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Alpha-Alpha Scattering in the Range 36.8 to 47.3 Mev*

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Absolute differential cross sections for the elastic scattering of alpha particles from helium have been obtained at 36.8, 38.8, 40.8, 41.9, 44.4, 46.1, 47.1, and 47.3 Mev. Measurements have been made at intervals of 2 degrees over an angular range from about 15 deg to beyond 90 deg in the center of mass system. The angular distribution shows a single minimum at 65 deg at the two lowest energies, and two minima, at about 35 and 70 deg, at the other energies.

INTRODUCTION

THE elastic scattering of alpha particles from helium has been investigated in detail in the energy range from 0.4 to 23 Mev,[1-3] at 30 Mev,[4] and from 23.1 to 41.2 Mev.[5,6] The 0.4- to 23-Mev data have been analyzed by the various authors in terms of the method of partial waves, and the nuclear phase shifts that were determined have given evidence for several virtual excited states in the compound nucleus, Be^8. The alpha-alpha differential cross sections are very strongly energy-dependent, and consequently data at several neighboring energies are needed to explore resonance effects in the phase shifts. Since it is expected that data at more closely spaced energy intervals above 23 Mev will become available soon,[6] we have explored the region from 37 to 47 Mev. It should then be possible to determine the phase shifts smoothly as functions of the energy up to 47 Mev.

In addition, at energies above 34.7 Mev there can be other end products of the interaction of two alpha particles, namely, Li^7+p, Be^7+n, He^4+t+p, He^4+He^3+n, and Li^6+d. These reactions may proceed through the compound nucleus, Be^8, or through a direct-interaction mechanism. Consequently, the technique of optical-model analysis may be very useful. The optical-model parameters determined from alpha-alpha scattering along with those determined for the elastic scattering of alpha particles from other elements should enable one to get an estimate of the size of the alpha-particle, a quantity which contributes to the size parameter determined by the optical-model analysis for other elements.

EXPERIMENTAL PROCEDURE

The general experimental details concerning the scattering chamber, the beam-monitoring, and the energy-measuring methods have been described earlier.[7] The external 48-Mev alpha-particle beam of the Crocker Laboratory 60-inch cyclotron was directed down an evacuated pipe and through sufficient absorber, placed at the entrance to the scattering chamber, to degrade it to the desired energy. An Al absorber was used except for the three lowest energies, at which Be was used in order to reduce the loss from multiple scattering. Following the absorber was a carbon collimation system consisting of three apertures of $\frac{1}{8}$, $\frac{1}{16}$, and $\frac{3}{16}$-in. diameter, separated by $10\frac{1}{2}$ and $6\frac{1}{2}$ in., respectively. Their respective functions were to (a) stop most of the excess beam, (b) define the cross-sectional area of the beam, and (c) act as an antiscattering baffle. Following the last collimator was a 0.001-in. Al vacuum foil (for the two 47-Mev runs, a 0.0005-in. Ni foil was substituted) through which the beam passed from the evacuated pipe into the helium-filled scattering chamber. The foil was $4\frac{1}{4}$ in. from the center of the chamber.

After passing through the chamber, the beam was collected in a Faraday cup and integrated. The mean energy of the beam was determined by measuring the range of the alpha particles in Al absorbers with the scattering chamber evacuated. The absorbers were located immediately in front of the Faraday cup. A plot of beam intensity at the Faraday cup versus thickness of Al absorber was used to determine the thickness of Al absorber corresponding to one-half maximum beam intensity. Range-energy tables[8] based on experimental proton range-energy data[9] were used.

These tables use projected ranges, and hence can be used directly to determine beam energy from thickness of Al absorber at half-maximum beam intensity. A correction to the energy was made for the length of path traversed by the alpha-particles in helium gas before arriving at the center of the scattering chamber. An estimate of the energy spread in the beam was obtained

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TABLE I. Differential cross sections for alpha-alpha scattering.

