PRODUCTION OF CHARGED π MESONS IN COLLISIONS OF NEUTRONS WITH PROTONS AT ~600 MeV

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We have used a multichannel magnetic spectrometer to measure over a wide range of angles the energy spectra of charged mesons produced in np collisions at a neutron energy of ~600 MeV. The spectra obtained are characterized by a large content of low-energy mesons. The peaks of the spectra are located at ~0.6 of the maximum possible energy. The angular distributions obtained for $\pi^{\pm}$ mesons, in the c.m.s., have the form of a quadratic in $\cos\theta$, as given by Eq. (15). The total cross section for meson production is found to be $\sigma_{np}(\pi^+) = \sigma_{np}(\pi^-) = (1.3 \pm 0.2) \times 10^{-27}$ cm^2. Analysis of the results shows that, in spite of the dominant role of the resonance production of pions, it is necessary to include the contribution of non-resonance transitions in the phenomenological considerations.

1. INTRODUCTION

At the present time considerable experimental data have been accumulated on the production of π mesons in nucleon-nucleon collisions. Production of positive and neutral pions in proton-proton collisions at energies from threshold to 1 BeV have received the most detailed study. Analysis of the data on pion production in this energy region is performed mainly with the aid of phenomenological theories. As the experimental data have accumulated and as the energy of the interacting nucleons has increased, several phenomenological models have been developed for the single production of mesons for different energy ranges of the incident nucleons.

Near threshold most of the experimental data have been successfully explained by the theory developed by Gell-Mann and Watson[1] and Rosenfeld.[2] Incident-nucleon energies of 600–700 MeV correspond to a resonance energy for interaction of the pion produced with one of the nucleons. Therefore the resonance nature of the interaction should show up most strongly here. An appropriate phenomenological model was developed by Mandelstam.[3] The results of most experiments on pion production in pp collisions in the energy region 500–700 MeV have turned out to agree with Mandelstam's theory.

In the phenomenological analysis, meson production processes are divided into two groups depending on the value of total isotopic spin of the system of two interacting nucleons, T = 1 or T = 0. Classification of the final states is carried out by segregation of a subsystem of two nucleons[1, 2] or a pion and one of the nucleons.[3, 4] The cross sections for all possible reactions are expressed in terms of three independent amplitudes. In the representation where a subsystem of two nucleons is introduced in the final state, the three partial cross sections corresponding to these amplitudes are written in the form σ_{10}, σ_{11}, and σ_{01}, where the indices indicate the value of total isotopic spin of the nucleons in the initial and final states. The total cross sections for production of mesons in the interaction of two nucleons in states with isotopic spin T = 1 and T = 0 are expressed in terms of the partial cross sections introduced, by the following relations:

$$\sigma_{T=1}(\pi) = \sigma_{10} + 2\sigma_{11}, \tag{1}$$

$$\sigma_{T=0}(\pi) = 3\sigma_{01}. \tag{2}$$

Naturally, information on the partial cross section σ_{01} and correspondingly on $\sigma_{T=0}(\pi)$ can be obtained only by investigating the interaction of a neutron with a proton. From this point of view it is most convenient to study the production of charged pions in the reactions

$$n + p \to \pi^+ + n + n, \quad n + p \to \pi^- + p + p. \tag{3}$$

The phenomenological expression for the total cross section for these reactions,

$$\sigma_{np}(\pi^+) = \sigma_{np}(\pi^-) = {}^1/_2(\sigma_{11} + \sigma_{01}), \tag{4}$$

involves, beside the cross section σ_{01} of interest to us here, only the total cross section for production of π^0 mesons in pp collisions, $\sigma_{pp}(\pi^0) = \sigma_{11}$, which has been well studied in the energy region from threshold to 660 MeV.[5]

In the resonance theory[3] it is assumed that production of mesons can occur only in states of the two-nucleon system with isotopic spin T = 1. Therefore the determination from experiments of the value of the cross section $\sigma_{T=0}(\pi)$ gives valuable information on the validity of the prediction of a dominant role for the $(^3/_2, {^3/_2})$ in meson production in the energy region ~ 600 MeV.

Only a few experimental studies have been made of the processes (3). The difficulties in study of these reactions are due to the relatively small cross sections and the low intensities of neutron beams, which always have a broad energy distribution. Yodh[6] has studied the reactions (3) at an energy of 400 MeV by means of an emulsion technique. At 600 MeV the production of $\pi^\pm$ mesons in np collisions has been studied in our laboratory.[7,8] Kazarinov and Simonov[7] used a scintillation counter telescope to study the cross section for reactions (3). Oganesyan and Yarba[8] measured the spectra of π^+ and π^- (in relative units) at 90° with a photoemulsion chamber.

The production of charged mesons in np collisions can be studied by comparing meson production in collisions of protons with deuterons and with protons. A deficiency in this method is the fact that the energy spectra and angular distributions obtained in the experiments with deuterons can be distorted in comparison with the characteristics of meson production in the elementary events, as a result of the intranuclear motion of the nucleons in deuterium. Therefore we decided to carry out a rather detailed study of the reactions (3) with a magnetic spectrometer in a neutron beam of energy ~600 MeV, incident on free protons.

Simultaneously with the present work, Kazarinov and Simonov[9] carried out a study of the cross sections and angular distributions of reactions (3) with a scintillation telescope. The results of their measurements agree with those of the present work.

