EVIDENCE FOR η^0 AND ω^0 MESON PRODUCTION IN THE REACTION $p + d \rightarrow \text{He}^3 + \text{MISSING MASS}$

H. Brody,[*] E. Groves,[*†] R. Van Berg,[*] and W. Wales[*]
University of Pennsylvania, Philadelphia, Pennsylvania 19104

and

B. Maglić,[‡] J. Norem,[‡] and J. Oostens[‡§]
Rutgers, The State University, New Brunswick, New Jersey 08903

and

G. B. Cvijanovich
Upsala College, East Orange, New Jersey 07019

and

R. A. Schluter[*]
Argonne National Laboratory, Argonne, Illinois 60439, and Northwestern University, Evanston, Illinois 60201

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Strong π^0, η^0, and ω^0 peaks have been observed in the reaction $p + d \rightarrow \text{He}^3$ + missing mass at incident proton momenta of 3.5-3.8 GeV/c and proton-to-meson momentum transfer $t = -1.5$ (GeV/c)^2. The mesons are produced with center-of-mass cross sections on the order of 10^{-34} cm^2/sr at a center-of-mass angle of about 60°. The missing-mass spectrometer combined the "Jacobian peak" and the orthogonal dispersion techniques.

We have observed the reaction

$$p + d \rightarrow \text{He}^3 + \pi^0 \tag{1}$$

and, for the first time, η^0 and ω^0 production in

$$p + d \rightarrow \text{He}^3 + \eta^0, \tag{2}$$

$$p + d \rightarrow \text{He}^3 + \omega^0, \tag{3}$$

at laboratory proton momenta (P_1) of 3.5-3.8 GeV/c. The center-of-mass differential cross sections ($d\sigma/d\Omega$) are of order of magnitude 10^{-34} cm^2/sr for mesons emitted at 60° (c.m.). The data, which are shown in Fig. 1 and listed in Table I, were obtained with a missing-mass spectrometer. Several interesting aspects of the data, in addition to the three obvious peaks, are mentioned below:

(1) A sharp shoulder appears at the 2π threshold which we have not been able to explain on the basis of pure phase space. Its appearance is different from the peaklike observations of the "ABC" effect.[1,2]

(2) The ρ^0 meson from the reaction

$$p + d \rightarrow \text{He}^3 + \rho^0 \tag{4}$$

is not apparent. However, because the shape of the multiparticle spectrum in the region of the ρ^0 meson is not known accurately, the cross section for Reaction (4) could be as high as that for Reaction (3).[3]

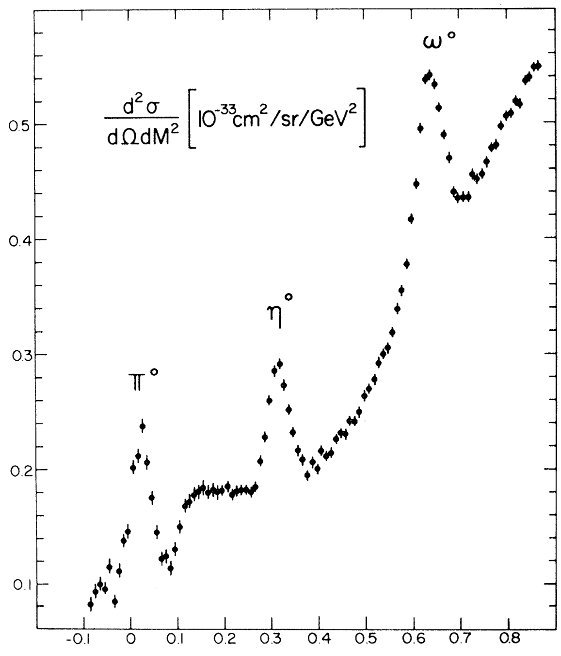

FIG. 1. The differential cross section as a function of the square of the missing mass. Each point corresponds to from 10 000 to 40 000 events. The points presented are the differences between full- and empty-target data. The empty-target distribution was smooth and constant. Because of the kinematics of our experiment $d^2\sigma/d\Omega_{\text{c.m.}}dm^2$ which we present is very similar in shape to $d^2\sigma/d\Omega_{\text{lab}}dp_{\text{lab}}$ which we detected.

Table I. Mesons observed in the reaction $p+d\rightarrow \mathrm{He}^3$ + missing mass at proton momentum of 3.8 BeV/c.[a]

Meson	Mass (MeV)	t (BeV/c)^2	u (BeV/c)^2	$d\sigma/d\Omega$ (c.m.) (10^{-34} cm^2/sr)
π^0	133 ± 3	−1.33	−5.54	0.8
η^0	550 ± 1	−1.44	−5.14	0.6
ω^0	783 ± 1	−1.60	−4.67	1.5
ρ^0	...	−1.60	−4.67	<1.6
"ABC"	300	−1.38	−5.40	...

