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INVESTIGATION OF THE (d,α) REACTION ON ALUMINUM 27

by Joseph R. Priest and John S. Vincent

Lewis Research Center
Cleveland, Ohio

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ERRATA

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Page 15: The subtitle for table I(e) should read

(e) Fourth excited state; total angular momentum number $J = 5/2^+$; quantum number $K = 1/2^+$; reaction energy $Q = +6.702 - 1.962$ MeV.

Page 16: The subtitle for table I(f) should read

(f) Eighth excited state; total angular momentum quantum number $J = 9/2^+$; quantum number $K = 5/2^+$; reaction energy $Q = +6.702 - 3.399$ MeV.

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Lewis Research Center

SUMMARY

The angular distributions of seven alpha-particle groups from the (d, α) reaction on aluminum 27 (Al^{27}) were measured. The deuteron energy was 20.9 MeV in the laboratory system. The angular distributions are all peaked in the forward direction and have little structure. The integrated differential cross sections for those reactions that leave the Mg^{25} nucleus in the $K = 5/2^+$ rotational states are, in general, more than one order or magnitude larger than those that leave Mg^{25} in the $K = 1/2^+$ rotational states. The angular distributions corresponding to a given rotational band in Mg^{25} are strikingly similar both in magnitude and shape.

Analysis of the energy level structure in terms of the rotational model indicates that the state in Mg^{25} at 5.47±0.03 MeV is the $11/2^+$ member of the $K = 5/2$ band.

INTRODUCTION

In a study of the reactions Al^{27} (p, α) Mg^{24} and Mg^{25} (p, d) Mg^{24} Nolen and Scherr (ref. 1) reported that the angular distributions corresponding to six states in magnesium 24 (Mg^{24}) have features that appear to depend on whether the transition is to the $K = 0$ or $K = 2$ rotational bands of Mg^{24}. Although it is impossible to derive from their abstract of the presentation what those features are, one can surmise that the angular distributions corresponding to $K = 0$ and $K = 2$ differ not only in magnitude and shape, but the angular distributions within each band are similar. Cosper, Lucas, and Johnson (ref. 2) who investigated the reaction Al^{27} (d, α) Mg^{25} for a deuteron energy of 9.2 MeV (laboratory) observed a noticeable similarity in the forward angle ($<90^o$) portion of the angular distributions of the α_0 and α_3 alpha-particle groups, which correspond to

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$5/2^+ (K = 5/2)$ and $7/2^+ (K = 5/2)$ states of magnesium 25 (Mg^{25}). Conversely, a noticeable dissimilarity exists in the forward angle portion of the angular distributions of the α_1, α_2, and α_4 alpha-particle groups that correspond to $1/2^+ (K = 1/2)$, $3/2^+ (K = 1/2)$, and $5/2^+ (K = 1/2)$ states of Mg^{25}. Theoretical interpretations (refs. 3 and 4) of Mg^{25} based on the unified model of Nilsson (ref. 5) indicate that the $K = 1/2$ states are admixtures of various Nilsson orbitals. This observation tempted Cosper and his coworkers to speculate that these theoretical interpretations might have some bearing on the forward angular dissimilarities.

The angular distributions of seven alpha-particle groups from the reaction $Al^{27} (d, \alpha) Mg^{25}$ have been measured at Lewis for a deuteron energy of 20.9 MeV (laboratory). The reaction features observed in references 1 and 2 and outlined in the previous paragraph have emerged even more strongly in this reaction. These results and some possible implications are reported herein.

SYMBOLS

A, a, B	constants that depend on rotational band in question
d	deuteron
$d\sigma/d\Omega$	center-of-mass differential cross section
E	energy
E_0	energy of ground state
E_α	incident alpha particle energy in laboratory system
$E/\hbar\omega_0$	energy units in terms of quantinized harmonic oscillator
J	total angular momentum quantum number
K	rotational quantum number, K is projection of total angular momentum along symmetry axis of nucleus
L	total orbital angular momentum quantum number
ℓ_d, ℓ_α	orbital angular momentum quantum numbers of initial and final system
m	mass of nucleus, amu
p	proton
Q	reaction energy
$\vec{q}$	momentum transfer vector
W	excitation energy, see eq. (4)

$1d_{5/2}$, $1s_{1/2}$	shell model configurations
α	alpha particle
$\alpha_0, \alpha_1, \alpha_2, \ldots$	alpha group in order of excitation
η	nuclear deformation
θ	reaction angle
Ω	solid angle

Subscripts:

exp	experimental
cal	calculated

PROCEDURE

A pure aluminum target area (density, 0.520 mg/cm^2) was bombarded with the 21.1±0.1-MeV deuteron beam from the Lewis Research Center cyclotron. The alpha particles from the aluminum 27 plus deuteron (Al^{27} + d) reaction were detected in four 5000-ohm-centimeter surface-barrier silicon detectors, the defining apertures of which were accurately spaced 5^{o} apart. Each aperture subtended a solid angle of 2.78×10^{-4} steradians. A block diagram of the electronics associated with a detector is shown in figure 1. The final output pulse from a given detector was routed into a particular 512-channel subsection of the 4096-channel pulse-height analyzer. The alpha particles were discriminated from charge 1 (Z = 1) reaction products (protons, deuterons, and tritons) by setting the reverse bias on the detectors until the depletion region was just sufficient to absorb the full energy of the most energetic alpha particle. A Z = 1 particle of the same energy would then deposit only a fraction of its energy within the sensitive region of the detector. The Q-value of +6.702 MeV for the $Al^{27}(d, \alpha)Mg^{25}$ reaction as compared with -2.756 MeV for $Al^{27}(d, He^3)Mg^{26}$, for example, easily allows the separation of the alpha-particle groups of interest from Z= 2 reaction products. The overall energy resolution of the system was about

