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SCATTERING OF ^{3}He AND ^{4}He FROM POLARIZED ^{3}He BETWEEN 7 AND 18 MeV

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Abstract: Polarization analyzing power of ^{3}He-^{3}He and ^{3}He-^{4}He elastic scattering is reported for bombarding energies between 7.5 and 17.9 MeV. A phase-shift analysis for ^{3}He-^{4}He elastic scattering incorporating this and other polarization data is presented. The analyzing power of ^{3}He-^{3}He elastic scattering is consistent with zero at $\theta_{\mathrm{c.m.}} = 66°$.

E | NUCLEAR REACTIONS $^3\vec{\mathrm{He}}(\alpha, \alpha)^3$He, E = 7.5–17.9 MeV; measured polarization analyzing power; deduced phase shifts. $^3\vec{\mathrm{He}}(\tau, \tau)^3$He, E = 9.3–17.5 MeV; measured polarization analyzing power.

1. Introduction and summary

The structure of the ^{7}Be nucleus has been studied previously through a number of ^{3}He-^{4}He and p-^{6}Li experiments which did not involve polarization measurements* [refs. [1–3]]. As a result of these experiments much of the level structure of ^{7}Be below an excitation energy of 11 MeV has been well established. Phase-shift analyses of ^{3}He-^{4}He scattering have indicated that a number of regions of high ^{3}He polarization were to be expected, and it has been verified [4]) that this scattering process is useful as an analyser of ^{3}He polarization. In order to supplement earlier studies of the ^{7}Be nucleus and to investigate a region that was potentially useful as a polarization analyser but not used in double-scattering work, a measurement of the polarization analyzing power for ^{3}He-^{4}He elastic scattering at c.m. angles of 79.3° and 114.0° was undertaken using a polarized ^{3}He target. Values of ^{7}Be excitation energies ranged

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* To obtain numerical tables of the data in ref. [2]) order document NAPS 01580 from ASIS National Auxiliary Publication Service, c/o CCM Information Corporation, 866 3rd Ave., New York, New York 10022; remitting \$2.00 for each microfiche or \$5.00 for each photocopy.

Numerical tables of the data in ref. [3]) may be found in: Robert John Spiger, Ph.D. Thesis, California Institute of Technology, 1966, available as order number 67-60609 from University Microfilms Inc., Ann Arbor, Michigan 48103.

from approximately 5.0 to 9.3 MeV (^{4}He lab energies from 7.5 to 17.9 MeV). This measurement is complimentary to polarization measurements reported in the previous paper [5]) and to other polarization measurements which have been reported for both p-^{6}Li and ^{3}He-^{4}He scattering. For the case of p-^{6}Li scattering, polarization measurements and a phase-shift analysis have been reported by Brown and Petitjean [ref. [6])] and by Petitjean *et al.* [7]). Double-scattering measurements of ^{3}He-^{4}He scattering have been reported by Armstrong *et al.* [4]) and by McEver *et al.* [8]). Polarization measurements are particularly helpful in that they can often provide a sensitive test of phase shifts which were derived on the basis of cross-section measurements alone. Therefore, the polarization data reported here and in the previous paper [5]), the polarization data of Armstrong *et al.* [4]) and of McEver *et al.* [8]), and the differential cross section measurements of Spiger and Tombrello [3]) have been combined in a phase-shift analysis of ^{3}He-^{4}He scattering. The results of the present phase-shift analysis substantially confirm previous phase-shift analyses and hence previously deduced properties of ^{7}Be levels.

Data on the scattering of ^{3}He from polarized ^{3}He for beam energies ranging from 9.3 to 17.5 MeV are also reported in this paper. The data were taken at a c.m. angle of 66.0° and indicate that the analyzing power at this angle is near zero. These results may be compared with the analysis of Bacher *et al.* [9]) who studied the scattering of ^{3}He from unpolarized ^{3}He for beam energies up to 19 MeV and reported good agreement with the resonating-group calculations of Thompson and Tang [10]). Both the analysis of ref. [9]) and the calculations of ref. [10]) attribute changes in the shapes of the excitation curves and angular distributions in ^{3}He-^{3}He scattering for beam energies above 12 MeV to a broad F-wave resonance. In these analyses, no splitting of any of the partial waves was assumed, and the absence of any asymmetry at $\theta_{c.m.}$ = 66.0° is consistent with these assumptions.

