general shape as that obtained by Baggett and Bame[7] who bombarded Li^6 with deuterons and detected all neutrons above 10 kev coming from the target with approximately equal efficiency using a boron trifluoride counter. It must be deduced, therefore, that either all three possible reactions have similar excitation functions, or that either or both of the other two reactions have a relatively smaller cross section. In order to determine the ratio of the intensities of neutrons resulting from reactions proceeding direct to the ground state of Be^7 to those to the first excited state, the spectrometer was used in a different way. The first, close-up, crystal was biased to accept protons recoiling from neutrons scattered in it which were then detected by the second counter. While it was not possible to resolve the two neutron groups adequately by this technique, it appeared that the transitions to the first excited state predominated at $E_d=600$ kev. This result is in contradiction to the results of Gibson and Green[24] using photoplate technique and working with $E_d=930$ kev.

If it is assumed that the isotropic character of the correlation at $E_d=400$ kev arises from the capture of s-wave deuterons, then the excitation curve may be corrected for the Coulomb penetrability at the low-energy end. This leads to the resonance shown in curve B of Fig. 10 which would correspond to an excited state in Be^8 at 22.6 Mev in accord with previous work.[6,7]

ACKNOWLEDGMENTS

We are indebted to the Atomic Energy of Canada, Ltd., for financial support which made this work possible. One of us (G.C.N.) gratefully acknowledges the award of a National Research Council of Canada fellowship.

[24] W. M. Gibson and L. L. Green, Proc. Phys. Soc. (London) **A63**, 494, (1950).

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Elastic and Inelastic Scattering of 31.5-Mev Alpha Particles by Light Nuclei*

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Using the 31.5-Mev alpha-particle beam of the Massachusetts Institute of Technology cyclotron, a study has been made of the angular distributions obtained in the (α,α) and (α,α') interactions on Li^6, C^{12}, and Mg^{24}. Separation of the alpha particles from other products of the alpha-induced reactions was accomplished by a dE/dx and E two-crystal technique developed at the cyclotron laboratory. The experimental inelastic angular distributions are shown to be in agreement with those predicted by the direct surface interaction theory. The experimental elastic angular distributions are compared with the diffraction of light by an opaque sphere. The probabilities of excitation of isotopic spin "forbidden" and "allowed" levels were also obtained for specified levels of Li^6 and N^{14}.

I. INTRODUCTION

It has long been recognized that a direct experimental study of the scattering of charged particles by atomic nuclei provides a valuable source of information concerning the force field of the nucleus. In recent years there has been a renewal of interest in the scattering of alpha particles, occasioned by the high energies to which they may be accelerated in the various types of particle accelerators. For the most part, these investigations have been confined to a study of elastic scattering phenomena,[1–4] and relatively little information[5,6] is available concerning the (α,α') interaction. The stable 31.5-Mev high intensity alpha-particle beam of the M.I.T. cyclotron, used in conjunction with a particle selection technique developed by Aschenbrenner,[7] has proven to be of great value in extending the scope of these investigations.

The primary object of this experiment was to obtain information concerning the (α,α') scattering process by a study of the inelastic angular distributions. Preliminary data disclosed a well-defined structure, asymmetric in the center-of-mass coordinate system and quite suggestive of the angular distributions predicted for a direct surface interaction.[8] The objective of comparing experimental data with this or any other theory imposed certain restrictions on the choice of target nuclei.

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† Lieutenant Commander, U. S. Navy, now on duty with Commander Joint Task Group 7.3.

[1] G. W. Farwell and H. E. Wegner, Phys. Rev. **95**, 1212 (1954).
[2] Wall, Rees, and Ford, Phys. Rev. **97**, 726 (1955).
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[8] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).

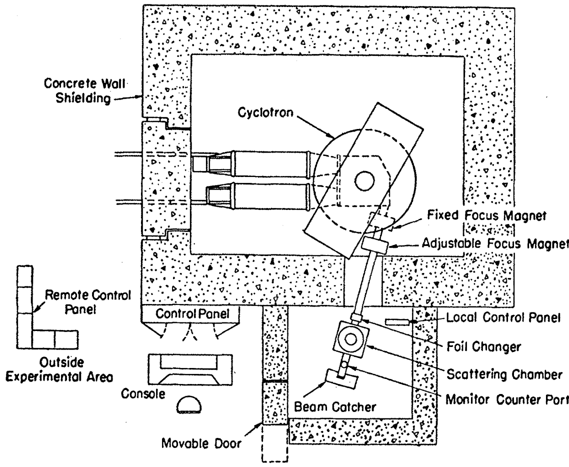

FIG. 1. Schematic diagram of cyclotron and scattering chamber.

First of all, the excitation energies and spins of the levels to be studied must be known. Furthermore, since it was desirable to investigate the scattering from at least two excitation levels of each nucleus, the energy resolution of the detecting equipment required that the first four energy levels be separated by at least 1 Mev. In addition, the targets could not be formed of compounds but must consist of a single element and, depending on the level structures, of a single isotope, to permit clean energy resolution of the separate alpha-particle groups. These requirements were all fulfilled by the four target nuclei Li^6, C^{12}, N^{14}, and Mg^{24}, chosen for investigation in this experiment.

The level structure and known quantum numbers[9,10] of Li^6 and N^{14} also permitted a measure of the validity of the isotopic spin selection rule in the (α,α') interactions. Since the alpha particle and the ground levels of these two target nuclei all have $T=0$, according to the isotopic spin selection rule the low-lying $T=1$ levels should not be excited appreciably. The experimental procedure of this investigation permitted a measure of the probability of excitation of these forbidden levels relative to the probability of excitation of the levels "allowed" by the isotopic spin selection rules.

The angular distributions of alpha particles elastically scattered by Li^6, C^{12}, and natural Mg were also obtained in order to augment the available information[11–13] on the elastic scattering of alpha particles by light nuclei.

