246-, 318-, 475-, and 540-kev transitions. The counting rates were not high enough to determine if the gamma rays with energies above 700 kev are also in coincidence with this transition.

The 0.48–0.54 Mev region of the pulse-height distribution is shown in Fig. 4. The normal pulse-height distribution is plotted in each part of the figure as a solid curve, and the distributions from gamma rays which are in coincidence with the 246-, 318-, and 475-kev photopeaks are plotted as dashed curves in (a), (b), and (c), respectively. From these curves one can conclude that the 475-kev gamma ray is in coincidence with both the 246- and 318-kev transitions, and that the 540-kev gamma ray is not in coincidence with the 246-, 318- or the 475-kev transitions. In a similar manner, it was established that the 246- and 318-kev radiations are not in coincidence with one another.

The proposed decay scheme for Pt^{199} is shown in Fig. 5. This scheme includes all of the beta rays and gamma rays which were detected in this study. The arrangement of the transitions is consistent with all of the coincidence measurements.

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Alpha-Alpha Particle Scattering in the Energy Range 12.3 to 22.9 Mev*†

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Absolute differential cross sections for alpha-alpha particle scattering have been measured at ten energies between 12.3 and 22.9 Mev. The laboratory angular range studied is 11° to 50°. The higher energy experiments at 21.65 to 22.9 Mev were concurrently carried out at two separate scattering chambers, one using nuclear emulsions as the detectors, the other, proportional counters. The experimental accuracy of these experiments is two percent or better at most angles. At the lower energies, 12.3 to 20.4 Mev, the study was made with nuclear emulsion detection only and the experimental accuracy is about three percent at most angles.

I. INTRODUCTION

The verification[1] of Mott's theory of scattering of identical particles[2] plus the experimental demonstration of nuclear forces other than inverse square law forces[3,4] are two early credits to the study of alpha-alpha particle scattering. Recently, however, the continuing interest in the energy level spectrum of Be^8 has focussed attention again on the interactions possible between two colliding alpha particles.

Wheeler, in 1941,[5] was the first to consider the usefulness of analyzing the scattering results in terms of excited levels in Be^8. Although, on the basis of the variation with energy of partial wave phase shifts, Wheeler assigned spin and parity 0^+ to the now well-known 2.9-Mev 2^+ level, his method of phase analysis is sound and the incorrect assignment was probably due to inaccuracies in the early data.

The experiments on alpha-alpha particle scattering now encompass most of the range of bombarding energies between 0.4 and 30 Mev.[6–11] This paper discusses the experimental results of three separate and independent groups of scattering experiments which have been completed at the University of Illinois during the four years, 1951 to 1955. Preliminary reports[10] have been given on the first two groups of experiments which were performed with incident alpha particles of energies between 21.65 and 22.9 Mev. These experiments were performed concurrently with both photographic and proportional counter detection methods. The third and latest groups of experiments (photographic detection only, 12.3 to 20.4 Mev) parallels the work of Steigert and Sampson.[8]

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Sufficient justification was felt in repeating the measurement of Steigert and Sampson, since their evidence for the much disputed 7.5-Mev level is at variance both with many recent particle reactions[12] and with the Be^8 energy level scheme predicted by either an alpha-particle model[13,14] or a central force model.[15,16] The results obtained in these experiments differ enough from those of Steigert and Sampson that the 7.5-Mev 0^+ state is now not needed in the interpretation of the scattering phase shifts. The theoretical implications of the scattering results will be dealt with in a subsequent paper.

II. GENERAL

Separate scattering chambers were employed for each detection method (proportional counters and photographic emulsions). The features which were common to both methods will be discussed first.

A reasonably monoenergetic external beam of alpha particles was obtained from the University of Illinois cyclotron (primary alpha-particle energy 23.5 Mev). The beam was magnetically deflected to either scattering chamber. The field of the deflecting magnet was accurately controlled and monitored by a proton nuclear magnetic resonance device.[17] Preceding the collimator of each chamber was either a 0.0002-in. nylon foil or an aluminum foil. The purpose of the nylon foil was to separate the helium in the scattering chamber from the cyclotron vacuum. An aluminum foil of proper thickness was substituted for the nylon foil in the experiments in which a beam energy reduction was required.

The collimating system in each chamber was composed of a series of defining slits and baffles. The design of each collimator is such that the beam is circular, small in cross section, and any scattering off slits and collimator walls is eliminated as much as possible. Reference to earlier reports on proton-proton[18] and proton-alpha[19] scattering experiments using the same scattering chambers as employed in these experiments tells where detailed descriptions and drawings of the apparatus can be found.

