perfect diamagnetic. To get a complete theory of the superconducting properties it would be necessary to re-examine the problem for the situation in which the magnetic field is confined to a thin surface layer corresponding to the penetration depth of the London theory.[5a]

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Angular Distribution of the $Al^{27}(d, \alpha)Mg^{25}$ Reaction and Energy Levels in Mg^{25}†

A. D. SCHELBERG, M. B. SAMPSON, AND R. G. COCHRAN
Department of Physics, Indiana University, Bloomington, Indiana

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The energy distribution and angular dependence of the alpha-particle groups from the nuclear reaction $Al^{27}(d, \alpha)Mg^{25}$ have been investigated. A magnetically analyzed beam of 11.1 Mev deuterons was used. Eleven alpha-particle groups were measured, corresponding to ten excited levels in Mg^{25} at 0.57, 0.96, 1.63, 1.97, 2.74, 3.36, 4.01, 4.81, 5.48, and 5.95 Mev. The ground state Q-value for the reaction was found to be 6.58 ± 0.03 Mev, giving a value for the mass difference $Al^{27}-Mg^{25}$ of 1.99626 ± 0.00003 mass units. The intensities of all the groups, with the exception of Q_2, show marked dependence on the angle of measurement. The average spacing of the levels in Mg^{25} is 0.6 Mev, and is nearly constant over the range studied.

I. INTRODUCTION

An excited level in Mg^{25} was first observed by McMillan and Lawrence,[1] from the $Al^{27}(d, \alpha)Mg^{25}$ reaction. Two groups of alpha-particles were found with an energy difference corresponding to an excited level at 0.7 Mev. Pollard, Sailor, and Wyly,[2] using 3.79 Mev deuterons, observed two additional groups showing three excited levels in the Mg^{25} nucleus. French and Treacy[3] repeated these measurements with 0.93 Mev deuterons, using an ionization chamber to count the alpha-particles and found five groups.

The present investigation of the $Al^{27}(d, \alpha)Mg^{25}$ reaction was undertaken to measure the angular distribution of the alpha-particle groups and to search for groups corresponding to states of higher excitation made feasible by the use of the 11-Mev deuteron beam of the Indiana University Cyclotron.

II. METHOD AND APPARATUS

The deuteron beam was led through a four-inch diameter, evacuated tube from the target chamber of the cyclotron to a magnetic analyzer situated outside the water shielding tanks; a distance of fifteen feet.

The analyzer magnet was constructed using a rectangular yoke with a cross section sixteen inches square. The pole pieces were made in the form of a truncated wedge with a gap of 2.0 inches. The lids of the magnet vacuum chamber are of one-half inch iron, leaving a net gap of one inch. The magnet coils require about one kilowatt of power to produce a maximum field of 12,000 Gauss. A field of 10,635 gauss was sufficient to deflect the 11-Mev deuteron beam through 56°. The current in the coils is supplied by a motor generator, and the use of an electronic stabilizer enables the current to be held constant within 0.2 percent. The magnetic field is measured with a flip coil and ballistic galvanometer, calibrated against a standard mutual inductance.

Scattering of the beam in the analyzer chamber is prevented by the use of suitable diaphragms to define the beam. Adjustable slits are placed at the entrance to the analyzer chamber and in the tube leading to the reaction chamber to define the beam to the target.

The magnetic analyzer was calibrated with alpha-particles of polonium and thorium active deposit. The source was placed on the axis of the beam tube, ten feet from the analyzer. A proportional counter located behind the focal slit was then used to count the alpha-particles as the magnetic field was varied. Alpha-particles from Po, ThC and ThC′ were used to give three points on the energy *versus* magnetic field curve at energies of 5.3, 6.05, and 8.78 Mev respectively. A linear relation was obtained between the alpha-particle energy and the square of the magnetic field. The energy of the deuteron beam striking the target could then be determined by using the relation:

$$E_D=(He\rho)^2/2mc^2,$$

where m is the deuteron mass, e is the charge, c is the velocity of light, and H is the magnetic field required to focus the deuteron beam of energy E_D on the target slit. ρ is the effective radius of curvature in the analyzer and was found equal to 64.1 cm from the alpha-particle

† This work was assisted by the joint program of the ONR and AEC.

[1] E. McMillan and E. O. Lawrence, Phys. Rev. **47**, 343 (1935).
[2] Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949).
[3] A. P. French and P. B. Treacy, Proc. Phys. Soc. London **63**, 665 (1950).

