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Differential Cross Sections of $^{3}H(p,n)^{3}He$ and of $^{6}Li(n,t)^{4}He$ by Using Triton Beams Between 5.95 and 19.15 MeV and a Reevaluation of the p-T Neutron Production Cross Sections up to 12 MeV

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by

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ABSTRACT

Six angular distributions and the zero degree excitation function of the reaction $^{1}H(t,n)^{3}He$ between 5.95 and 19.15 MeV were measured to provide back angle data for the $^{3}H(p,n)^{3}He$ reaction between 2.0 and 6.4 MeV proton energy. Together with relative angular distributions at 2.22 and 3.00 MeV these data are the backbone of a new evaluation which gives appreciably higher back angle yields than previous ones. Consistency of the data base is not very good resulting in maximum scale errors of ±4% and maximum shape error of the angular distributions of ±3%.

Data of the reaction $^{4}He(t,n_{x})^{6}Li$ can contribute to the knowledge of the cross section standard $^{6}Li(n,t)^{4}He$, the time-reversed reaction. New data for triton energies between 11.9 and 16.4 MeV (corresponding to neutron energies for n-^{6}Li between 2.3 and 5.3 MeV) are presented both for the

population of the ground state in ^{6}Li and the first excited state. In addition, data of the same reaction obtained in a previous experiment were revised above 12.8 MeV taking a 0.1% impurity of hydrogen into account.

I. INTRODUCTION

By exchanging the projectile and the target in the $^{3}H(p,n)^{3}He$ reaction back angle cross sections can be measured at forward angles of the reaction $^{1}H(t,n)^{3}He$. Similarly cross sections of the cross section standard $^{6}Li(n,t)^{4}He$ can be measured by the time-reversed reaction $^{4}He(t,n)^{6}Li$. In both cases, the target is a gas, the projectiles are tritons and the detected particles are neutrons. Using an identical experimental arrangement allows accurate ratio measurements (i.e. the application of the quasi-absolute method[1]). Whereas the $^{4}He(t,n_{x})^{6}Li$ data were measured to widen the data base of the R-Matrix analysis of the ^{7}Li system[2] the $^{1}H(t,n)^{3}He$ data were used to improve the evaluation of the differential neutron production cross sections of the $^{3}H(p,n)^{3}He$ reaction.

II. EXPERIMENTAL TECHNIQUE

The data were taken by time-of-flight technique using a pulsed triton beam from the tandem Van de Graaff of the Los Alamos National Laboratory. The apparatus including the detector (NE213) and its neutron detection efficiency has been described before[3,4]. In the present case, the areal density of the helium gas was 0.49mg/cm^2 except for the measurement at 16.42 MeV where it was 0.32mg/cm^2, and that of the hydrogen 0.21mg/cm^2 except for the data at 16.42 and 19.15 MeV where it was 0.13mg/cm^2. The experimental procedure and the data reduction are described in some detail in the previous report[3]. However, in the present experiment no direct comparison with a cross section reference was performed. The t-H and t-He data were measured relative to each other and the scale was established by normalizing to previous t-H and t-He data[3].

III. DATA OF THE ^{4}He(t,n_x)^{6}Li REACTION

A. *Revision of Previously Published Data*

The previous data[3] are corrected in this paper for a 0.1% impurity of hydrogen in the helium gas. Because of the huge ^{1}H(t,n)^{3}He cross sections this small impurity results in corrections of up to 10% in those cases when the neutron lines of the two reactions overlapped. This happens only for triton energies above 12.8 MeV. The revised data are collected in Table I. The scale errors are unchanged, increasing from 2.3% at 12.9 MeV to 2.6% at 16.5 MeV.