2. Target and beams

The ^{3}He target was polarized by the method of optical pumping [11]). The optical-pumping apparatus used was similar to that reported by Baker *et al.* [12]) and by Hardy *et al.* [13]). The scattering chamber employed allowed the observation of left-right scattering asymmetries at a single lab angle of 33.0° and was constructed according to the procedure described in ref. [13]). The particles were detected at θ_{lab} = 33.0° by a pair of silicon surface-barrier detectors placed symmetrically about the beam axis in the plane perpendicular to the direction of the ^{3}He target polarization. The overall c.m. rms angular resolution, due to beam collimation, multiple scattering in the entrance foil of the chamber and collimation of the scattered particles varied from 1.85° to 3.34° and is given along with the asymmetry data in tables 1 and 2.

The target polarization, which ranged from 0.10 to 0.12, was determined by optical measurements as described in ref. [12]). The parameter f, which appears in the optical determination of the ^{3}He polarization and which is defined in ref. [12]), was taken to be 0.7. As discussed in ref. [12]), uncertainty in the value of f results in a systematic uncertainty in the target polarization. As a result, all of the experimental asymmetries given in tables 1 and 2 may be multiplied by a single factor ranging from 0.85 to 1.15. However, considering the values reported in table 1 for ^{4}He-^{3}He scattering at $\theta_{c.m.}$ =

TABLE 1

Analyzing powers A_y and errors (standard deviation) for ^{3}He-^{4}He elastic scattering

	$\theta_{c.m.} = 79.3°$		$\theta_{c.m.} = 114.0°$	
E_3 (MeV)	A_y	$\Delta\theta_{c.m.}$ (deg.)	A_y	$\Delta\theta_{c.m.}$ (deg.)
5.65	0.86±0.03	3.3	0.29±0.06	2.5
6.06	0.69±0.03	3.3	0.31±0.06	2.5
6.46	0.61±0.02	3.2	0.25±0.05	2.4
6.86	0.71±0.02	3.1	0.24±0.04	2.3
7.26	0.80±0.05*	3.0	0.20±0.03	2.3
7.66	0.84±0.06*	2.9	0.06±0.03	2.2
8.06	0.75±0.02	2.9	0.04±0.03	2.2
8.45	0.11±0.02	2.8	−0.06±0.02	2.1
8.85	−0.59±0.02	2.8	−0.15±0.03	2.1
9.24	−0.94±0.03	2.7	−0.27±0.03	2.1
9.63	−1.05±0.09*	2.7	−0.38±0.07	2.0
10.02	−0.95±0.12*	2.7	−0.39±0.08	2.0
10.80	−0.95±0.04	2.6	−0.53±0.10	2.0
11.58	−0.90±0.04	2.5	−0.50±0.12	1.9
12.36	−0.90±0.05	2.5	−0.66±0.12	1.9
12.74	−0.70±0.05	2.5	−0.63±0.10	1.9
13.13	−0.37±0.05	2.5	−0.53±0.08	1.9
13.52	−0.16±0.05	2.4	−0.41±0.08	1.9

Values of the c.m. rms angular resolution $\Delta\theta_{c.m.}$ are also given. The asterisks indicate data points for which errors in the 79.3° data were increased as described in subsect. 3.1. The errors given do not include the possible systematic error discussed in sect. 2.

TABLE 2

Polarization analyzing power in ^{3}He-^{3}He elastic scattering

E_3 (MeV)	$\theta_{c.m.} = 66.0°$	
	A_y	$\Delta\theta_{c.m.}$ (deg.)
9.27	0.03±0.04	2.3
10.32	0.01±0.04	2.2
11.36	0.02±0.04	2.1
12.40	0.02±0.04	2.1
13.44	−0.18±0.06	2.0
14.46	0.01±0.06	2.0
15.49	−0.05±0.05	1.9
17.53	0.04±0.04	1.9

Analyzing power A_y and errors (standard deviation) for ^{3}He-^{3}He elastic scattering are given. Values of the c.m. rms angular resolution $\Delta\theta_{c.m.}$ are also given. The errors do not include the possible systematic error discussed in sect. 2.