Preliminary results of the present work were reported at the Conference on High Energy Physics at Kiev in 1959[10] and at Rochester in 1960.[11]

2. EXPERIMENTAL APPARATUS

The multichannel magnetic-spectrometer technique allows the most complete and efficient study of the spectra of mesons of both signs over a wide range of angles, particularly under conditions of low neutron-beam intensity and the relatively small cross sections for production of charged mesons in np collisions.

The experimental apparatus used is shown in Fig. 1. It consists of an electromagnet with a maximum field strength of 19,000 G, a system of counters, and remotely controlled electronics. Pions produced by the neutron beam in the target pass through a collimator in the vertical leg of the magnet yoke, intersecting counters C_1 and C_2, and enter the magnet gap where they are analyzed in momentum by counters C_3, C_4, and C_5.

The π-meson spectra could be measured at any angle from 0 to 150° with respect to the neutron-beam direction. For this purpose the electromagnet was rotated by means of an electric motor about a vertical axis passing through the center of the neutron beam. The target was located on the axis of rotation and identical geometrical conditions were thus maintained for all measurement angles. The experimental conditions provided the possibility of simultaneous detection of mesons of both signs by a multichannel system covering the entire spectrum of mesons produced.

Two liquid-hydrogen targets were used for measurements at different angles. One of these

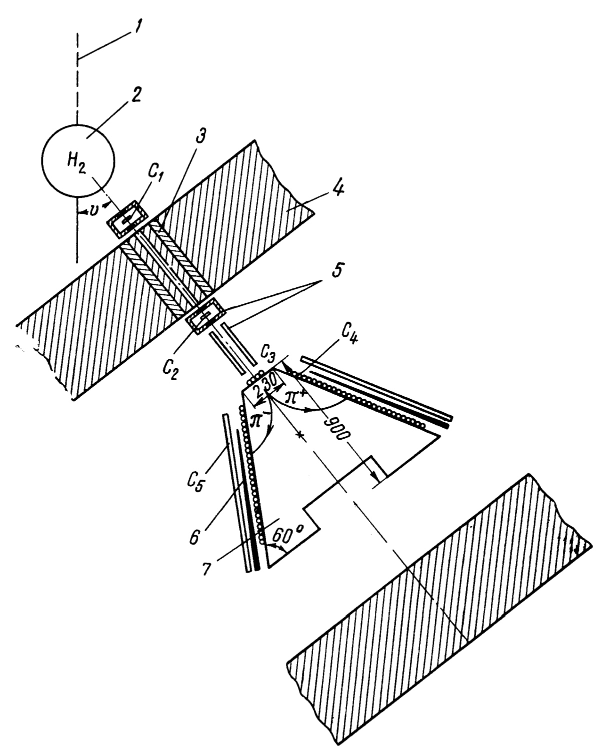

FIG. 1. Experimental arrangement: 1 – neutron beam, 2 – target, 3 – multilayer collimator (Fe,Al), 4 – magnet yoke, 5 – magnetic shield, 6 – absorber, 7 – magnet pole, C_1, C_2 – scintillation telescope counters, C_3 – front counters, C_4 – coordinate counters, C_5 – selection counters.

was a three-liter glass Dewar vessel with an inside diameter of 140 mm, and the other consisted of a stainless-steel cylinder with 0.1 mm thick walls. The cylinder was connected by a tube to a reservoir filled with liquid hydrogen. The hydrogen reservoir was surrounded by a liquid-nitrogen jacket. The entire assembly was located inside a Styrofoam casing.

The detecting system was a combination of gas-discharge and scintillation counters. The counter arrays C_3, C_4, and C_5 (Fig. 1) consisted of gas-filled counters operating in the limited-proportionality regime. Group C_3 (the front counters), consisting of eight counters, served to reduce the background of accidental coincidences. The coordinate counters C_4 were divided into nine groups (channels) on each side, with eight counters in each group. The arrays of selection counters C_5, with one array on each side, were arranged to have the possibility of placing a wedge-shaped copper absorber between counters C_4 and C_5 to remove proton background. Counters C_1 and C_2 formed a scintillation telescope which served to define the π-meson beam and to reduce the number of accidental coincidences. The scintillators consisted of plastic and had dimensions $35 \times 35 \times 1$ mm. The electronic equipment detected coincidences between pulses from the scintillation telescope (counters C_1 and C_2) and the groups of front counters (C_3), coordinate counters (C_4), and selection counters (C_5).

The design of the magnetic spectrometer allowed us to carry out a series of control measurements. First, the symmetry of the apparatus made it possible to perform measurements with direct and reversed field. This procedure allowed us to control the correctness of operation of all counter channels and of the electronics and to avoid (particularly in measurement of the ratio of π^+ to π^- yields) possible errors due to unequal efficiencies of the various channels and circuits of the two halves of the spectrometer. Another means of controlling the spectrometer efficiency consisted of measuring a spectrum at one angle for different values of magnetic field strength. The same purpose was served by a third control experiment in which the entire system of coordinate and selection counters was mechanically shifted in a track along the pole-piece edges with the magnetic field held constant.

The π-meson spectra studied are broad energy distributions whose study does not present particularly severe requirements on spectrometer resolution. The resolution depends on a number of factors: the place of production of the meson in the target, the angle of emission of the meson from the target, the energy loss in the target and in the material in the path of the particles in the spectrometer, and particle scattering. The resolution was calculated by numerical integration. The calculated values of resolution $\Delta E/E$ change, with decreasing energy of the detected π mesons, from 15 to 30%. The angular resolution of the spectrometer was determined by the width of the telescope of scintillators and amounted to $1°45'$.

