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Elastic Scattering of Tritons by Helium-4

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ELASTIC SCATTERING OF TRITONS BY HELIUM-4

by

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ABSTRACT

Angular distributions of the differential cross section and of the analyzing power have been measured for the ${}^4\text{He}(t,t){}^4\text{He}$ reaction at 19 energies from 6 to 17 MeV. The relative errors of the cross section and analyzing power range from 2.0 to 2.5% and 0.005 to 0.01, respectively, and the scale errors are 1% in each case. Complete data tables are presented, and the experimental procedure is described for the present measurements and for earlier cross-section measurements. Graphs of the data are presented, as well as the curves resulting from an energy-independent phase-shift analysis.

I. INTRODUCTION

The elastic scattering of tritons by ${}^4\text{He}$ is important in studying the physics of the mass-7 nuclear system and in determining the parameters of the ${}^6\text{Li}(n,t){}^4\text{He}$ reaction, a primary standard for neutron flux measurements.¹ Comparisons of the ${}^4\text{He}(t,t){}^4\text{He}$ data may be made with predictions of the Resonating Group Method² (RGM) and of an R-Matrix analysis.³ The experimental data of Spiger and Tombrello⁴ have been used to establish the energy level scheme of ${}^7\text{Li}$ (Fig. 1) from about 4 to about 10 MeV of excitation. We have increased our knowledge of this system by measuring analyzing powers, as well as additional and more accurate differential cross sections. Nineteen angular distributions were measured for triton beam energies from 6 to 17 MeV. Some earlier data have been reported in Los Alamos Scientific Laboratory (LASL) report LA-6188,⁵ and some of the present work was included in a preliminary report.⁶ The present data, which include the bulk of the analyzing power measurements, were measured with the apparatus described below.

II. EXPERIMENTAL APPARATUS

The experiment was performed at the LASL Van de Graaff facility and made use of the FN tandem Van de Graaff accelerator and the Lamb-shift polarized triton source.^{6,7} The scattering chamber used was a 61-cm cube called the "supercube."⁸ References 5 and 6 describe the polarized triton source and the method of extracting analyzing powers. Additional experimental information is given in Ref. 9. The ${}^4\text{He}$ target gas was contained in a 9.7-cm-diam cell with a beam-entrance snout about 6-cm long. A 2.5- μm -thick Havar* foil covered the 2.5-mm-diam beam-entrance aperture on the snout, and a 7- μm -thick Kapton** foil covered the 300° cell opening through which the beam and detected particles emerged. This gas target was operated at room temperature and in a pressure range of 250-310 torr; the gas purity was better than 99.5%. The target tem-

*Havar is the trade name for a cobalt "superalloy" manufactured by Hamilton Technology, Inc., Lancaster, Penn.

**Kapton is a polyimide film made by E.I. Du Pont de Nemours & Co., Washington, Del.

Fig. 1.

Energy level diagram from Ref. 19. The energies are in MeV. There is possibly a very broad $3/2^+, 1/2$ level at 9.5 MeV (12.33 MeV E_t).

perature was measured with a thermocouple attached to the cell. The target pressure was measured with a capacitance manometer whose digital read-out could be transmitted to an on-line computer.

Each of two detector assemblies, left and right of the beam direction, consisted of a stack of three silicon surface-barrier detectors mounted behind a standard gas-target collimator arrangement, which had a geometry factor G_{00} of 7.0×10^5 cm-sr and an angular acceptance of $1/2^\circ$ to 1° full width at half-maximum (FWHM). The relative and scale errors of the center of mass scattering angle are 0.05° and 0.1° , respectively. The nominal thicknesses of the detectors in a stack were 17, 150, and 1500 μm from front to back. We used the 17- and 150- μm detectors to perform ΔE - E mass identification of the α -particles and simultaneously used the 150- and 1500- μm detectors to identify the tritons. The electronic circuitry was approximately as shown in Fig. 3 of Ref. 9. The polarized beam used had intensities up to 100 nA and polarizations in the range 0.75 to 0.85.

On-line data processing and control of some of the supercube and ion-source functions were carried out with an SDS-930 computer.

III. ERROR ANALYSIS

A. Beam Energy

The estimated uncertainties in the above-quoted beam energies include a scale error arising from the absolute calibration of the beam analyzing magnet and relative errors stemming from nonlinearity of the analyzing magnet and uncertainties in the calculated beam-energy losses in the target.

The tandem Van de Graaff energy calibration is based on a measurement of the ${}^{12}\text{C}(p,p){}^{12}\text{C}$ isospin-forbidden resonance at 14.23075 ± 0.00020 MeV.¹⁰ We believe the scale error in the calibration of the analyzing magnet from this measurement to be not more than ± 1 keV. The relative calibration error arising from nonlinearities in the analyzing magnet and from magnet-recycling and slit-setting procedures has not been studied completely. However, we estimate this error to be at most ± 3 keV. The uncertainty in the energy-loss calculations for tritons entering the gas cell is about ± 2 keV. The uncertainty in the thickness of the Havar entrance foil on the gas cell contributes an additional relative error of ± 11 keV. A quadratic sum of all these relative errors gives an overall energy uncertainty of ± 12 keV.

The energy spread of the incident beam at the target is dominated by straggling in the Havar entrance foil and the target gas in the cell. Calculations with the code STRAGL¹¹ give mean straggling widths of 29 keV in the Havar foil and 16 keV in the ${}^3\text{He}$ target gas. The variation in these values is less than ± 1 keV over the triton energy range. When the Havar and gas straggling widths are folded quadratically with the estimated ± 4 -keV terminal ripple of the Van de Graaff, the total energy spread in the incident beam is calculated to be 33 keV FWHM.

B. Analyzing Power

The relative errors in the analyzing power A_y arise from (1) counting statistics, including the background; (2) the method used to subtract the background; (3) random fluctuations in the measurement of the beam polarization by the quench-ratio method;¹² and (4) other

random contributions, such as position instability in the beam. The errors shown in Table B-I are relative errors and are obtained by quadratically combining the counting statistics error with 0.005, which we believe to be a reasonable estimate of the errors caused by the other factors mentioned above. This value for the random systematic error is based on experience with repeatability of data for this type of experiment.

The scale error for A_y arises solely from various errors in determining the absolute value of the beam polarization using the quench-ratio technique because all other scale errors cancel for data taken with symmetric geometry.¹³ The sources of scale error include

- (1) the presence of an unpolarized, negatively charged background in the incident beam that masquerades as a polarized beam when electric, rather than magnetic, fields are used for quenching;
- (2) enhancement of the polarization by slit-edge scraping as the beam goes from the analyzing-magnet Faraday cup (where the quench ratio is measured) to the target;^{12,14}
- (3) the small, negative polarization in the quenched beam;¹² and
- (4) depolarization caused by residual gas in the terminal of the tandem Van de Graaff.¹⁵

In checking the effect of (1) periodically during the experiment, we discovered that the discrepancies between electric- and magnetic-field quench ratios were typically 0.010-0.015 with infrequent excursions to as much as 0.025. Polarization enhancement caused by beam scraping is believed to contribute no more than a 0.01 scale error. The error caused by small, negative polarization is probably on the order of 0.005 (Ref. 14). Both polarization enhancement and the small, negative polarization in the quenched beam tend to compensate for the error caused by (1). Terminal depolarization reduces the vector polarization by no more than 0.001 (Ref. 15). We estimate that all these effects cause a scale error of ± 0.01 times A_y (1%) in our A_y measurements. This number is substantiated by the results of Ref. 6.

At the larger scattering angles of the recoil ^4He particles, multiple scattering of the detected particles in the gas cell exit foil may be significant. Using the methods in Ref. 9, we found these effects not to contribute a significant error in this experiment.