The helium was supplied by Linde Air Products and mass-spectrographic analyses indicated no impurity other than nitrogen. The helium pressure was measured by a specially constructed manometer which contained Dow-Corning diffusion pump oil type 703. The number of incident particles passing through the scattering volumes was determined by collecting the undeflected particles in a Faraday cup and measuring the charge collected on a one-microfarad polystyrene condenser connected to the cup. A vibrating-reed electrometer was employed to measure the voltage.

III. PROPORTIONAL COUNTER METHOD

Two experiments at bombarding energies of 21.8 and 22.9 Mev were carried out using the proportional counter detectors.

Experimental Apparatus and Procedure

A brief description of the experimental apparatus and the procedure will be given here; a more detailed description can be found in reference 18.

The scattered particles were detected by two proportional counter telescopes, each consisting of two counters. The telescopes were mounted on arms which could be rotated azimuthally about a fixed pivot. The counters in each telescope were operated in coincidence to reduce the background counting rate. Previously a thin foil had been used to cover the entrance window of each counter telescope. This foil was removed in order to eliminate the loss of particles which were so scattered in the foil that after triggering the first counter they missed the second counter. After removal of the foil, the "missed coincidence" correction, required in the earlier experiments using this chamber, was not necessary. With windowless counters scattering gas and counter gas are identical. Hence, it became necessary to add a small amount of methane (0.04 cm Hg) to the helium to prevent spurious gas multiplication avalanches in the counters.

The pulses from the proportional counters were amplified by a preamplifier and a model 100 amplifier. Pulses originating in the front and rear counters of each telescope were fed to coincidence circuits having a resolving time of 10 microseconds. This insured that only particles originating in the scattering volume, were counted. In each telescope the pulses produced by the proportional counter nearest to the scattering volume, were sorted in amplitude by pulse-amplitude analysers of 10 and 12 channels respectively. Since the scattered particles at each angle have a unique energy, the pulse-height analysis was helpful in distinguishing background radiation or contaminant scattering. The number of pulses due to gas-contaminant scattering and background radiation traversing the chamber never exceeded 0.3%.

Evaluation of Cross Sections: Corrections

The cross sections are calculated from the measured quantities as described in reference 18.

A correction for the presence of methane in the scattering volume was determined by a separate scattering experiment in which methane alone was used. The methane pressure (4.25 cm Hg) was adjusted to

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[12] These reactions will be discussed in a subsequent paper.

[13] R. R. Haefner, Revs. Modern Phys. **23**, 228 (1951). An extension of Haefner's alpha-particle model to $L=4$ is made in a subsequent paper.

[14] G. H. Humphrey (private communication).

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[18] Zimmerman, Kerman, Singer, Kruger, and Jentschke, Phys. Rev. **96**, 1322 (1954).

[19] Kreger, Jentschke, and Kruger, Phys. Rev. **93**, 837 (1954).

TABLE I. Cross sections (c.m.) from proportional counter experiments.