II. EXPERIMENTAL PROCEDURE

A. Cyclotron and Emergent Beam

The alpha particles used in this experiment were produced in the M.I.T. cyclotron[14] by accelerating doubly ionized helium atoms to an energy of 31.5 ± 0.4 Mev. By means of a focusing magnet, the external beam is directed into the scattering chamber through a tube containing tantalum baffles which prevent small angle scattered particles from reaching the target. The baffled tube terminates in a defining and antiscattering slit system at the entrance to the scattering chamber. The focusing system produces, at the center of the target, a spot which is $\frac{1}{4}$ inch wide and $\frac{5}{16}$ inch high. A foil changer, located between the baffled tube and the slit system, makes it possible to insert aluminum foils in the alpha-particle beam to reduce the beam energy at the target. A schematic diagram of the cyclotron and scattering chamber is shown in Fig. 1.

B. Scattering Chamber

The scattering chamber was designed by Haffner.[15] Its principal features are:

1. The chamber contains mounting arms for two counters. Each arm can be rotated from 0 to ±170

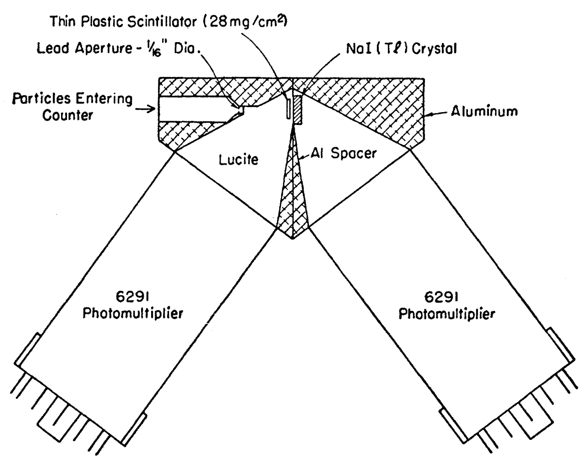

FIG. 2. Schematic diagram of particle selective counter.

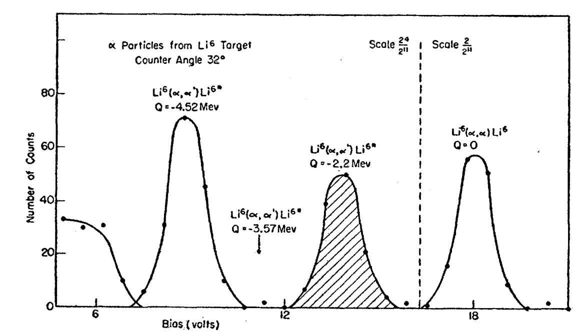

FIG. 3. Energy spectrum of alpha particles from Li^6 bombarded with 31.5-Mev alpha particles; counter angle 32 degrees.

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
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[14] M. S. Livingston, J. Appl. Phys. **15**, 2 (1944).
[15] J. W. Haffner, Ph.D. thesis, Massachusetts Institute of Technology, 1955 (unpublished).

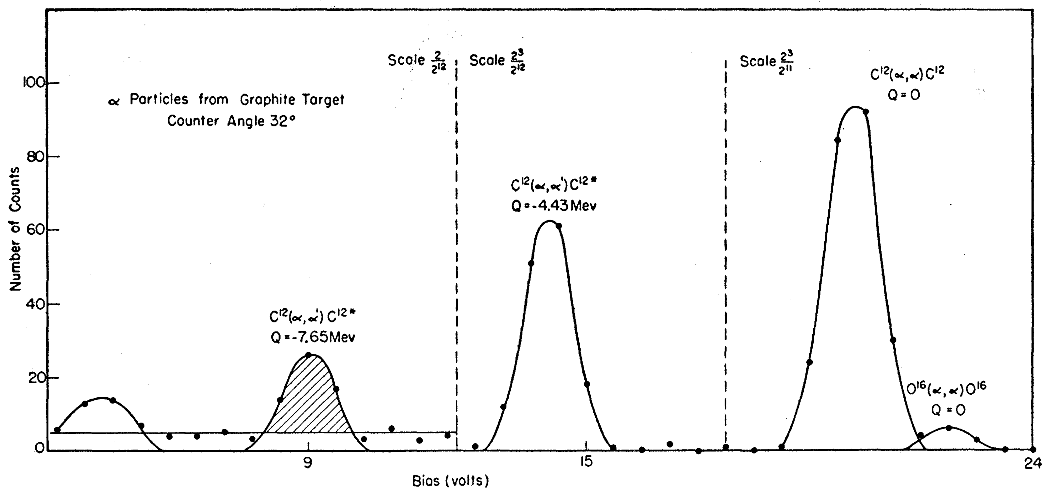

FIG. 4. Energy spectrum of alpha particles from C^{12} bombarded with 31.5-Mev alpha particles; counter angle 32 degrees.

degrees with an accuracy of ±0.3 degree. This provides versatility in that the arrangement is excellent for particle-gamma coincidence measurements and for angular correlation studies.

2. The target holder has a capacity of four and can be rotated through 360 degrees. Target choice and angular position can be controlled remotely from the outside area. The targets can be raised into the bell jar hydraulically, in which position the scattering chamber is sealed off, and completely isolated from the bell jar, and targets can be changed without affecting the scattering chamber vacuum. In addition, an evaporator is contained in the bell jar permitting targets to be made and subsequently bombarded without exposure to air.

3. The angular position of counter arms and target is measured by bridge circuits which contain precision helipots. This provides the positioning accuracy of 0.3 degree previously mentioned.

4. The angular position of counter arm or target and the choice of target can be controlled remotely from the outside area or from within the scattering chamber vault. The Plexiglas windows permit visual observation of the scattering chamber interior.

C. Particle Selection Technique

Identification of the charged particles which result from alpha-particle induced reactions was accomplished by the method described by Aschenbrenner.[7] This technique is excellent in that it permits complete separation of reaction products of different charge and/or mass. However, due to the necessity of traversing the plastic scintillator, an undesirable restriction is imposed on the maximum angle at which a scattered particle has sufficient energy for detection at the NaI crystal. In order to improve the angular resolution in the present experiment, the particle selective counter was redesigned, as shown in Fig. 2, to allow an increase of target to counter-aperture distance within the confines of the scattering chamber. In addition, the energy resolution of the counter was improved by decreasing the plastic scintillator thickness to 20 mg/cm². Figures 3–5 show the intensities of the alpha-particle groups, observed at a laboratory angle of 32 degrees, which result from the 31.5-Mev alpha-particle bombardment of Li^6, C^{12}, and natural Mg, respectively.