C. Differential Cross Sections

The laboratory cross sections σ_o were computed from the formula

$$\sigma_o(\theta_o) = \frac{Y \sin \theta_o}{nNG} ,$$

where Y is the number (yield) of scattered particles (corrected for background and dead time), θ_o is the laboratory scattering angle, n is the number of beam particles, N is the number of target particles per unit volume, and G is the gas-target geometry factor.¹⁶ For our symmetric geometry, the yield is the average of the yield of the left and right detectors. Cross sections are not quoted for $\theta_{c.m.} = 25^\circ$ or 155° ($\theta_o = 12.5^\circ$) because the detector collimator assemblies intercepted some of the beam leaving the gas target.

The relative errors in the cross-section data arise mainly from (1) reading the capacitance manometer pressure gauge, (2) counting statistics, (3) the method of background subtraction, (4) random pressure and temperature fluctuations in the target, (5) beam-current integration, and (6) beam-position instability and/or detector-position uncertainty. We estimate that the total error caused by items (1), (3), (4), (5), and (6) is 1.0%, based on previous LASL experiments with similar targets and on the geometry of the supercube scattering chamber. We expected the total relative error to equal the statistical error plus 1.0%, but it became apparent, even with a small statistical error, that an unknown systematic error was dominating the relative error. A careful study of this systematic effect resulted in the assignment of a relative error of $\pm 2.0\%$ for triton detection and $\pm 2.5\%$ for alpha detection.

The scale errors for the cross section may be traced to (1) calibration of the pressure gauge, (2) calibration of the current integrator, (3) purity of the target gas, and (4) geometry factor G . The error caused by calibration of the pressure gauge is 1.0%, whereas that caused by calibration of the current integrator is of the order 0.2%.¹⁷ The slits used in the experiments were measured with a Lietz split-image optical comparator: from these measurements, we can estimate the G factor to $\pm 0.2\%$

accuracy. The first-order correction to G (Ref. 16, Eq. (5c).1) is 0.07%, so deviations of G from G_{00} are of no consequence. The overall scale error we assign to our data is, therefore, 1.1%.

At higher energies, the sharpness of the forward- and backward-angle minima and the steep slopes in the angular distributions suggest a possible need for multiple-scattering corrections.^{9,18} We estimated these corrections and found them to be small.

For both analyzing power and cross section, the $\pm 0.02^\circ$ (lab angle) uncertainty in the detector position possibly could contribute to the relative error in regions where the angular distribution has a steep slope. Calculations with the present data showed this effect to be negligible.

IV. DATA ANALYSIS

Table I summarizes the energies and the number of data points at each energy and provides information on ^7Li energy levels for the reader's convenience.¹⁹ The items marked with an asterisk are previous data from LASL report LA-6188⁵ and are repeated here for convenience. Appendix A is a complete numerical listing of the data. The superscripts "t" and "α" on the lab angle indicate whether the triton or alpha particle was detected. The errors given for A_y are relative errors; the relative errors for the differential cross sections are $\pm 2.0\%$ for the triton-detected data and $\pm 2.5\%$ for the alpha-detected data. In several cases where the triton and alpha data overlap, there is good agreement.

The data were taken in two groups. In the experiment measuring the data of group 2 (set 2 in Table I), the G -factor was not known precisely, so the absolute values of the cross sections were normalized to the accurate data of LASL report LA-6188⁵ by comparison of several overlapping points at 8, 9, and 10 MeV. The data of group 1 (set 1 in Table I) were absolute measurements. Twelve-MeV data were also measured previously, as reported in LASL report LA-6188.⁵ Comparison with this more accurate previous data ($\pm 0.4\%$ scale error) provided a verification of our present absolute errors. For our alpha-detected data we agreed to 1.3%, and for the triton-detected data we agreed to 0.2%. This good agreement reassured us that our gas purity, current integration, and other absolute scale factors were well understood. The experimental procedure for the LASL report LA-6188 cross-section data⁵ has never been published and is given in Appendix B to support our present results.

TABLE I
DATA SUMMARY
AND ENERGY LEVEL INFORMATION^a

Lab Triton Energy (MeV)	Number of σ (θ) Data or [J^π, T]	Number of A_y Data or [width (keV)]	Data Set
3.793	[7/2 ⁻ , 1/2]	[93]	---
6.000	11	14	2
7.000	20	26	2
7.387	[5/2 ⁻ , 1/2]	[875]	---
8.000	25	25	2
8.388	⁶ Li+n threshold	---	---
8.748	[5/2 ⁻ , 1/2]	[90]	---
8.788	17*	29*	---
9.000	29	28	2
10.000	27	27	2
10.815	26	38*	1
11.000	29	28	2
12.000	30	30	1
12.250	26	26*	1
12.630	[7/2 ⁻ , 1/2]	[400]	---
12.626	30	30	1
12.800	31	31	2
12.945	[3/2 ⁻ , 1/2]	[1200]	---
13.000	30	30	1
13.270	30	30	2
13.548	30	30	2
13.748	31	31	2
14.000	31	31	1
15.000	31	32	1
15.383	[3/2 ⁻ , 3/2]	[260]	---
16.000	31	32	1
17.000	30	31	1

^aAsterisks indicate previous data from Ref. 5.

Out of 1065 data points measured, 46 were discarded for the following reasons: equipment malfunction, 9 points; detector-assembly interception of the beam at low angles and low energies, 2 points; excessive change in detector efficiency, 29 points; and excessive beam polarization changes, 6 points. In addition, four analyzing power points and one cross-section point deviated anomalously from the smooth curve of nearby points (with $\chi^2 > 16$) and were discarded. The occasional gross changes in detector efficiency were not understood.

V. DISCUSSION

Figures 2-8 show the angular distributions of the differential cross sections and of the analyzing power A_y at the various bombarding energies. They demonstrate remarkable changes in the shape of the analyzing powers as a function of energy. Of particular note is the $A_y = -1$ extremum⁶ in the region of 10.185 MeV at about 90°

c.m. We are analyzing the data with an energy-independent phase-shift code HALBNUL developed by F. D. Correll. This code derives from the Zürich code EINSNUL²⁰ and uses the minimization program MINUIT.²¹ The dotted lines in Figs. 2-8, which have converged in most cases with a reasonable χ^2 per degree of freedom, are the preliminary results of the analysis. Our data at 17.000 MeV have been compared²² with the predictions of an RGM calculation² with reasonable agreement.

ACKNOWLEDGEMENTS

This project has benefited from the assistance of many people, in particular Dave M. Stupin, Richard F. Haglund, Jr., Louis Morrison, Rudy Martinez, and the operating staff of the Van de Graaff accelerators. We are also grateful to R. V. Poore, P. A. Schmelzbach, B. D. Anderson, and P. A. Lovoi.

(c)

(b)

(a)

Fig. 2.

$^4\text{He}(t,t)^4\text{He}$ cross sections and analyzing powers at (a) 6.000, (b) 7.000, and (c) 8.000 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

(c)

(b)

(a)

Fig. 3.
 $^4\text{He}(t,t)^4\text{He}$ cross sections and analyzing powers at (a) 8.788, (b) 9.000, and (c) 10.000 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

(c)

(b)

(a)

Fig. 4.

${}^4\text{He}(t,t){}^4\text{He}$ cross sections and analyzing powers at (a) 10.815, (b) 11.000, and (c) 12.000 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

Fig. 5.

${}^4\text{He}(t,t){}^4\text{He}$ cross sections and analyzing powers at (a) 12.250, (b) 12.626, and (c) 12.800 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

Fig. 6.

${}^4\text{He}(t,t){}^4\text{He}$ cross sections and analyzing powers at (a) 13.000, (b) 13.270, and (c) 13.548 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

(c)

(b)

(a)

Fig. 7.
 $^4\text{He}(t,t)^4\text{He}$ cross sections and analyzing powers at (a) 13.748, (b) 14.000, and (c) 15.000 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

(b)

(a)

Fig. 8.

