Magnetic Analysis of the $Mg^{25}(d,p)Mg^{26}$, $Mg^{26}(d,p)Mg^{27}$, and $Mg^{25}(d,\alpha)Na^{23}$ Reactions*

P. M. ENDT,† J. W. HAFFNER, AND D. M. VAN PATTER
Physics Department and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge 39, Massachusetts

(Received January 24, 1952)

Targets of magnesium oxide, enriched in Mg^{25} and Mg^{26} content, have been bombarded by 1.8-Mev deuterons. Proton and alpha-particle groups observed at an angle of 90 degrees to the incident beam have been studied with a high-resolution magnetic spectrograph. Eleven proton groups have been assigned to the $Mg^{25}(d,p)Mg^{26}$ reaction; two proton groups were assigned to the $Mg^{26}(d,p)Mg^{27}$ reaction; and three alpha-particle groups were attributed to the $Mg^{25}(d,\alpha)Na^{23}$ reaction. The Q-values for the ground-state transitions are 8.880 ± 0.010, 4.207 ± 0.006, and 7.019 ± 0.013 Mev, respectively.

The following level excitations have been measured:

Mg^{26}: 1.825, 2.972, 3.969, 4.353, 4.863, 4.924, 5.270, 5.322, 5.502, and 6.147 Mev;
Mg^{27}: 0.987 Mev;
Na^{23}: 0.43 and 2.07 Mev.

I. INTRODUCTION

THE element magnesium in its natural form has three isotopes with the following abundances: Mg^{24}, 78.6 percent; Mg^{25}, 10.1 percent; and Mg^{26}, 11.3 percent. If natural magnesium is bombarded with 1.8-Mev deuterons, four reactions can produce charged particles with energies greater than 4 Mev. These are the $Mg^{24}(d,p)Mg^{25}$, $Mg^{25}(d,p)Mg^{26}$, $Mg^{26}(d,p)Mg^{27}$, and $Mg^{25}(d,\alpha)Na^{23}$ reactions. An investigation of the $Mg^{24}(d,p)Mg^{25}$ reaction, using magnetic analysis, has been described in a separate publication.[1] The present paper is concerned with the remaining three reactions.

The reaction energy for the $Mg^{25}(d,p)Mg^{26}$ ground-state transition has not been previously published. A value of 9.06 ± 0.15 Mev may be calculated from the masses listed by Mattauch and Flammersfeld.[2] Pollard and Humphreys[3] reported levels of Mg^{26} at 1.85 and 3.00 Mev from an investigation of the proton groups from natural magnesium bombarded by deuterons. States of Mg^{26} can also be excited by means of the $Na^{23}(\alpha,p)Mg^{26}$ reaction. The results of several measurements of this reaction have been summarized by Alburger and Hafner,[4] who list values of 0.44, 1.91, 2.85, 4.0, and 5.0 Mev for the level positions.

Allan *et al.*[5] have reported a value of 4.21 ± 0.10 Mev for the $Mg^{26}(d,p)Mg^{27}$ ground-state transition from a study of the proton groups from an enriched Mg^{26} target bombarded by 0.93-Mev deuterons. No excited states have been reported by Mg^{27}.

The $Mg^{25}(d,\alpha)Na^{23}$ ground-state Q-value has been reported as 7.2 Mev[6] from a rough estimate of the range of the alpha-particles.[7] An excited state of Na^{23} at 3.03 Mev[8] is observed from the beta-decay of Ne^{23}. A preliminary study of the inelastic scattering of 14-Mev deuterons from sodium by the MIT Cyclotron Group[9] indicated seven excited states of Na^{23}, of which the two lowest were 1.9 and 2.6 Mev.

In view of the large ground-state Q-values of the $Mg^{25}(d,p)Mg^{26}$ and $Mg^{25}(d,\alpha)Na^{23}$ reactions and the paucity of precise data concerning the level schemes of Mg^{26}, Mg^{27}, and Na^{23}, it was decided to investigate the charged-particle reaction products from the deuteron bombardment of magnesium enriched in Mg^{25} and Mg^{26}. Bombardment of thin targets of natural magnesium has shown[1] the presence of many charged-particle groups of low intensity, which could not be assigned to the Mg^{24} isotope. It was necessary to use enriched targets in order to identify correctly these groups either with the Mg^{25} or the Mg^{26} isotope.

