Angular Distributions of T(p,n)He^3 Neutrons for 3.4- to 12.4-Mev Protons*

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Angular distributions of the neutrons from the T(p,n)He^3 reaction have been obtained for incident laboratory proton energies of 3.4, 4.3, 5.0, 6.5, 8.0, 8.8, 10.3, 11.5, and 12.4 Mev. The neutrons were detected by a plastic scintillator, and standard time-of-flight techniques were used to separate the monoenergetic neutron group from background neutrons and gamma rays. The distributions in the center-of-mass system show substantial backward peaking. Above about 8-Mev proton energy, a broad maximum appears at about 80° (c.m.) and persists through the highest energy measured. The absolute 0° cross sections and the total integrated cross sections are in excellent agreement with previous measurements.

INTRODUCTION

THE $T(p,n)$He^3 reaction, with a Q of -0.7634 Mev,[1] is a useful source of monoenergetic fast neutrons. From threshold at 1.019 Mev to 1.148-Mev laboratory proton energy, the neutrons are confined to a gradually opening cone which contains two energy groups. Above 1.148 Mev, the reaction provides a strictly monoenergetic group of neutrons until the threshold at 8.34 Mev for the T(p,pn)D tritium breakup reaction is reached. For higher proton energies, techniques must be used that will distinguish the monoenergetic group from the breakup group, which groups are well resolved in energy from each other.

Previously reported angular yield measurements for laboratory proton energies greater than 2 Mev[2–6] were made with "flat-response" long counters.[7] The variation of the sensitivity of such a counter with energy has recently been shown[8] to be neither flat nor smooth, the principal deviations being strongly correlated with the shapes of the variation with energy of the total cross section of carbon. The results of this work indicate that long-counter measurements may be subject to systematic errors of as much as 20%. The Los Alamos group has measured[8] angular distributions for T(p,n)He^3 neutrons, for incident laboratory proton energies between 1.5 and 5.5 Mev, using a proton recoil counter telescope to determine the detailed energy sensitivity of their particular long counter.

From the theoretical point of view, the broad peak in the total cross section for this reaction,[3,4] with a maximum at about 3 Mev, has been interpreted[4,9] as indicating an excited state of He^4. On the other hand, Selove[10] has pointed out that the broad maximum, and also the shape of the angular distributions, can be explained in terms of a simple picture which invokes a direct interaction mechanism and implies that a compound-nucleus state is not involved. Young and Stein[11] have done an extensive analysis of this reaction, based on the Selove model, in which they represent the triton as a cluster-model system (deuteron core plus neutron), and treat in Born approximation the direct processes involved; i.e., the proton either "knocks on" the neutron or "picks up" the deuteron core. The calculations are compared with the experimental data,[8] and reasonably quantitative agreement is found. In particular, the observed dependence of backward-to-forward scattering upon energy is well represented.

The present work provides angular distributions for neutrons from the T(p,n)He^3 reaction, for incident laboratory proton energies of 3.4, 4.3, 5.0, 6.5, 8.0, 8.8, 10.3, 11.5, and 12.4 Mev. Above 7 Mev, the only previously published[5] angular yield curves are at 8.9 and 12.0 Mev.

EXPERIMENT

The protons were provided by the external beam of the Livermore variable-energy cyclotron. The tritium gas (at just under 1 atm pressure) was contained within a stainless steel cylinder 4 in. long×1 in. diam. A 0.020-in tantalum beam stopper prevented proton bombardment of the stainless end wall. The protons entered the target through a 0.00025-in. (about 12 mg/cm^2) tantalum foil. The energy of the incident protons is determined by means of a differential range measurement in aluminum. The uncertainty in the beam energy due to the range measurement, the intrinsic energy spread of

