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Booth, Norman E.
Chamberlain, Owen
Rogers, Ernest H.

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ABSTRACT

A search has been made for a neutral meson of zero I spin by means of the reaction $d + d \rightarrow He^4 + \pi_0^0$. No evidence was found for the existence of the π_0^0 in the mass range zero to 1.8 times the $\pi^\pm$ mass. The upper limit of the cross section was 7×10^{-32} cm^2 for $\pi_0^0 \approx \pi^\pm$ mass. The reaction was studied by using 460-Mev deuterons from the Berkeley 184-inch cyclotron and a liquid deuterium target. Alpha particles produced at 0 deg in the laboratory system were selected by momentum analysis and by a counter telescope which measured time of flight, dE/dx, and differential range. The experiment may also set a limit on the validity of charge independence.

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1. INTRODUCTION

Several authors[1-8] have postulated the existence of a neutral meson of isotopic spin zero (called the π_0^0 or ρ_0 meson) and suggested means of verifying its existence. Mass estimates vary from a few Mev less than the ordinary π^0 mass to about three times the $\pi^\pm$ mass (μ). At least one experimental test has been made.[9] The experiment described here is concerned with a search between the mass limits of 0 and 1.8 μ by means of a reaction first suggested to the authors by Steiner[1] and independently by Baldin,[2]

$$d + d \rightarrow He^4 + \pi_0^0 . \qquad (1)$$

Since the three heavy particles in (1) all have I spin zero, the ordinary π^0 meson cannot be produced in place of the π_0^0 in this reaction, at least to the extent that isotopic spin is conserved. The upper limit of 1.8 μ was set by the maximum kinetic energy of the deuterons available from the Berkeley 184-inch cyclotron, namely 460 Mev. No evidence was found for the existence of the π_0^0. The upper limit obtained for the cross section of (1) depended upon the value of the π_0^0 mass assumed; it was 20×10^{-32} cm^2 for zero mass and 0.2×10^{-32} cm^2 for 1.8 times the $\pi^\pm$ mass (assuming isotropy in the center-of-mass system. See Fig. 3).

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2. EXPERIMENTAL ARRANGEMENT

A. General

Reaction (1) was studied by searching for alpha particles produced at zero degrees when a liquid deuterium target was bombarded with 460-Mev deuterons. The momentum of the alpha particles depends of course upon the mass of the π_0^0, and for given mass is double-valued, corresponding to emission at both 0 and 180 deg in the barycentric system.

The experimental arrangement is shown in Fig. 1 and details are given in Table I. The deuteron beam obtained by regenerative extraction from the 184-inch cyclotron was focused on the liquid D_2 target. The system of bending and focusing magnets selected particles of a certain effective momentum p/Z, which came off at 0 deg, and delivered them outside the shielding into an area of relatively low background. A system of counters separated He^4 nuclei from the other components of this mono-momentum secondary beam. The momentum of the secondary beam was varied to cover the range of He^4 momentum from reaction (1) for any mass of π_0^0 between 0 and 1.8 μ.

B. Deuteron Beam and Target

The external 460-Mev deuteron beam was collimated and focused to give a spot 1 × 1-1/2 in. at the D_2 target. The beam position was checked periodically by exposing an x-ray film immediately behind the target. This ensured that the beam always passed cleanly through the target cylinder.

Two ion chambers were used to monitor the beam, one in front of the D_2 target and another after M_1. For some of the runs, after intercalibration, the first ion chamber was removed. The ion-chamber multiplication factor was calculated from the calibration performed by Chamberlain, Segrè, and Wiegand[10] and the values of dE/dx for 345-Mev protons and 460-Mev deuterons.

For most of the measurements the beam intensity was 1.5 to 5×10^8 deuterons per sec.

The deuterium container was a cylinder 3 in. in diameter with a length of 0.94 ± 0.05 g cm^2 of D_2 in the beam direction. The target windows and vacuum chamber windows were each 0.010-in. Mylar. An aluminum heat shield 0.0015 in. thick surrounded the target cylinder. The target was equiped with a reservoir and heater so that it could be emptied or filled in a few minutes.

C. Magnetic Analysis

The spectrometer was set to accept particles of a particular effective momentum p/Z. The required magnet currents were determined beforehand by the wire-orbit method. Quadrupole Q_1 brought particles leaving the D_2 target to a focus at f_1. Because of the dispersion in the bending magnet M_1, only particles whose effective momentum was within 2-1/2% of the central value passed through the 4 × 4 - in. collimator at f_1. These particles were deflected again and focused at f_2, and refocused at S_3. The images at f_2 and S_3 had unit magnification and no dispersion. The beam size was therefore approx 1 × 1 - 1/2 in. at f_2 and S_3. Helium bags were used throughout the system to reduce multiple scattering in order to maintain sharp images at f_2 and S_3, and to reduce the energy loss between the D_2 target and S_3.