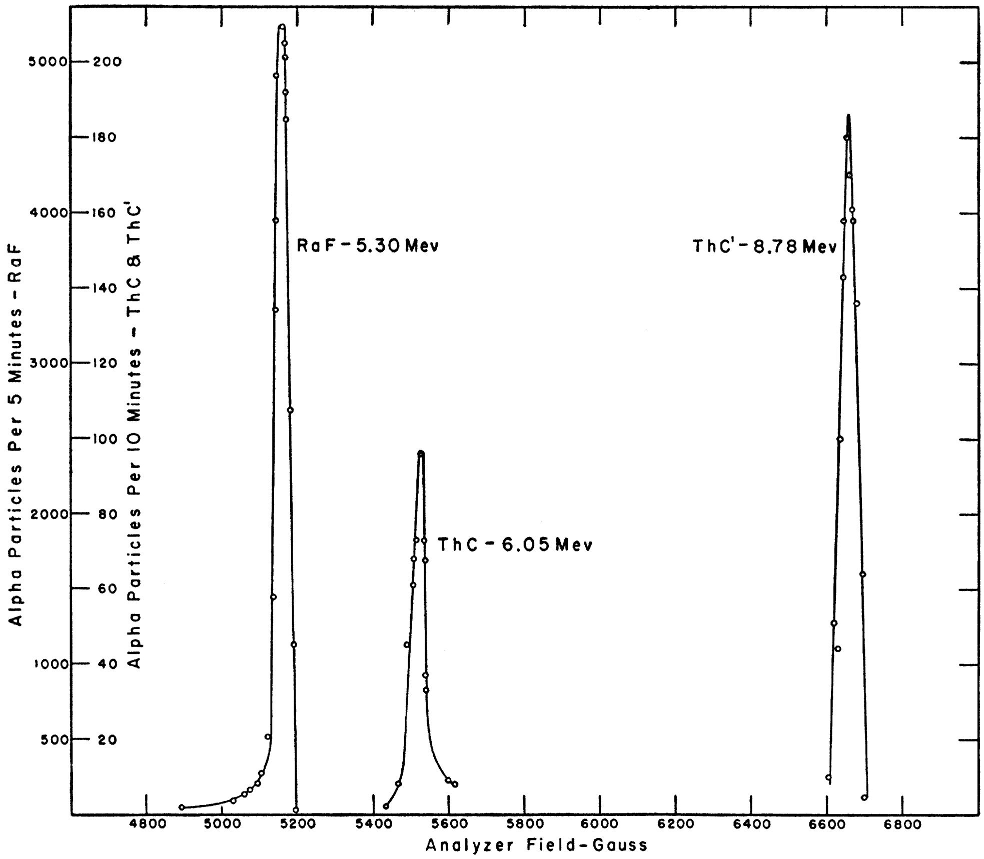

FIG. 1. Curves obtained in calibrating the beam analyzer. The value of the magnetic field at the position of each peak was used together with the corresponding mean energy to determine the effective radius of curvature $\rho = 64.1$ cm.

calibration. Figure 1 shows the three calibration curves obtained.

The beam is spread out into an energy spectrum across the target slit by the analyzer magnet. The adjustment of this slit then allows the selection of the energy spread in the beam striking the target. With a beam current of about 0.05 μamp. on the target the energy spread was found to be ± 70 kev at a beam energy of 11.1 Mev, for a slit width of 0.2 inch.

The evacuated tube and analyzer were adjusted to align the beam path with the center of the target. The following method was found convenient in aligning the beam and determining the position and size of the beam in the reaction chamber. An ordinary lantern slide plate is placed in the tube where it is desired to know the position and size of the beam, and bombarded for a few seconds. Upon removal from the vacuum the plate is blackened and shows clearly the location and intensity distribution of the beam. It is quite unnecessary to shield the plate from light either before or during the bombardment.

The target chamber, shown schematically in Fig. 2, was adjusted to make the ion beam incident on the target at the center of the chamber. The slits were adjusted to confine the region of the target foil hit by the beam to an area 0.2 inch wide by 0.6 inch high. The angular spread of the emergent particles was then determined by the chamber ports which were 0.5 inches in diameter and located on a radius of 5.5 inches from the chamber center. This arrangement sufficed to provide "good geometry" according to the criterion of Livingston and Bethe.[4]

Nine windows situated on one side of the target chamber permitted the measurement of the angular distribution of the alpha-particles emitted in the reaction. The oven shown in the drawing of the chamber was incorporated to provide for the evaporation of other target materials in future experiments.