II. EXPERIMENTAL PROCEDURE

A beam of 1.8-Mev deuterons accelerated by the air-insulated electrostatic generator at MIT was analyzed by means of a 90-degree deflecting magnet. The deuteron beam was then used to bombard a thin target of magnesium or magnesium oxide. A small fraction of the charged particles emitted at an angle of 90 degrees to the incident beam was deflected by the magnetic field of a 180-degree focusing spectrograph and detected by means of nuclear-track emulsions. Details of the experimental arrangement have been published previously.[10–12]

* This work has been assisted by the joint program of the ONR and AEC.
† On leave from the University of Utrecht, Utrecht, Netherlands.
[1] Endt, Enge, Haffner, and Buechner (to be published).
[2] J. Mattauch and A. Flammersfeld, Z. Naturforsch. (1949) (special edition).
[3] E. Pollard and R. F. Humphreys, Phys. Rev. **59**, 466 (1941).
[4] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).
[5] Allan, Wilkinson, Burcham, and Curling, Nature **163**, 210 (1949).
[6] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).
[7] Lewis, Livingston, and Lawrence, Phys. Rev. **44**, 55 (1933).
[8] H. Brown and V. Perez-Mendez, Phys. Rev. **78**, 812 (1950).
[9] MIT, Lab. for Nuclear Sci. and Eng., Progress Report, July 1, 1950.
[10] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).
[11] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).
[12] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

On each nuclear-track plate, a small spectrum of charged particles was recorded, covering a range of 10 percent in energy. By successively exposing a series of such plates over a wide range of field strengths of the spectrograph, a continuous spectrum of groups with energies from 4.0 to 10.5 Mev was obtained from the overlapping of several small spectra. The observed track-density distributions were normalized to the same beam exposure and area of plate counted so that the observed relative intensities of the groups could be correctly represented in the final plot.

A thin target of natural magnesium was prepared by evaporating magnesium ribbon in vaccum onto a platinum backing. The thickness of this target was 15 kev for the ground-state $Mg^{24}(d,p)Mg^{25}$ proton group at 1.8-Mev deuteron bombarding energy.

The enriched material was obtained from the Stable Isotopes Division of the AEC, Oak Ridge in the form of magnesium oxide, in which the Mg^{25} and Mg^{26} concentrations were considerably higher than in natural magnesium. Attempts to evaporate this compound in vacuum were unsuccessful because of its high boiling point. It was therefore not possible to prepare thin targets of the enriched material in the usual way. The method finally adopted did not give very thin targets but was satisfactory for the present purposes. First, the enriched material was finely ground in a procelain crucible. A suspension of fine powder in acetone was then prepared. In a few minutes, when the coarser crystals had sunk to the bottom of the crucible, a platinum backing was placed in the suspension a few millimeters below the surface. After several hours, the acetone evaporated, and a thin layer of magnesium oxide had settled onto the target backing.

The $Mg^{25}O$ target prepared in this fashion had a thickness of 130 kev for the ground-state $Mg^{25}(d,p)Mg^{26}$ proton group at 1.8-Mev bombarding energy. The $Mg^{26}O$ target was 100-kev thick for the $Mg^{26}(d,p)Mg^{27}$ reaction ground-state group. Precise determinations of the Q-values of reaction groups observed from these targets were not possible. However, these enriched targets could be used to identify the proton and alpha-particle groups observed from the thin target of natural magnesium, for which Q-values could be calculated with probable errors of 6 to 15 kev.

III. RESULTS

The $Mg^{25}(d,p)Mg^{26}$ Reaction

The spectrum of proton groups with energies from 4.0 to 10.5 Mev observed from the bombardment of the natural magnesium target by 1.8-Mev deuterons is shown in Fig. 1A. This spectrum consists of two parts, which are divided by a change in scale of a factor of five. The proton groups with energies greater than 6.9 Mev were recorded using beam exposures five times that used for the lower energy region. The two parts of the spectrum were recorded on different occasions, resulting in considerable uncertainty for the relative intensities of the groups over the whole spectrum.