3. NEUTRON SPECTRUM AND EFFECTIVE ENERGY

One of the features of fast neutron beams obtained from accelerators is their broad energy distribution. The neutron spectrum from the JINR synchrocyclotron[12] has a sharply expressed peak at an energy of 610 MeV with a half-width of ~100 MeV, located 70 MeV away from the upper limit of the spectrum (~680 MeV). This portion of the spectrum is the important one for the experiments being described.

Let us attempt to see in what degree the presence of a broad spectrum of neutrons can be reflected in the interpretation of our results.

Let us dwell at first on the determination of cross sections. The experimentally measured effective value of the cross section for meson production σ_{eff} can be expressed as

$$\sigma_{\text{eff}} = \int \sigma(E) N_n(E)\,dE \Big/ \int N_n(E)\,dE, \qquad (5)$$

where $\sigma(E)$ is the excitation function for the production of $\pi^{\pm}$ mesons in np collisions, and $N_n(E)$ is the neutron spectrum. However, as the result of the fact that the neutron spectrum has a sharply expressed peak, the result of the cross-section measurement turns out to be not very sensitive to the excitation function $\sigma(E)$. A calculation shows that quite different excitation functions lead to very nearly the same values of effective neutron energy E_{eff}. This means that measurement of cross sections in a neutron beam can be considered, in this sense, to be the equivalent of measurements in beams with negligible energy spread.

The effective neutron energy for the chosen neutron-detection threshold of 450 MeV is 585 ± 15 MeV. It must be kept in mind that the value of effective energy introduced in this way is used only for comparison of absolute cross-section values obtained in these experiments with meson-production cross sections at other energies.

Let us now consider the effect of the neutron spectrum on such basic parameters as the energy corresponding to the peak of the π-meson distribution, E^{π}_{max}, and the half-width of the π-meson spectra. To carry out an analysis of this type, the experimental energy distributions of π mesons are represented as the sum of partial spectra of π mesons of different shape for definite neutron energies. The problem is to find the dependence of the shape of the partial spectra and the location of the peaks on neutron energy, such that the calculated combined π-meson spectra obtained as the result of integration over the neutron spectrum agree best with the experimental spectra.

As the result of such an analysis, we obtained an estimate of the deformation of the spectrum shape and of the shift in the energy corresponding to the peak of the π-meson spectrum. For all the variants of the partial spectra used, the peak of the combined spectrum turns out to be shifted by 12–15% toward low energies with respect to the peaks of the assumed spectra of mesons produced by monochromatic 600-MeV neutrons.

The shape of the π-meson spectra themselves is more substantially deformed. The existence of the wide energy distribution of neutrons leads to an increase of the half-width of the partial π-meson spectrum corresponding to a neutron energy of 600 MeV by 25–35%, depending on the angle of measurement.

The angular distributions of π mesons in the incident-nucleon energy region 400–650 MeV undergo considerably less relative change in comparison with the spectra, so that in the analysis of the angular distributions we can assign the distributions obtained to a neutron energy of ~600 MeV.

4. MEASUREMENTS AND ANALYSIS OF RESULTS

Measurements were made at five angles: 16, 30, 60, 90, and 123° in the laboratory system. The measurement procedure consisted of the successive collection of sets of data with hydrogen and with an empty target at these angles, and also of the measurement of the yield of recoil protons from elastic np collisions at an angle of 60°. The latter measurements were made to determine the absolute values of the differential cross sections for meson production.

The ratio of the effect from the target with hydrogen and the empty-target background depends on the angle of measurement. As a function of angle, the background for π^+ mesons varied from 15 to 35%, and for π^- mesons—from 35 to 65%. The considerably larger background for π^- mesons compared to π^+ mesons is due to the fact that the main source of background is the target walls (without the target the background is practically absent), and is explained by the preferential production of π^- mesons by neutrons in complex nuclei.

Corrections were made to the experimental results which took into account the electron and μ-meson impurity, π-meson decay, and nuclear absorption of π mesons in the absorber. The data were reduced to the same energy interval and the same solid angle.

A. Electron background. The sources of electrons incident on the spectrometer are γ rays and Dalitz pairs from decay of π^0 mesons produced in the target. Because of the difficulties of direct measurements to determine the electron background, we utilized known data on the production of π^0 mesons in nucleon-nucleon collisions, and calculated the spectra and angular distributions on this basis. To determine the absolute number of electrons, we normalized the spectra, which were obtained in relative units, to the experimental results on the basis that in the measurements at large angles (90 and 123°) the events in the first channel of the spectrometer can be assigned entirely to electrons. The latter situation occurs because the energy loss results in the π-meson detection efficiency by the first channel at these angles becoming negligibly small (μ mesons from decay of π mesons from other energy channels, a calculation shows, can be completely neglected).

We present below the results of the determination of the ratio of the number of electrons to the yield of π mesons:

Angle, deg:	16	30	60	90	123
N_{e^+}/N_{π^+}:	0.073	0.095	0.120	0.174	0.215
N_{e^-}/N_{π^-}:	0.073	0.095	0.124	0.192	0.252

B. Decay of π mesons and impurity of μ mesons. Calculation of the corrections associated with π-meson decay is complicated by the fact that, in addition to removing π mesons which have decayed in flight, it is necessary to take into account at the same time the probability of detecting the μ mesons produced in the decay of these π mesons. As in the case of electrons, the experimental determination of the μ-meson impurity is practically impossible, as the result of the difficulty of identification and the low counting rate.

