New Limit for Isotopic Spin Conservation in Strong Interactions from an Experimental Limit on $\sigma(d+d \rightarrow He^4+\pi^0)$†

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(Received 3 December 1962)

The strong reaction $d+d \rightarrow He^4+\pi^0$, which is forbidden by isotopic spin conservation, has been looked for with a 460-MeV deuteron beam from the Berkeley 184-in. cyclotron. Preliminary results were reported elsewhere. A more comprehensive analysis of this same experiment has recently been completed. From this analysis, an upper limit for the differential cross section for the reaction in the c.m. system at about $\Theta_{c.m.}=90$ deg is found to be $(0.097\pm0.027)\times10^{-33}$ cm^2/sr. The data are consistent with no π^0 production. From a comparison of this upper limit with the theoretical prediction of the cross section for this reaction if isotopic spin need not be conserved, we conclude that isotopic spin is at least $(99.74\pm0.08)\%$ conserved in this strong interaction.

I. INTRODUCTION

In recent years experiments have been performed to test the validity of the hypothesis of charge independence or isotopic spin conservation in strong interactions.[1] One such method is to study experimentally the relationships among two or more cross sections that can be theoretically predicted on the assumption that isotopic spin is conserved. For example, the ratio of the cross section $\sigma(p+d \rightarrow H^3+\pi^+)$ to $\sigma(p+p \rightarrow He^3+\pi^0)$ is predicted to be 2.0 on the basis of isotopic spin conservation. For these reactions there are, however, electromagnetic effects that tend to raise the expected ratio.[2] Experimental measurements of these cross sections[3] agree with the corrected theory to within 3% with a 6% error.

A more sensitive test of this conservation law is the investigation of a single reaction,

$$d+d \rightarrow He^4+\pi^0. \tag{1}$$

This π^0 reaction, which is a strong interaction, is forbidden by isotopic spin conservation, since the isotopic spin of each of the heavy particles is zero, while that of the ordinary π^0 (member of the charge multiplet π^+, π^0, π^-) is one; therefore, the reaction requires a change in isotopic spin of +1. A measurement of the cross section of reaction (1) would, therefore, indicate directly any possible deviations from isotopic spin conservation. By comparing this experimentally measured cross section with the theoretical cross section computed on the assumption that isotopic spin need not be conserved,[4] one can determine, quantitatively, the degree of nonconservation of isotopic spin. That is, the ratio of these two numbers is a measure of the probability of nonconservation of isotopic spin.

Previous experiments on the π^0 reaction (1) gave upper limits for the total cross section of 70×10^{-33} cm^2 at 460 MeV,[5] and 20×10^{-33} cm^2 at 400 MeV.[6] Preliminary results of our investigation of this reaction at 460 MeV have already been reported.[7] New results based on a more comprehensive analysis of the data of this same experiment are presented here. The electromagnetic process

$$d+d \rightarrow He^4+\gamma, \tag{2}$$

at 460-MeV deuteron energy is also re-examined.

II. EXPERIMENTAL METHOD

The two-body final state of the π^0 reaction (1) was studied by observing α particles produced from a gas deuterium target bombarded by a beam of deuterons of 460-MeV (lab) kinetic energy from the Berkeley 184-in. cyclotron. The kinematics for the π^0 and γ reactions (1) and (2) for incident deuterons of 460-MeV (lab) kinetic energy are shown in Fig. 1. The experimental arrangement is shown in Fig. 2, and details are given in Table I. Two slits of lead (not indicated in Fig. 2) were placed between the target and the first quadrupole in order to (a) fix the angle (lab) of the α particles at 8.7 ± 0.6 deg (this angular region is indicated by two horizontal lines in Fig. 1), and (b) prevent the α-selecting magnet system from seeing the intersection of the deuteron beam with the entrance and exit domes of the gas target. In order to accept as many α's as possible that are produced from the π^0 reaction (1) in the above angular interval (lab), the magnet system was

† This work was done under the auspices of the U. S. Atomic Energy Commission.

