THE $n + p \to \pi^0 + d$ REACTION FOR NEUTRONS OF 600 Mev EFFECTIVE ENERGY AND THE CHARGE-INDEPENDENCE HYPOTHESIS*

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The angular distribution and total cross section for the production of π^0 mesons in the $n + p \to \pi^0 + d$ reaction have been measured for 600-Mev neutrons. The experimental arrangement permitted the recording of coincidences between the deuteron and one of the π^0-meson decay quanta. Gamma quanta were recorded with a scintillation-counter telescope containing a lead converter. The deuterons were analyzed by means of a multichannel magnetic spectrometer. The angular distribution, $(0.220 \pm 0.222) + \cos^2 \theta$ (in the c.m.s.), and the total cross section for the reaction, $(1.5 \pm 0.3) \times 10^{-27}$ cm^2, confirm the charge-independence hypothesis.

INTRODUCTION

ONE of the foundations of the contemporary phenomenolgical theory of strong interactions is the hypothesis of charge invariance of nuclear forces. An elementary analysis shows that none of our present experimental knowledge of strong interactions conflicts with this hypothesis. The most promising method of proving the conservation of isotopic spin at high energies is an exact quantitative study of pion production processes. We can obtain valuable information in this connection by comparing the pion production cross sections in the reactions

$$p + p \to \pi^+ + d, \tag{1}$$

$$n + p \to \pi^0 + d. \tag{2}$$

In 1952 Yang pointed out that if isotopic spin is conserved in meson-nucleon interactions the differential cross sections for the given reactions should obey the simple relation

$$\sigma_2(\theta) = \frac{1}{2}\sigma_1(\theta). \tag{3}$$

In other words, the pions produced in reactions (1) and (2) should have identical angular distributions while the total cross sections should have the ratio 2:1.

Reaction (1) has been studied in detail by many workers (see the review in reference 1 as well as references 2 to 6) and we now possess information concerning this reaction from threshold up to proton energies of 900 Mev. The synchrocyclotron of the Joint Institute for Nuclear Research has been used to investigate this reaction systematically in the energy region 460 to 900 Mev.[4-6]

There are many difficulties associated with the study of reaction (2) compared with (1). These result mainly from the small intensity of the neutron beams, the broad neutron energy spectrum and, finally, the relative difficulty of identifying the reaction, since one of the produced particles (the π^0 meson) is neutral and decays practically instantaneously. These conditions are apparently the principal reason that only two studies of reaction (2) have thus far been reported in the literature (references 7 and 8) and at only a single neutron energy of 400 Mev. In reference 7 only the π^0-meson angular distribution was determined; the result obtained was $(0.20 \pm 0.06) + \cos^2 \theta$. In reference 8 measurements of both the angular distribution and the total cross section were given. It must be pointed out, however, that whereas the latter article gave the total cross section with accuracy $\sim 20\%$ ($\sigma_t = (0.41 \pm 0.07) \times 10^{-27}$ cm^2), the accuracy of the angular distribution was clearly inadequate. As a whole these experiments with the given accuracy provided evidence of the fulfillment of Yang's relation.[3]

The investigations which will be described here were performed for the purpose of testing the charge independence of meson-nucleon interactions through a study of reaction (2) at an energy considerably above the meson production threshold.

EXPERIMENTAL METHOD

Because of the relatively weak neutron beam obtained from the synchrocyclotron (3×10^4 cm^{-2}
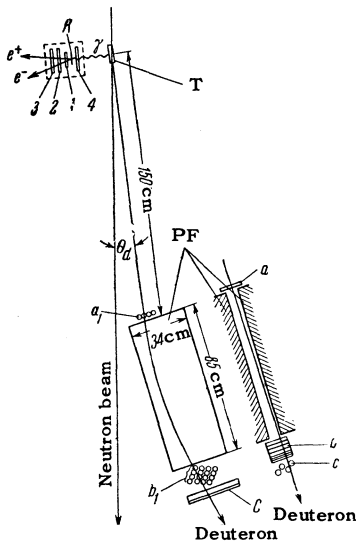

FIG. 1. Experimental arrangement. C) — Pb converter, T) — target (CH_2 or C), PF — pole faces of electromagnet; 1, 2, 3, 4) — scintillation counters

sec^{-1}) the experimental method and the apparatus must be as efficient as possible. We therefore used a system of recording the coincidence between the deuteron and only a single γ quantum from the π^0-meson decay. With 600-Mev neutrons this setup possesses an efficiency that is greater by a factor of several tens than that employed in reference 7, where three telescopes were used to register the simultaneous production of two γ quanta and the deuteron.