Lab angle (degrees)	Number of counts	2nd-order geometry corr. (%)	Error in σ due to angle uncert. (%)	Contaminant scatt. and background (%)	Methane scatt. contrib. (%)	$\sigma_{\text{c.m.}}$ (mb/sterad)
(a) 21.8-Mev incident particle energy						
13	107 522	+0.00	±0.5	<0.05	1.4	943.1±5.7
14	64 747	−0.06	±0.8	<0.05	2.0	708.4±6.4
16	28 406	−0.37	±0.9	<0.05	0.3	369.7±4.1
18	12 441	−1.09	±0.8	<0.05	0.2	182.8±1.8
19	8800	−1.58	±0.5	<0.05	0.1	139.8±1.4
20	7688	−1.72	±0.1	<0.05	0.1	126.6±1.1
21	7363	−1.14	±0.3	<0.05	0.1	130.2±1.3
23	9154	−0.21	±0.3	<0.05	0.1	179.1±1.6
25	8147	+0.13	±0.2	<0.05	0.1	221.4±2.0
27.5	4649	+0.34	±0.1	<0.05	0.1	237.8±2.6
30	3653	+0.33	±0.3	<0.05	0.1	202.1±2.4
32.5	2148	+0.17	±0.5	<0.05	0.1	134.0±2.0
35	1024	−0.38	±0.8	0.1	0.1	67.3±1.5
37.5	434	−1.16	±0.8	0.2	0.1	30.7±1.0
40	282	−1.34	±0.0	0.3	0.5	20.5±0.88
45	330	+0.20	±0.0	0.3	0.3	31.6±1.2
(b) 22.9-Mev incident particle energy						
13	315 691	+0.04	±0.4		1.6	1041.6±6.2
14	54 316	−0.04	±1.1	<0.05	2.3	748.2±9.0
15.3	43 401	−0.32	±1.0	<0.05	2.3	454.2±5.0
17	19 009	−1.36	±1.1	<0.05	0.2	202.3±2.6
18	11 070	−2.61	±1.0	<0.05	0.1	120.2±1.6
19	10 058	−3.34	±0.4	0.1	0.1	84.7±0.85
20	10 195	−3.11	±0.2	0.1	0.2	81.1±0.81
21	9942	−2.06	±0.5		0.2	101.0±1.0
22.5	14 492	−0.76	±0.5	<0.05	0.2	157.0±1.4
24.3	19 488	+0.07	±0.3	<0.05	0.2	231.8±1.9
26	16 393	+0.47	±0.1	<0.05	0.1	283.1±2.0
27.4	19 934	+0.37	±0.1	<0.05	0.1	285.7±2.0
30	14 171	+0.44	±0.2	<0.05	0.1	241.8±1.9
32.5	10 197	+0.18	±0.4	<0.05	0.1	150.2±1.4
35.1	9407	−0.51	±0.5	0.2	0.2	60.3±0.60
38.1	1357	−6.68	±0.9	1.0	0.9	7.2±0.17
41	575	−3.14	±0.7	1.2	1.9	6.3±0.21
43	909	+0.81	±0.4	0.4	0.7	17.2±0.43
45	1137	+1.73	±0.0	0.4	0.5	21.1±0.46
57.5	893	−0.05	±1.1			155.9±3.9
62.6	9307	+0.41	±0.1	<0.2	<0.2	279.0±1.9
67.5	939	−0.24	±0.6	<0.2	<0.2	148.3±3.4
70.0	526	−2.70	±0.2	<0.2	<0.2	78.8±3.5
73.0	1252	−2.72	±1.3	<0.2	<0.2	220.6±5.1
74.7	991			<0.2	<0.2	300.1

give the same stopping power as the helium (20 cm Hg) used during the scattering runs. The methane scattering contribution never exceeded 2.3% at any angle. A second order geometry correction was made to correct for the divergence and the finite size of the beam and for the variation of scattering angle and of the cross section over the finite solid angle subtended by the detector at any one angular setting. This correction was based on a formulation worked out by Critchfield and Dodder.[20]

The experimental results are tabulated in Table I. The largeness of some of the second order geometry corrections shown in column three arises from the fact that the first and second derivatives of the cross section with respect to angle become quite large at certain angles. Reference to the plots of the differential cross sections in the following article will show this great angular dependence. The cross sections are center-of-mass values and the angles are laboratory angles.

Discussion of Errors

The root-mean-square errors listed for the cross sections in Table I were calculated in the usual way and result from the following uncertainties: statistical fluctuations in the number of particles detected; uncertainty in the number of pulses greater than a certain pulse height which were attributed to events different from alpha-alpha scattering; errors associated with the methane correction, background correction, second order geometry correction; uncertainty in the angular position of the counters; uncertainties in total charge collected, in gas temperature, in gas pressure, in the solid angle subtended by the rear counter slit at the center of the scattering volume, in the length of the scattering volume, and in the numerical constants.

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

IV. PHOTOGRAPHIC EMULSION METHOD

Three experiments at bombarding energies 21.65, 22.25, and 22.81 Mev were performed with photographic emulsions as detectors, concurrently with the two proportional counter experiments. Five additional and more recent experiments at 12.3, 15.2, 17.8, 19.1, and 20.4 Mev have been also carried out with the photographic scattering chamber.

Experimental Apparatus and Procedure

The photographic scattering chamber, which is described in detail elsewhere[18,19] is so constructed that particles scattered over a wide range of angles can be recorded simultaneously on six nuclear-plates. The nuclear plates are mounted around the periphery of a cylindrical plate holder or cassette and lie parallel to the beam axis. A ring-shaped or annular slit whose axis coincides with the beam axis permits only particles which have been scattered at a given angle θ to be recorded at a give position on each of the six nuclear plates. Data were taken with two annular slits; one allowing the recording of scattered particles at angles between 12° and 30° and the other between 21° and 52°.

Both Ilford C-2 and Kodak NTB, 100-micron, 1×3 inch, nuclear plates were used to detect the alpha particles. After processing, the plates were scanned and counted with a Spencer binocular microscope using 6× eyepieces and 53× oil-immersion objectives. The length and width of a swath scanned was one cm and 0.0310 cm, respectively. Up to a maximum of seven swaths per angle per plate could be scanned to obtain sufficient statistics without sacrificing too much angular resolution.