$^4\text{He}(t,t)^4\text{He}$ cross sections and analyzing powers at (a) 16.000 and (b) 17.000 MeV. The angles are in degrees, and the curves are fits by an energy-independent phase-shift analysis.

APPENDIX A

DIFFERENTIAL CROSS SECTION AND ANALYZING POWER DATA

The energies given here are approximate (see Table I).

${}^4\text{He}(t,t){}^4\text{He}$ at 600 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1167.	26.26	401.8	-0.387	0.007
20.00°	773.7	34.95	275.5	-0.506	0.007
25.00°	497.1	43.59	184.6	-0.521	0.006
30.00°	310.4	52.16	121.2	-0.418	0.009
40.00°	192.1	69.00	79.66	0.231	0.009
45.00°	98.80	77.23	47.66	0.865	0.016
50.00°	104.0	85.29	33.93	0.855	0.011
40.00°	36.94	99.98	29.58	0.677	0.011
35.00°	104.9	109.98	30.28	0.296	0.012
30.00°	138.9	119.98	38.25	0.138	0.008
25.00°	192.4	129.98	51.16	0.365	0.007
20.00°		139.99		0.672	0.007
15.00°		149.99		0.921	0.007

${}^4\text{He}(t,t){}^4\text{He}$ at 800 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	2591.	26.26	869.3	-0.190	0.006
17.50°	1856.	30.62	630.2	-0.164	0.006
20.00°	1350.	34.96	464.9	-0.134	0.006
22.50°	946.7	39.29	330.8	-0.100	0.006
25.00°	622.7	43.60	221.7	-0.039	0.005
27.50°	389.5	47.89	141.4	0.031	0.006
30.00°	229.0	52.16	85.02	0.145	0.006
32.50°	128.0	56.42	48.69	0.248	0.007
35.00°	74.62	60.64	29.14	0.199	0.008
37.50°	52.64	64.84	21.16	-0.172	0.009
40.00°	54.31	69.01	22.52	-0.654	0.009
42.50°	66.44	73.14	26.50	-0.856	0.008
45.00°	83.51	77.24	37.16	-0.842	0.007
47.50°	101.4	81.29	46.91	-0.780	0.007
49.00°	144.4	84.97	53.46	-0.723	0.007
45.00°	174.9	89.97	61.85	-0.622	0.007
40.00°	190.1	99.97	62.03	-0.467	0.007
35.00°	145.9	109.97	44.52	0.316	0.007
30.00°	93.40	119.97	27.52	0.051	0.007
27.50°	98.61	124.98	21.84	0.370	0.007
25.00°	138.2	129.98	38.11	0.542	0.006
22.50°	219.2	134.98	59.26	0.523	0.007
20.00°	355.0	139.98	94.37	0.433	0.007
17.50°	536.6	144.98	140.6	0.354	0.007
15.00°	775.7	149.98	200.6	0.273	0.009

${}^4\text{He}(t,t){}^4\text{He}$ at 700 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1743.	26.26	591.9	-0.623	0.030
17.50°	1362.	30.61	469.0	-0.698	0.021
20.00°	1029.	34.95	360.0	-0.735	0.005
22.50°	756.0	39.28	269.2	-0.787	0.005
25.00°	529.5	43.59	192.3	-0.795	0.005
27.50°		47.89		-0.824	0.005
30.00°		52.16		-0.791	0.006
35.00°	147.3	60.64	57.54	-0.437	0.010
37.50°	95.92	64.84	38.36	0.059	0.010
40.00°	75.54	69.00	31.32	0.640	0.010
42.50°	77.34	73.14	33.18	0.925	0.009
45.00°	91.23	77.23	40.58	0.868	0.009
47.50°	110.3	81.28	51.02	0.699	0.013
50.00°	125.5	85.29	60.52	0.531	0.010
45.00°	192.1	89.97	67.93	0.387	0.009
42.50°	228.5	94.97	77.47	0.266	0.008
40.00°	247.4	99.97	80.72	0.143	0.008
37.50°	248.6	104.98	78.30	0.057	0.007
35.00°	239.2	109.98	72.99	0.009	0.007
32.50°		114.98		0.017	0.010
30.00°		119.98		0.112	0.007
27.50°		124.98		0.321	0.007
22.50°	344.7	134.98	93.21	0.715	0.006
20.00°	440.4	139.98	117.1	0.785	0.006
17.50°	559.2	144.98	146.4	0.817	0.021
15.00°		149.98		0.749	0.030

${}^4\text{He}(t,t){}^4\text{He}$ at 879 MeV (lab)
(scale errors $\Delta\sigma = 4\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
12.50°	254.9	21.90	846.5	-0.169	0.007
15.00°		26.27		-0.157	0.007
17.50°		30.62		-0.132	0.007
20.00°		34.96		-0.103	0.007
22.50°		39.29		-0.075	0.007
25.00°	539.1	43.59	191.9	-0.055	0.007
27.50°		47.89		-0.003	0.007
30.00°		52.17		0.045	0.007
32.50°	240.8	56.41		0.090	0.007
35.00°		60.65		0.045	0.007
37.50°		64.84			
40.00°	72.25	64.97	29.06	-0.332	0.007
42.50°	62.28	69.00	25.83	-0.339	0.007
45.00°	66.26	73.14		-0.364	0.007
47.50°		77.25	29.47	-0.664	0.007
50.00°	76.43	81.29		-0.715	0.007
52.50°		85.29	36.86		
55.00°	74.50	89.25		-0.634	0.007
57.50°		93.17	39.40	-0.615	0.011
60.00°		97.00		-0.575	0.007
62.50°	88.85	99.96		-0.563	0.007
65.00°		104.96	27.99	-0.526	0.007
67.50°	70.10	109.97	21.38	-0.458	0.007
70.00°	51.82	114.97	15.36	-0.258	0.011
72.50°	41.10	119.97	11.85	0.168	0.010
75.00°		124.97		0.388	0.009
77.50°		129.97		0.627	0.008
80.00°		134.98		0.717	0.007
82.50°	76.25	139.99	21.02	0.710	0.007
85.00°		144.99		0.575	0.007
87.50°	225.5	149.99	59.94	0.446	0.007
90.00°		154.99		0.350	0.007
92.50°	388.0	159.99	101.2		
95.00°	485.0		125.4	0.257	0.007
97.50°	638.1		163.2		

${}^4\text{He}(t,t){}^4\text{He}$ at 900 MeV (lab)
(scale errors $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	196.1	26.27	657.8	-0.048	0.005
17.50°	142.3	30.62	483.2	-0.006	0.005
20.00°	106.1	34.96	365.3	0.048	0.005
22.50°	754.2	39.29	263.7	0.115	0.006
25.00°	526.0	43.60	187.2	0.175	0.006
27.50°	361.6	47.89	131.3	0.258	0.006
30.00°	242.1	52.17	89.86	0.309	0.006
32.50°	162.5	56.41	61.80	0.314	0.007
35.00°	115.1	60.65	44.96	0.179	0.008
37.50°	92.36	64.83	37.12	-0.110	0.009
40.00°	82.03	69.01	34.02		
42.50°	82.29	73.15	35.29	-0.762	0.008
45.00°	81.85	77.24	36.41	-0.912	0.008
47.50°	84.17	81.29	38.94	-0.948	0.007
50.00°	84.27	85.30	40.65	-0.936	0.007
52.50°	81.41	89.26	41.08	-0.882	0.008
55.00°	76.14	93.16	40.32	-0.823	0.008
57.50°	66.32	97.00	36.97	-0.751	0.009
60.00°	54.86	100.78	32.31	-0.705	0.010
62.50°	44.04	104.49	27.49	-0.645	0.012
65.00°	42.41	109.97	19.33	-0.557	0.009
67.50°	35.50°	114.97	12.57	-0.417	0.011
70.00°	29.43	119.97	8.492	-0.042	0.012
72.50°	35.22	124.97	9.920	0.421	0.011
75.00°	68.53	129.97	18.89	0.409	0.008
77.50°	135.1	134.98	36.53	0.300	0.008
80.00°	237.6	139.98	63.14	0.207	0.007
82.50°	370.3	144.98	96.98	0.141	0.006
85.00°	540.9	149.98	139.9	0.089	0.006