Two characteristics of a spectrometer are of prime importance. These are the fractional momentum bite $\Delta p/p$ transmitted through the system, and the solid angle $\Delta\Omega$ into which particles from the target must fall in order to arrive at S_3. Both these quantities can be calculated crudely from the geometry. In a production experiment such as we performed the product $(\Delta\Omega)(\Delta p/p)$ enters the analysis. This quantity was measured directly and found to be 1.16×10^{-5}. (See Appendix 1.)

D. Counters and Electronics

The counter telescope was required to pick out He^4 nuclei from other particles with the same p/Z determined by the magnet settings. Time of flight between S_1 and S_2 fixed the velocity and therefore M/Z. Deuterons were then the only contamination. The differences in range and dE/dx for deuterons and alpha particles were used to reject deuterons. The Cu absorbers A_1 and A_2 were chosen so that alpha particles were counted in S_3 but not in S_4, while deuterons of this momentum had sufficient range to be counted in S_4. Alpha particles were selected by the coincidence $S_1S_2S_3\bar{S}_4$.[11] However, this system also counted a small fraction of the vast number of deuterons passing through the telescope, presumably those that underwent stripping or other nuclear reactions in S_3 or A_2 and did not give a pulse in S_4. These were eliminated by a second coincidence which required, in addition toe the fast coincidence $S_1S_2S_3\bar{S}_4$, that the pulses in S_1, S_2, and S_3 be above a given height. This was accomplished by feeding pulses from the three counters into pulse-height discriminators[12] and placing the outputs in a slow coincidence[13] with the fast coincidence $S_1S_2S_3\bar{S}_4$. Differential range curves taken by varying the absorber A_1 showed that this system counted only alpha particles at the beam intensities used. The entire system was thoroughly checked periodically by accelerating alpha particles in the cyclotron and degrading them before the D_2 target. This procedure also measured the efficiency of the telescope at each momentum used. As a check on the electronics the pulses from the individual counters were photographed on moving film during part of the run and checked with the electronics.

3. PRODUCTION OF ALPHA PARTICLES IN COMPLEX NUCLEI

Although considerable care had been taken to minimize the thickness of the materials (other than liquid deuterium) in the beam, an unexpectedly large background of alpha particles was observed from the ion chamber, target windows, etc. in the vicinity of the target. Their origin was confirmed by placing additional foils of various elements in the deuteron beam and measuring their production of alpha particles. The results showed that the materials normally in the beam accounted (within the errors) for the observed yields of alpha particles.

In order to calculate production cross sections it is useful to consider particle momentum as a function of range X, in g/cm^2 of Cu equivalent, particularly because the momenta of the alpha particles change drastically from the point where they are produced to where they are detected. If we let $R(MT, p_s)$ be the observed rate for the D_2 target empty and the magnets set for momentum p_s at M_1, and let $R(MT + x, p_s)$ be the rate with an additional foil of thickness x, then we can write

$$R(MT + x, p_s) - R(MT, p_s) = N_0 \; \frac{Nx}{A} \; {\frac{\Delta p \Delta\Omega}{p}}_s \; p_s \; {\frac{d^2\sigma}{dp\,d\Omega}}_p \; \frac{(dp/dX)_p}{(dp/dX)_s} \,, \tag{2}$$

where N_0 is the number of incident deuterons, N is Avogadro's number, A is the atomic weight of the additional foil, and $(d^2\sigma/dp\,d\Omega)_p$ is the production cross section at the momentum p. Figure 2 shows the cross-section data for Cu. The yields per g/cm^2 from lighter elements (C and Al) were greater by a factor of about two.

4. ALPHA PARTICLES FROM DEUTERIUM

The observed counting rates at various momenta are given in Table II. The observation of more alpha particles with the target empty than with the target full is to be expected, if no alpha particles are produced in the D_2, because of the alpha particles produced in the foils ahead of the target. The following factors contribute:

(a) Production of alpha particles in complex nuclei is a sensitive function of the momentum of the produced alpha particles, production being greater for lower momentum. The extra stopping power in the system when the target is full causes a significant increase in the momentum and decrease in the momentum spread with which alpha particles must be produced if they are to enter the magnet system and be counted. In more quantitative terms we say the counting rate is reduced when the target is full because the quantity $(d^2\sigma/dp\,d\Omega) \times (dp/dX)$ is a decreasing function of the momentum p of the produced alpha particle.