Calculations have shown that the μ-meson impurity varies within a rather small range from 3 to 7.5% as a function of the measurement angle and the channel number. Therefore, the possible errors in the numerical calculations cannot be very great. The values of the corrections for the decrease in the number of π mesons as the result

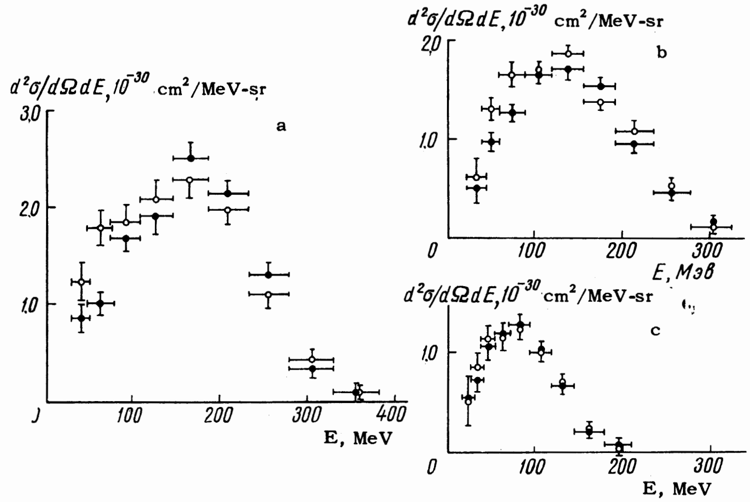

FIG. 2. Spectra of π^+ and π^- mesons produced a – at an angle of 16° (lab.), b – at an angle of 30° (lab.), c – at 60° (lab.): ● – π^+ mesons, o – π^- mesons.

of their decay, taking into account the μ-meson impurity, are as follows:

Angle, deg:	16	30	60	90	123
Correction, %:	10	12.5	20	30	36

C. Protons and nuclear absorption of π mesons. The ranges in matter of protons and π mesons having identical momenta are substantially different. Therefore the protons are easily excluded by the wedge-shaped copper absorber which was placed in the gap between the groups of coordinate and selection counters (see Fig. 1). At the same time, the presence of the absorber leads to the necessity of introducing corrections for absorption of π mesons, associated with inelastic collisions. The values of these corrections were calculated on the basis of data on the cross sections for the inelastic interaction of π mesons of the appropriate energies. It was necessary to introduce corrections for nuclear absorption only for angles less than 90°, where they amounted to 10, 6, and 3% for angles of 16, 30, and 60°, respectively.

5. RESULTS

The experimentally measured spectra of π^+ and π^- mesons at five angles in the laboratory systems are shown in Figs. 2–4. For 90° and 123° the π^+ and π^- spectra are shown separately. The large background made the measurements at these angles difficult. Therefore, in order to increase the accuracy of the results, the measurements here were made with two different targets and two different values of magnetic field.

The threshold energy of mesons detected was ~25 MeV and was determined by the amount of material in the path of the mesons in the spectrometer. In the measurements at large angles, this threshold distinctly limited the detectable portion of the spectrum, leading to the necessity of introducing large corrections in determination of the differential cross sections. For all of the angles the upper limit of the meson spectrum is in agreement with the maximum energy kinematically possible for the neutron spectrum used.

Figure 5 shows the spectra averaged over both signs of π mesons, in the center-of-mass system. The curves drawn for the spectra in Fig. 5 have been constructed so as to provide the best agreement with the experimental points.

The results of the differential cross section measurements are shown in the table. The errors listed in the table include only the statistical errors of the relative measurements. Normalization of the absolute values was performed by compar-

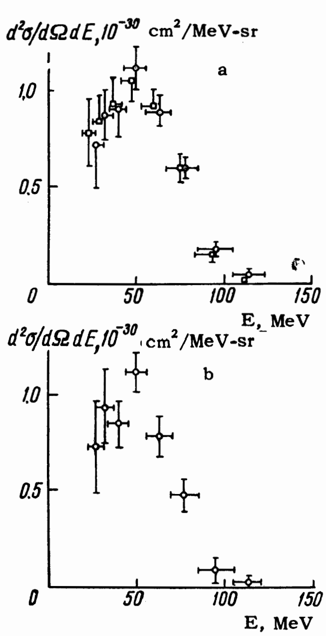

FIG. 3. Spectrum of π^+ mesons (a) and π^- mesons (b) produced at an angle of 90° (lab.): o–measurements with Styrofoam target. □–measurements with Dewar target.

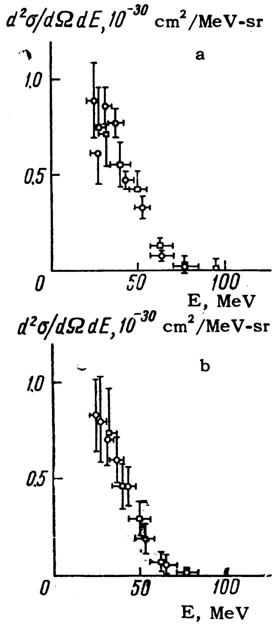

FIG. 4. Spectrum of π^+ mesons (a) and π^- mesons (b) produced at an angle of 123° (lab.): ○ – measurements at 9000 G, □ – measurements at 6000 G.