The target was an aluminum foil of 0.5 mg/cm² surface density. The use of a thinner foil was found to give inadequate counting rates with the beam currents used in this experiment. The foil was mounted on a one-inch diameter brass ring which insured that the beam hit only the target foil. The foil mount was so arranged that the angle with the incident beam could be changed

[4] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 278 (1937).

through a Wilson vacuum seal. Provision was also made for positioning the foil in front of the oven.

The target support was insulated to allow the measurement of the target current. The use of thin foils in this experiment, however, allowed the collection of the beam current in a deep cylindrical Faraday cage. The current to the Faraday cage was measured with a current integrator.[5] The deep cage also served to minimize scattering of the beam into the observation ports after passing through the target foil.

The alpha-particles were detected with a double proportional counter. The design of the counter is shown in the inset in Fig. 2. The counter was filled with 10 cm of argon and one cm of carbon dioxide. The counter wires were 3 mil tungsten. This construction was adopted with the aim of eliminating the unsymmetrical end effects in the usual type of coaxial construction. This counter showed a marked uniformity of pulses from the two seconds and good resolution was obtained in counting alpha-particles in the presence of large numbers of protons from the (d, p) reaction in the target.

The counter was mounted in a steel box which also contained two cathode-follower pre-amplifiers. The pre-amplifiers were followed by another amplifier and a mixer stage, a second cathode-follower and a scaler. The counter and pre-amplifier voltages were supplied by batteries since some trouble was experienced with transients caused by sparks in the cyclotron chamber.

III. PROCEDURE

The counter was adjusted to give a good differential range curve by setting the discriminator bias on the scaler so that only those alpha-particles which passed through the first section and ended their range in the second section were recorded. The effective absorption in the counter was obtained by taking an absorption curve of a thin source of thorium active deposit. The value for the mean range of the ThC′ alpha-particles, 8.570 cm, was taken from the work of Holloway and Livingston.[6] A typical absorption curve is shown in the inset of Fig. 3. The scale has been shifted to make the peak come at 8.57 cm of air. The range of the disintegration alpha-particles may then be determined by direct comparison with the calibration, thus eliminating the difficult measurement of an absolute range.

The experimental procedure was to take an absorption curve of the alpha-particles at each of the angular positions. Aluminum foil absorbers were interposed between the chamber window and the counter. These foils were varied in 0.5-mil steps and interpolated between in steps of 0.2 cm of air by varying the air gap between the counter and the chamber window. The absorption in the target was taken as one half the target thickness divided by an angle factor dependent on the target position and the angle to the observation port. The total absorption then included the target thickness correction, the chamber window, the aluminum foil absorbers, the air gap, and the counter equivalent. The total absorption was then converted to the air equivalent by use of the method described in Livingston and Bethe.[4]

The target foil was set at an angle of 45° with the beam to make measurements at the backward angles, 138°, 124°, and 110°. The target was set at 135° to take readings at the forward angles of 90°, 74°, 60°, 46°, and 32°. Reliable measurements could not be made at angles less than 32° because of the larger number of scattered deuterons at these angles.

The effective thickness of the foil presented to the beam was calculated from the measured surface density to be 35 kev for the 11.1 Mev deuterons.