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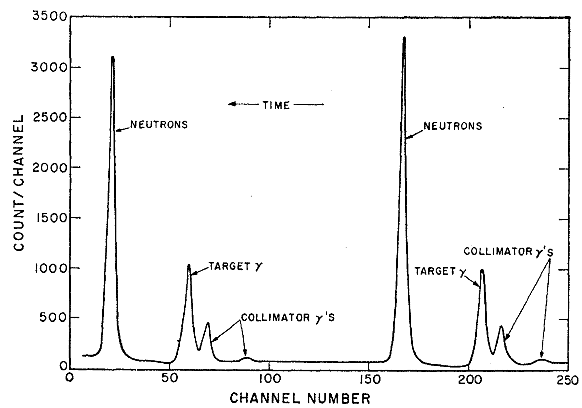

FIG. 1. Typical time-of-flight spectrum. The incident proton energy is 8.0 Mev, and the neutron angle is 0° with respect to the proton direction. The double display results from using one stop pulse for every two rf cycles in the time-to-pulse height converter (reference 12).

the cyclotron beam, and drifting of the beam energy is about ±2%.

The neutron detector was mounted on a remotely controllable angle changer, which was pivoted directly under the center of the gas target. The selsyn control in the counting area permitted accurate changes in steps of about 0.2° and was reproducible to better than 0.5°.

The time-of-flight system used has been previously described.[12] The plastic scintillator neutron detector was a cylinder, 1-in. diam and 1-in. thick, mounted on an RCA 6655A phototube. The bias level for the detector was set with respect to the Compton edge of the annihilation radiation (0.511 Mev) from a Na^{22} source. A bias setting equal to the Compton edge was used for the highest-energy neutrons, and bias settings of one-half and one-quarter the Compton edge were used for successively-lower-energy neutrons. The efficiency at each bias setting was calculated[13] and compared with an absolute measurement using the $D(d,n)He^3$ reaction.[14]

The angular resolution as determined by the target size, crystal size, and target-to-crystal spacing was about 1.2° at 0° and about 4° at 90° for energies up to 6.5 Mev, and about 0.7° at 0° and 2.5° at 90° for 8.0 Mev and above. The position of 0° was determined by telescopic alignment of collimators, target, and crystal, and was good to an estimated accuracy of ±0.5°.

The neutron production was monitored by collecting the charge accumulated by the tritium gas target.

RESULTS

A typical time-of-flight spectrum, as displayed on a 256-channel pulse-height analyzer, is shown in Fig. 1.

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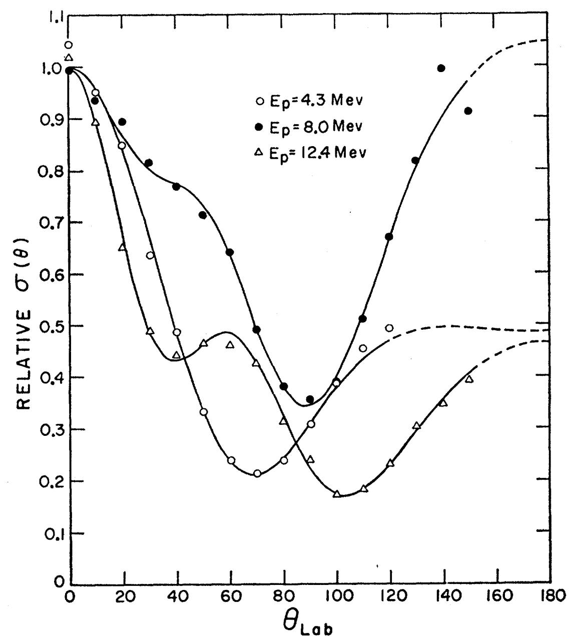

FIG. 2. Typical relative angular distribution data. The curves are least-squares fits to the data. The dashed portions are values of the least-squares curves outside the range of the experimental data.