${}^4\text{He}(t,t){}^4\text{He}$ at 1000 MeV (lab)
(scale errors $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1469	26.27	492.8	0.083	0.006
17.50°	1103	30.62	374.5	0.148	0.006
20.00°	841.4	34.96	289.6	0.224	0.006
22.50°	633.0	39.28	221.4	0.297	0.006
25.00°	456.7	43.60	162.6	0.360	0.006
27.50°	388.4	47.89	122.9	0.414	0.006
30.00°	246.4	52.17	91.46	0.418	0.006
32.50°	216.4	56.42	81.35	0.393	0.006
35.00°	185.6	60.65	70.58	0.353	0.006
37.50°	145.2	64.84	56.69	0.195	0.007
40.00°	117.5	69.02	47.22	-0.056	0.008
42.50°	102.1	73.14	42.31	-0.335	0.008
45.00°	91.47	77.24	39.23	-0.598	0.008
47.50°	80.08	81.29	37.04	-0.912	0.009
50.00°	64.23	85.30	32.41	-0.993	0.010
52.50°	55.91	89.26	29.60	-0.986	0.011
55.00°	45.39	93.17	25.30	-0.926	0.013
57.50°	37.50°	96.98	22.50°	-0.873	0.008
60.00°	30.84	104.96	15.81	-0.829	0.010
62.50°	24.94	109.96	9.409	-0.743	0.013
65.00°	14.94	114.96	4.428	-0.497	0.013
67.50°	10.59	119.97	2.577	-0.096	0.021
70.00°	8.931	124.97	5.154	-0.279	0.015
72.50°	18.23	129.97	27.21	-0.009	0.010
75.00°	100.7	134.97	47.44	-0.062	0.009
77.50°	274.4	139.98	71.86	-0.089	0.008
80.00°	388.1	144.98	100.3	-0.114	0.007

${}^4\text{He}(t, t){}^4\text{He}$ at 1082 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1169.	26.27	39.19	0.216	0.009
16.00°		28.01			
17.50°	907.4	30.62	308.0	0.279	0.009
18.00°		31.49			
20.00°	709.0	34.97	244.0	0.340	0.009
22.50°	558.1	39.29	195.1		
24.00°		41.88		0.444	0.009
25.00°	426.9	43.61	151.9		
26.00°		45.33		0.478	0.009
27.50°	324.9	47.90	118.0		
30.00°	246.2	48.76		0.490	0.009
32.50°	188.9	52.18	91.39	0.477	0.009
35.00°	149.1	55.58		0.421	0.009
36.00°		56.43			
37.50°	119.2	60.65	58.23	0.237	0.009
38.00°		62.34		0.143	0.009
40.00°	102.3	64.85	47.92	0.003	0.009
42.50°	90.62	65.69		-0.045	0.009
45.00°	81.43	69.02	42.42	-0.267	0.009
47.50°	75.28	73.15	38.85	-0.531	0.009
50.00°	67.60	77.25	36.22	-0.732	0.009
46.00°		81.30	34.83	-0.869	0.009
48.00°		85.31	32.61	-0.946	0.009
49.00°		87.96		-0.981	0.009
44.00°		89.96		-0.999	0.009
46.00°		91.96		-1.006	0.009
52.00°		94.71		-0.997	0.009
58.00°		95.96		-1.002	0.009
40.00°	58.68	97.77		-0.979	0.011
37.50°	41.22	99.96	19.15	-0.968	0.009
35.00°	22.28	104.96	12.98	-0.965	0.009
34.00°		109.96	6.979	-0.965	0.009
32.50°	9.501	111.96		-0.907	0.014
30.50°		114.96	2.814		
30.00°		115.96		-0.566	0.019
29.00°	6.207	118.96	1.791	0.153	0.021
28.00°		119.96		0.375	0.021
27.50°		121.97		0.430	0.017
27.00°	17.58	123.97	4.950	0.302	0.014
25.50°		125.97		0.150	0.014
25.00°		128.97		0.004	0.010
24.00°	46.82	129.97	12.90		
22.50°	94.94	131.97	25.66	-0.089	0.009
22.00°		134.97			
20.00°	159.0	135.97		-0.174	0.009
17.50°	252.6	139.97	42.27	-0.204	0.011
16.00°		144.98	60.91		
15.00°	319.9	147.98		-0.266	0.011
		149.98	82.70		

${}^4\text{He}(t, t){}^4\text{He}$ at 1100 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1117.	26.27	374.9	0.223	0.006
17.50°	902.0	30.62	306.2	0.306	0.006
20.00°	707.6	34.96	243.5	0.392	0.005
22.50°	546.4	39.28	191.0	0.452	0.006
25.00°	428.7	43.60	152.6	0.507	0.005
27.50°	328.7	47.92	119.4	0.528	0.006
30.00°	248.5	52.18	92.23	0.506	0.006
31.25°	212.1	54.31	79.70	0.482	0.006
32.50°	186.4	56.43	70.88	0.425	0.006
33.75°	163.0	58.55	62.81	0.363	0.006
35.00°	143.9	60.66	56.14	0.271	0.007
37.50°	116.6	64.85	46.88	0.016	0.007
40.00°	98.94	69.02	41.02	-0.266	0.007
42.50°	79.04	73.15	38.91	-0.540	0.008
45.00°	79.04	77.25	35.15	-0.750	0.007
47.50°	71.92	81.31	33.26	-0.890	0.008
50.00°	65.58	85.31	31.64	-0.960	0.008
52.00°	57.61	89.96	18.79	-0.989	0.007
55.00°	39.67	104.96	12.50	-0.989	0.008
57.50°	21.11	109.96	6.440	-1.012	0.009
60.00°	8.503	114.96	2.519	-0.745	0.015
62.50°	5.368	117.46	1.574	-0.222	0.023
65.00°	6.024	119.97	1.966	0.461	0.024
67.50°	18.89	124.97	5.309		
70.00°	48.39	129.97	13.62		
72.50°	49.85	134.97	26.45	-0.179	0.008
75.00°	162.6	139.98	43.20	-0.261	0.006
77.50°	234.3	144.98	61.32	-0.289	0.007
80.00°	312.0	149.98	80.67	-0.326	0.007

${}^4\text{He}(t, t){}^4\text{He}$ at 1200 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	990.3	26.27	332.1	0.584	0.006
17.50°	828.5	30.63	281.1	0.663	0.006
20.00°	689.3	34.97	237.2	0.726	0.005
22.50°	555.9	39.30	194.4	0.763	0.005
25.00°	432.1	43.61	153.8	0.783	0.005
27.50°	324.5	47.91	117.8	0.776	0.005
30.00°	277.0	50.05	101.7	0.762	0.005
32.50°	236.2	52.18	87.66	0.738	0.006
35.00°	198.7	54.37	74.67	0.697	0.006
37.50°	166.4	56.43	63.26	0.639	0.006
40.00°	117.6	60.66	45.90	0.424	0.007
42.50°	85.98	64.86	34.55	0.095	0.008
45.00°	66.30	69.03	28.43	-0.332	0.009
47.50°	45.00°	73.16	24.43	-0.876	0.008
49.00°	66.95	77.25	29.78	-0.877	0.008
50.00°	98.11	89.95	34.69	-0.949	0.007
52.50°	94.84	94.96	32.15	-0.943	0.007
55.00°	80.08	99.96	26.13	-0.924	0.007
57.50°	57.31	104.96	18.91	-0.921	0.007
60.00°	35.90	109.96	10.95	-0.782	0.009
62.50°	32.50°	114.96	5.720	-0.219	0.014
65.00°	19.31	117.38	4.604	0.353	0.012
67.50°	15.74	119.96	4.750	0.751	0.010
70.00°	16.46	122.46	6.407	0.667	0.009
72.50°	22.48	124.96	9.487	0.384	0.009
75.00°	33.68	129.97	19.74	-0.125	0.007
77.50°	71.64	134.97	34.99	-0.424	0.006
80.00°	129.5	139.97	52.68	-0.599	0.006
82.50°	198.3	144.97	70.74	-0.725	0.007
85.00°	270.2	149.98	88.74	-0.804	0.006