79.3°, which are already near maximum, a multiplying factor as large as 1.15 would be very improbable. Also, fig. 1 of ref. [14]) indicates reasonable agreement with the double scattering data of ref. [4]), and the proper systematic correction is probably smaller than 15 %.

The CIT-ONR tandem accelerator furnished ^{4}He and ^{3}He beams which had characteristic energy uncertainties of ± 15 keV over the energy ranges used. Beam currents were typically 0.45 μA for beams below 13 MeV and 0.15 μA for beams above 13 MeV. The aluminium entrance foil of the scattering chamber had a thickness of 2.30 ± 0.05 mg/cm^2, and the energies of the incident ^{4}He or ^{3}He beams were corrected for energy losses in the entrance foil. The uncertainty in the thickness of the entrance foil resulted in an additional uncertainty of approximately ± 15 keV in the beam energy.

3. The ^{3}He-^{4}He scattering

3.1. DETERMINATION OF ANALYZING POWER

Data were obtained at eighteen ^{4}He beam energies ranging from 7.5 to 17.9 MeV. The equivalent ^{3}He lab energy E_3, defined in sect. 1, ref. [5]), ranged from 5.7 to 13.5 MeV. Both scattered ^{4}He and recoil ^{3}He were detected at $\theta_{lab} = 33.0°$. The ^{4}He, which were of lower energy than the recoil ^{3}He, corresponded to elastic scattering at $\theta_{c.m.} = 79.3°$. The ^{3}He corresponded to elastic scattering at $\theta_{c.m.} = 114.0°$.

Pulses from the two detectors were processed in such a way that no corrections were necessary due to dead time in the electronics. At $\theta_{lab} = 33°$ the ^{4}He and ^{3}He groups were well separated in energy, and in the pulse-height spectra obtained the separation between the peaks due to the two species of particles resulted in peak-to-valley ratios which were generally in excess of 50 : 1. The number of ^{4}He events was determined by simply summing the spectrum over the region of the ^{4}He peak and then subtracting the estimated number of backgrounds events which were included in the peak integration. The number of ^{3}He events was obtained in a similar manner except the estimated background was zero. The separation between the ^{4}He and ^{3}He peaks was sufficiently good so that the number of ^{3}He events included as background in the ^{4}He integrations (or vice versa) was negligible. There was, however, other background present in the ^{4}He peaks. The estimated number of background events included in the integration of these peaks decreased from 1.8 % of the number of elastic scattering events at the lowest energy point to no background at the three highest energy points. The maximum error introduced by performing the background subtraction was in all cases much less than the uncertainty due to statistics alone.

The values of the polarization analyzing power A_y for ^{3}He-^{4}He elastic scattering are presented in table 1. The errors given are standard deviations due to counting statistics (including statistical effects in background corrections) except for the energy points indicated by asterisks in table 1. For these data points a nominally zero quantity, which provides a consistency check of the data and which is discussed in ref. [12]),

TABLE 3

Phase-shift parameters deduced for ^3He-^4He scattering corresponding to the equivalent ^3He lab energy E_3 for each value of J^π used in the analysis