For deuteron momentum discrimination we used a magnetic spectrometer which permitted the definition of a relatively narrow energy interval in the primary neutron spectrum. The experimental procedure also took into account the necessity of excluding particles from the reaction

$$n + p \rightarrow \pi^0 + n + p, \qquad (4)$$
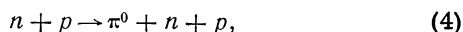
which could seriously distort the results. This was easily accomplished by the method of using the magnetic spectrometer in the deuteron-recording channel.

A diagram of the experimental setup is shown in Fig. 1. The neutron beam passed through a collimator in the form of a vertical slit and struck a polyethylene (CH_2) or graphite (C) target. The effect due to hydrogen was determined from the difference of the CH_2 and C effects. For different deuteron-energy intervals (different angular intervals in the center-of-mass system) two different pairs of targets were used (with CH_2 thicknesses of 6 g/cm^2 and 2 g/cm^2) in order to minimize the corrections for multiple scattering of deuterons in the targets. The graph-

ite and polyethylene targets contained the same number of carbon nuclei. The results obtained with targets of different thicknesses agreed in general.

The γ quanta from π^0-meson decay were registered by a telescope set up in the direction of π^0-meson motion in the laboratory system. The telescope consisted of three scintillation counters (with diameters of 90, 120 and 125 mm) preceded by a lead converter of 7 mm thickness and 90 mm diameter. The fourth counter, which was in front of the converter, was connected in anticoincidence with the others and served to reduce the background from charged particles. The scintillation counters contained solutions of terphenyl in toluene or phenylcyclohexane, the containers of which were made of duraluminum or plexiglas.

To eliminate the influence of the magnetic field, the photomultipliers were screened by iron 5 mm thick. Additional screening was provided by the external iron jackets of the counters. The effectiveness of the screening was tested by the γ count with the magnetic field on and off. At the high voltage of the photomultipliers the telescope plateau was about 200 v with a slope of not more than 10%. The energy threshold of the γ-ray telescope, which was determined by the thickness of the scintillators, was quite low ($\sim$ 25 Mev). The low threshold was necessary in order to minimize the variation of telescope efficiency as the gamma-ray energies varied within the limits 140 $\leq E_\gamma \leq$ 400 Mev.

THE MAGNETIC SPECTROMETER

The spectrometer was constructed with an electromagnet of 18,000 Oe maximum field and 60 mm gap. An analysis of all the required experimental conditions (the required energy and angular resolutions, maximum efficiency with minimum background, minimum number of channels, etc.) led to the spectrometer shown in Fig. 1.

The fast-deuteron detectors were thin-walled (0.15 mm steel) counters filled with methylal (CH_2OCH_3) operating with "limited proportionality" at high voltages (1700 to 2100 v). These counters were arranged in three groups along the deuteron trajectory close to the edges of the pole faces. Figure 1 shows the counter system for registering deuterons in coincidence with a single γ-ray telescope. When permitted by the geometry, the time required for the measurements was reduced by the use of two such systems with a common target. The counters of groups a and b had the following dimensions:
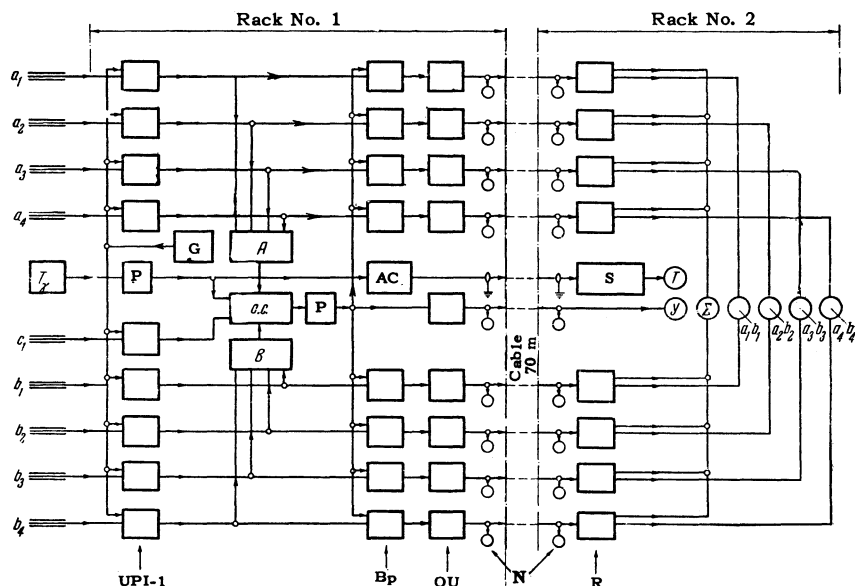
FIG. 2. Block diagram of the electronic circuit. T_γ) γ telescope, P) pulse-shaping univibrator, G) test-pulse generator, AC) amplifier and cathode follower, S) scaler, N) neon lamps; the rest of the notation is explained in the text.

diameter 10 mm and length 100 mm; the dimensions of group c were 18 and 300 mm, respectively.

