Elastic scattering of deuterons by ^{4}He between 30 and 40 MeV*

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Differential cross sections for elastic scattering of deuterons by ^{4}He were measured at laboratory energies of 29.8, 32.3, 34.8, 37.3, and 39.8 MeV. The angular range extended from 15 to 160° cm in steps of about 5°. The average relative error was 2%, and the uncertainty in the absolute normalization was 2%.

[NUCLEAR REACTIONS ^{4}He(d,d), $E=29.8$, 32.3, 34.8, 37.3, 39.8 MeV; measured (E,θ_l); $\theta_c=16°$ to 159°.]

I. INTRODUCTION

Differential cross sections for the reaction ^{2}H$(\alpha,t)^3$He at center-of-mass energies between 16.1 and 27.4 MeV exhibit an asymmetry about 90° cm,[1-3] in violation of the Barshay-Temmer theorem.[4] Several possible causes of the asymmetry have been proposed. Polarization of the deuteron in the Coulomb field of the ^{4}He nucleus[5] can perhaps be ruled out because of the strong energy dependence of the asymmetry.[6] Isospin mixing of compound nuclear levels in ^{6}Li has been suggested.[7] Suitable excited states have been predicted near 22 MeV by the resonating group theory.[8] Experimental evidence for such levels might be observable in the energy dependence of the elastic scattering cross sections for the ^{2}H+^{4}He system.

A third explanation involves distorted-wave Born-approximation (DWBA) calculations of single nucleon transfer, assuming a coherent superposition of slightly different amplitudes for the transfer of neutrons and protons.[3,9] Fairly good information on ^{2}H+^{4}He elastic scattering is required for these calculations, in order to be able to derive good optical model potential parameters for the entrance channel.

The elastic scattering of deuterons by ^{4}He has been studied extensively at laboratory energies below 12 MeV,[10,11] and to a lesser extent at energies up to 28 MeV.[12-16] The analyzing power for $d+{}^4$He elastic scattering has recently been measured at 12, 14, and 17 MeV.[17] Optical model parameters derived for data up to 24.85 MeV (center-of-mass energy 16.56 MeV)[18] were used in the DWBA calculations of Ref. 9, while preliminary cross section data at 27.1–39.6 MeV (center-of-mass energy 18.1–26.4 MeV)[19] were used to find the optical model parameters for the entrance channel in Ref. 3. An improved analysis should soon be possible in view of recent measurements of the vector polarization of deuterons elastically scattered by ^{4}He in the center-of-mass energy range 17–30 MeV.[20]

These vector polarization measurements provided the incentive for an improvement on the preliminary data of Ref. 19, both for use in the DWBA analysis of the ^{2}H$(\alpha,t)^3$He reaction data of Refs. 1–3, and as a step towards an improved understanding of the ^{2}H+^{4}He system generally. This experimental information should also prove useful for dealing with final state interactions in studies of the $(d,d\alpha)$ reaction. In the present work, we have measured differential elastic scattering cross sections at laboratory energies between 30 and 40 MeV in 2.5 MeV steps. Deuterons were observed at laboratory angles from 10.5 to 79.5° in 3° steps, and the recoil α particles from 10.5 to 43.5°. This resulted in cross sections at center-of-mass angles from 15 to 160° in steps of 4 to 6°.

II. EXPERIMENTAL ARRANGEMENT

The experiment was performed with the external deuteron beam of the 183 cm isochronous cyclotron of the Crocker Nuclear Laboratory, with a gas target at the center of the Laboratory's 76 cm scattering chamber. Beam switching and energy analysis was accomplished by deflecting the deuterons twice, 50° left and 50° right. Three magnetic quadrupole doublets were used to focus the beam through a collimator of 5 mm diam, placed 50 cm from the center of the target. This collimator was followed by an antiscattering collimator of 6 mm diam, at 30 cm from the center of the target. After passing through the target, the beam was refocused by another quadropole doublet, and collected in a Faraday cup, located 3.3 m from the target center. Beam currents between 5 and 30 nA were used. The fraction of the beam stopped by the collimator was monitored continuously, and was typically about 5%. The beam energy was known to ±0.2 MeV from the cyclotron and beam optics operating parameters, as confirmed by numerous kinematic and time-of-flight measurements during other recent experiments.