B. *New Data*

The new data were intended to supplement the previous ones. The triton energy of 11.873 MeV (corresponding to 2.316 MeV neutron energy for n-^{6}Li) was chosen to allow a direct comparison with some recent data[5]. The new cross sections are given in Table II. The scale error consists of a 2.8% uncertainty in the reference values plus an adjustment error of 1.4% (stemming mainly from uncertainties in the areal densities of the targets). At 16.416 MeV, the error of the adjustment factor is 2.4%.

The errors shown in the table include statistical errors, background subtraction uncertainties and uncertainties in the corrections. Also, for neutron energies less than twice the bias energy, a neutron detection efficiency error was added. Above that energy, the uncertainty in the shape of the (relative) efficiency curve of 2% per 10 MeV energy difference was not included.

C. *Discussion*

In the few MeV range, data are sparse and usually not in agreement. This situation was not improved by the addition of the present data, because there is no agreement with the 2.3 MeV data[5)] of n-^{6}Li. However, the new 16.42 MeV data agree within the (rather big) errors with the previous 16.46 MeV data. The main contribution for an R-matrix analysis of ^{7}Li lies in the data involving the first excited state of ^{6}Li.

IV. THE ^{3}H(p,n)^{3}He REACTION

A. *Data From Previous Experiments*

Table III gives previously unpublished relative angular distributions of ^{3}H(p,n)^{3}He at 2.22 and 3.00 MeV which were measured several years ago. The scale of these data as shown in the table has been obtained by the present evaluation.

Table IV gives differential cross sections of $^{1}H(t,n)^{3}He$ between 9.51 and 16.45 MeV. These data were taken together with already published t-^{4}He data[3] using the identical cross section references resulting in a scale error of 2.8%.

B. *Data of the Present Experiment*

Table V lists the $^{1}H(t,n)^{3}He$ cross sections which were measured in the present experiment together with the t-^{4}He data of Section III. B. Three of these (incomplete) angular distributions are shown in Fig. 1 together with the complete curves obtained from the present evaluation. Fig. 2 gives the zero-degree excitation function of this reaction.

In the center-of-mass system, these data can be used for the inverse reaction $^{3}H(p,n)^{3}He$ by changing θ to $180^{o} - \theta$ and by dividing the incoming energy by 2.9937. In this way, additional data for the p-T reaction for proton energies between 1.99 and 6.40 MeV were obtained. The error assessment is equal to that in Section III. B.

C. *Reevaluation of the Differential Cross Sections of the $^{3}H(p,n)^{3}He$ Reaction*

Among the hydrogen reactions producing monoenergetic neutrons (p-T,d-D,d-T) the cross sections of p-T are most poorly known for proton energies below 10 MeV[6]. This was primarily caused by the missing back angle data and the steepness of the slopes on both sides of the resonance near 3.1 MeV which requires a careful energy determination.

Although the present data have rather large scale errors and do not cover all of the necessary energy range they provide back angle data at several energies which were not available up to now. So an evaluation in a similar manner as done before[7)] was performed. Table VI shows the results of this evaluation for energies up to 12 MeV. As a convenience, also the data for energies up to 16 MeV are shown, taken from the previous evaluation[7)]. The presentation in Table VI follows Liskien and Paulsen[8)]. The absolute differential C.M. cross section at an angle θ is given by

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma(0^\circ)}{d\Omega} \cdot \Sigma A_i P_i (\theta)$$

where P_i are the Legendre polynomials and A_i reduced Legendre coefficients.

The main feature of the new evaluation is 5 to 10% higher p-T cross sections at 180° as shown in Fig. 2 when compared with the previous evaluation[8)] in this energy range. There is a reasonably good agreement with unpublished relative angular distributions[8)] measured with solid targets at 3 MeV, near the maximum of the resonance.

The scale error which is about ± 1.5% between 10 and 16 MeV increases to about 4% at 3 MeV and lower energies. The shape error of the angular distributions is estimated to be less than ± 3% over most of the energy range, but somewhat higher near 2 MeV. The uncertainty in the 0° position is typically ± 0.1° with a maximum of ± 0.6° near 3 MeV. The energy uncertainty is generally less than ± 0.02 MeV.