The coincidence combinations of counters were based on the required form of the resolution curve. Each counter of group a was connected in coincidence with only a single tray of counters b (four counters) and with all the counters of group c. The energy resolution was thus determined by the width of a single counter of a and of a single row of group b. For each angle the readings of four coincidence groups of type $a_i + b_i$ were added. The angular resolution of the system, as determined by the width of counter tray a, was selected to be 1.5° in the laboratory system.

The angle at which deuterons were registered was varied by shifting the counter groups a and b along the edges of the pole faces. The entire interval of deuteron angles (with 14° maximum laboratory-system angle of deuteron emission) was covered in two positions of the magnet with respect to the neutron beam.

The counters were adjusted on the deuteron trajectory by means of a current-carrying filament in the magnetic field. For most angles the error in the cross section that was associated with the adjustment of the counter positions did not exceed 1 or 2%, but the error was 7% for four c.m. angles of deuteron emission into the backward hemisphere. This relatively large error resulted from the fact that for different neutron energies the deuterons have very close energies in the laboratory system. The relative positions of counters a and b gave only the energy threshold, which corresponded to ~550-Mev neutrons. The maximum deuteron energy was determined by the upper

limit of the neutron spectrum.

A block diagram of the electronic circuit of the spectrometer is shown in Fig. 2.* Pulses from counters a, b and c were fed to standard UPI-1 pulse-converting amplifiers with a passband of 1 Mc and gain of 10^4, in the output stages of which 4 or 5×10^{-7}-sec 8-volt pulses were formed. The total number of amplification channels for the two systems of gas-filled counters was 18 (Figs. 1 and 2 show only one of these systems). Signals formed in UPI-1 were "split" in each channel except channel c and were fed to the mixer (A or B) and bandpass circuit Bp. Standardized pulses from the two mixers, γ-ray telescope, and selecting counters c were fed to a fourfold coincidence circuit cc (resolving time 5×10^{-7} sec), which sent a master pulse to the bandpass circuits Bp. The latter passed pulses from gamma-deuteron coincidences to "slow" output univibrators (OU) and almost completely prevented accidental ground pulses from reaching these univibrators.

The required combinations of discharged coordinated counters following the passage of a particle were selected by the relays R in the plate circuits of the output univibrators. These combinations and their sums were counted by electromechanical counters (T, Y, Σ, a_1b_1, a_2b_2 etc.).

CONTROL EXPERIMENTS

1. To verify that the particles registered by the spectrometer were actually deuterons we measured

*For a portion of the electronic equipment of our spectrometer we used the circuits placed at our disposal by the designers of the multi-channel γ-ray spectrometer developed at the Laboratory for Nuclear Problems.[9]

FIG. 3. Curves of deuteron absorption in copper.
a) $\theta_d = 6°$; b) $\theta_d = 9°$.
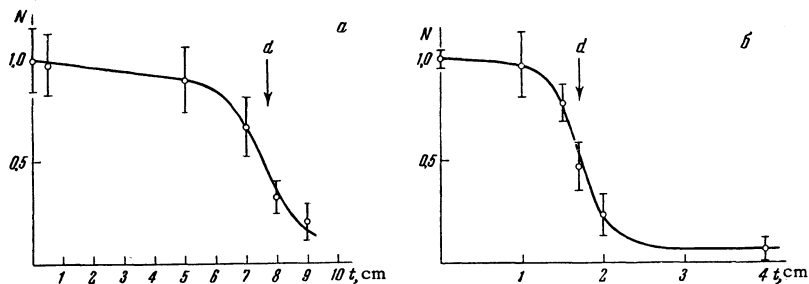
the absorption curves of these particles in copper for two angles of π^0-meson emission, $\theta_\pi^* = 34$ and 146°.* The resulting curves (Fig. 3) leave no doubt that the events recorded by the apparatus were coincidences between γ quanta and deuterons. The steep slopes of the curves are located exactly at the centers of the range distributions which can be expected from the kinematics of the reaction (the arrows d in Fig. 3). The range of protons with the same momentum is approximately double the range of the deuterons.

2. The use of a magnetic field to register deuterons and the selected energy threshold ($E_\pi = 550$ Mev) permits the complete exclusion of particles from reaction (4) for most investigated π^0-meson angles. The angular range where such extraneous particles are absent corresponds to deuterons emitted forward in the c.m. system and having "large" momentum in the laboratory system [in Fig. 4 the branches of the curve that lie above the limit of possible momenta of protons from reaction (4)]. It also follows from Fig. 4 that, on the contrary, in the "small" momentum region corresponding to deuterons emitted "backward" in the c.m. system (the branches of the curves that lie below the dotted line) a proton contribution is possible. Four points in this region were measured on the π^0-meson angular distribution curve (at $\theta_\pi^* = 27$, 34, 40 and 50°). For two of these angles ($\theta_\pi^* = 34$ and 50°) the percentage of protons coinciding with π^0 mesons was determined by means of filters placed in front of counters c. Reaction (4) was easily distinguished because of the different ranges of deuterons and protons with the same momentum. The measurements indicated a small proton component: For $\theta_\pi^* = 34°$ it was $(6.5 \pm 5.9)\%$ and for $\theta_\pi^* = 50°$ it was $(0.2^{+5.7}_{-0.2})\%$ of the principal effect [reaction (2)]. For the other two angles the percentage was determined by linear interpolation and extrapolation of the data.