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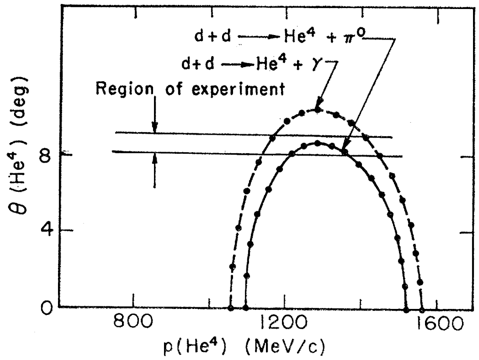

FIG. 1. Angle of the α particle as a function of momentum in the laboratory frame for the π^0 reaction (1) and the γ reaction (2). (Points plotted for 10-deg intervals of c.m. angle.)

designed to accept momenta that deviated by as much as -6% or $+5\%$ from the mean value. Energy loss and multiple scattering of the α's were minimized by providing a vacuum over their entire path length (except for regions in the immediate vicinity of the target and the counters).

The target was 37.5 in. long and 6 in. in diameter, with 1/32-in.-thick aluminum entrance and exit windows. It was filled with gas to a pressure of 390 psi (absolute) and cooled to liquid-nitrogen temperature. Fillings of hydrogen and deuterium were alternated.

The 460-MeV deuteron beam from the cyclotron was collimated and focused to give a spot about 1/2 in. wide and 1.5 in. high at the deuterium target. The beam was very nearly parallel in the horizontal plane; the maximum angular spread of the deuteron beam in this plane was ± 0.14 deg. Because of the geometry of the target and the angle of the α beam, interactions taking place at different positions inside the target produce α's that travel through different path lengths in the deuterium. This creates a problem because of the large mean energy loss of the α's in the target, viz., an average of 57 MeV for the case of the π^0 reaction (1). It is possible to partially equalize the differences in energy loss by placing a wedge of energy-degrading material (described in Table I) close to the target exit.

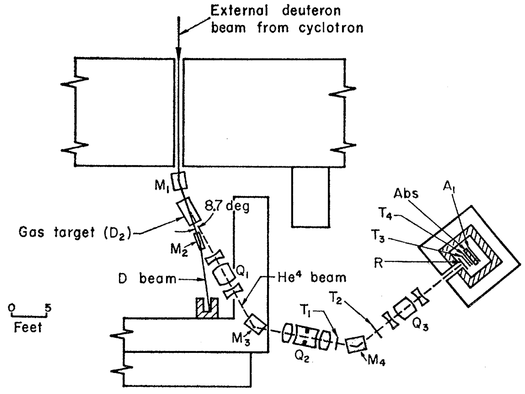

FIG. 2. Plan view of the experiment.

TABLE I. Magnet system and counter telescope components.

Item	Designation	Description
Bending magnets	M_1	H magnet with 7-in. gap, 29×36-in. rectangular pole tips, 21-deg bend.
	M_2	C magnet with 3.5-in. gap, 6×26-in. rectangular pole tips, 15-deg bend.
	M_3 and M_4	H magnet with 8-in. gap, 18×36-in. rectangular pole tips, 50-deg bend.
Quadrupole magnets	Q_1, Q_2, and Q_3	8-in.-aperture quadrupole focusing magnet of three elements (16–32–16-in.) operated DCD (divergent-convergent-divergent in the horizontal plane), CDC, and DCD, respectively.
Counter telescope	$T1$, $T2$, $A1$	Plastic scintillator, 6.5×6.5×0.020 in.
	R, $T3$, $T4$	Plastic scintillator, 4×4 in. R was 0.063 in. thick, $T3$ and $T4$ were 0.020 in.
	Absorber	CH_2 of thickness = 0.876 and 0.584 g/cm² for magnet-system momenta of p(He⁴) = 1060 MeV/c and 872 MeV/c, respectively.
He⁴ beam collimator		Collimator consisting of two lead slits; the aperture of each was 0.7 in. wide and 8 in. high. They were located 22 in. and 70 in. from the target center, along the He⁴ beam direction.
Momentum-defining slit		2-in.-thick brass slit, 4 in. wide, located at the center of the field lens Q_2.
Vacuum system		Aluminum pipes, 1/4 in. thick, 7-in. i.d. in the quadrupoles. The aluminum vacuum boxes inside the bending magnets did not restrict the solid angle of the α beam in either plane.
Shielding surrounding the final counters		1-ft thickness of steel inside 2 ft of paraffin.
Wedge		Mylar, 0.7 in. wide×8 in. high, whose thickness varied, over its width, from 0 to 0.21 g/cm². Located at the first He⁴ beam collimator.
Beam optics		The beam optics were symmetric about the energy slits at the center of Q_2. Q_1 was operated to image the target onto the energy slits in the horizontal plane and onto the center of M_3 in the vertical plane. Q_2 was operated so as to image the center of M_2 onto M_4 in both planes.

