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Neutral Meson Production in n-p Collisions*

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The angular distribution of neutral pions formed by 400-Mev neutrons in the process $n+p\rightarrow d+\pi^0$ has been measured using an experimental arrangement in which both of the π^0 decay gamma-rays are detected in coincidence with the deuteron. The results can be described in the center-of-mass system by the function $\cos^2\theta+0.2$. The agreement between this distribution and the π^+ distribution of the process $p+p\rightarrow d+\pi^+$, which has been measured by Whitehead and Richman and by Durbin, Loar, and Steinberger, gives evidence in support of the hypothesis of charge independence in meson-nucleon interactions.

I. INTRODUCTION

YANG has observed that a comparison of the reactions

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

and

$$p+p\rightarrow d+\pi^+ \qquad (2)$$

should provide a severe test for the hypothesis of charge independence in meson-nucleon interactions.[1–8]

If we do not assume charge independence then we have no reason to expect any similarity between the angular distributions of the pions produced in these two reactions nor have we reason to expect any simple relationship between the cross sections. But if we do assume conservation of isotopic spin, in accordance with the charge independence hypothesis, and if we assume that the π^0 and π^+ both have isotopic spin one, then the pion angular distributions should be identical and the cross sections should be in the ratio 1:2 for reactions (1) and (2), respectively.

These simple relationships arise because under the assumptions just made the states of the end products of the two reactions must be regarded as identical except for the value of the charge variable. Similarly the initial p-p state is identical with that part of the n-p state which can contribute to the reaction, again except for the value of the charge. The angular distributions must, then, be the same since in the charge independence hypothesis we assume that meson-nucleon interactions are invariant under rotations in isotopic spin space. The 1:2 ratio of the cross sections results from the fact that the $n+p$ system is in a mixed state containing two equal parts with isotopic spins 0 and 1, only the latter part of which has the required isotopic spin, whereas the $p+p$ system is in a pure state of isotopic spin 1, all of which can contribute.

A strong angular dependence of the π^+ distribution has been observed by Whitehead and Richman[9] and by Durbin, Loar, and Steinberger[10] in their extensive experiments on reaction (2) and its inverse. The form of the distribution, which is nearly independent of energy, is well described by the function $\cos^2\theta+0.2$. The striking nature of this distribution makes the comparison of the π^0 and π^+ angular distributions a particularly severe test of charge independence.

In order to make this comparison the author is now investigating reaction (1) at a neutron energy of 400 Mev. By doing the experiment at this energy it is possible to compare the results directly with the highest energy measurements of Durbin, Loar, and Steinberger, since in each case the pion energy in the center-of-mass system is 53 Mev.

II. EXPERIMENTAL ARRANGEMENT

The important feature of the experiment is that the deuteron and both of the π^0 decay gamma-rays are detected in coincidence. This system makes it possible to distinguish between bound deuterons and free protons in the final system and it allows the selection of events caused by neutrons in a narrow energy range.

The experiment is only possible because of the large flux of neutrons well above the reaction threshold which is available at the University of Chicago synchrocyclotron. The flux density of the collimated beam in the experimental area is about 5×10^5 neutrons cm^{-2} sec^{-1}. The spectrum extends from about 300 to 450 Mev with a peak a little below 400 Mev.

The neutral mesons are detected by means of their two decay gamma-rays in a manner similar to that used by Panofsky, Steinberger, and Steller[11] in studying π^0 production by photons. Each photon detector consists of a 0.63-cm thick lead plate to convert the γ-rays to electron pairs followed by a thin scintillator and a Čerenkov counter to count the electrons. The Čerenkov

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[1] This test, originally suggested by C. N. Yang, unpublished, is a special case of a relationship given by Brueckner and Watson [Phys. Rev. 83, 1 (1951)]. This, and further tests, are discussed in references 2 to 8.

[2] R. L. Garwin, Phys. Rev. **85**, 1045 (1952).

[3] A. M. L. Messiah, Phys. Rev. **86**, 430 (1952).

[4] M. Ruderman, Phys. Rev. **87**, 383 (1952).

[5] J. M. Luttinger, Phys. Rev. **86**, 571 (1952).

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[8] K. M. Watson, Phys. Rev. **85**, 852 (1952).

[9] M. N. Whitehead and C. Richman, Phys. Rev. **83**, 855 (1951).

[10] Durbin, Loar, and Steinberger, Phys. Rev. **84**, 581 (1951).

[11] Panofsky, Steinberger, and Steller, Phys. Rev. **86**, 180 (1952).

counter,[12] which is filled with water, has the advantage of excluding the large background of heavy charged particles. The thin scintillator prevents counts due to photons which are converted in the relatively thick Čerenkov counter. Using this arrangement the ratio of the coincidence rates with and without the lead converters is about 100 to 1. Since good voltage plateaus are obtained, it is likely that the efficiency is nearly constant throughout the energy range of the experiment. The solid angle subtended by the photon detector is limited by the scintillation counter which is 5 cm in diameter and is placed 14 cm from the target.