D. Beam Energy Determination

To determine the alpha-particle beam energy, a thin Li^7 target is inserted in the beam at the center of the scattering chamber and a 274-mg/cm² aluminum absorber is placed in front of the counter aperture. The particle-selective counter is then used to identify the two proton groups resulting from the reactions $Li^7(\alpha,p)Be^{10}$, $Q=-2.56$ Mev, and $Li^7(\alpha,p)Be^{10*}$, $Q=-5.94$ Mev. If we define E_p and $E_{p'}$ as the energies of the protons incident on the NaI crystal from the

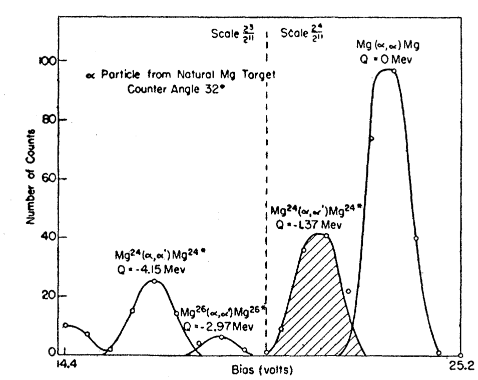

FIG. 5. Energy spectrum of alpha particles from natural Mg bombarded with 31.5-Mev alpha particles; counter angle 32 degrees.

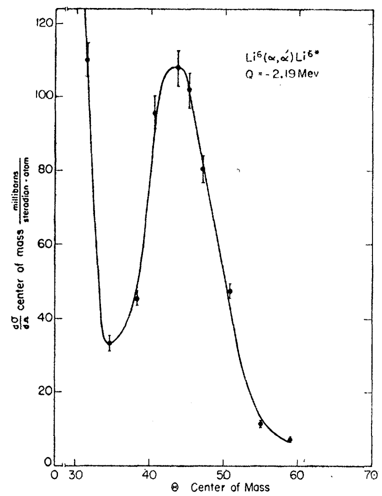

FIG. 6. Experimental angular distribution of alpha particles scattered inelastically from the 2.19-Mev level of Li^6.

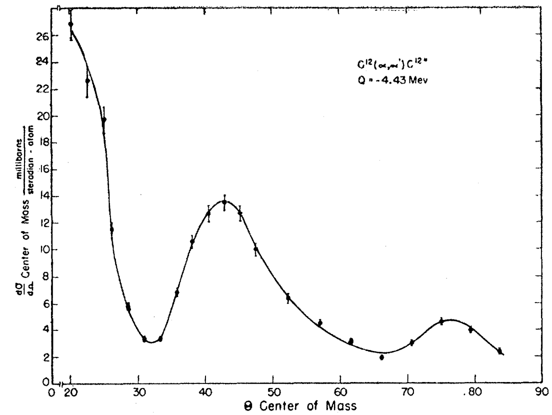

FIG. 8. Experimental angular distribution of alpha particles scattered inelastically from the 4.43-Mev level of C^{12}.

ground and first excited levels of Be^{10}, respectively, then the beam energy can be determined by the ratio $E_p/E_{p'}$ since this ratio varies rapidly with beam energy.

E. Target Preparation

All targets were $1\frac{1}{8}$ inches by $1\frac{1}{8}$ inches in size, self-supporting and free of any backing material, and were mounted in aluminum target frames. It was experimentally determined that a thickness of from 1.0 to 2.0 mils, depending on the particular element, gave the best compromise between acceptable energy resolution and counting statistics. The magnesium target material was obtained commercially in 1.5-mil sheet form and, after removal of surface oxidation by lapping in rouge, was maintained under vacuum. Carbon targets of from 0.3 to 1.5 mils thickness were prepared from a colloidal dispersion of graphite in alcohol,[16] by spraying the dilute dispersion on a glass surface with an artist's air brush. When the glass surface is immersed in water, the thin target floats to the surface and can be picked up on the target frame. The separated Li^6 isotope was obtained in metallic form from the U. S. Atomic Energy Commission. Targets of from 1.0 to 1.4 mils thickness were prepared by rolling the lithium within sheets of thin aluminum between a set of micrometer controlled rollers. The material was rolled under dried mineral oil which was later removed in successive baths of dried naptha after which the target material was maintained under vacuum. Targets of N^{14} were lapped down from the 3- to 4-mil thick pieces of the "flash" obtained in the moulding of a filler-free melamine formaldehyde resin.[17]

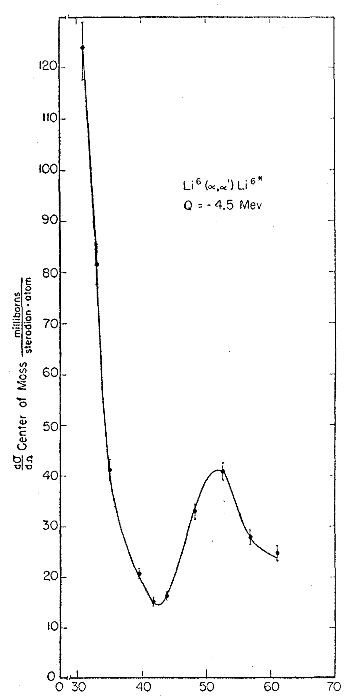

FIG. 7. Experimental angular distribution of alpha particles scattered inelastically from the 4.5-Mev level of Li^6.

