# Inelastic Scattering of Deuterons from the Magnesium Isotopes*

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Natural and enriched magnesium targets were bombarded with 15-Mev deuterons from the University of Pittsburgh cyclotron. The reaction products were magnetically analyzed and detected by a scintillator or by nuclear emulsions. Angular distributions were obtained for the deuterons inelastically scattered from the $Mg^{24}$ 1.37-, $Mg^{25}$ 1.61-, and $Mg^{26}$ 1.83-Mev states. The results are compared to the predictions of the plane-wave Born approximation theory and of the inelastic diffraction scattering model. The curves obtained from the Born approximation give better over-all correspondence with the experimental points. The inelastic diffraction scattering model, however, allows one to extract directly the effective values of the nuclear deformation parameter $\beta$. One obtains $|\beta|=0.20$, 0.19, and 0.17 for $Mg^{24}$, $Mg^{25}$, and $Mg^{26}$, respectively. The spectra of deuterons inelastically scattered from $Mg^{25}$ and $Mg^{26}$ were also observed, at $\theta_{lab}\approx 12°$, 30°, and 60°. The only large cross sections in $Mg^{25}$ were those for the 1.61-Mev ($\frac{7}{2}^+$) level and for a level near 3.4 Mev. The strength of the reaction to the latter level suggests that it is the $9/2^+$ member of the ground-state rotational band which, in analogy with $Al^{25}$, should appear at approximately this energy. The results tend to confirm the selection rule that favors collective excitations over single-particle excitation in inelastic scattering. In $Mg^{26}$ strong scattering was observed only from the first two excited states. A previously unreported $Mg^{26}$ state was found at the excitation energy of $3.614\pm 0.020$ Mev.

## I. INTRODUCTION

THE low-lying states of nuclei in the mass region $A\approx 25$ have been extensively studied experimentally[1–4] and it has become clear that many properties of these nuclei can be explained by the rotational (strong-coupling) model.[2,5,6] The study of the inelastic scattering of deuterons from the stable magnesium isotopes, $A=24$, 25, and 26, should yield further information on these nuclei and on the mechanism of the scattering itself. Several relatively simple theoretical expressions for direct reaction inelastic scattering are available, based upon either the plane-wave Born approximation[7–9] or the adiabatic approximation,[10] and it should be useful to determine the validity of their predictions for the present reactions.

Angular distributions for the $Mg^{24}(d,d')$ reaction leading to the first three excited states have been published previously by Hinds *et al.*[11] (8.9-Mev incident energy), and to the first excited state alone by Haffner[12] (15.1 Mev), Holt and Young[13] (7.5 Mev), and Blair *et al.*[14] (21 Mev).

In the following sections we outline the experimental procedure and present and discuss the results.

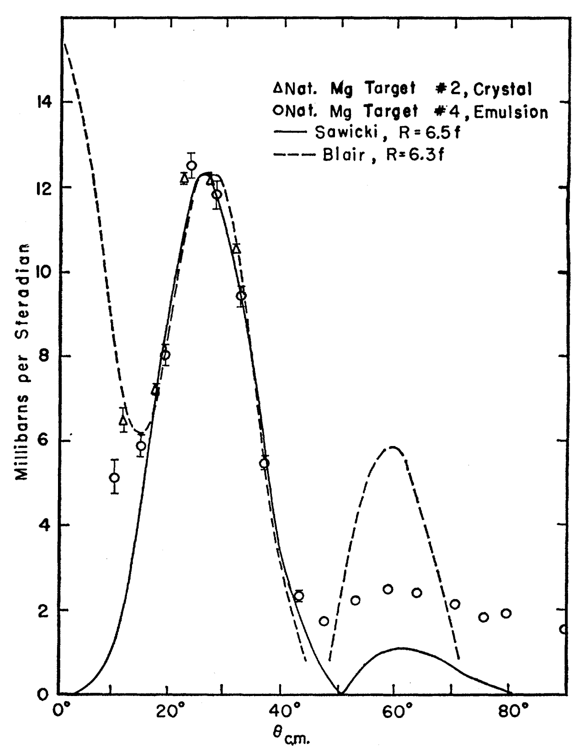


FIG. 1. Angular distribution for the $Mg^{24}(d,d')Mg^{24*}$ 1.37-Mev reaction. The points represent data obtained with various targets and detection systems, as specified on the figure. The solid line results from the plane-wave Born approximation expression of Sawicki, and the dashed line results from the inelastic diffraction scattering theory of Blair (see references 8 and 10). The errors shown are statistical.

