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Absolute Differential Cross Sections for Neutron Production by the $^{2}H(d,n)^{3}He$ Reaction with E_d from 6 to 17 MeV and by the $^{3}H(p,n)^{3}He$ Reaction with E_p from 6 to 16 MeV

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ABSOLUTE DIFFERENTIAL CROSS SECTIONS FOR NEUTRON PRODUCTION BY THE $^{2}H(d,n)^{3}He$ REACTION WITH E_d FROM 6 TO 17 MeV AND BY THE $^{3}H(p,n)^{3}He$ REACTION WITH E_p FROM 6 TO 16 MeV

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ABSTRACT

Differential cross sections of the $^{2}H(d,n)^{3}He$ reaction at 6, 7, 8, 10, 11, 12.305, 14, and 17 MeV and of the $^{3}H(p,n)^{3}He$ reaction at 7, 8.6, 9, 10, 11, 12, 13, 13.6, 14, 15, and 16 MeV have been measured using time-of-flight techniques. The absolute scales were established by using accurate $^{2}H(d,^{3}He)n$ cross sections at 10.0 MeV and $^{3}H(p,^{3}He)n$ cross sections at 13.6 MeV as cross-section standards. The scale uncertainty for our $^{2}H(d,n)^{3}He$ data is ± 1.5%; that for our $^{3}H(p,n)^{3}He$ data, ± 1.8%. Complete angular distributions were measured for the $^{2}H(d,n)^{3}He$ reaction. The data measured for the $^{3}H(p,n)^{3}He$ reaction were used to convert previously published relative distributions into absolute ones. The typical relative error is close to ± 2%.

I. INTRODUCTION

This report provides the results of the $^{2}H(d,n)^{3}He$ experiment performed in November 1971 and September 1972 and gives improved cross sections for the $^{3}H(p,n)^{3}He$ reaction.[1] The revision of the latter cross sections is based on additional, independently measured, individual differential cross sections and on improved knowledge of the neutron detector efficiency. Because some published cross sections[1] (at back angles of the 14-, 15-, and 16-MeV distributions) appear to be off by up to 40%, this revision proved necessary.

II. EXPERIMENTAL

The basic experimental arrangement and the general experimental procedure have been described in Refs 1, 2, and 3. Improvements were made possible by using a better efficiency curve for the neutron detector, improved measuring techniques, and a different measuring philosophy.

A. Improved Efficiency Curve of the Neutron Detector

The neutron detector was a 12-cm-diam by 6-cm-long liquid scintillator (NE-213). Its relative efficiency was determined originally by means of a $^{1}H(n,n)^{1}H$ scattering experiment.[3] Subsequently, this efficiency curve was improved by comparing the angular dependence of the neutron yield for the reactions $^{3}H(p,n)^{3}He$ at 13.6 MeV and $^{3}H(d,n)^{4}He$ at 13.356 MeV with the corresponding accurate charged-particle cross sections for $^{3}H(p,^{3}He)n$ at 13.6 MeV[4] and $^{2}H(t,^{4}He)n$ at 20.0 MeV.[5] Because the errors in these charged-particle experiments are small, the uncertainty in the ratio of the efficiency at 25 MeV to that at 10 MeV was reduced to about ± 1.5%.

Additional information on the shape of the efficiency curve could be derived from differential efficiency data. These data were obtained by measuring neutron yields--not only during the original efficiency measurements[3] but also during other neutron experiments[1,2,6,7]--simultaneously for two different pulse-height bias settings. The lower bias coincided with the break of the Compton distribution produced by the 0.66-MeV gamma ray from ^{137}Cs (called 1 x Cs), the other with twice this pulse height (2 x Cs). A more detailed description of this method will be given elsewhere.[8]

B. Improved Measuring Techniques

A serious problem in some of the previous neutron production cross-section runs[1,2] was the high counting rate. This counting rate can be controlled by appropriate choice of the detector system, the thickness of the neutron target, and the intensity of the charged-particle beam. We chose to use the above-mentioned neutron detector because its efficiency was well known. The areal density of the gas target could not be reduced to arbitrarily small values because the background, mainly from the beam stop, could not be reduced correspondingly. Therefore, the counting rate was controlled by adjusting the beam intensity. In using a pulsed beam and time-of-flight (TOF) techniques, one must make sure that the probability for multiple events (more than one count in the detector per beam pulse) is small enough that the TOF spectrum is not distorted. There is no straightforward way to correct for this distortion, because it is caused by the following two effects. First, it is more probable to record early events, thus affecting the time distribution, and second, the pile-up of pulses increases the effective efficiency of the detector by generating pulse heights above the bias even if each event falls below the bias. The beam current for this experiment was typically held below 10 nA, resulting in a multiple event probability of less than 1%. This low current was close to the lower limit for stable accelerator operation.

