PHYSICAL REVIEW VOLUME 100, NUMBER 5 DECEMBER 1, 1955

Reaction $\pi^- + d \rightarrow 2n + \pi^0$; Parity of the Neutral Meson*

W. CHINOWSKY† AND J. STEINBERGER
Columbia University, New York, New York

(Received August 31, 1955)

The branching ratio between the capture reactions $\pi^- + d \rightarrow 2n + \pi^0$ and $\pi^- + d \rightarrow 2n + \gamma$ has been determined to be $<0.1\%$. Comparison with the previously measured branching ratio between the corresponding processes in hydrogen provides strong evidence for pseudoscalar π^0 parity.

I. INTRODUCTION

THE experimental results of Panofsky, Aamodt, and Hadley[1] have shown that the dominant reactions of π^- mesons stopped in deuterium are:

$$\pi^- + d \rightarrow 2n, \tag{1}$$

$$\pi^- + d \rightarrow 2n + \gamma, \tag{2}$$

with 70% of the captures proceeding through reaction (1). The existence of this process, plus the known value of the meson spin of zero[2] establishes that the negative pion is pseudoscalar. The rate for the charge-exchange capture reaction,

$$\pi^- + d \rightarrow 2n + \pi^0, \tag{3}$$

compared to the rate of the corresponding reaction in hydrogen, can provide information on the parity of the neutral pion. If the π^- and π^0 have the same parity, angular momentum and parity conservation and the Pauli principle require that the two neutrons emitted in reaction (3) be in a ^3P state and the π^0 be in a P state relative to the center of mass of the two neutrons. Opposite parity for the negative and neutral mesons would permit a ^1S two-neutron state. Since the total available kinetic energy is only ~ 1 Mev and the overlap of P and S states is small, the reaction is highly forbidden if the π^- and π^0 have the same parity. However, from considerations of phase space alone the π^0/γ branching ratio is expected to be only $\sim 5\%$ of that in hydrogen, the latter measured by Panofsky *et al.* to be 0.94 ± 0.20. The Panofsky result for the branching ratio in deuterium,

$$\frac{R(\pi^- + d \rightarrow 2n + \pi^0)}{R(\pi^- + d \rightarrow 2n + \gamma)} = -0.026 \pm 0.073,$$

is not then of sufficient accuracy to decide whether a parity selection rule is required to explain the decreased charge-exchange absorption rate in deuterium.

To determine more precisely the relative rate of this reaction, we have performed an experiment to detect the two γ rays from the decay of the neutral mesons in coincidence with incident negative mesons, some of which come to rest in a liquid deuterium target. The results indicate that the process is highly forbidden and give evidence for pseudoscalar parity for the neutral meson.

This result is of course implicit in any charge-independent theory of the meson-nucleon interaction. Since charge independence has now a large and convincing experimental basis, this conclusion about the relative parity of charged and neutral pions is therefore not new, but only serves to strengthen the already existing evidence.

II. EXPERIMENTAL PROCEDURE

The arrangement used to detect the π^0-decay γ rays is shown in Fig. 1. Negative mesons produced at an internal target of the Columbia University 380-Mev Cyclotron are collimated in a channel of the 8-ft iron shielding wall, further analyzed in momentum by a