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1 P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
2 A. E. Litherland, H. McManus, E. B. Paul. D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).
3 A. E. Litherland, H. E. Gove, and A. J. Ferguson, Phys. Rev. **114**, 1312 (1959).
4 E. W. Hamburger and A. G. Blair, Phys. Rev. **119**, 777 (1960).
5 A. Bohr and B. Mottelson, Kgl. Danske Videnskab. Selskab, Mat-fys. Medd. **27**, No. 16 (1953).
6 G. Rakavy, Nuclear Phys. **4**, 375 (1957).
7 S. T. Butler, Phys. Rev. **106**, 272 (1957).
8 J. Sawicki, Nuclear Phys. **6**, 613 (1958).
9 S. Hayakawa and S. Yoshida, Proc. Phys. Soc. (London) **A68**, 656 (1955).
10 J. S. Blair, Phys. Rev. **115**, 928 (1959).
11 S. Hinds, R. Middleton, and G. Parry, Proc. Phys. Soc. (London) **A70**, 900 (1957).
12 J. W. Haffner, Phys. Rev. **103**, 1398 (1956).
13 J. R. Holt and C. T. Young, Nature **164**, 1000 (1949).
14 J. S. Blair, G. W. Farwell, and D. K. McDaniels, Nuclear Phys. **17**, 641 (1960).

## II. EXPERIMENTAL PROCEDURE

The University of Pittsburgh cyclotron produces a magnetically focused and analyzed deuteron beam whose energy ≈14.8 Mev, and whose intensity ≈1 μa. The details of the scattering system are discussed elsewhere.[15,16] Reaction particles from the target are analyzed by a magnetic spectrometer, which can be rotated about the target, and are detected either by means of a CsI(Tl) crystal and photomultiplier assembly, whose output is fed into a pulse-height analyzer, or by means of a nuclear emulsion system.

The targets used in the present experiment were the same as those previously used,[4] i.e., self-supporting foils of natural magnesium, and magnesium enriched to approximately 99% in $Mg^{25}$ and $Mg^{26}$, respectively.

The absolute cross-section scale is the same as in previous work[4] and is believed to be accurate within ±25%. Relative cross sections should be accurate within ±10%.

## III. RESULTS AND DISCUSSION

### A. Angular Distributions

#### *a. Results*

Angular distributions of deuterons inelastically scattered from the first excited ($J^\pi=2^+$) state of $Mg^{24}$, the third excited ($\frac{7}{2}^+$) state of $Mg^{25}$, and the first excited ($2^+$) state of $Mg^{26}$, are shown in Figs. 1, 2, and 3, respectively. These three excited states all have the property of being the lowest excited state belonging to the same rotational band as the ground state. This is a well-established fact for $Mg^{24}$ and $Mg^{25}$,[2] and is probably also approximately true for $Mg^{26}$.

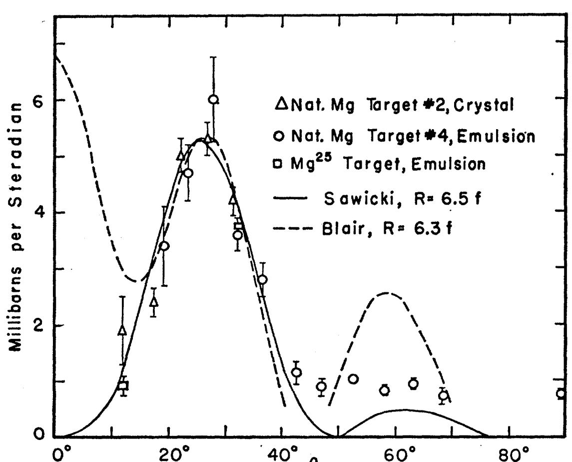


FIG. 2. Angular distribution for the $Mg^{25}(d,d')Mg^{25*}$ 1.61-Mev reaction. See caption for Fig. 1.