V. CONCLUSIONS

Although the present results widen the data base both for the n-^{6}Li and the p-T reactions, there is much more work needed in this field. New n-^{6}Li data in the MeV region[9)] should be supplemented by data of the time-reversed reaction avoiding problems associated with neutron flux determinations[3)]. There is need of more p-T data below 10 MeV. However, a careful determination of the projectile energy and of the actual zero-degree direction will be as important as the cross section measurement itself, because errors in these parameters can dominate the total uncertainty of the measurement.

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TABLE I

REVISED LABORATORY CROSS SECTIONS OF THE REACTION $^4He(t,n_x)^6Li$

E_t (MeV)	θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)
	$^4He(t,n_o)^6Li$		
8.979[a)]	0.0	50.0	2.9
12.888	30.0	20.0	4.0
	40.0	18.1	5.8
14.986	0.0	25.8	8.9
16.457	0.2	29.2	10.8
	10.0	26.0	13.0
	20.0	20.8	10.5
	30.0	14.9	8.2
	40.0	11.6	7.0
	$^4He(t,n_1)^6Li^*$		
16.457	50.0	17.3	15.0

a) correction of misprint only

TABLE II

NEW LABORATORY CROSS SECTIONS OF THE REACTION $^4He(t,n_x)^6Li$

E_t (MeV)	θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)	σ_{Lab} (mb/sr)	Error (%)
		$^4He(t,n_o)^6Li$		$^4He(t,n_1)^6Li^*$	
11.873	0.0	21.8	1.8		
	15.0	19.4	1.8		
	29.9	19.9	2.3		
	60.0	12.6	3.0		
	80.0	5.9	5.2		
	90.0	4.2	8.6		
	100.0	2.6	20.4		
13.907	0.0	25.2	2.8	52.7	2.4
14.405	0.0	25.2	2.7	60.3	2.2
16.416	0.0	27.3	13.4	58.4	6.2
	15.0	21.0	16.2	40.3	12.1
	19.5	15.8	13.1	40.3	6.5
	30.0	15.6	10.9	27.9	9.5
	49.7	10.0	14.8	18.6	18.0
	59.6	8.8	22.9	14.9	28.3

T A B L E III

RELATIVE ANGULAR DISTRIBUTIONS IN THE LABORATORY SYSTEM FOR THE REACTION $^{3}H(p,n)^{3}He$

(Scale adjustment within ±3%)

E_p = (2.22 ± 0.02)MeV			E_p = (3.00 ± 0.01)MeV		
θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)	θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)
30.4	53.43	1.2	29.3	69.46	1.0
45.4	38.77	1.5	44.3	40.95	1.0
55.4	34.12	1.5	54.3	29.63	1.2
75.4	35.00	1.2	64.3	26.22	1.5
90.4	38.37	1.5	74.3	28.57	1.2
105.4	38.95	2.5	89.3	38.06	1.5
120.4	40.40	15.	104.3	44.51	1.5
			119.3	47.56	1.5

TABLE IV

DIFFERENTIAL CROSS SECTIONS IN THE LABORATORY SYSTEM FOR THE REACTION $^{1}H(t,n)^{3}He$

($^{4}He(t,n)^{6}Li$ used as a cross section standard, scale error 2.8%)

θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)	θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)
	E_t = 9.51 MeV			E_t = 16.45 MeV	
0.0	628.7	1.0	0.0	482.1	2.0
11.2	527.6	1.0	5.1	461.5	1.2
14.3	463.6	1.5	10.7	381.4	1.5
17.7	399.4	1.0	12.0	356.2	1.5
21.3	324.8	1.0	15.8	293.2	1.5
25.2	248.9	1.3	19.5	233.6	3.0
29.8	168.9	1.5	25.4	138.2	1.2
31.6	143.2	1.5	29.8	90.9	1.2
33.8	118.9	1.5	34.5	58.2	3.3
36.1	96.7	1.5	39.3	41.4	2.0
40.8	70.6	2.0	44.4	39.5	5.5
45.5	67.7	2.5	49.7	43.2	6.8
47.7	74.5	3.1	54.8	48.8	6.0
51.9	104.2	3.5	59.6	52.4	6.6

