Excited States of Mg^{25} from the $Al^{27}(d,\alpha)Mg^{25}$ and $Mg^{24}(d,p)Mg^{25}$ Reactions*

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The alpha-particle groups from thin aluminum targets bombarded with 1.8-, 2.0-, and 2.1-Mev deuterons have been studied with a high resolution magnetic spectrograph. Eleven of these groups have been assigned to the $Al^{27}(d,\alpha)Mg^{25}$ reaction, corresponding to the ground state and ten excited states of Mg^{25} in a region of excitation from zero to 4.0 Mev.

The proton groups from a thin natural magnesium target were also studied at deuteron bombarding energies of 1.5, 1.8, and 2.0 Mev. Eleven of the observed proton groups could be assigned to the $Mg^{24}(d,p)Mg^{25}$ reaction, corresponding to the transition to the ground state of Mg^{25} and the same ten excited levels found from the $Al^{27}(d,\alpha)Mg^{25}$ reaction.

The excited states in Mg^{25} found from these two reactions are at 0.583, 0.976, 1.611, 1.957, 2.562, 2.736, 2.799, 3.405, 3.898, and 3.969 Mev.

I. INTRODUCTION

THE most extensive investigation of the energy levels of Mg^{25} has been the recent work of Toops, Sampson, and Steigert.[1] From the $Al^{27}(d,\alpha)Mg^{25}$ reaction, using nuclear-emulsion technique, they found levels in Mg^{25} at 0.58, 0.93, 1.62, 2.09, 2.74, 3.36, 3.96, 4.12, 4.87, 5.56, 5.93, 6.98, 7.85, 8.62, 9.06, 9.75, 10.78, and 11.89 Mev with an average error of 40 kev. The second level is also excited by the beta-decay[2] of Na^{25}.

The $Mg^{24}(d,p)Mg^{25}$ reaction has also been used[3,4] to obtain information on the excited states of Mg^{25}. The results from this reaction have been summarized by Alburger and Hafner,[5] together with earlier work on the $Al^{27}(d,\alpha)Mg^{25}$ reaction. They present levels at 0.58, 0.98, 1.58, and 2.54 Mev.

Since both the $Al^{27}(d,\alpha)Mg^{25}$ and the $Mg^{24}(d,p)Mg^{25}$ reactions have relatively high ground-state Q-values (6.694±0.010 and 5.094±0.010 Mev[6]), an investigation of the Mg^{25} levels by means of both reactions was possible with the 2-Mev electrostatic generator and magnetic spectrograph that have previously been used for similar studies. The $Al^{27}(d,\alpha)Mg^{25}$ reaction has the advantage that aluminum occurs naturally as a single isotope, so that a definite assignment of the alpha-particle groups observed can be made. Natural magnesium, on the other hand, contains the isotopes Mg^{25} (10.11 percent) and Mg^{26} (11.29 percent), in addition to Mg^{24} (78.60 percent). This makes the correct assignment of the proton groups from a deuteron-bombarded natural magnesium target more difficult.

However, the Q-values obtained from (d,p) reactions are generally more accurate than are those from (d,α) reactions. Thus, an investigation of the $Al^{27}(d,\alpha)Mg^{25}$ and the $Mg^{24}(d,p)Mg^{25}$ reactions presents the advantages of both accurate assignment and high precision. This situation is very similar to that encountered in the work on the excited states of Si^{29} from the $P^{31}(d,\alpha)Si^{29}$ and $Si^{28}(d,p)Si^{29}$ reactions.[7] Phosphorus in nature occurs as a single isotope, while in natural silicon, in addition to Si^{28}, Si^{29} and Si^{30} are also present. Therefore, the $P^{31}(d,\alpha)Si^{29}$ reaction was used for identification of the Si^{29} levels, and the $Si^{28}(d,p)Si^{29}$ reaction provided the more accurate Q-values.

II. EXPERIMENTAL PROCEDURE

Deuterons were accelerated by the M.I.T. 2-Mev air-insulated electrostatic generator and analyzed in a 90-degree magnet. The alpha-particles and protons emerging from the thin aluminum or magnesium targets were deflected and focused in a 180-degree magnetic spectrograph and were detected by means of nuclear-track plates. The analysis was at 90 degrees with the incoming deuteron beam. Details of the experimental arrangement have been published previously.[6,8,9]

The targets used for the $Al^{27}(d,\alpha)Mg^{25}$ reaction consisted of thin layers of aluminum evaporated in vacuum onto thin Formvar backings. The thickness of the aluminum targets was approximately 10 kev for the $Al^{27}(d,\alpha)Mg^{25}$ ground-state group at 2.1-Mev bombarding energy.