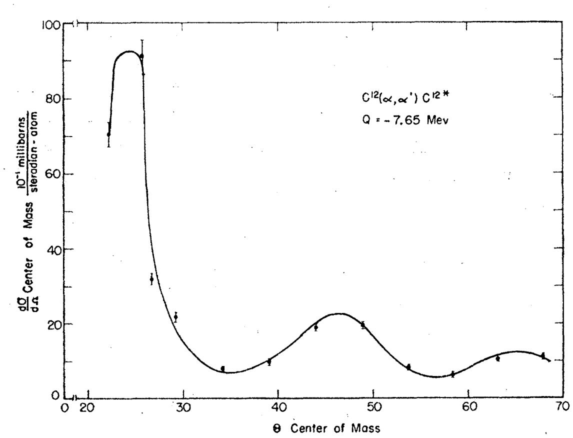

FIG. 9. Experimental angular distribution of alpha particles scattered inelastically from the 7.65-Mev level of C^{12}.

[16] Dag 154, a product of the Acheson Colloids Company was used.

[17] Melmac 404, a product of the American Cyanamid Company was used.

III. EXPERIMENTAL RESULTS

A. Angular Distributions

The angular distributions of alpha particles scattered inelastically by Li^6, C^{12}, and Mg^{24} are shown in Figs. 6 to 11. The indicated errors include all uncertainties affecting a comparison of relative intensities. Where no errors are indicated, the uncertainty lies within the limits of the finite point size or the width of the curve. An additional error of 2% should be included to account for the uncertainty in absolute differential cross-section values. The positions of the maxima and minima for each observed inelastic angular distribution are indicated in Table I.

TABLE I. Angular positions (in the center-of-mass system) of maxima and minima experimentally observed in the inelastic alpha-particle angular distributions.

Target nucleus	Excitation level (Mev)	Maximum or minimum	Center-of-mass angle	Intensity mb/sterad-atom
Li^6	2.19	min	34.5	33
	2.19	max	44.0	108
	4.5	min	42.5	14
	4.5	max	52	41
C^{12}	4.43	min	32	3
	4.43	max	43	13.5
	4.43	min	66	2.0
	4.43	max	75	4.8
	7.65	max	24.5	9.25
	7.65	min	35	0.75
	7.65	max	46	2.25
	7.65	min	56.5	0.60
	7.65	max	65	1.25
Mg^{24}	1.37	min	25	4.5
	1.37	max	32	20.5
	1.37	min	40.5	4.0
	1.37	max	46.5	9.0
	1.37	min	57	1.0
	1.37	max	64.5	2.5
	4.12	min	29.5	1.70
	4.12	max	33.5	2.56
	4.12	min	43	0.88
	4.12	max	51	1.32
	4.12	min	60.5	0.52
	4.12	max	69	1.00
	4.12	min	80	0.60

The well-defined structure in the angular distributions of Figs. 6 to 11 was quite suggestive of a direct interaction process; however, one must study the scattered intensity at large angles in order to determine whether or not any angular symmetry exists. To accomplish this, the plastic scintillator was removed from the particle selective counter and only the NaI scintillator was used for particle detection. This eliminated some 20 mg/cm^2 of absorbing material and removed the previous limitation on the maximum permissible angle of observation. Since the response of NaI to protons, deuterons, and alpha particles is known[18] it was possible to identify the alpha-particle groups

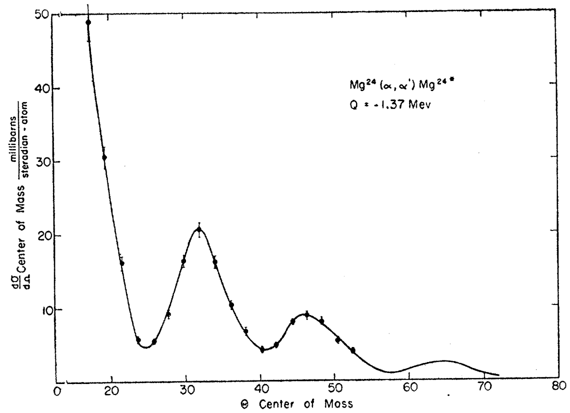

FIG. 10. Experimental angular distribution of alpha particles scattered inelastically from the 1.37-Mev level of Mg^{24}.

previously observed with the particle selective counter, by the percentage pulse-height change produced by inserting selected absorbers in front of the counter aperture. In the scattering from carbon, for example, it was determined by this expedient that the differential cross section for scattering of any detectable alpha-particle group at angles greater than 90 degrees was less than 0.8 mb/steradian-atom. From this it appears that, at least in the case of C^{12}, the inelastic scattering is confined primarily to the forward quadrant.

In the present experiment, the beam energy was known to vary as much as 0.4%, depending on the power level of the cyclotron, largely due to variations in the rf heating and the subsequent mechanical motion of the dees. The continuous reproducibility of data, regardless of the cyclotron power level, implied that the differential cross sections were not strongly energy dependent. To verify the insensitivity to small changes in beam energy, angular distributions of the alpha groups corresponding to the ground, first, and second excited levels in both C^{12} and Mg^{24} were also taken with reduced beam energies of 30.9 Mev and 30.4 Mev. Angular distributions obtained at both reduced

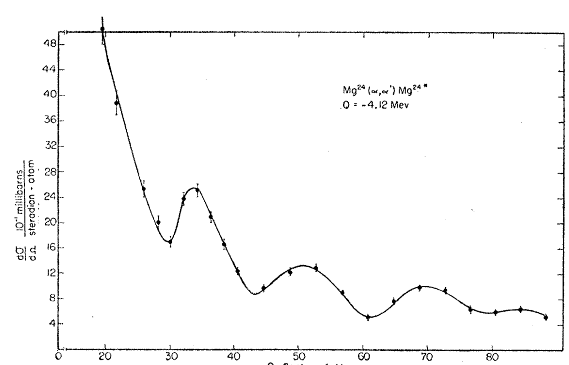

FIG. 11. Experimental angular distribution of alpha particles scattered inelastically from the 4.12-Mev level of Mg^{24}.

[18] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. 84, 1034 (1951).