3. In order to verify that the recorded γ quanta are actually decay products of π^0-mesons from reaction (2) we have investigated the angular correlation of the γ quanta and deuterons. This experiment was performed at $\theta_\pi^* = 108°$. The results are shown in Fig. 5, where the abscissas are the angles between the telescope axis and the direction of π^0-meson motion. The curve in the figure was calculated for a mean neutron energy of 600 Mev. The correlation is clearly observed.

EFFICIENCY OF THE γ-RAY TELESCOPE

The telescope when pointed in the direction of π^0-meson motion registered the most energetic γ quanta resulting from decays (from 150 to 400 Mev, depending on the angle of observation). To determine the relation between the telescope efficiency k_γ and γ-quantum energy, we performed additional experiments on the passage of fast electrons through converters of different thicknesses. The results of these experiments make it considerably easier to calculate the efficiency. When
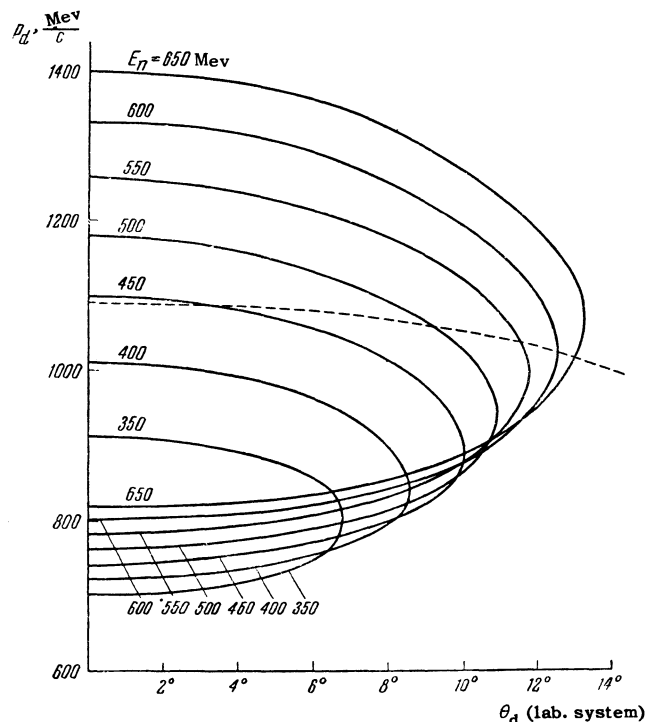

FIG. 4. Momentum of deuterons from reaction (2) as a function of their laboratory system emission angle and incident neutron energy. Dotted line — maximum momentum of protons from the reaction $n + p \rightarrow \pi^0 + n + p$, $E_n = 650$ Mev.
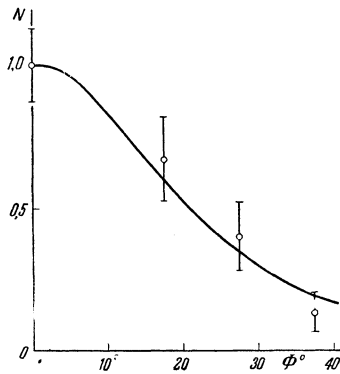
*Here and henceforth the symbol * denotes angles in the c.m. system of colliding nucleons.

FIG. 5. Counting rate as a function of the angle Φ between the telescope axis and the direction of π^0-meson motion. The solid curve represents the function $(1-\beta^2)/(1-\beta \cos \Phi)^2$.

experiment gives us the probability of registering an electron q^- and of a positron q^+ the probability of registering the pair is easily determined to be

$$\eta = 1 - (1 - q^-)(1 - q^+). \qquad (5)$$

The probability W of electron-positron pair production is easily calculated from the experimental cross sections[10] for γ-ray absorption (where we can neglect the Compton effect and, with even greater justification, the photoelectric effect for energies on the order of 100 Mev). The probability product ηW gives the telescope efficiency for γ rays of a given energy.

Figure 6 is a diagram of the experiment for determining q. The lead target produced electrons of the required energy by converting γ rays, which are always present in high-energy neutron beams. These γ rays are derived from the π^0 mesons produced in the internal target of the synchrocyclotron. The conversion electrons were deflected by the magnetic field, passed through the collimator of 2 cm diameter and entered the telescope (anticoincidence counter 4 (Fig. 1) was removed in these experiments). This experiment compared the telescope counting rate when the converter was used with the primary electron beam intensity. The variable parameters were the converter thickness t, the positron energy E^+, and the distance r from the center of the last scintillator to the beam axis.

