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Informal Report

The ^{3}H(p,n)^{3}He Differential Cross Sections Below 5 MeV and the n-^{3}He Cross Sections

University of California

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ABSTRACT

Complete angular distributions for the ^{3}H(p,n)^{3}He reaction were measured at 2.5 and 4.0 MeV with the ^{1}H(t,n)^{3}He reaction used to obtain the backward yields. Because the distributions are peaked about 17% more strongly in the backward direction than the best previous evaluation suggests (based on extrapolated data), the ^{3}H(p,n)^{3}He reaction cross sections below 5 MeV were re-evaluated without the extrapolated data. The results were compared with recent total n-^{3}He cross-section results.

INTRODUCTION

Neutron production cross sections are used frequently as references in the determination of neutron-detector counting efficiency. Reliable data are available for neutron energies between about 2 and 30 MeV.[1] Cross sections of the ^{3}H(p,n)^{3}He reaction appear to be the best choice at lower energies. Evaluated low-energy reference cross sections for this reaction are available,[2] but their 7% uncertainty is too large for a 2% efficiency curve. An attempt to use them in spite of the large uncertainty failed because of internal inconsistencies of the order of 10%.[3] These inconsistencies were detected by measuring the 2.5- and 4.0-MeV angular distributions using the quasi-absolute measuring technique.[1] This method removes almost all scale differences between data points of different angular distrubutions and thus makes the yield ratios at equal neutron energies the same as the corresponding cross-section ratios. The two complete angular distributions give about 17% stronger backward peaking than extrapolation of previous data gave. A new evaluation, including the new data, reduced the scale uncertainties to 3-5%. Besides, it is shown that the use of recent 5% higher total n-^{3}He cross sections[4] resolves the discrepancy between the sum of the partial cross sections of n-^{3}He interactions and the total cross section[5] for neutrons below 4 MeV.

EXPERIMENTAL DATA

Differential cross-section data of the ^{3}H(p,n)^{3}He reaction were taken between 0° and 90° at 2.50 and 4.00 MeV at the Los Alamos Scientific Laboratory (LASL) vertical Van de Graaf using the time-of-flight technique. The detector was 3-cm-thick NE 213, with the liquid in direct contact with the photomultiplier face. It was biased in the minimum between the 26- and 59-keV gamma rays of ^{241}Am.

The experimental details and efficiency determination are described in Refs. 1 and 3. The back-angle cross sections at 2.50 and 4.00 MeV were obtained from the $^1H(t,n)^3He$ reaction at 7.484 MeV and 11.975 MeV, respectively, measured at the LASL tandem Van de Graaf with the same detector and electronics.

Quasi-absolute measurements are essential to this experiment. Because experimental conditions (especially the number of target nuclei and the solid angle of the detector) were kept as constant as possible for all measurements, all data have the same scale. As a consequence, the ratio of the cross sections is the ratio of the yields (independent of the efficiency) at equal neutron energies. Quasi-absolute measurements also help in combining incomplete angular distributions because the adjustment factor must be the same for all pairs of two sets. In this experiment we obtained the best fits for the 2.5- and 4.0-MeV distributions with adjustment factors for the $^1H(t,n)^3He$ part differing by only 0.2%.

Quasi-absolute measurements also need only one normalization point. Additional reference cross sections allow either reduction of the normalization error or recognition of faulty reference values. In the present experiment, the 0° values at 2.5 and 4.0 MeV of the following evaluation were taken as reference. To achieve optimum agreement, the experimental energies must be increased (or the reference energies must be decreased) by 0.03 MeV, an amount about equal to the energy uncertainty in the present experiment. Table I summarizes the new measured data. Table II gives the Legendre coefficients from single-energy fits. The (common) scale error is 3.2% if the errors in the evaluation are realistic but, in any event, should be less than 5%.

EVALUATION

The main purpose of the evaluation was to establish the scale of the two measured angular distributions. However, the final answer also gives new insight into the whole 2- to 5-MeV energy range.