Several proton groups appear in the spectrum of Fig. 1A that are attributed to contaminants of C^{12}, C^{13}, N^{14}, Si^{28}, and S^{32}. The silicon and sulfur contaminants probably originate from the silicone stopcock grease used in the vacuum system. Several of the remaining groups were attributed to the $Mg^{24}(d,p)Mg^{25}$ reaction, as described in a separate publication.[1] There remain several low intensity groups that can be attributed to either the Mg^{25} or Mg^{26} isotope.

The proton spectrum in the same energy range observed from the $Mg^{25}O$ target is shown in Fig. 1B. This spectrum was obtained from a series of plates exposed consecutively using the same beam bombardment. The relative intensities of the groups in Fig. 1B are considered to be more reliable than in Fig. 1A. However, since many of the groups overlap considerably, it is difficult to estimate their relative intensities.

The $Mg^{25}O$ target contained an isotopic abundance of 86.8 percent Mg^{25} compared with the 10.1 percent of Mg^{25} in natural magnesium. Comparing Figs. 1A and 1B, it can be seen that eleven proton groups from the $Mg^{25}O$ target have increased considerably in intensity, indicating they can be assigned to the $Mg^{25}(d,p)Mg^{26}$ reaction. These groups are numbered (0) through (10) and correspond to the ground state and ten excited states of Mg^{26}. It is possible that additional low-intensity $Mg^{25}(d,p)Mg^{26}$ groups were present which were not detected in the spectrum of Fig. 1A because of lack of intensity or in the spectrum in Fig. 1B because of the poor resolution provided by the thick $Mg^{25}O$ target. The $Mg^{25}(d,p)$ group (4) does not stand out clearly in Fig. 1A because it is situated on the high energy slope of the intense $Mg^{24}(d,p)$ group (1). However, the intensity of this group from the $Mg^{25}O$ target was sufficient so as to leave no doubt concerning its existence. It is also noted that the proton groups attributed to the Mg^{24} and Mg^{26} isotopes are relatively less intense from the $Mg^{25}O$ target, as expected from their isotopic abundances in the $Mg^{25}O$ target.

In Table I are listed the Q-values calculated for the eleven proton groups assigned to the $Mg^{25}(d,p)Mg^{26}$ reaction, together with the resulting level positions for Mg^{26}. A level diagram for Mg^{26} incorporating these results is shown in Fig. 3. No estimates have been given for the relative intensities of the groups because of the uncertainties already noted. Comparison has been made with the levels in Mg^{26} listed in Alburger and Hafner[4] from the $Na^{23}(\alpha,p)Mg^{26}$ reaction. The agreement is quite good except for the level given at 0.44 Mev, which has been reported only once[13] while the remaining levels have been observed by several groups of experimenters. A $Mg^{25}(d,p)Mg^{26}$ proton group corresponding to this level would occur at $Hr=452$ kilo-

[13] H. T. Motz and R. F. Humphreys, Phys. Rev. 74, 1232 (1948).