[15] R. S. Bender, E. M. Reilley, A. J. Allen, R. Ely, J. S. Arthur, and H. J. Hausman, Rev. Sci. Instr. **23**, 542 (1952).
[16] E. W. Hamburger, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

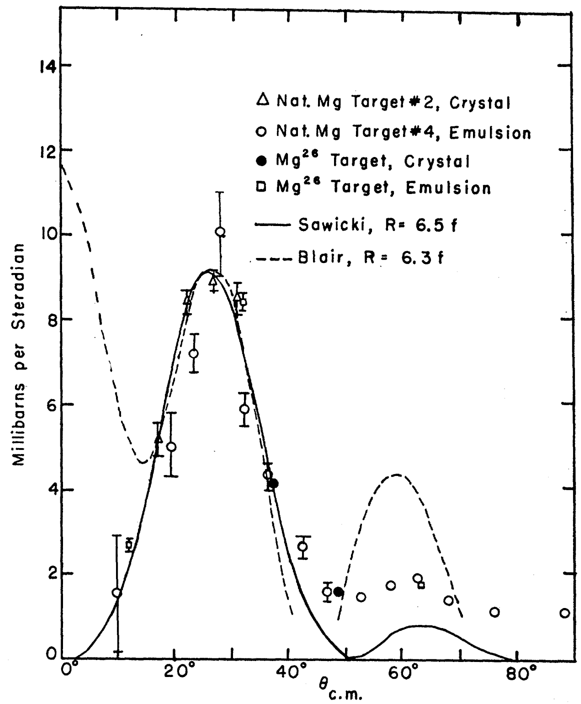


FIG. 3. Angular distribution for the $Mg^{26}(d,d')Mg^{26*}$ 1.83-Mev reaction. See caption for Fig. 1.

The $Mg^{24}$ data can be compared with those from previous experiments,[11–14] and this is done in Fig. 4 for all but the experiment of Haffner. The differential cross section divided by $k_i^2$ is plotted vs the transfer

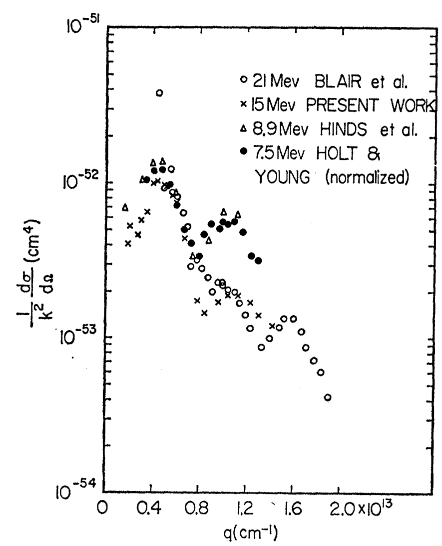


FIG. 4. The differential cross section for the $Mg^{24}(d,d')Mg^{24*}$ 1.37-Mev reaction, divided by the square of the incident deuteron wave number, is plotted vs the transfer momentum $q$. Data are shown for different incident energies: 21 Mev (reference 14), 15 Mev (present work), 8.9 Mev (reference 11), and 7.5 Mev (reference 13). In the experiment at 7.5 Mev no absolute cross sections were measured; the data were therefore normalized to agree with the present data at the first peak.

momentum $q=|\mathbf{k}_i-\mathbf{k}_f|\approx 2k_i\sin(\theta/2)$, where $\mathbf{k}_i$ and $\mathbf{k}_f$ are the initial and final deuteron wave vectors, respectively. The inelastic diffraction model, which will be discussed below in more detail, predicts that the resulting curves should be "universal," i.e., independent of energy.[10] This prediction is borne out quite well for alpha-particle scattering (see Fig. 8 of reference 14), but Fig. 4 shows that in this respect the model does not seem to be so applicable to deuteron inelastic scattering. Only at the first peak of the angular distribution do the points from the four different energies agree. The secondary peak at $q\approx 1.1$ appears sharp at the lower energies but is washed out at the higher energies. It is interesting to note that the positions of the peaks as a function of $q$ do not change, indicating that the effective radius of interaction does not depend on the energy.

