Evidence for an Anomaly in the Excitation Function of the Reaction $^2H(p, \gamma)^3He$†

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The excitation function of the capture reaction $^2H(p, \gamma)^3He$ has been measured in the range $E_p = 10-17.5$ MeV. An anomaly was observed and is interpreted as a broad resonance in ^3He at an excitation energy of 14.5 ± 0.5 MeV with a width of about 2 MeV.

The study of possible excited states in the three-nucleon system was initiated both experimentally and theoretically when Ajdacić *et al.*[1] reported evidence for the existence of a bound trineutron in the reaction $^3H(n, p)nnn$. In the inelastic reaction $^3He(p, p')^3He$, Kim *et al.*[2] also reported evidence for three excited states in ^3He at excitation energies of 8.2, 10.2, and 12.6 MeV. Both reactions were subsequently repeated and the results were not confirmed. Thereafter, many searches have been made by means of a variety of nuclear reactions.[3] Most of them gave no indication of the existence of excited states in the three-nucleon system.

A theoretical investigation of the resonance behavior in the three-nucleon system has been performed by Benöhr.[4] With a simple soft-core two-nucleon potential and a variational technique, he found three broad resonances with quantum numbers $(L, S, T) = (1, \frac{1}{2}, \frac{3}{2})$, $(1, \frac{3}{2}, \frac{1}{2})$, and $(1, \frac{1}{2}, \frac{1}{2})$. In the phase-shift analysis of nucleon-deuteron scattering,[5] the quartet p-wave shift shows a positive excursion of about 40° for $E_p = 2-5$ MeV, and the doublet p-wave phase shift has a small positive rise at high energy. These preliminary results could indicate the existence of negative-parity resonances in the three-nucleon system. Theoretical Argand plots[6] for $^{2S+1,2T+1}T_L$ $[T = (i\pi q)^{-1} \times (\eta e^{2i\delta} - 1)$, where q is the nucleon momentum and η the absorption coefficient] indicate a broad ^{42}P $(\equiv {}^{2S+1,2T+1}L)$ resonance at $E + \frac{1}{2}i\Gamma \simeq 14 - 5i$ MeV and another broad ^{22}P resonance at $E + \frac{1}{2}i\Gamma \simeq 18 - 8i$ MeV. It is unlikely that these p-wave resonances would stand out in the excitation curves of the nucleon-deuteron elastic scattering when superimposed on a nonresonant background. Indeed, it has been suggested[6] that the most expedient way to detect the p-wave resonances would be an analysis of experimental phase shifts.

If one wants to observe the suggested p-wave resonances directly, one has to choose a nuclear reaction which would preferentially select the p-wave process. One nuclear reaction which possesses this selectivity is the capture reaction $^2H(p, \gamma)^3He$. Since $E1$ radiation dominates in this reaction,[7] the contribution of p waves in the entrance channel is also dominant. Recently, Van der Woude *et al.*[8] reported evidence for the existence of a broad $T = \frac{1}{2}$ resonance in ^3He in the excitation function for the radiative capture of deuterons by protons, $^1H(d, {}^3He)\gamma$. The resonance is at an excitation energy of 19.5 ± 0.5 MeV with a width of about 2 MeV. In this Letter we report an anomaly in the excitation function of the reaction $^2H(p, \gamma)^3He$, which could be interpreted as a broad resonance in ^3He at an excitation energy of 14.5 ± 0.5 MeV with a width of about 2 MeV.

The proton beam was obtained from the Stanford FN tandem Van de Graaff. The proton energy was varied from 10 to 17.5 MeV in 0.5-MeV steps (from 12 to 14 MeV, 0.25-MeV steps were taken). γ rays resulting from the capture process were detected with a 24-cm × 24-cm NaI(Tl) detector surrounded by plastic scintillators operated in an anticoincidence mode. Details of this γ-ray spectrometer have been described elsewhere.[9] Excitation curves were taken with the spectrometer fixed at 90° in the laboratory system. Because of the low cross section (peak cross section $\simeq 1$ μb/sr) and low Q value (+5.495 MeV) of the reaction $^2H(p, \gamma)^3He$, it was necessary to reduce the background γ rays resulting from neutron capture in the NaI crystal itself and in the surrounding material. To accomplish this, the target and the detector were shielded by paraffin. In addition, a pulsed beam combined with the time-of-flight technique was used. Details of this method are described elsewhere.[10] Briefly, a fast negative signal from the photomultiplier of the detector starts a time-to-amplitude converter (TAC). The logic signal which stops the TAC is obtained from the beam pulsing system. The TAC output is both stored and sent to timing single channel analyzers to route linear signals from the NaI detector.