The two completely measured distributions have about 17% stronger backward peaking than extrapolation of previous data[2,6] suggests. (Of course, such an extrapolation depends on the number of Legendre coefficients used in the fit.) Because integration of the extrapolated angular distributions does not give reliable answers for the total $^3H(p,n)^3He$ cross sections, derivation of 0° data from the total reaction values (and vice versa) with the help of the first Legendre coefficient[2] should not be done in this case. Therefore, we included only actual experimental data (but no derived data) in the evaluation. Table III sumarizes the absolute-scale information for the total reaction , 0°, and 180° cross sections of $^3H(p,n)^3He$. Because of the complete angular distributions at 2.5 and 4.0 MeV, the scales can be compared and combined reliably at these energies. To include as much information as possible, the shape of the energy dependence of these cross sections was established first by including relative data. The curve of the total reaction cross section (Fig. 1) was established by the (relative) data of Gibbons et al.,[7] the data normalized to long counters,[8,9] and the individual data depending on the total n-^3He cross sections.[10-12] The individual data include both $^3He(n,p)^3H$ data measured as a fraction of the n-^3He cross section[10,11] (and converted by detailed balance to the p-^3H system) and data derived from the total n-^3He cross section by subtraction of the integrated elastic n-^3He cross section.[12] Uncertainties in the total n-^3He cross sections affect these two types of individual data quite differently. Data at very low energies[13] and at higher energies (for example, the evaluated values of Ref.1) are also shown on the curve, but they were not used for the scale determination because of unknown systematic shape uncertainties.

The excitation function at 0° (Fig. 2) depends heavily on counter telescope data.[6] Note that the data shown use LRL[14] constrained reference cross sections rather than Gammel's estimate[15] of the 180° cross section of $^1H(n,n)^1H$ used for the original results. Also shown are the long-counter data,[16-18] the relative proportional-counter data at lower energies,[19] and the data at higher energies.[1,20,21] The energy scale of one set of long-counter data[18] was increased by 3.7% to give optimum agreement in shape. One set of the higher energy data,[20] which extends downward to 4.3 MeV, depends on a calculated efficiency curve of a time-of-flight neutron detector that neglects carbon interactions. It is not surprising that the high-energy data (above 8.5 MeV) are about 10% higher than the low-energy data because of the carbon interactions.[3] For the comparison in Table III, we assumed that the detector was calibrated at the higher energies, and we applied a correction using the latest values for the

TABLE I

DIFFERENTIAL CROSS SECTIONS IN THE CENTER-OF-MASS SYSTEM FOR THE REACTION $^3H(p,n)^3He$

θCM (deg)	σCM (mb/sr)	Error (%)	σCM (mb/sr)	Error (%)
	$^3H(p,n)^3He$ at 2.5 MeV		$^1H(t,n)^3He$ at 7.484 MeV	
0.0	46.2	0.8	---	---
44.9	31.9	1.5	---	---
68.8	22.3	1.0	22.4	1.8
76.3	---	---	21.5	1.8
84.1	---	---	22.0	1.6
89.1	23.1	1.5	23.4	1.0
97.0	26.9	1.0	27.4	1.0
109.3	36.5	1.0	37.1	1.0
117.0	---	---	44.7	0.8
122.6	---	---	51.7	1.0
132.8	---	---	66.1	1.5
144.8	---	---	81.8	1.5
162.9	---	---	104.2	1.0
179.8	---	---	111.4	0.8
	$^3H(p,n)^3He$ at 4.0 MeV		$^1H(t,n)^3He$ at 11.957 MeV	
0.0	46.0	0.8	----	----
34.0	36.1	1.5	---	---
55.6	---	---	25.7	2.5
63.6	19.4	2.0	20.3	2.0
68.8	---	---	18.6	1.5
79.8	---	---	14.9	1.5
86.7	14.4	1.0	14.2	1.2
91.2	---	---	15.2	1.5
99.5	18.4	1.2	18.2	1.3
109.1	26.3	1.2	26.1	1.5
121.6	---	---	42.6	1.5
135.7	---	---	67.4	1.2
142.5	---	---	79.9	1.2
157.3	---	---	106.3	1.2
179.8	---	---	128.4	1.0

TABLE II

CENTER-OF-MASS CROSS SECTIONS AND LEGENDRE COEFFICIENTS A_l FROM SINGLE-ENERGY FITS.