The only major departure from the experimental procedure described in reference 18 and 19 was the introduction (in the latest group of experiments) of energy-reducing aluminum foils and the use of a pair of strong-focusing electrostatic lenses. The aluminum foils were placed immediately in front of the collimating system and none of the foil-scattered components of the beam could reach the scattering volume without a second scattering off one of the thin slits inside the collimator. The reduction in beam intensity effected by the foils was partially made up by the focusing action of the electrostatic lenses. The alpha currents into the Faraday cup ranged between 10^{-10} and 10^{-12} ampere depending on the experiment.

Evaluation of Cross Sections: Corrections

The cross sections were calculated in the same manner as described by Leiter.[21] A slit penetration correction was calculated using the formula of Rodgers.[22] No background correction was necessary as a careful count of low-angle scattering events, recorded during a run when no helium had been admitted to the scattering chamber and when the chamber was allowed to outgas for a time equivalent to a scattering run, revealed less than one track per angle. In addition, it was found from the rate of pressure rise, measured before each scattering run, that the value of the contaminant pressure extrapolated to the end of the run never exceeded 0.06% of the helium pressure. Tracks due to neutron background were shown to be negligible by counting one nuclear plate of the 22.81-Mev run which had been placed in the cassette so that the glass side had been exposed to the scattered particles.

For a given run, each angle represented scattering at a slightly different energy since the scattering chamber was so constructed that the position of the scattering volume and hence the distance the particles traveled in the helium changed with the scattering angle. To convert the cross sections to one energy value it was, therefore, necessary to make a small energy correction at each angle. The energy corrections were based on curves of the cross section *vs* energy which were drawn at each angle from the present data. In addition, when, because of cyclotron conditions the incident energy for a pair of high- and low-angle runs differed slightly, an energy correction similar to the one just described was made to adjust the cross sections all to one energy.

The charging rates of the condenser connected to the Faraday cup were sometimes so low as to give some concern about charge leakage and electrometer drift. Extensive measurements were made to determine how well a charge could be retained on the condenser. In the earlier runs (21.65 to 22.81 Mev) the leakage resistance of the condenser was determined with enough precision so that a charge leakage correction could be applied to the data. This correction never exceeded one percent. In the more recent experiments (12.4 to 20.4 Mev) the random drift of the electrometer seemed to overshadow the charge leakage and measurements indicated that the drift rate was not greater than 10^{-5} volt/minute. An error based on a 10^{-5} volt/minute drift rate, which allows for the largest possible error in the charge measurement, was assigned to the charge measurements. The largest charge measurement error was ±2% for the high-angle 12.3-Mev data.

Second-order geometry corrections were made to take into account the fact that the incident beam has a finite size and is divergent and that both angle and cross section vary over the finite swath area of the nuclear plate detectors. This correction was calculated similarly to the one of Critchfield and Dodder[20] for a different geometry. The correction becomes quite large at angles where the cross section varies the most.

Owing to the finite size of the annular slit and the finite size of the detection area, the scattering angles represented within the swaths counted at a given position on the nuclear plate will lie within an angular interval. This angular spread is defined as the angular resolution and varied between ±0.4° and ±2.8°.

Table II presents the results for all of the eight photographic experiments. The column headings are

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[21] Leiter, Rodgers, and Kruger, Phys. Rev. **78**, 663 (1950).

[22] Rodgers, Leiter, and Kruger, Phys. Rev. **78**, 656 (1950).

TABLE II. Cross sections (c.m.) from photographic plates.