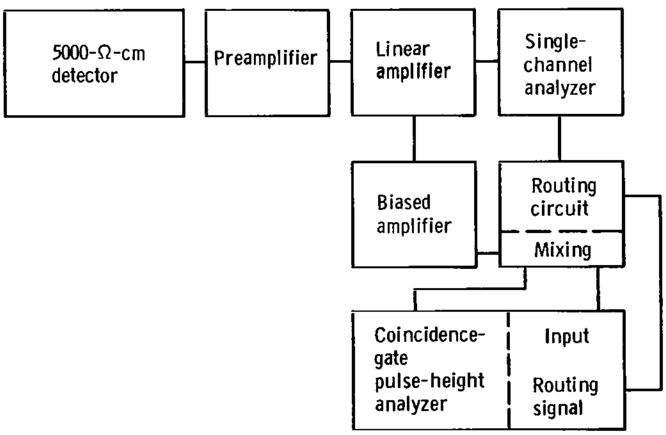


Figure 1. - Electronics associated with a single counter.

Peak	Rotational quantum number, K	Total angular momentum quantum number, J	Excitation energy, W, MeV
1			5.47±0.03
2	5/2	9/2+	[a]3.399
3	1/2	3/2+, 5/2+	2.803
	1/2		2.736
		1/2+	2.565
4	1/2	5/2+	[a]1.962
5	5/2	7/2+	[a]1.611
6	1/2	3/2+	[a].976
7	1/2	1/2+	[a].584
8	5/2	5/2+	[a]0

[a]Resolved energy levels.

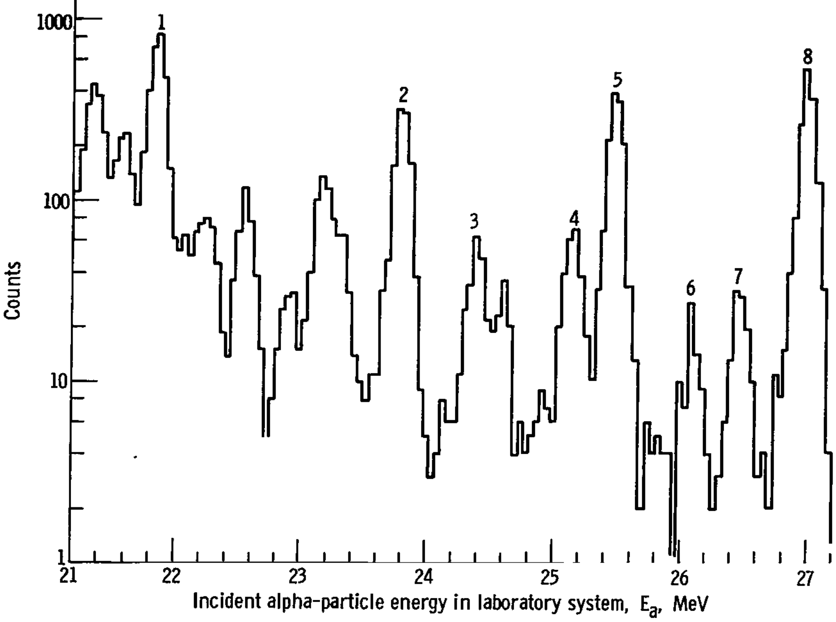


Figure 2. - Typical spectrum for $Al^{27}(d,\alpha)Mg^{25}$ reaction. Reaction energy Q = 6.702 MeV; deuteron energy E_α = 20.9 MeV(lab); laboratory scattering angle θ_{lab} = 17.5°.

300 keV (full width at half maximum). A typical histogram spectrum is shown in figure 2.

RESULTS

The overall energy resolution was sufficient to allow the separation of six alpha-particle groups corresponding to the ground and five excited states of Mg^{25}. The energy level scheme of Mg^{25} and the levels resolved in this experiment are shown in figure 2 of reference 6. The experimental results of this study are presented in table I. The experimental results plotted in the form of center-of-mass differential cross sections (μb/sr) against center-of-mass reaction angle (deg) are shown in figures 3 and 4. The errors shown are those due to statistical uncertainties, and if not specified, are less

