Radiative Decay of Some Low-Lying States of Mg^{27}†

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The gamma-ray de-excitation of several low-lying states of Mg^{27} has been observed by measuring proton–gamma-ray coincidences. The levels in Mg^{27} were populated using the $Mg^{26}(d,p)Mg^{27}$ reaction. The results are as follows: the 0.984-MeV level decays to the ground state 100%; the 1.69-MeV level decays to the ground state 100% with no observed transition to the 0.984 state (limit $<1\%$); the 1.94-MeV level decays to the first excited state $70\pm4\%$ and to the ground state $30\pm7\%$ with no observed transition to the 1.69-MeV second excited state (limit $<1\%$); and the 3.11-MeV state was observed to decay to the 1.94-MeV level, however, there may be other branches. The 3.47- and 3.48-MeV doublet (unresolved) decays to the ground state 100%—limits on cascades through the 0.984- and 1.69-MeV states are $<6\%$ and $<3\%$, respectively; the 3.56-MeV level decays primarily to the ground state $\sim100\%$—limits for cascades through the 0.984- and 1.69-MeV states are $<4\%$ and $<5\%$, respectively; and the 3.76- and 3.78-MeV doublet (unresolved) decays to the 1.69-MeV level $\sim100\%$—limits for the ground-state transition and the cascade through the 0.984-MeV state are both $<4\%$.

I. INTRODUCTION

MANY nuclei in the ($1d$-$2s$) shell have been extensively studied. The large body of information concerning the position, spin and parity, stripping width, and radiative decay of individual states in this mass region is summarized in the compilation of Endt and Van der Leun.[1] Detailed comparisons of these properties with the predictions of various models have been made.[2–5]

Mg^{27} has received a relatively small amount of attention both theoretically and experimentally. Most of the information about the excited states of Mg^{27} has been obtained using the $Mg^{26}(d,p)$ reaction, usually with magnetic analysis of the outgoing protons. The high resolution work of Hinds, Marchant, and Middleton[6] located many levels in Mg^{27} up to about 7-MeV excitation energy. Other (d,p) studies have determined l_n values and reduced widths for several of these excited states.[1] Campion and Bartholomew[7] have studied the gamma radiation following thermal neutron capture in natural magnesium, and assigned some of the gamma rays which they observed to Mg^{27}. They report primary transitions to the ground state and to the first excited state, and a gamma ray of energy (3.552 ± 0.014) MeV which can be fitted into the Mg^{27} decay scheme $(3.55\rightarrow0)$. However, they point out that the 3.55-MeV gamma ray is difficult to assign, as the measured intensity of this gamma ray exceeds the contribution expected from Mg^{27} due to neutron capture by Mg^{26}.

Since the available information on the radiative decay of the low-lying states of Mg^{27} is so sparse, we have investigated the de-excitation of some of these states. The $Mg^{26}(d,p)$ reaction was used to populate states in Mg^{27} and the subsequent gamma rays were observed in coincidence with the protons. The pulse-height spectra corresponding to coincident events were displayed on a two-dimensional pulse-height analyzer. We have also measured the angular distribution of the 1.69-MeV gamma ray from the second excited state of Mg^{27}.

II. BRANCHING RATIO MEASUREMENTS

A. Experimental Procedure

Mg^{26} targets were prepared by evaporation of enriched MgO (greater than 97% Mg^{26}) onto thin (500 $\mu g/cm^2$) nickel backings. The target thickness was about 300 $\mu g/cm^2$. Deuterons incident on the target were accelerated to 2.8 MeV using the Brookhaven National Laboratory Van de Graaff accelerator. The average beam current on the target was about 5×10^{-9} A.

