Various cross sections for $A \leq 3$ nuclei*

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Differential cross section data, accurate to an error of less than 1%, are presented for several different elastic scatterings and reactions, in the region of 10–14 MeV. The data are for various processes stemming from the bombardment of hydrogen, deuterium, ^{3}He, and tritium by protons and deuterons.

[NUCLEAR REACTIONS $A(b,c)D$, $A = {}^1$H, ^{2}H, ^{3}H, ^{3}He, $b = p, d, t$, $E = 10$–13.6 MeV, measured $\sigma(\theta)$, various angles, $\Delta\theta = 0.03°$, $\Delta\sigma(\theta) = 0.5$–$1.0\%$.]

I. INTRODUCTION

In this paper are presented a number of measurements of a diverse sort. Some are cross sections measured auxiliary to a larger program; some are data measured to contribute to an extensive phenomenological analysis, and the publication of such analysis program appears to have been slowed indefinitely or has been published separate of the data. Thus, we have felt the need to present the final data formally without full phenomenological analysis, because of many requests and the possibility time would leave them unpublished permanently.

The experimental apparatus is described in detail by Jarmie *et al.*[1] and by Detch.[2] Exceptions or additions will be noted in each section. Errors will be quoted as scale and relative errors (standard deviations) where the scale error is defined as:

$$(\text{absolute error})^2 = (\text{scale error})^2 + (\text{relative error})^2.$$

In each case the energy of the bombarding beam is known to ±15 keV with a full width at half maximum spread of 20 keV including the effects of foil and target-gas straggling and machine energy resolution. The angular accuracy including all effects was ±0.03°.

Data are reported for

$d+d$ elastic scattering 12.305 MeV,

$d+d = p+t$ 12.305 MeV,

$d+{}^3\text{He} = d+{}^3\text{He}$ 10.000 MeV,

$d+{}^3\text{He} = p+\alpha$ 10.000 MeV,

$t+p$ elastic scattering 13.600 MeV,

$t+p = d+d$ 13.600 MeV,

$p+p$ elastic scattering 13.600 MeV.

TABLE I. ^{2}H$(d,p)^3$H differential cross sections at 12.305 ± 0.015 MeV.

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
14.44	36.38	20.93	17.61	0.98	0.43
21.09	13.33	30.48	6.619	0.95	0.43
24.12	8.104	34.80	4.085	1.01	0.43
30.21	4.491	43.39	2.347	1.02	0.43
42.54	6.724	60.37	3.877	0.84	0.43
61.47	5.582	84.88	3.992	1.05	0.43
74.46	4.882	100.26	4.220	1.12	0.43
24.12 [a]	18.58	122.56	3.651	0.66	0.43
21.09 [a]	14.01	129.98	2.705	0.92	0.43
14.44 [a]	24.13	145.97	4.513	1.20	0.43

[a] At these angles the triton was detected. The center of mass angle listed is the corresponding proton angle.

TABLE II. Differential cross sections. $d+d$ elastic scattering, 12.305 ± 0.015 MeV.

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
10.00	1859	20.03	470.5	0.37	0.43
12.50	1600	25.04	408.4	0.42	0.43
15.00	1368	30.05	353.1	0.48	0.43
17.50	1141	35.05	298.3	0.46	0.43
20.00	937.3	40.06	248.8	0.47	0.43
22.50	752.8	45.07	203.2	0.46	0.43
25.00	616.5	50.07	169.7	0.49	0.43
27.50	507.0	55.08	142.6	0.40	0.43
30.00	424.9	60.08	122.5	0.58	0.43
32.50	363.9	65.08	107.7	0.58	0.43
35.00	329.2	70.09	100.3	0.52	0.43
37.50	297.7	75.09	93.72	0.51	0.43
40.00	279.5	80.09	91.14	0.49	0.43
42.50	266.6	85.09	90.35	0.52	0.43
45.00	250.2	90.09	88.43	0.53	0.43
47.50	242.4	95.09	89.71	0.55	0.43
50.00	235.8	100.09	91.74	0.50	0.43

TABLE III. Differential cross sections. $d + {}^3\mathrm{He}$ elastic scattering, 10.000 ± 0.015 MeV (20 keV full width at half-maximum).