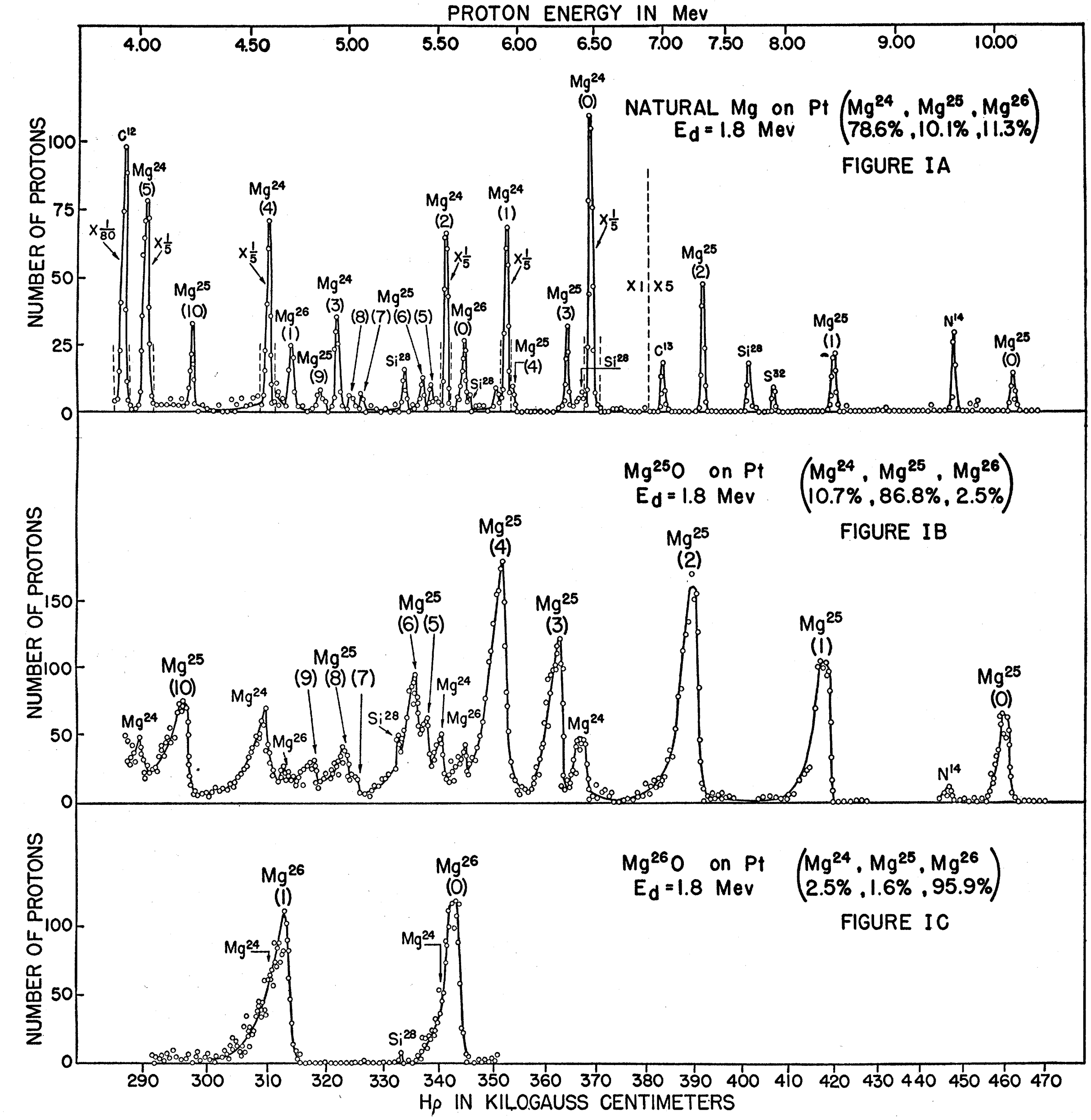

FIG. 1. Proton groups from targets of natural magnesium and magnesium oxide enriched in Mg^{25} and Mg^{26} content bombarded by 1.8-Mev deuterons.

gauss-centimeters in Fig. 1B, where no trace of a group was observed.

It is possible to estimate the ground-state Q-value for the $Mg^{25}(d,p)Mg^{26}$ reaction from a combination of other nuclear disintegration energies. By using the Q-values for the $Mg^{26}(d,p)Mg^{27}$ reaction (4.207 ± 0.006 Mev, as measured in the present experiment), the $Mg^{27}(\beta^-)Al^{27}$ disintegration (2.62 ± 0.06 Mev[14,15]), and the $Al^{27}(d,\alpha)Mg^{25}$ reaction (6.694 ± 0.010 Mev[12]), together with the mass differences $2D^2-He^4$(23.834 ± 0.007 Mev[16]) and $2H^1-D^2$(1.443 ± 0.002 Mev[16]), a value of 8.87 ± 0.06 Mev may be calculated for the $Mg^{25}(d,p)Mg^{26}$ reaction. Since the highest energy $Mg^{25}(d,p)Mg^{26}$ group observed in the present experiment had a measured Q-value of 8.880 ± 0.012 Mev, it is concluded that this group represents the ground-state transition.

