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The Reactions $T(p,n)He^3$ and $T(p,\gamma)He^4$

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A differential cross-section curve for neutrons emitted at 0° from the reaction $T(p,n)He^3$ has been measured from threshold to 5.09 Mev. A broad maximum appears at 3 Mev. Angular distributions were taken at approximately 0.4-Mev intervals and are nonsymmetrical about the 90° plane in the center-of-mass system. An 80° relative yield curve of gamma-rays from the $T(p,\gamma)He^4$ reaction was obtained from 1 to 5 Mev. It increases up to 3-Mev proton energy and then levels off.

I. INTRODUCTION

The reaction $T(p,n)He^3$ has been previously studied in some detail from its threshold of 1.019 Mev[1,5] to 2.8 Mev by the group at Los Alamos.[1,6] From their measurements they infer a p wave resonance in He^4 at a proton energy of less than 3 Mev.

A 20-Mev gamma-ray is obtained from the $T(p,\gamma)He^4$ reaction, and its properties have been measured at Los Alamos[7,8] up to 2.5 Mev, while Falk and Phillips' data[9] extend to 3.4 Mev. Rochlin[10] has measured the spectrum and yield of this gamma-ray at 0.96 Mev.

Because of the interest in an excited state in He^4, it was thought worth while to measure some of the constants of these reactions up to 5-Mev proton bombarding energy.

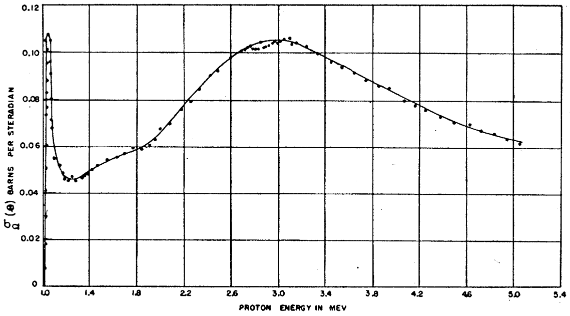

FIG. 1. The differential cross section in the laboratory system for neutrons emitted from the $T(p,n)He^3$ reaction at 0°.

II. PROCEDURE

Analyzed protons from the 5.5-Mev Van de Graaff at Oak Ridge were used to bombard a thin T—Zr target[11] backed with 20-mil tungsten. This backing material and the rather large amount of brass in the target holder caused considerable absorption and "in-scattering" of the neutrons at laboratory angles of 60° to 140°. Therefore, these measurements were repeated with a thin-walled gas target cell of tritium and a 0.2-mil Al foil window. A conventional type integrator monitored the beam current.

Neutrons were detected with a flat response long counter[12] located about 100 cm from the target. The background of neutrons scattered by the floor, walls, and magnet, as determined by interposing a 25-cm shadow cone of paraffin between the target and detector, was subtracted, a correction which varied from 2 to 11 percent, the latter being at the minimum of the angular distributions and at the highest proton energy.

Figure 1 shows the differential cross section for neutrons emitted in the forward direction (laboratory system). The absolute magnitude was obtained by normalizing our relative yield data to the cross section at 1.4 Mev observed at Los Alamos.[6] This curve exhibits the well known "geometric peak" just above threshold, indicating a target thickness of 35 kev, and a broad maximum at 3 Mev. The slight dip just below the maximum was repeated several times and is real.

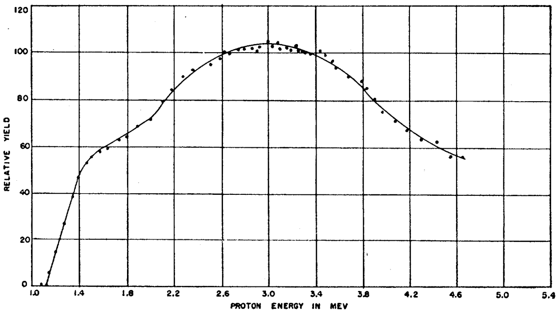

FIG. 2. A relative curve of neutrons emitted at 0° as measured by a propane-hydrogen recoil counter, uncorrected for efficiency.

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[1] Taschek, Jarvis, Argo, and Hemmendinger, Phys. Rev. **75**, 1268 (1949).