	2.5 MeV	4.0 MeV
σ_0 (mb/sr)	46.6	45.8
A_0	0.8915	0.8159
A_1	−0.5920	−0.6073
A_2	0.7831	1.0132
A_3	−0.1032	−0.2648
A_4	0.0206	0.0431
A_5	---	−0.0173
A_6	---	0.0172
σ_{180}(mb/sr)	111.3	127.4
σ_t (mb)	521.5	470.0

^{2}H(d,n)^{3}He data[1] that were used as reference. Not shown in Fig. 2 are the unreasonably low data of Ref. 22.

The excitation function at 180° is shown in Ref. 1. Two absolute data points near 5 MeV fix the uncertainty near this energy at about 5%.

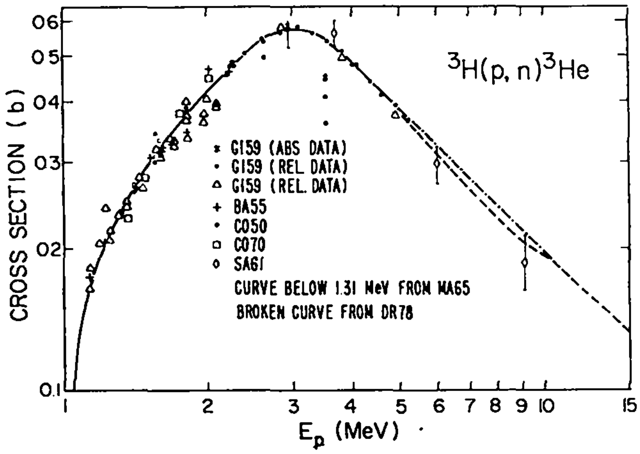

Fig. 1.

Total cross section of the ^{3}H(p,n)^{3}He reaction. The data are treated like relative data to establish the shape. The scale is from the present evaluation; the dashed curve is from a previous evaluation; and the dash-dotted curve is a straight connection to high-energy values. (DR78 is from Ref. 1; for other symbols see Ref. 2.)

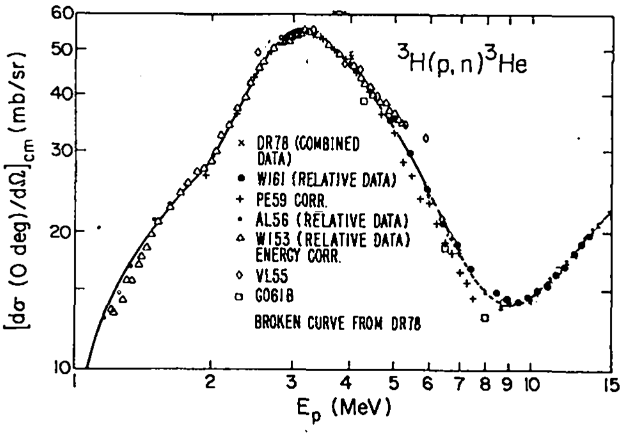

Fig. 2.

Zero-degree excitation curve of the ^{3}H(p,n)^{3}He reaction in the center-of-mass system. The data are treated like relative data to establish the shape. The scale is from the present evaluation, and the dashed curve is from a previous evaluation.[1] (DR78 is from Ref. 1; for other symbols see Ref. 2.)