The magnesium target was prepared by evaporating natural magnesium in vacuum onto a platinum backing. The thickness of this target was 15 kev for the

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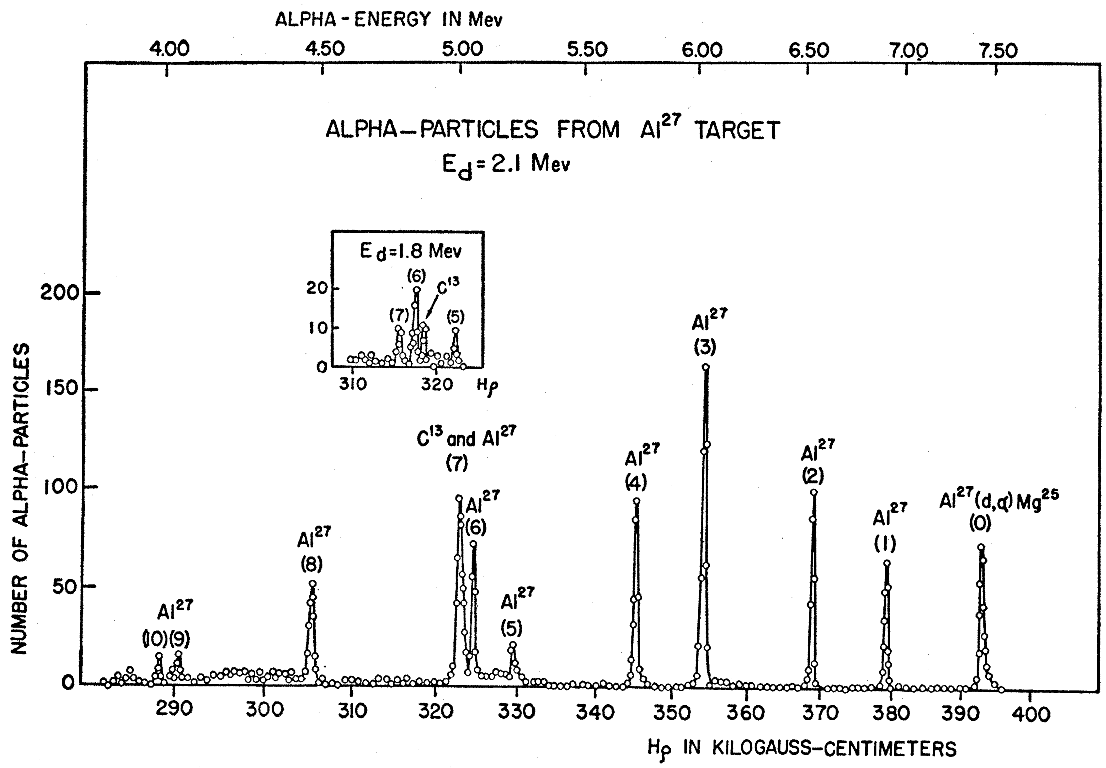

FIG. 1. Spectrum of alpha-particles observed from deuteron bombardment of a thin aluminum target.

$Mg^{24}(d,p)Mg^{25}$ ground-state group at 1.8-Mev deuteron bombarding energy.

Several surveys of alpha-particle groups from aluminum targets on Formvar backings were made. One survey at 2.1-Mev bombarding energy extended from 7.5-Mev down to 1.6-Mev alpha-particle energy. No curves from the region below 3.8-Mev alpha-particle energies are presented in this paper, however, for the following reasons: The $H\rho$ region 248 to 282 kilogauss-centimeters, corresponding to alpha-particle energies of 2.9 to 3.8 Mev, is partly obscured by the presence of one strong alpha-particle group from the $O^{16}(d,\alpha)N^{14}$ reaction and three strong groups of deuterons elastically scattered from Al^{27}, O^{16}, and C^{12} nuclei; and, below 2.9 Mev, no alpha-particle group could be discerned from the background which amounted to about 5 percent of the ground-state group. A calculation indicates that the escape probability through the Coulomb barrier for alpha-particles with energy less than 4 Mev is very low when compared with that of particles from competing reactions.