[2] Hemmendinger, Jarvis, and Taschek, Phys. Rev. **75**, 1291 (1949).

[3] Taschek, Jarvis, Hemmendinger, Everhart, and Gittings, Phys. Rev. **75**, 1361 (1949).

[4] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **76**, 168 (1949).

[5] Taschek, Argo, Hemmendinger, and Jarvis, Phys. Rev. **76**, 325 (1949).

[6] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **79**, 929 (1950).

[7] Argo, Gittings, Hemmendinger, Jarvis, Mayer, and Taschek, Phys. Rev. **76**, 182 (1949).

[8] Argo, Gittings, Hemmendinger, Jarvis, and Taschek, Phys. Rev. **78**, 691 (1950).

[9] C. E. Falk and G. C. Phillips, Phys. Rev. **83**, 468 (1951).

[10] R. S. Rochlin, Phys. Rev. **84**, 165 (1951).

[11] This target was loaned to us through the courtesy of Professor T. W. Bonner of the Rice Institute.

[12] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

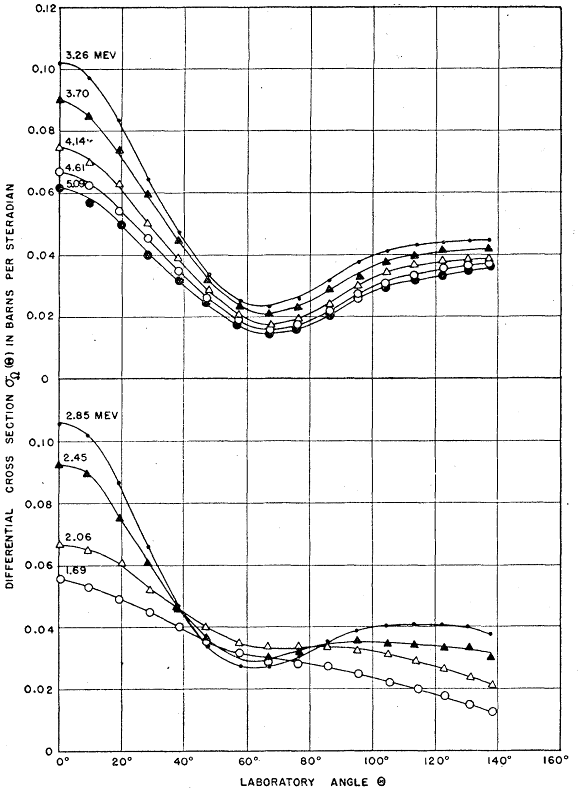

FIG. 3. Differential cross sections in the laboratory system for the T(p,n)He^3 reaction.

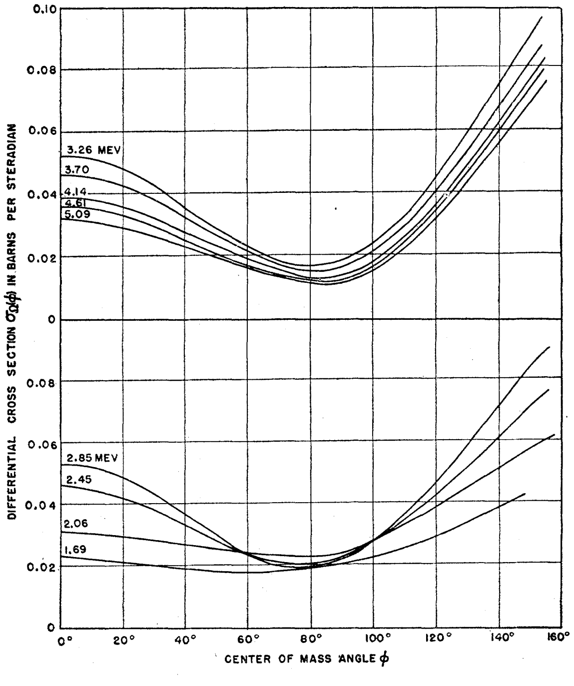

FIG. 4. Differential cross sections in the center-of-mass system for the T(p,n)He^3 reaction.