[a] The three masses are fitted by a two-parameter fit for beam energy and angle calibration. Neither the ρ^0 nor the "ABC" was observed as a peak. The absolute values of the cross sections are good to within only a factor of 2 because of uncertainties in normalization and calibration of the absolute proton beam intensity. The relative values of $d\sigma/d\Omega$ (c.m.) are good to 10%.

(3) The cross section for Reaction (1) at 3.8 GeV/c (this experiment) is a factor of 1600 lower than the cross section found in an earlier experiment at 1.5 GeV/c.[1,4]

(4) The cross section for nonresonant production rises rapidly with missing mass. This could be due to the effects of multiparticle phase space. (On the basis of the momentum transfer to the meson or the probability of the He^3 sticking together, the lower masses should be slightly favored.)

An important aspect of Reactions (1)-(4) is that the mesons are produced at momentum transfers which are in order of magnitude higher than the momentum transfers involved in typical resonance production studies. If t is defined as the deuteron-to-He^3 (proton-to-meson) momentum transfer and u as the proton-to-He^3 (deuteron-to-meson) momentum transfer, then for this experiment t lies in the range from −1.33 to −1.6 (GeV/c)^2 and u lies in the range from −5.54 to −4.67 (GeV/c)^2 for meson masses between 0.135 and 0.782 GeV.

The experimental setup is shown in Fig. 2. The external proton beam (2×10^{11} protons/sec) of the Princeton-Pennsylvania Accelerator (PPA) was incident on a 10-in.-long liquid-deuterium target. The He^3 particles were bent vertically through an angle of 25° by a conventional magnet with an 8-in. gap. Identification of the He^3 was made by combining information from the pulse height in the counters, flight time, and momentum for each particle entering the system. All of the counters were attenuated to be sensitive only to particles with more than five times minimum ionization. The time of flight of the He^3 was determined by a coincidence between the rf structure of the proton beam (the extracted proton beam at PPA consists of 2-nsec pulses every 33 nsec) and a signal from the scintillation counters.[5]

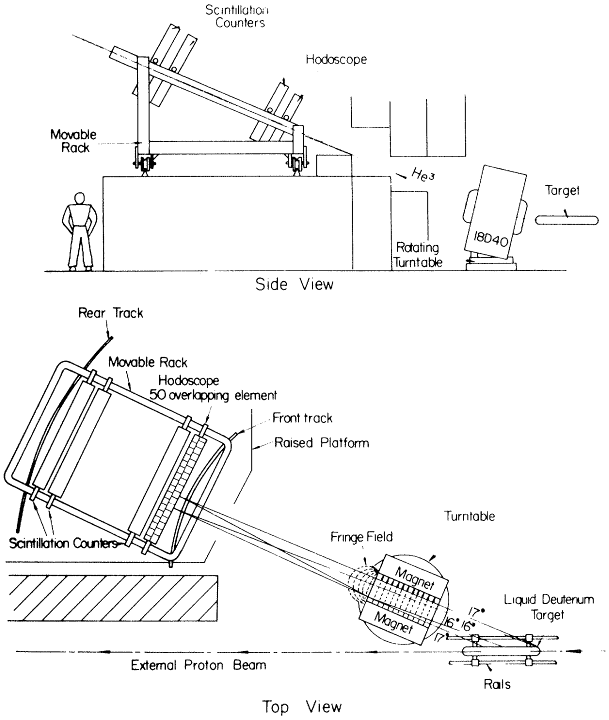

FIG. 2. Missing-mass spectrometer used at PPA. The plan view shows He^3 trajectories deflected vertically by a conventional bending magnet which was turned on its side. Parallel rays from the right are focused at the same lateral position at the left by the fringe field of the magnet. Since the He^3 angle is directly related to the mass of the missing meson, the lateral position in the 50-element hodoscope placed in the focal plane indicates the missing mass. Each hodoscope element was 1.5 in. wide. Coincidence between the overlapping sets of counters in the front and the rear of the hodoscope system provided lateral resolution of $\frac{3}{4}$ in. The momentum bite was defined by (1) the vertical size of the beam ($\frac{1}{4}$ in.); (2) a 2-in. vertical collimator before and in the magnet (not shown); (3) the aperture of the last two counters. The target dimensions (10 in. long) and the gap width (8 in.) were exaggerated for visibility.

The spectrometer was set to the momentum corresponding to the Jacobian peak.[6] The laboratory angle of the He^3 (θ_3) determines the mass of the missing meson. The momentum of the He^3 was measured only to about 7% without significantly affecting the mass resolution. The kinematics for the reaction are shown in Fig. 3.