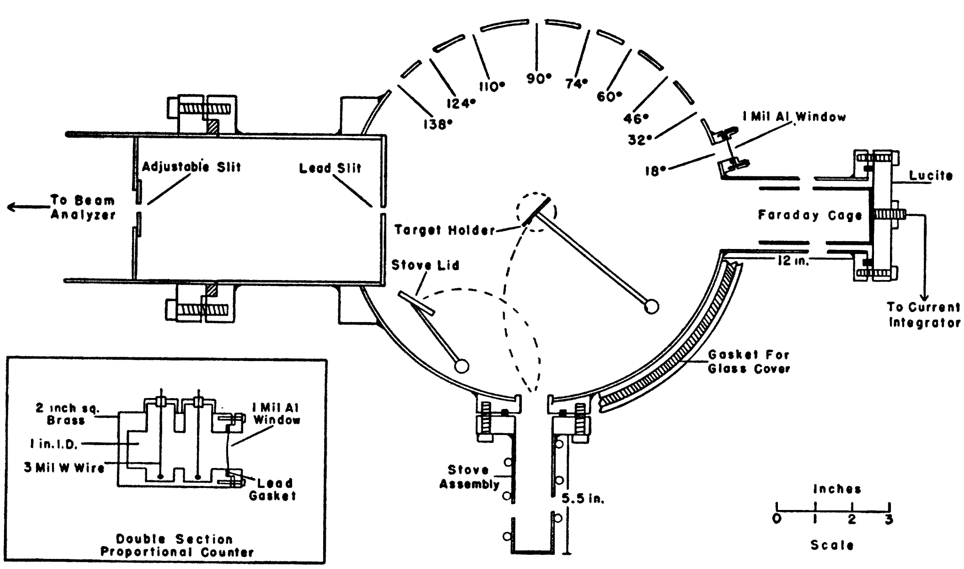

FIG. 2. Schematic of the 10-inch O.D. reaction chamber with 1 of the 9 window assemblies shown in detail at 18°. The inset shows the counter which was used to detect the alpha particles emerging at the various angles.

[5] H. T. Gittings, Rev. Sci. Inst. **20**, 325 (1949).
[6] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

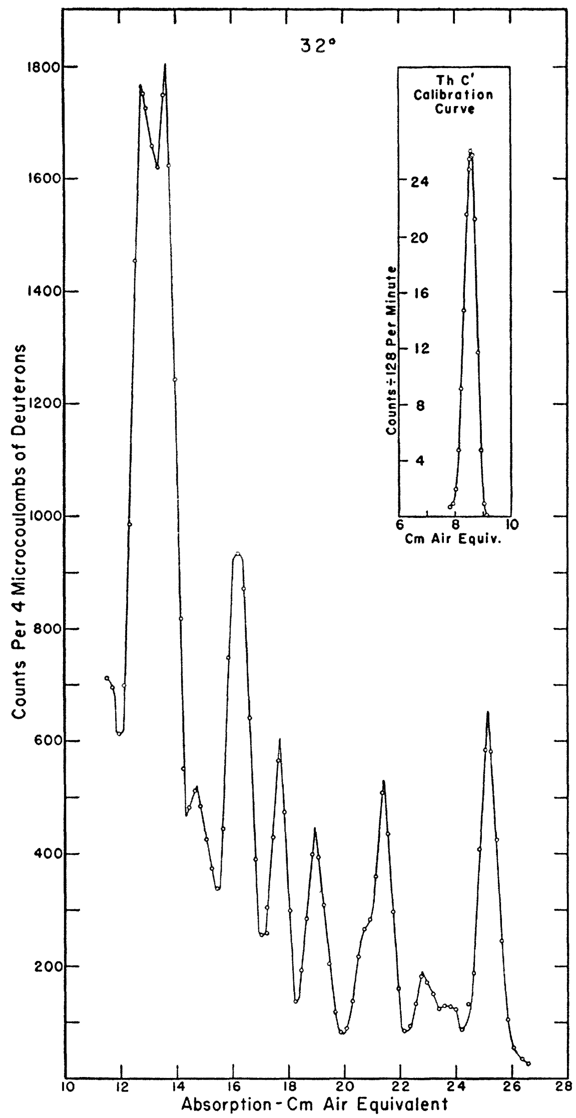

FIG. 3. Energy spectra of the alpha-particles from the reaction $Al^{27}(d, \alpha)Mg^{25}$ at 32°. The inset shows the counter calibration curve obtained using the alpha-particles from ThC′.