Lab angle (degrees)	Number of counts	2nd-order geometry corr. (%)	Angular resol. (deg)	Energy corr. (mb/sterad)	$\sigma_{c.m.}$ (mb/sterad)
		(a) 12.3-Mev incident particle energy			
11[a]	743	− 0.22	±0.5	+31	1357 ±39
12	1565	− 0.68	±0.5	+22	1203 ±40
13	1614	− 0.28	±0.6	+18	1074 ±24
14	1495	+ 0.07	±0.6	+12	870 ±20
15	1478	+ 0.62	±0.7	+ 5	759 ±16
16	1455	+ 0.79	±0.7	+25	688 ±17
17.5	1185	+ 1.33	±0.8	+ 2	467 ±12
20	1191	+ 2.19	±1.1	+ 1	271 ± 7
21	1688	+ 3.29	±0.9	0	196 ± 4.1
22.5	677	+ 3.17	±1.3	+ 1	130 ± 3.6
23	1322	+ 5.52	±1.1	0	93.9 ± 2.2
24	865	+ 6.24	±1.2	0	57.0 ± 1.5
25	177	+ 6.76	±1.4	− 0.5	29.4 ± 1.6
25	525	+ 7.68	±1.3	0	32.5 ± 1.1
26	207	+ 9.32	±1.3	+ 0.2	12.3 ± 1.0
27.5	32	−49.8	±1.6	− 0.72	2.28± 0.4
27.5	75	−45.5	±1.5	+ 0.07	2.55± 0.6
30	227	−18.0	±1.7	0	24.2 ± 1.3
30	735	−23.0	±1.7	0	24.7 ± 0.7
32.5	852	− 6.8	±2.0	+ 1.8	94.3 ± 2.6
32.5	1846	− 8.3	±1.6	− 0.3	86.5 ± 2.0
35	1487	− 4.5	±2.2	+ 2	157 ± 3.6
35	2424	− 5.3	±1.4	− 1	174 ± 3.8
37.5	1349	− 2.7	±1.1	− 1	270 ± 6.5
40	1802	− 1.5	±1.2	− 1	337 ± 7.4
42.5	2322	− 0.44	±1.3	− 2	408 ± 8.2
45	2475	− 0.61	±1.4	− 2	418 ± 8.3
50	2155	− 2.24	±1.5	− 1	347 ± 7.6
		(b) 15.2-Mev incident particle energy			
11[a]	1427	+ 0.32	±0.4	+15	1091 ±23
12	1526	+ 0.18	±0.5	+10	991 ±20
13	1552	+ 0.04	±0.5	+ 8	870 ±17
14	1516	− 0.18	±0.5	+ 5	742 ±14.5
15	1575	− 0.38	±0.6	+ 5	683 ±13.3
16	1415	− 0.66	±0.6	0	545 ±10
17.5	1320	− 1.16	±0.7	+ 1	449 ± 9
20	1571	− 2.23	±0.9	+11	255 ± 5
21	1132	+ 2.61	±0.9	0	190 ± 4.5
22.5	1237	− 2.68	±1.3	0	119 ± 2.4
23	1028	+ 3.82	±1.1	0	105 ± 2.5
24	766	+ 4.79	±1.2	+ 0.1	72.6 ± 2.0
25	554	− 2.1	±1.4	− 1.5	44.2 ± 1.4
25	508	+ 5.39	±1.3	+ 0.1	45.1 ± 1.7
26	352	+ 3.28	±1.3	+ 0.2	28.6 ± 1.5
27.5	320	+ 4.08	±1.6	− 1.7	20.2 ± 2.2
27.5	275	− 5.53	±1.5	+ 0.2	18.6 ± 1.3
30	569	+10.24	±1.7	− 0.4	32.8 ± 3.6
30	510	−13.9	±1.7	+ 0.1	27.0 ± 0.9
32.5	1183	+ 6.86	±2.0	0	65.8 ± 1.4
32.5	1424	− 8.44	±1.9	0	69.7 ± 1.5
35	1701	+ 3.96	±2.2	+ 2	130 ± 3
35	2000	− 4.73	±1.8	− 1	125 ± 2.7
37.5	1962	− 3.04	±1.5	− 2	190 ± 3.8
40	2845	− 1.64	±1.7	− 2	257 ± 5.4
42.5	1145	− 0.75	±1.3	− 2	292 ± 7.6
45	1295	+ 0.31	±1.4	− 2	317 ± 8
50	1127	+ 3.64	±1.5		267 ± 6.7
		(c) 17.8-Mev incident particle energy			
21	1444	+ 1.06	±0.9	0	186 ± 4.0
23	1212	+ 1.77	±1.0	0	131 ± 3.1
24	1106	+ 1.73	±1.0	0	110 ± 3.2
25	1385	+ 1.61	±1.3	+ 0.4	91.5 ± 2.9
26	1295	+ 1.14	±1.3	+ 0.5	79.3 ± 2.8
27.5	1186	− 0.11	±1.5	+ 0.7	65.1 ± 2.9
30	1339	− 2.87	±1.7	+ 0.9	61.9 ± 2.8
32.5	1342	− 3.44	±1.6	+ 0.3	74.9 ± 1.9
35	1993	− 3.12	±1.8	− 0.4	98.5 ± 2.1
37.5	1720	− 2.23	±1.5	− 1	130 ± 3.5
40	2328	− 1.39	±1.7	− 2	163 ± 4.4
42.5	2847	− 0.51	±1.8	− 2	188 ± 4.9
45	3162	+ 1.52	±1.9	− 2	204 ± 5.9
50	2807	+ 3.33	±1.2	− 2	172 ± 4.5

