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DIFFERENTIAL CROSS SECTIONS FOR $p+{}^4\text{He}$ SCATTERING FROM 19.5 TO 47.5 MeV

by

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ABSTRACT

Differential cross sections for ${}^4\text{He}(p,p){}^4\text{He}$ elastic scattering have been measured at 11 energies from 19.5 to 47.5 MeV. The most forward center-of-mass angle for the angular distributions varies from 10.1 to 12.4° , and the most backward angle varies from 163.2 to 173.4° . The relative errors are usually less than 2%, and the scale error is 1.5%. The present data and the existing vector-analyzing power and total-reaction cross-section data are being analyzed in this energy range using the Los Alamos Scientific Laboratory R-matrix code EDA.

I. INTRODUCTION

The mass-4 system is very fundamental to the study of the nuclear interaction and the internal structure of nuclear systems. The breakthrough by Faddeev¹ in solving the three-body problem has inspired efforts to find extensions for treating more general systems.

The first results of such formulations for four nucleons have recently appeared in the literature.²⁻⁴ Data for elastic scattering of protons by ${}^4\text{He}$ in the present energy range should contribute to these developments. Additionally, such data should be useful to compare with shell-model work⁵ or resonating-group calculations.⁶

In the energy region below 20 MeV, Hale et al.⁷ performed an energy-dependent phase-shift analysis using an R-matrix parameterization. One of the main purposes of the study of the $p+{}^4\text{He}$ system that we have undertaken is to extend this type of analysis into the higher energy region. Thus, we first measured⁸ the $p+{}^4\text{He}$ total reaction cross section σ_R at 10 energies from 18 to 48 MeV. In the second phase of this work, we made accurate measurements

of the elastic differential cross section at 11 energies from 19.5 to 47.5 MeV over the approximate angular range 10 to 173° (c.m.). While this work was in progress, Watson et al.¹⁰ were measuring the proton vector analyzing power A_y at 21.44, 24.84, 27.26, and 30.12 MeV. We felt it would be worthwhile to attempt a preliminary fit to the three data sets just mentioned using the Los Alamos Scientific Laboratory (LASL) R-matrix code EDA,¹¹ so such an effort is under way.¹²

Further experiments are planned to obtain more information on spin-dependent observables, which is badly needed to perform a definitive phase-shift analysis in this energy range.

II. EXPERIMENT

The experiment was performed using the University of Manitoba sector-focussed cyclotron. The incident beam energy was known to within 100 keV, with a spread of about 150 keV.

The scattering chamber used has a 115-cm i.d. and contains a movable array of eight detectors at

10.00° intervals, thus spanning a range of 70°. The angle extremes capable of being reached are 7.5° forward and 170° backward, and the array can be positioned to an accuracy of 0.01°. The detector positions with respect to one another are known to 0.02°. Thus, a contribution to the relative error of 0.03° times the slope of the cross section was included. The detectors used were either silicon surface barrier or sodium iodide (Tl) scintillation detectors, depending on the energy of the scattered protons.

The ³He target gas of better than 99.8% purity was contained in a 8.6-cm-diam cell with a 1.6-cm-high window, which extends over a 275° angular range and is covered by a 50-μm-thick Kapton foil. The ³He gas in the cell was kept at a pressure of about 1.5 atm and was flushed regularly to prevent the buildup of contaminants. A thermistor, calibrated to 0.1%, was embedded in the lid of the cell and allowed the temperature to be read to a relative accuracy of ±0.5 K. A pressure gauge (Wallace-Tiernan, model FA 141), calibrated to 0.5%, was used to read the gas pressure to a relative accuracy of ±2.5 Torr.

The gas scattering geometry was defined by means of parallel-sided front slits at a distance of 5.471 ± 0.005 cm from the scattering chamber center, and rectangular rear apertures at a distance of 32.768 ± 0.008 cm, whose areas (about 0.58 cm²) are known to better than 0.25%. Antiscattering baffles were mounted between the front and rear geometry-defining apertures.

A calibrated Brookhaven Instruments Current Integrator (model 1000) was used for charge integration, with electron suppression on the carbon-lined 1.74-m-long Faraday cup to ensure accurate particle collection. Because of the possible presence of a small beam halo to the incident proton beam, the uncertainty in the beam integration was conservatively taken to be 0.5% relative and 1.2% absolute. The direction of the incident beam was periodically monitored by means of detectors having nearly identical geometry and viewing particles scattered from a Ni foil at 15.0° left and right of the incident beam. The beam cross section at the center of the scattering chamber was typically 0.3 cm wide by 0.8 cm high.