A well-established efficiency curve allows comparison of any individual cross section with a standard if they are measured under identical experimental conditions. Therefore, each cross section itself is tied to the standard and there is no need to tie the distributions to an absolutely measured 0° excitation function as is frequently done (e.g., in Refs. 1 and 2).

III. RESULTS AND ERRORS

A. $^{2}H(d,n)^{3}He$ Reaction

Energies of 6, 7, 8, 10, 11, 12.3, 14, and 17 MeV were chosen to allow intercomparison with other authors' work and use of known charged-particle cross sections of the $^{2}H(d,^{3}He)n$ reaction as cross-section standards. In particular, the 12.3-MeV distribution was measured so that direct comparison could be made with N. Jarmie's charged-particle data[9] at the same energy. Because Jarmie's data have not yet been released, we used Thornton's[10] 10-MeV distribution as the primary cross-section standard. The cross sections were measured in two sets almost one year apart. The first set covered incident neutron energies from 6 to 12.3 MeV; the second set, the energy range from 12.3 to 17 MeV. Whereas we could use Thornton's data for the scale adjustment of the first set, we had to adjust the second set to the previously measured 12.3-MeV cross sections, which were used as a secondary standard. Table I compares our present 10-MeV data with those calculated from Thornton's Legendre coefficients. Although the overall agreement is excellent, there seems to be a slight systematic difference that could be caused by omission of higher order coefficients in Thornton's analysis. The scale adjustment factor used to normalize our 10-MeV data in this table was used for all distributions, because all the data were obtained under identical experimental conditions. The reproducibility of our data proved better than 0.5%, even

TABLE I

10-MeV C.M. CROSS SECTIONS. COMPARISON OF CROSS-SECTION STANDARD (CALC FROM REF. 9) WITH SCALE-ADJUSTED DATA OF THIS EXPERIMENT

n Lab Angle	C.M. Angle	Calc Cross-Section Standard	Meas Data (Adjusted in Scale)	% Deviation
0.0	0.0	46.22	46.16	-0.13
5.0	7.3	42.07	41.89	-0.43
10.0	14.5	31.63	31.43	-0.64
15.0	21.7	19.48	19.63	0.76
20.0	28.9	9.786	10.14	3.49
25.0	36.0	4.291	4.280	-0.26
30.0	43.1	2.360	2.414	2.24
40.0	56.9	3.186	3.191	0.16
50.0	70.3	4.520	4.587	1.46
60.0	83.1	4.908	4.879	-0.59
71.5	83.1	4.908	4.876	-0.66

for data taken over several days and as much as 90 runs apart. Thus our data should agree among each other in scale, at least at this level. Adding an ajustment error of about 0.8% and the intrinsic, approximately 1% scale error of Thornton's data gives a total scale error of less than 1.5%. The scale error for the second data set (14 and 17 MeV) is higher, as these data are tied to our 12.3-MeV secondary cross-section standard rather than to the original 10-MeV standard. For this reason, and because of the rather large energy displacement from the main standard at 10.0 MeV, we assumed scale errors of ± 2% at 14 MeV and of ± 2.5% at 17 MeV. The main sources of relative errors in the individual cross sections are not statistical errors, but uncertainties in the shape of the efficiency curve, in the background subtraction, and in the angular position. Although the angle was known to better than ± 0.1°, this uncertainty contributes as much as ± 2% to the total error in the steepest part of the distribution. The combined relative error is typically less than ± 2%, as shown in the results in Table II. At higher energies, especially at 17 MeV, the uncertainty in the background subtraction owing to peaks in the background causes the larger relative errors.

