Improved Evaluation of the Differential Cross Sections of the $^{3}H(d,n)^{4}He$ Reaction for Deuteron Energies Between 3 and 7 MeV

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ABSTRACT

For deuteron energies below 7 MeV, the evaluation of the differential cross sections of the $^{3}H(d,n)^{4}He$ reaction was improved by including three associated ^{4}He particle excitation functions between 4 and 11 MeV. Above 7 MeV, the scale agrees within error limits with that of a previous evaluation, and no energy-dependent systematic deviations between measured and predicted values are observed. However, deviations of up to 20% from the Liskien and Paulsen evaluation are observed.

I. INTRODUCTION

The status of the neutron production cross sections by the hydrogen isotopes was reviewed only recently.[1] The original evaluation by Liskien and Paulsen[2] covered charged-particle energies up to 10 MeV. In a previous evaluation,[3] unified cross sections for $^{3}H(p,n)^{3}He$, $^{2}H(d,n)^{3}He$, and $^{3}H(d,n)^{4}He$ were derived, which extended the energy range to about 17 MeV. In the case of the $^{3}H(d,n)^{4}He$ reaction, the energy range covered by this evaluation was 5 to 19 MeV. This evaluation relied strongly on previous experimental data between 7 and 16.5 MeV.[3]

The three excitation functions[4] included here cover deuteron energies from 4 to 11 MeV. They were not used by Liskien and Paulsen[2] or in the previous evaluation.[3] Their inclusion is valuable because they give information on energy-dependent systematic errors and provide back-angle data for the angular distributions. Thus, the previous evaluation [3] was noticeably improved below 7 MeV and its range was lowered to 3 MeV.

II. METHOD

The three excitation functions included here were measured by the associated-particle method via the reaction $^{3}H(d,\alpha)n$ for the α-particle angles of 18.0, 27.3 and 37.0°.[4] An angular uncertainty of 0.1°, a scale error of 3%, and a typical differential error of 4% are given for these data. By comparison with the predictions of the previous evaluation,[3] a scale difference of 2.8% was determined, which is within the error limits given. All three excitation functions have the identical scale difference (above 7 MeV). This is very important because it shows that both the data and the previous evaluation (above 7 MeV) are trustworthy. Deviations below 7 MeV (Fig. 1) can be explained by the lack of reliable data at these energies.[3]

For this evaluation the following conditions had to be met.

(1) The three experimental excitation functions must be reproduced within their error limits, also below 7 MeV.

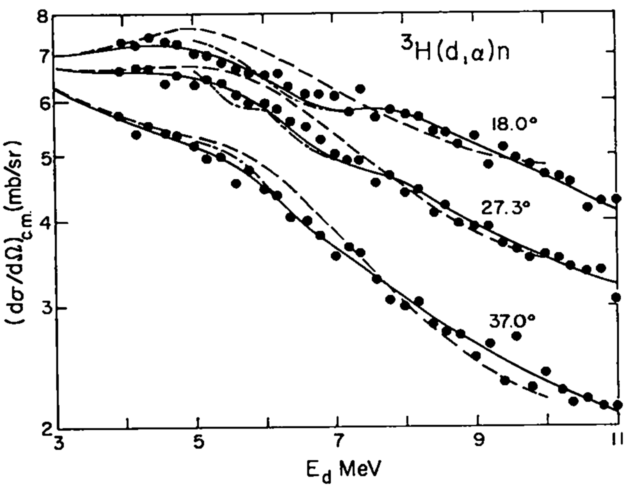

Fig. 1.
Excitation functions of the reaction ^{3}H(d,α)n for the three lab angles 18.0, 27.3, and 37.0°. Data points are from Ref. 4. The full curve is from the present evaluation, the dashed curve is from Ref. 2, and the dashed-dotted curve shows the deviation of the previous evaluation[3] from the present.

(2) Other experimental data, especially the data of Bame and Perry,[5] must be consistent with the solution.
(3) The Legendre coefficients, the 0° cross sections, the 180° cross sections, and the integrated cross sections must vary smoothly from the well-established values at 7 MeV to the values of Liskien and Paulsen[2] at some energy below 4 MeV.

However, complications arise
(1) from the fluctuations in the excitation functions, which are not purely statistical as can be seen in Fig. 1;
(2) from the Legendre presentation of the Bame and Perry data,[5] as the lack of high-order coefficients makes the distributions not enough forward peaked, as was pointed out previously;[3] and
(3) from the presence of a resonance near 5-MeV deuteron energy corresponding to the 19.9-MeV level in ^{5}He.[6] Therefore, no simple interpolation between 7 MeV and the lower energies is possible.