All He^3 emitted at a given angle from the long

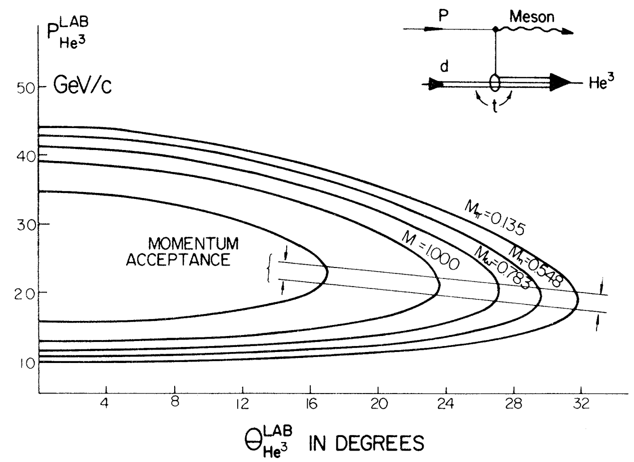

FIG. 3. Laboratory momentum of He^3 as a function of its laboratory angle. Each curve gives an angle-momentum correlation for a different missing meson. The PPA missing-mass spectrometer accepted a 7% momentum band around the maximum angle for each mass.

target were focused to a single spot in the horizontal plane by the fringe field of the vertical bending magnet.[7] Examples for rays at 16° and 17° are shown in Fig. 2. Wire measurements indicate that angle trajectories intersected to within $\frac{1}{4}$ in. at the focal plane. The angle θ_3 was determined by measuring a single lateral position along the He^3 trajectory with a 50-element hodoscope placed at the focal plane.

Because the momentum of the extracted proton beam at the PPA varied from 3.5 to 3.8 GeV/*c* during each spill cycle, it was possible to perform a number of different experiments simultaneously at slightly different bombarding energies to test the invariance of the mass of a peak with respect to changes in P_1. The value of P_1 was measured for each He^3 triggered by measuring the magnetic field of the synchrotron at that time of the trigger and storing the value in one side of a two-dimensional pulse height analyzer. The angle θ_3 was simultaneously recorded in the other dimension of the analyzer. Each run then contained an angular distribution for each of 55 P_1 intervals. Photographs (a) and (b) in Fig. 4 show typical angular distribution at a given P_1. Photograph (c) shows a three-dimensional display in which a specific missing mass appears as a ridge.

Each deuterium run was followed by an empty-target run lasting about half as long. The ratio of the He^3 counting rates for full to empty target was 2:1 for the π mass region and 4:1 for the ω mass region. The typical counting rate was 10 000 He^3/h with the target full. Runs were also taken with liquid hydrogen in the target, with a short carbon target, and with a long Mylar target. These runs permitted a calculation of the geometric response of the system. For each setting of the magnet angle runs were taken with the hodoscope and counter telescope set at the same angle as the magnet and at ±0.35° from the nominal angle. The angular acceptance of the counters was ±1° at each setting. The overall system could be rotated from 20° to 32°.

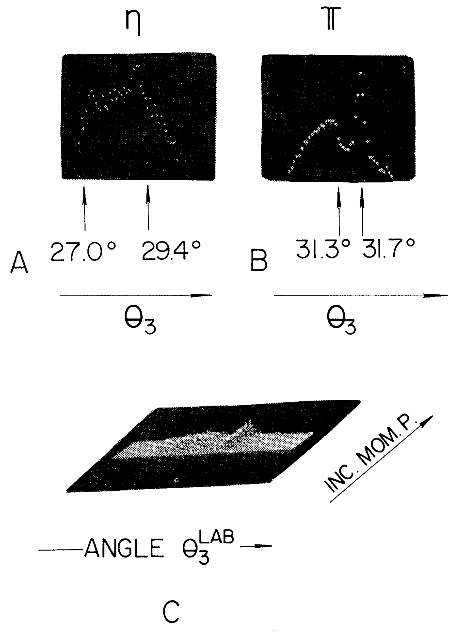

FIG. 4. Examples of hodoscope distributions observed directly on pulse-height analyzer after two hours of running. The η and π peaks are clearly seen in photographs (a) and (b), respectively. One such distribution was obtained for each value of incident proton momentum. When angular distributions for many incident momenta are displayed in three dimensions a real particle appears as a ridge, as shown in photograph (c).

Mass spectra from different runs have been combined with a computer program which normalizes the data on the basis of monitor counts, corrects for the shape of the P_1 distribution and for the geometric response, and subtracts empty-target points from corresponding full-target points. Figure 1 is a combined mass spectrum containing about 10^6 events obtained in about ten days of running. The half-width resolution calculated from the observed widths of the π and η peaks is

$$\Delta M^2 = 0.025 \pm 0.003 \text{ GeV}^2. \qquad (5)$$

This resolution is very weakly dependent on M^2.