$E_{lab}=36.85\pm0.21$ Mev (147.64±1.5 mg/cm² Al)		$E_{lab}=38.83\pm0.07$ Mev (161.73±0.50 mg/cm² Al)		$E_{lab}=40.77\pm0.05$ Mev (176.04±0.40 mg/cm² Al)		$E_{lab}=41.90\pm0.02$ Mev (184.56±0.15 mg/cm² Al)	
$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)
		11.7	979 ± 42			12.2	2197 ± 43
13.7	1391 ± 11	13.7	910 ± 28			14.0	1824 ± 35
15.7	1116 ± 12					16.0	1466 ± 23
17.7	971 ± 9	17.7	717 ± 8			17.8	1132 ± 17
19.7	818 ± 12					19.8	954 ± 18
21.7	691 ± 10	21.7	620 ± 7			21.6	786.1 ± 11.6
23.7	626 ± 8					23.4	569.4 ± 5.6
25.7	505 ± 6	25.7	444 ± 5			25.2	392.3 ± 3.5
27.7	425 ± 5	27.7	383 ± 4	27.3	177 ± 2	27.0	268.3 ± 2.9
29.7	351 ± 5	29.7	324 ± 4			28.8	173.8 ± 1.7
31.7	290 ± 4	31.7	275 ± 3	31.3	29.5 ± 1.1	30.6	94.4 ± 1.1
33.7	241 ± 3	33.7	242 ± 3	33.3	12.3 ± 0.9	32.4	45.0 ± 0.6
35.7	189 ± 3	35.7	217 ± 3	35.3	8.82 ± 0.54	34.2	16.20 ± 0.31
37.7	159 ± 3	37.7	187 ± 2	37.2	33.2 ± 1.2	36.2	12.89 ± 0.30
39.7	132 ± 2	39.7	162 ± 2			38.0	26.79 ± 0.32
41.7	108 ± 2	41.7	136 ± 2	39.3	66.6 ± 1.4	39.8	50.9 ± 0.7
43.7	97.7 ± 1.4	43.7	120 ± 2	41.3	105 ± 2	41.8	83.0 ± 0.8
45.7	86.9 ± 1.8	45.7	102 ± 2	43.3	137 ± 3	43.6	114.7 ± 1.2
47.7	79.8 ± 1.2	47.7	82.7 ± 1.0			45.8	143.0 ± 1.5
49.7	70.4 ± 1.3	49.7	60.2 ± 1.3	47.3	184 ± 4	47.8	167.6 ± 1.8
51.7	61.0 ± 1.0	51.7	48.8 ± 0.8	51.3	182 ± 4	50.0	184.4 ± 1.8
53.7	49.1 ± 1.1	53.7	32.8 ± 0.8	53.2	172 ± 3	52.0	184.7 ± 1.8
55.7	41.7 ± 0.7	55.7	26.1 ± 0.6	55.3	153 ± 5	54.2	171.2 ± 1.6
57.7	30.8 ± 0.8	57.7	14.7 ± 0.5			56.2	145.0 ± 1.6
59.7	20.4 ± 0.6	59.7	10.7 ± 0.3	59.3	89.4 ± 1.1	58.4	120.3 ± 1.3
61.7	11.4 ± 0.4	61.7	7.90 ± 0.58	61.3	60.3 ± 1.7	60.6	86.2 ± 0.9
63.7	4.80 ± 0.29	63.7	4.09 ± 0.25	63.3	32.2 ± 1.5	62.8	51.5 ± 0.6
65.7	4.63 ± 0.41	65.7	4.10 ± 0.56	65.3	14.0 ± 0.7	65.0	25.66 ± 0.34
67.7	7.72 ± 0.50	67.7	5.54 ± 0.38	67.3	5.31 ± 0.58	67.0	7.77 ± 0.18
69.7	18.3 ± 0.7	69.7	8.95 ± 0.57	69.3	4.39 ± 0.55	69.2	2.22 ± 0.15
71.7	30.4 ± 0.9	71.7	12.8 ± 0.5	71.3	14.2 ± 1.1	71.4	9.83 ± 0.25
73.7	56.4 ± 1.2	73.7	18.0 ± 0.8	73.3	26.9 ± 1.1	73.6	31.2 ± 0.5
75.7	76.3 ± 1.5	75.7	25.8 ± 0.6	75.3	57.6 ± 2.3	75.8	61.8 ± 0.8
77.7	101 ± 2	77.7	29.7 ± 1.0	77.3	91.2 ± 2.7	78.0	95.1 ± 1.3
79.7	129 ± 2	79.7	32.8 ± 0.8	79.3	121 ± 3	80.2	144.8 ± 1.7
81.7	160 ± 3			81.3	176 ± 4	82.2	187.5 ± 2.4
83.7	175 ± 4	83.7	37.6 ± 1.4	83.3	184 ± 4	84.4	223.4 ± 2.6
85.7	199 ± 3	85.7	40.0 ± 1.6	85.3	213 ± 4	86.4	243.9 ± 3.3
87.7	202 ± 4	87.7	42.5 ± 1.7	87.3	235 ± 4	88.4	256.7 ± 3.5
89.7	209 ± 3	89.7	40.8 ± 1.4	89.3	246 ± 4	90.4	268.1 ± 4.2
91.7	194 ± 5	91.7	43.9 ± 1.9			92.4	258.3 ± 4.0
93.7	192 ± 3	93.7	40.9 ± 2.2			94.4	230.0 ± 5.8
95.7	179 ± 4	95.7	35.5 ± 2.2			96.4	207.7 ± 4.3
97.7	150 ± 4	97.7	32.7 ± 2.3			98.4	159.2 ± 5.6
99.7	115 ± 5	99.7	24.8 ± 1.9			100.4	117.4 ± 4.6