[a] **Italics indicate low angle slit, nonitalics indicate high angle slit.**

TABLE II.—*Continued.*

Lab angle (degrees)	Number of counts	2nd-order geometry corr. (%)	Angular resol. (deg)	Energy corr. (mb/sterad)	$\sigma_{\text{c.m.}}$ (mb/sterad)
(d) 19.1-Mev incident particle energy					
21	1598	+ 0.24	±0.7	0	183 ± 3.6
23	2466	− 0.51	±1.0	0	140 ± 2.6
24	1544	− 0.48	±0.8	+ 1	136 ± 3.0
25	1646	+ 0.43	±0.9	+ 1	135 ± 4.0
26	1631	+ 0.36	±0.9	0	124 ± 4.4
27.5	1635	+ 0.62	±1.0	+ 1	113 ± 5.0
30	1735	+ 0.29	±1.1	+ 1	103 ± 3.6
32.5	1733	− 0.33	±1.3	+ 0.3	89.2 ± 1.9
35	2002	− 1.43	±1.4	− 0.3	90.1 ± 1.8
37.5	2410	− 2.36	±1.5	− 1.2	97.2 ± 2.7
40	3241	− 1.25	±1.7	− 1.9	121 ± 4.0
42.5	1319	− 0.28	±1.3	− 2.5	140 ± 4.8
45	1411	+ 0.30	±1.4	− 2.5	143 ± 5.0
50	1298	+ 1.66	±1.5	− 2.1	125 ± 4.5
(e) 20.4-Mev incident particle energy					
11[a]	3545	− 0.14	±0.4	+ 6	1061 ±15
12	3603	+ 0.07	±0.5	+ 4	920 ±12
13	3799	− 0.10	±0.5	+ 5	837 ±11
14	3490	+ 0.51	±0.6	− 1	670 ±11
15	3117	+ 0.88	±0.6	− 8	523 ± 8
16	2499	+ 1.06	±0.6	−13	449 ±10
17.5	1995	+ 1.07	±0.7	−17	296 ± 9.5
20	1563	+ 0.35	±0.8	− 5	190 ± 3.8
21	2117	− 0.80	±0.9	+ 3	163 ± 3.2
22.5	1464	− 0.33	±0.9	0	152 ± 2.7
23	2290	− 0.92	±1.0	− 3	141 ± 2.5
24	2417	− 1.03	±1.0	− 1	139 ± 2.4
25	1846	− 0.41	±1.0	− 3	134 ± 2.5
25	2599	− 0.80	±1.1	0	140 ± 2.5
26	2633	− 0.67	±1.1	− 4	128 ± 3.2
27.5	2005	+ 0.08	±1.1	+ 2	134 ± 2.4
27.5	2815	− 0.30	±1.2	− 5	127 ± 2.3
30	1860	+ 0.68	±1.2	+ 1	112 ± 1.9
30	2795	+ 0.29	±1.4	− 2	108 ± 2.2
32.5	1703	+ 0.31	±1.4	+ 2.1	95.8 ± 1.9
32.5	2687	− 0.19	±1.6	− 1.3	90.5 ± 1.6
35	2573	− 0.50	±1.4	− 2.1	78.8 ± 1.6
35	2579	− 0.91	±1.8	+ 0.8	78.3 ± 1.4
37.5	2871	− 1.93	±1.9	+ 2.3	80.4 ± 2.2
40	3482	− 1.33	±2.1	+ 3.9	92.0 ± 3.6
42.5	4067	− 0.89	±2.3	+ 4.3	101 ± 3.7
45	4605	− 1.08	±2.5	+ 4	108 ± 3.7
50	4192	+ 1.12	±2.8	+ 3.9	94.5 ± 3.7