Comparisons with Thornton's cross sections show very good consistency throughout the overlapping energy range, whereas we found no similar agreement with Dietrich's[11] data (from 12 to 18 MeV). Dietrich's cross sections seem to be high by at least 20% at 18 MeV and 15% at 16 MeV.

B. $^3H(p,n)^3He$ Reaction

Two angular distributions (at 13.0 and 13.6 MeV) and two excitation functions (for 0 and 50°) were measured from 10 to 16 MeV to give absolute cross sections using the final efficiency curve of the neutron detector. In this frame of absolute cross sections, we fitted the (revised) relative distributions of Ref. 1 and got absolute cross sections for all distributions. We got some back-angle data at 14, 15, and 16 MeV by interpolation with data at higher energies[12] and believe them to be closer to the true values than the original data which differ from these new cross sections by up to 40%. Some unresolved lines in the background are suspected to be the reason for these discrepancies.

TABLE II

ABSOLUTE DIFFERENTIAL CROSS SECTIONS FOR THE REACTION $^2H(d,n)^3He$ IN THE LABORATORY SYSTEM

θ_{Lab}	E_d (MeV)							θ_{Lab}	$\theta_{c.m.}$	E_d(MeV)
(deg)	6.00	7.00	8.00	10.00	11.00	14.00	17.00	(deg)	(deg)	12.305
0	80.9 ±0.8	86.8 ±0.9	92.2 ±0.9	97.5 ±1.0	97.7 ±1.0	98.0 ±1.0	94.9 ±1.9	0.0	0.0	100.5±1.5
5	74.5 ±0.8	79.7 ±0.8	83.7 ±0.9	88.2 ±0.9	87.0 ±0.9	86.3 ±0.9	79.5 ±2.3	5.0	7.4	88.1 ±1.1
10	60.7 ±0.6	62.7 ±0.6	64.9 ±0.6	65.7 ±0.7	63.3 ±0.7	60.6 ±0.9	53.1 ±1.1	10.0	14.8	63.9 ±1.0
15	42.9 ±0.6	42.2 ±0.6	42.7 ±0.6	40.5 ±0.6	38.8 ±0.5	32.8 ±0.5	28.0 ±0.6	16.4	24.0	30.2 ±0.45
20	26.9 ±0.4	24.7 ±0.4	24.0 ±0.4	20.5 ±0.4	19.26±0.38	15.10±0.35	11.5 ±0.7	20.6	30.1	14.88±0.34
25	14.08±0.30	12.25±0.29	11.14±0.28	8.45±0.27	7.90±0.26	5.90±0.15	---	24.8	36.2	7.12±0.16
30	7.67±0.15	6.32±0.13	5.54±0.11	4.62±0.10	4.41±0.09	4.21±0.10	4.46±0.64	29.1	42.3	4.39±0.08
40	4.82±0.06	4.95±0.06	5.06±0.07	5.66±0.07	6.17±0.08	6.78±0.14	6.68±0.65	33.5	48.5	4.53±0.06
45	---	---	---	---	---	7.21±0.15	6.88±0.63	38.0	54.8	5.90±0.08
50	7.09±0.08	7.18±0.08	7.26±0.08	7.38±0.08	7.22±0.08	6.80±0.15	5.85±0.58	42.6	61.2	6.94±0.08
60	8.19±0.09	7.89±0.09	7.77±0.09	6.96±0.09	6.58±0.10	5.22±0.14	3.92±0.16	47.4	67.6	7.12±0.09
67.8	---	---	---	---	---	4.39±0.10	---	52.4	74.3	6.95±0.09
70.0	7.69±0.12	7.20±0.12	---	---	---	---	---	57.7	81.1	6.22±0.07
71.5	---	---	---	5.90±0.12	---	---	---	60.2	84.4	5.78±0.06
73.7	---	---	6.44±0.13	---	---	---	---	63.3	88.2	5.53±0.07

TABLE III

ZERO-DEGREE ABSOLUTE CROSS SECTIONS FOR THE REACTION $^3H(p,n)^3He$ IN THE LABORATORY SYSTEM
(Data are given in mb/sr, scale error is $\pm$ 1.8%.)