We note that our results show a cross section which is decreasing toward $\theta=0°$; Haffner's experiment,[12] at essentially the same energy, gave a rising cross section in this region. Similar disagreements with Haffner's work have appeared in other reactions studied at this laboratory.[16,17] Blair *et al.*, at 21 Mev, also find a cross section rising toward 0°. However, Fig. 4 shows that, except for their lowest angle point, their data agree with ours; they do not reach the small $q$ values reached in our work and in the 8.9-Mev work of Hinds *et al.* The behavior of the cross section near 0° is important because the inelastic diffraction model predicts a cross section rising toward 0° while the plane-wave Born approximation predicts a decreasing cross section. Our results for $Mg^{24}$, and also for $Mg^{25}$ and $Mg^{26}$, favor the Born approximation in this respect.

The angular distributions for $Mg^{25}$ and $Mg^{26}$ (Figs. 2 and 3) are very similar to the $Mg^{24}$ distribution (Fig. 1). However the second peak, at $\theta\approx 60°$, is less pronounced for $Mg^{25}$ than for $Mg^{24}$ and $Mg^{26}$.

### *b. Plane Wave Theories*

Each of the angular distributions is compared to the theoretical predictions of Sawicki[8] and of Blair,[10] who consider inelastic scattering from different points of view. Sawicki calculates in plane-wave Born approximation, taking collective model wave functions for the initial and final states of the target nucleus. It is assumed that only one nucleon in the deuteron interacts with the target nucleus and the form of the interaction is taken as a potential well of constant depth $V_0$ and spheroidal boundary. The nucleus is assumed to be transparent to the deuteron, i.e., only a refractive potential is considered.

We have plotted in Figs. 1, 2, and 3 the first term of Sawicki's expression for the cross section; this term is proportional to the square of the nuclear deformation parameter $\beta$. There are correction terms proportional to higher powers of $\beta$ whose principal effect is to fill in the valleys.[8] The angular variation is given by the spherical Bessel function $[j_2(qR)]^2$ modified by a form factor. Here $R$ is the radius parameter, which we have chosen to give the best fit at the first maximum.

Other authors have considered inelastic scattering in plane-wave Born approximation: Hayakawa and Yoshida[9] find an angular dependence given by $[j_2(qR)]^2$ alone; such an expression actually fits our experimental data at the second maxima ($\theta\approx 60°$) better than does Sawicki's expression. A curve which follows the experimental points equally well is obtained[18] by using the expression of Butler,[7] $[(q^2+K^2)^{-1}W_2(qR)]^2$, in which $K$ is the sum of the wave numbers of the struck particles in the initial and final state and $W_2(qR)$ is the same Wronskian which appears in the stripping formula.[19]

Before describing Blair's calculation, we consider the results of the plane-wave theories for the absolute cross section. Apart from kinematical factors, it is predicted to be proportional to $(\beta V_0)^2(J2K0|J'K')^2$,[8] where the last factor is a Clebsch-Gordan coefficient; $J$, $J'$ are the total angular momenta of the initial and final states and $K$, $K'$ are their projections on the nuclear symmetry axis. In our case $K=K'=J$.

Since the three reactions under discussion proceed under very similar kinematical conditions and since one may expect $(\beta V_0)^2$ to have approximately the same value for the three magnesium isotopes, it follows that the cross sections should be proportional to the vector coupling coefficient. This conclusion also follows from the Blair expression for the cross section [see Eq. (1) below]. The vector coupling coefficient takes on the values 1, 10/21, and 1 for magnesium 24, 25, and 26, respectively, while the experimental cross sections at the peak of the angular distributions are 12, 5.5, and 10 mb/sr, respectively. The agreement is good.

If one uses the experimental data and the formula of Sawicki to determine the values of $|\beta V_0|$, one obtains 0.64 Mev for $Mg^{24}$, 0.62 for $Mg^{25}$, and 0.53 for $Mg^{26}$. We discuss in a later paragraph corroborating evidence that $\beta$ decreases slightly from $Mg^{24}$ to $Mg^{26}$. Here we merely note that if one takes $|\beta|\approx 0.2$, as deduced from other experiments,[2,6,20] one gets $V_0\approx 3$ Mev, a not uncommon result from plane wave Born approximation treatments of inelastic scattering.[20,21] The values of $|\beta V_0|$ deduced using Hayakawa and Yoshida's formula[9] are of the same order of magnitude as the above.