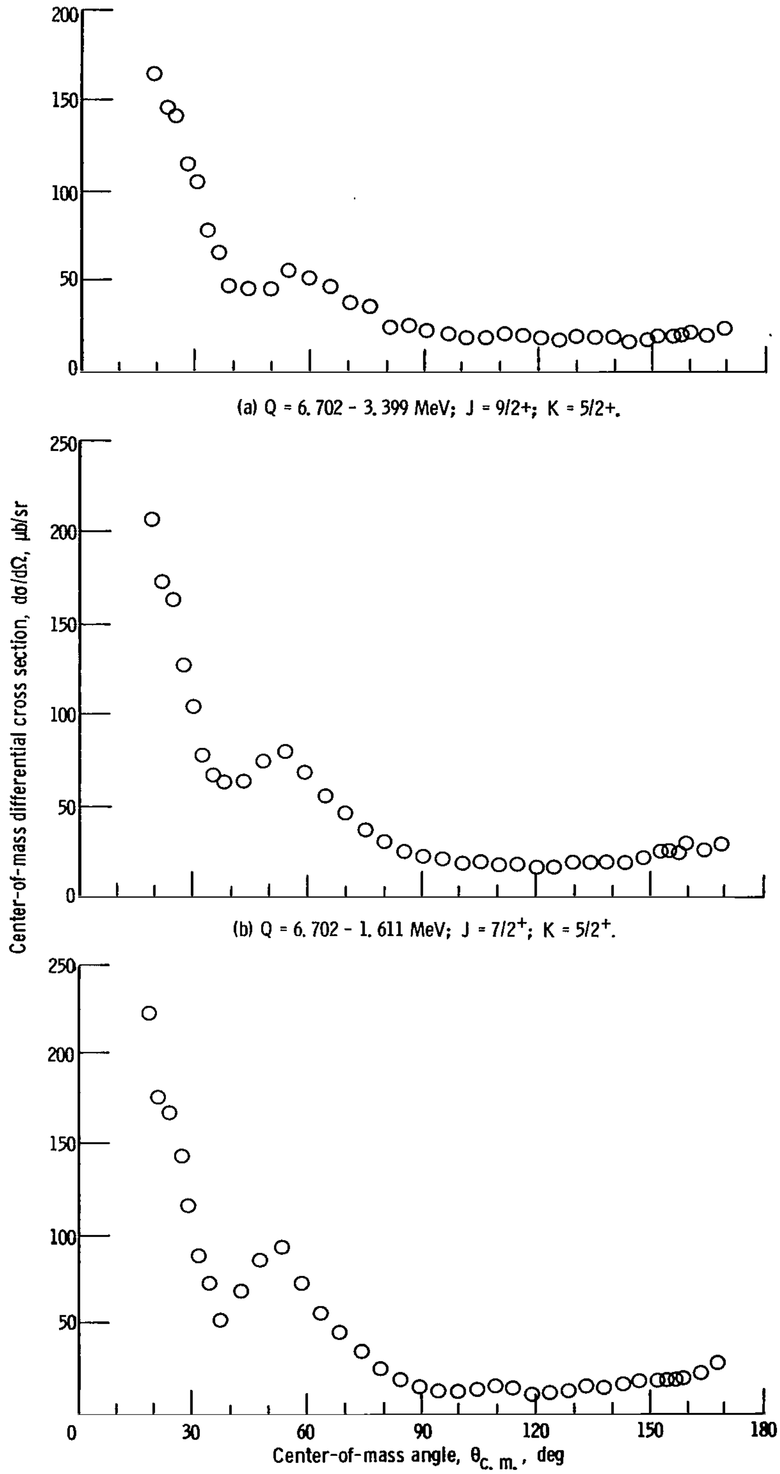
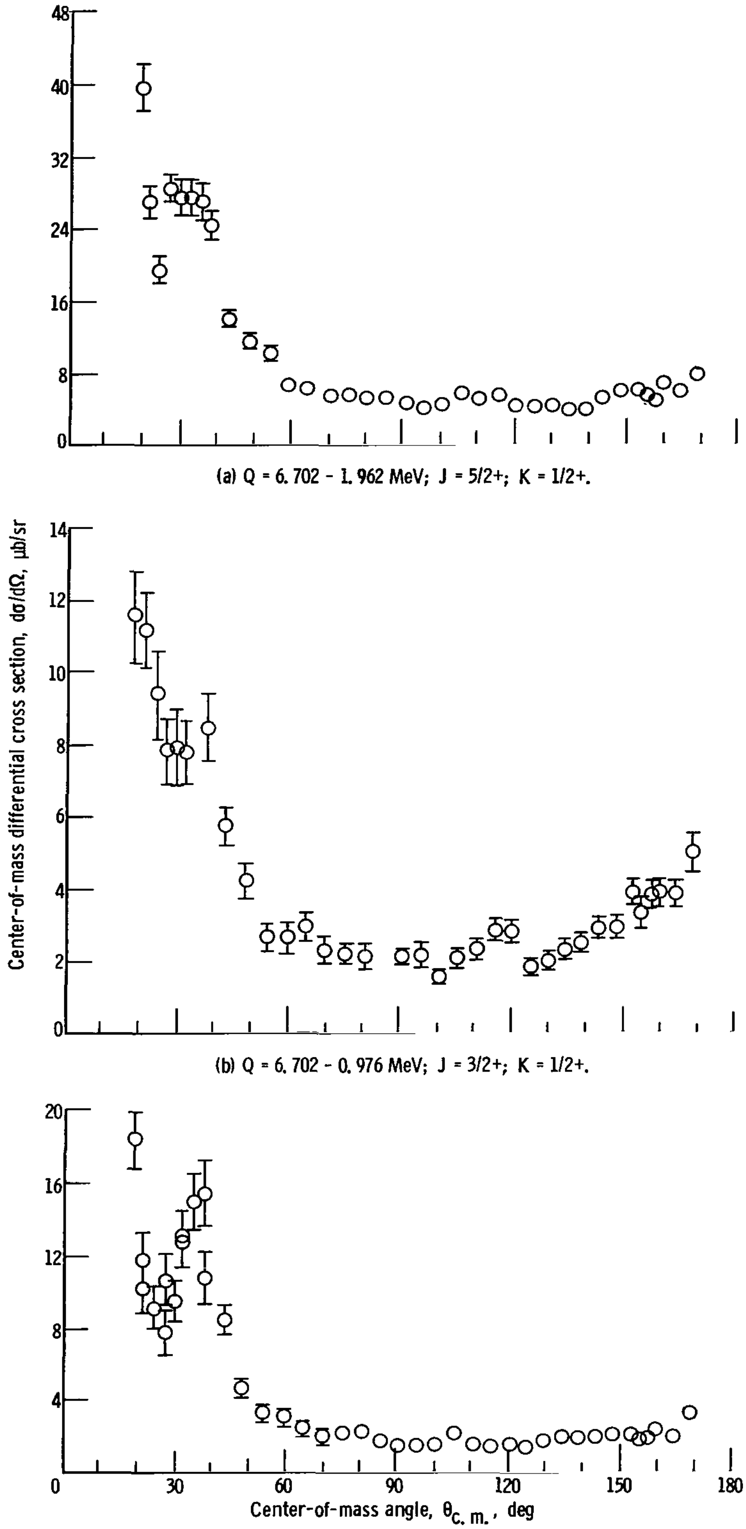