Resulting gamma radiation was detected with a 3-in.-diam by 3-in.-thick NaI(Tl) scintillator optically

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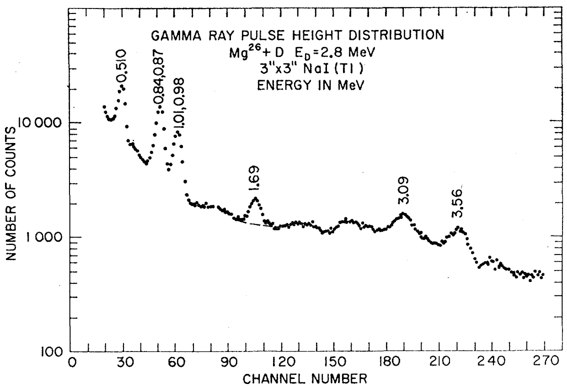

FIG. 1. Observed pulse-height distribution of gamma radiation produced by 2.8-MeV deuterons incident on the Mg^{26} target. Gamma radiation was detected with a 3-in.×3-in.-diam NaI(Tl) crystal. Prominent gamma rays are labeled according to energy in the figure.

coupled to a Dumont-6363 photomultiplier tube. The scintillator was mounted in a fixed position such that the front face of the detector was $\frac{3}{4}$ in. from the point of intersection of the beam and the target and was centered over the target. The axis of the NaI(Tl) crystal was at right angles to the plane defined by the incident beam and the charged particle detector. Particle groups were detected with p-n junction detectors. Initially the protons were detected with a diffused detector (0.5 cm wide by 1.5 cm tall) of resistivity greater than 10 000 Ω-cm. Before the experiments were completed, this detector was no longer available, and a surface barrier type detector (0.5 cm diam) with a nominal resistivity of 3000 Ω-cm was used for the remainder of the experiment. The particle detector was located $\frac{3}{4}$ in. from the intersection of the beam and target. Most of the data were collected with $\theta p=135°$; data were also collected with $\theta p=90°$, but proved less satisfactory. These last data were used primarily to check some of the conclusions drawn from the 135° data.

Preamplified pulses from the detector assemblies were amplified with double delay line amplifiers, and proton–gamma-ray coincidences were detected with a fast ($\sim$50 nsec)-slow ($\sim 2\ \mu$sec) coincidence circuit. When the coincidence conditions imposed on the amplified pulses were satisfied, a 64×64-channel two-dimensional analyzer[8] was gated on, and the appropriate amplifier pulses were sorted and stored. Two distinct sets of data were taken at each angle of the proton detector. In one set the charged particle pulses were limited to proton groups corresponding to p_1, p_2, and p_3; in the other, proton pulse heights were limited to the region corresponding to p_4 through p_{10}.

B. Results

Throughout this paper the levels of Mg^{27} are identified according to the results of Hinds *et al.*[6] Other information is taken from the compilations of Endt and Van der Leun[1] and Ajzenberg and Lauritsen.[9] Figure 1 indicates a pulse-height distribution of the gamma radiation produced by 2.8-MeV deuterons incident on the Mg^{26} target. The observed gamma radiation is associated with the reactions and decays indicated in Table I. As this pulse-height distribution indicates, the 0.98-MeV gamma ray from Mg^{27} is not resolved from the 1.01-MeV gamma ray following the β^- decay of Mg^{27}.[1] The peak labeled 3.56 MeV is complex, and includes contributions from the $C^{12}(d,p\gamma)$ reaction and gamma radiation from either one or both of the 3.47- and 3.48-MeV states as well as the 3.56-MeV state of Mg^{27}.

TABLE I. Gamma radiation observed during the deuteron bombardment of the Mg^{26} target.

Reaction or decay	E_γ (MeV)
$Mg^{26}(d,p\gamma)Mg^{27}$	3.56, 1.69, 0.98
$Mg^{27} \xrightarrow{\beta^-} Al^{27}$	1.01, 0.84
$C^{12}(d,p\gamma)C^{13}$	3.09, 3.68
$O^{16}(d,p\gamma)O^{17}$	0.87

Figure 2 exhibits the observed pulse-height distribution of the charged particles. Pulse-height selection was used to exclude pulses corresponding to elastically scattered deuterons. The peaks labeled p_i correspond to proton groups from the $Mg^{26}(d,p)$ reaction. The proton group corresponding to p_4 is quite weak; several proton groups are unresolved. The intense particle groups observed from the $C^{12}(d,p)$ and $O^{16}(d,p)$ re-