### *c. Inelastic Diffraction Scattering Model and DWBA*

We have discussed, up to here, the plane-wave Born approximation theories, and have found fairly good agreement with the data. It is known, however, that

[17] E. W. Hamburger and J. R. Cameron, Phys. Rev. **117**, 781 (1960).

[18] B. J. Raz (private communication).

[19] S. T. Butler, *Nuclear Stripping Reactions* (John Wiley & Sons, New York, 1958).

[20] P. C. Gugelot and M. Rickey, Phys. Rev. **101**, 1613 (1956).

[21] E. Rost and N. Austern, Phys. Rev. **120**, 1375 (1960).

the incident wave will be considerably distorted from the plane-wave limit owing to the nuclear absorption,[10,21] so that direct-reaction scattering should be treated using the distorted-wave Born approximation (DWBA).[22] It may even be that the agreement between plane-wave theory and experiment is largely "accidental."

Accurate DWBA calculations are laborious. In our case, however, we can use a simplified version of the DWBA, viz., the inelastic diffraction scattering model.[10,23] In effect, Rost and Austern[21] have recently shown that, in the limit of small deformations, the adiabatic method[24] is equivalent to the method of DWBA for the calculation of inelastic scattering cross sections. Thus they were able to show that the adiabatic calculations of Blair (in Fraunhofer approximation) for alpha particles scattered inelastically by strongly absorbing nuclei are essentially equivalent to a simplified DWBA.

We have therefore compared our data with the inelastic diffraction scattering model,[10,23] whose predictions are shown as dashed curves in Figs. 1, 2, and 3. The model yields the following expression for the cross section:

$$\frac{d\sigma}{d\Omega}=(J2J0|J'J)^2(kR)^2\frac{\beta^2}{4\pi}[\tfrac{1}{4}J_0^2(qR)+\tfrac{3}{4}J_2^2(qR)], \quad (1)$$

where the magnitude of the initial and final deuteron momenta are considered approximately equal ($|\mathbf{k}_i|\approx|\mathbf{k}_f|=k$) so that $q=2k\sin(\theta/2)$, and $J_0$, $J_2$ are ordinary Bessel functions. The curves are normalized to the experimental results at the first maximum. Equation (1) predicts higher second maxima (at $\theta=60°$) than do the plane-wave calculations. The experimental points lie between the two theoretical curves in this region.

The calculations of Rost and Austern,[21] when applied to the present $(d,d')$ results, yield[25] curves very much like the Blair curves, as they must. In addition, if, in their calculation, one takes into account the fact that $|\mathbf{k}_i|\neq|\mathbf{k}_f|$, the predicted angular distribution near 0° is changed, bringing it closer to the experimental values. There is still a small maximum near 0°, however.

The inelastic diffraction scattering model allows the direct determination of $\beta^2$ from the experimental data [see Eq. (1)]. We obtain for $Mg^{24}$, $Mg^{25}$, and $Mg^{26}$, respectively, $|\beta|=0.20$, 0.19, and 0.17. The relative values are similar to those obtained above from the plane wave theories.

Relative values of $\beta$ can also be deduced from the spacings of the energy levels and compared to the above. The spectra yield moments of inertia $\mathcal{I}$ given by $\hbar^2/2\mathcal{I}=0.23$, 0.23, and 0.30 Mev for $Mg^{24}$, $Mg^{25}$, and $Mg^{26}$, respectively. The moment of inertia is expected to vary with the mass number $A$ in some way intermediate between $\mathcal{I}(\text{rigid body})\propto A(1+0.31\beta)$ and $\mathcal{I}(\text{irrotational})\propto A\beta^2$.[26] The observed decrease of $\beta$ with $A$ is therefore consistent with evidence from the spectra.