${}^4\text{He}(t,t){}^4\text{He}$ at 1225 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1123.	26.27	376.5	0.727	0.007
17.50°	935.1	30.63	317.3	0.801	0.007
20.00°	752.9	34.97	259.1	0.851	0.007
22.50°	584.9	39.30	204.5	0.886	0.007
25.00°	435.8	43.61	155.1	0.909	0.007
27.50°	307.2	47.91	111.5	0.896	0.007
30.00°	205.1	52.18	76.13	0.867	0.007
32.50°	132.2	56.44	50.27	0.795	0.007
35.00°	78.07	60.66	30.48	0.578	0.007
37.50°	52.64	64.86	21.15	0.124	0.007
40.00°	41.16	69.03	17.07	-0.505	0.008
42.50°	45.43	73.16	19.48	-0.851	0.007
45.00°	52.70	77.26	23.44	-0.933	0.007
47.50°		81.31		-0.895	0.007
49.50°		84.96		-0.873	0.007
51.00°	110.3	89.95	39.01	-0.819	0.009
53.00°	117.5	94.95	39.38	-0.810	0.008
55.00°	112.2	99.95	36.60	-0.806	0.007
57.00°	91.36	104.95	28.78	-0.772	0.009
59.00°	67.37	109.96	20.55	-0.580	0.009
61.00°	45.78	114.96	13.56	-0.117	0.009
63.00°	37.57	119.96	10.83	0.202	0.010
65.00°	28.75°	124.96	14.42	0.591	0.009
67.00°	51.21	129.96	23.33	0.467	0.008
69.00°	84.65	134.97	38.52	-0.062	0.008
71.00°	142.5	139.97	58.22	-0.481	0.007
73.00°	219.1	144.97	82.03	-0.746	0.007
75.00°	313.3	149.97	106.8	-0.889	0.007
77.00°	413.1			-0.950	0.007

${}^4\text{He}(t,t){}^4\text{He}$ at 1280 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1508.	26.27	505.5	0.402	0.007
17.50°	1088.	30.63	369.0	0.462	0.007
20.00°	760.3	34.97	261.6	0.518	0.007
22.50°	510.4	39.30	178.3	0.557	0.008
25.00°	403.8	43.61	142.3	0.564	0.012
27.50°	319.0	47.91	113.5	0.561	0.012
30.00°	238.8	52.18	70.36	0.531	0.02
32.50°	173.5	56.44	43.49	0.467	0.010
35.00°	117.2	60.66	28.08	0.364	0.011
37.50°	50.55	64.86	19.74	0.231	0.013
40.00°	42.48	69.03	17.07	0.314	0.012
42.50°	41.14	73.16	17.06	0.509	0.012
45.00°	40.06	77.26	17.61	0.654	0.012
47.50°	39.60	81.31	17.90	0.647	0.013
49.50°	38.73	85.32	17.90	0.471	0.013
51.00°	44.45	89.28	22.42	0.173	0.013
53.00°	64.77	93.95	22.90	-0.132	0.013
55.00°	82.25	98.95	27.89	-0.194	0.012
57.00°	99.73	104.95	32.54	-0.472	0.010
59.00°	114.9	109.95	36.19	-0.596	0.009
61.00°	114.6	114.96	34.93	-0.565	0.009
63.00°	96.28	119.96	28.51	-0.439	0.012
65.00°	68.93	124.96	19.90	-0.260	0.010
67.00°	38.64	129.96	10.88	0.14	0.011
69.00°	20.58	134.97	5.672	0.437	0.017
71.00°	22.58	139.97	10.62	0.435	0.018
73.00°	37.27	144.97	10.62	-0.267	0.016
75.00°	105.3	149.97	27.98	-0.804	0.026
77.00°	239.6		62.73	-0.925	0.008
79.00°	443.2		114.5	-0.760	0.008
81.00°				-0.613	0.008

${}^4\text{He}(t,t){}^4\text{He}$ at 1263 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
12.50°	1419.	21.91	475.8	0.448	0.006
15.00°	1061.	26.27	360.0	0.524	0.005
17.50°	748.2	30.63	257.5	0.607	0.006
20.00°	522.6	34.97	182.6	0.697	0.006
22.50°	341.4	39.30	121.5	0.745	0.005
25.00°	198.2	43.61	71.95	0.793	0.006
27.50°	158.7	47.91	58.25	0.776	0.006
30.00°	106.5	52.18	39.52	0.792	0.006
32.50°	53.23	56.44	20.24	0.752	0.007
35.00°	27.01	60.66	10.54	0.667	0.009
37.50°	18.84	64.86	7.570	0.504	0.012
40.00°	26.99	69.03	11.57	0.451	0.013
42.50°	36.05	73.16	16.04	0.484	0.016
45.00°	44.09	77.26	20.39	0.402	0.013
47.50°	51.89	81.31	24.50	0.135	0.012
50.00°	91.89	85.32	32.50	-0.407	0.009
52.50°	111.8	89.95	37.69	-0.578	0.008
55.00°	128.2	94.95	41.83	-0.640	0.007
57.50°	136.4	99.95	42.98	-0.598	0.007
60.00°	125.0	104.95	38.74	-0.566	0.008
62.50°	129.2	107.46	39.40	-0.463	0.007
65.00°	110.1	109.96	32.60	-0.212	0.008
67.50°	79.68	114.96	22.98	0.139	0.009
70.00°	60.99	119.96	17.38	0.380	0.009
72.50°	53.40	124.96	15.04	0.520	0.009
75.00°	48.47	129.96	13.35	0.192	0.010
77.50°	78.39	134.97	21.19	-0.620	0.008
80.00°	156.2	139.97	41.50	-0.903	0.008
82.50°	289.5	144.97	75.80	-0.913	0.006
85.00°	482.7	149.98	124.7	-0.783	0.006
87.50°		154.98		-0.651	0.006

${}^4\text{He}(t,t){}^4\text{He}$ at 1300 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1350.	26.27	452.6	0.303	0.006
17.50°	969.5	30.63	328.9	0.354	0.006
20.00°	686.7	34.97	236.2	0.388	0.006
22.50°	463.5	39.30	162.0	0.423	0.005
25.00°	373.4	43.61	131.7	0.428	0.005
27.50°	300.2	47.91	106.8	0.424	0.006
30.00°	193.1	52.18	70.09	0.392	0.006
32.50°	128.9	56.44	47.83	0.309	0.006
35.00°	76.52	60.66	35.59	0.219	0.007
37.50°	68.12	64.86	29.87	0.179	0.007
40.00°	61.34	69.03	25.43	0.231	0.008
42.50°	53.38	73.16	22.89	0.347	0.008
45.00°	45.93	77.26	20.43	0.468	0.008
47.50°	38.29	81.31	17.71	0.544	0.009
50.00°	44.02	84.95	16.29	0.513	0.010
52.50°	48.13	89.95	19.92	-0.057	0.009
55.00°	58.75	94.95	19.92	-0.415	0.008
57.50°	75.21	99.95	24.54	-0.534	0.007
60.00°	89.99	104.95	28.35	-0.535	0.007
62.50°	94.23	109.95	28.74	-0.441	0.007
65.00°	83.24	114.96	24.65	-0.297	0.007
67.50°	58.22	119.96	16.79	-0.099	0.008
70.00°	27.09	124.96	7.628	0.280	0.010
72.50°	7.625	129.96	2.101	0.685	0.014
75.00°	8.262	134.97	2.735	-0.420	0.014
77.50°	19.47	139.97	5.462	-0.919	0.008
80.00°	81.53	144.97	21.66	-0.746	0.008
82.50°	204.0	149.97	53.41	-0.562	0.008
85.00°	388.2	149.98	100.3	-0.443	0.007