In the present work, the survey of proton groups from the $Mg^{24}(d,p)Mg^{25}$ reaction was extended down to 2-Mev proton energy. In the lower energy region, the nuclear-track plates were covered by thin aluminum foils to stop deuterons elastically scattered from the thick target backing.

Studies of the particle groups from each target were made at several deuteron energies. As in much of our previous work, the measured shift in energy of the various groups as the deuteron energy was varied provided a check on the assignment of the groups to the target nuclei involved.

III. RESULTS

The $Al^{27}(d,\alpha)Mg^{25}$ Reaction

The alpha-particle groups observed from an aluminum target bombarded with 2.1-Mev deuterons are shown in Fig. 1. Eleven groups numbered (0) through (10) have been assigned to this reaction. In addition to the survey at 2.1-Mev bombarding energy presented in Fig. 1, other surveys were made at 1.8 and 2.0 Mev.

From the results of surveys on other targets, only one relatively strong contaminant group of alpha-particles was to be expected in the energy region presented. This is the group from the ground-state transition of the $C^{13}(d,\alpha)B^{11}$ reaction. C^{13} is present in the natural-carbon contamination layer (1.1 percent C^{13}) on the surface of the target and in the Formvar backing of the target. At 2.1-Mev bombarding energy, the carbon group coincides with group (7) from the $Al^{27}(d,\alpha)Mg^{25}$ reaction. To show that group (7) is not entirely caused by the carbon contamination, an insert is given in Fig. 1 presenting the relevant energy region at 1.8-Mev bombarding energy. The carbon group in the figure is well separated from the groups that are due to the $Al^{27}(d,\alpha)Mg^{25}$ reaction.

The Q-values for the $Al^{27}(d,\alpha)Mg^{25}$ reaction are given in Table I. The relative intensities presented in Column 2 apply to 2.1-Mev bombarding energy. The Q-values listed for groups (0) through (8) are averages of results obtained from at least two different bombarding energies. The spread in energy among the individual determinations was less than 10 kev. Groups (9) and (10), however, have only been observed at 2.1-Mev bombarding energy, their yield being too low at 1.8 Mev and 2.0 Mev. Their assignment to the $Al^{27}(d,\alpha)Mg^{25}$ reaction is based principally on the good agreement of the corresponding levels in Mg^{25}, listed in Table II, with those calculated from the $Mg^{24}(d,p)Mg^{25}$ reaction.

TABLE I. Q-values and relative intensities.

Group	$Al^{27}(d,\alpha)Mg^{25}$ Rel. int.	$Al^{27}(d,\alpha)Mg^{25}$ Q-value in Mev	$Mg^{24}(d,p)Mg^{25}$ Rel. int.	$Mg^{24}(d,p)Mg^{25}$ Q-value in Mev
(0)	1.0	6.694±0.010	1.0	5.097±0.007
(1)	0.5	6.110±0.010	0.7	4.515±0.006
(2)	0.8	5.717±0.008	0.7	4.121±0.006
(3)	1.5	5.084±0.008	0.07	3.485±0.005
(4)	0.8	4.736±0.008	0.7	3.140±0.005
(5)	0.2	4.136±0.008	1.2	2.532±0.005
(6)	0.7	3.965±0.008	0.3	2.355±0.006
(7)	0.5	3.903±0.012	0.4	2.291±0.005
(8)	0.6	3.290±0.008	0.5	1.692±0.005
(9)	0.1	2.798±0.012	0.2	1.198±0.005
(10)	0.1	2.729±0.012	0.2	1.125±0.009
(11)	...	...	0.6	(0.832±0.004)
(12)	...	...	0.2	(0.676±0.008)

The $Mg^{24}(d,p)Mg^{25}$ Reaction

The proton groups observed from the natural magnesium target bombarded with 1.8-Mev deuterons are shown in Fig. 2. Data have also been taken at 1.5- and 2.0-Mev bombarding energies, but they served only to confirm the presence of the groups found at 1.8 Mev and presented no new aspects.

Eleven groups were assigned to the $Mg^{24}(d,p)Mg^{25}$ reaction, numbered (0) through (10) in the figure. Three of the other groups were attributed to the usual contaminants C^{12} and O^{16}. The assignment of proton groups to the $Mg^{24}(d,p)Mg^{25}$ reaction was done primarily by checking the positions of the Mg^{25} levels calculated from them with those observed from the $Al^{27}(d,\alpha)Mg^{25}$ reaction. A second check was obtained by measuring the energy shift of the proton groups connected with a change in bombarding energy. In this case, the bombarding voltage was varied from 1.5 to 2.0 Mev, thereby making it possible to determine the mass of the target nucleus responsible for the reaction to within about 3 mass units.