### *d. Conclusion*

It appears that $(d,d')$ reactions are at least quantitatively different from $(\alpha,\alpha')$ reactions, which agree reasonably well with the inelastic diffraction scattering model.[27] The chief differences are the washing out of the diffraction structure at large angles for $(d,d')$ and the drop in cross section at small angles—although it should be pointed out that very few $(\alpha,\alpha')$ experiments have reached scattering angles below $\theta_{c.m.}\approx 20°$. However, one would still expect the Blair-Drozdov model to be more applicable to deuteron scattering than the plane-wave Born approximation theories because the latter theories assume the nucleus to be transparent to the deuterons. The Blair assumption of an opaque nucleus seems more realistic.[10] On the other hand, the washing out of the deuteron angular distribution relative to the alpha-particle distributions is probably due to the large size and the loose structure of the deuterons, which make the validity of the assumption of a sharp surface for the interaction rather doubtful.

It is clear that experimental results for $\theta_{c.m.}<10°$ would be very interesting.

## B. Other $Mg^{25}$ States

Spectra from the $(d,d')$ reactions on $Mg^{25}$ and $Mg^{26}$ were recorded at three or four angles; nuclear emulsions were used to detect the analyzed reaction products.

The $Mg^{25}$ results are shown in Table I. Only the level at 1.61 Mev and the level which we determine to be slightly lower than, but within 30 kev of, 3.40 Mev, appear with large cross sections.

It has recently been suggested[28] that the most probable excitations in inelastic scattering reactions are of the collective, and not single-particle, type. Inelastic scattering on $Mg^{25}$ affords a good test of this hypothesis because the level structure is well understood.

Figure 5 shows the configuration describing the ground ($\frac{5}{2}+$) state of $Mg^{25}$, according to the rotational model. The odd (13th) neutron is in Nilsson orbit[29]

[22] W. Tobocman, Phys. Rev. **115**, 98 (1959); C. A. Levinson and M. K. Banerjee, Ann. Phys. **2**, 471 (1957).
[23] S. I. Drozdov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 734 (1955); **28**, 736 (1955) [translation: Soviet Phys.-JETP **1**, 591, 588 (1955)]. E. V. Inopin, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 901 (1956) [translation: Soviet Phys.-JETP **4**, 764 (1957)].
[24] D. M. Chase, Phys. Rev. **104**, 838 (1956).
[25] E. Rost and N. Austern (private communication).
[26] K. Alder, A. Bohr, T. Huus, B. R. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).
[27] See, e.g., L. Seidlitz, E. Bleuler, and D. J. Tendam, Phys. Rev. **110**, 682 (1958), and reference 14.
[28] B. L. Cohen, Phys. Rev. **116**, 426 (1959); B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1658 (1958).
[29] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955); B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).

TABLE I. $Mg^{25}(d,d')Mg^{25*}$ cross sections.

| Level (Mev) | $J^{\pi}$ [a] | Orbit No.[b] | $\theta_{lab}=13.5°$ [c] $\sigma$(mb/sr) | Error (%) | $\theta_{lab}=29.7°$ [c] $\sigma$(mb/sr) | Error (%) | $\theta_{lab}=63.9°$ [c] $\sigma$(mb/sr) | Error (%) |
|---|---|---|---|---|---|---|---|---|
| 0.58 | $\frac{1}{2}^+$ | 9 | <0.22 | | 0.14 | 16 | 0.05 | 35 |
| 0.98 | $\frac{3}{2}^+$ | 9 | <0.18 | | 0.13 | 15 | 0.04 | 40 |
| 1.61 | $\frac{7}{2}^+$ | 5 | 0.92[e] | 20 | 3.75 | 2.5 | 0.80 | 5 |
| 1.96 | $\frac{5}{2}^+$ | 9 | <0.15[e] | | 0.23 | 11 | 0.06 | 30 |
| 2.56 | $\frac{1}{2}^+$ | 11 | <0.13 | | 0.22 | 11 | <0.02 | |
| 2.74 | $(\frac{7}{2}^+)$ | 9 | <0.13 | | 0.11 | 25 | <0.02 | |
| 2.80 | $\frac{3}{2}^+$ | 11 | 0.64 | 20 | 0.33 | 20 | <0.02 | |
| 3.40 | $\frac{3}{2}^-$ [d] | [d] | 1.02 | 4 | 1.52 | 4 | 0.43 | 7 |
| 3.90 | $(\frac{5}{2}^+, \frac{3}{2}^+)$ | (11, 8) | 0.47 | 25 | 0.25 | 10 | | |
| 3.97 | $\frac{7}{2}^-$ | | <0.09 | | <0.06 | | | |
| 4.05 | | | 0.61 | 20 | 0.62 | 8 | | |

