) = (1/4\pi)\,\sigma(np \to \pi).$$

The "isotropic" angle ϑ_i can be easily found in our case, considering that the obtained angular distribution of π mesons in the c.m.s. does not contain terms higher than $\cos^2\vartheta$, and can be written in the form

$$\sigma_{\pi^+}(\vartheta) + \sigma_{\pi^-}(\vartheta) = a + b\cos^2\vartheta,$$

where ϑ is the meson emission angle, and a and b are constants. As it is well known, $\vartheta_i = \cos^{-1} \times (1/\sqrt{3})$ and corresponds, in our case, to the angle $\Phi = 30°$ (l.s.). Using the value of N_π/N_p given for that angle in Table II, we find that the cross section is equal to

$$\sigma(np \to \pi^+) = \sigma(np \to \pi^-) = (1.7 \pm 0.4)\cdot 10^{-27}\ \text{cm}^2.$$

The obtained values of the cross-section are very close to each other. This fact indicates, probably, that the assumptions made in reducing the data have not distorted seriously the angular distribution.

Determination of the Effective Energy. In the method used, the detector recorded π mesons produced in the collisions of particles, the energy of which varied in a very wide range, from 300 to 670 Mev. It was therefore especially important to determine the mean effective energy E_{eff}. This was done by finding the dependence of E_{eff} on the excitation function of the studied reaction for a given shape of the neutron-energy spectrum. The excitation function was taken as

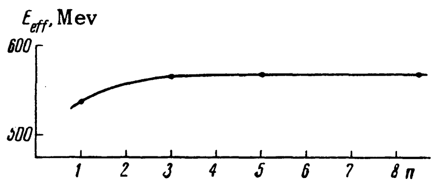

FIG. 3. Dependence of the effective neutron energy on the power exponent of the maximum π-meson momentum in Eq. (1).

$$\sigma(np \to \pi^+) \sim \eta_{max}^n\,, \tag{1}$$

where η_{max} is the maximum π-meson momentum in the c.m.s. It was found that, under the given conditions, the mean effective energy is practically constant for power exponent $n \geq 3$ in Eq. (1) and does not depend on n (Fig. 3). Taking this into account, we find from the known value of $\sigma(np \to \pi^+)$ at 409 Mev that, for our case, $E_{eff} = (586 \pm 15)$ Mev.

DISCUSSION OF RESULTS

A comparison of the obtained value $\sigma(np \to \pi^+) = (2.0 \pm 0.5) \times 10^{-27}\ \text{cm}^2$ with the cross-section at 409 Mev, $\sigma(mp \to \pi^+) = (0.16 \pm 0.04) \times 10^{-27}\ \text{cm}^2$ (reference 1) shows that the total cross section for π^+- and π^--meson production in n—p collisions increases by more than a factor of ten for the energy increase from 409 to 586 Mev. The dependence of the cross section on the maximum π-meson momentum η_{max} can be written in the form

$$\sigma(np \to \pi^+) \sim \eta_{max}^{4.7 \pm 0.8}.$$

This relation is in a satisfactory agreement with the relation $\sigma(pn \to \pi^+) \sim \eta_{max}^{4\pm1}$ given in reference 10, which was obtained from values of the cross section calculated for a wide energy region on the basis of the known cross-sections $\sigma(pp \to \pi^0)$, $\sigma(pp \to \pi^+)$, and $\sigma(pn \to \pi^0)$, assuming charge independence of the nuclear forces. It should be noted, however, that the authors of reference 10 give a slightly lower value for the cross-section $\sigma(pn \to \pi^+)$ at 580 Mev, equal to $(10.8 \pm 1.1) \times 10^{-27}\ \text{cm}^2$. This nevertheless, is within the limit of the errors and does not contradict the value obtained in the present work.

The value found is also in a good agreement with the predictions of the isotopic invariance hypothesis, according to which we should have

$$\sigma(np \to \pi^+) = \sigma(np \to \pi^0) + \sigma(pp \to \pi^0) - {}^1/_2\,\sigma(pp \to \pi^+). \tag{2}$$

If we put $\sigma(np \to \pi^0) = (5.7 \pm 1.5) \times 10^{-27}\ \text{cm}^2$,[5]

$\sigma(pp \to \pi^0) = (1.6 \pm 0.2) \times 10^{-27}$ cm^2,[10] and $\sigma(pp \to \pi^+) = (8.5 \pm 0.7) \times 10^{-27}$ cm^2,[11] we find that $(np \to \pi^+) = (3.1 \pm 1.6) \times 10^{-27}$ cm^2, which coincides with the measured value within the limits of accuracy.