Finally, the region above the carbon group was also surveyed with targets enriched in either Mg^{25} or Mg^{26}. This work will be reported in a separate paper. It served to identify thirteen low intensity groups as either due to the $Mg^{25}(d,p)Mg^{26}$ reaction or to the $Mg^{26}(d,p)Mg^{27}$ reaction. Four of the most intense of these groups have been indicated in Fig. 2. This work also served to show that groups (0) through (4) assigned to Mg^{24} were not due either to Mg^{25} or to Mg^{26}.

Two additional intense proton groups appear in Fig. 2 at $H\rho=226$ and $H\rho=216$ kilogauss-centimeters; these have been attributed tentatively to the $Mg^{24}(d,p)Mg^{25}$ reaction, although the possibility is not entirely excluded that one or both of them are due to either Mg^{25} of Mg^{26} as the target nucleus. The corresponding Mg^{25} levels could not have been detected in our work on the $Al^{27}(d,\alpha)Mg^{25}$ reaction because of low yield.

The Q-values calculated for the proton groups from the $Mg^{24}(d,p)Mg^{25}$ reaction are presented in Table I. The corresponding energy levels in Mg^{25} are listed in Table II, column 2.

Relative intensities of the proton groups at 1.8-Mev bombarding energy have been included in Table I, column 4. A rather large uncertainty must be assigned

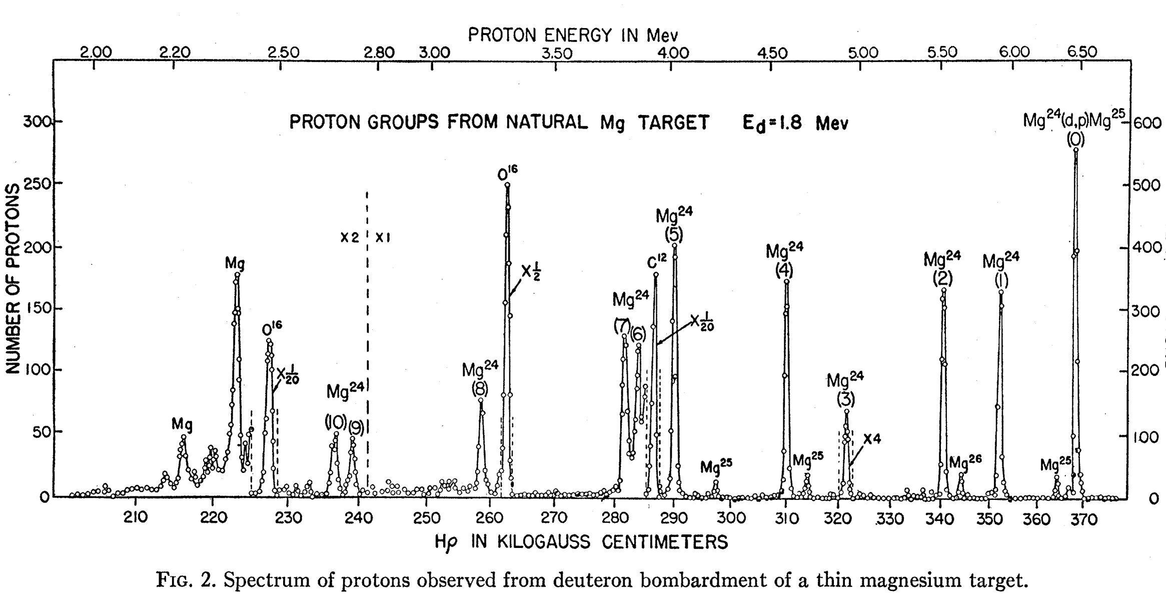

FIG. 2. Spectrum of protons observed from deuteron bombardment of a thin magnesium target.