The target gas was high-purity helium. It was held in a cylindrical target of 26 cm diam. A Kapton foil of 5 mg/cm^2 thickness extended for 360° around the target, overlapping over an angular range of about 5°. In the overlap region and at 120° to either side, three support posts blocked an angular range of about 3° each. The target temperature was read to 0.2°C accuracy with a mercury thermometer, and the pressure was determined with a mercury manometer to 0.05 cm Hg. Readings were taken whenever the experimental area was entered. The values at the time of each run were obtained by interpolation. The target pressure was set initially at about 50 cm Hg, and was found to decrease at a very nearly constant rate, on the order of 0.2 cm Hg/h.

Charged particles were observed with 3 mm thick Si(Li) detectors and a 0.7 mm thick surface barrier detector. In addition to the elastically scattered deuterons and recoil α particles, protons, tritons, ^{3}He and α particles from the follow-

TABLE I. Cross sections for ^{4}He$(d,d)^4$He elastic scattering. An asterisk denotes angles at which the recoil ^{4}He nucleus was observed. Δ denotes the relative error. The normalization error is ±2%.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	E_d = 29.8 MeV $d\sigma/d\omega$ (mb/sr)	Δ (%)	E_d = 32.3 MeV $d\sigma/d\omega$ (mb/sr)	Δ (%)	E_d = 34.8 MeV $d\sigma/d\omega$ (mb/sr)	Δ (%)	E_d = 37.3 MeV $d\sigma/d\omega$ (mb/sr)	Δ (%)	E_d = 39.8 MeV $d\sigma/d\omega$ (mb/sr)	Δ (%)
10.5	15.8	638	2.5			718	2.0	698	2.1	665	2.2
13.5	20.3	459	2.1	468	2.1	541	2.0	511	2.2	486	2.0
16.5	24.8	298	2.3	307	2.3	329	2.3	310	2.5	313	2.3
19.5	29.3	177.0	2.6	177.5	2.6	186.3	2.6	179.1	2.7	174.4	2.7
22.5	33.7	95.5	2.7	92.0	2.8	94.8	2.9	89.0	3.2	89.0	2.9
25.5	38.1	50.4	2.7	47.8	2.7	48.9	2.7	45.8	2.7	44.2	2.8
28.5	42.5	30.8	1.8	30.2	1.7	30.5	1.7	28.9	1.7	28.0	1.9
31.5	46.9	26.4	0.9	27.8	0.8	26.9	0.9	26.8	1.0	25.5	1.1
34.5	51.2	28.9	0.7	31.4	0.7	29.3	0.7	29.5	1.0	28.8	1.1
37.5	55.5	32.5	0.7	34.0	0.8	32.4	0.7	32.8	0.9	31.1	1.1
40.5	59.8	33.7	0.8	35.2	0.8	35.2	0.9	32.9	1.0	29.7	1.1
43.5	64.0	31.9	0.9	32.7	1.2	33.2	1.0	31.0	1.2	29.6	1.2
46.5	68.1	29.3	1.4	29.1	1.6	28.6	1.6	26.0	1.4	24.8	1.4
49.5	72.2	24.0	1.6	22.2	1.9	22.9	1.7	20.3	2.2	19.23	1.6
52.5	76.2	19.56	1.4	18.53	1.6	19.19	1.8	14.95	2.0	14.09	1.9
55.5	80.2	15.60	1.4	13.86	1.9	14.82	1.9	10.99	2.1	10.15	2.1
58.5	84.1	13.34	1.7	11.61	2.0	11.23	2.2	8.78	1.9	7.45	2.5
61.5	88.0	12.13	2.1	10.19	2.1	8.05	2.4	6.40	2.0	5.81	3.6
64.5	91.7	11.33	2.2	9.44	2.1	7.44	2.6	5.76	2.1	5.01	2.5
*43.5	92.9			9.13	1.5	6.83	1.7	5.63	1.7	4.64	1.9
67.5	95.4	11.23	2.1	9.31	1.7	7.18	2.5	5.54	2.1	4.77	2.6
*40.5	98.9	11.21	1.2	9.15	1.5	6.95	1.5	5.65	2.4	4.68	1.7
70.5	99.0	11.33	1.6	8.97	1.7	7.25	3.0	5.70	3.1	4.57	2.7
73.5	102.5	10.60	2.0	8.95	2.1	6.76	3.5	5.05	3.5	4.26	2.8
*37.5	104.9	10.80	1.0	8.85	1.3	6.86	1.1	4.99	2.3	4.11	2.5
76.5	106.0			9.09	3.4			5.06	5.0	4.34	5.5
79.5	109.4			8.74	3.8			4.40	6.9	3.89	6.8
*34.5	110.9	9.77	0.9	8.00	1.3	5.97	1.2	4.55	2.1	3.88	2.3
*31.5	116.9	8.20	0.8	6.65	1.1	4.99	1.3	3.69	1.5	3.86	2.5
*28.5	122.9	6.94	1.0	5.65	1.1	3.83	1.9	3.02	1.9	2.43	2.5
*25.5	128.9	6.10	1.3	5.07	1.2	3.68	1.9	3.02	1.6	2.63	2.1
*22.5	134.9	5.58	1.6	5.04	1.3	3.97	1.8	3.54	1.6	3.15	2.6
*19.5	140.9	5.93	1.1	5.48	1.2	5.12	2.7	4.39	2.4	3.52	2.0
*16.5	146.9	6.41	1.1	5.78	1.2	5.50	1.7	5.02	1.9	4.02	1.4
*13.5	153.0	6.34	1.5	5.83	1.1	5.19	1.7	4.32	1.4	3.75	1.2
*10.5	159.0	6.45	2.5	5.53	1.1	4.70	1.9	3.59	1.4	2.95	1.1