It is well known that, according to the charge independence hypothesis, the cross sections for all π-meson production processes in nucleon-nucleon collisions can be expressed by means of three partial cross-sections σ_{10}, σ_{11}, σ_{01}.* The cross-sections σ_{11} and σ_{10} were investigated in Ref. 10 for a wide energy region. The value $\sigma(np \to \pi^+)$ found made it possible to determine σ_{01} at 586 Mev; we have $\sigma_{01} = 2\sigma(np \to \pi^+) - \sigma_{11} = (2.4 \pm 0.9) \times 10^{-27}$ cm^2. It is known, furthermore,[10] that $\sigma_{01} = (0.23 \pm 0.09) \times 10^{-27}$ cm^2 at 409 Mev. The value of σ_{01} increases therefore sharply with the energy and the dependence of σ_{01} on the maximum meson momentum can be written in the form:

$$\sigma_{01} \sim \eta_{\max}^{4.4 \pm 1.0}.$$

The total cross-section for π-meson production in $n-p$ collisions at 586 — 590 Mev is $\sigma(np \to \pi^{+0}) = (np \to \pi^0) + 2\sigma(np \to \pi^+) = (9.7 \pm 1.8) \times 10^{-27}$ cm^2. The total cross-section for the $n-p$ interaction is $(36 \pm 2) \times 10^{-27}$ cm^2. About 30% of the $n-p$ collision events is, therefore, accompanied by the production of a π meson.

In conclusion, we shall compare the probabilities of π-meson production in the collisions of two nucleons with different isotopic spin, using our result and those of references 5, 10, and 11. It can be shown[12] that the total cross-section for π-meson production in $n-p$ collisions $\sigma(np \to \pi^{\pm,0})$ can be written in the form

$$2\sigma(np \to \pi^{\pm,0}) = \sigma_\pi^1 + \sigma_\pi^0. \quad (3)$$

where σ_π^1 and σ_π^0 are the cross-sections for π-meson production in collisions of two nucleons in the states with isotopic spin $T = 1$ and $T = 0$ respectively. On the basis of the values given above we have

$$\sigma_\pi^1 = \sigma(pp \to \pi^0) + \sigma(pp \to \pi^+) = (10.1 \pm 0.73) \cdot 10^{-27} \text{ cm}^2;$$

$$\sigma(np \to \pi^{\pm,0}) = 2\sigma(np \to \pi^+) + \sigma(np \to \pi^0)$$
$$= (9.7 \pm 1.8) \cdot 10^{-27} \text{ cm}^2,$$

and Eq. (3) yields

$$\sigma_\pi^0 = (9.3 \pm 3.7) \cdot 10^{-27} \text{ cm}^2.$$

The probabilities of π-meson production in interactions of nucleons in the states $T = 0$ and $T = 1$ are thus comparable, and the nucleons in these states interact with equal intensity.

The approximate equality of σ_π^0 and σ_π^1 indicates also that in the processes studied, at approximately 600 Mev, the transitions which result in the π-meson-nucleon system having total isotopic spins $T = 3/2$ and $T = 1/2$ have approximately the same probability. This is, evidently, the chief reason for the fact that the ratio $\sigma(pp \to \pi^+)/\sigma(mp \to \pi^+)$, equal in our case to 3.9 ± 1, is considerably less than ten. The latter value was predicted in reference 12 from the principle of isotopic invariance under the assumption that the π meson-nucleon system is always in the $T = 3/2$ state. It should be noted, however, that the value of the ratio given in reference 12 was obtained under simplifying assumptions and may, in reality, be somewhat different.

The authors would like to thank L. I. Lapidus for a discussion of the results and N. S. Amaglobeli for his help in carrying out the experiments.

*The indices refer to the total isotopic spin of the system of two nucleons in the initial and final states (before and after meson production).

[1] G. B. Yodh, Phys. Rev. **98**, 1330 (1955).
[2] V. M. Sidorov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 727 (1955), Soviet Phys. JETP **1**, 600 (1955).
[3] V. S. Kiselev and B. V. Fliagin, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 962 (1957), Soviet Phys. JETP **5**, 786 (1957).
[4] Iu. M. Kazarinov and Iu. N. Simonov, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 169 (1956), Soviet Phys. JETP **4**, 161 (1957).
[5] Dzhelepov, Oganesian, and Fliagin, J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 886 (1955), Soviet Phys. JETP **2**, 757 (1956).
[6] L. C. L. Yuan and S. J. Lindenbaum, Phys. Rev. **103**, 404 (1956).
[7] R. M. Sternheimer, Phys. Rev. **101**, 384 (1956).
[8] A. A. Tiapkin, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 1150 (1956), Soviet Phys. JETP **3**, 797 (1956); Iu. D. Prokoshkin, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 732 (1956), Soviet Phys. JETP **4**, 618 (1957).
[9] A. Rosenfeld, Phys. Rev. **96**, 146 (1954).
[10] Iu. D. Prokoshkin, and A. A. Tiapkin, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 750 (1957), Soviet Phys. JETP **5**, 618 (1957).
[11] A. G. Meshcheriakov and B. S. Neganov, Dokl. Akad. Nauk SSSR **100**, 677 (1955); B. S. Neganov and O. V. Savchenko, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 1265 (1957), Soviet Phys. JETP **5**, 1033 (1957).
[12] L. I. Lapidus, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 865 (1956), Soviet Phys. JETP **4**, 740 (1957); D. C. Peaslee, Phys. Rev. **92**, 1085 (1954).

Translated by H. Kasha
10