${}^4\text{He}(t, t){}^4\text{He}$ at 13.27 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	130.1	26.28	436.2	0.275	0.007
17.50°	950.0	30.63	322.3	0.294	0.007
20.00°	673.4	34.97	231.6	0.319	0.007
22.50°	466.6	39.30	163.1	0.350	0.008
25.00°	381.5	41.46	134.5	0.355	0.008
27.50°	314.0	43.62	111.7	0.353	0.031
30.00°	220.2	47.93	79.93	0.326	0.036
32.50°	153.7	52.19	57.02	0.196	0.031
35.00°	120.9	56.44	45.97	0.166	0.036
37.50°	101.4	60.67	39.58	0.167	0.036
40.00°	88.35	64.86	35.50	0.190	0.036
42.50°	75.51	69.03	31.31	0.229	0.011
45.00°	62.77	73.17	27.91	0.303	0.013
47.50°	49.26	77.26	21.91	0.354	0.014
50.00°	37.43	81.31	17.31	0.355	0.015
52.50°	29.01	85.32	13.99	0.282	0.015
45.00°	25.47	89.28	12.85	-0.002	0.021
45.00°	35.64	89.95	12.60	-0.024	0.015
42.50°	39.96	94.95	14.79	-0.397	0.013
40.00°	52.46	99.95	17.12	-0.558	0.036
37.50°	64.05	104.95	20.18	-0.568	0.036
35.00°	71.18	109.95	21.71	-0.428	0.036
32.50°	64.03	114.95	18.97	-0.342	0.036
30.00°	43.56	119.96	12.56	-0.201	0.036
27.50°	19.38	124.96	5.458	0.032	0.016
25.00°	3.189	129.96	0.879	0.216	0.041
22.50°	14.47	134.96	3.912	-0.756	0.015
20.00°	66.95	139.97	17.79	-0.532	0.010
17.50°	170.7	144.97	44.68	-0.402	0.008
15.00°	322.6	149.98	83.37	-0.314	0.008

${}^4\text{He}(t, t){}^4\text{He}$ at 13.75 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1096.	26.28	367.4	0.222	0.006
17.50°	818.4	30.63	277.7	0.263	0.005
20.00°	591.1	34.97	203.3	0.300	0.005
22.50°	426.3	39.30	149.0	0.329	0.006
25.00°	299.3	43.62	106.5	0.350	0.006
27.50°	255.5	45.76	81.81	0.330	0.006
30.00°	223.4	47.91	62.38	0.319	0.007
32.50°	168.1	52.19	44.00	0.273	0.007
35.00°	133.5	56.44	30.75	0.208	0.008
37.50°	112.7	60.67	23.30	0.143	0.008
40.00°	97.34	64.87	17.35	0.111	0.009
42.50°	82.67	69.03	12.70	0.119	0.010
45.00°	68.99	73.17	9.415	0.131	0.010
47.50°	52.39	77.26	7.76	0.127	0.012
50.00°	34.32	81.36	6.137	0.116	0.013
52.50°	25.00	85.32	4.918	0.093	0.014
45.00°	26.63	89.95	4.15	0.064	0.017
45.00°	25.95	94.95	3.796	-0.096	0.016
42.50°	34.66	99.95	11.31	-0.402	0.015
40.00°	45.62	104.95	14.37	-0.504	0.013
37.50°	51.18	109.95	15.61	-0.466	0.010
35.00°	47.11	114.95	13.95	-0.391	0.011
32.50°	33.76	119.96	9.737	-0.258	0.012
30.00°	15.42	124.96	4.341	-0.228	0.013
27.50°	8.436	129.96	2.350	-0.364	0.014
25.00°	16.14	134.96	4.918	-0.753	0.024
22.50°	60.70	139.97	16.13	-0.641	0.015
20.00°	144.9	144.97	37.93	-0.389	0.008
17.50°	264.3	149.97	68.29	-0.305	0.006
15.00°				-0.236	0.007

${}^4\text{He}(t, t){}^4\text{He}$ at 13.55 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1154.	26.28	366.8	0.233	0.005
17.50°	848.9	30.63	288.0	0.276	0.005
20.00°	609.5	34.97	209.7	0.309	0.005
22.50°	437.5	39.30	151.2	0.337	0.006
25.00°	313.8	43.62	111.7	0.353	0.006
27.50°	251.7	45.76	90.46	0.348	0.006
30.00°	223.0	47.91	80.95	0.331	0.006
32.50°	161.7	52.19	59.98	0.272	0.007
35.00°	126.7	56.44	48.17	0.224	0.008
37.50°	108.5	60.67	42.35	0.167	0.009
40.00°	95.06	64.87	38.20	0.152	0.009
42.50°	81.41	69.03	33.75	0.154	0.009
45.00°	65.90	73.17	28.26	0.180	0.009
47.50°	50.78	77.26	22.58	0.207	0.010
50.00°	36.88	81.36	17.06	0.243	0.012
52.50°	35.48	84.95	13.13	0.155	0.014
55.00°	26.70	88.32	10.6	0.073	0.013
57.50°	29.98	89.95	10.82	-0.073	0.011
60.00°	31.93	94.95	13.40	-0.385	0.011
62.50°	41.07	99.95	16.79	-0.509	0.010
65.00°	53.30	104.95	17.75	-0.494	0.010
67.50°	58.20	109.95	15.73	-0.426	0.010
70.00°	53.09	114.95	12.75	-0.345	0.010
72.50°	37.01	119.96	10.67	-0.255	0.012
75.00°	16.77	124.96	4.723	-0.160	0.016
77.50°	3.988	129.96	1.099	-0.506	0.028
80.00°	15.09	134.96	4.079	-0.692	0.013
82.50°	62.44	139.97	16.59	-0.448	0.008
85.00°	152.4	144.96	39.90	-0.335	0.006
87.50°	284.1	149.96	73.42	-0.262	0.006

${}^4\text{He}(t, t){}^4\text{He}$ at 14.00 MeV (lab)
(scale errors: $\Delta\sigma = 10\%$, $\Delta A_y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	1032.	26.28	345.9	0.217	0.006
17.50°	776.6	30.63	263.4	0.260	0.005
20.00°	564.7	34.97	194.3	0.293	0.005
22.50°	409.1	39.30	143.0	0.324	0.005
25.00°	291.8	43.62	103.8	0.332	0.006
27.50°	248.9	45.77	89.44	0.325	0.006
30.00°	212.8	47.91	77.22	0.311	0.006
32.50°	161.5	52.19	59.92	0.265	0.006
35.00°	132.6	56.44	49.94	0.193	0.006
37.50°	112.6	60.67	43.95	0.130	0.007
40.00°	97.66	64.87	39.24	0.082	0.007
42.50°	83.58	69.04	34.64	0.071	0.008
45.00°	68.19	73.17	29.24	0.060	0.008
47.50°	51.42	77.26	22.87	0.080	0.009
50.00°	36.55	81.32	16.90	0.074	0.011
52.50°	24.36	85.33	11.75	0.021	0.013
55.00°	33.96	88.95	12.57	0.016	0.011
57.50°	24.35	89.95	8.610	-0.165	0.012
60.00°	22.89	94.95	7.759	-0.418	0.012
62.50°	29.92	99.95	12.47	-0.478	0.010
65.00°	39.58	104.95	14.01	-0.350	0.009
67.50°	45.93	109.95	12.72	-0.437	0.009
70.00°	42.94	114.95	9.055	-0.293	0.009
72.50°	31.40	119.95	4.309	-0.266	0.009
75.00°	15.31	124.96	2.513	-0.324	0.010
77.50°	9.024	129.96	1.817	-0.504	0.013
80.00°	6.594	134.96	5.053	-0.830	0.013
82.50°	18.70	139.97	16.16	-0.642	0.009
85.00°	60.84	144.97	36.77	-0.393	0.007
87.50°	140.3	149.97	64.71	-0.293	0.007
90.00°	250.4			-0.218	0.008