Critical scanning of Table III shows that only five independent sets of data can be used to establish the scale of the ^{3}H(p,n)$_3$He cross section. Four experiments,[8,9,16,17] which used long counters, appear to give systematically low answers. Three experiments depend on the knowledge of the total n-^{3}He cross sections. Use of the best previous values[23,24] resulted in a discrepancy[5] below 5 MeV, but a new, 5% higher measurement[4] has resolved the discrepancy. In the present evaluation, the arithmetic mean between the old and new data was taken with an assumed uncertainty of 2.5%.

Note that different data are not necessarily independent data. In the evaluation by Liskien and Paulsen,[2] two sets of data from the same laboratory have almost coinciding energies.[6,17] However, we conclude from an internal report[25] that the later data[6] contain the earlier data in revised form.

The present procedure of establishing the energy dependences separately does not take systematic errors into account. Figure 2 shows that the data of Perry et al.[6] deviate systematically above 5 MeV from our curve. Because the shape agrees piecewise both above and below 5 MeV, the difference could be due to a changed experimental condition (for example, a switch to a thicker conversion foil in the counter telescope) at this energy. Because the

TABLE III

DEVIATION OF DATA FROM PRESENT ABSOLUTE SCALE OF $^3H(p,n)^3He$ CROSS SECTIONS BELOW 5 MeV

(Symbols are in accordance with Ref. 2)

Symbol	Author	Ref.	Remarks	Adjustment Factor[a]	Combined Values	Final Values
Total-Reaction Cross Sections						1.000 ± 0.038
G159	Gibbons et al:	7		0.965 ± 0.097		0.980 ± 0.042
CO70	Costello et al:	10	measured as fraction of σ_T of n-^{3}He	0.958 ± 0.027	0.984 ± 0.047[b]	
SA61	Sayres et al:	11		1.016 ± 0.049		
SE60	Seagrave et al:	12	by substraction from σ_T of n-^{3}He	1.026 ± 0.107		
BA55	Batchelor et al:	8	depending on long counter	1.065 ± 0.090	1.070 ± 0.087	
CO50	Coon	9		1.130 ± 0.334		
MA65[c]	Macklin et al:	13	low energies only	1.011		
DR78[c]	Drosg	1	high energies only	0.983		
Diff 0° Cross Sections						1.000 ± 0.057
PE59	Perry et al:	6.	counter telescope[d]	0.957 ± 0.067		
VL55	Vlasov et al:	16	long counter	1.087 ± 0.109		
JA56B[c]	Jarmie et al:	17		1.083		
GO61B[c]	Goldberg et al:	20	high energies only[e]	0.995		
DR78[c]	Drosg	1	high energies only	0.983		
Diff 180° Cross Sections						
DR78[c]		1.	from $^1H(t,n)^3He$	1.037 ± 0.054		

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[a] Other data must be multiplied by this factor to coincide in scale.

[b] Common systematic error owing to σ_T taken into account.

[c] Not used.

[d] Corrected for latest $^1H(n,n)$ ^1H reference cross sections.

[e] Energies >8.5 MeV corrected for $^2H(d,n)^3He$ reference cross sections.

documentation of the Perry experiment is no longer available, there is no way to find out.

From the data compiled in Table III, the scale of the total reaction cross section has been determined within 3.8%, and the scale of the 0° differential cross sections has been determined within 5.7%. Common scale errors were extracted before the individual data sets were combined. The combined adjustment factors show that all data taken with long counters are about 8% low. A method-inherent systematic error of this magnitude is not unlikely. If the long-counter data were excluded, the solution would be a few per cent higher and the uncertainties would be larger.

When angular distributions are presented by Legendre coefficients A_l in the form[2]

$$\frac{d\sigma\ (E,\theta)}{d\Omega} = \frac{d\sigma\ (E,0\ \mathrm{deg})}{d\Omega} \cdot \sum_i A_i P_i\ (\cos\theta)\ ,$$

A_0 is the ratio of the total and the 0° cross sections divided by 4π. Figure 3 shows the two measured A_0 values of the present work, the extrapolated A_0 values of many other authors,[6,16-18,20,21,26-31] and the curve obtained by assuming that the scales and shapes of Figs. 1 and 2 are correct.