(b) Nuclear interactions in the deuterium also remove alpha particles formed in the foils ahead of the target.

With these considerations, and a knowledge of the materials in the beam and their alpha-particle production cross sections, we can correct the target-full data to find the yield of alpha particles from the deuterium, $R(D_2, p_s)$ given in the last column of Table II. Details of the calculation are given in Appendix 2.

5. CROSS-SECTION LIMITS

The laboratory-system differential cross section for the production of alpha particles at 0 deg is given by

$$R(D_2, p_s) = N \left(\frac{d\sigma}{d\Omega}\right)_L \left(\frac{\Delta p \Delta\Omega}{p}\right)_s \frac{p_s}{(dp/dX)_s} \frac{N}{A} \frac{(dE/dX)_{Cu}}{(dE/dx)_{D_2}} . \tag{3}$$

The last factor corrects for the fact that we measure range in gm/cm^{2}Cu equivalent. A is the atomic weight of deuterium. The effective thickness of the D_2 target is determined by the momentum bite of the magnet system provided we have

$$\left(\frac{\Delta p}{p}\right)_s \frac{p_s}{(dp/dX)_s} \frac{(dE/dX)_{Cu}}{(dE/dx)_{D_2}} \leqslant 0.94 \text{ g/cm}^2 \text{ of } D_2 .$$

This was true in all cases except at the highest momentum. The differential cross section in the c.m. system is given by $(p^*/p)^2 (d\sigma/d\Omega)_L$ where p^* is the momentum in the c.m. system. From the data of Table II we can calculate an upper limit for the differential cross section of (1) as a function of the mass of the π_0^0. (In this calculation the upper limit on the observed rate, R, is taken to be R + 1.7 ΔR when R is positive and 1.7 ΔR when R is negative.) Figure 3 shows the way in which the upper limit depends upon the assumed mass. The cross-section limit is best near 1.8 $\pi^\pm$ masses, but this is not to be taken seriously because here we are near threshold.

6. CHARGE INDEPENDENCE

The principle of I-spin conservation or charge independence forbids the reaction

$$d + d \rightarrow He^4 + \pi^0 .$$

Our measurements set an upper limit on the cross section for this reaction, assuming isotropy, of about 7×10^{-32} cm^2. This result is a test of charge independence provided we can estimate what the cross section should be if I spin were not conserved.

Unfortunately it is not easy to make this estimate. However, we can compare our upper limit with the cross section for the reaction

$$d + d \rightarrow He^4 + \gamma .$$

Our data give an upper limit on the latter of about 10^{-31} cm^2. Measurements on the inverse[14, 15] give, by detailed balancing, about 10^{-32} cm^2. Thus the π^0 production cross section is at most only a few times the radiative capture at an energy well above the threshold for π^0 production.

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APPENDIX I. ACCEPTANCE OF THE MAGNET SYSTEM

The acceptance of a spectrometer such as the one used in this experiment is defined as the product of the solid angle and the fractional momentum bite. The acceptance of this magnet system was measured as follows:

The alpha beam from the cyclotron was degraded with copper, part of which was in the form of 45-deg wedges, at the position of the D_2 target. The momentum distribution of this degraded beam was flat over a region large compared with the momentum bite of the magnet system. The aperture of Q_1 was uniformly illuminated. A scintillation counter 6 in. wide was placed at f_1. This geometry defined a fractional momentum bite $(\Delta p/p)' = 0.0963$. The rate R_1' in this counter was measured as a function of the aperture of a collimator placed at the entrance of Q_1. From this measurement, the effective aperture of Q_1 without collimation was found to be $\Delta\Omega' = 4.36 \times 10^{-3}$ steradian for this case. With the counter at f_1 removed, the rate R in the alpha-particle telescope was measured. Since $\frac{R'}{\Delta\Omega'}\left(\frac{p}{\Delta p}\right)' = \frac{R}{\Delta\Omega}\left(\frac{p}{\Delta p}\right)$, we obtain $\Delta\Omega\Delta p/p = 1.16 \times 10^{-5}$, where p is defined at M_1^1.