⁴He(l,t)⁴He at 15.00 MeV (lab)

(scale errors: $\Delta\sigma = 10\%$, $\Delta y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	866.3	26.28	290.4	0.190	0.006
17.50°	655.5	30.63	222.3	0.222	0.005
20.00°	496.1	34.98	170.6	0.250	0.005
22.50°	363.1	39.31	126.9	0.264	0.005
25.00°	264.2	43.62	93.98	0.268	0.005
26.25°	225.9	45.77	81.17	0.259	0.006
27.50°	197.1	47.92	71.53	0.238	0.006
30.00°	151.0	52.19	56.02	0.171	0.006
32.50°	125.5	56.45	47.70	0.092	0.006
35.00°	108.0	60.67	42.15	0.012	0.007
37.50°	97.70	64.87	39.25	-0.036	0.007
40.00°	82.30	69.04	34.11	-0.065	0.007
42.50°	66.85	73.17	28.67	-0.098	0.008
45.00°	51.21	77.27	22.77	-0.124	0.008
47.50°	35.34	81.32	16.35	-0.143	0.010
50.00°	22.48	85.33	10.84	-0.140	0.009
50.00°	47.62	84.94	18.53	-0.204	0.010
47.50°	30.40	89.94	6.398	-0.324	0.012
45.00°	18.10	94.94	4.659	-0.524	0.013
42.50°	13.75	99.94	5.794	-0.423	0.011
37.50°	26.12	104.95	8.228	-0.282	0.010
35.00°	33.56	109.95	10.24	-0.201	0.009
32.50°	33.39	114.95	9.891	-0.159	0.009
30.00°	25.92	119.95	7.475	-0.142	0.009
27.50°	14.44	124.95	4.065	-0.267	0.011
26.25°	9.934	127.46	2.766	-0.512	0.012
25.00°		129.96		-0.808	0.011
22.50°	18.21	134.96	4.919	-0.698	0.009
20.00°	50.92	139.96	13.52	-0.436	0.007
17.50°	107.4	144.97	28.12	-0.300	0.007
15.00°	189.6	149.97	49.00	-0.237	0.009

⁴He(l,t)⁴He at 16.00 MeV (lab)

(scale errors: $\Delta\sigma = 10\%$, $\Delta y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
15.00°	790.5	26.28	264.9	0.126	0.021
17.50°	603.6	30.64	205.4	0.142	0.021
20.00°	440.0	34.98	151.3	0.153	0.012
22.50°	329.1	39.31	115.0	0.189	0.007
25.00°	280.7	41.47	98.96	0.185	0.012
26.25°	238.3	43.62	84.76	0.181	0.012
27.50°	206.3	45.86	74.15	0.135	0.071
30.00°	177.2	47.92	64.31	0.150	0.006
32.50°	137.1	52.20	50.86	0.088	0.008
35.00°	113.8	56.45	43.26	0.013	0.008
37.50°	101.0	60.68	39.42	-0.043	0.008
40.00°	90.86	64.88	36.50	-0.084	0.008
42.50°	80.03	69.04	33.17	-0.118	0.009
45.00°	72.57	71.52	30.70	-0.120	0.009
47.50°	66.95	73.18	28.71	-0.117	0.009
45.00°	51.27	77.27	22.80	-0.134	0.010
42.50°	48.29	79.94	18.79	-0.148	0.010
40.00°	30.02	84.94	11.11	-0.195	0.011
37.50°	26.49	90.94	6.453	-0.222	0.012
35.00°	28.31	104.94	8.634	-0.120	0.011
32.50°	30.16	114.94	8.933	-0.086	0.010
30.00°	24.53	119.95	7.074	-0.098	0.011
27.50°	15.08	124.95	4.243	-0.205	0.012
25.00°	9.214	129.95	2.539	-0.629	0.013
23.75°	10.75	132.46	2.931	-0.707	0.011
22.50°	16.41	134.96	4.435	-0.626	0.010
17.50°	87.94	144.97	23.01	-0.232	0.021
15.00°	149.5	149.97	38.63	-0.179	0.021

⁴He(l,t)⁴He at 17.00 MeV (lab)

(scale errors: $\Delta\sigma = 10\%$, $\Delta y = 10\%$)

θ_{lab} (deg)	$\sigma(\theta)_{\text{lab}}$ (mb/sr)	θ_{cm} (deg)	$\sigma(\theta)_{\text{cm}}$ (mb/sr)	A_y	ΔA_y
17.50°	558.9	30.64	189.5	0.115	0.005
20.00°	419.7	34.98	144.3	0.123	0.005
22.50°	303.2	39.31	105.9	0.127	0.006
23.75°	255.4	41.47	90.02	0.115	0.006
25.00°	216.0	43.63	76.81	0.118	0.006
26.26°	187.9	45.79	67.50	0.104	0.006
27.50°	155.4	47.92	56.36	0.103	0.006
30.00°	119.2	52.20	44.21	0.045	0.006
32.50°	99.56	56.45	37.83	0.008	0.007
35.00°	90.79	60.68	35.43	-0.026	0.007
37.50°	84.43	64.88	33.92	-0.070	0.007
40.00°	77.03	69.05	31.93	-0.070	0.007
42.50°	66.31	73.18	28.43	-0.096	0.008
45.00°	52.48	77.28	23.34	-0.126	0.008
47.50°	36.27	81.33	16.77	-0.148	0.010
47.50°	30.97	84.94	11.46	-0.180	0.010
45.00°	14.77	89.94	5.223	-0.316	0.013
42.50°	6.826	94.94	2.314	-0.576	0.017
40.00°	8.273	99.94	2.699	-0.335	0.016
37.50°	15.95	104.94	5.023	-0.154	0.012
35.00°	24.80	109.94	7.565	-0.064	0.010
32.50°	27.81	114.94	8.235	-0.054	0.010
30.00°	23.79	119.94	6.860	-0.065	0.010
27.50°	15.15	124.95	4.264	-0.178	0.011
26.26°	11.80	127.43	3.287	-0.289	0.012
25.00°	9.708	129.95	2.674	-0.411	0.014
23.75°		132.45		-0.465	0.013
22.50°	15.14	134.95	4.089	-0.400	0.011
20.00°	36.39	139.96	9.666	-0.242	0.008
17.50°	72.66	144.96	19.01	-0.176	0.007
15.00°	122.5	149.97	31.63	-0.133	0.006

APPENDIX B

EXPERIMENTAL PROCEDURE FOR ${}^4\text{He}(t,t){}^4\text{He}$ CROSS-SECTION DATA GIVEN IN LASL REPORT LA-6188

I. INTRODUCTION

The accurate cross-section data published in LASL report LA-6188⁵ provide the normalization for much of the differential cross-section data of this report (see Sec. IV of the main text). The experimental procedure for LASL report LA-6188 cross-section data⁵ has never been published and is given below to support our present results.