The deuterons are detected by two scintillation counters which are separated a few centimeters to allow insertion of absorbers for range measurements. The deuteron detector is placed in the plane which contains the neutron beam and the bisector of the angle between the photon detectors which is approximately the direction of the π^0. The deuteron, neutron, and the pion must, therefore, move in the same plane in order for a sixfold coincidence[13] to occur between the two counters of the deuteron detector and the four counters of the photon detectors. The requirement of coplanarity greatly reduces the chance of detecting pions formed within the carbon nuclei of the polyethylene and graphite targets because of the lateral component of momentum of the bound carbon nucleons. Accordingly the sixfold coincidence rate drops to $\frac{1}{5}$ of its former value when the polyethylene target is replaced by a graphite target of the same carbon content whereas the fourfold coincidence rate between the two photon detectors alone drops only to $\frac{2}{3}$. Thus, besides providing for a more positive identification of the reaction, the inclusion of the deuteron detector greatly reduces the error in determining the net count due to collisions with free protons.

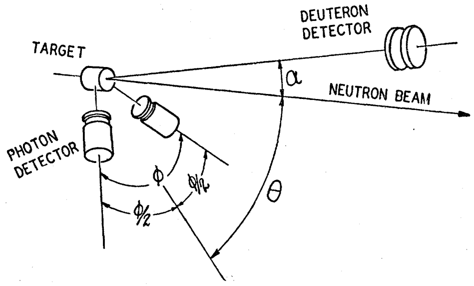

FIG. 1. Arrangement of detectors.

Counting rates are obtained in terms of a BF$_3$ monitor. The ratio of coincidence to monitor counts remains constant as the beam intensity is varied and measurements can be successfully repeated. Hence the monitor is believed to be reliable.

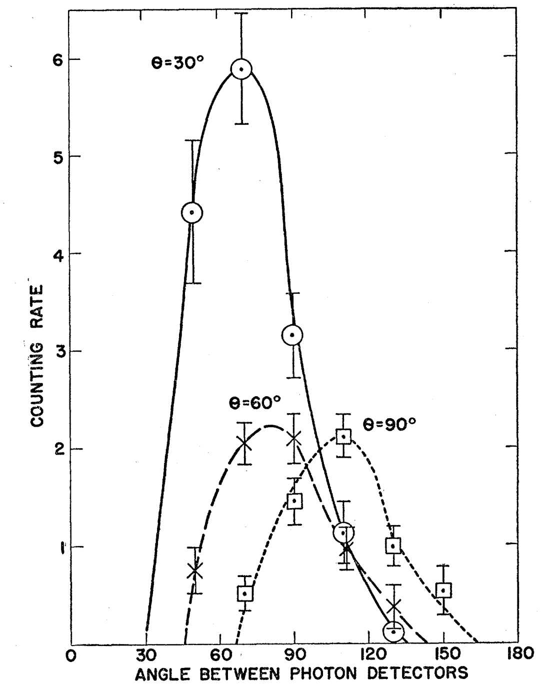

FIG. 2. Relative counting rates as a function of the photon correlation angle ϕ for three values of the angle θ. Arbitrary curves are drawn to aid in distinguishing the three sets of points.

III. ANGULAR CORRELATIONS

If we assume, as is shown below, that the pion is formed in a two body ($d+\pi^0$) system and not in a three body ($n+p+\pi^0$) system then we expect a unique relationship between θ and α (the directions of the π^0 and deuteron) for a given neutron energy (see Fig. 1). The angle ϕ between the photons in the laboratory system depends not only on the velocity of the pion but also on the angle between the photon pair and the direction of motion of the pion measured in the π^0 frame. However, the distribution in ϕ, which has been given by Panofsky *et al.*,[11] favors the minimum laboratory angle $\phi_c=2\sin^{-1}\gamma^{-1}$, $(\gamma=E/E_0)$ so strongly that ϕ is also almost uniquely determined by θ and the neutron energy.

IV. PRELIMINARY EXPERIMENTS

As the angle between the photon counters is varied, counting rates are obtained corresponding to different parts of the neutron energy spectrum. Figure 2 shows the variation in counting rate as a function of ϕ for three different values of the pion angle θ. It will be seen that the peaks of these curves shift to the right as the angle θ is increased. This is to be expected since the meson energy decreases as θ increases. The locations and widths of the peaks agree well with predictions based on the known neutron energy distribution and the assumption of a two-body system. A three-body system should

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[12] The Čerenkov counter construction is described by the author in a laboratory and shop note submitted to *The Review of Scientific Instruments*.

[13] The high speed, multi-channel coincidence analyzer which was used was designed by R. L. Garwin. A description by Garwin will appear in *The Review of Scientific Instruments*.