	E_t = 10.47 MeV		
0.1	0.2	608.0	1.5
	E_t = 13.46 MeV		
0.1	0.2	542.3	1.5
	Et = 14.96 MeV		
0.1	0.2	516.4	1.7

TABLE V

DIFFERENTIAL CROSS SECTIONS IN THE LABORATORY SYSTEM FOR THE REACTION $^1H(t,n)^3He$

(Normalized to the $^4He(t,n)^6Li$ cross section. Common scale error = 2.8%, additional individual scale errors are 1% for each set, except for sets 4 and 5 where each is 2%.)

θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)	θ_{Lab} (deg)	σ_{Lab} (mb/sr)	Error (%)
SET 1:			**SET 2:**		
	E_t = 5.950 MeV			**E_t = 7.448 MeV**	
0.3	425.2	1.0	0.1	589.3	1.0
4.7	415.0	1.0	10.0	513.3	1.0
9.7	383.1	1.0	14.9	429.8	1.0
14.9	329.1	1.0	20.0	335.2	1.0
19.7	274.8	1.0	24.9	252.1	1.0
24.7	218.4	1.0	29.9	176.3	1.0
29.9	165.4	1.2	34.9	123.8	1.2
32.4	143.8	1.5	39.9	96.6	1.2
34.7	130.9	2.0	44.9	100.8	1.2
			SET 3:		
	E_t = 7.448 MeV			**E_t = 10.440 MeV**	
0.3584.6	1.0	0.1	630.6	1.0	
			15.0	438.5	1.0
	E_t = 8.961 MeV		29.9	156.2	1.2
			34.8	100.4	1.5
0.3	636.1	1.0	39.9	66.7	1.2
			44.9	59.6	1.2
	E_t = 10.440 MeV		49.9	73.2	1.5
			50.1	74.5	1.5
0.3	611.7	1.0	**SET 4:**		
	E_t = 11.896 MeV			**E_t = 16.417 MeV**	
0.3	589.4	1.0	0.0	477.7	1.5
4.6	567.1	1.0	15.0	315.2	1.8
14.6	414.6	1.2	19.5	223.8	1.8
29.6	137.4	1.5	30.0	90.0	2.5
34.6	87.7	2.0	34.5	56.2	3.0
39.6	59.5	2.5	**SET 5:**		
45.2	49.5	2.0		**E_t = 19.150 MeV**	
47.5	51.5	2.2			
50.0	58.2	2.0	0.0	444.1	1.5
52.5	69.3	2.5	15.1	269.1	1.5
55.0	81.3	2.5	25.1	113.9	1.8
			30.0	68.2	1.8
			40.2	35.2	2.0
			45.0	35.4	2.0

TABLE VI. 3H(p,n)3He REACTION: PROTON ENERGY E-in, c.m. DIFFERENTIAL CROSS SECTION AT ZERO DEGREE S-0, REDUCED LEGENDRE COEFFICIENTS Ai, c.m. DIFFERENTIAL CROSS SECTION AT 180 DEGREE S-pi, AND INTEGRATED CROSS SECTION S-t.