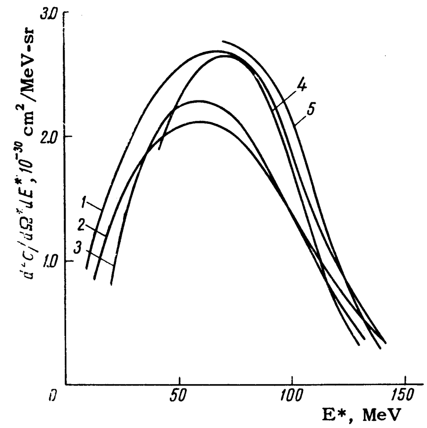

FIG. 5. Spectra of π mesons, averaged over both signs, in the c.m.s.: curve 1 – for an angle of 31°, 2 – 56°, 3 – 101°, 4 – 130°, 5 – 155° (c.m.s.).

ing the meson counting rate with the counting rate of recoil protons from elastic np scattering, the differential cross section for which has been measured by Kazarinov and Simonov.[13]

The total cross section for production of mesons was determined by integration of the experimentally determined angular distribution (see the table). In addition the total cross section was determined from measurement of the $\pi^{\pm}$-meson yields at the two isotropic angles, which correspond for our neutron energies to angles of 31 and 90° in the laboratory system. The total cross section for π-meson production obtained as the result of integration of the angular distribution agreed satisfactorily with the values determined from measurements at the isotropic angles. The averaged value of the total cross section is

$$\sigma_{np}(\pi^+) = \sigma_{np}(\pi^-) = (1.3 \pm 0.2) \cdot 10^{-27}\ \mathrm{cm}^2. \quad (6)$$

6. DISCUSSION OF RESULTS

A. Total cross sections. The hypothesis of charge independence establishes a certain ratio between the total cross sections for production of charged and neutral mesons in nucleon-nucleon collisions:[4]

$$[\sigma_{pp}(\pi^+) + \sigma_{np}(\pi^+) + \sigma_{np}(\pi^-)] \,/\, 2[\sigma_{pp}(\pi^0) + \sigma_{np}(\pi^0)] = 1. \quad (7)$$

Substitution into (7) of the cross-section value determined, Eq. (6), together with the values of the cross sections for the remaining processes[5, 14–16] at an energy of 585 MeV leads to a value of 0.90 ± 0.08. If we take into account the fact that the cross-section values used have been obtained by different authors and by different methods, we can consider that the value determined for the ratio (7) is completely compatible with the charge independence hypothesis, which has been proved rather strictly at the present time.

One of the main results which can be obtained from the experimental cross-section value (6) is the determination of the partial cross section σ_{01}:

$$\sigma_{01} = 2\sigma_{np}(\pi^+) - \sigma_{pp}(\pi^0) \quad (8)$$

and thereby the cross sections for production of pions in a system of two nucleons having total isotopic spin zero. According to Dunaĭtsev and Prokoshkin,[5] at the energy of 585 MeV of interest to us,

$$\sigma_{pp}(\pi^0) = \sigma_{11} = (1.72 \pm 0.12) \cdot 10^{-27}\ \mathrm{cm}^2. \quad (9)$$

Substituting (6) and (9) into (8), we obtain

$$\sigma_{01} = (0.9 \pm 0.4) \cdot 10^{-27}\ \mathrm{cm}^2 \quad (10)$$

and correspondingly, according to (2),

$$\sigma_{T=0}(\pi) = (2.7 \pm 1.2) \cdot 10^{-27}\ \mathrm{cm}^2. \quad (11)$$

At the same incident-nucleon energy the cross section for production of mesons in a system of two nucleons with total isotopic spin unity is

$$\sigma_{T=1}(\pi) = (10.1 \pm 0.6) \cdot 10^{-27}\ \mathrm{cm}^2. \quad (12)$$

This allows us to draw the first conclusion: at an energy of 600 MeV the production of π mesons in the two-nucleon-system state T = 1 is predominant. This result reflects the fact that the production of pions occurs mainly through the intermediate state of the pion-nucleon system with $T = J = {}^3/_2$. To evaluate the factor enhancing the matrix element for interaction of the nucleon with the produced pion in a $({}^3/_2, {}^3/_2)$ state, it is necessary to compare identical classes of transitions for reactions in which the resonance interaction occurs with reactions in which it is impossible. Difficulties associated with separation of the contributions of individual transitions make it impossible to carry out an accurate evaluation of the enhancement factor in this way. Therefore, we can use an approximate evaluation, comparing the partial cross sections σ_{10} and σ_{01}. The experimental data allow us to assume that the dominant contribution to these cross sections is given by Sp transitions,[1)] particularly for the σ_{10} transition to the final state $^3S_1p_2$, and for the σ_{01} transition to the state $^1S_0p_1$. Then, including the correction for the statistical weight, which is determined by the factor $2J + 1$, the ratio of these partial cross sections is ~ 4. The ratio found shows that about 25% of the transitions in σ_{10} must go by the nonresonance channel.

This estimate is in agreement with the work of Guzhavin et al.[17] who studied pion production in pp collisions at 650 MeV. The contribution of states with the nucleon-pion subsystem total isotopic spin $T_{\pi N} = 1/2$ determined by Guzhavin et al. is (28 ± 3)%. As a result we can uniquely draw a second conclusion: it is impossible to neglect the contribution of nonresonance transitions in meson production. It follows from comparison of quantities (9) and (10) that the latter conclusion applies to a still greater degree to the reactions (3) being studied. About half of the mesons produced in np collisions are produced via the nonresonance channel.