Figure 3. - Angular distributions corresponding to the K = 5/2+ states of magnesium 25.



(c) = 6.702 - 0.584 MeV; J = 1/2+; K = 1/2+.

Figure 4. - Angular distributions corresponding to the K = 1/2+ states of magnesium 25.

than the size of the point. For purposes of illustration, the angular distributions corresponding to the K = 5/2 and K = 1/2 bands of Mg^{25} indicated in figure 2 are grouped together.

DISCUSSION

Effects of Rotational Structure on Differential Cross Sections

Several features of the preceding results are worthy of mention:

(1) All angular distributions are peaked in the forward direction with very little, if any, enhancement in the backward direction. This feature is in sharp contrast with the data at 0.2 MeV (ref. 2) where a significant backward peaking was observed.

(2) The angular distributions corresponding to the K = 5/2 states are nearly one order of magnitude greater than those corresponding to the K = 1/2 states. In order to illustrate this further, the differential cross sections were integrated from 20° to 170°. The results are shown in table II.

These data also show clearly that the approximate proportionality between the integrated cross sections and 2J + 1 observed for the same reaction for 10.1 MeV deuterons (ref. 7) does not hold for 21 MeV deuterons.

(3) A striking similarity exists both in magnitude and shape between the angular distributions corresponding to the K = 5/2 states. The integrated differential cross sections for these three angular distributions differ from the average value of 450 microbarns by less than 6 percent.

(4) Some similarity is apparent in the shapes of the angular distributions corresponding to the $K = 1/2^{+}$ states. The shallow minimum at about 27° and the maximum at about 38° appear in all three cases.

The systematics observed in these angular distributions seem to be more than just accidental. Obviously, the transitions to the $K = 1/2^{+}$ states are being inhibited. The systematics of the data suggest that this inhibition is associated with the rotational state characterized by the quantum number K.

Considerable evidence from other types of reactions support this hypothesis. For example, the reactions $Mg^{24}(\alpha, \alpha')Mg^{24}$ and $Mg^{25}(\alpha, \alpha')Mg^{25}$ for $E_{\alpha} = 40$ MeV which leave the residual nuclei in known collective rotational states, have been analyzed successfully by Blair (ref. 8) in terms of his adiabatic theory. In the reaction $Mg^{25}(d, d')Mg^{25}$ Blair and Hamburger (ref. 9) observed that the ground state, 1.611 MeV, and the 3.399 MeV $K = 5/2^{+}$ states were preferentially excited. Their interpretation of this result is that the formation of the $K = 5/2^{+}$ states only requires excitation of a rotational collective mode, while the formation of a $K = 1/2^{+}$ state requires the excitation of a single particle from Nilsson orbit 5 to orbits 9, 11, or 8. The experiment and theoretical interpretations of Blair and Hamburger (ref. 11) are consistent with the fact that collective states are easier to excite than single particle states. Furthermore, the ratio of the differential cross sections for this scattering at 29.7° for the $9/2^{+}$ ($K = 5/2^{+}$) and the $7/2^{+}$ ($K = 5/2^{+}$) states is in good agreement with the theoretical expectation of the simple inelastic diffraction scattering model (ref. 10). A similar interpretation seems appropriate for the results of the $Al^{27}(d, \alpha)Mg^{25}$ reaction. The ground states of both Al^{27} and Mg^{25} have a spin and parity of $5/2^{+}$, and these states are the first members of a $K = 5/2^{+}$ rotational band. Both nuclei are prolate spheroids and have very nearly the same ground state quadrupole moment of ≈ 0.15 barns (ref. 11) and rotational moment of inertia (ref. 4). The single particle configurations for these nuclei are similar since Al^{27} has five $1d_{5/2}$ protons coupled to $J = 5/2^{+}$, and Mg^{25} has five $1d_{5/2}$ neutrons coupled to $J = 5/2^{+}$. In the collective rotational model scheme of the ground states of Al^{27} the last $1d_{5/2}$ proton and the last two $1d_{5/2}$ neutrons of Al^{27} are in the fifth Nilsson orbit. For Mg^{25} the last two $1d_{5/2}$ protons are in the seventh Nilsson orbit, and the last $1d_{5/2}$ neutron is in the fifth Nilsson orbit. This is illustrated in the Nilsson diagram (refs. 4 and 9) for Al^{27} reproduced in figure 5. The corresponding diagram for Mg^{25} is the same except that a $1d_{5/2}$ proton and $1d_{5/2}$ neutron are removed. The validity of this model is strengthened by the careful study of the mirror nuclei Al^{25} and Mg^{25} by Litherland, et al (ref. 3). If the reaction $Al^{27}(d, \alpha)Mg^{25}$ proceeds by a pickup of a neutron and proton from Al^{27}, then the $K = 5/2^{+}$ states could be formed simply by exciting rotational modes. The formation of the $K = 1/2^{+}$ states, however, would require not only rotational excitation but also the promotion of the $1d_{5/2}$ neutron in the fifth Nilsson orbit to a $2s_{1/2}$ state in the ninth Nilsson orbit. In addition, the rotational moment of inertia of the $K = 1/2^{+}$ states is substantially larger than that for the $K= 5/2^{+}$ states (ref. 3), and therefore considerable rearrangement of the nucleons would be required. Thus, the $K = 1/2^{+}$ transitions should be inhibited.