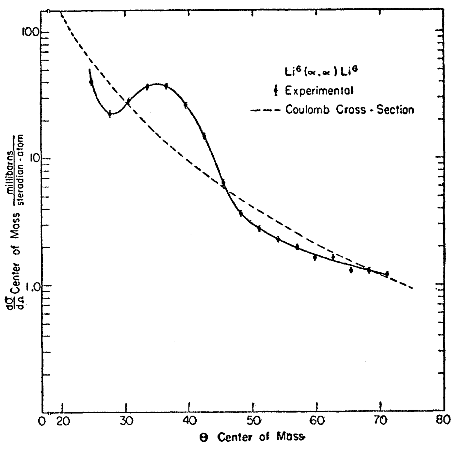

FIG. 12. Experimental angular distribution of alpha particles elastically scattered by Li^6.

energies fell within the experimental uncertainties of those taken at 31.5 Mev.

The angular distributions of elastically scattered alpha particles are shown in Figs. 12 to 14 where the calculated Coulomb cross sections are indicated by a dashed line.

B. Excitation of Isotopic-Spin-Forbidden Levels

It is clearly evident from Fig. 3 that at 32 degrees, excitation of the $T=1$, 3.57-Mev level of Li^6 is quite small relative to excitation of the levels "allowed" by the isotopic spin selection rules. A study of the spectrum at all angles of observation indicates that excitation of this level occurs with a probability of less than 4% of that of either of the two "allowed" levels which were excited. Similarly, it was found that, over a range of from 14.8 degrees to 64.1 degrees, excitation of the 2.31-Mev level of N^{14}, which is "forbidden" by the isotopic spin selection rules occurred with a probability of less than 6% of that of the allowed 3.95-Mev level which was excited.

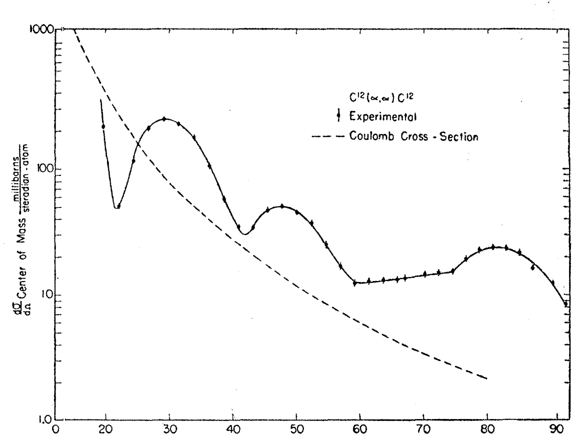

FIG. 13. Experimental angular distribution of alpha particles elastically scattered by C^{12}.

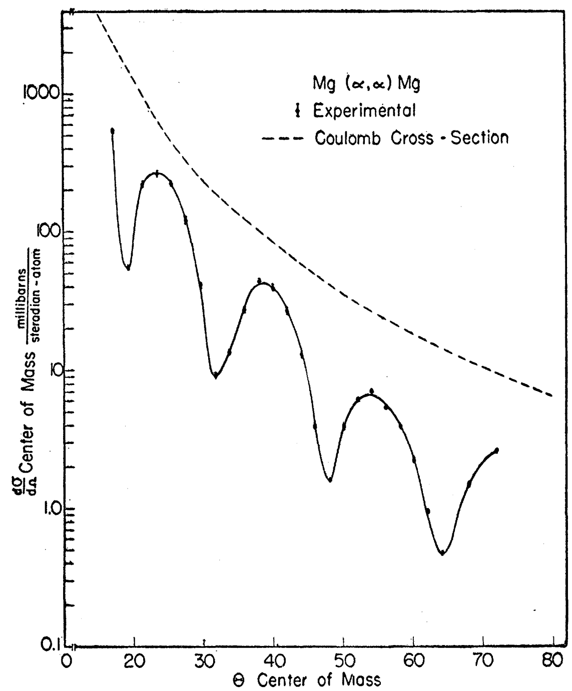

FIG. 14. Experimental angular distribution of alpha particles elastically scattered by natural Mg.

IV. DISCUSSION

A. Inelastic Scattering

It is assumed that a contribution to the observed cross sections due to electric excitation would not be

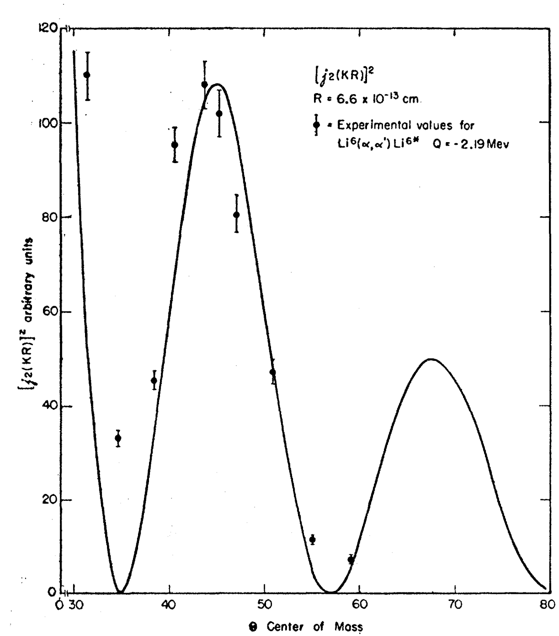

FIG. 15. Experimental data for the interaction $Li^6(\alpha,\alpha')Li^{6*}$, $Q=-2.19$ Mev, compared with theoretical angular distribution.

of sufficient magnitude to permit detection. This assumption is believed to be valid for the following reasons: 1. The electric excitation mechanism is most important when the bombarding energies are below the Coulomb barrier, a condition not fulfilled in this experiment. 2. For bombarding energies above the barrier, the electric excitation effect would probably be masked by the large nuclear scattering. 3. If we optimize conditions of bombarding energy and order of multipole moment involved, the theoretical maximum *total* cross section for electric excitation is less than most of the *differential* cross sections obtained for excitation of the individual levels observed.