from the measured integral range curve. The width of the differential range curve derived from it, reduced by the theoretical width due to range straggling alone, gave the range spread in the beam itself. This corresponds to a 0.75% energy spread in the incident beam.

The elastically scattered alpha-particles were detected with a CsI(Tl) scintillator placed approximately 10 in. from the center of the chamber. A collimating system, consisting of a 0.125-in. diam aperture immediately in front of the scintillator and a 0.133 in. wide vertical slit placed 6.75 in. in front of the aperture, defined the target volume and the solid angle subtended by the counter. The angular resolution achieved with this geometry was 1.4 deg. The counter collimation system in the scattering chamber was aligned radially by optical methods.

At laboratory angles less than about 12 deg, the counter and its associated mounting obscured the Faraday cup from the direct beam. Under these conditions, another scintillation counter was used as a beam monitor. It was placed outside the chamber at a fixed laboratory angle near 19 deg. It viewed the chamber through a window port with defining apertures attached, so that it detected alpha particles scattered only from the central region of the scattering chamber. Calibration was done directly by recording its total counts and the corresponding charge collected in the Faraday cup while running at large angles where there was no possibility of the counter obscuring the Faraday cup.

Pulses from the scintillation counter were amplified and fed into a 10-channel pulse-height analyzer. Figure 1 shows a typical spectrum obtained from this counter. At the higher energies, the background was quite low except at angles near the minima in the cross section. At the lower energies, however, the correction for background became quite appreciable.