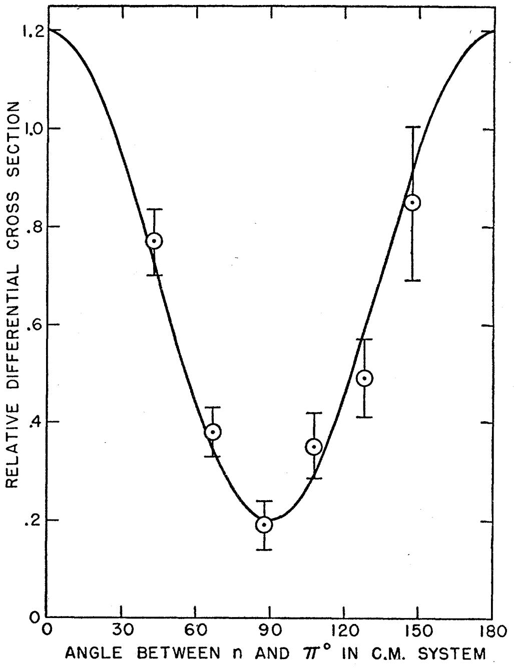

FIG. 3. Angular distribution of neutral mesons formed in *n-p* collisions. The function $\cos^2\theta+0.2$ corresponding to π^+ production in *p-p* collisions is drawn for comparison.

give a lower and more diffuse π^0 spectrum. By integration of these curves with appropriate geometrical corrections, one can obtain the relative flux of pions at the various angles θ due to the whole neutron beam. This has been done and the results agree with those given below: however, the transformation to the center-of-mass system is not unique if the whole neutron spectrum is included. The principal value of the curves in Fig. 2 is not to give the pion angular distribution but to confirm the assumption we have made that the pion is usually formed in a two-body ($d+\pi^0$) system.

The assumption that the neutron and proton of the final system are usually bound is also confirmed by range measurements. Since, at this neutron energy, the velocity of either a deuteron or an unbound proton will be primarily due to the motion of the center of mass, the deuteron will have about twice the momentum of the proton and the two charged particles can easily be distinguished by their range. Still further evidence for the two-body system is the disappearance of coincidence counts when the deuteron detector is displaced from the plane of the π^0 and neutron beam. A measurement of the fraction of unbound protons is in progress.

V. MEASUREMENT OF π^0 DISTRIBUTION

The π^0 angular distribution has been measured by choosing values of ϕ and α at each of six angles θ to correspond to events caused by neutrons near the peak of the neutron distribution. The value of ϕ which was used was the median angle ϕ_m which is a few degrees larger than the minimum angle ϕ_c. The energy resolution, which is determined by the range in ϕ covered by the photon detectors, is good enough to establish a neutron energy of 400±20 Mev. The corresponding energy of the pion in the center-of-mass system is 53±8 Mev. The range of neutron energy ΔK which is accepted depends, somewhat, on the value of ϕ. Hence a factor $d\phi/dK$ must be included in calculating relative cross sections from the counting rates. This is easily calculated from the kinematics of the reaction if we assume that ϕ is uniquely related to the meson velocity by the expression for the median angle $\phi_m=2\sin^{-1}[2/(3\gamma^2+1)^{\frac{1}{2}}]$. (Nearly the same result is obtained if we use the relationship for the minimum angle $\phi_c=2\sin^{-1}\gamma^{-1}$.) The probability that the two photons shall be in a plane which contains the two photon detectors also depends on ϕ. This introduces a factor $\sin\phi$ in calculating the cross sections. Of course, a solid angle transformation is also included in order to express the results in the center-of-mass system. These factors are shown in Table I with the results. In Fig. 3 the angular distribution measurements are shown together with the function $\cos^2\theta+0.2$.

TABLE I. Results.[a]

Angular settings			Counting rate	Correction factors			Relative differential cross-sections	
θ_{lab}	α	ϕ		$d\phi_m/dk$[b]	$\sin\phi_m$	$d\Omega_{\text{lab}}/d\Omega_{\text{c.m.}}$		$\theta_{\text{c.m.}}$
25°	5.3°	74°	4.46±0.42	0.485	0.961	0.369	7.7±0.7	43°
40°	7.4°	81°	1.77±0.24	0.500	0.988	0.432	3.8±0.5	67°
55°	8.5°	90°	0.67±0.16	0.520	1.000	0.552	1.9±0.5	88°
70°	8.4°	101°	0.85±0.16	0.540	0.982	0.767	3.5±0.7	108°
90°	7.5°	115°	0.78±0.12	0.575	0.906	1.214	4.9±0.8	128°
115°	5.4°	129°	0.79±0.15	0.625	0.777	2.210	8.5±1.6	147°

[a] Neutron energy =400 Mev.
[b] Degrees in ϕ per Mev neutron energy.

VI. CONCLUSIONS

The experiments on the reaction $n+p\rightarrow d+\pi^0$ may be summarized by the following observations:

(a) The reaction does occur and its cross section is of the same order of magnitude as that of the reaction $p+p\rightarrow d+\pi^+$.

(b) The measurements of the π^0 angular distribution can be fit by the function $\cos^2\theta+0.2$.

(c) The agreement between this distribution and the π^+ distribution of the reaction $p+p\rightarrow d+\pi^+$ gives evidence in support of the hypothesis of charge independence.

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