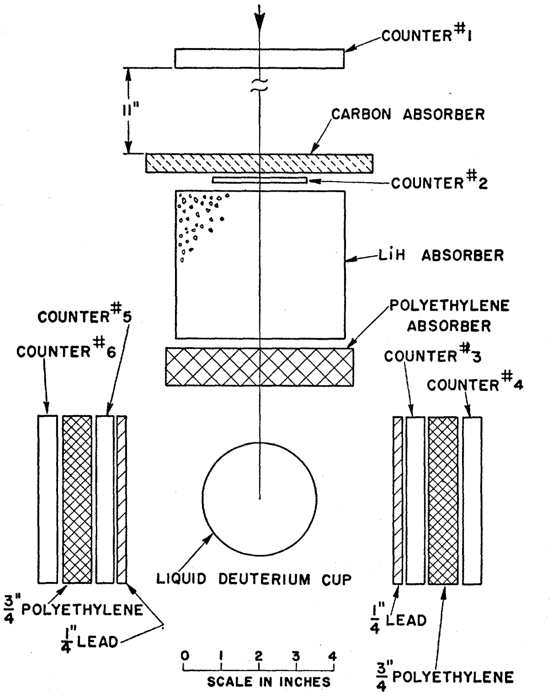

FIG. 1. Experimental arrangement to detect γ rays from decay of the π^0 produced in the reaction $\pi^- + d \rightarrow 2n + \pi^0$ and single γ rays from radiative capture.

* This research was supported by the Joint Program of the U. S. Atomic Energy Commission and the Office of Naval Research.

† Now at Brookhaven National Laboratory, Upton, Long Island, New York.

[1] Panofsky, Aamodt, and Hadley, Phys. Rev. 81, 565 (1951).

[2] Durbin, Loar, and Steinberger, Phys. Rev. 83, 646 (1951); Clark, Roberts, and Wilson, Phys. Rev. 83, 649 (1951).

double-focusing magnet and the beam-defining counters No. 1 and No. 2. Counter No. 1 is a liquid scintillator $4\frac{1}{2}$ inches in diameter and $\frac{5}{8}$ inch thick; counter No. 2 is a stilbene crystal $2\frac{1}{4}$ inches horizontally by $2\frac{3}{4}$ inches vertically by $\frac{1}{8}$ inch thick. The incident beam is degraded in energy in absorbers of 2 g/cm^2 carbon, 5 g/cm^2 LiH and 2.7 g/cm^2 polyethylene. The total absorber thickness is chosen to maximize the meson flux which stops in the deuterium. The liquid deuterium target cup is a vertical cylinder, of 0.004 inch thick stainless steel, 3.1 inches in diameter and $4\frac{1}{2}$ inches high, with $3\frac{3}{4}$ inches vertically exposed by the thin wall of the vacuum chamber. Details of the target system have been given elsewhere.[3,4]

Counters 3, 4, 5, and 6 are plastic scintillators $4\frac{1}{2}$ inches in diameter and $\frac{1}{2}$ inch thick. The two telescopes 3–4 and 5–6, each preceded by a converter of $\sim$1 radiation length, are γ-ray detectors with an efficiency of $\sim$30% for 70-Mev γ rays. The four counters have a common axis passing through the center of the deuterium cylinder, with counters No. 4 and No. 6 at $5\frac{7}{8}$ inches from the target cup center. The two counters of each telescope are separated by $\frac{3}{4}$ inch thick polyethylene absorbers. The electronics is arranged to record coincidences between signals from 1–2, 3–4, and 5–6. These are then further mixed to yield coincidences 1234 and 123456. The system is insensitive to low-energy charged particles. In particular, charged secondaries created by neutrons from the three capture reactions are of insufficient energy to traverse the polyethylene.

The quadruple events 1234 are a measure of the single γ rate, primarily from the radiative capture reaction. The sextuple events 123456 are a measure of the γ-γ coincidence rate, primarily due to the π^0 decays. All rates are measured with the deuterium target alternately full and empty to check the origin of the events, and with the $\frac{1}{4}$-inch lead converters replaced by $\frac{3}{8}$-inch aluminum pieces to check the identification as γ rays.

III. EXPERIMENTAL RESULTS

Figure 2 shows the dependence of the quadruple rate 1234 on the amount of absorber in the incident beam. The absorber thickness chosen for the remainder of the experiment is 9.7 g/cm^2 carbon equivalent. This maximizes the number of pions which come to rest in the target.