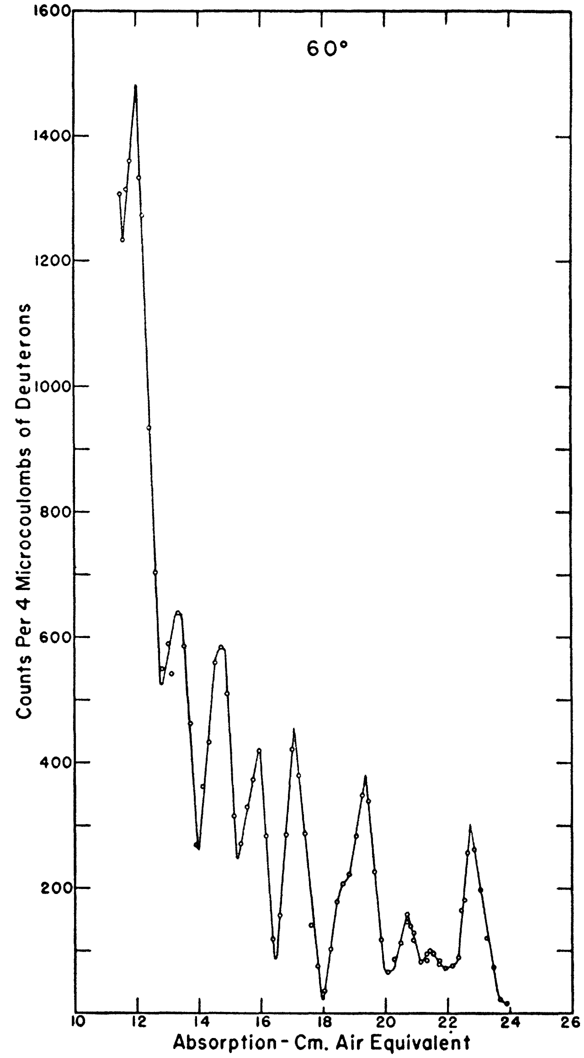

FIG. 4. Energy spectra of the alpha-particles from the reaction $Al^{27}(d, \alpha)Mg^{25}$ at 60°.

The absorption curves were obtained by taking the alpha-particle counts recorded while a given amount of charge was collected by the beam current integrator. The counts at each point were thus normalized even when the beam current varied during a run.

IV. RESULTS AND DISCUSSION

The absorption curves obtained from measurements made at four representative angles with the deuteron beam are shown in Figs. 3–6. More alpha-particle groups are observed at the forward angles because of the greater momentum contribution from the beam. The counter and reaction chamber windows plus the minimum air gap limited the counting of alpha-particles from the target to those with a range greater than 11.5 cm of air. The curve taken at 32° shows nine of the groups well resolved with definite evidence of two additional groups, Q_1 and Q_4, that are not completely resolved. The width of the groups agrees well with the straggling in the absorbers to be expected at these energies. A calibration curve of ThC′ alpha-particles is shown in the inset of Fig. 3 for comparison.

The mean ranges of the alpha-particle groups were obtained by locating the position of the ThC′ alpha-particle peak on the absorption curve and then adding the differences to the mean range of the ThC′ alpha-particles. The conversion of the range to energy was then made from the range-energy curves of Livingston and Bethe.[4]

The Q-values were calculated for the alpha-particle groups from the data taken at each of the eight angles and are presented in tabular form in Table I. The agreement at the different angles is well within the probable

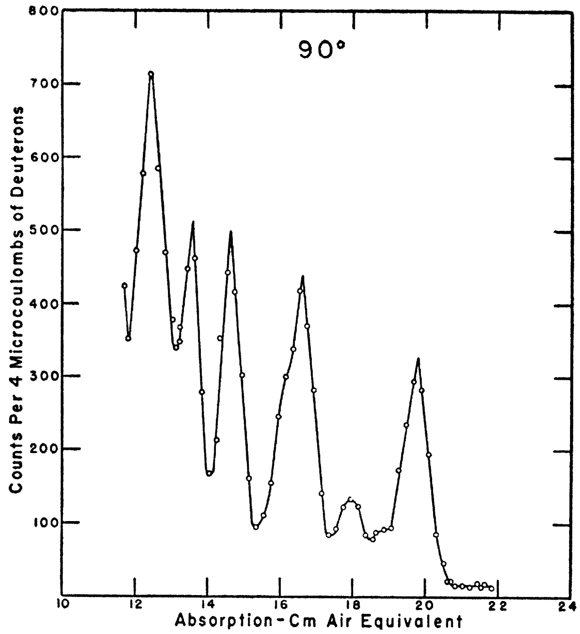

FIG. 5. Energy spectra of the alpha-particles from the reaction $Al^{27}(d, \alpha)Mg^{25}$ at 90°.

error, indicating that all of the alpha-particle groups originate from the deuteron reaction on aluminum rather than from any contaminant on the target foil.

The mass difference $Al^{27}-Mg^{25}$ can be calculated from the Q value for the most energetic group of alpha-particles, which leaves the Mg^{25} nucleus in the ground state. Taking the average value of 6.58±0.03 Mev for Q_0 and the value for the deuteron and alpha-particle masses from Bethe's[7] table, the value obtained for the $Al^{27}-Mg^{25}$ mass difference is 1.99626±0.00003 a.m.u.