Cross sections were measured successively left and right of the incident beam direction and then averaged in order to cancel out any first-order effects that would have resulted from the beam either being

off-center at the target or being not quite coincidental with the chamber axis. This averaging procedure can also be shown to cancel practically all error that could result from a systematic deviation in the scattering angles. Pulse height spectra were accumulated by standard electronic techniques using ADC's and a PDP-15 computer system, and recorded on magnetic tape. For further details regarding the experimental arrangement and procedure see Ref. 13.

III. DATA REDUCTION

The data were reduced to differential cross sections in two steps. First, uncorrected differential cross sections were obtained, and second, the necessary corrections were applied to these cross sections. The proton elastic-scattering peaks were resolved from the spectra by subtracting the background using smooth background functions and, at extreme forward angles, by subtracting the contributions that resulted from the small amount of impurities present in the gas cell. The statistical error in the yields includes the error in the background subtraction. The uncertainty in the subtraction of contaminant yields was taken to be 20% of the correction. Similarly the uncertainty in the deadtime correction was taken to be 20% of the correction. Three further corrections were applied to the data for: (1) the effects of multiple scattering in the gas and exit foil of the target cell, (2) the loss of elastically scattered protons in the detector material due to nuclear reactions, and (3) the effects of finite geometry. The corrections for multiple scattering were estimated using the expression given by Chase and Cox¹⁴ and were found to be very small. The fraction of elastically scattered protons lost from the main peak in the spectra was interpolated from the published results¹⁴ for sodium iodide and silicon. The fraction for sodium iodide varied between 0.5% at 21 MeV and 2.9% at 50 MeV with an absolute uncertainty of ±0.04%. The finite geometry corrections take into account that the measurements were done with a finite solid angle, a beam of finite size traversing a gas target, and a beam that in first approximation converges towards the target. The finite geometry correction factor of Kan¹⁵ was adapted to the particular conditions of the present experiment. The maximum correction occurred at forward angles, but was always less than 1%. The various contributions

to the relative error in the cross sections are indicated in Table I, and those to the scale error are given in Table II. Except for the 40-MeV angular distribution, the relative errors are mostly smaller than 2%, and the scale error is 1.5%.

IV. EXPERIMENTAL RESULTS

Figure 1 shows our measurements at 19.5 MeV along with the results of Ref. 17 at 19.48 MeV. It is seen that the two data sets agree quite well. Figure 2 shows our measurements at 30.0 MeV along with the results of Ref. 18 at 30.0 MeV and the results of Ref. 19 at 30.6 MeV. The latter two data sets show more scatter than the present set, as is to be expected because of their larger quoted experimental uncertainties.

TABLE I

CONTRIBUTIONS TO THE RELATIVE UNCERTAINTIES IN THE DIFFERENTIAL CROSS SECTIONS

Type of Uncertainty	Uncertainty
Counting statistics (including background subtraction)	<1% (except at 40 MeV)
Dead time correction	$\pm 20\%$ of the correction
Subtraction of contaminant yields	$\pm 20\%$ of the correction
Integration of the beam current	$\pm 0.5\%$
Detector angle	$\pm 0.03^\circ$
Pressure	± 2.5 Torr
Temperature	± 0.5 K
Finite geometry correction	$\pm 0.1\%$

TABLE II

CONTRIBUTIONS TO THE UNCERTAINTY IN THE ABSOLUTE SCALE OF THE DIFFERENTIAL CROSS SECTIONS

Type of Uncertainty	Uncertainty
Pressure	$\pm 0.5\%$
Temperature	$\pm 0.1\%$
Geometry factor	$\pm 0.5\%$
Gas purity	$\pm 0.1\%$
Integration of the beam current	$\pm 1.2\%$
Energy of the incident proton beam	$\pm 0.4\%$
Energy-degraded-proton contamination of the incident beam	<0.1%
Correction for reactions in the NaI(Tl) or Si detectors	$\pm 0.04\%$

Fig. 1.

Present $p+^3\text{He}$ elastic differential cross section at a lab proton energy of 19.5 MeV and the measurements of Ref. 17 at 19.48 MeV.

Fig. 2.

Present $p+{}^3\text{He}$ elastic differential cross section at a lab proton energy of 30.0 MeV, the measurements of Ref. 18 at 30.0 MeV, and the measurements of Ref. 19 at 30.6 MeV.

The complete set of our measurements is shown in Figs. 3 and 4. The differential cross sections at 19.5, 21.3, 25.0, 27.5, and 30.0 MeV are illustrated in Fig. 3, and those at 32.4, 35.0, 37.5, 40.0, 45.0, and 47.5 MeV are plotted in Fig. 4. The errors are usually smaller than the size of the plotting symbols. Note that data were taken at 2.5° intervals at forward angles and 5° intervals at backward angles. The occasional gaps that appear in the angular distributions were caused by a deterioration in some of the NaI(Tl) detectors during data acquisition. The angular distributions show a smooth behavior as a function of

Fig. 3.