The results of the search for π^0-decay γ rays are shown

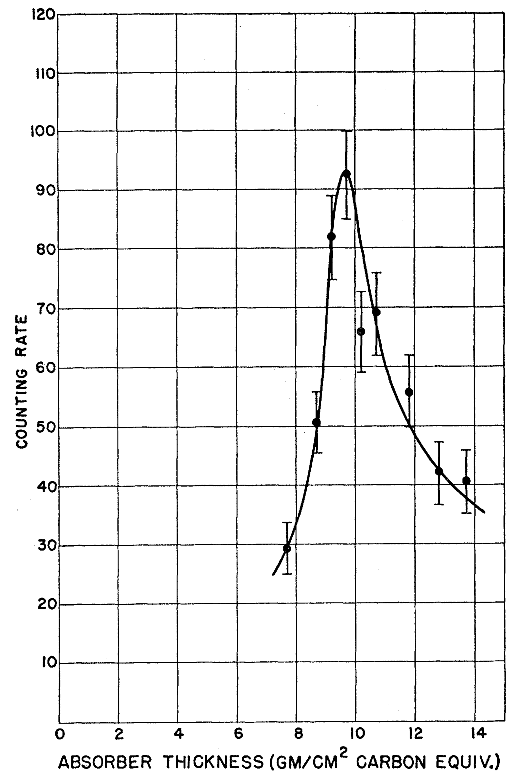

FIG. 2. Variation of single γ-ray counting rate with thickness of absorber in the incident π^- beam.

in Table I. Rates with target filled and aluminum converter were approximately the same as the rates with lead converter and without deuterium in the target. We therefore take the net rate, (target full−target empty), with lead converter, as that due to γ-ray pairs from deuterium. On the average, the incident beam intensity as measured in the 1–2 telescope was 2×10^7 counts/hr. The sixfold coincidence rate was $\sim$8 counts per hour with deuterium in the target and the empty-target rate approximately one-fourth this value. A total of 27 sixfold coincidences was recorded with the cup filled. This corresponds to a net rate of 0.36 ± 0.11 per 10^6 monitor counts.

As a check on the identification of the events with π^0 decay γ rays, the over-all coincidence rate was measured with the two detecting telescopes subtending an angle of 140° at the target. With deuterium in the target, the rate decreased to 0.13 ± 0.07 per 10^6 monitor counts. This indicates that the particles observed in coincidence have correlation angles near 180°.

TABLE I. γ-γ coincidence and single γ-ray rates, due to the processes $\pi^-+d\rightarrow2n+\pi^0$, and $\pi^-+d\rightarrow2n+\gamma$. Rates are per 10^6 incident mesons as measured in 1–2 coincidence.

Converter	Counts with D_2		Counts without D_2		Net due to D_2	
	1234	123456	1234	123456	1234	123456
$\frac{1}{4}$ in. Pb	759 ± 4	0.48 ± 0.09	271 ± 3	0.12 ± 0.06	488 ± 5	0.36 ± 0.11
$\frac{3}{8}$ in. Al	308 ± 3	0.07 ± 0.05				

[3] Bodansky, Sachs, and Steinberger, Phys. Rev. **93**, 1367 (1954).
[4] W. Chinowsky and J. Steinberger, Phys. Rev. **95**, 1561 (1954).

IV. CALCULATION OF THE BRANCHING RATIO

The branching ratio between neutral meson and γ-ray emission,

$$R=\frac{\pi^-+d\rightarrow2n+\pi^0}{\pi^-+d\rightarrow2n+\gamma},$$

is calculated from the expression

$$R=\frac{\mathrm{CR}_{\gamma\gamma}}{\mathrm{CR}_{\gamma}}\frac{\epsilon_{\gamma}}{\epsilon_{\gamma\gamma}^{2}}\frac{G_{\gamma}}{G_{\mathrm{D}}}-\frac{f_{\pi^0\mathrm{H}}}{f_{\gamma\mathrm{D}}}\frac{G_{\mathrm{H}}}{G_{\mathrm{D}}}N_{\mathrm{H}},$$