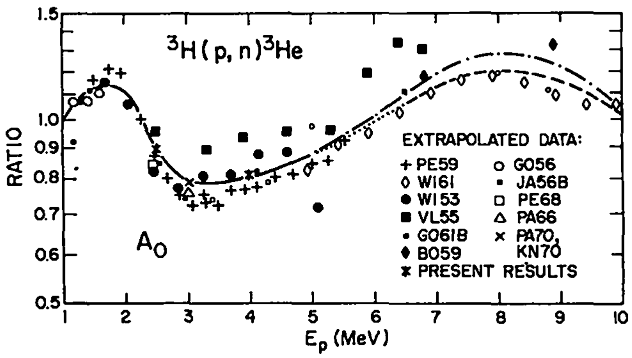

Fig. 3.
Energy dependence of the reduced Legendre coefficient A_0 as obtained by dividing the curves of Fig. 1 by the curve of Fig. 2. All but the present two data points were derived by extrapolating fits. The authors' symbols are from Ref.2.

Table IV compares A_0 values at 2.5 and 4.0 MeV. Agreement between the measured and evaluated values of the low solution is excellent. The table does not support exclusion of the long-counter data, which give the high solution. Using the measured A_0 values, one can combine the scales of both the total and the 0° cross sections to arrive at a scale error of 3.2%. (The combined high solution is 2.6% higher with a scale error of 3.7%.)

The scale established this way also agrees well with other data listed in Table III but not used in our evaluation. For example, the scale is about 2% lower than the value suggested by extrapolation of the previous high-energy evaluation.[1] Near 5 MeV it gives 180° differential cross sections about (3.7 ± 5.4) % higher than the experimental values.[1]

Compared to the best available evaluation in this energy range,[2] the new evaluation shows the following differences.

- Between 3 and 8 MeV, the previous total cross sections almost coincide with the lower curve in Fig. 1; below 3 MeV, the new curve is typically 4% lower. (Shifting the new curve to about 50 keV lower energies would give even better agreement.)
- Below 2 MeV and above 5.5 MeV, the 0° excitation functions are nearly identical. Between these energies, the new curve is up to 10% lower.
- The angular distributions are peaked more strongly in the backward direction than in the previous evaluation.

CONCLUSION

Complete angular distributions at 2.5 and 4.0 MeV show that extrapolated distributions are not peaked enough at 180°. Consequently, the integrated cross sections (and the Legendre coefficient A_0) of extrapolated distributions are too low and should not be included in the evaluation. The scale of the present evaluated data is consistent with all available independent absolute data, which are, however, not very accurate. This is true even for those data dependent on the total n-^{3}He cross sections if the latest values, which are about 5% higher than the previous ones,[4] are used. These new total n-^{3}He cross sections resolved a previously unexplained discrepancy for the integrated elastic n-^{3}He cross section below 5 MeV, but it has produced discrepancies in the elastic 6-MeV and 7.9-MeV data.[32] The

TABLE IV

RATIO OF TOTAL TO DIFFERENTIAL ZERO-DEGREE CROSS SECTION (A_0) OF ^{3}H(p,n)^{3}He

	Present Work			
E$_p$ (MeV)	Measured	Evaluation Low Solution	Evaluation High Solution	LI 73 (Ref.2)
2.5	0.892	0.902	0.869	0.856
4.0	0.816	0.811	0.795	0.753
Error	± 1.5%	± 6.9%	± 8.2%	± 3%

deviation of the 0° counter telescope data[6] above 5 MeV also has not been explained.

The steepness of the energy-dependence curves for most energies below 8 MeV makes accurate measurements and data comparisons difficult. Therefore, an accurate absolute measurement of the complete angular distribution at about 3.1 MeV (near the maximum) would be most beneficial both for evaluations and for low-energy efficiency measurements. An accurate measurement of the shape of the 0° excitation curve between 4 and 9 MeV also would help clarify the situation.

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