In calculating the probability of recording a pair the quantities calculated by means of (5) were
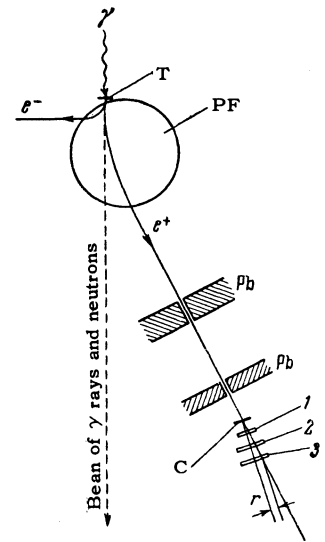

FIG. 6. Diagram of experiments for determining γ-telescope efficiency. T) Pb target (t = 2 mm), PF) pole faces of electromagnet, C) Pb converter of variable thickness; 1, 2, 3) scintillation counters.

averaged over a number of values of E^+, r, and the converter area. In this calculation it was assumed that the telescope possesses identical efficiency for electrons and positrons of different energies. Integration of the telescope efficiency (the product ηW) over the converter thickness t gives the coefficient k_γ for a given γ-ray energy. Because of the geometry employed (large converter area), a fraction of the electrons may not reach the rear counter even if emitted from the converter in the direction of the γ rays. As a result some portions of the converter are less efficient. Therefore the effective solid angle is smaller than the actual angle viewed by the converter in the telescope.

The results for k_γ, reduced to the effective solid angle, which in the majority of measurements was 8.5×10^{-2} radians, are given in Table I.

The accuracy of the relative efficiencies was quite high (above 5%). In measurements of the absolute yield of reaction (2) the error in the absolute value of k_γ was reduced by the use of an unusually small converter (4 mm thickness, 60 mm diameter).

By means of the foregoing method of calculating the efficiency, we also determined corrections for its dependence on the distance between the telescope and target (in measurements at small angles the telescope was moved away from the target so that the neutron beam would not strike its walls).

TABLE I

θ^*_π, degrees	27~49	94	132	146	152	164
Average γ-ray energy (lab. system), Mev	400	280	200	173	163	150
Telescope efficiency, k_γ	0.61	0.58	0.56	0.54	0.53	0.51

The efficiency ratio of the two γ-ray telescopes used in the experiments was measured separately. For this purpose one telescope was replaced by the other at one of the test angles (the apparatus recorded the reaction $n + p \rightarrow \pi^0 + d$). From the ratio of the counting rates in these two instances, $N_1 : N_2 = 0.97 \pm 0.05$, it can be inferred that the telescopes possessed nearly identical efficiency, despite the small difference of geometry.

MEASUREMENTS

In each series of measurements the effect of the CH_2 and C targets was determined with and without the presence of the converter. As a control, the background was also measured in the absence of the target. The effect produced by the reaction under investigation was determined by the difference

$$A = (N^c_{CH_2} - N^{nc}_{CH_2}) - (N^c_C - N^{nc}_C). \tag{6}$$

Here N is the counting rate for different targets. The superscripts c and nc denote "with converter" and "no converter", respectively.

Under the given experimental conditions the counting rates for the thin targets ($2g/cm^2$ CH_2) which were used in most of the measurements had the following average values:

TABLE II

Target	Counting rate with converter, pulses/hour	Counting rate without converter, pulses/hour
CH_2	12	3
C	3	1.5
Background	~0.5	~0.5

The results show that a carbon target produces a relatively small effect. This fact is of independent interest since it indicates a characteristic of π^0-meson production in reaction (2) with nucleons of complex nuclei. In the given experiment the smallness of N^c_C compared with $N^c_{CH_2}$ played a very important part, since it enabled us to obtain results of sufficiently high accuracy in a reasonable period of time.

Measurements in which we introduced an artificial delay of pulses fed from the telescope to the common coincidence circuit (cc in Fig. 2) showed that accidental coincidences of pulses from the telescope and spectrometer were responsible for most of the count in the absence of the converter. The rise of the background and of the count without the converter as well as the reduced useful effect due to the necessity of separating the telescope from the target in measurements at angles close to 0° and 180° were the principal difficulties in meas-

urements near these angles.

For measurements of deuteron absorption in copper and the determination of the contribution of particles from reaction (4), it was very important to take into account the background of accidental coincidences of the entire system with the last layer c of spectrometer counters. This background was determined by shifting counters c away from the deuteron trajectory.