III. RESULTS AND DISCUSSION

Using the three criteria of Sec. II, the new evaluation must extend down to 2.7 MeV to smoothly join the Liskien and Paulsen values.[2] However, the difference at 3 MeV is still small, as can be seen in Table I. Table I gives the new recommended Legendre coefficients and the new scales between 3 and 10 MeV. The values at 7.0 and 10.0 MeV are identical with those of the previous evaluation.[3] The other distributions above 7 MeV are slightly changed because of the inclusion of the three excitation functions. The changes are, however, much smaller than the uncertainties. Only the changes below 7 MeV must be considered.

Figure 2 shows the energy dependence of the integrated cross section and of the differential cross sections at 0° and 180°. For comparison, the values of Liskien and Paulsen[2] are given also.

Figure 3 compares the predictions for the angular distribution at 5.5 MeV. When matching the distributions at 0°, the maximum deviation from Liskien and

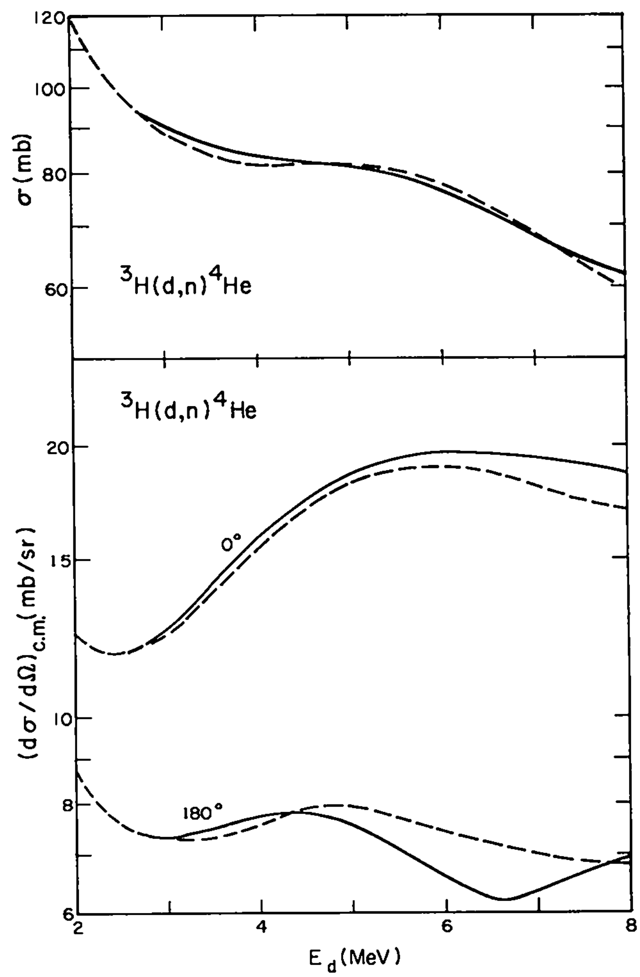

Fig. 2.
Energy dependence of the integrated, the 0°, and the 180° cross sections of the reaction ^{3}H(d,n)^{4}He. The full curves are the present results and the dashed curves are from Ref. 2.

TABLE I

$^3H(d,n)^4He$ RECOMMENDED VALUES FOR σ(0° CM), LEGENDRE COEFFICIENTS Ai, σ(180° CM), AND σ(TOTAL)[a]

E_d (MeV)	σ_0 (mb/sr)	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	σ_{180} (mb/sr)	σ_t (mb)
3.0[b]	12.3	571	130	180	37	25	42	15								7.16	88.5
3.0	12.60	571.0	129.0	181.5	37.9	23.5	42.0	15.1								7.34	90.4
3.5	14.09	485.8	123.7	229.1	53.5	29.9	56.3	21.7								7.51	86.0
4.0	15.86	419.5	121.0	258.9	64.3	35.9	70.5	28.4	0.0	0.8	0.7					7.72	83.6
4.5	17.46	375.4	120.0	267.9	71.4	41.6	84.6	35.0	0.0	2.8	1.3					7.77	82.4
5.0	18.56	348.2	119.4	261.1	74.2	47.6	98.9	42.4	1.8	4.4	2.0					7.58	81.2
5.5	19.24	328.4	118.2	243.9	71.6	55.8	114.9	50.5	8.3	5.8	2.6					7.10	79.4
6.0	19.58	311.0	116.7	221.9	65.0	69.9	131.6	59.2	14.4	7.0	3.3					6.62	76.5
6.2	19.61	303.4	116.0	211.1	61.7	78.5	137.9	63.3	16.8	7.7	3.5	0.1				6.44	74.8
6.5	19.61	293.8	113.1	196.6	55.3	90.6	147.2	70.7	20.0	8.5	3.9	0.3				6.30	72.4
7.0[c]	19.4	280.0	100.9	181.8	43.0	109.3	161.9	82.8	24.6	10.2	4.6	0.6	0.3			6.40	68.3
7.5	19.1	271.0	84.8	176.2	29.0	119.7	175.8	94.7	29.5	12.2	5.2	1.1	0.6	0.2		6.67	64.9
7.9	18.8	264.9	75.7	172.6	17.8	125.8	183.5	103.8	33.2	14.0	5.5	1.6	0.8	0.8		6.89	62.4
8.4	18.3	258.8	69.1	168.0	4.6	131.4	188.3	115.2	36.8	16.7	6.1	2.3	1.1	1.6		7.11	59.5
9.1	17.8	249.0	64.5	161.9	−7.7	133.2	191.7	132.1	40.0	21.0	6.7	3.4	1.5	2.7		7.23	55.6
9.5	17.5	243.9	63.2	158.5	−13.5	132.3	192.1	141.7	41.5	24.1	7.1	4.1	1.7	3.3		7.29	53.8
10.0[c]	17.3	237.3	62.2	154.3	−20.2	129.9	192.9	153.6	43.1	27.3	7.6	5.1	2.0	4.2	0.7	7.32	51.5