Data were taken in steps of 10° from 0° to 150° with respect to the incident proton direction. At lower proton energies (3.4, 4.3, and 5.0 Mev), the rapidly decreasing scintillator efficiency due to the cutoff imposed by the bias setting rendered the back-angle points increasingly uncertain. When the uncertainty was estimated to be greater than 10%, the points were not used. Each cross section measured was corrected for dead time of the pulse-height analyzer, which was occasionally as high as 20% but was more typically 10%. In addition, the data at back angles were corrected for neutron attenuation due to the flanges of the gas target, the target foil retaining assembly, and the beam pipe. The correction ranged from about 5% at 90° to about 25% at 150°.

Typical relative angular distribution data are shown in Fig. 2. The proton energies are 4.3, 8.0, and 12.4 Mev. An uncertainty of 5% can be assigned to all the data points except for the 110° and 120° points at 4.3 Mev and the 140° and 150° points at 8.0 Mev, where the uncertainty is 10%. The curves are least-squares fits (see below), and the data are normalized so that the cross sections are unity at 0°.

When the absolute data are transformed to the center-of-mass system they can be least-squares fitted by a sum of powers of the cosine, i.e., $\sigma(\theta)=\Sigma_n a_n \cos^n\theta$. The order n used for the fitting was determined by a chi-square test. The values of the expansion coefficients for each proton energy are tabulated in Table I. The variation of these coefficients with incident proton energy, shown in Fig. 3, provides a means of constructing angular yield curves for any energy through the

TABLE I. Expansion coefficients (in mbs/sr) resulting from fitting angular distributions with a sum in powers of the cosine. Total cross sections (in mb) from integration of the cosine sum.

E_p(Mev)	a_0	a_1	a_2	a_3	a_4	σ_T
3.4	19.6±0.7	−15.5±2.6	58.4±5.4	−9.5±6.4		491
4.3	13.6±0.4	−9.8±1.5	56.6±3.2	−19.0±4.1		408
5.0	12.1±0.4	−4.4±1.6	47.8±5.2	−23.8±5.2		345
6.5	9.8±0.3	4.9±1.1	22.9±2.6	−41.0±2.1	23.3±3.4	278
8.0	11.1±0.3	9.5±0.9	1.2±2.3	−36.5±2.1	29.4±3.1	219
8.8	11.2±0.3	9.8±0.8	−5.5±2.1	−33.9±1.6	32.6±2.5	200
10.3	12.4±0.3	9.2±0.8	−16.3±2.0	−29.2±1.4	39.1±2.4	186
11.5	12.0±0.3	8.7±0.7	−21.7±1.8	−23.4±1.3	40.9±2.2	162
12.4	10.7±0.3	6.1±0.5	−20.7±1.6	−14.3±1.0	35.1±1.8	136

range covered. Due to uncertainties in the validity of the least-squares curves outside the range of the data, these portions of the angular distribution curves are always presented as dashed lines.

The angular distributions in the center-of-mass system are displayed in a three-dimensional plot in Fig. 4. Figure 5 shows the laboratory angular distributions resulting when these least-squares curves are transformed to the laboratory system.

Two striking features of the angular distributions can be seen in Fig. 4. The first is the appearance of an additional broad maximum in the curves around 80° for proton energies of 8.0 Mev and above. The second feature is the strong backward peaking. The variation of the ratio of the cross sections at 180° and 0° with proton energy is shown in Fig. 6. No errors are indicated since the 180° values are uncertain (see above). The ratios from the data of Bogdanov *et al.*[5] and from some of the data of Perry *et al.*[8] are also plotted. The calculations of Young and Stein[11] at lower proton energies (up to 5.5 Mev) have had considerable success in reproducing this strong backward peaking, and the same mechanisms would presumably account for the higher-energy data. The broad maximum feature of the angular distributions at 80° c.m. could probably be accounted for by modifications of the *t*-matrix and the single-particle bound-state wave functions of the Young-Stein calculation.[15]

The available information on the variation with proton energy of the cross section at 0° is displayed in Fig. 7. Two corrections were applied to the data of this experiment. By mass spectrometry, the gas sample used was determined to contain 93.5% tritium, 1.2% deuterium, 3.3% hydrogen, and traces of other gases. Since (p,n) reactions in the gases other than tritium would not contribute to the monoenergetic peak, the data were simply corrected for the fact that the tritium content was not 100%. Due to the health hazard of tritium, the tantalum entrance window was supported by a gold grid which contained an array of close-packed holes, $\frac{1}{8}$ in. in diam. The transmission of this grid was calculated to be 85%, and the data were corrected accordingly.