[a] From references 1, 2, and 3.
[b] From reference 2 and M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).
[c] The laboratory angles correspond approximately to $\theta_{c.m.}=14.7°$, 32.2°, and 68.5°, respectively.
[d] May be $9/2^+$, orbit No. 5. See text.
[e] Data taken at $\theta_{lab}=11.2°$, corresponding to $\theta_{c.m.}=12.2°$.

No. 5 and all orbits below this are filled; the nuclear deformation parameter $\beta$ is approximately 0.2. There is a rotational band based upon the ground-state configuration; its first $(\frac{7}{2}^+)$ member has been identified at 1.61-Mev excitation. The second $(9/2^+)$ member is known in the mirror nucleus $Al^{25}$, where it appears at 3.44 Mev,[1,3] but in $Mg^{25}$ it has not been reported in the published literature.

When the odd neutron is moved to the next higher orbit, No. 9, another rotational band appears with the spin sequence $\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \cdots$. The states at 0.58, 0.98, and 1.96 Mev in $Mg^{25}$ belong to this band. Appearing at higher energies are other bands, formed by placing the odd neutron in orbit Nos. 11 and 8, and so on.[2,3]

Table I shows that the 1.61-Mev level, which belongs to the rotational band based on the ground state, is excited more than ten times as strongly as the neighboring levels, which do not belong to this band and are, in fact, due to single-particle excitations from the ground state. This result supports the selection rule mentioned above, that collective excitation is much more probable than single-particle excitation in inelastic scattering.

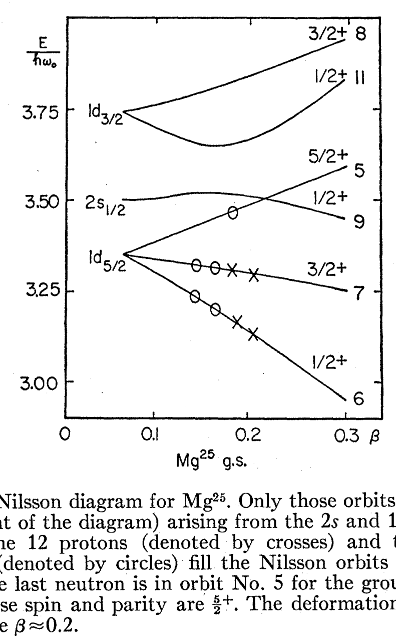


FIG. 5. Nilsson diagram for $Mg^{25}$. Only those orbits (numbered at the right of the diagram) arising from the 2*s* and 1*d* states are shown. The 12 protons (denoted by crosses) and the first 12 neutrons (denoted by circles) fill the Nilsson orbits up through No. 7. The last neutron is in orbit No. 5 for the ground state of $Mg^{25}$, whose spin and parity are $\frac{5}{2}^+$. The deformation parameter has a value $\beta\approx0.2$.

We now try to explain why the reaction to the level near 3.40 Mev also proceeds with a large cross section. There is a well-known $\frac{3}{2}^-$ level at 3.40 Mev in $Mg^{25}$; it does not belong to the rotational band based on the ground state, but results from the promotion of the odd neutron to a negative-parity orbit (not shown in Fig. 5). On the other hand, the $9/2^+$ state of the ground state band is expected in this energy region. It is therefore quite probable that the group near 3.40 Mev which is excited strongly in the present experiment actually corresponds to two close-lying levels, and that the predominant reaction is the excitation of the $9/2^+$ rotational state. Recent work at the University of Michigan has, in fact, indicated the presence of this state.[30] *Note.* S. Hinds, A. E. Litherland, and R. Middleton [*Proceedings of the International Conference on Nuclear Structure*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 946; and private communication] have recently resolved the 3.40-Mev level in $Mg^{25}$ into two components, separated by approximately 9 kev. The relative intensities of the members of the doublet, as observed via the $(d,\alpha)$ reaction, suggest that the new level, at $3.398\pm0.007$ Mev, has spin 9/2.