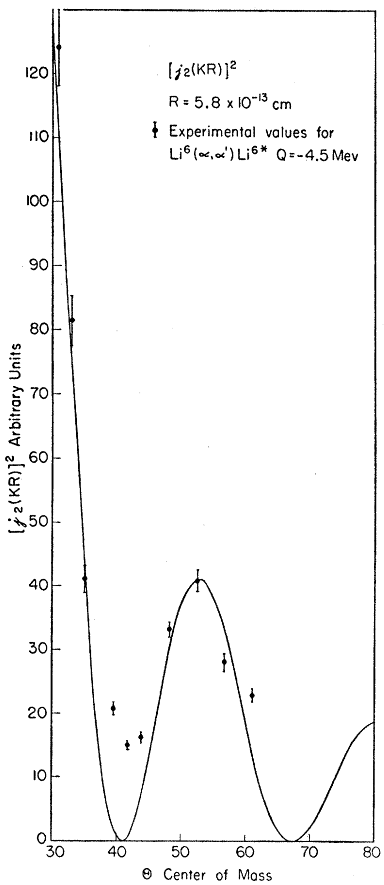

FIG. 16. Experimental data for the interaction $Li^6(\alpha,\alpha')Li^{6*}$, $Q=-4.5$ Mev, compared with theoretical angular distribution.

It is further concluded that no contributions to the observed angular distributions from compound nucleus interactions were experimentally observable. This conclusion is based on the evidence that the inelastic scattering is asymmetric in the center-of-mass coordinates, being confined primarily to the forward quadrant, and is further verified by the fact that the cross sections are insensitive to changes in beam energy.

The direct surface interaction theory of Austern *et al.*[8] proposes a mechanism in which the reaction proceeds by a direct interaction between the incoming particle and one of the nucleons at the surface of the

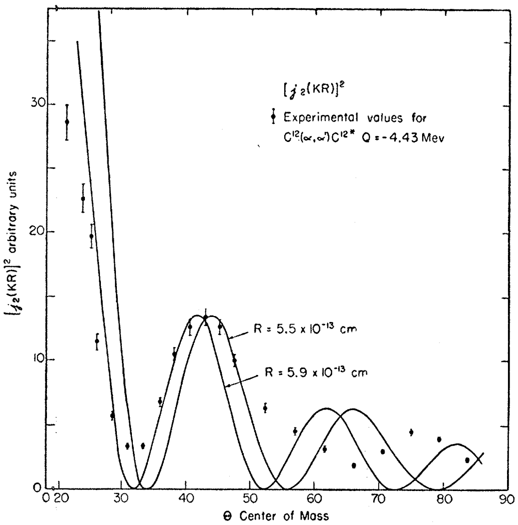

FIG. 17. Experimental data for the interaction $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-4.43$ Mev, compared with theoretical angular distribution.

nucleus. The experimental data of the present investigation are compared with the predictions of this theory in Figs. 15 to 20. It must be stated that, because of the approximations made in this theory, the predictions are expected to be most accurate at forward angles and the position of the first maximum is most desirable for determining the l value involved.

Experimental difficulties prohibited observations at laboratory angles less than 14.8 degrees, an angle greater than the predicted position of the first maxima in most of the interactions. In all but one case studied here, however, the l values can be obtained since the quantum numbers of the levels involved have been determined in other experiments.[9,10] The theoretical curves were compared with the experimental data, using a value of R which gave the best fit with the first observable maximum and minimum.

(a) $Li^6(\alpha,\alpha')Li^{6*}$.—The ground level of Li^6 has $J=1$, the 2.19-Mev level $J=3$, and the 4.5-Mev level $J=2$, all of even parity. In both cases the theory predicts an angular distribution which varies as $|j_2(KR)|^2$. The values of R required to fit the data are

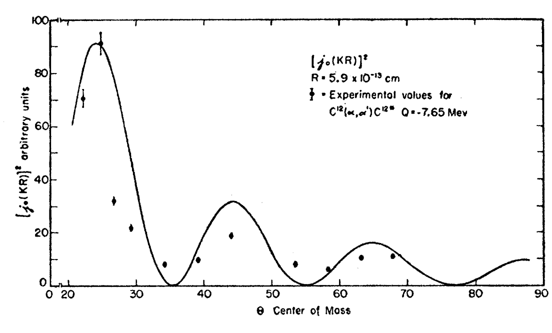

FIG. 18. Experimental data for the interaction $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-7.65$ Mev, compared with theoretical angular distribution.

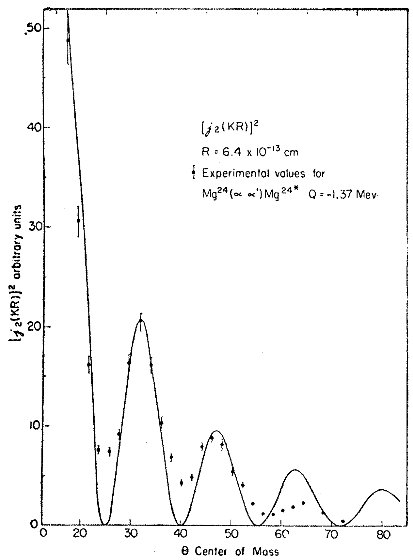

FIG. 19. Experimental data for the interaction $Mg^{24}(\alpha,\alpha')Mg^{24*}$, $Q=-1.37$ Mev, compared with theoretical angular distribution.

quite large. However, this is not considered too serious since the "radius" of Li^6 is a rather nebulous concept. Using the relationship $R=r_0A^{\frac{1}{3}}$ with $r_0=1.5\times10^{-13}$ cm, alpha-particle radii of 3.0×10^{-13} cm, and 3.9×10^{-13} cm were required to fit the data for the 4.5 Mev- and 2.19 Mev-levels. There is some evidence[19,20] for a large alpha-particle radius based on (n,α) scattering experiments; however, the values given above are considered excessive. The fit obtained is quite good, however, and is shown in Figs. 15 and 16.