II. EXPERIMENTAL EQUIPMENT

A triton beam from the LASL tandem Van de Graaff accelerator entered a 76.2-cm scattering chamber (30 in. ORTEC chamber) and passed through a ${}^4\text{He}$ gas target with thin 2.3- μm Havar foil windows. The experimental apparatus is described in detail by Jarmie et al.¹⁷ Scattered particles were detected by a single E- ΔE detector arrangement using solid-state detectors 44- μm thick (area 100 mm^2) and 695- μm thick (area 150 mm^2). Beam currents incident on the target ranged between 10 and 600 nA at a level adjusted to keep the counting rate safe. Amplified pulses from both detectors, gated by the E- ΔE counter, were digitized and sent to an on-line computer for mass analysis and storage.

Purity of the spectroscopic grade ${}^4\text{He}$ gas was determined by measuring the yield of the contaminant peaks in the triton spectra at a standard lab angle and standard incident triton energy (42.5° and 9.844 MeV). These measurements were made at regular intervals during the course of the experiment so that the purity could be determined by interpolation for any time during the experiment. Cross sections for the contaminants were measured directly at the standard lab angle and energy in the scattering chamber with a known quantity of the contaminant gas in the gas target. Typical ${}^4\text{He}$ purity was 0.997 ± 0.002 ; carbon, oxygen, and hydrogen were the major contaminants. Gas in the target was changed approximately once a day. The pressure and temperature in the gas target were typically 160 torr and 25°C. The pressure was measured with an accuracy of ± 0.2 torr with a diaphragm capacitance-bridge transducer; the

temperature was measured to $\pm 0.2^\circ$ with a Chromel-Alumel thermocouple. The geometry factor (G) of $1.2 \times 10^{-5} \text{ cm} \cdot \text{sr}$ was determined by a double slit system of precision-machined nickel slits as described in Ref. 17.

III. EXPERIMENTAL PROCEDURE

To obtain a complete spectrum in the center of mass system, two methods were used to measure the cross section. In the first method, the recoil tritons and alpha particles were detected at forward angles where the recoil energies were conveniently high. Triton (and alpha) spectra were measured in the manner described in Ref. 17 using the E- ΔE telescope. At angles greater than $\sim 15^\circ$, the energy of the recoil alphas was too low for these particles to pass through the ΔE detector into the E detector, and these events could not be mass-analyzed. The second method was used to measure the ${}^4\text{He}(t,\alpha)\text{T}$ cross section at angles greater than $\sim 15^\circ$: the singles spectra from the ΔE detector alone were recorded simultaneously with E- ΔE coincidence events. When alpha peaks in the ΔE spectra were separate from the triton peaks and had low flat backgrounds, accurate cross sections could be extracted.

The accuracy of the single-counter technique was tested in the following manner. At angles where the kinetic energy of either the alphas or tritons was sufficient to obtain a mass-analyzed spectrum of the detected particle, the mass-identified spectrum was compared with the spectrum from the single detector. In these cases, the computed cross sections for the alphas or tritons from both spectra agreed to within statistical error.

Examples of spectra are shown in Figs. B-1—B-4. The logarithmic yield scale should be noted. In these spectra, the structure has been simplified for convenience in drafting the figures. The low background in the coincidence spectrum of Fig. B-1 is due to slit-edge scattering and contributed a subtraction to the main peak of from 0.5 to 1.0% for the triton spectra and the better alpha

Fig. B-1

$^4\text{He}(t,t)^4\text{He}$ coincidence spectrum at 8.980 MeV, 37.50° (lab angle). The peak contains 58 000 counts over a background of 500 counts. Further details are given in the text.

Fig. B-2

$^4\text{He}(t,\alpha)^3\text{H}$ singles spectrum at 8.980 MeV, 30.00° (lab angle). The alpha peak contains 10 000 counts over a background of 200 counts.

Fig. B-3

$^4\text{He}(t,\alpha)^3\text{H}$ singles spectrum at 12.000 MeV, 35° (lab angle). The alpha peak contains 11 000 counts over a background of 310 counts.

Fig. B-4

$^4\text{He}(t,\alpha)^3\text{H}$ singles spectrum at 12.000 MeV, 20° (lab angle). The alpha peak contains 22 000 counts over a background of 340 counts.

spectra. The error in the cross section caused by this correction was no more than 0.1%. In some of the poorer alpha spectra, the background subtraction was as much as 3%, contributing an error of 0.5% (Fig. B-3). In Fig. B-1, the peaks marked C and O are tritons scattered from contaminant carbon and oxygen. As discussed elsewhere, these peaks were used for gas purity estimation. Even at the smallest angles, the contaminant peaks were separable from the main peak. The edge "E" denotes the cutoff resulting from an electronic window.

Figure B-2 shows a typical singles spectra from particles striking the front ΔE detector. Peaks caused by tritons and alphas are evident. Events in channels less than R_t result from the large number of tritons passing through the detector; R_t denotes the energy equivalent to the range of a triton in the ΔE detector. The main alpha peak is marked "α." In Fig. B-3, the bombarding energy and angle are such that the energy of recoil alphas almost corresponds to the range (R_α) of alpha particles in the detector. In Fig. B-4, the alphas pass through the detector with the spectrum folding back. The data in Fig. B-4 are still useful but with increased uncertainty in the background subtraction.

Spectra were analyzed off-line to give cross sections with the accuracies cited. On-line analysis available during the experiment gave approximate cross sections to monitor the progress of the experiment. The cross sections were calculated from the yield and other measured parameters in a straightforward way.¹⁷ Corrections were negligible for reactions in the silicon detectors, rate pileup, beam heating of the target gas, multiple scattering compensation in the target exit foil, multiple scattering losses in the beam current collection, and second-order terms in the geometry factor G .¹⁶

Specific tests were made in several cases. Multiple scattering losses in the Faraday cup were tested by accurately measuring the yield at a given angle with and without an extra foil in the beam at the target exit.

Agreement was observed to $0.08\% \pm 0.3\%$ for triton beam energies of 7 MeV and above.

To test for multiple scattering compensation, extra foils were placed over the target foil where the recoil particles exit. Negligible compensation error was found for alphas with energies greater than 4.2 MeV and tritons with energies greater than 2.9 MeV. This includes all the particle energies of this experiment.

Significant contributions to the cross-section errors are shown in Table B-I. The larger error in the background and dead time was found in certain alpha spectra. Dead times were usually kept to 1% or less, with a negligible error. Errors in the data tables are quoted as scale and relative errors (standard deviations) where the scale error is defined so that the absolute error is the quadratic sum of the scale and relative error. In each case, the energy of the bombarding beam is known to ± 15 keV with a FWHM spread of 40 keV, including the effects of foil thickness variation, foil and target-gas straggling, and machine energy resolution. The relative energy of adjacent runs in an excitation function is accurate to ± 5 keV. Data were taken successively left and right of the beam to decrease both the statistical error and certain mechanical asymmetries. For example, tests showed that the "indicated zero" of the detector arm angle was 0.16° counterclockwise of true zero. The left-right run average avoided any correction caused by this zero shift. The total included angle of the detector slit system was 0.3° , and the final accuracy of the measured angle was $\pm 0.03^\circ$.

The resulting data were consistent in several ways. Besides the agreement between the singles and coincidence spectra already noted, agreement within the calculated error was observed for duplicated data points. The duplicated data points include angular distributions that were repeated after 9 months and overlap between the angular distributions and excitation functions where the energy and angle were duplicated.

TABLE B-I

Scale		Relative	
Source	% Error	Source	% Error
Pressure	0.1	Yield	$100/\sqrt{N}$
Temperature	0.07	Background	0.1-0.5
Purity	0.2	Dead time	0.0-0.3
Geometry	0.2		
Beam	0.2		

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