E_3 (MeV)	$\delta_{\frac{1}{2}}^+$	$\delta_{\frac{1}{2}}^-$	$\delta_{\frac{3}{2}}^-$	$\delta_{\frac{3}{2}}^+$	$\delta_{\frac{5}{2}}^+$	$\delta_{\frac{5}{2}}^-$	$\delta_{\frac{7}{2}}^-$
	$\alpha_{\frac{1}{2}}^+$	$\alpha_{\frac{1}{2}}^-$	$\alpha_{\frac{3}{2}}^-$	$\alpha_{\frac{3}{2}}^+$	$\alpha_{\frac{5}{2}}^+$	$\alpha_{\frac{5}{2}}^-$	$\alpha_{\frac{7}{2}}^-$
5.69	−45.9	132.6	149.4	−1.5	−1.0	8.0	157.4
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.19	−47.7	134.9	141.9	−6.9	−4.8	10.6	166.2
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.45	−50.3	133.9	140.9	−6.6	−4.8	11.9	167.6
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
6.95	−54.1	131.0	137.5	−1.8	−3.1	18.6	169.6
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.20	−52.0	131.1	136.5	−1.5	−3.7	23.9	170.9
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7.70	−56.5	130.0	135.5	3.0	2.7	36.1	171.0
	0.989	1.000	0.989	0.989	0.989	1.000	1.000
7.95	−56.9	127.9	133.8	3.0	3.9	46.7	172.0
	0.985	1.000	0.985	0.985	0.985	1.000	1.000
8.20	−62.0	125.1	131.0	0.2	0.7	56.7	173.0
	0.981	1.000	0.981	0.981	0.981	1.000	1.000
8.46	−63.5	125.5	132.5	−0.3	0.0	68.2	173.0
	0.977	1.000	0.977	0.977	0.977	1.000	1.000
8.71	−62.0	125.8	134.1	−3.3	−2.6	80.7	174.0
	0.968	1.000	0.968	0.973	0.973	1.000	1.000
8.96	−68.3	123.9	133.1	−3.9	−3.3	89.2	174.3
	0.969	1.000	0.969	0.974	0.974	0.980	1.000
9.21	−66.6	120.5	132.7	−2.1	−3.0	101.0	174.7
	0.963	1.000	0.963	0.973	0.973	0.955	1.000
9.71	−62.8	118.6	129.9	1.1	−1.9	116.8	175.4
	0.953	1.000	0.953	0.958	0.958	0.860	1.000
9.96	−64.3	116.2	128.7	−0.2	−2.8	119.4	174.6
	0.938	1.000	0.938	0.953	0.953	0.860	1.000
10.96	−69.4	113.1	123.8	1.3	−1.4	132.8	175.3
	0.903	1.000	0.903	0.923	0.923	0.960	1.000
11.47	−75.0	114.5	119.0	−3.3	3.7	133.0	177.0
	0.883	1.000	0.883	0.915	0.915	0.980	1.000
11.97	−80.0	112.0	115.2	2.2	1.9	133.1	179.4
	0.855	1.000	0.855	0.895	0.895	0.980	0.965
12.47	−73.6	110.4	116.4	0.4	0.9	133.2	183.8
	0.835	1.000	0.835	0.865	0.865	0.980	0.860
12.72	−76.4	109.2	113.3	−2.0	−1.0	134.0	188.0
	0.825	1.000	0.825	0.860	0.860	0.980	0.657
13.00	−84.3	106.1	109.6	−0.6	2.4	133.0	185.7
	0.813	1.000	0.813	0.853	0.853	0.980	0.473
13.22	−84.2	103.0	110.0	0.3	0.7	136.0	184.5
	0.800	1.000	0.800	0.840	0.840	0.980	0.314
13.47	−83.5	102.0	111.0	2.6	−1.5	141.0	171.4
	0.803	1.000	0.803	0.843	0.843	0.980	0.240

The upper numbers are the real parts of the complex phase shifts, given in degrees and denoted by $\delta_J{}^\pi$. The lower numbers are the imaginary parts, given in terms of the damping parameters $\alpha_J{}^\pi = \exp(-2\gamma_J{}^\pi)$, where $\gamma_J{}^\pi$ is the imaginary part of the J^π phase shift. This is the same notation as that of ref. [3]).

was found to be more than 2.25 statistical standard deviations from zero. The errors quoted for these data were arbitrarily increased to bring the nominally zero quantity corresponding to each within one standard deviation from zero.

3.2. THE ^{3}He-^{4}He PHASE SHIFTS

A phase-shift analysis of ^{3}He-^{4}He scattering was performed for equivalent ^{3}He energies from 5.69 to 13.47 MeV, and the derived phase-shift parameters are given in table 3. The energy range covered in this analysis overlaps slightly that of the previous paper [5]). The differential cross-section measurements of Spiger and Tombrello [3]), the double-scattering measurements of Armstrong *et al.* [4]) and of McEver *et al.* [8]), the polarization data of Boykin *et al.* [5]), and the data of this work were combined in the phase-shift searches.