The α particles were identified by means of (a) effective momentum, p/Z, which was determined by the magnets and the energy slit; (b) velocity, which was determined by time-of-flight coincidences between counters $T1$, $T2$, and $T4$; (c) their range, which was observed to be less than the polyethylene absorber placed in front of the anticoincidence counter $A1$; and (d) ionization energy loss, by requiring the pulse height from counters $T3$ and $T4$ to be high enough to trigger a discriminator. These four criteria overdetermine the charge and mass of the α particle. The pulses from every counter were recorded on a 4-gun oscilloscope for each event that satisfied all the above criteria. The electronics were adjusted by using an α beam from the cyclotron, and consistency checks were made periodically during the experiment. The R counter, shown in Fig. 2, was not used during the data-taking runs but was allowed to remain in position as part of the absorber arrangement.

We think that our α telescope was at least $(96\pm5)\%$ efficient for registering α's (perhaps too efficient, as we found out later). This limit comes from comparing the plateaued singles counting rate in either $T3$ or $T4$ with the counting rate in the multiple-coincidence circuit [which registered the simultaneous satisfaction of requirements (b) plus (c) plus (d) listed above] while using an α beam from the cyclotron. With a deuteron beam from the cyclotron we then studied the counting rate from a polyethylene target placed in the same position as our deuterium target ordinarily occupied. The polyethylene target provided us with higher counting rates and enabled us to see that the electronics counting rates were linear with deuteron beam intensity. (At full beam intensity the α counting rate as registered on the scalers was about 6 times the rate from the deuterium target, although the background deuteron counting rate of the 2 targets was about the same.) These considerations are important, particularly since $T1$ was in a region of high-singles counting rate and the heights of its output pulses at full-beam intensity were considerably below their calibrated value. The laboratory-system cross section for deuterons on polyethylene,

$$\frac{d^2\sigma}{d\Omega dp}(d+\mathrm{CH_2}\rightarrow \mathrm{He^4}+\text{residue}), \tag{3}$$

as obtained from these measurements is 400×10^{-33} cm^2/(sr-MeV/c) for α particles of 1060 MeV/c momentum (lab) and an angle (lab) of 8.7 deg.

III. COLLECTION OF DATA

The data runs were cycled among four settings: The system was set for 1275-MeV/c α's (at target center) to observe the π^0 reaction (1), and then for 1427-MeV/c α's to observe the γ reaction (2) at $\Theta_{\text{c.m.}}=65$ deg, first with deuterium and then with hydrogen in the target. The setting for 1275-MeV/c α's with a deuterium target filling was sensitive to the production of a neutral particle with a mass of 120 to 155 MeV. The 1427-MeV/c setting with a deuterium target was sensitive to a mass of 0 to 110 MeV (see Fig. 1). For reasons described in Sec. IV, the data taken with a hydrogen target were treated as background runs. The magnet system was set in all cases at $p(\mathrm{He^4})=1060$ MeV/c. The target-center momentum of 1275 MeV/c was calculated by considering the energy loss in the target and Mylar wedge corrector, while the target-center momentum of 1427 MeV/c was obtained by adding 1.03 g/cm^2 of polyethylene degrader at the target exit with the same magnet settings. Most of our data was taken under the conditions specified in this paragraph; the final numerical limit for the cross sections comes entirely from these runs.

A small amount of data was taken, however, with magnet current settings to accept $p(\mathrm{He^4})=872$ MeV/c. These data gave additional information on (a) the π^0 reaction (1) at $\Theta_{\text{c.m.}}\approx90$ deg by running with a 0.525-g/cm^2 polyethylene degrader at the target exit, and (b) the γ reaction (2) at $\Theta_{\text{c.m.}}\approx135$ deg by running with no degrader and the target pressure reduced to 350 psia. As with the higher momenta data, runs were alternated between deuterium and hydrogen in the target. For data taken under the conditions described in this paragraph, the R counter was physically removed from the system.