E_p	Present Results	Counter Telescope[a]	McDaniels et al.[b]	Combined Data	Recommended Values[c]
4.00	---	---	99.2 $\pm$ 2.3	99.2 $\pm$ 2.3	98.0 $\pm$ 2.3
5.00	---	---	71.6 $\pm$ 1.6	71.6 $\pm$ 1.6	70.0 $\pm$ 1.6
6.00	---	---	48.8 $\pm$ 1.1	48.8 $\pm$ 1.1	48.8 $\pm$ 1.1
7.00	36.42 $\pm$ 0.46	---	36.2 $\pm$ 0.8	36.37 $\pm$ 0.40	36.0 $\pm$ 0.4
8.00	---	---	29.1 $\pm$ 0.7	29.1 $\pm$ 0.7	29.1 $\pm$ 0.7
8.60	27.53 $\pm$ 0.40	---	---	27.53 $\pm$ 0.40	27.7 $\pm$ 0.4
9.00	27.52 $\pm$ 0.40	---	27.7 $\pm$ 0.6	27.58 $\pm$ 0.33	27.4 $\pm$ 0.4
10.00	28.37 $\pm$ 0.48	28.0 $\pm$ 0.4	28.1 $\pm$ 0.6	28.12 $\pm$ 0.27	28.2 $\pm$ 0.3
11.00	31.14 $\pm$ 0.37	31.1 $\pm$ 0.5	30.6 $\pm$ 0.7	31.04 $\pm$ 0.27	30.8 $\pm$ 0.3
12.00	33.80 $\pm$ 0.34	33.4 $\pm$ 0.5	34.3 $\pm$ 0.8	33.74 $\pm$ 0.27	33.9 $\pm$ 0.3
13.00	36.81 $\pm$ 0.54	37.8 $\pm$ 0.6	37.0 $\pm$ 0.9	37.21 $\pm$ 0.37	37.4 $\pm$ 0.4
13.60	39.82 $\pm$ 0.63	---	---	39.82 $\pm$ 0.63	39.5 $\pm$ 0.5
14.00	39.86 $\pm$ 0.50	40.1 $\pm$ 0.6	41.1 $\pm$ 0.9	40.14 $\pm$ 0.35	40.6 $\pm$ 0.6
15.00	43.29 $\pm$ 0.54	42.6 $\pm$ 0.7	43.9 $\pm$ 1.0	43.17 $\pm$ 0.39	43.3 $\pm$ 0.4
15.50	---	---	43.9 $\pm$ 1.0	43.9 $\pm$ 1.0	44.5 $\pm$ 0.7
16.00	45.75 $\pm$ 0.56	---	---	45.75 $\pm$ 0.56	45.6 $\pm$ 0.6

[a]Same data as in Ref. 1, but with scale adjustment of 1.105.
[b]Data of Ref. 1.
[c]Obtained from smooth curve.

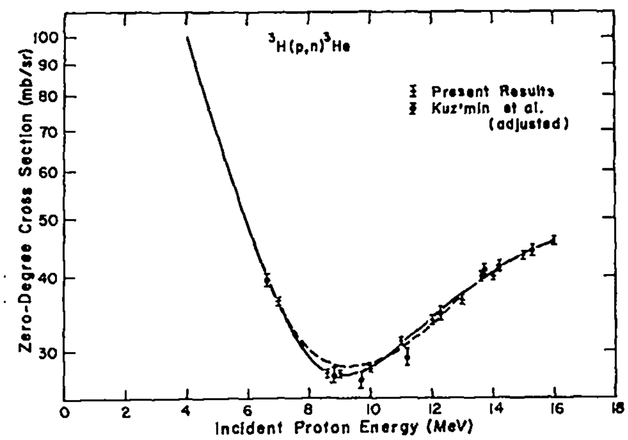

Fig. 1

Absolute 0° cross sections for the $^3H(p,n)^3He$ reaction in the laboratory system. Solid curve gives the recommended values, dashed curve is taken from Wilson[13] with scale adjustment.