The average level spacing is 0.6 Mev and is seen to be nearly constant up to the highest measured level at 5.95 Mev. The general trend may be noted for the higher values of the relative intensities, of the alpha-particle groups which leave the residual nucleus in a higher state of excitation.

The energy levels in Mg^{25} are tabulated in Table II, together with the values for the levels given by other authors for comparison. The values of Pollard, Sailor, and Wyly lie between the values given in this paper and seem to be the composite value of unresolved groups. The agreement with the levels found by French and Treacy is quite good. The fourth column in Table II gives the levels found by Allan, Wilkinson, Burcham, and Curling[8] for the reaction $Mg^{24}(d, p)Mg^{25}$. The two energy levels in column 5 were obtained by Fulbright and Bush[9] in the inelastic scattering of protons from Mg. The lines appeared very weak and could well be attributed to the levels in Mg^{25} at 1.97 and 2.74 Mev.

The β-decay of Na^{25} to Mg^{25} was studied by Bleuler and Zünti[10] by absorption methods. Their absorption curve indicated a β-group of about 3.4 Mev energy. They also found a weak γ-ray of energy greater than 0.5 Mev. They proposed a complex decay scheme in which a 3.7 Mev β-ray goes to the ground state of Mg^{25} in 55 percent of the disintegrations, and a 2.7 Mev β-ray goes to an excited level in Mg^{25} in 45 percent of the disintegrations. The emission of a 1 Mev γ-ray from this level would account for the observed γ-ray. This

TABLE I. Q-values of $Al^{27}(d, \alpha)Mg^{25}$ (values are in Mev).

	32°	46°	60°	74°	90°	110°	124°	138°	Average
Q_0	6.55	6.61	6.55	6.58	6.60	6.58	6.61	6.58	6.58±0.03
Q_1	5.92	6.04	5.96	6.04	6.05	6.07	5.99	6.03	6.01±0.08
Q_2	5.54	5.65	5.61	5.64	5.66	5.69	5.62	5.56	5.62±0.07
Q_3	4.92	4.96	4.96	5.00	4.95	4.95	4.98	4.92	4.95±0.03
Q_4	4.59	4.61	4.55	4.73	4.58				4.61±0.06
Q_5	3.78	3.88	3.80	3.87	3.85	3.85	3.84		3.84±0.04
Q_6	3.19	3.19	3.25	3.23	3.27	3.19			3.22±0.04
Q_7	2.45	2.60	2.60	2.62	2.57				2.57±0.05
Q_8	1.68	1.81	1.83						1.77±0.08
Q_9	1.11	1.10	1.08						1.10±0.04
Q_{10}	0.61	0.65							0.63±0.04

TABLE II. The energy levels in Mg^{25}.

This report	Pollard, Sailor, and Wyly[a]	French and Treacy[b]	Allan *et al.*[c]	Fulbright and Bush[d]
0.57±0.05 Mev		0.58±0.05 Mev	0.58 Mev	
0.96±0.05	0.81±0.07 Mev	0.94±0.05	0.98	
1.63±0.04	1.58±0.07	1.54±0.05		
1.97±0.05		1.87±0.05		1.98 Mev
2.74±0.04	2.54±0.07			2.64
3.36±0.04				
4.01±0.05				
4.81±0.05				
5.48±0.05				
5.95±0.05				

[a] Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949).
[b] A. P. French and P. B. Treacy, Proc. Phys. Soc. London **63**, 665 (1950).
[c] H. R. Allan *et al.*, Nature **163**, 210 (1949).
[d] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).

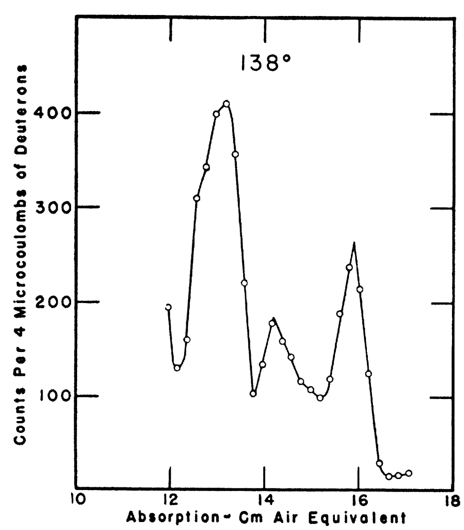

FIG. 6. Energy spectra of the alpha-particles from the reaction $Al^{27}(d, \alpha)Mg^{25}$ at 138°.