(b) $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-4.43$ Mev.—The theory predicts an angular distribution varying as $|j_2(KR)|^2$

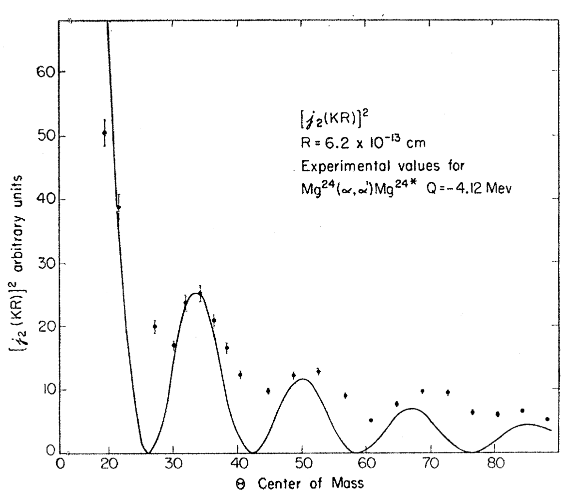

FIG. 20. Experimental data for the interaction $Mg^{24}(\alpha,\alpha')Mg^{24*}$, $Q=-4.12$ Mev, compared with theoretical angular distribution. Ɨ should be added next to experimental values.

[19] Bashkin, Mooring, and Petree, Phys. Rev. **82**, 378 (1951).
[20] R. K. Adair, Phys. Rev. **86**, 155 (1952).

for excitation from the $J=0^+$ ground level to the $J=2^+$ first excited level in C^{12}. Figure 17 shows the fit with experimental observations and also illustrates the sensitivity of the spherical Bessel function to a small change in R. The value of R which gave the best agreement at forward angles required an alpha-particle radius of 2.5×10^{-13} cm for $r_0=1.5\times10^{-13}$ cm. This is not incompatible with the previously mentioned evidence for a large alpha-particle radius. It is noted that the data deviate from the theoretical curve at angles greater than 50 degrees as expected from the discussion of its range of validity.

(c) $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-7.65$ Mev.—In this case, a $|j_0(KR)|^2$ curve is predicted since the ground and second excited levels are both $J=0^+$. Agreement between theory and experiment is illustrated in Fig. 18 where the fit is seen to be extremely good. The value of R is the same as was used for the first excited level of C^{12}. Since the first maximum shown is actually the first maximum occurring beyond zero degrees for the j_0 curve, agreement at larger angles should be somewhat better than in the previous case. This is illustrated quite well in Fig. 18.

(d) $Mg^{24}(\alpha,\alpha')Mg^{24*}$, $Q=-1.37$ Mev.—Because of the kinematics of the interaction, the center-of-mass angular range of observation is increased for interactions involving heavier target nuclei. For a ground level spin of $J=0$ and a $J=2$ excited level, both of even parity, the theory predicts a $|j_2(KR)|^2$ angular distribution. The experimental data fit the theoretical curve extremely well and this agreement continues past the third maximum of the spherical Bessel function (second maximum shown), as indicated in Fig. 19. With a unit radius $r_0=1.5\times10^{-13}$ cm, an alpha-particle radius of 2.1×10^{-13} cm was required to fit the curve. By bombarding magnesium with 42-Mev alpha particles, Gugelot and Rickey[21] have obtained almost identical results. Their data are approximated by a $|j_2(KR)|^2$ curve and require a radius $R=(1.5A^{\frac{1}{3}}+2.21)\times10^{-13}$ cm.

(e) $Mg^{24}(\alpha,\alpha')Mg^{24*}$, $Q=-4.12$ Mev.—The level of excitation involved in this interaction is actually a doublet.[10] The lower level has been determined to be $J=4^+$ for which the theory would predict a $|j_4(KR)|^2$ angular distribution. However, the nuclear radius required to fit the data to this curve is too large to be considered physically meaningful. The agreement between experimental observations and a $|j_2(KR)|^2$ spherical Bessel function, illustrated in Fig. 20, is seen to be extremely good. The theoretical curve was obtained by using a unit radius $r_0=1.5\times10^{-13}$ cm and an alpha-particle radius of 1.9×10^{-13} cm. This result can be interpreted to indicate that the higher level, having a spin $J=2$, is excited and that in this interaction, excitation of the $J=4$ level is discriminated against because of the higher angular momentum transfer which would be involved.

[21] P. C. Gugelot and M. Rickey (unpublished).

The inelastic scattering process has more recently been described for even-even nuclei in terms of the excitation of Bohr-Mottelson surface vibrations.[22] When this model is used, a simple Born approximation calculation shows that the angular distributions of scattered nucleons are identical with those predicted by the direct interaction model in the 0 to 2^+ transitions.[21] In this collective description of the scattering process, the alpha-particle interacts with the nuclear surface and the necessity of a large momentum transfer to a single surface nucleon, a controversial feature of the direct interaction process, does not occur.

In Table II, the experimentally obtained positions of maxima and minima are compared with those predicted by the direct surface interaction theory. These results show that a direct interaction picture at least represents the angular distribution data. If a collective model can be used to predict more quantitative results, one may better be able to understand the

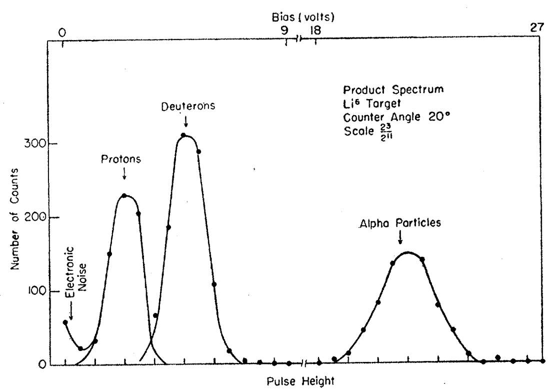

FIG. 21. Relative intensities of protons, deuterons, and alpha particles from the 31.5-Mev alpha-particle bombardment of Li^6.

process primarily responsible for the inelastic scattering angular distributions.

B. Elastic Scattering

The reasons for the smooth cross-section variation from 60-78 degrees shown in Fig. 13 are not understood. The diffraction pattern is apparently masked by interference with some other process occurring in the interaction and this appears to warrant further investigation. A similar phenomenon was observed in the elastic scattering of 48-Mev alpha particles by carbon[6] and also in the elastic scattering of deuterons from oxygen.[23]

The large (α,p) and (α,d) cross sections observed in this experiment (Fig. 21) have been reported by others and are interpreted as indicative that nuclei are opaque to high-energy alpha particles. In Table III, the elastic scattering angular distributions of the present experiment are compared with those predicted for scattering from an opaque sphere. The theoretical curves were fitted, using values of R which gave an exact fit at the position of the first experimental maximum.