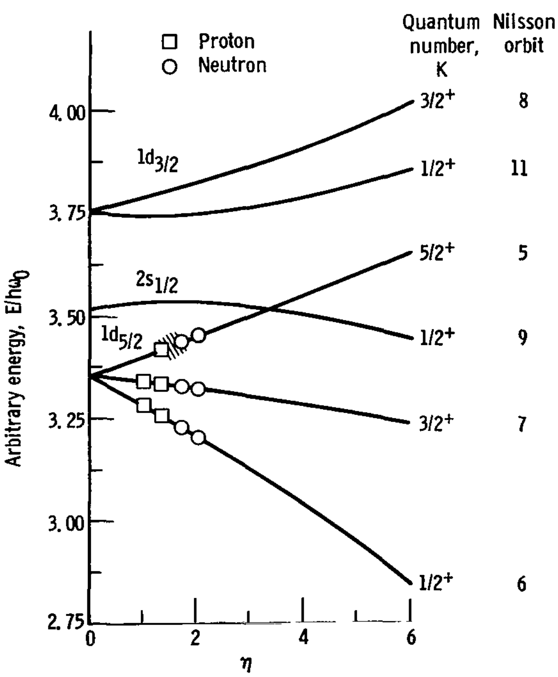


Figure 5. - Nilsson diagram for aluminum 27.

The very nature of the forward peaking observed in all seven angular distributions suggests a DWBA (distorted wave Born approximation) analysis in terms of a direct interaction knockout or pickup mechanism.

Limited experience with DWBA direct reaction knockout calculations (ref. 12) using the FORTRAN code in reference 13 for the reactions $F^{19}(d, \alpha)O^{17}$ and $N^{15}(d, \alpha)C^{13}$ have shown that reasonable fits can be obtained if only a single L-value is required or if a single L-value dominates. The magnitude of the orbital angular momentum L is given by the selection rule

$$\vec{J}_{Mg^{25}} = \vec{J}_{Al^{27}} + \vec{\ell}_d - \vec{\ell}_\alpha + \vec{S}_{deuteron} = \vec{J}_{Al^{27}} + \vec{L} + \vec{S}_d$$

Since $\left|\vec{J}_{Al^{27}}\right| = 5/2$ and $\left|\vec{S}_d\right| = 1$ only one case exists $(5/2^+ \rightarrow 1/2^+)$ where less than three L-values are allowed. From the shape of the angular distributions and the lack of a distinct oscillatory behavior, it can be concluded that more than one L-value is contributing; however, it is very difficult to ascertain the proportion in which the various L-values contribute. Hopefully, the analyses of other less complicated (d, α) reactions will lead to some systematic set of DWBA parameters that will allow a logical fitting of the $Al^{27}(d, \alpha)Mg^{25}$ data.

Analysis for 5.47 MeV State in Magnesium 25

The unusually high intensity of the group of alpha particles corresponding to an excitation of 5.47±0.03 MeV makes it possible to extract an approximate cross section and Q-value. The overall energy resolution of approximately 300 keV and the number of levels at this excitation is such that certainly more than one level is excited. The width of the peak, however, indicates that perhaps a single level is preferentially excited. A reasonable estimate of the background contribution to this group was made, therefore, and the differential cross section was calculated. The results are shown in figure 6. The shape of the angular distribution is very similar to those corresponding to the excitation of the $K = 5/2^+$ states of Mg^{25}. The peak at about 65°, however, appears at a slightly larger angle. If the reaction leading to the $K = 5/2^+$ states proceeds by picking up a neutron and a proton, the angular dependence of the differential cross sections according to simple theory