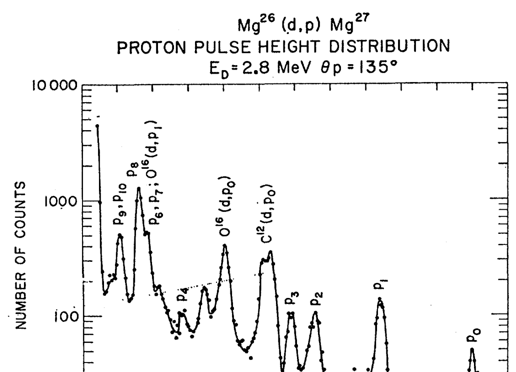

FIG. 2. Observed pulse-height distribution of protons produced by 2.8-MeV deuterons incident on the Mg^{26} target. Proton groups from the $Mg^{26}(d,p)$ reaction are labeled p_i in the figure; proton groups from the $O^{16}(d,p)$ and $C^{12}(d,p)$ reactions are also identified in the figure. The protons were detected with p-n junction detectors.

[8] R. L. Chase, IRE Natl. Conv. Record **9**, 196 (1959).

[9] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

actions are also labeled in Fig. 2. Groups not labeled in the figure were associated with unidentified contaminants; several of these groups also appeared in a pulse-height spectrum taken under similar conditions with a VYNS target.

As described in the experimental procedure, the coincidence spectra were displayed on a two-dimensional analyzer. By integrating over appropriate proton channels, the gamma-ray spectra in coincidence with the various proton groups were obtained. Figures 3 and 4 display the pulse-height distributions obtained with $\theta p = 135°$. No corrections for background have been made in these pulse-height distributions. Figure 3 indicates gamma-ray spectra in coincidence with the proton groups p_1, p_2, and p_3. The contribution of the 1.69-MeV gamma ray to the (p_3,γ) spectrum is due to the tail of the p_2 group. Figure 4 indicates the gamma-ray spectra obtained for proton groups p_4, p_8, and $p_{9,10}$. No distribution for $p_{6,7}$ is shown, since it is not observed favorably at this angle. This distribution did appear at $\theta p = 90°$. The p_5 group did not appear at either angle.

Branching ratios were determined using the following procedure. The full energy peaks were integrated numerically. (The dashed lines in Figs. 3 and 4 indicate the assumed background.) The peak-to-total ratios and efficiencies for a 3×3-in. NaI(Tl) detector were taken

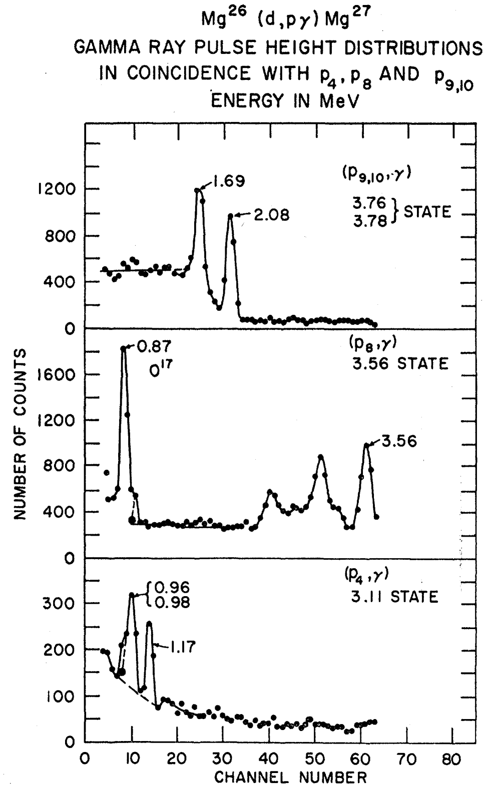

FIG. 4. Gamma-ray pulse-height distributions in coincidence with proton groups p_4, p_8, and $p_{9,10}$ from the $Mg^{26}(d,p\gamma)$ reaction. Data were collected with a two-dimensional analyzer; the pulse-height distributions were obtained by integrating over selected channels in the particle pulse-height distribution.