E-in	S-0	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	S-pi	S-t
MeV	mb/sr		mb/sr	mb									
1.20	14.9	1.072	-0.150	0.078								19.4	201.
1.30	17.55	1.1070	-0.2460	0.1389								26.2	244.2
1.40	19.55	1.1365	-0.3550	0.2185								33.4	279.2
1.50	21.22	1.1688	-0.4593	0.2947	-0.0042							40.9	311.7
1.60	22.56	1.1985	-0.5455	0.3615	-0.0145							47.8	339.7
1.70	23.67	1.2229	-0.6252	0.4265	-0.0263	0.0022						54.5	363.7
1.80	24.60	1.2396	-0.6918	0.4868	-0.0376	0.0046	-0.0017					60.6	383.2
1.90	25.94	1.2281	-0.7285	0.5460	-0.0481	0.0068	-0.0043					66.5	400.4
2.00	28.39	1.1789	-0.7280	0.6023	-0.0556	0.0086	-0.0062					73.2	420.6
2.10	31.69	1.1149	-0.7035	0.6470	-0.0613	0.0098	-0.0069					80.6	444.0
2.20	35.38	1.0515	-0.6725	0.6817	-0.0650	0.0107	-0.0074	0.0008				88.1	467.6
2.30	39.50	0.9860	-0.6365	0.7129	-0.0680	0.0114	-0.0075	0.0017				95.7	489.3
2.40	43.60	0.9300	-0.6032	0.7370	-0.0704	0.0119	-0.0076	0.0022				103.0	509.5
2.50	47.03	0.8877	-0.5812	0.7603	-0.0745	0.0125	-0.0076	0.0028				109.4	524.6
2.60	50.15	0.8495	-0.5597	0.7796	-0.0779	0.0131	-0.0076	0.0032				114.9	535.3
2.70	52.28	0.8254	-0.5469	0.7948	-0.0828	0.0137	-0.0077	0.0035				118.9	542.3
2.80	53.86	0.8067	-0.5348	0.8060	-0.0885	0.0145	-0.0078	0.0038				121.9	546.0
2.90	54.93	0.7920	-0.5250	0.8160	-0.0949	0.0157	-0.0079	0.0042				123.9	546.7
3.00	55.72	0.7806	-0.5195	0.8269	-0.1015	0.0170	-0.0079	0.0045				125.8	546.5
3.20	56.23	0.7624	-0.5138	0.8515	-0.1168	0.0198	-0.0084	0.0053				128.1	538.7
3.40	55.55	0.7551	-0.5175	0.8767	-0.1355	0.0240	-0.0090	0.0062				129.1	527.1
3.60	53.84	0.7556	-0.5281	0.9042	-0.1584	0.0295	-0.0098	0.0070				128.8	511.2
3.80	51.48	0.7618	-0.5418	0.9336	-0.1868	0.0359	-0.0108	0.0080				127.6	492.8
4.00	48.96	0.7709	-0.5571	0.9633	-0.2178	0.0435	-0.0119	0.0090				126.0	474.4
4.50	42.37	0.8123	-0.5998	1.0241	-0.3024	0.0691	-0.0153	0.0120				120.1	432.6
5.00	36.36	0.8616	-0.6520	1.0866	-0.3958	0.1047	-0.0197	0.0155	-0.0009			114.1	393.7
5.50	30.88	0.9170	-0.7163	1.1700	-0.5122	0.1499	-0.0256	0.0196	-0.0024			108.5	355.8
6.00	26.27	0.9750	-0.7761	1.2513	-0.6454	0.2078	-0.0329	0.0246	-0.0043			102.9	321.8
6.50	22.28	1.0404	-0.8454	1.3330	-0.7903	0.2809	-0.0423	0.0305	-0.0066			97.3	291.3
7.00	19.06	1.1117	-0.9068	1.3914	-0.9372	0.3673	-0.0550	0.0373	-0.0089			91.8	266.3
7.50	16.77	1.1745	-0.9374	1.4040	-1.0607	0.4580	-0.0706	0.0440	-0.0117			86.6	247.5
8.00	15.30	1.2045	-0.9294	1.3542	-1.1202	0.5423	-0.0871	0.0500	-0.0144			81.1	231.6
8.50	14.54	1.1931	-0.8758	1.2566	-1.1144	0.6035	-0.1017	0.0547	-0.0160			75.8	218.0
9.00	14.29	1.1555	-0.7892	1.1221	-1.0631	0.6473	-0.1135	0.0571	-0.0162			70.9	207.5
9.50	14.53	1.0955	-0.6851	0.9790	-0.9722	0.6587	-0.1200	0.0581	-0.0141			66.6	200.1
10.00	14.91	1.0338	-0.5834	0.8480	-0.8807	0.6559	-0.1213	0.0584	-0.0108			62.5	193.7
11.00	16.15	0.8780	-0.4057	0.6399	-0.6787	0.6245	-0.1090	0.0557	-0.0046			54.8	178.2
12.00	17.85	0.7328	-0.2624	0.4940	-0.4948	0.5708	-0.0956	0.0548	0.0005			48.3	164.4
13.00	19.73	0.6131	-0.1527	0.4052	-0.3520	0.5084	-0.0809	0.0526	0.0049	0.0014		42.6	152.0
14.00	21.50	0.5219	-0.0684	0.3437	-0.2478	0.4571	-0.0677	0.0510	0.0081	0.0039	-0.0018	37.7	141.0
15.00	23.02	0.4530	-0.0036	0.3023	-0.1725	0.4117	-0.0543	0.0504	0.0108	0.0069	-0.0047	33.3	131.0
16.00	24.38	0.3983	0.0445	0.2761	-0.1151	0.3710	-0.0423	0.0505	0.0133	0.0095	-0.0058	29.5	122.0