Lab angle (degrees)	Number of counts	2nd order geometry corr. (%)	Energy corr. (mb/sterad)	$\sigma_{\text{c.m.}}$ (mb/sterad)
(f) 21.65-Mev incident particle energy				
20.90	11 368	+ 2.1	+ 1.7±1.0	135 ± 2.9
24.19	12 455	+ 1.6	− 4.8±4.8	186 ± 5.3
24.88	8963	+ 1.4	− 5.7±4.5	193 ± 5.1
27.26	11 629	+ 0.5	− 4.3±3.0	213 ± 3.7
29.86	11 665	− 1.2	− 1.7±1.0	188 ± 2.5
34.85	11 601	− 2.8	0 ±0	74.7± 2.0
37.95	8160	− 0.4	− 0.5±0.3	36.0± 0.61
39.84	11 965	+ 3.2	− 0.6±0.3	29.9± 0.42
44.84	11 711	− 1.1	− 1.1±0.6	43.0± 0.74
49.84	9236	+ 0.1	− 1.2±0.6	31.0± 0.71
51.75	8153	+ 6.9	− 1.0±0.6	31.8± 0.91
(g) 22.25-Mev incident particle energy				
12.93[a]	8769	− 0.9	− 4.3±3.6	979 ±14
13.93	8681	− 1.3	− 1.6±1.6	732 ±10
15.19	13 189	− 2.0	+ 2.5±2.5	484 ± 7.3
17.91	11 918	− 1.9	+ 3.4±2.0	171 ± 4.2
18.52	11 952	+ 0.4	+ 3.0±1.8	138 ± 2.6
19.90	12 539	+ 3.7	+ 2.6±1.5	113 ± 1.9
21.00	3928	+ 2.2	+ 1.6±1.2	120 ± 2.7
21.88	11 881	+ 4.7	+ 2.0±1.5	136 ± 2.4
24.19	12 889	+ 2.2	+ 1.2±1.2	203 ± 2.5
24.30	10 355	+ 2.8	+ 0.6±0.6	202 ± 2.5
24.89	11 762	+ 2.0	+ 0.4±0.4	219 ± 2.5
25.88	12 447	+ 1.0	− 0.6±0.4	236 ± 2.2

[a] **Italics indicate low angle slit, nonitalics indicate high angle slit.**

TABLE II.—*Continued.*

Lab angle (degrees)	Number of counts	2nd-order geometry corr. (%)	Energy corr. (mb/sterad)	$\sigma_{\text{c.m.}}$ (mb/sterad)
		(g) 22.25-Mev incident particle energy		
26.00	11 545	+ 0.9	− 0.2±0.1	241 ± 2.3
26.38	12 225	+ 0.7	− 0.5±0.3	243 ± 2.3
26.87	12 539	+ 0.4	− 0.6±0.3	243 ± 2.2
27.24	12 870	+ 0.2	− 0.6±0.3	245 ± 2.3
27.37	10 832	+ 0.3	− 0.2±0.1	248 ± 2.2
27.88	13 182	− 0.3	− 0.6±0.3	245 ± 2.2
28.32	13 075	− 0.6	− 0.7±0.3	240 ± 2.3
29.00	10 633	− 1.3	− 0 ±0	233 ± 2.5
29.14	12 934	− 1.3	− 0.5±0.2	232 ± 2.5
29.86	10 005	− 1.5	− 0 ±0	209 ± 2.8
29.86	12 325	− 2.2	− 0.5±0.2	217 ± 2.7
32.00	8672	− 2.3	0 ±0	156 ± 2.9
35.07	9325	− 5.2	− 0.1±0.05	69.4± 3.5
38.10	2563	+ 1.2	− 0.4±0.1	20.2± 0.52
40.00	2093	+ 4.7	− 0.3±0.1	15.0± 0.28
42.50	3077	+ 3.2	− 0.2±0.1	21.1± 0.51
45.00	3885	− 3.3	− 0.2±0.1	27.1± 0.40
47.50	3409	− 3.4	− 0.3±0.1	22.8± 0.62
50.00	1877	+ 4.2	− 0.6±0.2	15.5± 0.36
51.90	2410	11.4	− 0.8±0.2	18.3± 0.66
		(h) 22.81-Mev incident particle energy		
13.00	10 964	− 1.2	−15 ±4.9	1026 ±15
14.00	10 091	− 1.5	− 6.5±3.5	747 ±12
15.27	9936	− 2.6	+ 2.0±2.0	458 ± 7.8
18.00	10 086	− 0.1	+ 1.7±0.6	123 ± 3.5
18.61	10 094	+ 5.4	+ 0.7±0.3	95.5± 1.8
20.00	10 227	+ 8.5	0 +0	81.8± 1.1
22.00	10 621	+ 6.7	+ 0.5±0.5	133 ± 2.7
24.30	10 822	+ 2.0	+ 2.0±0.6	225 ± 3.0
26.00	9959	+ 0.8	+ 3.0±0.9	269 ± 2.7
26.50	10 376	+ 0.5	+ 3.0±0.9	275 ± 2.6
27.00	10 556	+ 0.2	+ 2.9±0.9	275 ± 2.6
27.37	10 777	+ 0.0	+ 2.8±0.9	277 ± 2.6
28.00	11 142	− 0.4	+ 2.7±0.9	278 ± 2.6
28.50	11 100	− 0.8	+ 2.5±0.9	273 ± 2.8
29.15	10 403	− 1.4	+ 2.1±0.9	254 ± 3.1
30.00	9765	− 1.7	+ 2.4±1.2	235 ± 3.3

[a] Italics indicate low angle slit, nonitalics indicate high angle slit.

self-explanatory. The cross sections are center-of-mass values and the angles are laboratory angles. The center-of-mass angle is just twice the laboratory angle, and the laboratory cross sections are related to the center-of-mass cross sections by a multiplication factor of four times the cosine of the laboratory angle.