TABLE I.—*Continued.*

E_{lab}=44.41±0.02 Mev (204.33±0.15 mg/cm² Al)		E_{lab}=46.12±0.02 Mev (218.24±0.15 mg/cm² Al)		E_{lab}=47.10±0.04 Mev (226.43±0.40 mg/cm² Al)		E_{lab}=47.28±0.03 Mev (227.93±0.25 mg/cm² Al)	
$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)	$\theta_{c.m.}$ (deg)	$(d\sigma/d\Omega)_{c.m.}$ (mb/sr)
12.2	1820 ± 37	12.2	1319 ± 35			18.3	639 ± 10
14.0	1602 ± 33	14.0	1012 ± 18	21.5	368 ± 3	20.3	437 ± 5
16.0	1263 ± 25	16.0	857 ± 15	23.5	275 ± 3	22.3	336 ± 4
17.8	1058 ± 21	17.8	666 ± 12	25.5	196.6 ± 1.8	24.3	228 ± 3
19.8	905 ± 15	19.8	580.0 ± 10.1	27.5	127.5 ± 1.4	26.3	155.0 ± 2.1
21.6	711.4 ± 14.9	21.6	456.1 ± 6.9	29.5	77.4 ± 0.7	28.3	104.5 ± 1.2
24.8	382 ± 5	25.8	224 ± 3	31.5	46.0 ± 0.7	30.3	59.3 ± 1.3
26.8	258 ± 3	27.8	147 ± 2	33.5	25.5 ± 0.4	32.3	34.0 ± 0.6
28.8	176 ± 2	29.8	95.1 ± 1.2	35.5	18.6 ± 0.3	34.3	24.5 ± 0.6
30.8	121 ± 2	31.8	48.8 ± 0.6	37.5	22.2 ± 0.4	36.3	17.8 ± 0.3
32.8	64.4 ± 0.8	33.8	23.7 ± 0.3	39.5	35.5 ± 0.5	38.3	27.3 ± 0.7
34.8	28.4 ± 0.3	35.8	15.3 ± 0.2	41.5	54.2 ± 0.9	40.3	43.1 ± 0.8
36.8	13.6 ± 0.2	37.8	17.4 ± 0.2	43.5	75.1 ± 1.3	42.3	67.0 ± 1.4
38.8	14.2 ± 0.2	39.8	31.7 ± 0.4	45.5	98.9 ± 1.6	44.3	85.6 ± 1.3
40.8	26.0 ± 0.3	41.8	50.8 ± 0.6	47.5	117.7 ± 1.8	46.3	111.1 ± 2.2
44.8	72.9 ± 0.7	43.8	75.2 ± 0.8	49.5	131.6 ± 2.0	48.3	120.9 ± 1.5
45.8	87.6 ± 0.9	45.8	93.4 ± 1.0	51.5	142.5 ± 2.1	50.3	136.9 ± 2.5
47.8	112.6 ± 1.1	47.8	115.5 ± 1.3	53.5	138.3 ± 2.1	52.3	132.8 ± 1.7
50.0	134.4 ± 1.3	50.0	131.3 ± 1.4	55.5	130.3 ± 2.1	54.3	135.1 ± 3.2
52.0	144.2 ± 1.4	52.0	137.9 ± 1.5	57.5	112.9 ± 1.9	56.3	114.9 ± 1.6
54.2	143.5 ± 1.4	54.2	137.5 ± 1.5	59.5	93.2 ± 1.6	58.3	108.1 ± 2.1
56.2	139.9 ± 1.4	56.2	125.4 ± 1.4	61.5	69.4 ± 1.2	60.3	74.7 ± 1.0
58.4	124.9 ± 1.2	58.4	110.1 ± 1.2	63.5	42.4 ± 0.7	62.3	46.2 ± 1.0
60.8	91.6 ± 0.9	59.8	85.6 ± 1.0	65.5	21.4 ± 0.4	64.3	29.0 ± 0.5
		61.8	53.7 ± 0.7	67.5	6.53 ± 0.16	66.3	11.2 ± 0.3
64.8	38.8 ± 0.4	63.8	34.4 ± 0.5	69.5	1.65 ± 0.07	68.3	2.19 ± 0.15
		65.8	15.5 ± 0.2	71.5	7.63 ± 0.20	70.3	2.15 ± 0.21
66.8	19.2 ± 0.3	67.8	4.13 ± 0.08	73.5	23.6 ± 0.4	72.3	9.6 ± 0.4
		69.8	2.07 ± 0.06	75.5	51.2 ± 0.9	74.3	28.3 ± 0.6
70.8	1.79 ± 0.04	71.8	9.7 ± 0.2	77.5	83.5 ± 1.5	76.3	55.3 ± 0.9
		73.8	25.7 ± 0.4	79.5	122.9 ± 1.3	78.3	88.6 ± 1.6
74.8	20.5 ± 0.4	75.8	52.9 ± 0.6	81.5	156.7 ± 2.8	80.3	123.5 ± 1.6
		77.8	84.7 ± 1.0	83.5	187.3 ± 3.2	82.2	151.3 ± 2.5
78.8	62.3 ± 0.7	79.8	118 ± 2	85.5	216.7 ± 3.5	84.3	176.1 ± 2.8
82.2	103.8 ± 1.4	81.8	136 ± 2	87.5	234.2 ± 2.1	86.3	205.9 ± 2.8
		84.4	181.7 ± 2.1	89.5	238.9 ± 2.1	88.3	216.5 ± 2.3
86.4	151.2 ± 1.9	86.4	203.9 ± 2.2	91.5	232.0 ± 3.0	90.3	222.0 ± 2.6
88.4	160.0 ± 2.3	88.4	216.2 ± 2.3	93.5	206.8 ± 1.9	92.3	207.9 ± 2.2
90.4	165.1 ± 2.3	90.4	219.4 ± 2.4	95.5	181.2 ± 2.0	94.3	185.1 ± 2.2
92.4	153.6 ± 2.3	92.4	206.5 ± 2.4	97.5	145.2 ± 1.6	96.3	152.7 ± 2.4
94.4	134.7 ± 2.6	94.4	192.4 ± 2.3	99.5	108.3 ± 1.6	98.3	124.0 ± 2.2
				101.5	68.1 ± 0.8	100.3	84.1 ± 2.1
				103.5	38.2 ± 0.7		
				105.5	13.5 ± 0.5		