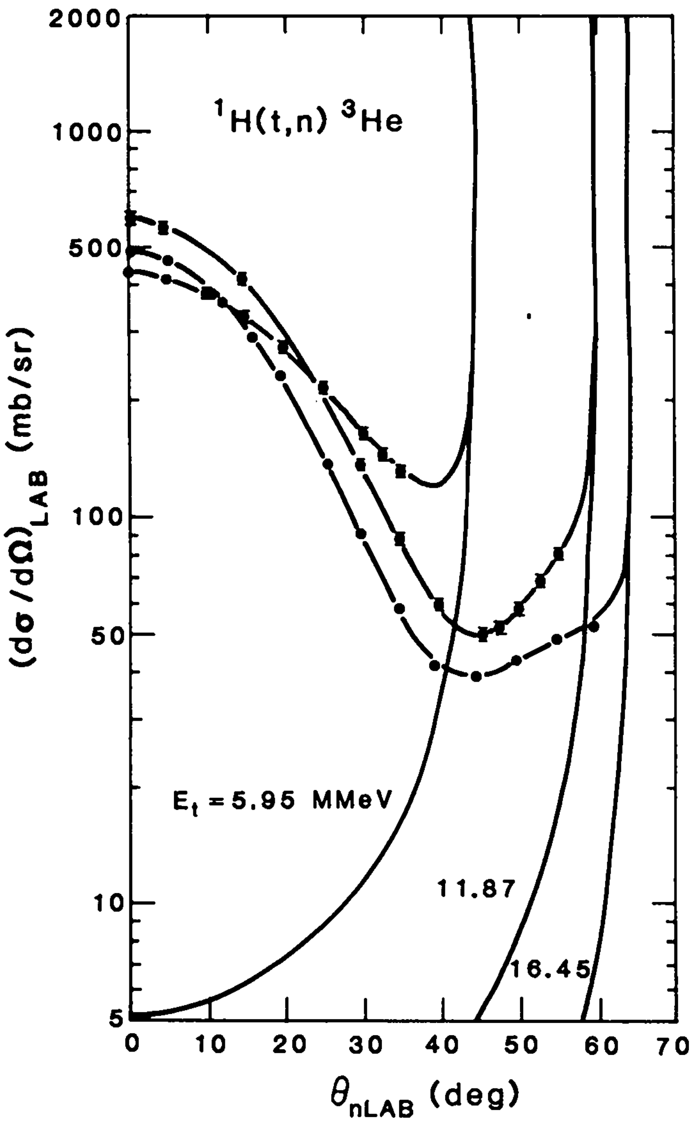

Fig. 1. Three examples of $^1H(t,n)^3He$ differential cross sections in the lab system. The curves were calculated from the appropriate coefficients of Table VI.