The parameters used in the analysis included the real and imaginary parts of the complex S-, P-, D- and F-wave phase shifts. Below the first proton threshold for the $^3He(\alpha, p)^6Li$ reaction at 7.0 MeV only the seven real parameters were used. Initial values for the phase shifts were determined from the phase shifts of ref. [3]). In contrast to the procedure of ref. [5]), the D-wave phase shifts were allowed to vary. As a result, the phase shifts reported here for equivalent ^{3}He lab energies below 7 MeV are consistent with but not identical to those reported in ref. [5]). The D-wave phase shifts deduced from this analysis did not exhibit any large or consistent departure from zero even at the highest energy investigated.

Several patterns of variation were tried in the analysis before the method described below was adopted. When both the real and the imaginary parts of the phase shifts were allowed to vary simultaneously, fits to the data were obtained, but the imaginary parts of the phase shifts did not vary smoothly with energy. Therefore, without attempting a simultaneous fit of the data at all energies, it appears that the existing data are not sufficient to specify all of the possible phase-shift parameters uniquely at each energy, and predictions of the polarization based only on the phase shifts and which are not verified by experiment should be used with caution. However, the results obtained suggested that (a) the imaginary parts of the $\frac{1}{2}^+$ and $\frac{3}{2}^-$ phase shifts were approximately the same, (b) the imaginary parts of the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ phase shifts were approximately the same, and (c) the imaginary part of the $\frac{1}{2}^-$ phase shift was near zero. The inelasticity in the $\frac{5}{2}^-$ channel was held equal to that of ref. [3]) since this parameter was in accordance with existing [15,16]) $^6Li(p, \tau)^4He$ data. In an effort to reduce the number of free parameters and to impose energy continuity on the imaginary parts of the phase shifts, values for the imaginary parts of the phase shifts were chosen which had a smooth variation with energy, which were consistent with the trends noted above, and which were such that the calculated total reaction cross section was in agreement with that used by Spiger and Tombrello [3]). With the values of the imaginary parts of the phase shifts thus fixed, various combinations of the S-, P-, D- and F-wave real phase shifts were then varied simultaneously, and satisfactory fits to the data were obtained. Phase-shift searches above 13.47 MeV, where no polarization data exist, were conducted in a similar manner using only the data of ref. [3]). Results were obtained for energies up to 16 MeV and are continuous in energy with the parameters reported here.

A contour map of the ^{3}He polarization based on phase-shift parameters slightly different from those reported here was presented in an earlier publication [14]). Polarizations calculated from the phase-shift parameters reported here give results very similar to those presented in ref. [14]).

4. The ^{3}He-^{3}He scattering

Data on scattering asymmetries in ^{3}He-^{3}He elastic scattering at $\theta_{\mathrm{c.m.}} = 66°$ were obtained at eight beam energies ranging from 9.3 to 17.5 MeV. The experimental apparatus, particle detection system, experimental procedure and data analysis employed were the same as that used in measuring the ^{3}He-^{4}He asymmetries. The estimated number of background events decreased from 11.0 % of the number of elastic scattering events at the lowest-energy point to 3.3 % at the highest-energy point. The maximum error introduced by performing the background subtraction was in all cases less than the uncertainty due to statistics alone. Values of A_y for ^{3}He-^{3}He elastic scattering were calculated as in the ^{3}He-^{4}He data analysis and are listed in table 2. Only one of the data points, that for 13.44 MeV, suggests that the asymmetry is non-zero. However there is nothing in the data of ref. [9]) to indicate that the value of A_y should be changing rapidly with energy near 13.4 MeV, and in view of the other polarization data presented the value of A_y at $\theta_{\mathrm{c.m.}} = 66.0°$ may be regarded as near zero throughout the energy range studied. In fact, even if it is assumed that the A_y is indeed zero in this range, there is a probability of 0.17 of obtaining a data set having a value of χ^2 greater than that calculated for the data of table 2.

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