Present $p+{}^3\text{He}$ elastic differential cross sections at the indicated lab proton energies.

Fig. 4.

Present $p+^3\text{He}$ elastic differential cross sections at the indicated lab proton energies.

energy, with a characteristic minimum near 120° that results from the interferences between forward-peaked direct processes and backward-peaked exchange processes.^{20,21} The Coulomb-nuclear interference region occurs at too small an angle to be studied in any great detail with the present experimental arrangement. The numerical values of the differential cross sections are listed in Tables III-XIII.

V. CONCLUSION

We report the accurate measurement of $p+^3\text{He}$ elastic differential cross sections at 11 energies in the proton lab energy range 19.5 to 47.5 MeV. These data, along with proton vector-analyzing powers A_y ²² and total-reaction cross sections σ_R are being subjected to an energy-dependent phase-shift analysis using the LASL code EDA.¹¹ The results of this analysis and a comparison of our data with a simple resonating-group⁷ calculation will be published in the near future.¹²

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TABLE III

DIFFERENTIAL CROSS SECTION
FOR ${}^4\text{He}(\text{p,p}){}^4\text{He}$ ELASTIC SCATTERING AT
19.5 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
10.00	249.5	13.38	140.3	1.0
12.50	239.3	16.71	136.2	0.9
15.00	249.8	20.04	142.0	0.9
17.50	253.1	23.35	144.9	0.8
20.00	253.3	26.66	146.2	0.9
22.50	246.5	29.98	143.6	0.9
25.00	234.2	33.24	137.8	0.9
27.50	219.1	36.51	130.4	0.9
30.00	205.8	39.78	124.0	0.9
32.50	188.3	42.99	115.0	0.9
35.00	172.2	46.21	106.7	0.9
37.50	155.7	49.40	98.0	0.9
40.00	139.3	52.58	89.1	0.9
42.50	125.2	55.73	81.5	0.9
45.00	111.7	58.85	74.1	0.9
47.50	94.3	61.95	63.8	0.9
50.00	85.3	65.03	56.9	0.9
52.50	74.9	68.08	52.8	1.0
55.00	64.6	71.09	46.6	0.9
57.50	55.1	74.08	40.7	1.0
60.00	48.0	77.03	36.3	0.9
62.50	40.4	79.96	31.3	1.2
65.00	34.3	82.87	27.3	0.7
67.50	29.0	85.70	23.7	1.2
70.00	24.4	88.52	20.5	0.6
72.50	20.1	91.3	17.3	1.8
75.00	16.6	94.05	14.7	0.7
77.50	13.7	96.76	12.5	1.8
80.00	10.9	99.43	10.3	0.7
85.00	7.14	104.85	7.14	0.8
90.00	4.84	109.73	5.15	1.1
95.00	3.55	114.84	4.02	1.2
100.00	3.30	119.40	3.96	1.3
105.00	3.75	124.01	4.82	1.4
110.00	4.70	128.47	6.43	1.3
115.00	6.14	132.79	8.92	1.3
125.00	9.50	141.02	15.5	1.2
130.00	11.4	144.56	19.8	1.2
135.00	13.2	148.78	23.9	1.1
140.00	14.9	152.80	28.2	1.1
145.00	16.6	156.14	32.8	0.9
150.00	18.0	159.69	36.8	0.9
155.00	19.1	163.18	40.3	0.9
160.00	20.4	166.61	44.2	0.9
165.00	21.1	170.00	46.7	0.9
170.00	21.7	173.36	48.7	1.2