Discussion of Errors

The probable rms errors in the cross sections are compounded from the individual errors in each measurement and are listed in Table II. The largest error is the statistical error which averages two to three percent for the 12.3- to 20.4-Mev group of experiments and averages about one percent for the 21.65- to 22.9-Mev group. The other uncertainties include human error in counting, uncertainties in the annular slit dimensions, uncertainties in gas pressure and temperature measurements, errors in the energy and second-order geometry corrections, uncertainties in the charge measurements, and errors introduced by the energy spread or by an energy shift of the incident particles.

V. ENERGY MEASUREMENTS AND RESOLUTION

The energies of the incident alpha particles were obtained by exposing a 100-micron Ilford C-2 or G-Special nuclear plate, for which reliable range-energy relations are known,[23,24] at a grazing angle to the beam of incident particles. The beam energy measurements were made immediately after each scattering experiment except for the 20.4-, 21.65-Mev experiments and the low-angle run of the 12.3-Mev experiment. For these experiments, the energies were determined by measuring the track lengths of the scattered particles of the actual scattering experiment. Comparisons of

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[23] The ranges of alpha particles (up to 19 Mev) have been determined to better than one percent in C-2 emulsions by Rotblatt, Nature **167**, 550 (1951). For higher energies (up to 24 Mev) Rotblatt's curve was extended by an extrapolation based on known range-energy data for protons of up to 6 Mev.

[24] Range-energy curves for G-5 plates (identical composition to *G*-Special plates) of Fay, Gottstein, and Hain, Nuovo cimento **11**, Suppl. 2, 234 (1954), are calculated on the basis of C-2 range curves by reducing the range by one percent. This one percent greater range in C-2 as compared to G-5 emulsions was verified by exposing both types of plates simultaneously to 15-Mev and 23.5-Mev alpha particles and comparing the ranges.

both methods of determining the beam energy showed that they are equally reliable.

If a beam of alpha particles with a certain initial energy spread passes through absorbers, this energy spread is increased, as is evident from the range-energy relations. Superposed on this energy spread which is due to the initial inhomogeneity of the beam, there is an additional energy spread which is the result of the straggling in the absorber. The primary alpha-particle beam from the cyclotron had an energy spread of about ±120 kev. The inhomogeneity in the energy of the alpha particles when reduced to 12.3 Mev was observed to be ±250 kev or about ±2% of the mean energy. The usefulness of the foil method to obtain energies below 10 or 12 Mev from the 23.5-Mev primary beam is questionable since the initial ±120 kev inhomogeneity in the primary beam begins to produce too large a spread in the energy of the particles penetrating the absorber. Yet, the resolution of levels in Be^8 by alpha-alpha scattering is not seriously impaired by the width of the incident beam as the levels observable by alpha-alpha scattering are necessarily broad.

The probable errors in the energy measurements lie between ±0.13 and 0.15 Mev and are caused both by the uncertainties in the range-energy curves and by the inaccuracy of the range measurements.

The variation of the energy in the earlier experiments (21.65 to 22.9 Mev) was accomplished by adjustment of the cyclotron's dee capacity. The aluminum foil thicknesses in the lower energy experiments ranged from a nominal 0.006 inch for the 12.3-Mev experiment to 0.002 inch for the 20.4-Mev experiment.

VI. RESULTS

The absolute differential cross sections for alpha-alpha scattering at ten different energies between 12.3 Mev and 22.9 Mev are presented in the Tables I(a) to II(b). An angular range between approximately 10° and 50° (laboratory system) has been covered.

The best evidence for the reliability of these results is the close agreement between the data of the two different detection methods at comparable energies.

The cross sections which were obtained at corresponding laboratory angles θ and $(90°-\theta)$ agree well.[25] This indicates that multiple scattering losses which could be due to the finite helium pressure (up to 20 cm Hg for the 22.9-Mev experiment) are negligible. The phase-shift analyses, theoretical interpretations, and comparisons with other scattering experiments, will be the subject of a following paper.

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[25] Symmetry of the center-of-mass cross section about laboratory angle 45° is imposed by the identity of incident and scattering particle.