where

$\mathrm{CR}_{\gamma\gamma}$ = 123456 coincidence counting rate,
CR_{γ} = 1234 single γ-ray counting rate,
ϵ_{γ} = efficiency for detecting, in the 3–4 telescope, γ rays from the reaction $\pi^-+d\rightarrow 2n+\gamma$,
$\epsilon_{\gamma\gamma}$ = efficiency for detecting, in 3–4 and 5–6, the decay γ-rays of the π^0 produced in the reaction $\pi^-+d\rightarrow 2n+\pi^0$,
N_{H} = fractional hydrogen impurity in the deuterium (a small hydrogen impurity contributes to the γ-γ rate via γ rays from the decay of the neutral meson produced in the reaction $\pi^-+p\rightarrow n+\pi^0$),
$f_{\pi^0\mathrm{H}}$ = fractional rate for the charge-exchange absorp- process in hydrogen,
$f_{\gamma\mathrm{D}}$ = fractional rate for the radiative capture reaction in deuterium,
G_{γ} = probability that single γ rays lie within the solid angle defined by counter No. 4; $G_{\gamma}=\Omega/4\pi$;
G_{D} = geometrical factor giving the average probability that a π^0 created within the deuterium cylinder will decay with γ rays emitted in such direction that one traverses the 3–4 telescope, the other the 5–6 telescope,
G_{H} = geometrical factor for decay γ rays of the neutral mesons produced in hydrogen.

An accurate calculation of the γ-ray detection efficiency is not practical because of the complications of multiple processes and scattering of the conversion electrons in the lead foil. Instead we use the results of Cocconi and Silverman,[5] who measured the efficiency directly, using a similar geometry. They find the energy dependence can be presented by

$$\epsilon=0.47[1-e^{-(E-25)/40}],$$

with E the γ-ray energy in Mev. The spectrum of γ rays from the process $\pi^-+d\rightarrow 2n+\gamma$ is sharply peaked at 129 Mev.[6] The spectrum of γ-ray energies from the maximum-energy π^0 produced in the charge-exchange reaction is flat between the limits 60 Mev and 76 Mev. The expression above then gives, for average detection efficiency in each distribution, $\epsilon_{\gamma}=0.44$ and $\epsilon_{\gamma\gamma}=0.31$.

A mass spectrograph analysis of samples of deuterium removed from the deuterium gas holder immediately after the run gave the fractional hydrogen impurity $N_{\mathrm{H}}=0.00523$.[7] The fractional rates measured by Panofsky *et al.* are $f_{\pi^0\mathrm{H}}=0.49\pm0.13$, $f_{\gamma\mathrm{D}}=0.29\pm0.04$.

The factors G_{H} and G_{D} are determined from the geometry of the detection system and the angular correlation of the π^0 decay γ rays. Since it is expected that the energy distribution of the neutral pions produced in the reaction $\pi^-+d\rightarrow 2n+\pi^0$ will be peaked near the maximum, because of the correlation in direction of the two neutrons, we consider only the γ-ray angular correlation for neutral pions with this energy, (velocity/c) $=\beta=0.11$. Because of the symmetry of the experimental geometry, we need consider only γ rays emerging from that $\frac{1}{8}$ of the cup volume included between two perpendicular planes through the axis of the deuterium cylinder and a plane perpendicular to these bisecting the axis. Further, let this volume be compressed to a single point, $x=0.62$ inch, $y=0.94$ inch, $z=0.62$ inch, where the y-axis is chosen along the cup axis and the origin of coordinates at the center of the cup. Let a pair of γ rays with correlation angle between ϕ and $\phi+d\phi$ be emitted from this point, one intersecting counter No. 4 in $dx'dy'$. The other γ ray will lie on the surface of a cone of half-angle $\pi-\phi$; the intersection of this cone and the plane of counter No. 6 is approximated by the arc of a circle of length $l(x',y',\phi)$. Let

$$N(\phi)\sin\phi d\phi=(1-\beta^2)^{\frac{1}{2}}\sin\phi d\phi/ (1-\cos\phi)^{\frac{3}{2}}\beta[(1-\cos\phi)/(1-\beta^2)-2]^{\frac{1}{2}}$$

be the probabilities that the π^0-decay γ rays have correlation angle between ϕ and $\phi+d\phi$. Then the quantities G_{H} and G_{D} are

$$G_{\mathrm{H,D}}=\int N_{\mathrm{H,D}}(\phi)\sin\phi d\phi\int\int\frac{dx'dy'}{2\pi R'^2}\frac{z'}{R'}\frac{l(x',y',\phi)}{2\pi R''\sin\phi}.$$