The $Mg^{26}(d,p)Mg^{27}$ Reaction

In Fig. 1C are shown the proton groups with energies from 4.1 to 5.9 Mev observed from an enriched

[14] Benes, Hedgran, and Hole, Arkiv Mat. Astron. Fysik 35A, No. 12 (1948).

[15] A. Hedgran (private communication).

[16] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).

$Mg^{26}O$ target bombarded by 1.8-Mev deuterons. This target contained an isotopic abundance of 95.9 percent of Mg^{26} compared with the 11.3 percent of Mg^{26} in natural magnesium. Two proton groups (0) and (1) are clearly indicated, which are both assigned to the $Mg^{26}(d,p)Mg^{27}$ reaction. These groups were also observed with considerably lower intensities from the natural magnesium target. The measured Q-values of these groups were 4.207 ± 0.006 and 3.320 ± 0.005 Mev, corresponding to the ground state of Mg^{26} and an excited state at 0.987 ± 0.006 Mev. The Q-value for the ground-state transition is in agreement with the previously reported value[5] of 4.21 ± 0.1 Mev obtained from range measurements. The level at 0.987 Mev has not been previously reported.

The $Mg^{25}(d,\alpha)Na^{23}$ Reaction

In the upper curve of Fig. 2 is shown the spectrum of alpha-particles with energies from 5.4 to 7.7 Mev observed from the natural magnesium target bombarded by 1.8-Mev deuterons. The energies of these alpha-groups are sufficiently high so that they cannot be attributed to either the Mg^{24} or the Mg^{26} isotope. In order to verify the assignment of these groups to the Mg^{25} isotope, a similar spectrum was observed from the enriched $Mg^{25}O$ target, which is shown in the lower curve of Fig. 2. It can be seen that, in each case, the intensity of the group is considerably greater from the $Mg^{25}O$ target, indicating that the groups may be attributed to the $Mg^{25}(d,\alpha)Na^{23}$ reaction. The spectrum of alpha-particles with energies from 4.0 to 5.4 Mev is not shown, because the yield of $Mg^{25}(d,\alpha)Na^{23}$ groups in this energy region was not sufficient to permit detection in the present experiment.

TABLE I. Q-values for the observed proton and α-particle groups.

Group	Q-value (Mev)	Mg^{26} levels ($Mg^{25}(d,p)Mg^{26}$)	Mg^{26} levels ($Na^{23}(\alpha,p)Mg^{26}$)
	$Mg^{25}(d,p)Mg^{26}$ reaction		
(0)	8.880 ± 0.012	0	0
...	...	...	0.44
(1)	7.055 ± 0.015	1.825 ± 0.005	1.91
(2)	5.908 ± 0.008	2.972 ± 0.010	2.85
(3)	4.911 ± 0.007	3.969 ± 0.010	4.0
(4)	4.527 ± 0.008	4.353 ± 0.011	...
(5)	4.017 ± 0.009	4.863 ± 0.011	...
(6)	3.956 ± 0.007	4.924 ± 0.011	5.0
(7)	3.610 ± 0.007	5.270 ± 0.011	...
(8)	3.558 ± 0.007	5.322 ± 0.011	...
(9)	3.378 ± 0.007	5.502 ± 0.011	...
(10)	2.733 ± 0.005	6.147 ± 0.011	...
	$Mg^{26}(d,p)Mg^{27}$ reaction		
Group	Q-value (Mev)		Mg^{27} levels
(0)	4.207 ± 0.006		0
(1)	3.320 ± 0.005		0.987 ± 0.006
	$Mg^{25}(d,\alpha)Na^{23}$ reaction		
Group	Q-value (Mev)	Na^{23} levels ($Mg^{25}(d,\alpha)Na^{23}$)	Na^{23} levels ($Na^{23}(d,d')Na^{23}$)
(0)	7.019 ± 0.013	0	0
(1)	6.592 ± 0.015	0.427 ± 0.018	...
(2)	4.946 ± 0.012	2.073 ± 0.015	1.9