In order to provide a check on the consistency of the results, the data were taken at alternate angles in such a way that each angular distribution was taken at least twice. In addition, several points on each distribution were remeasured one or more times to ensure that no electrical or mechanical drift was present in the apparatus. Since the scattering of identical particles imposes angular-distribution symmetry with respect to 90 deg c.m., some check-points were taken at center of mass (c.m.) angles larger than 90 deg.

Second-order geometry corrections to the cross sections were made, based on the calculation of Critchfield and Dodder.[10] These corrections became as large as 35% at the narrow minima of the angular distributions. At other angles they were of the order of 1% or less.

The pressure of the helium gas in the chamber was measured with a mercury manometer, and the temperature was measured with a thermometer in thermal contact with the chamber.

ERRORS

The charge-collecting system was calibrated against voltage and capacitive standards and was estimated to have an over-all accuracy of ±0.50% relative, and ±0.75% absolute, for each cross section.

The helium gas used in the scattering chamber was supplied by Liquid Carbonic Company from the U. S. Bureau of Mines bottling service at Amarillo, Texas, and was specified to have less than 0.005% of impurity, mainly air and hydrogen. The measurement of temperature and pressure of the helium gas in the chamber was estimated to introduce an absolute error in the determination of the density of the helium gas varying from ±0.3% to ±1.0%. This depended mainly on the helium gas pressure for each run, and the percentage accuracy with which it could be determined.

[10] C. L. Critchfield and D. C. Dodder, Phys. Rev. 75, 419 (1949).

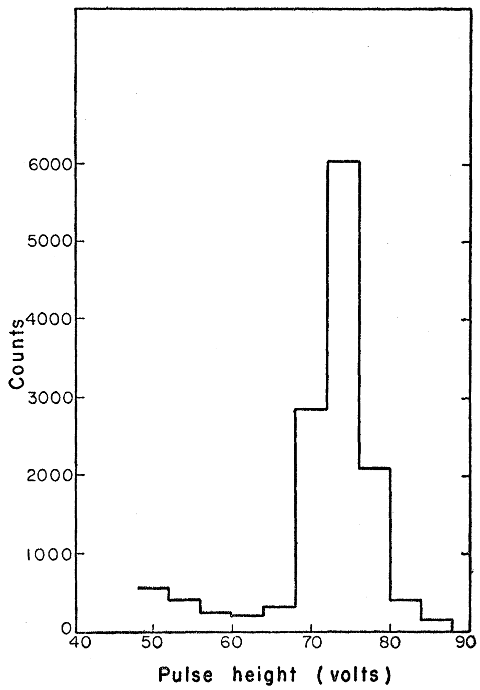

FIG. 1. Pulse-height spectrum of alpha particles scattered from helium at $E_{\rm lab}=41.9$ Mev; $\theta_{\rm lab}=32.5°$.