In order to check instrumental difficulties, a hydrogen recoil counter (propane gas at 1 atmosphere) was used to measure the forward neutrons. Figure 2, uncorrected for counter efficiency, presents these data. Low energy neutrons were biased against, and hence no geometrical peak was observed. Since there is no minimum between 2.6 and 3.1 Mev, we have concluded that the long counter has a small decrease in sensitivity for neutrons of about 2.1 Mev due to the large scattering resonance in carbon at this energy.[13]

Angular distributions of the neutrons were taken at proton energies of 1.69, 2.06, 2.45, 2.85, 3.26, 3.70, 4.14, 4.61, and 5.09 Mev and at laboratory angles of 0=1°, 9.7°, 19.3°, 28.9°, 38.6°, 48.2°, 57.7°, 67.3°, 76.8°, 86.2°, 95.5°, 104.6°, 113.6°, 122.8°, 130.4°, and 137.8°. Our beam makes a 15° angle with the horizontal, and the above angles result from measuring 10° intervals in the horizontal plane. These data corrected for background and normalized to the 0° differential cross section are plotted in Fig. 3. All measurements were monitored with a BF$_3$ Bonner-Butler-type counter[14] held in the −90° position, as well as by the beam current.

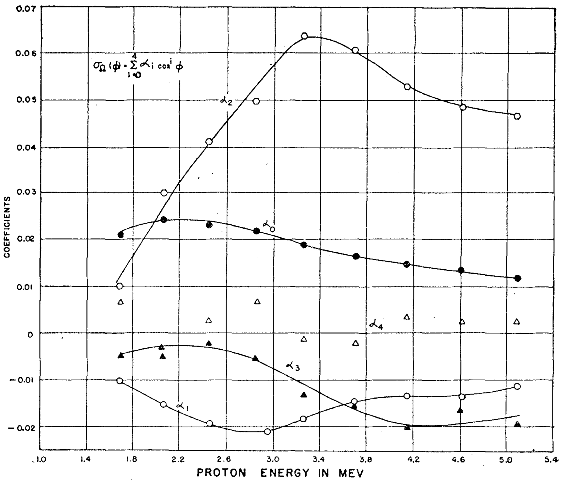

FIG. 5. Coefficients for the expansion $\sigma_\Omega(\varphi)=\sum_{i=0}^{4}\alpha_i\cos^i\varphi$.

Center-of-mass cross sections were obtained by the usual conversion formulas, and Fig. 4 shows the results as a function of the angle $\varphi_{\text{c.m.}}$. Analysis of these curves was made in terms of a series expansion of $\cos\varphi_{\text{c.m.}}$.

$$\sigma_\Omega(E_p,\varphi)=\sum_{i=0}\alpha_i(E_p)\cos^i\varphi, \qquad (1)$$

where terms through $i=4$ were sufficient to obtain a fit within the limits of experimental error. The energy dependence of the coefficients $\alpha_i(E_p)$ appears in Fig. 5.

The total cross section for the T(p,n)He^3 reaction

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[13] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).

[14] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).

may be obtained by integration of Eq. (1) to give

$$\sigma_{\text{total}}=\int \sigma_\Omega E_p(\varphi)d\Omega=4\pi(\alpha_0+\tfrac{1}{3}\alpha_2+\tfrac{1}{5}\alpha_4+\cdots). \quad (2)$$

Our calculated values of σ_{total} as a function of E_p are drawn as a smooth curve in Fig. 6.

Gamma-rays were detected with a NaI scintillation counter located at 80° and subtending a half angle of 15°. All data were obtained with the T—Zr target. Differential pulse-height curves taken as 0.98, 1.13, and 4.99 Mev are shown in Fig. 7. The rise in curve *A* below a setting of 200 units is due to the gamma-rays of zirconium. A sharper rise appears in curve *B*, just above the neutron threshold, and is due to neutron capture in the iodine. Both curves have an end point of about 350 units caused by the gamma-ray from the proton capture in tritium. Curve *C* shows the effect of increasing the excitation energy both on the neutron capture in iodine, and the end point of the T(p,γ)He^4 gamma-ray. The ordinate scale factor for curve *C* is approximately twice that for curves *A* and *B*. A relative yield curve at 80°, Fig. 8, was obtained by setting the differential pulse-height selector at 275 units and correcting only for the energy variation of the gamma-ray absorption coefficient in NaI. Integral data, when corrected for the increase in pulse-height setting with gamma-ray energy, are in agreement with this curve.