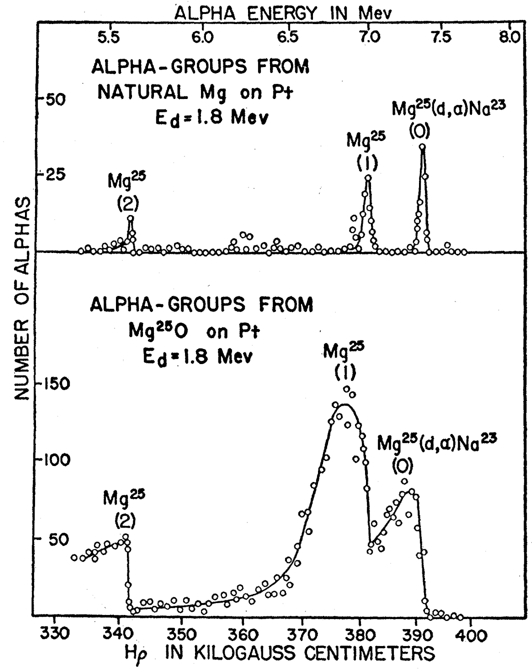

FIG. 2. Alpha-particles from targets of natural magnesium and magnesium oxide enriched in Mg^{25} bombarded by 1.8-Mev deuterons.

The measured Q-values for the three $Mg^{25}(d,\alpha)Na^{23}$ groups were 7.019 ± 0.013, 6.592 ± 0.015, and 4.946 ± 0.012 Mev, corresponding to the ground state and excited states of Na^{23} at 0.427 ± 0.018 and 2.073 ± 0.015 Mev, respectively. The level at 2.07 Mev probably corresponds to the 1.9-Mev level reported from inelastic scattering of deuterons from sodium.[9] The level at 0.43 Mev has not been reported before. An attempt was made to confirm the existence of this level by investigating the $Na^{23}(p,p')$ and $Na^{23}(d,d')$ inelastic scattering for bombarding energies of 1.8 and 2.0 Mev. The target used for this investigation consisted of a thin layer of sodium iodide evaporated in vacuum onto a 0.1-micron nickel backing. No group of particles inelastically scattered from the sodium-iodide target at 90 degrees was observed with an intensity greater than 1 percent of the elastically scattered group.

The Q-value of 7.019 ± 0.013 Mev measured for the $Mg^{25}(d,\alpha)Na^{23}$ ground-state transition is in agreement with the early value of 7.2 Mev from range measurements.[6,7] It is also possible to estimate this value from a combination of the ground-state Q-values of the $Na^{23}(d,p)Na^{24}$ reaction (4.731 ± 0.009 Mev),[12] the $Na^{24}(\beta^-)Mg^{24}$ disintegration (5.512 ± 0.006 Mev),[15,17] and the $Mg^{24}(d,p)Mg^{25}$ reaction,[1] together with the mass differences $2D^2-He^4$ and $2H^1-D^2$. The Q-value resulting from this calculation is 7.051 ± 0.016 Mev, which is 32

[17] K. Siegbahn, Phys. Rev. **70**, 127 (1946).