REDUCTION OF EXPERIMENTAL RESULTS

The relative counting rates for different angles of deuteron emission are proportional to

$$A(\theta_d) \sim \int_0^\infty \sigma(\theta_d^*, E_n) [d\cos\theta_d^* / d \cos\theta_d]$$
$$\times \xi_d(\theta_d, E_n) \xi_\pi(\theta_d^*, E_n) N_n(E_n) dE_n. \tag{7}$$

Here θ_d^* is the c.m. deuteron angle, θ_d is the deuteron angle in the laboratory system, $\sigma(\theta_d^*, E_n)$ is the c.m. differential cross section of reaction (2), $\xi_d(\theta_d, E_n)$ is the curve of spectrometer resolving power, $N_n(E_n)$ is the energy spectrum of the neutron beam (known from reference 11), $\xi_\pi = k_\gamma(1 - \beta^2)/[1 - \beta \cos \Phi(E_n)]^2$ is the efficiency of π^0-meson registration, where Φ is the angle between the telescope axis and the π^0-meson path (laboratory system), β is the π^0-meson velocity (laboratory system) and k_γ is the telescope efficiency for γ rays (see above). All quantities are given in arbitrary units. The function $(1 - \beta^2)/(1 - \beta \cos \Phi)^2$ expresses in relative units the angular distribution of γ rays from the decay of π^0 mesons.

The resolving power curves $\xi_d(\theta_d, E_n)$ are determined from the spectrometer geometry and target dimensions. These curves were first calculated analytically for a parallel incident beam; the results were then integrated numerically over the angles of deuteron entrance into the spectrometer. The calculation took into account the finite dimensions of the target and counters. The resolving power curves obtained in this manner had the shape of trapezoids with rounded corners.

It is impossible to determine exactly the form of the function $\sigma(\theta^*, E_n)$ from measurements performed with a relatively broad neutron spectrum and a detector with constant energy threshold. In the present experiments, in order to overcome this difficulty, the angular distribution of products of reaction (2) and the absolute value of the total cross section were obtained for an average effective value of neutron energy. It was assumed that the angular distribution of reaction products is independent of neutron energy in the energy range

covered by the detector, i.e., that

$$\sigma\,(\theta^*, E_n) = f\,(\theta^*)\,\sigma\,(E_n). \tag{8}$$

Using (8) in (7), we obtain

$$A\,(\theta_d) \sim \int\limits_0^\infty f\,(\theta_d^*)\,\frac{d\cos\theta_d^*}{d\cos\theta_d}\,\xi_d \xi_\pi \sigma\,(E_n)\,N_n\,(E_n)\,dE_n$$

$$= \int\limits_0^\infty N\,(E_n)\,\sigma\,(E_n)\,dE_n. \tag{9}$$

In the second integral $N(E_n)$, the meaning of which is clear from the equation, has the same dimensions as the neutron spectrum, so that it can be called the effective neutron spectrum. This new designation is introduced for simplicity in what follows. Figure 7 shows a neutron beam energy spectrum[11] measured with a magnetic spectrometer and a typical effective neutron spectrum.

Since the integrand contains the still undetermined function $f(\theta_d^*)$ the experimental results were treated by the method of successive approximations. In the first approximation it was assumed that the neutron energy spectrum can be represented by a straight line at the height of its maximum (at 600 Mev). The angular distribution is then easily obtained by means of the simplified equation which follows from (9):

$$f_1\,(\theta_d^*) \sim A\,(\theta_d)\,/\,[d\cos\theta_d^*\,/\,d\cos\theta_d]\,\xi_\pi\,(\theta_d^*). \tag{10}$$

$f_1(\theta_d^*)$ obtained in this manner was already close to its final form. The second approximation was determined from the first approximation by taking into account the neutron-energy dependence of all quantities in (9). Corrections to the first approximation amounted to less than 8% for all π^0-meson angles and were occasioned mainly by the earlier assumption regarding the shape of the spectrum. The calculation could thus be confined to the second approximation for $f(\theta^*)$.

It must be noted that the angular distribution thus obtained depends on the assumed form of the excitation function $\sigma(E_n)$ for the given reaction. For the purpose of determining the sensitivity of
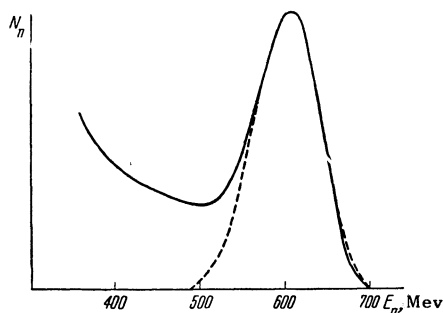
the results to the form of this function the cross sections were calculated for several angles using two extremely different excitation functions: (1) One excitation function describing the cross section for meson production in reactions (1) and (2) at low energies was

$$\sigma \sim 0.14\eta + 1.0\eta^3, \tag{11}$$

where η is the c.m. meson momentum; (2) the other excitation function for reaction (1) with 460 to 660 Mev protons is that given in references 4 to 6.