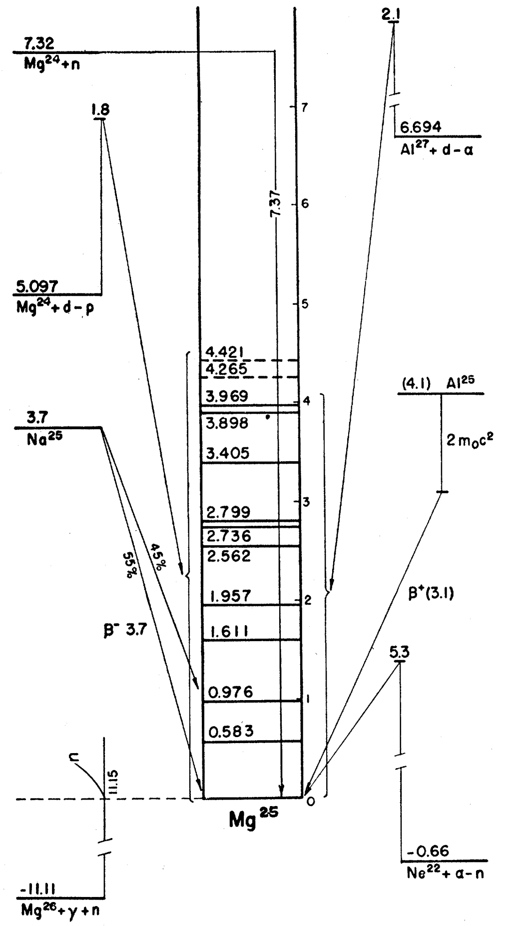

FIG. 3. Energy-level diagram of Mg^{25}.

to them, however. The spectrum in Fig. 2 has been obtained by successive exposures of twenty nuclear-track plates at different field strengths of the analyzing magnet. Apart from the other drawbacks of this method for intensity comparison, it was observed after the completion of the survey that about 75 percent of the original amount of magnesium on the target had disappeared, indicating that relative intensities may be wrong by as much as a factor of 4.

The small relative intensity of group (3) at 1.8-Mev deuteron bombarding energy is remarkable, since at 2.0 Mev this group is of the same intensity as that for groups (2) and (4). Groups (11) and (12) have been included in Table II in brackets because their assignment is not certain. The Q-value for the ground-state transition (5.097 ± 0.007 Mev) is in agreement with the one published previously[6] (5.094 ± 0.010 Mev). The new value is based on six determinations, compared with the old value that was based on only two.

IV. CONCLUSIONS

From Table II, it can be seen that there is agreement between the level schemes found from both reactions within the experimental error. Levels (6) and (7) show the largest differences (13 and 15 kev), but rather large experimental errors were also assigned to the corresponding groups from both reactions because these groups are situated near intense contaminant groups.

There is also agreement between the level positions found from this work and those found from the work of Toops, Sampson, and Steigert,[1] as well as from the Alburger and Hafner[5] compilation.

In Fig. 3, a level diagram of Mg^{25} is presented, incorporating the present results. Kinsey, Bartholomew,

TABLE II. Energy levels in Mg^{25} (excitation energy in Mev).

Group	$Mg^{24}(d,p)Mg^{25}$	$Al^{27}(d,\alpha)Mg^{25}$	Toops *et al.*[a]	Alburger[b]
(1)	0.582 ± 0.006	0.584 ± 0.006	0.58 ± 0.02	0.58
(2)	0.976 ± 0.006	0.977 ± 0.010	0.93 ± 0.04	0.98
(3)	1.612 ± 0.006	1.610 ± 0.010	1.62 ± 0.03	1.58
(4)	1.957 ± 0.006	1.958 ± 0.010	2.09 ± 0.05	···
(5)	2.565 ± 0.006	2.558 ± 0.010	···	2.54
(6)	2.742 ± 0.008	2.729 ± 0.010	2.74 ± 0.03	
(7)	2.806 ± 0.007	2.791 ± 0.015	···	
(8)	3.405 ± 0.007	3.404 ± 0.012	3.36 ± 0.03	
(9)	3.899 ± 0.008	3.896 ± 0.015	···	
(10)	3.972 ± 0.010	3.965 ± 0.015	3.96 ± 0.04	
(11)	(4.265 ± 0.007)	···	4.12 ± 0.04	
(12)	(4.421 ± 0.010)	···	···	

[a] See reference 1.
[b] See reference 5.

and Walker[10] have recently measured the energies of gamma-rays from the capture of slow neutrons by natural magnesium. Only one of their gamma-rays, the one leading to the Mg^{25} ground state has been included in the diagram. This is the only $Mg^{24}(n,\gamma)Mg^{25}$ gamma-ray that can be assigned at present unambiguously because of the complications introduced by the presence of Mg^{25} and Mg^{26} in the natural magnesium.

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