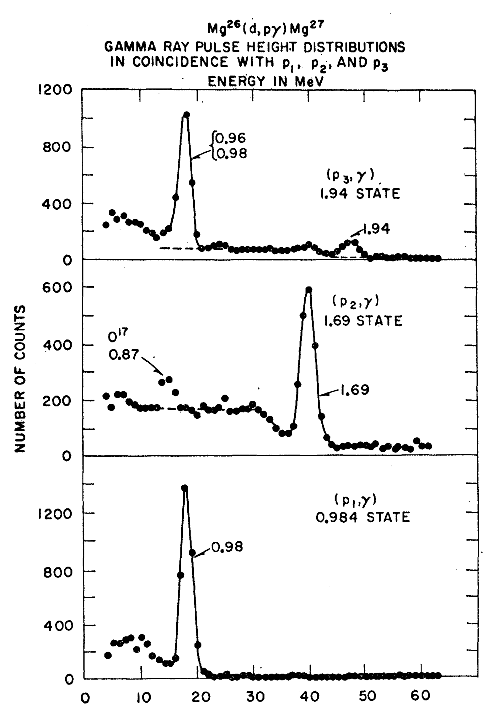

FIG. 3. Gamma-ray pulse-height distributions in coincidence with proton groups p_1, p_2, and p_3 from the $Mg^{26}(d,p\gamma)$ reaction. Data were collected with a two-dimensional analyzer; the pulse-height distributions were obtained by integrating over selected channels in the particle pulse-height distribution.

from the work of Vegors, Marsden, and Heath[10] and were used to calculate the gamma-ray yields, and thus the branching ratios. In the case of the (p_3,γ) coincidence spectrum mentioned above, it was necessary to correct the observed pulse-height distribution for sum events and for the contribution from the nearby proton group p_2. Adjacent pulse-height distributions were used to estimate the line shape of the p_2 group, and the (p_3,γ) coincidence spectrum was corrected for the contribution from the (p_2,γ) coincident events.

The proposed decay scheme for Mg^{27} is presented in Fig. 5. Upper limits for possible weak branches were calculated by examining the pulse-height distributions for the $0.98 \rightarrow 0$- and the $1.69 \rightarrow 0$-MeV transitions after estimating the background. No correction was made for chance coincidence events in obtaining these limits. The decay of the 3.11-MeV state is still uncertain. This level has a branch to the 1.94-MeV level. The measured intensity ratio of the photopeak at 0.98-MeV to the 1.17-MeV ($3.11 \rightarrow 1.94$) photopeak is approximately 1.3. This ratio is expected if the 3.11-MeV state cascades through the 1.94-MeV level, as indicated

[10] S. H. Vegors, Jr., L. L. Marsden, and R. L. Heath, Phillips Petroleum Company Report IDO-16370, 1958 (unpublished).

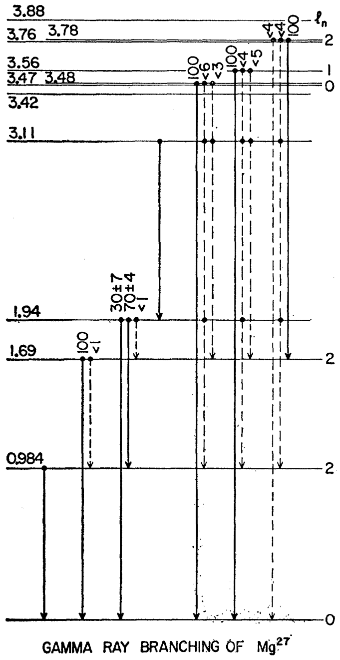

FIG. 5. Proposed decay scheme for Mg^{27}. The position of the energy levels of Mg^{27} has been taken from the compilation of Endt and Van der Leun; all the gamma-ray decays are from this work.

in Fig. 5. However, it is difficult to determine from the observed pulse-height distribution what other branches, if any, are associated with the gamma decay of this level. In particular, there may also be a ground-state transition.

III. ANGULAR DISTRIBUTION OF 1.69 → 0-MeV TRANSITION

The Mg^{26} target described above was placed on a tantalum backing and mounted in a quartz target chamber. The target was bombarded with 2.0- and 2.8-MeV deuterons. The lower energy was chosen to reduce the intensity of the gamma radiations from the $C^{12}(d,p)$ reaction. The beam current was about 0.1 μA. Resulting gamma radiation was observed with a 3-in. diam by 3-in.-long NaI(Tl) crystal which rotated about the target. The crystal was shielded from stray radiation by several inches of lead; radiation from the target impinged on the crystal axially through a 1-in.-diam lead collimator. The front face of the crystal was located 10 in. from the target.