[a]The coefficients are multiplied by 1000 to make the numbers easier to read. For errors, see the text.
[b]From Ref. 2 for comparison.
[c]From Ref. 3, unchanged.

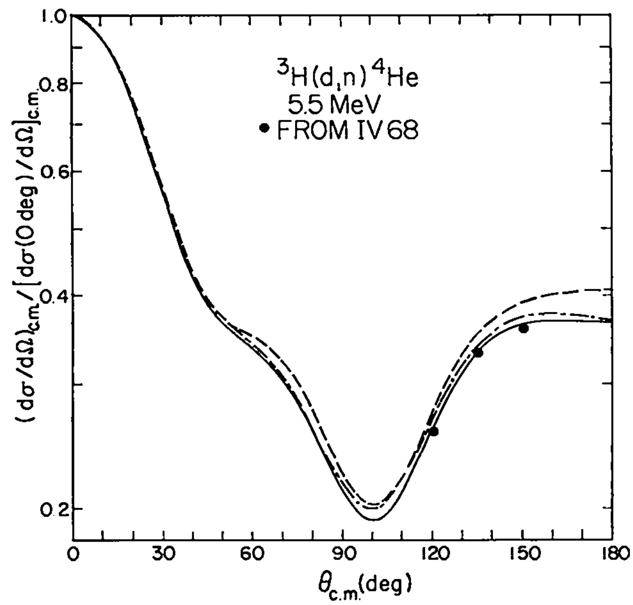

Fig. 3.
Normalized angular distribution of the $^3H(d,n)^4He$ reaction at 5.5 MeV. The full curve is the present result, the dashed-dotted curve is the previous solution, and the dashed curve is from Ref. 2. The data points are from Ref. 4.

Paulsen[2] is 10.6% at 180°, and from the previous evaluation,[3] is 4.6% at 106°. The latter is within the estimated uncertainty of ±3%.[3] At 6.5 MeV, the maximum deviations are 20% at 180° for Liskien and Paulsen[2] and 2% at 104° for the previous evaluation.[3]

Like the other charged-particle data of the $^3H(d,n)^4He$ reaction, these data also have a lower scale than the recommended scale of the previous evaluation.[3] However, the difference is not important. The combined scale difference (combined with the data of Table XVIII of Ref. 3) is (1.49 ± 0.75)%, which is within the scale uncertainty of 1.5% of the recommended data. As was pointed out before,[3] this scale difference could be removed by raising the high-energy part of the efficiency curve. However, such a procedure would not be consistent with the neutron-detection efficiency curve derived independently.[3]

The use of the three excitation functions with no obvious energy-dependent systematic error allows us to transfer the scale from above 7 MeV to lower energies, so that a 2% scale uncertainty for 4 MeV seems realistic. The scale uncertainty of the low-energy data of Liskien and Paulsen[2] is given as 4%. Therefore, the errors increase below 4 MeV because of the necessity of a smooth transition from the present evaluation to the low-energy part of Liskien's and Paulsen's evaluation.[2] This not only affects the scale uncertainty, but will also increase the differential error from ±2% for energies above 5 MeV to ±3% at 3 MeV.

IV. CONCLUSION

The inclusion of three excitation functions over the rather wide energy range from 4 to 11 MeV was very important for three reasons.

(1) Above 7 MeV, it independently confirmed the previous evaluation.[3]

(2) For energies between 4 and 7 MeV, it gave enough additional information to improve the evaluation and to reduce the uncertainties there.

(3) Like the other charged-particle data, it indicated that the scale of the recommended $^3H(d,n)^4He$ data is slightly too large, although within the uncertainties.

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