ing reactions were observed:

$^4He(d, t)^3He$,

$^4He(d, p)^5He \rightarrow n + ^4He$,

$^4He(d, n)^5Li \rightarrow p + ^4He$.

The surface barrier detector was sufficiently thick to stop the most energetic ^3He and α particles. At the higher energies and at forward angles, two Si(Li) detectors were stacked facing each other, in order to stop the protons and deuterons. Entry through the relatively thick dead layer at the backside of the first detector resulted in considerable energy loss by the ^3He and α particles in these cases. Deuterons scattered by the small amount of impurities in the target were resolved from those scattered by helium at all angles except $\theta_l = 10.5°$.

The detector collimators consisted of "infinitely" high front slits about 18 cm from the target center and circular rear apertures directly in front of the detectors and about 29 cm from the target center. The mean angle subtended in the horizontal plane was 1.6° full width at half maximum. The central value of the scattering angle was known to ±0.1°.

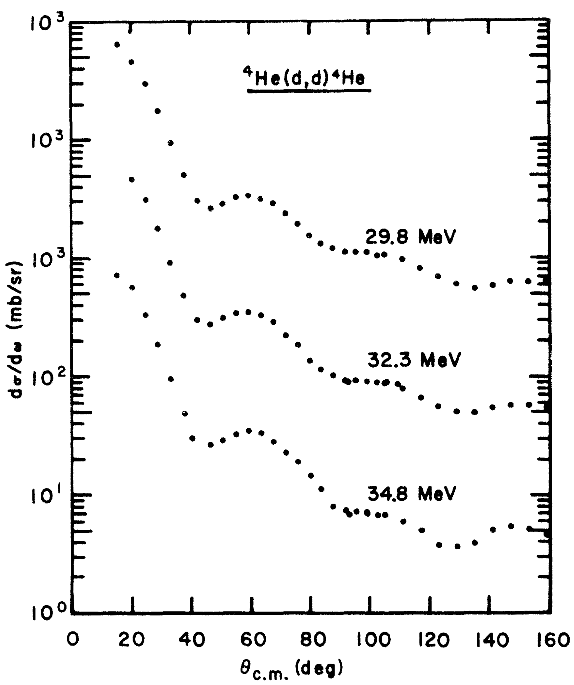

FIG. 1. Center-of-mass cross sections as a function of scattering angle for $E_d = 29.8$, 32.3, and 34.8 MeV. The ordinate scale for successive deuteron energies differs by factors of 10.

III. RESULTS

Differential cross sections were obtained from the data by using the leading term of the expression derived by Silverstein.[21] Corrections due to the higher order terms were found to be less than 0.13%, and corrections due to the finite diameter of the beam less than 0.03%.