TABLE IV

DIFFERENTIAL CROSS SECTION
FOR ${}^4\text{He}(\text{p,p}){}^4\text{He}$ ELASTIC SCATTERING AT
21.3 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
10.00	232.7	13.38	130.8	1.2
12.50	225.7	16.72	127.5	1.1
15.00	236.2	20.04	134.2	1.1
17.50	238.4	23.36	136.4	1.1
20.00	233.9	26.67	134.9	1.2
22.50	236.4	29.97	131.8	1.1
25.00	214.2	33.25	126.0	1.1
27.50	200.1	36.52	119.0	1.1
30.00	186.7	39.77	111.8	1.1
32.50	168.8	43.01	103.0	1.1
35.00	154.0	46.22	95.4	1.1
37.50	138.8	49.42	87.3	1.1
40.00	124.0	52.59	79.3	1.2
42.50	110.2	55.74	71.7	1.2
45.00	96.9	58.87	64.2	1.3
47.50	84.7	61.97	57.3	1.2
50.00	71.0	65.05	49.0	1.4
52.50	65.5	68.09	46.2	1.3
55.00	56.3	71.11	40.6	1.1
57.50	48.5	74.10	36.8	1.4
60.00	41.3	77.06	31.2	1.4
62.50	36.5	79.96	27.5	1.7
65.00	29.9	82.87	23.7	1.1
67.50	25.1	85.72	20.5	1.7
70.00	20.6	88.54	17.3	1.2
72.50	16.8	91.32	14.5	2.3
75.00	14.2	94.07	12.6	1.1
80.00	9.92	99.45	9.24	1.2
85.00	6.28	104.87	6.28	1.4
90.00	4.23	109.75	4.80	2.0
95.00	3.14	114.86	3.56	1.2
100.00	2.81	119.42	3.39	1.7
105.00	3.02	124.03	3.88	1.7
110.00	3.85	128.49	5.27	1.4
115.00	4.86	132.89	7.06	1.3
125.00	7.89	141.68	12.9	1.9
130.00	9.49	144.97	16.3	1.9
135.00	11.0	148.79	19.9	1.6
140.00	12.9	152.51	24.4	1.9
145.00	14.0	156.15	27.6	1.4
150.00	15.3	159.70	31.3	1.4
155.00	16.5	163.19	34.9	1.4

TABLE V

DIFFERENTIAL CROSS SECTION
FOR $^{238}\text{Pu}(p,p)^{238}\text{Pu}$ ELASTIC SCATTERING AT
25.0 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\sigma_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
8.50	220.1	11.39	123.2	3.4
10.00	186.3	13.39	104.5	2.3
12.50	192.1	16.73	108.3	2.1
15.00	201.2	20.06	114.1	2.2
17.50	203.3	23.36	116.2	2.0
18.50	205.7	24.70	117.9	1.9
20.00	202.3	26.09	116.5	1.7
22.50	192.3	29.99	111.8	1.6
25.00	178.9	33.27	105.1	1.7
27.50	165.4	36.54	99.9	1.6
28.50	159.5	37.86	95.2	1.9
30.00	149.4	39.80	89.9	1.6
32.50	134.5	43.03	82.0	1.6
35.00	120.2	46.25	74.4	2.1
37.50	106.6	49.45	67.0	1.6
38.50	103.8	50.72	65.7	2.1
40.00	94.4	52.63	60.3	1.6
42.50	83.2	55.78	54.1	1.7
45.00	72.2	58.91	47.8	1.8
47.50	63.8	62.01	43.1	1.7
48.50	57.3	63.24	39.0	2.6
50.00	54.3	65.09	37.4	1.6
52.50	48.9	68.13	33.0	1.9
55.00	39.3	71.15	26.3	1.1
57.50	35.1	74.14	25.9	2.2
60.00	29.3	77.10	22.1	1.6
62.50	24.5	80.02	19.0	2.2
65.00	20.6	82.91	16.4	1.1
67.50	17.6	85.76	14.4	2.2
70.00	15.0	88.58	12.6	2.0
75.00	10.4	94.11	9.23	1.3
80.00	7.06	99.49	6.67	0.9
85.00	4.61	104.72	4.61	1.1
90.00	3.08	109.78	3.28	1.8
95.00	2.33	114.70	2.64	1.3
100.00	2.02	119.46	2.44	1.3
105.00	2.11	124.06	2.72	1.3
110.00	2.50	128.52	3.42	1.2
115.00	3.17	132.83	4.61	2.0
120.00	4.06	137.01	6.27	1.9
130.00	6.59	144.99	11.4	1.1
135.00	7.74	148.81	14.0	0.9
145.00	9.97	156.16	19.7	0.9
150.00	11.2	159.71	23.0	0.9
155.00	12.1	163.20	25.6	0.9
160.00	12.8	166.63	27.8	0.9
165.00	13.4	170.01	29.7	0.9
170.00	13.9	173.36	31.3	1.2