B. Energy distributions. The high-energy parts of the π^+- and π^--meson spectra agree within experimental error for all measurement angles. In the low-energy part of the spectrum at angles of 16 and 30° (Figs. 2a and b) the predominance of the π^--meson yield is noticeable. It follows from charge symmetry that for larger angles in the laboratory system in the same part of the spectrum a larger yield of π^+ mesons should be observed. However, the relatively high energy threshold and lower accuracy of the measurements at these angles (Fig. 3 and 4) do not allow us to determine this difference very reliably. The observed difference of the spectra in the low-energy region is evidently due to the large asymmetry of the π-meson angular distribution which Yodh's data[6] show to be present at neutron energies of ~400 MeV. In the discussion of the angular distributions below we will dwell on this point in more detail.

An angle of 60° in the lab corresponds to 100° in the c.m.s., i.e., so close to 90° in the c.m.s. that, according to charge symmetry, we would expect identical spectra for both signs of mesons. Figure 2c shows that the π^+- and π^--meson spectra at 60° are in good agreement.

The π^+- and π^--meson spectra obtained at 90° are somewhat "harder" than the spectra measured by Oganesyan and Yarba[8] with an emulsion chamber.

As we have noted above, calculation shows that for the case of a monoenergetic spectrum of 600-MeV neutrons, the energy E^{π}_{max} should be increased in comparison with the experimentally determined value by 12–15%, and the half-width of the spectrum reduced by 25–35% as a function of the measurement angle. When this effect is included the averaged energy for the location of the π-meson spectrum peak in the c.m.s. is 70–75 MeV, and the half-width of the spectrum is 70–80 MeV.

A characteristic feature of the spectra of pions obtained in collisions of neutrons with protons is the high content of low-energy mesons. A similar situation has been observed by Rushbrooke et al.[18] They obtained pion energy spectra for four neutron-energy intervals from the meson-production threshold to 970 MeV. Direct comparison of the shape of the meson spectra obtained in the present work with the results of Rushbrooke is difficult even for the same neutron energy intervals, as the result of the fact that the neutron spectra themselves are substantially different in the two experiments. However, we can use as a quantitative characteristic of the shape of the spectra the position of the peak of the energy distributions E^{π}_{max} with respect to the upper limit of the energy spectra E_{lim}. This characteristic is relatively insensitive to the nonmonochromaticity of the neutron beam.

The peak of the spectrum in the c.m.s. in the present measurements for 600-MeV neutrons occurs at an energy of $(0.59 \pm 0.05)E_{lim}$. The same ratio can be determined from the data of Rushbrooke et al. for neutrons with an average energy of 620 MeV. It turns out to be $E^{\pi}_{max}/E_{lim} = 0.63$, in agreement with our measurements.

The substantial content of low-energy pions in the spectra obtained can be explained by the large contribution of nonresonance transitions in the reactions being studied. For this purpose let us compare the energy distributions obtained with the

[1)]Here and subsequently we use the designation employed by Rosenfeld.[2] The large letters correspond to the angular momentum of the two-nucleon system, and the small letters to the angular momentum of the pion.

Angle in lab., deg	$d\sigma/d\Omega$, 10^{28} cm²/sr		Angle in c.m.s.	$d\sigma^*/d\Omega^*$, 10^{28} cm²/sr	
	π^+	π^-		π^+	π^-
16	4.50 ± 0.28	4.88 ± 0.28	31°	1.17 ± 0.08	1.29 ± 0.08
30	2.92 ± 0.21	3.22 ± 0.23	55°30′	0.96 ± 0.07	1.05 ± 0.08
60	1.35 ± 0.18	1.37 ± 0.08	101°	0.95 ± 0.06	0.97 ± 0.06
90	0.60 ± 0.03	0.58 ± 0.03	130°	1.05 ± 0.06	1.02 ± 0.06
123	0.32 ± 0.04	0.30 ± 0.04	155°	1.31 ± 0.15	1.23 ± 0.15

spectra of π^0 mesons produced in pp collisions. The π^0-meson spectra have been studied at proton energies of 650 MeV[17, 19] and 560 MeV.[20] The earlier studies,[19] employing electronics, obtained a value $E^{\pi^0}_{max}/E_{lim} = 0.55$. Gushavin et al.,[17] using a hydrogen bubble chamber, found the π^0-meson spectrum to be harder: $E^{\pi^0}_{max}/E_{lim} = 0.81$. For 560-MeV protons Baldoni et al.,[20] also using a bubble chamber, found $E^{\pi^0}_{max}/E_{lim} = 0.76$. The errors do not exceed 10% for all of the ratios given. Thus, a definite difference exists between the spectra of π^0 mesons obtained with electronics and with a bubble chamber.