If the nucleus is represented as being completely opaque out to the radius R, then the differences ΔR, between these values of R and the interaction radii required to fit the theoretical curves to the inelastic scattering experimental data, can be interpreted as indicative of the diffuseness of the nuclear surface. This model of the nucleus is similar to the optical scattering model which can be deduced from the

TABLE II. Angular positions of maxima and minima of the inelastic alpha-particle angular distributions. Experimental data compared with theoretical predictions for the direct surface interaction model.

Target nucleus	Excitation level (Mev)	Maximum or minimum	Center-of-mass angle (deg) Experiment	Theort.
Li^6	2.19	min	34.5	35
	2.19	max	44	45
	4.5	min	42.5	41
	4.5	max	52	53
C^{12}	4.43	min	32	32
	4.43	max	43	42
	4.43	min	66	52
	4.43	max	75	62
	7.65	max	24.5	24.5
	7.65	min	35	35.5
	7.65	max	46	44.5
	7.65	min	56.5	55.5
	7.65	max	65	65
Mg^{24}	1.37	min	25	25
	1.37	max	32	32
	1.37	min	40.5	40
	1.37	max	46.5	47
	1.37	min	57	55
	1.37	max	64.5	63
	4.12	min	29.5	26.5
	4.12	max	33.5	34
	4.12	min	43	42.5
	4.12	max	51	50.5
	4.12	min	60.5	59
	4.12	max	69	67
	4.12	min	80	77

TABLE III. Angular positions of the maxima observed in the elastic scattering angular distributions compared with those predicted for scattering from an opaque sphere.

Natural c.m. angular Mg position of maxima (deg) Expt.	Opaque sphere $R=5.4$ $\times10^{-13}$ cm	C^{12} c.m. angular position of maxima (deg) Expt.	Opaque sphere $R=4.4$ $\times10^{-13}$ cm	Li^6 c.m. angular position of maxima (deg) Expt.	Opaque sphere $R=4.5$ $\times10^{-13}$ cm
24	24	29	29	33.5	33.5
39	41	48	50		
55	55	...	69		
		83	89		

[22] S. Hayakawa and S. Yoshida, Proc. Phys. Soc. (London) **A68**, 656 (1955); Progr. Theoret. Phys. Japan **14**, 1 (1955).
[23] Freemantle, Gibson, Prowse, and Rotblatt, Phys. Rev. **92**, 1268 (1953).

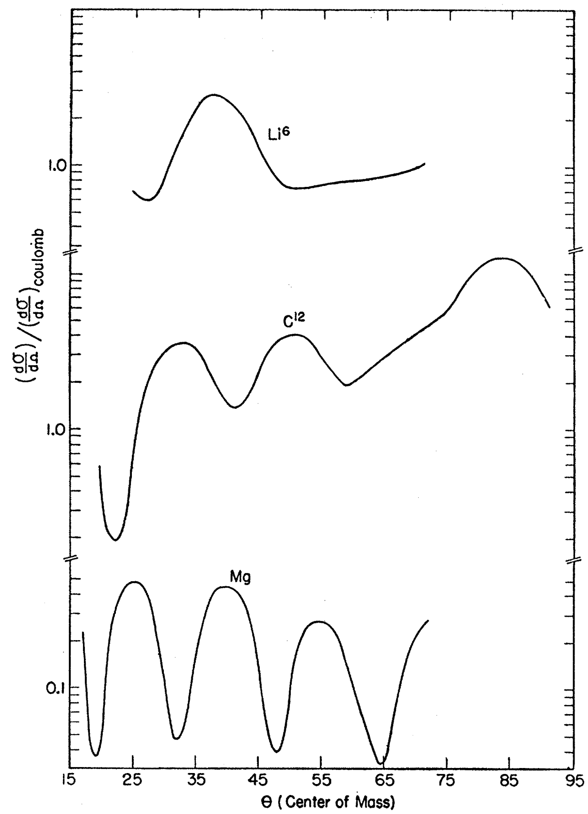

FIG. 22. Ratio of differential cross section to Coulomb differential cross section for the elastic scattering of 31.5-Mev alpha particles from Li^6, C^{12}, and natural Mg.

results of a recent survey[24] of total reaction cross-section data and is also compatible with the direct surface interaction model used to interpret the inelastic scattering data of the present experiment. The values of ΔR obtained in this comparison of elastic and inelastic interaction radii are: Li^6, 1.7×10^{-13} cm; C^{12}, 1.3×10^{-13} cm; Mg^{24}, 0.9×10^{-13} cm. These results are of the order of magnitude of the diffuseness of the nuclear surface estimated by Porter[25] and the values of R required for a fit are comparable to those calculated by Shapiro[26] for a totally black nucleus.

[24] H. G. Blosser and T. H. Handley, Phys. Rev. **100**, 1340 (1955).
[25] C. E. Porter, Phys. Rev. **99**, 1400 (1955).
[26] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).

The concept of a diffuse surface opaque nucleus, a model consistent with that employed in an analysis of the inelastic scattering data, predicts results in close agreement with the elastic angular distributions as indicated in Table III. This cannot be interpreted as verification of the validity of the model, however, since equally good agreement is obtained by comparing the experimental data with that predicted for scattering by a square-well potential on which the superposed Coulomb potential is cut off at the nuclear radius.

A recent, and as yet unpublished, elastic alpha-particle scattering experiment was performed to study the angular dependence of

$$\left(\frac{d\sigma}{d\Omega}\right)\bigg/\left(\frac{d\sigma}{d\Omega}\right)_{\text{Coulomb}}$$

at 40 Mev over a range of elements from carbon to silver.[27] A composite plot of these data shows the details of the gradual change from the diffraction to exponential behavior with increasing atomic number. The data of the present investigation are illustrated in this same form in Fig. 22 to facilitate a comparison of the behavior at the bombarding energy of 31.5 Mev used in this experiment. The general characteristics of both composite plots are quite similar.

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[27] Igo, Wegner, and Eisberg, Phys. Rev. 101, 1508 (1956).