[7] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley & Sons, Inc., New York, 1947).

[8] Allan, Wilkinson, Burcham, and Curling, Nature **163**, 210 (1949).
[9] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).
[10] E. Bleuler and W. Zünti, Helv. Phys. Acta **20**, 195 (1947).

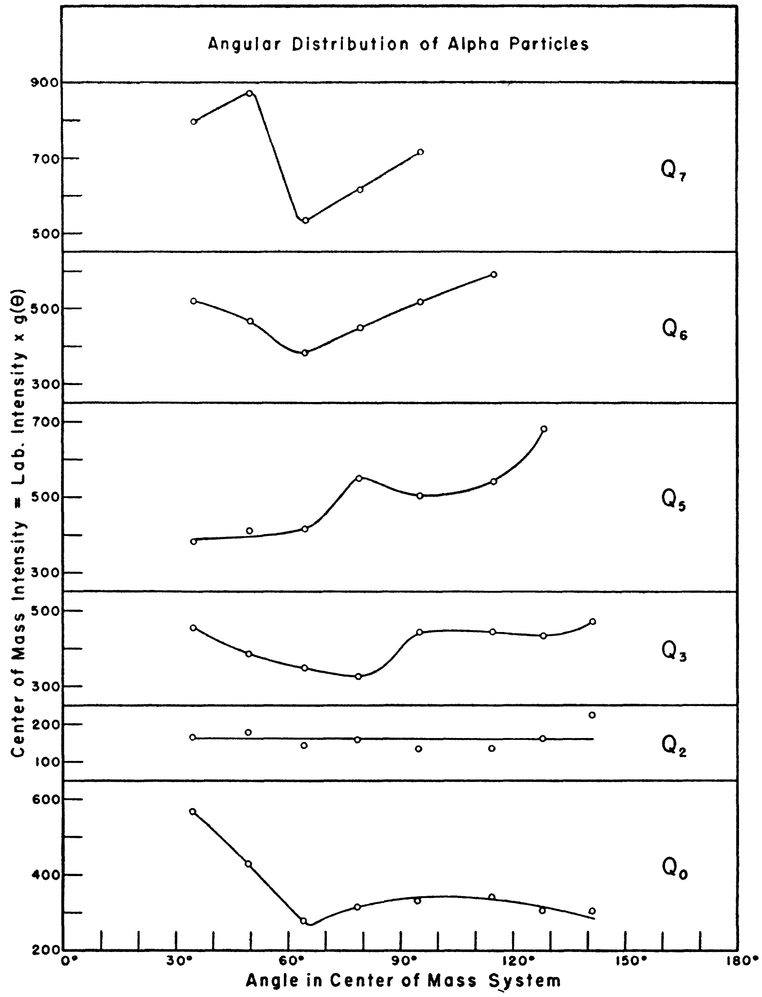

FIG. 7. Angular distribution of alpha-particles from the reaction $Al^{27}(d, \alpha)Mg^{25}$.

excited state could very well be the same one found at 0.96 Mev in the reaction $Al^{27}(d, \alpha)Mg^{25}$.

The angular dependences of the intensities of the alpha-particle groups are shown in Fig. 7 for each of the angles measured. The angles in the laboratory system were converted to the center of mass system by the relation:

$$\sin^2(\theta_r-\theta)/\sin^2\theta = m_1m_2E_1/m_3(m_0E_1+MQ).$$

The subscripts 0, 1, 2, 3 refer to the target nucleus, the incident particle, the product particle and the residual nucleus respectively, and M is the total mass in the reaction; θ and θ_r are the laboratory and center of mass angles respectively.

The observed intensity in the laboratory system must then be converted to the true intensity in the center of mass system since the solid angle defined by the detector aperature is different in the two systems. This conversion factor is:

$$g(\theta) = (\sin^2\theta/\sin^2\theta_r)\cos(\theta_r-\theta).$$

It may be remarked that the curves in Fig. 7 show a marked dependence of the alpha-particle yield on the angle for all the groups except Q_2. This group is isotropic within the probable error of the measurements.

The authors wish to thank Professor Allan C. G. Mitchell for his interest in this work. They would also like to acknowledge the help given by the Indiana University cyclotron crew and in particular the assistance of Mr. E. Toops in plotting some of the graphs.