If we compare the charged-meson spectra with the π^0-meson spectra measured in a bubble chamber,[17, 20] which we consider more reliable, we can draw the conclusion that the former are substantially "softer." According to Mandelstam[3] the position of the peak in the π^0-meson spectrum should occur at an energy roughly $^2/_3$ of the maximum energy. From the point of view of phenomenological theory, the difference in the spectra of π^+ mesons from np collisions and π^0 mesons from pp collisions is determined by the partial cross section σ_{01}. If the contribution of σ_{01} is small, then the production of π^0 and $\pi^\pm$ mesons will be determined only by the partial cross section σ_{11}, and their spectra will be similar. In the region being considered the main contribution to the cross section σ_{11} is given by resonance transitions, which lead to a shift of the pion spectra in the high energy direction.[3] Therefore the observed relative "softness" of $\pi^\pm$-meson spectra indicates the important role of nonresonance transitions in σ_{01}.

C. Angular distributions. A phenomenological analysis of the angular distribution of mesons in reactions (3) is convenient to carry out for the combined differential cross section for mesons of both signs. The combined cross sections measured for five angles are shown in Fig. 6. We have determined the analytic form of the angular distribution function from these data by the method of least squares. For an angular distribution of the form $A + C\cos^2\theta$ we have obtained the expression

$$d\sigma^*/d\Omega^* = [(1.84 \pm 0.08) + (0.71 \pm 0.18)\cos^2\theta] \times (1.00 \pm 0.15) \cdot 10^{-28}\ \text{cm}^2/\text{sr}. \quad (13)$$

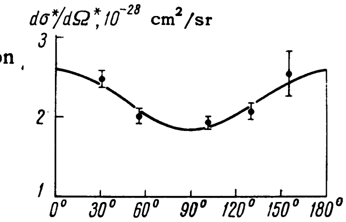

FIG. 6. Angular distribution of the combined yield of π^+ and π^- mesons (c.m.s.). The curve was computed by the method of least squares.

This distribution is plotted in Fig. 6. The value of χ^2 found for distribution (13) is 2.59 and is in good agreement with the expected value of 3. This result shows that, for the energy of the present experiment, we can limit ourselves to discussion of s and p states of mesons in analysis of the main characteristics of the process being studied. The angular distribution found, Eq. (13), is characterized by a low value of anisotropy (about 80% of the mesons are distributed isotropically).

Let us compare the angular distribution obtained here with the angular distribution of π^0 mesons produced in pp collisions. Dunaĭtsev and Prokoshkin[5] obtained for π^0 mesons an angular distribution close to isotropic over practically the entire energy range studied from 400 to 660 MeV. For an energy of 590 MeV the coefficient $b_{\pi 0}$ in the π^0-meson angular distribution written in the form $^1/_3 + b_{\pi 0}\cos^2\theta$, according to Prokoshkin,[21] is 0.05 ± 0.06. The coefficient for the same expression obtained in the present work is $b_{\pi\pm} = 0.13 \pm 0.03$. Thus, the angular distribution obtained for charged mesons in np collisions is the same within experimental error as the distribution of π^0 mesons produced in pp collisions. These angular distributions enable us to determine the angular distribution of pions produced in collisions of nucleons with isotopic spin T = 0:

$$(d\sigma^*/d\Omega^*)_{T=0} \sim {}^1/_3 + (0.32 \pm 0.18)\cos^2\theta. \quad (14)$$

For a neutron energy of ~400 MeV Yodh[6] found a substantial asymmetry in the angular distribution of π mesons of one sign: in the c.m.s. the π^- mesons were emitted mainly in the direction of the primary neutron, and the π^+ mesons were emitted preferentially backward. In the present measurements we obtained a small value for this asymmetry. The ratios of the yields of π^+ and π^- mesons are listed below:

Angle (lab.), deg.:	16	30	60	90	123
N_{π^+}/N_{π^-}:	0.92 ± 0.05	0.91 ± 0.08	0.98 ± 0.06	1.04 ± 0.07	1.07 ± 0.10

The ratios found for yields of mesons of different signs have allowed us to determine the coefficient of the $\cos\theta$ term in the angular distributions. The corresponding angular distributions of $\pi^\pm$ mesons in the c.m.s. have the form

$$(d\sigma^*/d\Omega^*)_{\pi^\pm} = [(0.92 \pm 0.04) \mp (0.052 \pm 0.025)\cos\theta + (0.36 \pm 0.09)\cos^2\theta]\cdot(1.00 \pm 0.15)\cdot 10^{-28}\ \mathrm{cm}^2/\mathrm{sr}. \tag{15}$$

The observed small value of asymmetry can be assigned to the effect of low-energy neutrons. It turns out that if we use the existing data[6] and take into account in our angular distributions the asymmetry due to this effect, the asymmetry disappears within experimental error.

The asymmetry in the pion angular distribution arises as the result of interference between definite transitions of the partial cross sections σ_{11} and σ_{01} and is a specific feature of π^+- and π^--meson production in np collisions. In order to have the possibility of interference it is necessary that the nucleons in these transitions be in initial states with identical spin and go to the same final state. These rules exclude the possibility of interference between σ_{10} and the two other partial cross sections. At the same time for reactions (3) the corresponding transitions in σ_{01} and σ_{11} take place, which also leads to a forward-backward asymmetry. The main Sp transition in σ_{01} can interfere only with the transition ${}^3P_0 \to ({}^1S_0, s)_{1,0}$, which is possible for the partial cross section σ_{11}. For energies below 500 MeV, according to Dunaĭtsev and Prokoshkin,[5] an appreciable contribution to the cross section σ_{11} is given by nonresonance Ss transitions, which appeerently leads also to a strong asymmetry in the meson angular distribution observed at an energy of $\sim$400 MeV. For a dominant role of the resonance interaction the main contribution to σ_{11} for neutron energies of $\sim$600 MeV must come from a Pp transition, which cannot interfere with the main Sp transition for σ_{01}. Thus, the absence of asymmetry in the angular distributions obtained by us indicates that a resonance Pp transition is the main transition in σ_{11} at $\sim$600 MeV, while an Sp transition is predominant for σ_{01}.