The scale, which was adjusted to the revised $^3H(p,^3He)n$ data at 13.6 MeV,[4] is good to $\pm$ 1.8%. Table III summarizes various sets of 0° cross sections. Figure 1 shows our 0° data, the curve from which the recommended values were taken (full line), the scale-adjusted curve of Wilson et al.,[13] and recent Russian data,[14] also adjusted in scale. Table IV compares our new data at 13.60 MeV with charged-particle data at the same energy.[4,12] The combined data of this table give an even better cross-section standard than was previously available. Our recommended values were obtained from the best fit to the Legendre polynomial expression

$$\sigma(\cos\theta) = (1/k^2)\cdot\sum_n B_n P_n(\cos\theta) \quad .$$

where θ is the neutron-emission angle and k is the relativistic proton wave number, both expressed in the center-of-mass system. All reasonable sets of Legendre coefficients for this energy gave data within $\pm$ 0.25% of one another. The small errors in the data at this energy and the small deviations of the measured data from the calculated data indicate that nonsystematic errors in the recommended values will probably be small. The systematic errors in these recommended values consist of the adjustment error between our data and those of Jarmie,[4] and of a possible $\pm$ 1%/10-MeV tilt in the efficiency curve in the energy range in question. Combining these two sources of error gives an estimated less than 0.9% relative error for the entire distribution. The Legendre coefficients in Table V were derived from our (revised) data under the constraint of a smooth energy dependence. Despite this constraint, all data agree with the calculated curve with a typical deviation of less than $\pm$ 1.3%. The laboratory cross sections calculated using these coefficients are given in Table VI. Their relative error increases from about $\pm$ 0.9% at 13.6 MeV to an estimated $\pm$ 2.5% at 16 MeV. At 10 MeV, it should be less than $\pm$ 2%.

Figure 2 shows our recommended smooth values for the Legendre coefficients together with individual points taken from McDaniels et al.[1] The difference, especially at 16 MeV, is obvious.

A comparison with the recent evaluation by Liskien et al.[15] which covers energies up to 10 MeV shows increasing disagreement both in scale and shape as the energy increases. This disagreement stresses the need for an independent, accurate, absolute measurement of a few points, preferably at 9 MeV, to support our energy-dependent analysis.

TABLE IV

ABSOLUTE C.M. DIFFERENTIAL CROSS SECTIONS
FOR THE REACTION $^3H(p,n)^3He$ AT 13.60 MeV
(Data are given in mb/sr, scale error is ± 1.8%.)

$\theta_{c.m.}$	Present Results	Jarmie et al.[a]	Allas et al.[b]	Combined Data	Recommended Values[c]
0.0	21.82 ± 0.35	---	---	21.82 ± 0.35	21.54
13.5	19.24 ± 0.20	---	---	19.24 ± 0.20	19.26
26.8	14.24 ± 0.16	---	---	14.24 ± 0.16	14.42
40.1	10.78 ± 0.18	---	---	10.78 ± 0.18	10.54
52.9	9.48 ± 0.15	---	---	9.48 ± 0.15	9.55
65.6	10.42 ± 0.12	---	---	10.42 ± 0.12	10.55
77.2	11.61 ± 0.10	12.0 ± 1.8	11.76 ± 0.21	11.64 ± 0.09	11.64
87.6	11.71 ± 0.26	11.73 ± 0.35	12.50 ± 0.22[d]	11.72 ± 0.21	11.71
98.0	10.60 ± 0.11	10.48 ± 0.13		10.55 ± 0.08	10.57
108.4	8.548 ± 0.081	8.552 ± 0.094	7.861 ± 0.116[d]	8.550 ± 0.061	8.57
118.6	6.940 ± 0.070	6.971 ± 0.056	6.825 ± 0.116	6.949 ± 0.042	6.94
128.9	7.460 ± 0.125	7.447 ± 0.060	7.524 ± 0.125	7.457 ± 0.051	7.41
139.2	---	11.52 ± 0.14	11.44 ± 0.17	11.50 ± 0.12	11.56
149.4	---	19.52 ± 0.21	17.24 ± 0.38[d]	19.52 ± 0.21	19.46
155.5	---	25.37 ± 0.51	---	25.37 ± 0.51	25.28

[a]From Ref. 4.
[b]From Ref. 12; scale adjusted to Ref. 4; original errors.
[c]From Legendre fit.
[d]Not used because errors seem too optimistically small.