The rate of change with angle of the cross section, the relativistic Jacobian, and sin θ_l, combined with the uncertainty in the scattering angle, made substantial contributions to the relative error of the cross sections at forward angles, becoming as large as 3%. As a check on the accuracy of the angle determination, data were taken on both sides of the beam for $\theta_l = 13.5$, 16.5, 19.5, and 22.5°. The mean deviation of these measurements from their averages was 1.3%, well below the estimated 2.4% average error of a single measurement at these angles.

Corrections for dead time losses were determined from "real time" and "live time" clocks in the electronics, and contributed less than 0.3% to the relative errors. Errors due to statistics and uncertainties in peak integrations varied between 0.2 and 6.8%, but were less than 2% for 85% of the data points. Corrections for counting losses due to reactions in the detectors were obtained from Cahill *et al.*[22]

The absolute normalization has an uncertainty of 2%, resulting from uncertainties of 1.5% in the

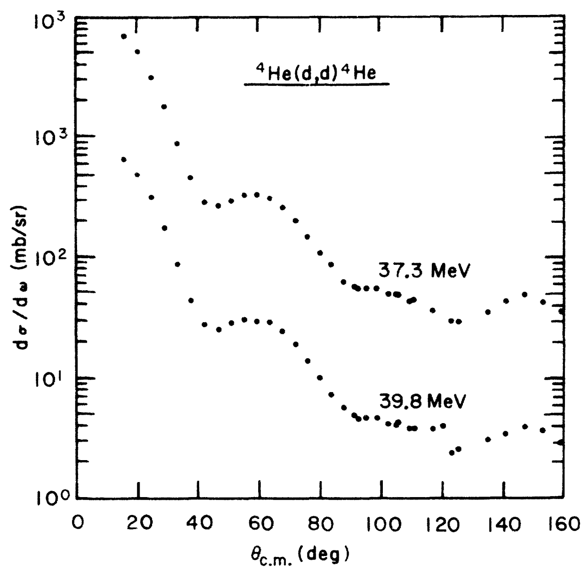

FIG. 2. Center-of-mass cross sections as a function of scattering angle for $E_d = 37.3$ and 39.8 MeV. The ordinate scale for successive deuteron energies differs by factors of 10.

collimator geometry, 0.7% in the gas density, and 1.0% in the beam current integration.

The cross sections are given in Table I and Figs. 1 and 2.

IV. DISCUSSION

The differential cross sections for $^4He(d,d)^4He$ elastic scattering between 25 and 40 MeV exhibit a smooth variation with energy at center-of-mass angles greater than about 80°, while at forward angles they are almost constant over this energy range. The present results agree well with previous work at lower energies.[14,15] At large angles, the cross sections decrease rapidly with increasing energy, changing by as much as a factor of 4.5 between 25 and 40 MeV. The minimum near 140° shifts towards 120° over the energy interval studied here, and a new maximum develops near 150°.

The smooth behavior of the data with energy gives no evidence of excited states in ^{6}Li as predicted by resonating group calculations.[8] The existence of such states, however, is not ruled out by the lack of resonance structure in these elastic scattering cross sections.

An optical model analysis of the present cross sections and the vector polarization data of Conzett and Dahme is in progress, and preliminary results give reasonable fits to the data.[20] A phase shift analysis of the results would be highly desirable. Such an analysis would be essentially meaningless, however, without additional experimental information. A standard semiclassical argument in terms of the deuteron's linear momentum and an impact parameter equal to the sum of the deuteron and ^{4}He radii shows that nonzero phase shifts should be expected for $l \leq 6$. In view of the large number of open reaction channels, the phase shifts must be taken as complex. Allowing for the deuteron's spin and for tensor coupling between states with the same total angular momentum and parity, this means 43 adjustable parameters.

The present cross section data could be fitted quite reasonably by a Legendre polynomial expansion:

$$\frac{d\sigma}{d\omega}(\theta_c) = \sum_{l=0}^{10} a_l P_l(\cos\theta_c).$$

Even the addition of the vector polarization data of Conzett and Dahme[20] will not permit going from 11 to 43 adjustable parameters without introducing totally unacceptable ambiguities. It is to be hoped that tensor polarization data will become avaliable for this energy range, along with additional experimental information on the various reaction channels and total reaction cross sections.

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