TABLE VI

DIFFERENTIAL CROSS SECTION
FOR $^{238}\text{Pu}(p,p)^{238}\text{Pu}$ ELASTIC SCATTERING AT
27.5 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\sigma_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
10.00	189.9	13.40	95.3	1.8
12.50	179.1	16.74	109.9	1.5
15.00	189.9	20.07	107.6	1.8
17.50	186.9	23.39	107.8	1.4
20.00	181.6	26.70	104.5	1.4
22.50	178.3	30.00	108.8	1.4
25.00	163.2	33.29	95.8	1.4
27.50	149.0	36.56	88.5	1.4
30.00	132.7	39.82	79.8	1.4
37.50	92.8	49.47	58.3	1.5
40.00	80.9	52.65	51.7	1.5
42.50	70.9	55.80	46.1	1.5
45.00	60.8	58.93	40.3	1.5
50.00	44.5	66.11	30.7	1.4
52.50	38.7	68.16	27.3	1.7
55.00	32.7	71.18	23.6	1.1
60.00	23.2	77.12	17.5	1.5
62.50	20.8	80.06	16.1	2.0
65.00	16.2	82.94	12.9	4.0
70.00	12.0	88.61	10.1	1.4
72.50	10.3	91.39	8.89	2.5
75.00	8.47	94.14	7.82	1.7
77.50	7.00	96.85	6.40	2.5
80.00	5.59	99.52	5.26	2.4
85.00	3.72	104.74	3.72	2.8
90.00	2.66	109.81	2.83	1.6
100.00	1.53	119.48	1.85	2.5
105.00	1.72	124.09	2.21	2.7
110.00	1.94	128.54	2.68	1.9
115.00	2.45	132.85	3.57	4.7
120.00	3.11	137.08	4.81	2.3
125.00	3.84	141.08	6.28	5.2
130.00	5.07	145.01	8.75	2.1
135.00	6.07	148.83	11.0	2.7
140.00	6.96	152.54	13.2	2.0
145.00	7.96	156.17	15.8	2.6
150.00	8.93	159.72	18.3	2.4
155.00	9.61	163.21	20.4	2.5
160.00	10.3	166.63	22.4	2.2
165.00	10.8	170.01	24.0	2.5
170.00	11.2	173.36	26.2	2.3

TABLE VII

DIFFERENTIAL CROSS SECTION
FOR ${}^4\text{He}(p,p){}^4\text{He}$ ELASTIC SCATTERING AT
20.0 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/er)	σ_{lab} (deg)	σ_{lab} (mb/er)	Relative Error (%)
10.00	154.3	13.40	98.4	1.3
12.50	169.3	16.74	96.3	1.1
15.00	179.4	20.08	101.6	1.0
17.50	180.6	23.40	103.0	1.1
20.00	172.5	26.71	99.2	1.2
22.50	161.6	30.02	93.9	1.1
25.00	149.9	33.30	87.9	1.1
27.50	135.0	36.58	80.1	1.1
30.00	120.7	39.83	72.5	1.1
32.50	106.5	43.07	64.6	1.1
35.00	93.4	46.29	57.7	1.1
37.50	81.0	49.49	50.6	1.2
40.00	70.6	52.67	45.1	1.2
42.50	60.4	55.83	39.2	1.2
45.00	51.7	58.98	34.2	1.2
47.50	44.0	62.06	29.7	1.3
50.00	37.4	65.14	25.8	1.2
52.50	31.7	68.19	22.3	1.3
55.00	27.0	71.21	19.4	1.2
57.50	22.6	74.19	16.7	1.7
60.00	19.3	77.15	14.6	1.2
62.50	16.2	80.07	12.5	1.7
65.00	13.8	82.98	11.0	1.2
67.50	12.1	85.82	9.86	2.2
70.00	9.75	88.64	8.16	1.4
72.50	8.31	91.42	7.17	2.2
75.00	6.86	94.17	6.11	1.4
80.00	4.80	99.55	4.82	1.3
85.00	3.35	104.77	3.35	1.4
90.00	2.37	109.84	2.62	1.5
95.00	1.78	114.75	2.02	1.7
100.00	1.31	119.51	1.56	2.7
105.00	1.43	124.11	1.84	2.1
110.00	1.78	128.56	2.44	1.9
115.00	2.06	132.86	2.99	1.6
120.00	2.66	137.05	4.11	1.6
125.00	3.23	141.10	5.38	1.6
130.00	3.94	145.02	6.80	1.4
135.00	4.72	148.84	8.57	1.3
140.00	5.50	152.56	10.5	1.2
145.00	6.29	156.19	12.5	1.2
150.00	7.02	159.73	14.4	1.1
155.00	7.75	163.21	16.4	1.1
160.00	8.23	166.64	17.9	1.0