The data of Perry *et al.*[8] in Fig. 7 were obtained with a proton recoil counter telescope, and have an esti-

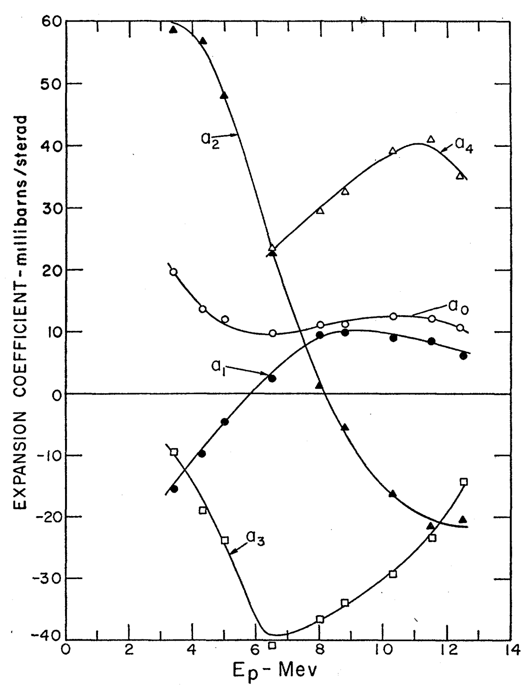

FIG. 3. The variation of the least-squares expansion coefficients with incident proton energy.

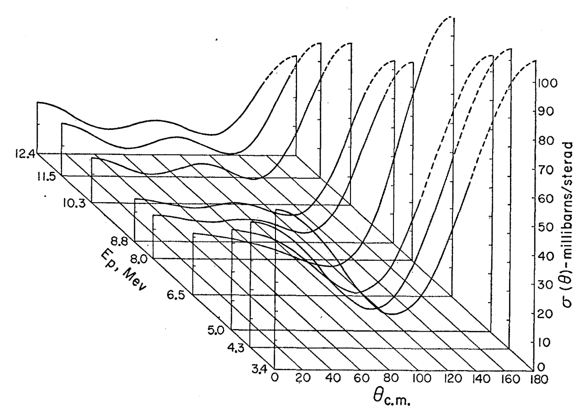

FIG. 4. Three-dimensional array of the angular distributions in the center-of-mass system.

[15] J. E. Young (private communication).

mated error of 7%. The Russian data (dashed line) in Fig. 7 were obtained by means of a long counter up to 7 Mev,[4] and by means of a counter telescope at higher energies.[5] The experiment was performed with broad energy resolution due to the use of lead foils to degrade the energy of the protons. The quoted estimate of error on the data is 10%. The data of Stewart, Frye, and Rosen[16] were obtained with nuclear emulsions, and are good to 20%. Recently, Wilson, Fossan, and Walter[17] have done a relative measurement of the 0° cross section, using a proton recoil counter telescope. The data were normalized to the Perry *et al.* curve in the 5- to 6-Mev interval. The solid-line curve through all of the data represents a weighted average of the data and is the best value for the 0° cross section, to an accuracy of 5%. All angular distributions in this paper have been normalized to this curve.