APPENDIX 2. CORRECTIONS

To be more explicit, we write

$$R(MT, p_s) = N_0 \left(\frac{\Delta p \Delta \Omega}{p}\right)_s p_s \left\{\left[\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)\left(\frac{dp}{dX}\right)\right]_f + \left[\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)\left(\frac{dp}{dX}\right)\right]_i\right\} \Big/ \left(\frac{dp}{dX}\right)_s$$

where the subscript f refers to the foils behind the target and i to the foils in front of the target. With the target full we have $R(FULL,_{ps} = R(D_2, p_s)$

$$+ N_0 \left(\frac{\Delta p \Delta \Omega}{p}\right)_s p_s \left\{\left[(1 - A_{dd})\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)\left(\frac{dp}{dX}\right)\right]_f + \left[(1 - A_{\alpha d})\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)'\left(\frac{dp}{dX}\right)'\right]_i\right\} \Big/ \left(\frac{dp}{dX}\right)_s \quad ,$$

where $R(D_2, p_s)$ is the rate from the D_2, A_{dd} is the attenuation of the deuteron beam in the D_2, $A_{\alpha d}$ that of the alpha particles in the D_2, and p' the momentum at which alpha particles must be produced in front of the target such that they come down the magnet system. We can get a measure of $(d^2\sigma / dpd\Omega)_i$ by setting the magnet system for a momentum p_s' such that we have

$$R(MT, p_s') = N_o \left(\frac{\Delta p \Delta \Omega}{p}\right) p_s' \left\{\left[\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)'\left(\frac{dp}{dX}\right)\right]_f + \left[\left(\frac{Nx}{A}\right)\left(\frac{d^2\sigma}{dpd\Omega}\right)'\left(\frac{dp}{dX}\right)'\right]_i\right\} \Big/ \left(\frac{dp}{dX}\right)_s' \quad .$$

If we substitute

$$\epsilon\, R(MT, p_s) = N_0 \left(\frac{\Delta p \Delta\Omega}{p}\right)_s p_s \left[\left(\frac{N_x}{A}\right) \left(\frac{d^2\sigma}{dp\, d\Omega}\right) \left(\frac{dp}{dX}\right) \right]_f \Big/ \left(\frac{dp}{dX}\right)_s ,$$

where ϵ is the ratio of the detected alpha particles that were produced behind the target to the total produced, behind and in front of the target, we have

$$R(D_{21}\, p_s) = R(FULL, p_s) - R(MT, p_s) \left\{ \epsilon (1 - A_{dd}) \right.$$
$$\left. + (1 - \epsilon') (1 - A_{dd}) \frac{p_s}{p_s'} \frac{(dp/dX)_i'}{(dp/dX)_i} \frac{R(MT, p_s')}{R(MT, p_s)} \right\} .$$

A_{dd} and $A_{\alpha d}$ were obtained by extrapolation of the results of Millburn et al.[16] On the inelastic cross sections of complex nuclei for high-energy deuterons and alpha particles. The total cross sections in D_2 assumed were 200 ± 100 mb for deuterons and 400 ± 100 mb for alpha particles. ϵ was determined from the production data. The quantity $R(MT, p_s') / R(MT, p_s)$ was determined from straight lines through the raw data obtained with target empty. Values of $R(D_2, p_s)$ are given in the last column of Table II.

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Table I

Spectrometer and counter telescope components indicated in Fig. 1

Item	Designation	Description
Magnets	Q_1 , Q_2 , Q_3	4-in. -aperture three-element quadrupole focusing magnets
	M_1	24×36-in. analyzing magnet with 7-in. gap, 46-deg bend
	M_2	18×36-in. analyzing magnet with 8-in. gap, 51-deg bend
Counters	S_1	plastic scintillator, 1/16 in., 5 in. diam
	S_2	plastic scintillator, 1/16 in., 3 in. diam
	S_3	plastic scintillator, 1/4 in., 4 in. diam
	S_4	plastic scintillator, 3/8 in., 5 in. diam
Absorbers	A_1 , A_2	variable-thickness copper

Table II

Observed counting rates (counts per 1.15×10^{11} deuterons)

Momentum at M_2 (Mev/c)	Target full	Target empty	$R(D_2, p_s)$ Full-empty (corrected)
980 Mev/c	9.11 ± 0.78	17.00 ± 1.17	- 1.6 ± 1.5
1104	10.67 ± 0.55	17.90 ± 0.88	- 1.5 ± 1.5
1214	9.94 ± 0.58	15.29 ± 1.01	- 0.8 ± 1.4
1298	9.69 ± 0.69	13.70 ± 1.18	- 0.5 ± 1.4
1390	12.61 ± 0.72	17.43 ± 0.80	+ 0.2 ± 1.5
1440	11.00 ± 0.95	14.90 ± 1.20	+ 0.2 ± 1.7
1494	15.11 ± 0.70	19.70 ± 0.86	- 0.04 ± 1.9

FIGURE LEGENDS

Fig. 1. Experimental arrangement.

Fig. 2. Production of alpha particles from copper by 460-Mev deuterons.

Fig. 3. Upper limit on the differential cross section of $d + d \rightarrow He^4 + \pi_0^0$. The two curves are for production angles of the He^4 of 0 deg and 180 deg in the c.m. system.