TABLE VIII

DIFFERENTIAL CROSS SECTION
FOR ${}^4\text{He}(p,p){}^4\text{He}$ ELASTIC SCATTERING AT
22.4 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/er)	θ_{lab} (deg)	σ_{lab} (mb/er)	Relative Error (%)
6.50	156.7	11.40	87.5	1.6
10.00	154.9	13.41	86.7	1.5
12.50	171.4	16.75	95.4	1.5
15.00	174.9	20.09	99.0	1.4
17.50	173.1	23.41	96.6	1.5
20.00	171.7	26.74	96.6	1.7
22.50	167.3	30.03	96.1	1.6
25.00	153.9	33.32	89.3	1.6
27.50	140.9	36.59	82.6	1.6
30.00	125.5	39.86	74.4	1.6
32.50	118.7	43.09	70.7	1.6
35.00	110.6	46.31	65.4	1.7
37.50	98.8	49.49	58.9	1.7
40.00	83.4	52.67	51.5	1.6
42.50	71.5	55.83	44.8	1.7
45.00	65.3	58.98	38.2	2.0
47.50	59.9	62.06	33.7	2.0
50.00	51.9	65.14	29.8	1.9
52.50	42.3	68.19	24.8	2.0
55.00	36.7	71.21	22.7	2.5
57.50	33.4	74.22	21.6	2.5
60.00	31.6	77.15	21.6	1.7
62.50	25.8	80.07	16.2	2.6
65.00	21.9	82.98	15.8	1.8
67.50	19.1	85.82	12.2	2.5
70.00	16.1	88.64	11.4	1.9
72.50	11.4	91.42	9.06	1.9
75.00	8.00	94.17	5.71	1.5
80.00	5.66	99.57	3.46	1.6
85.00	3.69	104.80	2.64	1.7
90.00	2.64	109.86	2.04	1.9
95.00	1.63	114.77	1.66	2.0
100.00	1.28	119.53	1.66	2.1
105.00	1.32	124.13	1.70	2.0
110.00	1.33	128.59	1.82	2.0
115.00	1.66	132.90	2.45	2.0
120.00	2.02	137.07	3.13	2.2
125.00	2.36	141.11	3.80	1.9
130.00	2.89	145.04	4.89	1.9
135.00	3.52	148.86	6.39	1.6
140.00	4.36	152.57	8.33	1.6
145.00	5.22	156.20	10.3	1.5
150.00	6.06	159.74	12.1	1.5
155.00	6.36	163.22	13.5	4.8
160.00	6.44	166.65	14.0	4.8
165.00	6.46	170.02	14.4	1.4
170.00	6.64	173.37	15.0	1.4

TABLE IX

DIFFERENTIAL CROSS SECTION
FOR $^{16}\text{O}(p,p)^{16}\text{O}$ ELASTIC SCATTERING AT
31.0 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\sigma_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
10.00	137.0	13.42	76.6	1.3
12.50	153.5	16.76	86.2	1.1
15.00	180.2	20.10	90.6	1.0
17.50	157.0	23.42	89.4	1.1
20.00	149.9	26.74	86.0	1.1
22.50	136.1	30.04	80.0	1.1
25.00	125.4	33.33	73.4	1.1
27.50	110.5	36.61	65.4	1.1
30.00	97.2	39.87	58.3	1.2
32.50	84.1	43.11	51.1	1.1
35.00	72.2	46.33	44.5	1.1
37.50	61.2	49.54	38.4	1.1
40.00	52.1	52.72	33.2	1.3
42.50	43.7	55.87	28.4	1.2
45.00	36.9	59.01	24.4	1.2
47.50	30.5	62.11	20.6	1.3
50.00	25.7	65.19	17.7	1.2
52.50	21.7	68.24	15.3	1.5
55.00	18.1	71.26	13.0	1.2
57.50	15.1	74.25	11.1	1.6
60.00	12.6	77.21	9.51	1.1
62.50	10.8	80.13	8.36	2.0
65.00	9.06	83.02	7.21	1.3
67.50	7.62	85.88	6.22	2.2
70.00	6.32	88.69	5.30	1.2
75.00	4.62	94.22	4.10	1.5
77.50	3.82	96.93	3.49	3.1
80.00	3.27	99.60	3.08	1.4
85.00	2.41	104.82	2.41	1.4
90.00	1.80	109.69	1.92	1.6
95.00	1.38	114.80	1.57	1.9
100.00	1.17	119.56	1.42	2.0
105.00	1.11	124.16	1.43	1.9
110.00	1.17	128.61	1.61	1.9
115.00	1.34	132.92	1.96	1.7
125.00	2.12	141.13	3.47	1.8
130.00	2.59	145.06	4.48	1.4
135.00	3.10	148.57	5.64	1.4
140.00	3.73	152.58	7.10	1.2
150.00	4.82	159.75	9.92	1.1
155.00	5.22	163.23	11.1	1.1
160.00	5.73	166.65	12.5	1.0