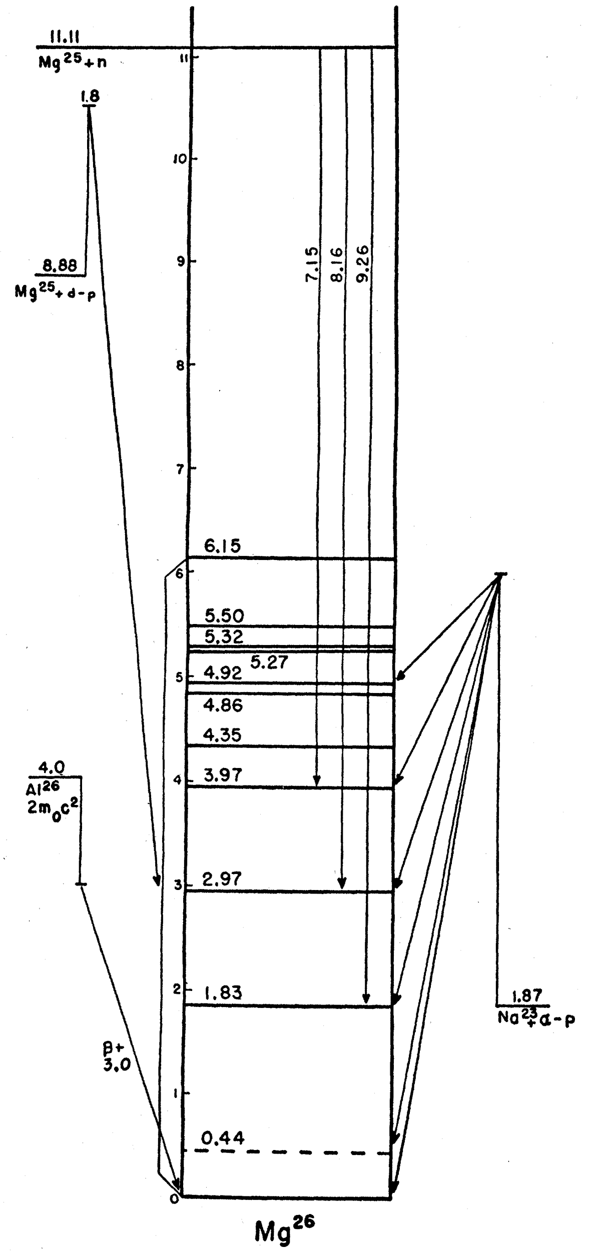

FIG. 3. Energy-level diagram for Mg^{26}.

kev lower than the measured value, indicating that there is some inconsistency between the nuclear reaction data and the $Na^{24}(\beta^-)Mg^{24}$ disintegration energy. However, the agreement is good enough to establish that the $Mg^{25}(d,\alpha)Na^{23}$ ground-state group has been correctly identified.

IV. CONCLUSIONS

Investigation of the $Mg^{25}(d,p)Mg^{26}$, $Mg^{26}(d,p)Mg^{27}$, and $Mg^{25}(d,\alpha)Na^{23}$ reactions using magnetic analysis has indicated the presence of several reaction groups not previously reported. In the case of each reaction, the measured Q-values for the ground-state transitions were in reasonable agreement with the Q-values of other reactions linking the same nuclei.

The results for the $Mg^{25}(d,p)Mg^{26}$ reaction indicated ten excited states of Mg^{26} in a region of excitation from 0 to 6.2 Mev, of which six have not been previously reported. A previously reported level[13] at 0.44 Mev from the $Na^{33}(\alpha,p)Mg^{26}$ reaction has not been verified.

Included in the level diagram for Mg^{26} (Fig. 3) are three of the gamma-rays observed by Kinsey *et al.*,[18] from the capture of thermal neutrons by magnesium. If these gamma-rays represent transitions from the capturing state of Mg^{26} at 11.11 Mev to excited states as indicated, then it is possible to compare their measured energies with the corresponding $Mg^{25}(d,p)Mg^{26}$ transitions to the same excited states. After subtracting 2.23 Mev for the deuteron binding energy, the corresponding $Mg^{25}(d,p)Mg^{26}$ Q-values are calculated to be 7.03 ± 0.04, 5.93 ± 0.03, and 4.92 ± 0.04 Mev, in excellent agreement with our measured Q-values of 7.055 ± 0.015, 5.908 ± 0.005, and 4.911 ± 0.007 Mev.

A hitherto unreported level at 0.987 ± 0.006 Mev in Mg^{27} was found by investigating the $Mg^{26}(d,p)Mg^{27}$ reaction. Excited states at 0.427 ± 0.018 and 2.073 ± 0.015 Mev were found for the nucleus Na^{23} from the $Mg^{25}(d,\alpha)Na^{23}$ reaction. The level at 0.43 Mev has not been reported previously.[19]

We wish to acknowledge the generous cooperation of our colleagues at the High Voltage Laboratory. We are particularly indebted to Miss Jane Pann, Mrs. Helene Harris, and Mr. W. A. Tripp for their care in counting the nuclear-track plates.

---

[18] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).

[19] The results of Stelson, Preston, and Goodman [Bull. Am. Phys. Soc. **27**, No. 1, 54, (1952)] for the gamma-rays from sodium bombarded by protons have recently been reported. They find a gamma-ray of energy 0.45 ± 0.01 Mev which they attribute to the Na^{23} level at 0.43 ± 0.02 Mev found in the present experiment.