In order to investigate the effect of any α-particle contamination of the incident deuteron beam, an α beam from the cyclotron was used with conditions the same as for studying the π^0 reaction and the γ reaction at $\Theta_{\text{c.m.}}=65$ deg. In both cases, the α-d inelastic scattering yielded 1.48 ± 0.03 times as many α counts as did α-p scattering. Thus, α contamination of the deuteron beam from the cyclotron or from deuteron interactions before the target would provide a net positive difference in α-particle yield between the deuterium and hydrogen targets. Alpha background produced from deuteron interactions in the target window was investigated by placing 0.090 in. of aluminum at the target entrance with deuterium gas in the target and with the system set for the π^0 reaction. The α counting rate on the scaler showed an increase of about 10% over that without the aluminum.

IV. DATA ANALYSIS AND RESULTS

A. Scaler Data

The data as recorded by the electronics are presented in Table II. The indicated errors are those of counting statistics only. In reference 7 the calculations of the cross sections for reactions (1), (2), and (3), which were based on the data counts recorded on scalars as listed in Table II of this paper, contained an error in the determination of solid angles. We correct this error here and also present new information from the same experiment which allows us to quote smaller limits for the cross sections investigated.

TABLE II. Electronics data.

Case	Magnet momentum $p(He^4)$ (MeV/c)	Momentum at target center $p(He^4)$ (MeV/c)	Counts per 10^{13} deuterons incident on target[a]				
			α counts			Deuteron counts[b]	
			D_2 target	H_2 target	Empty target	D_2 target	H_2 target
$d+d \to He^4+\pi^0$	1060	1275	62.2±1.7	45.0±1.4		6×10^4	4×10^4
$d+d \to He^4+\gamma$	1060	1427	67.2±2.1	47.8±1.8		6×10^4	4×10^4
Evacuated target	1060	1140			32.7±2.1[c]		
$d+d \to He^4+\pi^0$	872	1275	21.6±1.8	12.3±1.1			
$d+d \to He^4+\gamma$	872	1150	25.2±1.4[d]	14.5±0.9[d]			

[a] The values listed in Table I of reference 7 are incorrect, being too low by a factor of 1.98. The correct values listed here were used, however, to obtain the final results in reference 7.
[b] These numbers should be considered only as indicative since the counter telescope was not plateaued for counting deuterons.
[c] Background counts for the deuterium data are given by a target filled with hydrogen (which has the same α energy loss as in the deuterium target).
[d] Counting rate normalized to a target pressure of 390 psia (data taken at 350 psia to minimize energy losses).

B. Oscilloscope Picture Analysis at the 1060-MeV/c Magnet Setting

An analysis of the pictures taken of an oscilloscope which recorded the pulses from all the counters in the experiment was recently undertaken. This analysis provides a much stronger conclusion to be drawn from the same experiment previously reported in reference 7. The pulse-height distribution and the timing of each counter output were measured. Calibrations of the timing and heights of the pulses were obtained by triggering the oscilloscope from time-of-flight coincidence circuits set for (a) protons, (b) deuterons, and (c) He^3's while using a scattered deuteron beam from the cyclotron; α calibration was obtained while using a scattered α beam from the cyclotron. As expected, the scan of the data film showed that all the events had a timing corresponding to that of α's (or deuterons, since for a given magnetic rigidity, deuterons have the same velocity as α's); moreover, no pulses from the anticoincidence counter, $A1$ are seen. Thus, all the data events recorded on the scalers had the timing and range of α's.