If the assignment of the strong group at 3.4 Mev to a $9/2^+$ state is correct, then the evidence in favor of the collective vs single-particle selection rule is strengthened considerably.

Assuming the assignment to be correct, we can compare the relative cross sections for formation of the $9/2^+$ and $\frac{7}{2}^+$ states with the theoretical prediction that they should be proportional to $(J2J0|J'J)^2$. The

[30] W. C. Parkinson (private communication).

TABLE II. $Mg^{26}(d,d')Mg^{26*}$ cross sections.

| Level (Mev) | $J^{\pi}$ [a] | $\theta_{lab}=11.2°$ [b] $\sigma$(mb/sr) | Error (%) | $\theta_{lab}=29.7°$ [b] $\sigma$(mb/sr) | Error (%) | $\theta_{lab}=59.0°$ [b] $\sigma$(mb/sr) | Error (%) |
|---|---|---|---|---|---|---|---|
| 1.83 | $2^+$ | 2.65 | 6 | 8.38 | 2.6 | 1.69 | 4.0 |
| 2.97 | $2^+$ | 1.65 | 7 | 1.72 | 4.7 | 0.41 | 9 |
| 3.61 | | 0.41 | 17 | 0.15 | 16 | 0.08 | 30 |
| 3.97 | $(2, 3)^+$ | 0.10 | 70 | 0.05 | 28 | 0.05 | 60 |
| 4.35 | $2^+$ | 0.48 | 15 | 0.65 | 7 | 0.40 | 12 |
| 4.86 | | 0.42 | 18 | <0.57 | | 0.09 | 40 |
| 4.92 | | 0.59 | 13 | 0.54 | 10 | 0.24 | 20 |
| 5.32 | | | | 0.27 | 12 | 0.16 | 17 |
| 5.50 | | | | 0.16 | 15 | | |

[a] From reference 1.
[b] The laboratory angles correspond approximately to $\theta_{c.m.}=12.1°$, 32.3°, and 63.5°, respectively.

observed ratio of cross sections at $\theta_{lab}=29.7°$ is 0.41, in good agreement with the predicted value of 0.35.

### C. Other $Mg^{26}$ States

The differential cross sections for deuterons inelastically scattered from the low-lying states of $Mg^{26}$ are shown in Table II, for the three angles studied.

The level structure of $Mg^{26}$ cannot be easily interpreted in terms of the rotational model. The first excited state is probably mainly a rotational level and is strongly excited in inelastic scattering. The relatively large cross section leading to the second excited state at 2.97 Mev suggests that some form of collective excitation is involved here also. However, no adequate interpretation of the present results can be made until the levels of $Mg^{26}$ are understood better.

The level at 3.61-Mev excitation has not been previously reported in the literature, but has recently been observed by the Michigan group.[30] After being seen in the present experiment, it was also studied in our laboratory by means of the $Mg^{25}(d,p)Mg^{26}$ reaction. Its excitation energy, as determined more precisely in the latter work, is $3.614\pm0.020$ Mev.

## IV. CONCLUDING REMARKS

The results of the present work suggest that studies of inelastic scattering on other nuclei which exhibit collective characteristics would be interesting. Such an experiment on $Si^{29}$ is under way at this laboratory.

The inelastic diffraction model[10] could be tested further if the angular distributions of deuterons *elastically* scattered from the magnesium nuclei were obtained. The prediction is that an extra ($l=2$) term in the expression for the cross section for $Mg^{25}$, which does not appear for $Mg^{24}$ and $Mg^{26}$, would fill in the valleys of the usual elastic pattern and qualitatively change the angular distribution at large angles.[10,31]

It would be useful to study the region near 3.4 Mev in $Mg^{25}$ with better resolution to verify the existence of the $9/2^+$ state. The complete angular distribution of the deuterons scattered from this state would also be interesting, as would the angular distributions for the weakly excited states: some of them appear to be very anisotropic (see Tables I and II).

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[31] J. S. Blair (private communication).