The total cross section for this reaction can be obtained by simple integration, using the cosine expansion

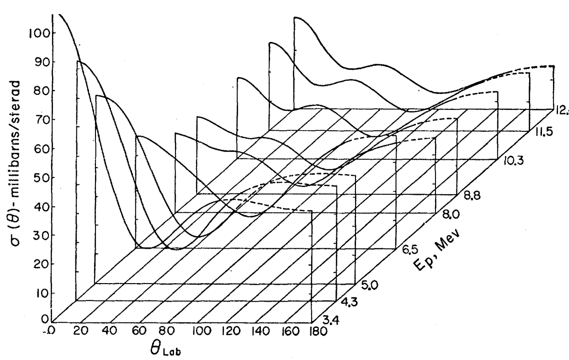

FIG. 5. Three-dimensional array of the angular distributions in the laboratory system.

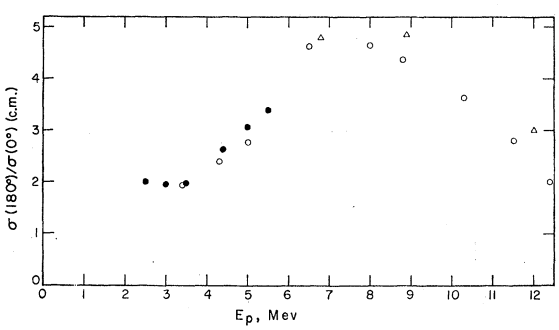

FIG. 6. Variation of the ratio of the cross sections at 0° and 180° in the center-of-mass system with incident proton energy. The open circles are the present data, the closed circles are the data of Perry *et al.* (reference 8), and the triangles are the data of Bogdanov *et al.* (reference 5).

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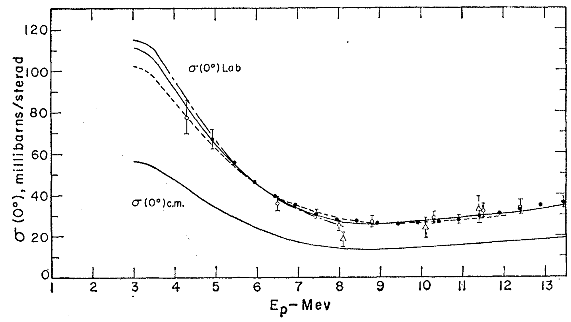

FIG. 7. Variation of the cross section at 0° with incident proton energy. The open circles are the present data; the closed circles are the data of Wilson *et al.* (reference 17); the triangles are the data of Stewart *et al.* (reference 16); the dashed line is the Russian data (references 4 and 5); and the long-short dashed line is from the data of Perry *et al.* (reference 8). The solid line is a weighted average of all the data and is accurate to about 5%.

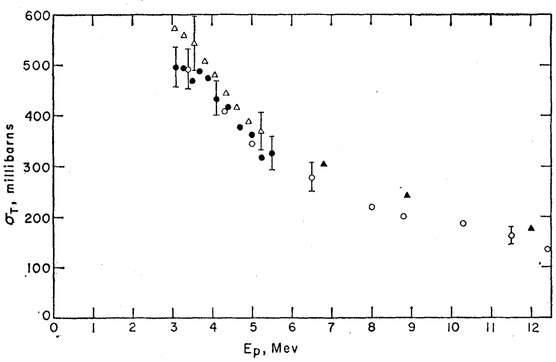

FIG. 8. Variation of the total cross section with incident proton energy. The open circles are the present data; the closed circles are the data of Perry *et al.* (reference 8); the open triangles are the data of Gibbons and Macklin (reference 18); and the closed triangles are the data of Bogdanov *et al.* (reference 5).

for the differential cross section. The calculated values at each energy are tabulated in Table I, and the variation with proton energy is shown in Fig. 8. The values of Perry *et al.*[8] have been renormalized to the best value of the 0° cross section (Fig. 7) at each energy. Included in Fig. 8 are the data of Gibbons and Macklin,[18] who used a large graphite sphere around the target to thermalize the flux at all angles and measure total-reaction cross sections. Though these data are consistently high, the agreement is still well within the errors.

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