However, an analysis of the heights of the pulses from the counters shows that a small fraction of these data events recorded on scalers are α's. The pulse-height distribution of each counter, obtained from the oscilloscope pictures, taken at a magnet setting of 1060 MeV/c, are shown in Fig. 3. The distributions with the system set to look for the π^0 or γ reactions and with the deuterium or hydrogen target are the same, within statistics; therefore, in Figs. 3 and 4 the data of all the settings were combined. Except for the $T1$ counter, the pulse-height data in Fig. 3 are based on a scan of approximately one-third of all the events. The pulse-height spectrum for counter $T1$ shows that its output is considerably below the calibrated value for α particles. For purposes of time-of-flight coincidences, however, $T1$ was shown to be counting alphas efficiently. The distributions for $T3$ and $T4$ in Fig. 3 each show a single broad peak, the center of which is at a slightly lower pulse height than that of the calibrated α distribution. The low pulse-height edges of the distributions for these two counters correspond to the setting of the lower level discriminator. The $T2$ counter pulse-height spectrum has two well-separated peaks; the position of the higher pulse height coincides with the calibrated α spectrum.

When the spectrum of the $T2$ counter suggested that α's constituted only a small fraction of the events, we tried to see if there was any correlation of the pulse heights in $T3$ and $T4$ with those in $T2$ in the high-momentum runs. We have plotted the events in which the $T2$ pulse height occurs in the higher peak by a

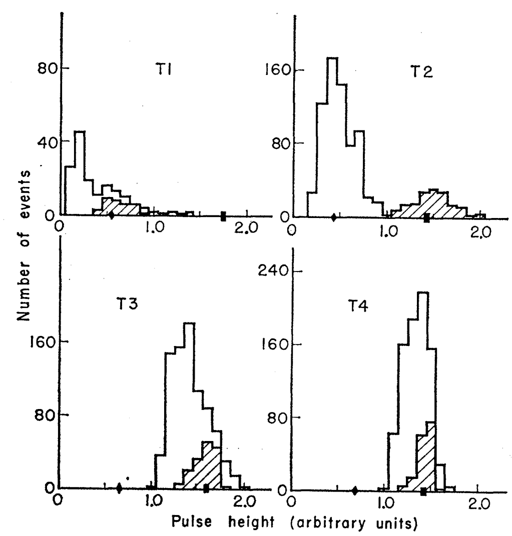

FIG. 3. Spectra of photomultiplier pulse heights for the high-momentum data. In these histograms events per bin are plotted in dark lines vs the pulse height of the photomultiplier pulses, which are measured in arbitrary units. The spectrum of $T1$ is based on only 160 events; the spectra of the other counters are based on 1/3 of all the data. Solid diamond: mean pulse height for the deuteron calibration; Solid square: mean pulse height for the α calibration. The shape of the calibration is, for $T2$, indicated by the data spectrum, since within statistics the calibration is the same and therefore not plotted. The cross-hatched area shows those pulse heights in the $T1$, $T3$, and $T4$ counters which correlated with pulse heights greater than 1.0 unit high in the $T2$ counter.

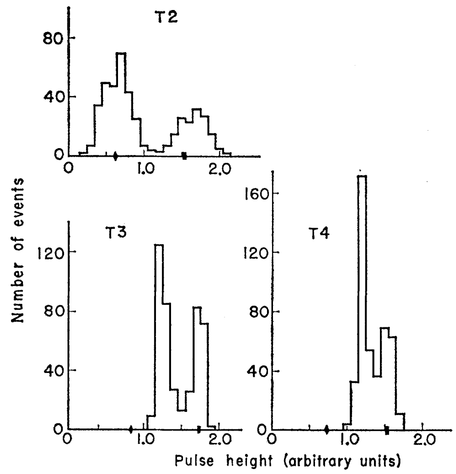

FIG. 4. Spectra of photomultiplier pulse heights for the low-momentum data. Events per bin are plotted vs the pulse height of the photomultiplier pulses, which are measured in arbitrary units. Solid diamond: mean pulse height for the deuteron calibration; solid rectangle: mean pulse height for the α calibration.

cross-hatched histogram in Fig. 3. A correlation in the pulse-height spectra is noted: For the events in which the $T2$ pulse height corresponds to that of α's, the output of counters $T3$ and $T4$ also corresponds to that for α's, while for those events which have a deuteron pulse height in $T2$, the pulse-height distributions for $T3$ and $T4$ appear displaced to lower pulse heights from those of the α's. This information, together with the fact that the timing for all the events is the same, indicates that a large fraction of the events that the scalers recorded as α's were really deuterons. These deuterons must have interacted near the final counters to produce particles that gave a large pulse height in $T3$ and $T4$ (and, therefore, triggered the discriminators placed on $T3$ and $T4$) and were stopped in the polyethylene absorber before reaching the anticoincidence counter, $A1$. The material in the beam upstream from and near the final counters was the R counter (0.063-in. plastic scintillator) and the 0.010-in.-thick Mylar window of the vacuum system.