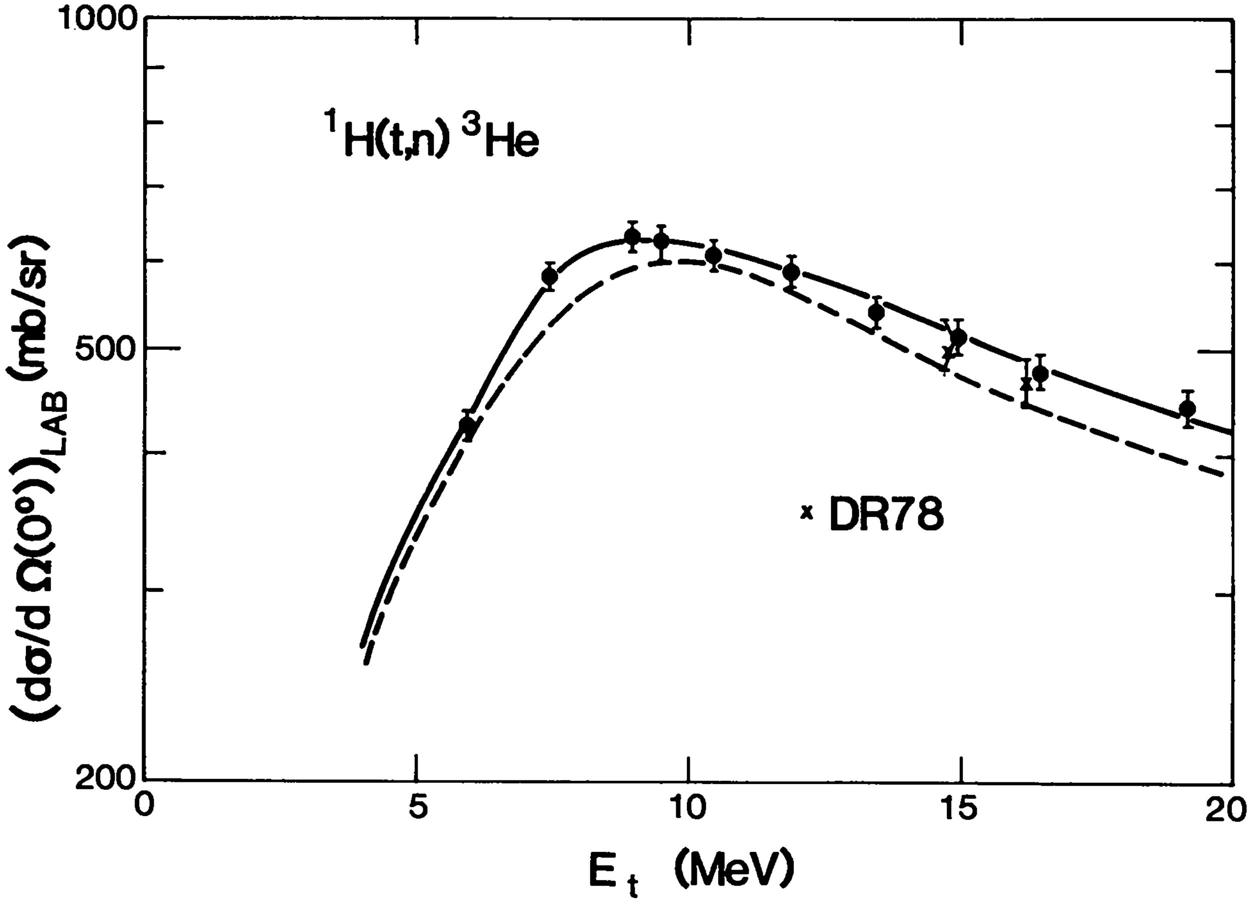

Fig. 2. Zero-degree excitation function of $^1H(t,n)^3He$. The two points marked DR78 are from Ref. 7.