TABLE X

DIFFERENTIAL CROSS SECTION
FOR $^{16}\text{O}(p,p)^{16}\text{O}$ ELASTIC SCATTERING AT
37.5 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\sigma_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
8.50	123.7	11.41	68.9	3.2
10.00	131.0	13.42	73.2	2.8
15.00	149.6	20.11	84.5	2.5
17.50	149.4	23.43	85.0	2.5
18.50	149.8	24.76	85.5	2.5
20.00	144.3	26.75	82.8	2.6
22.50	132.5	30.06	76.7	2.5
25.00	115.8	33.35	67.7	2.5
27.50	103.5	36.63	61.3	2.5
28.50	98.2	37.93	58.4	1.5
30.00	88.8	39.89	53.2	1.6
32.50	78.0	43.13	46.2	1.6
35.00	64.5	46.36	39.8	1.6
37.50	54.5	49.56	34.1	1.7
38.50	50.2	50.83	31.7	1.7
47.50	23.7	62.14	16.0	3.2
50.00	20.2	65.21	13.9	3.0
55.00	14.7	71.29	10.8	1.7
57.50	12.3	74.28	9.06	3.2
58.50	11.9	75.46	8.86	3.2
60.00	10.5	77.23	7.93	2.6
65.00	7.44	83.06	5.91	2.7
70.00	5.26	86.72	4.41	1.5
75.00	3.76	94.25	3.34	1.5
80.00	2.55	99.63	2.40	1.6
85.00	1.95	104.85	1.95	1.7
90.00	1.41	109.92	1.50	1.8
95.00	1.09	114.83	1.24	2.1
100.00	0.981	119.58	1.19	2.1
105.00	0.911	124.18	1.18	2.0
110.00	0.970	128.63	1.33	1.9
115.00	1.11	132.94	1.62	1.9
120.00	1.24	137.11	1.92	2.0
130.00	1.84	145.07	3.18	1.8
135.00	2.27	148.86	4.13	1.6
140.00	2.68	152.60	5.11	1.6
145.00	3.45	156.22	6.86	1.5
150.00	3.99	159.76	8.01	1.4
155.00	4.30	163.24	9.14	3.7
160.00	4.79	166.66	10.5	3.7

TABLE XI

DIFFERENTIAL CROSS SECTION
FOR ${}^4\text{He}(\text{p,p}){}^4\text{He}$ ELASTIC SCATTERING AT
46.0 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
7.50	151.4	10.08	84.1	7.0
10.00	126.2	13.43	70.4	6.9
12.50	142.6	16.78	80.0	6.8
15.00	143.4	20.12	80.9	6.8
17.50	135.5	23.45	77.0	4.4
20.00	129.7	26.77	74.3	3.2
22.50	118.3	30.07	66.4	3.2
25.00	105.5	33.37	61.7	3.2
27.50	92.1	36.64	54.5	3.2
30.00	78.3	39.91	46.9	3.0
32.50	66.5	43.15	40.4	3.0
35.00	55.9	46.38	34.4	3.0
37.50	47.4	49.58	29.7	3.3
40.00	38.5	52.76	24.5	3.3
42.50	32.3	55.92	20.9	3.1
45.00	26.8	59.05	17.7	3.1
47.50	22.1	62.16	14.9	3.7
52.50	14.8	68.29	10.4	3.2
55.00	12.3	71.31	8.85	4.1
57.50	10.3	74.30	7.58	4.1
60.00	8.49	77.28	6.41	3.5
62.50	7.03	80.19	5.44	3.3
65.00	6.04	83.08	4.80	3.2
67.50	5.16	85.93	4.21	4.3
70.00	4.34	88.75	3.64	3.7
72.50	3.64	91.53	3.14	3.8
75.00	3.14	94.28	2.79	3.3
77.50	2.80	96.99	2.56	5.0
80.00	2.34	99.66	2.21	3.8
82.50	2.20	102.29	2.14	7.7
85.00	1.76	104.88	1.76	4.2
90.00	1.36	109.94	1.45	3.3
95.00	1.06	114.85	1.20	4.3
100.00	0.902	119.60	1.09	4.2
105.00	0.813	124.20	1.06	3.4
110.00	0.847	128.65	1.16	3.4
120.00	1.16	137.13	1.80	4.1
125.00	1.33	141.17	2.18	4.2
130.00	1.67	145.09	2.89	3.2
135.00	2.06	148.90	3.75	3.2
140.00	2.41	152.61	4.60	3.2
145.00	3.00	156.23	5.96	3.8
150.00	3.23	159.77	6.66	3.0
155.00	3.55	163.25	7.56	3.4
160.00	3.91	166.67	8.54	3.1
165.00	4.11	170.04	9.17	6.8
170.00	4.29	173.38	9.71	6.8