The angular position of the counter with respect to the beam direction was reproducible to ±0.1 deg in the laboratory system (or ±0.2 deg in the c.m. system). This affects the calculation of the cross section through a $\tan\theta_{\rm lab}$ factor, causing a relative error varying from $\pm0.54\%$ at a laboratory angle of 20 deg to $\pm0.36\%$ at 45 deg.

The calculation of the solid angle subtended by the counter telescope was affected mainly by the accuracy of measurements of the 0.125-in. diam collimation aperture directly in front of the crystal. The resulting absolute error in the solid angle was estimated to be $\pm3\%$. The calculation of the effective length of the target volume of helium gas also depends mainly on the accuracy of measurement of the crystal collimation aperture. Since this is a linear quantity, the resulting absolute error is only $\pm2\%$.

At each angle, the energy spectrum was obtained with sufficient points above and below the peak corresponding to elastically scattered alpha particles to enable the background curve to be well determined. This curve was then extrapolated into the elastic peak, and those counts arising from background were subtracted from the total counts in the peak. The background correction was quite small, and generally negligible at the higher energies, except at angles near minima in the cross

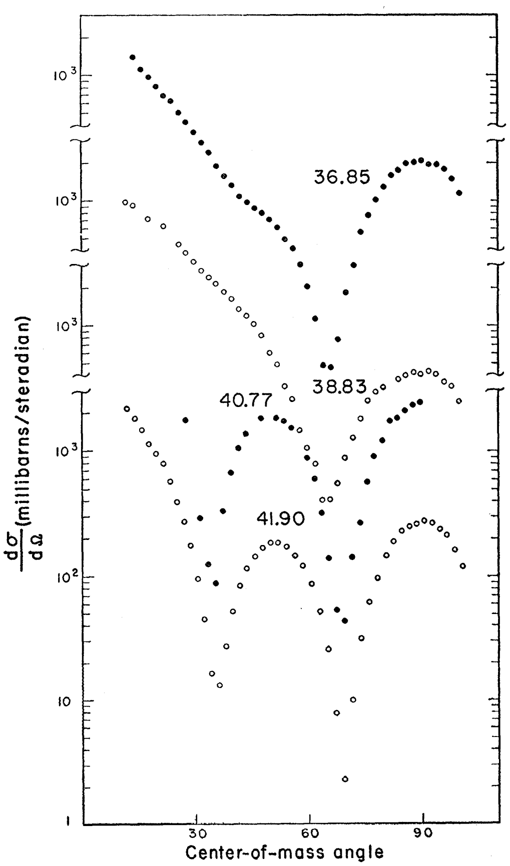

FIG. 2. Differential cross sections for elastic alpha-alpha scattering at laboratory energies from 36.85 to 41.90 Mev.