The pulse height as a function of energy loss was calculated from our calibration data. The calibration of the proton, deuteron, and helium-3 peaks fitted a formula of Gooding and Pugh,[8] while that for the α particle did not; it is quite possible that the photomultiplier tubes themselves had started to saturate somewhere between the helium-3 peak and the α peak. With this calibration it was shown that whatever particles produce the pulse height of the lower peak in $T3$ or $T4$, they could not be doubly charged, since for a charge of $2e$ the median pulse height of the lower peak in counter $T3$ would require a velocity of 0.34 c. This velocity would imply a kinetic energy in excess of the kinetic energy of the 72-MeV deuterons and a range in excess of the 0.876-g/cm^2 polyethylene absorber. Similar arguments rule out charges greater than two. These lower pulse-height events must, therefore, be produced by singly charged particles. A likely source is the 0.063-in. scintillator of the R counter and the 0.010-in. Mylar vacuum window; we are thus led to consider deuteron-carbon reactions as a source for these events of reduced pulse heights in $T3$ and $T4$. A cross section for 70-MeV deuterons incident on carbon and producing singly charged secondaries with velocity $\leqslant 0.18c$ of $(d^2\sigma/dpd\Omega)\Delta p\Delta\Omega = 90\times 10^{-27}$ cm^2 would account for all the counts in the lower pulse-height peak in $T3$ and $T4$. This cross section is consistent with the results of Schechter *et al.*[9] extrapolated to 70-MeV deuteron kinetic energy. Since the particles with pulse height $\geqslant 1.0$ in the $T2$ counters are consistent with α particles and those lower in pulse height consistent with deuteron-carbon reaction products, the number of true α counts were determined by counting only those pulse heights $\geqslant 1.0$ in $T2$. The results of such a scan of all the film data are listed in Table III.

TABLE III. Oscilloscope film data. True α counts per 10^{13} deuterons incident on target.

Case	Magnet momentum $p(He^4)$ (MeV/c)	$p(He^4)$ at target center (MeV/c)	α counts[a] D_2 target	H_2 target	Empty target
$d+d \to He^4+\pi^0$	1060	1275	12.7 ± 0.8	9.1 ± 0.7	
$d+d \to He^4+\gamma$	1060	1427	15.9 ± 1.2	10.5 ± 0.8	
Target-empty background	1060	1140			9.6 ± 1.2
$d+d \to He^4+\pi^0$	872	1275	8.1 ± 1.1	4.4 ± 0.6	
$d+d \to He^4+\gamma$	872	1150	9.3 ± 0.8[b]	5.3 ± 0.5[b]	

[a] Errors are those of counting statistics only.
[b] Counting rate normalized to a target pressure of 390 psia (data taken at 350 psia to minimize energy losses).

C. Oscilloscope Picture Analysis at 872 MeV/c

The pulse-height spectra from $T2$, $T3$, and $T4$ with the magnet system set for 872-MeV/c α's are shown in Fig. 4. At this momentum there is a clear resolution between the α pulses and the lower pulse heights in all the counters. This lends added weight to the conclusions reached in Sec. B. The results of a scan of all of the low-momentum data are also listed in Table III.

D. Results of the Oscilloscope Data at 1060 MeV/c

Since the conservation of baryon number forbids the production of α particles from deuteron-proton collisions, the hydrogen data were treated as background and subtracted from the deuterium data to yield the net α signal from d-d collisions. (The data taken with an empty target cannot be used as a measure of the background because energy losses inside the full deuterium target are large; thus, the α's are at quite a

[8] T. J. Gooding and H. G. Pugh, Nucl. Instr. Methods **7**, 189 (1960).