TABLE XII

DIFFERENTIAL CROSS SECTION
FOR ${}^3\text{He}(\text{p,p}){}^3\text{He}$ ELASTIC SCATTERING AT
46.0 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/sr)	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr)	Relative Error (%)
8.50	109.7	11.43	60.9	1.7
10.00	120.9	13.44	67.3	1.5
12.50	129.7	16.79	72.6	1.7
15.00	130.7	20.14	73.6	1.4
17.50	124.3	23.47	70.5	1.4
18.50	122.8	24.80	69.9	1.8
20.00	116.2	26.79	66.5	1.5
22.50	103.6	30.10	59.8	1.5
25.00	90.1	33.40	52.6	1.5
27.50	77.6	36.68	45.8	1.4
38.50	34.8	50.90	21.9	2.5
40.00	30.2	52.81	19.2	1.5
42.50	24.4	55.97	15.8	1.5
45.00	19.8	59.10	13.1	1.5
47.50	15.9	62.21	10.7	1.6
50.00	12.9	65.29	8.87	1.6
52.50	10.6	68.34	7.45	1.9
55.00	8.56	71.37	6.15	1.6
60.00	5.83	77.32	4.40	1.6
65.00	4.14	83.13	3.29	1.6
70.00	2.98	88.81	2.50	1.4
75.00	2.27	94.34	2.02	1.5
80.00	1.70	99.71	1.60	1.5
85.00	1.32	104.93	1.32	1.6
90.00	1.02	110.00	1.09	1.6
95.00	0.876	114.90	0.996	1.9
100.00	0.715	119.65	0.867	2.1
105.00	0.626	124.25	0.809	1.9
110.00	0.614	128.70	0.845	1.8
115.00	0.659	133.00	0.964	1.9
120.00	0.754	137.17	1.17	1.8
125.00	0.969	141.20	1.58	1.8
130.00	1.11	145.12	1.93	1.5
140.00	1.60	152.64	3.08	1.4
160.00	2.73	166.68	5.98	1.3
170.00	3.00	173.38	6.81	1.3

TABLE XII
DIFFERENTIAL CROSS SECTION
FOR $^{16}\text{O}(\alpha,\alpha)^{16}\text{O}$ ELASTIC SCATTERING AT
67.5 MeV (LAB)

θ_{lab} (deg)	σ_{lab} (mb/ster)	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/ster)	Relative Error (%)
8.50	108.8	11.44	57.6	2.4
10.80	115.0	13.45	64.8	1.7
12.80	124.5	16.80	68.6	1.5
15.80	121.9	20.15	68.6	1.4
17.50	118.1	23.48	65.9	1.4
18.50	114.7	24.81	65.2	1.9
20.00	109.2	25.80	62.4	1.6
22.50	97.1	30.11	56.0	1.5
25.00	84.3	33.41	49.2	1.5
27.50	71.1	36.89	41.9	1.5
28.50	30.3	50.92	19.1	2.6
40.00	26.4	52.83	16.8	1.7
42.50	21.3	55.99	13.6	1.7
45.00	17.1	59.13	11.3	1.7
47.50	13.8	62.24	9.29	1.7
50.00	11.0	65.32	7.56	1.7
52.50	8.78	68.37	6.17	2.0
55.00	7.29	71.39	5.24	1.6
57.50	6.05	74.38	4.45	1.8
60.00	5.06	77.34	3.82	1.4
62.50	3.95	80.27	3.05	2.6
65.00	3.48	83.16	2.76	1.7
67.50	2.98	86.02	2.43	2.3
70.00	2.52	88.84	2.11	1.5
75.00	1.89	94.38	1.68	1.5
80.00	1.49	99.74	1.40	1.6
85.00	1.18	104.96	1.18	1.6
90.00	0.931	110.02	0.994	1.7
95.00	0.764	114.93	0.889	1.9
100.00	0.629	119.68	0.763	1.9
105.00	0.560	124.27	0.724	1.9
110.00	0.543	128.72	0.746	1.8
115.00	0.573	133.02	0.839	1.9
120.00	0.629	137.18	0.978	1.9
125.00	0.761	141.22	1.25	1.8
130.00	0.925	145.14	1.61	1.5
135.00	1.12	148.94	2.04	1.5
140.00	1.35	152.65	2.58	1.4
145.00	1.57	156.26	3.13	1.4
150.00	1.81	159.80	3.74	1.3
155.00	2.08	163.27	4.44	1.3
160.00	2.30	166.68	5.04	1.3
165.00	2.44	170.05	5.46	1.4
170.00	2.52	173.39	5.72	1.7