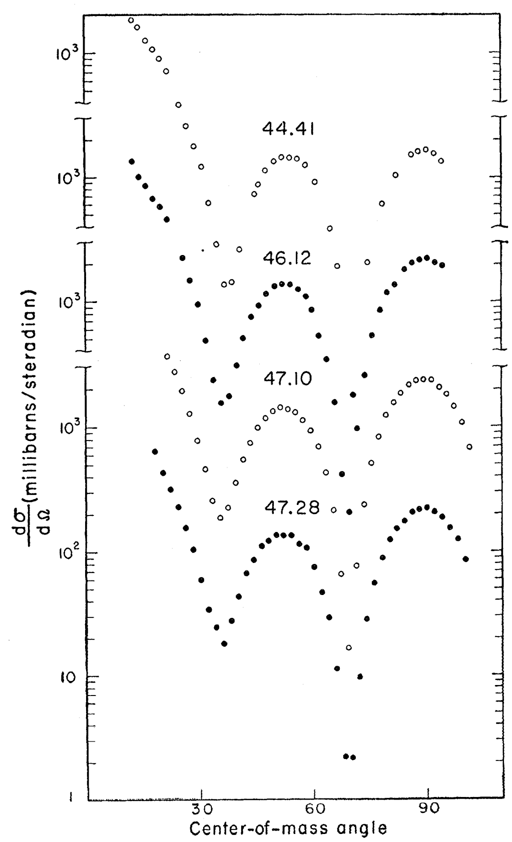

FIG. 3. Differential cross sections for elastic alpha-alpha scattering at laboratory energies from 44.41 to 47.28 Mev.

section. Below 41.9 Mev, however, the size of this background correction became considerably larger, and, consequently, at the lower energies the error associated with this background correction accounts for most of the tabulated relative error on each cross section.

At the low pressures of helium gas in the chamber, the possibility of the loss of some beam from the Faraday cup by multiple scattering in the gas was negligible, and was calculated to be less than 0.1%.

The errors listed in Table I are relative errors. The absolute errors were compounded separately and result in a ±3.8% error which should be applied to the ordinates of each bombarding energy.

RESULTS

The measured differential cross sections are tabulated with their relative errors in Table I and plotted in Figs. 2 and 3. Angles and cross sections are in the c.m. system. The single prominent minimum seen at 36.85 and 38.83 Mev, gives way to two minima at the higher energies. This transition from one to two minima with increasing energy is also present in the 12- to 23-Mev alpha-alpha data, where resonance scattering from a virtual excited state (4+) around 11 Mev in Be^8 is observed.[11]

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[11] R. Nilson, W. K. Jentschke, G. R. Briggs, R. O. Kerman, and J. S. Snyder, Phys. Rev. 109, 850 (1958).

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Optical Model Analysis of the Scattering of Alpha Particles from Helium*

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An optical model analysis using a complex potential

$$\frac{V+iW}{1+\exp[(r-r_0)/d]}$$

has been made of the elastic scattering of alpha particles from helium. In the data which are analyzed the bombarding energy ranges from 23.1 Mev to 47.1 Mev. The best agreement with the angular distributions taken at eight different bombarding energies was obtained when the parameters V, W, r_0, and d were −112 Mev, −1 Mev (for bombarding energies near 40 Mev), 1.8×10^{-13} cm, and $0.6\pm0.1\times10^{-13}$ cm, respectively. The value −112 Mev for V is an average value; V decreases by 15% when the bombarding energy is increased from 23 Mev to 47.1 Mev. Since W is small, the central depth of the real part of the potential V has significance. This is in contrast to the scattering of alpha particles from heavier elements where the absorption is so large that the central part of the potential is not easily determined. No lower limit was placed on r_0, however, r_0 must be less than 2.7×10^{-13} cm. The phase shifts obtained from this analysis are in good agreement with the preliminary results of Snyder below 42 Mev. Above 42 Mev they continue to vary slowly with no new states of Be^8 appearing up to 47.1 Mev.

INTRODUCTION

The optical model has been quite successful in describing the scattering of complex particles from nuclei. So far, optical model analyses of the scattering of alpha particles,[1–3] deuterons,[4] and nitrogen ions[5] have been reported. The parameters r_0 and d which enter into the Woods-Saxon potential[6]

$$(V+iW)/\{1+\exp[(r-r_0)/d]\},$$

are expected to be increased due to the finite size of the projectile. By analyzing the scattering of alpha particles from helium, the contribution to r_0 due to the finite size of the alpha particle may be estimated.

The scattering of alpha particles from nuclei[3] (and the scattering of nitrogen ions from nitrogen[5]) determine the real part of the potential in the surface region, and

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