[9] L. Schechter, W. E. Crandall, G. P. Millburn, D. A. Hicks, and A. V. Shelton, Phys. Rev. **90**, 633 (1953).

different momentum from those from an empty target.) If we assume that all the net α counts obtained from Table III were due to the π^0 reaction (1), we obtain a center-of-mass cross section at $\Theta_{c.m.} \approx 90$ deg of

$$d\sigma^{c.m.}/d\Omega = (0.097 \pm 0.027) \times 10^{-33} \text{ cm}^2/\text{sr}. \quad (4)$$

We do not believe, however, that all these α's were actually produced by the π^0 reaction (1), for the following reasons:

(a) For test purposes we used an α beam from the cyclotron and found that the inelastic scattering of α's from a deuterium target produced a counting rate in our α telescope which was 1.48 ± 0.03 times that obtained with a hydrogen target. Thus α contamination of the deuteron beam from the cyclotron would provide a positive net counting rate when we subtracted the hydrogen (background) counting rate from the deuterium data.

(b) With a deuteron beam under normal running conditions an increase in α counting rate was obtained when additional aluminum was placed in the beam at the target entrance. Therefore, α production from deuteron interactions at or before the target entrance, together with scattering in the gas of the target, produces a net positive yield of α's obtained from a D_2-H_2 subtraction of the data.

(c) From Table II we see that there were more deuterons scattered down our channel with a deuterium target than from the hydrogen target. This also means that the deuterium target scattered more deuterons to the aluminum target walls, which could interact there to produce α's that could get down our magnetic channel. This process would also produce a net positive yield of α's from D_2-H_2 subtraction of the data.

(d) The data obtained with the magnet-system momentum set at $p(\text{He}^4) = 872$ MeV/c provide additional information. Making reasonable assumptions about the momentum dependence of the background which are consistent with the 872-MeV/c data, one can derive a result of zero π^0 yield from the π^0 reaction (1).

We conclude, therefore, that the cross section listed in (4) is an upper limit for the π^0 reaction (1) and that our results are consistent with zero cross section. This value is to be compared with a theoretical prediction for this cross section at our energies at the same angle,

$$d\sigma^{\text{theory}}/d\Omega = (38 \pm 5) \times 10^{-33} \text{ cm}^2/\text{sr}, \quad (5)$$

which was computed with the assumption that isotopic spin need not be conserved.[4]

From the oscilloscope film data in Table III at 1060 MeV/c, the differential cross section in the center-of-mass system for the γ reaction (2) at $\Theta_{c.m.} = 65$ deg was also calculated, and the value obtained is

$$\frac{d\sigma^{c.m.}}{d\Omega}(d+d \to \text{He}^4 + \gamma) \leqslant (0.23 \pm 0.06) \times 10^{-33} \text{ cm}^2/\text{sr}. \quad (6)$$

IV. CONCLUSIONS

We observe experimentally a cross section which is only about 1/400 that which one would expect if isotopic spin need not be conserved. If we state the ratio of Eq. (4)/Eq. (5) as a measure of the nonconservation of isotopic spin we obtain an upper limit of 0.0026 ± 0.0008; or stated alternatively, isotopic spin is at least $(99.74 \pm 0.08)\%$ conserved in this π^0 interaction (1).

No evidence was found for the reaction $d+d \to \text{He}^4 + \pi_0{}^0$, where the $\pi_0{}^0$ is a neutral meson of zero isotopic spin[10] with a rest mass in the interval 120 to 155 MeV. If the $\pi_0{}^0$ existed, then this reaction, which is a strong interaction, would be allowed by isotopic spin conservation and, therefore, should have been detected. For a $\pi_0{}^0$ of the same mass as that of the ordinary π^0, we find

$$d\sigma^{c.m.}/d\Omega(d+d \to \text{He}^4 + \pi_0{}^0) \leqslant (0.097 \pm 0.027) \times 10^{-33} \text{ cm}^2/\text{sr}$$

at $\Theta_{c.m.} \approx 90$ deg.

ACKNOWLEDGMENTS

We should like to thank Jim Carroll, William Bowman, Richard Eandi, Dale Dickinson, and Donald Hagge for help throughout the experiment; Professor Moyer for discussions, and James Vale and the cyclotron crew for their cooperation.