Figure 1(a) shows a typical time-of-flight spectrum taken at $E_p = 11.0$ MeV; Fig. 1(b) shows an

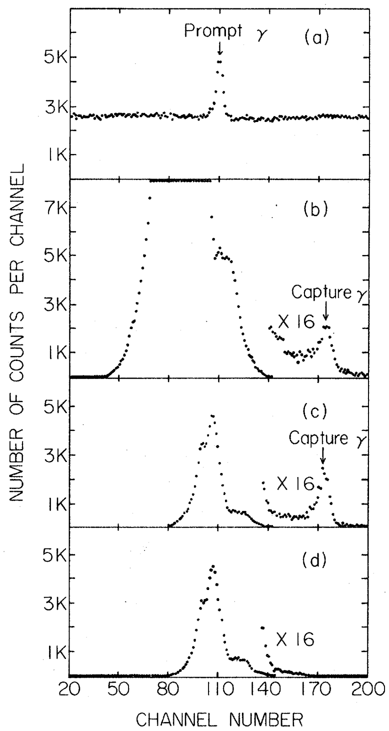

FIG. 1. Typical $^2H(p,\gamma)^3He$ run taken at $E_p = 11.0$ MeV and $\theta_{lab} = 90°$. (a) TAC spectrum; (b) ungated γ spectrum; (c) and (d) γ spectra obtained by gating the pulse-height analyzer by windows set on the prompt γ peak and on the flat background, respectively, in the TAC output.

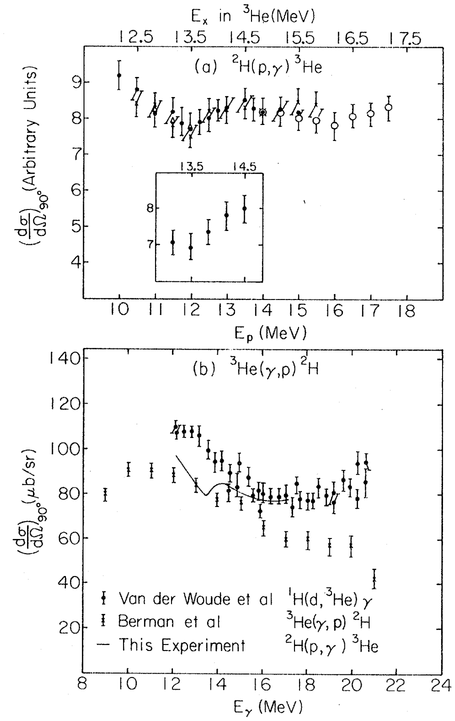

FIG. 2. (a) 90° yield curve for $^2H(p,\gamma)^3He$ obtained by fitting an appropriate line shape to each γ spectrum gated by the "γ window." Different symbols correspond to different runs. Inset, results when the gas-out runs were subtracted from the gas-in runs for $E_p = 11.5$ to 13.5 MeV; (b) Comparison of the present results, converted to photodisintegration data, with those of Refs. 9 and 13.

ungated γ spectrum; Figs. 1(c) and 1(d) show γ spectra obtained by gating the pulse-height analyzer by windows set on the prompt γ peak and on the flat background, respectively, in the TAC output. It is evident that the analysis of the ungated spectrum, Fig. 1(b), would require extrapolating a background curve into the photopeak region of the capture γ rays. No such extrapolation is required for the spectrum gated by the "γ window," Fig. 1(c).