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
10.00	2492.	16.68	905.9	0.60	0.33
12.00	2014.	20.01	736.4	0.55	for
15.00	1585.	24.98	586.4	0.44	the
17.00	1343.	28.29	501.0	0.51	entire
20.00	989.2	33.24	374.9	0.55	group
25.00	539.4	41.44	211.0	0.68	
30.00	239.2	49.56	97.31	0.65	
35.00	84.84	57.59	36.18	0.79	
40.00	42.48	65.49	19.15	0.84	
45.00	62.94	73.25	30.25	0.76	
50.00	100.2	80.84	51.85	0.63	
55.00	126.4	88.24	71.07	0.67	
60.00	132.1	95.41	81.56	0.67	
65.00	116.7	102.32	79.92	0.73	
70.00	92.02	108.94	70.71	0.67	
35.00 [a]	221.0	109.95	67.40	1.00	
75.00	62.01	115.24	54.04	0.81	
30.00 [a]	142.60	119.96	41.13	0.59	
25.00 [a]	81.29	129.96	22.40	1.59	
23.00 [a]	84.89	133.96	23.03	0.67	
20.00 [a]	133.1	139.97	35.35	0.61	
17.00 [a]	242.4	145.97	63.28	0.74	
15.00 [a]	365.2	149.98	94.39	0.73	
12.00 [a]	601.7	155.98	153.6	0.72	
10.00 [a]	783.0	159.98	198.5	0.74	

[a] At these angles, the recoil ^{3}He was detected. The center of mass angle listed is the corresponding deuteron angle.

II. $d+d=p+t$ 12.305 MeV
$d+d=d+d$ 12.305 MeV

The deuterium target gas was approximately 98% pure, the major contaminant being hydrogen. During bombardment, the ionized deuterium interacts with organic compounds slowly increasing the fraction of hydrogen. This process was monitored carefully, and during this experiment the gas decreased in purity only by 0.4%. Corrections were made for this effect. The results are given

TABLE IV. Differential cross sections. $^3\mathrm{He}(d,p)^4\mathrm{He}$, 10.000 ± 0.015 MeV.

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
120.00	2.70	130.27	3.42	2.50	0.33
155.00	3.35	159.99	5.09	1.68	0.33
166.00	3.58	168.85	5.59	2.35	0.33
168.00	3.60	170.45	5.66	1.14	0.33

TABLE V. Differential cross sections. $^3\mathrm{H}(p,p)^3\mathrm{H}$, 13.600 ± 0.015 MeV (20 keV full width at half-maximum).

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
12.00	512.6	16.03	290.0	0.45	0.70
15.00	500.0	20.00	284.8	0.45	0.70
20.00	460.2	26.62	266.2	0.50	0.70
50.00	128.5	64.95	88.78	0.50	0.70

in Tables I and II. The data in Table II have been previously reported at a conference[3] and compared to other work, and it is included for completeness.

Since that time, another experiment on $d+d$ elastic scattering has been done from 11 to 19 MeV by Hegland and Brown.[4] Their results at 12.305 MeV agree well with ours in angular shape but appear to be 1.9% lower than our data in absolute normalization. A review of experimental factors by both groups has not uncovered a reason for the difference; the discrepancy remains unresolved.

III. $d+{}^3\mathrm{He}=d+{}^3\mathrm{He}$ 10.000 MeV
$d+{}^3\mathrm{He}=p+\alpha$ 10.000 MeV

The purity of the ^{3}He target gas was 99.6 ± 0.02%. The results are given in Tables III and IV. These data are being used in an R-matrix analysis of the mass-5 system.[5]

IV. $t+p=t+p$ 13.600 MeV
$t+p=d+d$ 13.600 MeV
$p+p=p+p$ 13.600 MeV

The additional experimental techniques concerning the use of a tritium target are described in Refs. 2 and 6.

The results are presented in Tables V–VII. Care should be taken to note that the $t+p=d+d$

TABLE VI. Differential cross sections. $^3\mathrm{H}(p,d)^2\mathrm{H}$, 13.600 ± 0.015 MeV (20 keV full width at half-maximum).

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
15.00 [a]	59.00	26.13	19.97	0.97	0.70
22.50	14.61	39.11	5.154	0.93	1.5
27.50	12.36	47.67	4.530	1.1	1.5
30.00	14.42	51.93	5.398	1.0	1.5
45.00	17.71	76.86	7.939	1.0	1.5
55.00	14.02	92.68	7.464	1.9	1.5

[a] New data; the other angles are our old data normalized 3.6% lower.

TABLE VII. Differential cross sections. $^1H(p,p)^1H$, 13.600 ± 0.015 MeV (20 keV full width at half-maximum).

θ_{lab} (deg)	$\sigma(\theta)_{lab}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$\sigma(\theta)_{c.m.}$ (mb/sr)	Relative error (%)	Scale error (%)
20.00	135.9	40.11	35.93	0.51	0.37
30.00	130.9	60.18	37.64	0.36	0.37

cross section is for the observation of *either* of the outgoing deuterons and may be a factor of 2 larger than those quoted by others. The $t+p$ elastic scattering data in Table V supplement Table II of Ref. 6, significantly improving the scale error. The normalization of 3.6% mentioned in the table comes from comparison of the new and old 15° data. This improved scale error stemmed from greater accuracy in the determination of the target gas directly and by normalization to $p+p$ elastic scattering data taken in this experiment the results of which are given in Table VII. These data agree with our earlier $p+p$ cross sections of Ref. 1 within one standard deviation.

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