APPENDIX

An evaluation of the differential cross section in terms of the observed counting rates involves a determination of the quantity

$$\int \Delta\Omega_{c.m.}(x) M(x) dx, \quad (7)$$

where M is the fraction of the α beam that is not scattered out of the magnet system as a result of multiple scattering, and $\Delta\Omega_{c.m.}$ is the center-of-mass solid angle subtended by the collimator and the magnet system. This quantity is a function of the momentum bite of the magnet system, the configuration of the magnet-system collimator, the kinematics of the particular reaction, and the position x inside the target. The dependence of these quantities on x has been explicitly indicated in (7), since the integral was evaluated by calculating these values for various target positions and numerically performing the indicated

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integration. For the π^0 and γ reactions with the magnets set for an α momentum of 1060 MeV/c, the acceptances were evaluated as 0.79 sr-cm and 0.47 sr-cm, respectively. The term $M(x)$ does not take into account the multiple scattering in the $T1$ and $T2$ counters. An additional correction was made for this effect which, for the π^0 cross section (5), was 3%.

To get a feeling for these numbers we could arbitrarily assign numerical values of 0.13 sr to $\Delta\Omega_{\text{c.m.}}$, 0.55 to M, and 11 cm to L, where L is an effective target thickness

$$L=\int_0^L dx. \tag{8}$$

The only meaning that should be attached to these three numbers is that their product equals the value given above (0.79 sr-cm) for the correct numerical evaluation of (7) for the π^0 reaction (1).

PHYSICAL REVIEW VOLUME 130, NUMBER 3 1 MAY 1963

Theory of the $J=\frac{3}{2}$, $I=\frac{3}{2}$ πN Resonance*

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(Received 10 December 1962)

We calculate the position W_R and width γ_{33} of the $J=\frac{3}{2}$, $I=\frac{3}{2}$ P-wave πN resonance, using partial-wave dispersion relations. In the present calculation we treat as given the nucleon and ρ-meson masses and coupling constants, which determine the long-range part of the forces. The parameters, which characterize the distant part of the left-hand cut, are fixed by using the expressions for the $(\frac{3}{2},\frac{3}{2})$ P-wave πN state given by fixed energy dispersion relations, in a region where they are valid without subtractions, in a way used by Balázs for the $\pi\pi$ problem. We then impose the self-consistency demand that the position and width of the $(\frac{3}{2},\frac{3}{2})$ resonance used as input values in the crossed channel in the fixed-energy dispersion relation be the same as the calculated values of the position and width. The preliminary results of the calculation are $W_R\approx m+2.35$ and $\gamma_{33}\approx 0.14$. The experimental values are $W_R=m+2.17$ and $\gamma_{33}\approx 0.12$, (where m is the nucleon mass and we use units in which $\hbar=c=m_\pi=1$). These results constitute the first part of the intended self-consistent calculation of the nucleon mass and $(\frac{3}{2},\frac{3}{2})$ resonance position, exploiting the "reciprocal bootstrap" mechanism discussed by Chew.

WE present here some preliminary results on the first part of a program of self-consistent calculation of the nucleon mass and the position of the 3/2–3/2 resonance of the πN system using unitarity and analyticity. The idea that is being exploited in this attempt is that the nucleon in the crossed channel provides the main force for the 3/2–3/2 resonance, and that the 3/2–3/2 resonance in the crossed channel provides the main force for the binding of the nucleon. The feasibility of such a "reciprocal bootstrap" mechanism has been discussed recently by Chew.[1]

The existence of this resonance and its width have been well understood on the basis of the Chew-Low theory[2] which brought out the dominant role played by the nucleon in the crossed channel. Its position, however, has defied all dispersion theoretical attempts so far, for want of a satisfactory method for taking into account the short-range effects whose importance was emphasized in the work of Frautschi and Walecka.[3] A new effective-range method has been developed recently by Balázs[4] for treating the distant part of the left-hand cut and successfully applied to the problems of $\pi\pi$ scattering[4] and the isovector part of the electromagnetic structure of the nucleon.[5] We show that it also leads to some very interesting results for the present problem.

In the present note we confine our discussion to the first part of the program, viz., determination of the position of the 3/2–3/2 resonance treating the nucleon in the crossed channel as a given fixed singularity. We use the N/D method, and the amplitude we choose is the

* This research was supported in part by USAEC and in part by the Air Force Office of Scientific Research Grant No. AF-AFOSR-42-63 received by one of us (B.M.U.)

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