Three separate yield curves were taken. For the first two, a stainless-steel, cylindrical gas cell 0.687 in. in diameter and 2.25 in. long was used. The gas cell was provided with an entrance and exit foil so that the proton beam passed through the cell and was stopped about 26 ft from the target in a beam dump buried in the wall. In the third run, the cell was lined with gold and had only one entrance foil; the beam was stopped at the other end of the cell by a gold stopper. In all three runs, the foils and the gold beam stopper were shielded with at least 2 in. of lead.

Figure 2(a) shows the 90° yield curve. Each point in this curve was obtained by a least-squares fit with an appropriate γ-ray line shape to the spectrum gated by the "γ window." The results obtained by fitting a γ-ray line shape to the "ungated" γ spectrum, Fig. 1(b), gave an excitation function with the same shape as that shown in Fig. 2(a), but lying about 10% higher. Corrections for detector efficiency and γ-ray attenuation through the paraffin surrounding the gas target have not been made to the results of Fig. 2(a) since these two factors tend to cancel each other, and the overall final results would not be changed by more than 3%.[11]

Broad structure is clearly seen in Fig. 2(a). This anomaly around $E_p = 13$ MeV could be interpreted as a broad resonance in ^3He at an excitation energy of 14.5 ± 0.5 MeV with a width of about 2 MeV. Two runs were made to look for possible extraneous causes which could give rise to the anomaly seen in Fig. 2(a). First, the gas cell was filled with air in order to observe the capture γ rays from $^{14}N(p,\gamma)^{15}O$ ($Q = 7.293$ MeV).

By comparing the yields of other capture γ rays to those of $^{14}N(p,\gamma_0)^{15}O$, it was concluded that the anomaly seen in Fig. 2(a) could not be caused by an air contaminant. Second, runs were taken with an empty gas cell for $E_p = 11.5$ to 13.5 MeV in order to determine the background γ-ray spectrum resulting from the window foils or gold stopper. The inset in Fig. 2(a) shows the results obtained by subtracting the gas-out runs from the gas-in runs. It is clear that the rise in the cross section beyond $E_p = 12.0$ MeV could not be caused by γ-rays from the gas cell.

Figure 2(b) shows our results together with the results of other measurements.[8,12] Our data have been converted to photodisintegration data by the principle of detailed balance, and are shown as a solid curve in Fig. 2(b). The absolute cross sections were obtained by normalizing the cross section at $E_p = 10$ MeV ($E_\gamma = 12.16$ MeV) to the previous measurement made at Stanford.[13] Our data do not extend to high enough energy to cover the region of the resonance reported by Van der Woude *et al.*[8] at 19.5 MeV. Also, the structure observed in the present experiment is not seen clearly in Ref. 8 in the region where the two experiments overlap. This could be explained if one assumes that the resonances reported in this Letter and in Ref. 8 are characterized by $(L, S, T) = (1, \frac{3}{2}, \frac{1}{2})$ and $(1, \frac{1}{2}, \frac{1}{2})$, respectively.[6] Since the lower $S = \frac{3}{2}$ resonance involves an extra spin flip, it might be expected to show up less prominently in the yield curve.

The very recent work[14-16] on the photodisintegration and electrodisintegration of ^{3}He fails to show any anomaly at $E_\gamma \simeq 20$ MeV, although a slight anomaly might be evident at $E_\gamma \simeq 15$ MeV.[14] Arvieux[17] has recently reanalyzed the available data on the nucleon-deuteron scattering cross section between 0 and 20 MeV. The main results of his analysis seem to indicate a large ^2P resonance centered around $E_x \simeq 15$ MeV in ^{3}He and perhaps a less pronounced ^4P resonance at $E_x \simeq 13$ MeV. Therefore, the assignment of the correct quantum numbers to the broad resonance reported in this Letter must await a more complete phase-shift analysis of the nucleon-deuteron scattering using a general formalism including the mixing parameters.[17]

Finally, it is interesting to note that a discrepancy exists in the excitation function beyond $E_\gamma \simeq 16$ MeV between the radiative p-d capture reaction and the inverse photodisintegration of ^{3}He [see Fig. 2(b) and Ref. 14]. The former curve seems to level off (or even increase) for $E_\gamma > 16$ MeV, while the latter continues to decrease in magnitude. The reason for this discrepancy is not known.

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