Here R' is the distance from x, y, z to x', y', z' on counter No. 4 and R'' the distance from x, y, z to the point x'', y'', z'', on counter No. 6 intersected by the projection of the line joining z, y, z and x', y', z'. The integral over x', y' is replaced by a sum over finite regions in x', y' space, the arc lengths are summed on a map measure fixed to a compass and the ϕ integral is evaluated numerically, yielding $G_{\mathrm{H}}=0.024$ and $G_{\mathrm{D}}=0.028$. With these values we find the branching ratio

$$R=\frac{\pi^-+d\rightarrow 2n+\pi^0}{\pi^-+d\rightarrow 2n+\gamma}=-0.0034\pm0.0043.$$

Included in the error are the statistical uncertainties in the counting rates and the Panofsky fractional rates, and estimates of errors $\pm15\%$ in ϵ_{γ} and $\epsilon_{\gamma\gamma}$, $\pm10\%$ in Ω and $\pm25\%$ in G_{H} and G_{D}.

V. DISCUSSION AND INTERPRETATION

The charge exchange absorption rate in deuterium is decreased relative to that in hydrogen because of the

[5] G. Cocconi and A. Silverman, Phys. Rev. **88**, 1236 (1952).
[6] R. H. Phillips and K. M. Crowe, Phys. Rev. **96**, 484 (1954).
[7] We wish to thank Mr. Harvey Goodspeed and the members of the staff of the Argonne National Laboratory who kindly performed the deuterium analyses.

decreased phase space available to the neutral meson. Only 1 Mev of kinetic energy of the reaction products is available. Consider then the reaction $\pi^- + d \rightarrow 2n + \pi^0$ in which the two neutrons are emitted in a ^1S-state and neglect any dependence of the matrix element on angle or π^0 momentum. The matrix element will be proportional to the n-n wave function evaluated for zero separation of the two neutrons. The transition rate per unit π^0 energy can then be written[8]

$$\frac{dT_{\pi^0\mathrm{D}}}{dE_{\pi^0}} \cong \mathrm{const} \times \Psi_{nn}{}^2(0) \times \frac{dN_{1S}}{dE_{\pi^0}} P^2{}_{\pi^0\mathrm{H}} \frac{dP_{\pi^0}}{dE},$$

where dN_{1S}/dE_{π^0} is the number of ^1S states of the two-neutron system per unit π^0 energy. Assuming a square well interaction of depth U and range r_0, the transition rate is

$$\frac{dT_{\pi^0\mathrm{D}}}{dE_{\pi^0}} = C_{\pi^0\mathrm{D}} \mu M^{\frac{3}{2}} \frac{(2\mu E_{\pi^0})^{\frac{1}{2}} (T_0 - E_{\pi^0}\mu/\mu^*)^{\frac{1}{2}} - M(T_0 - E_{\pi^0}\mu/\mu^* + U)}{M(T_0 - E_{\pi^0}\mu/\mu^*) + MU \cos^2\{[M(T_0 - E_{\pi^0}\mu/\mu^* + U)]^{\frac{1}{2}} r_0/\hbar c\}},$$

where T_0 is the available kinetic energy, M and μ the neutron and π^0 masses, respectively, and $\mu^* = 2M\mu/(2M+\mu)$ the reduced mass. Similar consideration for the reaction $\pi^- + d \rightarrow 2n + \gamma$ yields

$$\frac{dT_{\gamma\mathrm{D}}}{dE_\gamma} = C_{\gamma\mathrm{D}} 2M^{\frac{3}{2}} \frac{[T_\gamma - E_\gamma(1 + E_\gamma/4M)]^{\frac{1}{2}} E_\gamma{}^2 M [T_\gamma - E_\gamma(1 + E_\gamma/4M) + U]}{M[T_\gamma - E_\gamma(1 + E_\gamma/4M)] + MU \cos^2\{[M(T_\gamma - E_\gamma(1 + E_\gamma/4M) + U)]^{\frac{1}{2}} r_0/\hbar c\}}.$$