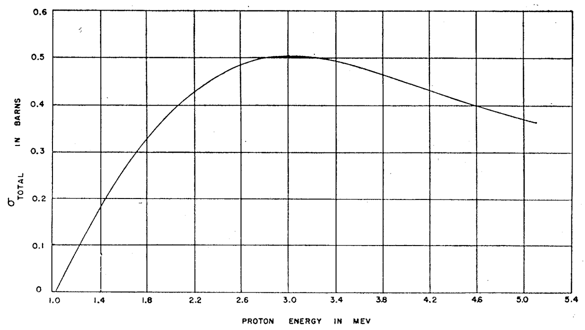

FIG. 6. The total cross section of the T(p,n)He^3 reaction.

III. DISCUSSION

The neutron data are in general agreement with that of Los Alamos, although our 0° yield curve does not show a rise between 2.0 and 2.8 Mev. More recent measurements from that laboratory extend to 4 Mev,[15] and the newer data are more nearly alike.

Comparison of the relative yield curves of gamma-rays indicates that the slope of our curve between 1 and 3 Mev is less than that obtained by either Los Alamos or Falk and Phillips. This may be due to background problems in the first case, and choice of pulse-height setting in the second and our case. Perry[16] and Bame at Los Alamos have re-run this yield curve up to 4 Mev and obtained results similar to ours.

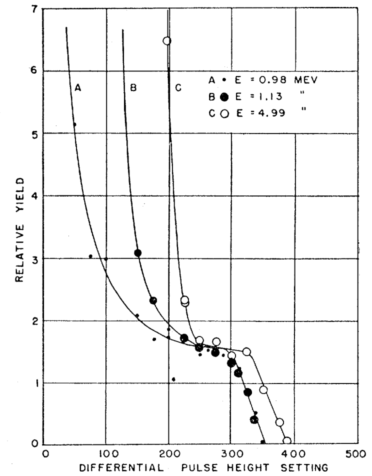

FIG. 7. Differential pulse-height curves for gamma-rays resulting from the proton bombardment of a T—Zr target: *A*. Just below the neutron threshold. The rapid rise below 200 units is due to proton capture in Zr; *B*. Just above the neutron threshold. The rapid rise below 250 units is due to neutron capture in the iodine of NaI crystal; *C*. At high proton energy. The more rapid rise of counting rate is due to the increased neutron energy available for excitation.

An attempt was made to fit the T(p,n)He^3 total cross section with the single level Breit-Wigner dispersion formula. This is the most general application, since both the proton and neutron level widths vary markedly with energy and angular momentum, and the level shift is not a negligible factor. Moreover, it is evident from the lack of symmetry in the center-of-mass distributions about the 90° plane, that at least two states of opposite parity are involved. In such light particle reactions where the level width is broad and hence the lifetime short, it is even somewhat questionable whether one can speak of a compound nucleus being formed. It was, therefore, not too surprising to find that a fit could be obtained with various sets of parameters. In view of this situation we feel safe in stating only that the interaction is predominantly *p* wave with a small admixture of *s* wave.

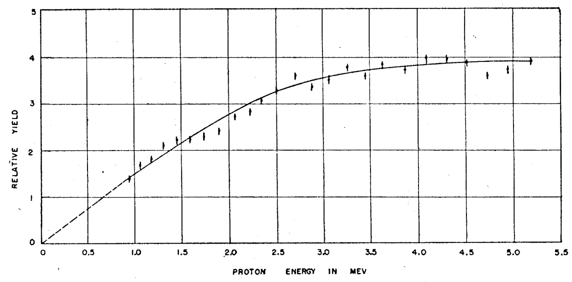

FIG. 8. A relative yield curve for gamma-rays emitted at 80° from the reaction T(p,γ)He^4.

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[15] G. A. Jarvis (private communication).

[16] J. E. Perry, Jr. and S. J. Bame, Jr., Bull. Am. Phys. Soc. **28**, No. 1, 51 (1953).