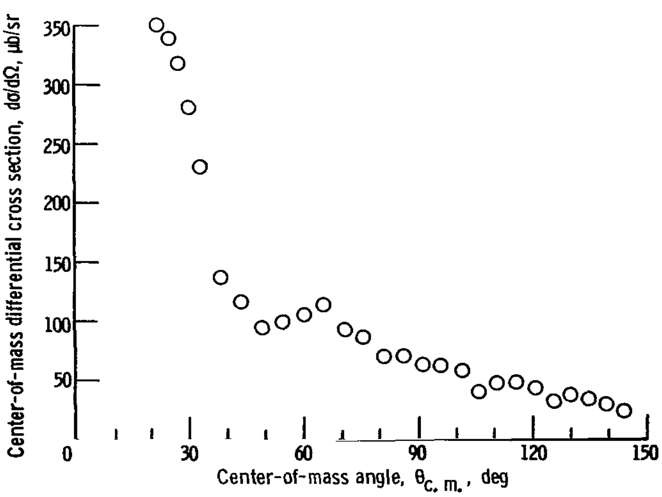


Figure 6. - Angular distribution of group corresponding to excitation of 5.47±0.03 MeV in magnesium 25; Q = 6.702 - 5.47 MeV.

should be characterized by the magnitude of the momentum transfer vector $\vec{q} = \left(m_{Mg^{25}}/m_{Al^{27}}\right) \vec{K}_d - \vec{K}_\alpha$ (ref. 14). The peaks at about 55^o and 65^o for the ground and the 5.47-MeV states correspond to $|\vec{q}| = 2.08\times10^{13}$ and 1.98×10^{13} centimeters^{-1}, respectively. Thus, the differential cross sections as a function of $|\vec{q}|$ are more nearly identical. It might be speculated that this level corresponds to the fourth member of the $K = 5/2^+$ rotational band with spin $J = 11/2^+$. Litherland's analysis (ref. 3) shows that the energies of the first few levels can be fitted well by the rotational model expression

$$E = A\left[J(J + 1) + a(-1)^{J+1/2}\left(J + \frac{1}{2}\right)\right] + B\left[J(J + 1) + a(-1)^{J+1/2}\left(J + \frac{1}{2}\right)\right]^2 \qquad (1)$$

where A, a, and B are constants that depend on the rotational band in question. For the $K = 5/2^+$ band, $a \equiv 0$, and Litherland found that $A = 272$ keV and $B = -1.69$ keV. The expression yields excitation energies of 1.614 and 3.446 MeV for the known $J = 7/2^+$, $K = 5/2^+$ and $J = 9/2^+$, $K = 5/2^+$ states. These compare very well with the measured values of 1.611 and 3.399 MeV. Substitution of $J = 11/2$ into this expression then gives an excitation energy of 5.313 MeV. The peak in question corresponds to an experimental excitation energy of 5.47±0.03 MeV. This result is reasonably consistent with the calculated value of 5.313 MeV for the proposed $J = 11/2^+$ state. The agreement, though, is less satisfying then that obtained for the 1.611- and 3.399-MeV states. The evaluation of the A and B coefficients, however, were based on a limited number of known $K = 5/2^+$ states. Litherland has indicated (ref. 3) that these values should be treated with caution.

Other evidence exists that supports this speculation for the $J = 11/2^+$ state. In a very careful study of the reaction $Mg^{24}(d, p)Mg^{25}$ at 10 MeV, Middleton and Hinds (ref. 15) report a level doublet corresponding to an excitation of 5.454 and 5.465 MeV in Mg^{25}. The 5.465-MeV state is assigned a spin and parity of $1/2^+$ as a result of an analysis using the Butler stripping theory. The 5.454-MeV level is very weakly excited, and no spin and parity assignment was possible. The 1.611 ($J = 7/2^+$, $K = 5/2^+$) and 3.399 ($J = 9/2^+$, $K = 5/2^+$) MeV states are also very weakly excited. The angular distribution for the 1.611-MeV state shows little resemblance to a stripping pattern, which for this transition would require a transfer of four units of angular momentum. Sheline and Harlan (ref. 16) studied the reaction $Al^{27}(d, \alpha)Mg^{25}$ at 7.5 to 8.5 MeV, and although they were not able to resolve the 5.454- and 5.465-MeV doublet, they were able to estimate from the intensity of the group and the barrier penetrability for alpha particles that the possible spins would lie between 5/2 and 13/2. Since the 5.465-MeV state has been found to have spin $J = 1/2^+$, the major contribution to this group must come from excitation of the 5.454-MeV state. The assignment of $J = 11/2^+$ to this state would then be consistent with the estimates of Sheline and Harlan.

With the assumption that the 5.454-MeV state is the $J = 11/2^+$ member of the $K = 5/2^+$ rotational band, the constants A and B in equation (1) were reevaluated. The procedure used was the following: Equation (1) for the energy of the $K = 5/2^+$ states can be written

$$E = Ax + Bx^2 \tag{2}$$

where $x = J(J + 1)$ and J is the spin quantum number of the state in Mg^{25}. The excitation energy W is then

$$W = E - E_0 = Ax + Bx^2 - E_0 \tag{3}$$

where E_0 is the energy of the ground state. A least squares fit to equation (3) was performed. The results are $A = 250$ keV $B = -1.08$ keV. A comparison of the experimental results with those calculated from equation (3) is shown in table III. As can be seen, the results are quite satisfactory. The excitation energy also suggests that this is possibly the fourth member of the $K = 5/2^+$ rotational band.

Although the level quantum numbers $J = 11/2^+$ and $K = 5/2^+$ cannot be assigned unambiguously to the 5.454-MeV state, these analyses yield results that are consistent with this assignment.