The calculations showed that the angular distribution is insensitive to the form of $\sigma(E_n)$. For a number of angles there is a variation of less than 5% in the ratio of the cross sections obtained using the two different functions. The second form for the energy dependence of the cross section will be used for the final results given in the present article.

Figure 8 gives the final angular distribution measurements for π^0 mesons from reaction (2). The indicated errors include the following: errors in determining the relative efficiency k_γ ($\sim 5\%$) as well as in measurement of the relative number of protons from reaction (4) at small angles (6%), errors associated with the arangement of the spectrometer counters (1 to 7%), inaccurate determination of relative telescope efficiency (5%), and statistical experimental errors. The solid curve in Fig. 8 was obtained by the method of least squares and represents the expression

$$f\,(\theta^*) = (0.220 \pm 0.022) + \cos^2\theta^*. \tag{12}$$

TOTAL CROSS SECTION MEASUREMENT

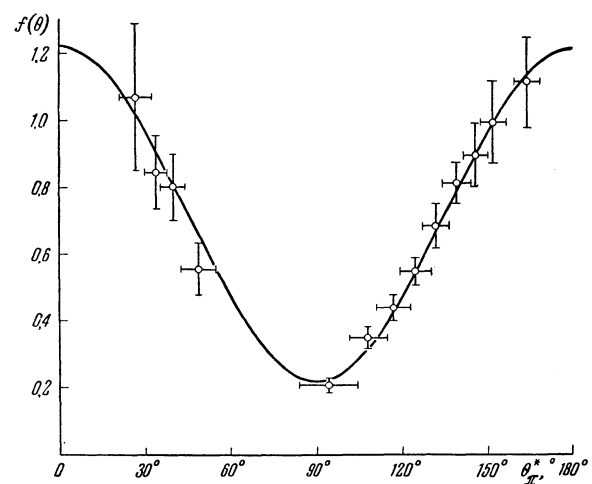Using the known angular distribution $f(\theta^*)$ (in relative units) the total cross section for the

FIG. 7. Solid curve — energy spectrum of neutron beam, broken line — effective neutron spectrum.

FIG. 8. Angular distribution (c.m. system) of π^0 mesons from the reaction $n + p \rightarrow \pi^0 + d$ with 600-Mev Neutrons.

TABLE III

Energy of incident nucleon, Mev	Reaction	Angular distribution	Total cross section 10^{-27} cm²	Reference
580	$p+p \to \pi^+ + d$	$(0.216 \pm 0.033) + \cos^2 \theta^*$	3.10 ± 0.24	[2]
600	$n+p \to \pi^0 + d$	$(0.220 \pm 0.022) + \cos^2 \theta^*$	1.5 ± 0.3	Present experiment
660	$p+p \to \pi^+ + d$	$(0.23 \pm 0.03) + \cos^2 \theta^*$	3.1 ± 0.2	[5]
610	$p+p \to \pi^+ + d$		3.15 ± 0.22	

reaction in question could be obtained by measuring the differential cross section in absolute units for one of the angles. This was accomplished through simultaneous measurement of the counting rate for the given reaction and the counting rate for recoil protons produced in the same target through elastic n-p scattering, the cross section for which is given in reference 12. Recoil protons were registered by one of the γ-ray detectors while excluding the anticoincidence cirucit and the converter. It was thus unnecessary to redetermine the relative efficiency of the telescopes used in the experiment. To permit direct use of the (n-p)-scattering data the proton detector contained an absorber which furnished an energy threshold (E_{th}) identical with that of the detector in reference 12. The proton counting rate was determined at laboratory system angle 60°, since in reference 12 the differential cross section for n-p scattering was determined most exactly at that angle.

If the effective energy is defined as the argument of the excitation function $\sigma(E_n)$ at $\sigma(E_n) = \bar{\sigma}$, where

$$\bar{\sigma} = \frac{\int_0^\infty \sigma(E_n) N(E_n) dE_n}{\int_0^\infty N(E_n) dE_n}, \quad (13)$$

our experiment determines the differential cross section at the effective energy (E_{eff}) to be

$$\frac{d\sigma(\theta_d^*)}{d\Omega} = \frac{d\sigma_{np}}{d\Omega} \frac{\Delta\Omega_p}{\Delta\Omega_d} \frac{A_\pi}{A_p} \frac{\int_{E_{th}}^\infty N_n(E_n) dE_n}{\int_0^\infty N'(E_n) dE_n}, \quad (14)$$

where $d\sigma_{np}/d\Omega$ is the laboratory system elastic (n-p)-scattering cross section; $\Delta\Omega_p$ and $\Delta\Omega_d$ are the solid angles seen by the proton and neutron detectors, respectively; A_π and A_p are the counting rates for π^0 mesons produced in reaction (2) and for recoil protons from elastic n-p collisions; $N_n(E_n)$ is the neutron spectrum; $N'(E_n)$ is the effective neutron spectrum for reaction (2), suitably normalized [unlike the unnormalized $N(E_n)$].