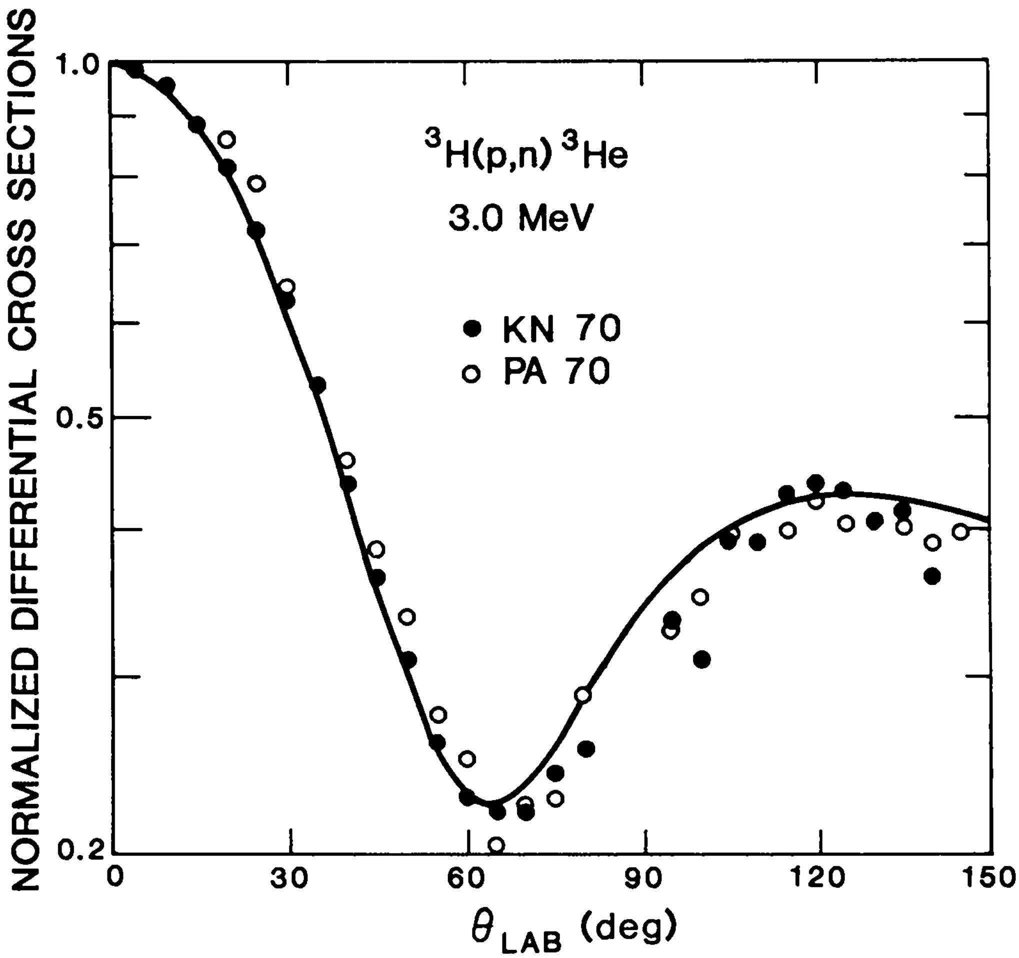

Fig. 3. Relative angular distributions of $^3H(p,n)^3He$ at 3.0 MeV. The curve is from the present evaluation, the data marked KN70 and PA70 are cited in Ref. 8.

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