The resolution in M may be obtained by dividing (5) by $2M$.

In this experiment the He^3 is emitted backward with respect to the proton in the center-of-mass system, at about 120°. We assume that this corresponds to the exchange diagram shown in the upper right-hand corner of Fig. 3. The upper vertex is the "fundamental" nucleon-antinucleon-meson vertex, which is open to all $I = 0, 1$ excitation channels, in contrast to the reaction of the type $\pi + p \rightarrow$ nucleon + meson, in which the type of meson produced depends strongly on the exchanged particle and its coupling to the pion.

Barshay[8] has attempted to explain the large decrease in the cross section from 1.5 to 3.8 GeV/c, using both a Regge and a Feynman propagator. A Regge propagator without damping at the He^3 vertex, $s^{2\alpha(t)-1}$ with $\alpha(t) = -0.35 + t$, gives a depression of 1:870 between 1.5 and 3.8 GeV/c and the corresponding t values. An alternative explanation, which introduces a damping at each of the vertices in the exchange diagram, gives a depression of the order of 1:720.

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§On leave from Laboratoire Saturne, Centre d'Etudes Nucléaires, Saclay, France.

[1] A. Abashian, N. Booth, K. Crowe, R. Hill, and E. Rogers, Phys. Rev. 132, 2296 (1963); N. E. Booth, Phys. Rev. 132, 2305 (1963); N. Booth *et al.*, Phys. Rev. 132, 2309 (1963); N. Booth and A. Abashian, Phys. Rev. 132, 2314 (1963). A complete list of previous references on Reaction (1) is in the first of these papers.

[2] J. Banaigs, J. Berger, J. Duflo, L. Goldzahl, M. Cottereau, and F. Lefebvres, presented at the Fifth International Conference on Elementary Particles, Lund, Sweden, 25 June-1 July 1969 (unpublished). See also B. Maglić, in *Proceedings of the Lund International Conference on Elementary Particles, Lund, Sweden, 25 June-1 July 1969,* edited by G. von Dardel (Berlingska Boktryckeriet, Lund, Sweden, 1970), p. 269.

[3] The apparent absence of Reaction (4) might be expected from the suppression of an $I = 1$ particle in the $I = 0$ state by a factor of 3. Purely on the basis of isospin considerations the cross section should be divided between the channels

$$p + d \rightarrow He^3 + \rho^0$$

and

$$p + d \rightarrow T^3 + \rho^+$$

in the ratio of 1:2. Also since the width of the ρ^0 is large the peak height should be much lower than that of an ω^0 of the same cross section.

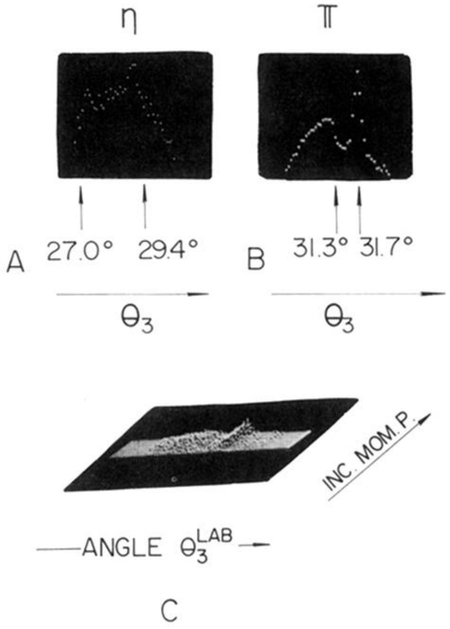
[4] Note that the c.m. angles in the two experiments are not quite the same. To compare our observed $d\sigma/d\Omega$ at the c.m. angle of 60° with that at $P_1 = 1.5$ GeV/c, we average the data from Ref. 1 and obtain a value of 1.3×10^{-31} cm^2/sr ($t = -0.35$, $s = 10.6$) which should be compared with our value of 0.8×10^{-34} cm^2/sr at 3.8 GeV/c ($t = -1.33$, $s = 19.17$).

[5] When the pulse-height rejection was applied, the time-of-flight spectrum showed the narrow He^3 peak clearly separated in time from the positions of the proton and the He^4-deuteron peaks; the typical signal-to-background ratio of the He^3 peak in the time-of-flight spectrum was about 10.

[6] B. Maglić and G. Costa, Phys. Letters 18, 185 (1965).

[7] W. Cross, Rev. Sci. Instr. 22, 717 (1951). See also C. M. Ankenbrandt, A. R. Clark, B. Cork, T. Elioff, L. T. Kerth, and W. A. Wenzel, IEEE Trans. Nucl. Sci. 12, No. 4, 113 (1965).

[8] S. Barshay, Princeton-Pennsylvania Accelerator Report No. PPAR-23, 1969 (unpublished).



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