Following the previously-described method,

Eq. (14) was used to determine the absolute cross section for reaction (2) at $\theta_\pi^* = 138°$. In determining the recoil proton flux A_p a correction was introduced for the π^+ mesons produced in n-p collisions. According to reference 12, this correction was 17%.

The differential cross section obtained by means of (14) is entirely independent of the form of the excitation function $\sigma(E_n)$. However, the effective energy to which the cross section refers varies somewhat with $\sigma(E_n)$. Calculations show that the effective energy at $\theta_\pi^* = 138°$ changes from 590 to 605 Mev for the two forms of $\sigma(E_n)$ given in the preceding section. The final value of the total cross section for reaction (2), which is given below, refers to an effective neutron energy of 600 ± 10 Mev.

From the obtained angular distribution $f(\theta^*)$ and the absolute cross section at $\theta_\pi^* = 138°$ the total cross section is given by

$$\sigma_t = (1.5 \pm 0.3) \cdot 10^{-27} \text{ cm}^2$$

The error in this cross section includes in addition to the statistical error of measurement (7.5%) the following: errors in determining the total and differential cross sections for elastic n-p scattering (12 and 6.5% respectively), errors in measuring the absolute efficiency of the γ-ray telescope (10%) and of the magnetic spectrometer (7%), the error in determining the relative efficiency of the telescopes (5%), and the error in extrapolating the angular distribution to large and small angles (2%).

DISCUSSION OF RESULTS

Let us examine our results from the point of view of charge invariance. For this purpose we shall compare our data with the measurements given in the literature for the angular distribution and total cross section for reaction (1) at energies close to 600 Mev. The data are summarized in Table III.

The table shows that the angular distributions of π mesons from reactions (2) and (1) at similar energies are the same with a good degree of accuracy. However, the total cross sections at practically equal energies differ by a factor of 2.

It may be noted here that reference 6 gives a somewhat larger value of the constant in the angular distribution of π^+ mesons from reaction (1) at proton energies of 633 and 660 Mev. However, when the energy dependence of this constant that is given in reference 6 is extrapolated to 600 Mev we obtain a value close to ours for reaction (2). Thus the experimental results obtained for reaction (2) and a comparison with the results for reaction (1) at identical nucleon energy (600 Mev) show that Yang's relation is fulfilled, thus confirming the charge invariance hypothesis for meson-nucleon interactions.

Independently of the existence of charge invariance, the rapid growth of the cross section for reaction (2) with increasing energy and the shape of the angular distribution permit us to infer that at 400 to 600 Mev π^0 mesons are produced principally in the p state. This conclusion is not in conflict with the conservation of isotopic spin. In addition, the fact that it is satisfied for meson-nucleon interactions permits the direct application to reaction (2) of a number of laws known for reaction (1). For instance, we can state that the energy dependence of the total cross section for reaction (2) is of resonant character similar to that which was established for reaction (1) in references 5 and 6. Furthermore, in experiments on the asymmetry of π^+-meson emission in reaction (1), which were recently performed using a polarized proton beam,[13] a d-wave component was detected. This can also be applied to reaction (2).

It is known that for a number of transitions that are accompanied by the emission of π mesons in the d state the angular distribution is characterized by the presence of a term that is proportional to $\cos^4 \theta$.* An attempt to detect this term through the representation of our experimental results by the polynomial $a + \cos^2 \theta* + \cos^4 \theta*$ showed that the coefficient of $\cos^4 \theta*$ is small and is determined with an error which is twice its own magnitude. Similar results for reaction (1) were previously given in reference 5. The authors of reference 13 state that their data are also in agreement with the assumption of small amplitudes for transitions with the emission of π^+ mesons in s and d states compared with the amplitude of the transition $^1D_2 \rightarrow \, ^3S_1p_2$ (in Rosenfeld's notation[1]).

When our results are considered in connection with the recently advanced hypothesis[14] of the existence of a pseudoscalar π_0^0 meson with zero isotopic spin and mass close to that of an ordinary π meson, we cannot exclude the possibility that the former are produced in the reaction $n + p \rightarrow$ $\pi_0^0 + d$. But the data permit us to infer that the given reaction would yield a relatively small number of π_0^0 mesons, if any, compared with the yield of π^0 mesons.* In this connection it must be remembered that the relatively small probability of the production of the hypothetical π_0^0 mesons could result from the resonant character of ordinary π^0-meson production in reaction (2) (with $T = \frac{3}{2}$, $J = \frac{3}{2}$).

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*We do not give a more exact quantitative estimate of the π_0^0-meson yield, which could in principle be obtained by using our data, since any such estimate would require a specific assumption regarding the form of the π_0^0-meson angular distribution.