CONCLUDING REMARKS

The distinct forward peaks observed in all seven angular distributions indicate that the reactions proceed by a direct interaction mechanism. Furthermore, the structure of Al^{27} and Mg^{25} led to the conclusion that this mechanism is the pickup of a neutron and proton from Al^{27}. The transition to the $K = 5/2^+$ states is envisaged as a pickup of a $1d_{5/2}$ neutron and proton and an excitation of a rotational collective mode. The excitation of the $K = 1/2^+$ states in this scheme would be a pickup of a $1d_{5/2}$ neutron and proton but with an excitation of a $1d_{5/2}$ neutron to a $2s_{1/2}$, $K = 1/2^+$ state. The inhibition of the transitions to the $K = 1/2^+$ rotational states is analogous to the corresponding situation in the inelastic scattering of deuterons and alpha particles. The 5.454 MeV state in Mg^{25} has been tentatively identified as the $J = 11/2^+$ member of the $K = 5/2^+$ rotational band built on the ground state of Mg^{25}.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 3, 1966,
129-02-04-06-22.

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TABLE I. - EXPERIMENTAL DATA FOR $Al^{27}(d, \alpha)Mg^{25}$

(a) Ground state; total angular momentum quantum number $J = 5/2^+$; quantum number $K = 5/2^+$; reaction energy $Q = +6.702$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.1	222.2	5.9
21.8	174.9	4.3
24.6	167.5	5.1
27.3	134.2	3.7
30.0	115.7	4.3
32.7	87.7	3.1
35.4	72.6	3.4
38.1	53.1	2.4
43.5	68.0	1.9
48.8	84.8	2.2
54.1	92.7	2.3
59.4	72.3	2.0
64.7	56.4	1.4
69.9	45.2	1.2
75.1	33.8	1.1
80.2	25.5	.9
85.3	19.3	.6
90.4	14.8	.6
95.4	13.7	.6
100.4	12.1	.5
105.3	14.0	.6
110.2	15.5	.7
115.1	14.0	.7
119.9	11.2	.6
124.7	12.0	.5
129.4	13.2	.5
134.1	15.1	.6
138.8	14.3	.6
143.5	16.2	.7
148.1	18.3	.8
152.7	18.7	.8
157.3	19.3	.8
155.0	18.8	.9
159.6	26.4	1.1
164.1	23.0	1.0
168.7	28.2	1.2

(b) First excited state; total angular momentum quantum number $J = 1/2^+$; quantum number $K = 1/2^+$; reaction energy $Q = +6.702 - 0.58$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
21.9	11.8	1.6
21.9	10.2	1.4
19.1	18.5	1.7
24.6	9.1	1.2
27.3	7.8	1.3
27.3	10.6	1.5
30.0	9.5	1.2
32.7	12.9	1.6
32.7	13.0	1.7
35.4	15.0	1.6
38.1	15.5	1.8
38.1	10.8	1.5
43.5	8.5	.7
48.9	4.7	.5
54.2	3.3	.4
59.5	3.1	.4
64.7	2.5	.3
70.0	2.0	.3
75.1	2.2	.3
80.3	2.2	.3
85.4	1.7	.2
90.5	1.5	.2
95.5	1.5	.2
100.5	1.5	.2
105.4	2.1	.2
110.3	1.4	.2
115.1	1.4	.2
120.0	1.5	.2
124.7	1.4	.2
129.5	1.7	.2
134.2	1.8	.2
138.9	1.8	.2
143.5	1.9	.3
148.1	2.0	.3
152.7	1.9	.3
157.3	1.7	.2
155.0	1.8	.3
159.6	2.3	.3
164.1	1.9	.3
168.7	3.2	.4

(c) Second excited state; total angular momentum quantum number $J = 3/2^+$; quantum number $K = 1/2^+$; reaction energy $Q = +6.702 - 0.976$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.2	11.6	1.3
21.9	11.2	1.1
24.6	9.4	1.2
27.3	7.9	.9
30.0	7.9	1.1
32.8	7.8	.9
35.5	6.2	1.0
38.2	8.5	1.0
43.5	5.7	.6
48.9	4.2	.5
54.2	2.6	.4
59.5	2.7	.4
64.8	3.0	.3
70.0	2.3	.3
75.2	2.2	.3
80.3	2.1	.3
85.4	3.0	.3
90.5	2.1	.2
95.5	2.2	.2
100.5	1.5	.2
105.4	2.0	.2
110.3	2.2	.3
115.2	2.8	.3
120.0	2.7	.3
124.8	1.8	.2
129.5	2.0	.2
134.2	2.2	.2
138.9	2.4	.2
143.5	2.8	.3
148.2	2.9	.3
152.8	3.8	.4
157.3	3.7	.4
155.0	3.2	.4
159.6	3.8	.4
164.2	3.8	.4
168.7	4.9	.5