7. CONCLUSION

1. We have measured over a wide range of angles the energy spectra of charged mesons produced in np collisions. A characteristic feature of the spectra studied is a large content of low-energy mesons. The peaks of the spectra are located at an energy of $\sim$0.6 of the maximum possible energy. A phenomenological analysis of the energy distributions found indicates an important role of the partial cross section σ_{01}.

2. The combined meson angular distribution found is characterized by a small anisotropy and is described by formula (13).

3. Data on the angular distributions of π^+ and π^- mesons show that there is practically no asymmetry. This can be explained by the hypothesis that at an energy of $\sim$600 MeV the main transitions in meson production are Sp transitions in σ_{01} and resonance Pp transitions in the partial cross section σ_{11}, which do not interfere with each other.

4. The measured value of the total cross section for production of $\pi^\pm$ mesons, $(1.3 \pm 0.2) \times 10^{-27}$ cm^2, is consistent with the relation between the cross sections which follows from the hypothesis of charge independence, and allows determination of the cross section for production of π mesons in nucleon-nucleon collisions with total isotopic spin equal to zero: $\sigma_{T=0}(\pi) = (2.7 \pm 1.2) \times 10^{-27}$ cm^2.

5. Comparison of the value found for $\sigma_{T=0}(\pi^+)$ with $\sigma_{T=1}(\pi) = (10.1 \pm 0.6) \times 10^{-27}$ cm^2 shows that, in spite of the preferential role of resonance processes, we are not justified in neglecting the contribution of nonresonance transitions in phenomenological models for meson production in nucleon-nucleon collisions.

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[1] M. Gell-Mann and K. Watson, Ann. Rev. Nucl. Sci. **4**, 219 (1954).

[2] A. H. Rosenfeld, Phys. Rev. **96**, 139 (1954).

[3] S. Mandelstam, Proc. Roy. Soc. **A244**, 491 (1958).

[4] L. I. Lapidus, JETP **31**, 865 (1956), Soviet Phys. JETP **4**, 740 (1957).

[5] A. F. Dunaĭtsev and Yu. D. Prokoshkin, JETP **36**, 1656 (1959), Soviet Phys. JETP **9**, 1179 (1959).

[6] G. B. Yodh, Phys. Rev. **98**, 1330 (1955).

[7] Yu. M. Kazarinov and Yu. N. Simonov, JETP **35**, 78 (1958), Soviet Phys. JETP **8**, 56 (1959).

[8] K. O. Oganesyan and V. A. Yarba, JETP **45**, 1835 (1963), Soviet Phys. JETP **18**, 1257 (1964).

[9] Yu. M. Kazarinov and Yu. N. Simonov, Preprint, JINR, R-2462, 1965.

[10] B. M. Pontecorvo, Rapporterskiĭ doklad, 9 Mezhdunar. konf. po fizike vysokikh energiĭ (Rapporteur's Report, IX Intern. Conf. on High Energy Physics), Kiev, 1959, AN SSSR, 1961, p. 60; English transl., Moscow, 1960, p. 83.

[11] V. P. Dzhelepov, V. S. Kiselev, K. O. Oganesyan, and V. B. Flyagin, Proc. 1960 Ann. Intern. Conf. on High Energy Physics at Rochester, Univ. of Rochester, 1960, p. 46.

[12] V. S. Kiselev, K. O. Oganesyan, R. Poze, and V. B. Flyagin, JETP **35**, 812 (1958), Soviet Phys. JETP **8**, 564 (1959).

[13] Yu. M. Kazarinov and Yu. N. Simonov, JETP **31**, 169 (1956), Soviet Phys. JETP **4**, 161 (1957).

[14] A. F. Dunaĭtsev and Yu. D. Prokoshkin, JETP **38**, 747 (1960), Soviet Phys. JETP **11**, 540 (1960).

[15] M. G. Meshcheryakov and B. S. Neganov, DAN SSSR **100**, 677 (1955).

[16] B. S. Neganov and O. V. Savchenko, JETP **32**, 1265 (1957), Soviet Phys. JETP **5**, 1033 (1957).

[17] V. M. Guzhavin, G. K. Kliger, V. Z. Kolganov, A. V. Lebedev, K. S. Marish, Yu. D. Prokoshkin, V. T. Smolyankin, A. P. Sokolov, L. M. Soroko, and Ts'ui Wa-Ch'uang, JETP **46**, 1245 (1964), Soviet Phys. JETP **19**, 847 (1964).

[18] J. G. Rushbrooke, D. V. Bugg, A. J. Oxley, J. A. Zoll, M. Jobes, J. Kinson, L. Riddiford, and B. Tallini, Nuovo Cimento **33**, 1509 (1964).

[19] Yu. D. Bayukov and A. A. Tyapkin, JETP **32**, 953 (1957), Soviet Phys. JETP **5**, 779 (1957).

[20] B. Baldoni, S. Focardi, H. Hromadnik, et al., Nuovo Cimento **26**, 1376 (1962).

[21] Yu. D. Prokoshkin, Preprint, JINR, D-569, Dubna, 1960.

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