TABLE V

LEGENDRE COEFFICIENTS FOR THE C.M. CROSS SECTIONS OF THE REACTION $^3H(p,n)^3He$

E_p (MeV)	k^2 (10^{27} cm^{-2})	B_0	B_1	B_2	B_3	B_4	B_5	B_6	B_7
6[a]	0.01626	0.4092	-0.3234	0.5260	-0.2659	0.0915	-0.0130	---	---
7[a]	0.01898	0.4069	-0.3259	0.4911	-0.3300	0.1370	-0.0200	0.0080	---
10	0.02712	0.4292	-0.2453	0.3496	-0.3567	0.2640	-0.0401	0.0196	---
11	0.02983	0.4337	-0.2007	0.3154	-0.3280	0.3020	-0.0470	0.0250	---
12	0.03255	0.4385	-0.1560	0.2967	-0.2925	0.3360	-0.0510	0.0300	---
13	0.03527	0.4405	-0.1044	0.2872	-0.2504	0.3619	-0.0530	0.0350	---
13.6	0.03690	0.4410	-0.0702	0.2855	-0.2251	0.3755	-0.0530	0.0380	---
14	0.03798	0.4400	-0.0500	0.2856	-0.2060	0.3832	-0.0519	0.0389	-0.0020
15	0.04070	0.4384	0.0017	0.2908	-0.1625	0.3960	-0.0475	0.0424	-0.0037
16	0.04342	0.4332	0.0530	0.2990	-0.1184	0.4035	-0.0418	0.0447	-0.0025

[a]Coefficients for these energies were derived without new data, assuming a smooth energy dependence.

TABLE VI

ABSOLUTE DIFFERENTIAL CROSS SECTIONS FOR $^{3}H(p,n)^{3}He$ IN THE LABORATORY SYSTEM (mb/sr)

θ_{Lab} (deg)	E_p (MeV) 10	11	12	13	14	15	16
0	28.47	30.75	33.82	37.13	40.25	42.81	44.92
10	26.33	27.97	30.38	33.10	35.75	37.92	39.68
20	22.05	22.27	23.18	24.50	25.95	27.16	28.08
30	19.34	18.33	17.81	17.74	17.83	17.95	17.99
40	19.17	17.71	16.48	15.55	14.74	14.06	13.43
50	19.58	18.42	17.21	16.05	14.93	13.90	12.87
60	18.46	17.93	17.14	16.15	15.13	14.07	12.93
70	15.46	15.42	15.06	14.40	13.59	12.67	11.67
80	11.82	11.85	11.64	11.92	10.57	9.85	9.08
90	9.22	8.83	8.43	7.95	7.38	6.79	6.19
100	8.69	7.61	6.77	6.01	5.31	4.72	4.15
110	10.30	8.49	7.13	5.97	5.00	4.25	3.57
120	13.34	10.95	9.12	7.57	6.27	5.26	4.39
130	16.88	14.12	11.96	10.09	8.49	7.21	6.10
140	20.19	17.24	14.88	12.79	10.97	9.46	8.13

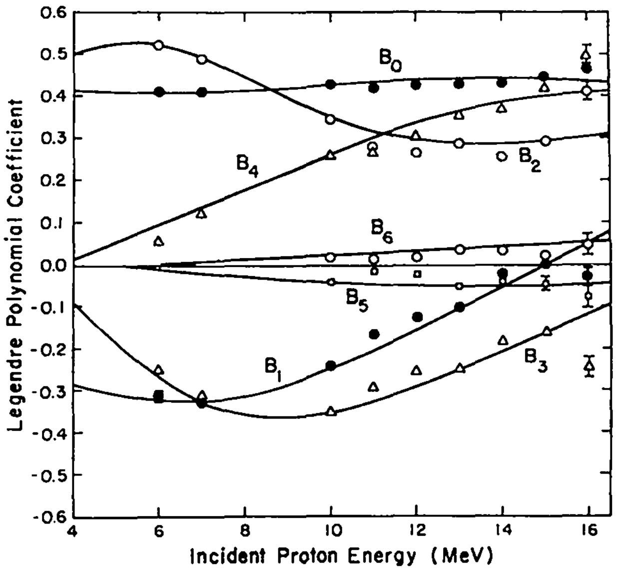

Fig. 2
Legendre coefficients for the center-of-mass cross sections. Curves represent our smooth, energy-dependent solutions. Data points are from Ref. 1.

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