TABLE I. - Continued. EXPERIMENTAL DATA FOR $Al^{27}(d, \alpha)Mg^{25}$

(d) Third excited state; total angular momentum quantum number $J = 7/2^+$; quantum number $K = 5/2^+$; reaction energy $Q = +6.702 - 0.976$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.2	206.[illegible]	5.7
21.9	172.0	5.9
24.6	161.8	5.0
27.4	127.3	5.1
30.1	104.1	4.1
32.8	77.1	4.0
35.5	65.8	3.2
38.2	63.4	3.6
43.6	63.1	1.9
48.9	73.7	2.0
54.3	78.8	2.1
59.6	68.2	2.0
64.8	55.4	1.4
70.1	46.1	1.2
75.2	36.2	1.1
80.4	30.3	1.0
85.5	25.1	.7
90.6	22.0	.7
95.6	20.4	.7
100.6	17.9	.6
105.5	18.8	.7
110.4	17.5	.7
115.2	17.5	.7
120.1	15.7	.7
124.8	15.6	.6
129.6	19.1	.6
134.3	19.1	.7
138.9	19.0	.7
143.6	18.8	.8
148.2	22.2	.9
152.8	25.3	.9
157.4	24.1	.9
155.1	24.9	1.1
159.6	29.2	1.2
164.2	25.6	1.1
168.7	29.4	1.2

(e) Fourth excited state; total angular momentum number $J = 5/2^+$; quantum number $K = 1/2^+$; reaction energy $Q = +6.702 - 1.962$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.2	39.6	2.5
21.9	26.9	1.7
24.7	19.3	1.7
27.4	28.3	1.7
30.1	27.5	2.1
32.8	27.5	1.7
35.5	26.9	2.1
38.2	24.5	1.6
43.6	14.1	.9
49.0	11.4	.8
54.3	10.2	.8
59.6	6.8	.6
64.9	6.3	.5
70.1	5.8	.4
75.3	5.8	.4
80.4	5.5	.4
85.5	5.3	.3
90.6	4.8	.3
95.6	4.3	.3
100.6	4.6	.3
105.5	6.0	.4
110.4	5.3	.4
115.3	5.7	.4
120.1	4.6	.4
124.9	4.5	.3
129.6	4.7	.3
134.3	4.2	.3
139.0	4.3	.3
143.6	5.5	.4
148.2	6.3	.5
152.8	6.4	.5
157.4	5.2	.4
155.1	6.1	.5
159.7	7.2	.6
164.2	6.3	.5
168.7	8.2	.6

TABLE I. - Concluded. EXPERIMENTAL DATA FOR $Al^{27}(d, \alpha)Mg^{25}$

(f) Eighth excited state; total angular momentum quantum number $J=9/2^+$; quantum number $K=5/2^+$; reaction energy $Q=+6.702 - 3.399$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.2	165.4	5.1
22.0	146.3	3.9
24.7	142.3	4.7
27.4	115.1	3.5
30.2	104.7	4.1
32.9	77.9	2.9
35.6	66.4	3.2
38.3	48.1	2.2
43.7	46.1	1.6
49.1	46.2	1.6
54.4	56.4	1.8
59.8	52.4	1.7
65.0	47.2	1.2
70.3	37.7	1.1
75.5	36.5	1.1
80.6	25.1	.9
85.7	26.5	.8
90.8	22.8	.7
95.8	21.4	.7
100.8	19.4	.7
105.7	19.0	.7
110.6	21.0	.8
115.5	19.6	.8
120.3	19.2	.8
125.0	17.6	.6
129.8	19.5	.7
134.4	20.4	.7
139.1	18.6	.6
143.7	17.4	.8
148.3	19.2	.8
152.9	21.1	.9
157.4	21.2	.9
155.2	20.4	1.0
159.7	22.2	1.0
164.2	21.2	1.0
168.8	24.9	1.1

(g) Excited state; proposed total angular momentum quantum number $J = 11/2^+$; quantum number $K = 5/2^+$; reaction energy $Q = +6.702 - 5.47$ MeV.

Center-of-mass angle, $\theta_{c.m.}$ deg	Differential cross section, $d\sigma/d\Omega$, $\mu b/sr$	Standard deviation, $\mu b/sr$
19.3	328.0	7.1
22.7	342.3	4.5
24.8	331.1	7.2
27.6	310.6	4.4
30.3	274.3	6.5
33.0	225.5	3.7
35.8	184.9	5.4
38.5	133.2	2.9
43.9	112.3	2.5
49.3	92.7	2.3
54.7	97.3	2.3
60.0	101.8	2.4
65.3	110.9	1.9
70.5	90.1	1.7
75.7	83.6	1.7
80.9	68.1	1.5
86.0	66.8	1.2
91.1	60.0	1.1
96.1	58.9	1.1
101.1	55.1	1.1
106.0	39.3	1.1
110.9	45.6	1.2
115.7	43.6	1.2
120.5	41.5	1.1
125.3	32.1	.8
130.0	37.0	.9
134.7	34.4	.9
139.3	29.4	.8
143.9	24.4	.9

TABLE II. - INTEGRATED DIFFERENTIAL CROSS SECTIONS

Total angular momentum quantum number, J	Quantum number, K	Integrated cross sections, μb
$1/2^+$	$1/2^+$	38
$3/2^+$	$1/2^+$	38
$5/2^+$	$1/2^+$	95
$5/2^+$	$5/2^+$	459
$7/2^+$	$5/2^+$	475
$9/2^+$	$5/2^+$	417

TABLE III. - COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF ENERGY LEVELS OF $K = 5/2^+$ ROTATIONAL BAND IN MAGNESIUM 25

Experimental excitation energy, W_{exp}, MeV (a)	Calculated excitation energy, W_{cal}, MeV	Difference between calculated and experimental excitation energy, $W_{cal} - W_{exp}$, keV
0	0.014	14
1.609	1.575	-34
3.398	3.425	27
5.454	5.447	-7

[a]Experimental data taken from ref. 13.

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