Here the available kinetic energy $T_\gamma = 136$ Mev. Taking $U = 13$ Mev and $r_0 = 2.6 \times 10^{-13}$ cm, corresponding to the values deduced from low-energy p-p scattering,[9] and numerically integrating the two energy distributions, we find $T_{\pi^0\mathrm{D}}/T_{\gamma\mathrm{D}} \cong C_{\pi^0\mathrm{D}}/C_{\gamma\mathrm{D}} \times 0.004$. The transition rates for π^- absorption in hydrogen, leading to π^0 or γ-ray emission are

$$T_{\pi^0\mathrm{H}} = C_{\pi^0\mathrm{H}} P^2{}_{\pi^0\mathrm{H}} \frac{dP_{\pi^0\mathrm{H}}}{dE},$$

$$T_{\gamma\mathrm{H}} = C_{\gamma\mathrm{H}} 2P^2{}_{\gamma\mathrm{H}} \frac{dP_{\gamma\mathrm{H}}}{dE},$$

where $P_{\pi^0\mathrm{H}}$, $P_{\gamma\mathrm{H}}$ are the neutral meson and γ-ray momenta, respectively. The constants will depend on the specific form of the interactions involved. In the ratio $(T_{\pi^0\mathrm{D}}/T_{\gamma\mathrm{D}})(T_{\pi^0\mathrm{H}}/T_{\gamma\mathrm{H}})$ however, the constants should approximately cancel. The branching ratio between π^0 and γ-ray emission from deuterium is then

$$\frac{\pi^- + d \rightarrow 2n + \pi^0}{\pi^- + d \rightarrow 2n + \gamma} \cong 0.004 \left[P^2{}_{\pi^0\mathrm{H}} \frac{dP_{\pi^0\mathrm{H}}}{dE} \Big/ 2P^2{}_{\gamma\mathrm{H}} \frac{dP_{\gamma\mathrm{H}}}{dE} \right] \cong \frac{0.004}{0.1} = 0.04,$$

on the basis of phase space considerations only.

The branching ratio calculated from such phase space considerations is strongly dependent on the $\pi^- - \pi^0$ mass difference. The error, $\pm 7\%$, in the mass difference,[10] leads to an uncertainty of $\pm 40\%$ in the calculated rate for the reaction $\pi^- + d \rightarrow 2n + \pi^0$, $\pm 5\%$ in the rate for $\pi^- + p \rightarrow n + \pi^0$ and therefore $\pm 35\%$ in the ratio in deuterium. Then, with an error $\pm 20\%$ in the measured value of the branching ratio in hydrogen, the total error in the deuterium branching ratio, due to the above uncertainties, is $\pm 40\%$.

In the absence of any parity selection rule, the branching ratio between π^0 and γ-ray emission would therefore be of the order of 5%. However, if the neutral pion is pseudoscalar, the two neutrons emitted in the charge exchange reaction are in P-states and the matrix element is greatly reduced. Meson theoretic calculations by Tamor[11] show that the rate for emission of a pseudoscalar π^0 is reduced by a factor ~ 10 relative to the rate for scalar π^0. The result obtained here, $(\pi^- + d \rightarrow 2n + \pi^0)/(\pi^- + d \rightarrow 2n + \gamma) \lesssim 0.1\%$, then is strong evidence for the odd parity of the neutral pion.

[8] See discussion of the reaction $p + p \rightarrow \pi^+ + n + p$ in E. Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951).

[9] J. D. Jackson and J. M. Blatt, Revs. Modern Phys. **22**, 77 (1950).

[10] W. Chinowsky and J. Steinberger, Phys. Rev. **93**, 586 (1954).

[11] S. Tamor, Phys. Rev. **82**, 38 (1951).