Angular distributions of the $1.69 \to 0$-MeV gamma ray were measured at both deuteron energies. The pulse-height distribution was similar to that shown in Fig. 1, and the dashed line indicates the assumed background. A monitor detector was used consisting of a second 3×3-in. NaI(Tl) crystal which was fixed in position. Simultaneous spectra were recorded, and the area under the 1.69-MeV photopeak observed with the fixed detector was used as a monitor count. The geometry was checked by bombarding a carbon target and measuring the isotropic angular distribution of the C^{13} $3.09 \to 0$ transition. The 1.69-MeV data was fitted using a least-squares program, including even Legendre polynomials up to order four. At 2.8 MeV, the angular distribution is of the form

$$W(\theta)\sim[1+(0.17\pm0.04)P_2(\cos\theta) - (0.01\pm0.05)P_4(\cos\theta)].$$

At 2.0 MeV the result is

$$W(\theta)\sim[1+(0.09\pm0.03)P_2(\cos\theta) - (0.02\pm0.04)P_4(\cos\theta)].$$

These results are presented in Fig. 6.

Since the ground-state spin of Mg^{27} is $\frac{1}{2}$, and the observed angular distribution requires a $P_2(\cos\theta)$ term, but not a $P_{(4)}(\cos\theta)$ term, the spin of the 1.69-MeV state is $\geq\frac{3}{2}$.

IV. DISCUSSION

Previous analysis[1] of stripping data indicated that the spin of the second excited state of Mg^{27} is either $\frac{3}{2}$ or $\frac{5}{2}$ (positive parity). The present angular distribution measurement of the gamma decay of the second excited state of Mg^{27} is in agreement with this result. It is interesting to note that in other nuclei with $Z=15$ or $N=15$ (for example, Si^{29}, P^{29}, P^{31}—all having spin sequences of $\frac{1}{2}+$, $\frac{3}{2}+$, $\frac{5}{2}+$) the second excited state decays nearly 100% to the ground state. The present measurements show that the second excited state of Mg^{27} also decays in this fashion; this, together with the stripping analysis and the angular distribution results suggests that the second excited state of Mg^{27} also has a spin and parity $\frac{5}{2}+$.

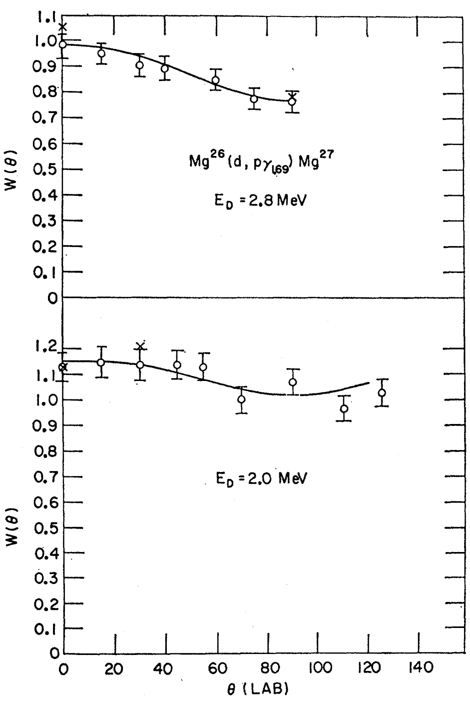

FIG. 6. Angular distribution of the $1.69 \to 0$-MeV gamma-ray transition in Mg^{27}.

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Nuclear Models and the Osmium Isotopes*

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The energies of, and transition probabilities involving, the ground-state rotation bands of Os^{186}, Os^{188}, and Os^{190} are compared with a diagonalized rotation-vibration theory in which vibrations are considered to three phonon order. Agreement even in the Os transition region is found to be excellent. The theory appears to be particularly successful in predicting two phonon states in Os^{190}.

INTRODUCTION

THE even-mass osmium isotopes occupy a transition region between highly deformed and spherical nuclei. They represent a kind of testing ground for nuclear models because deviations from pure rotational bands can be expected to be large. In the nucleus Os^{190}, the Bohr-Mottelson model, even with empirical rotation-vibration interaction, is completely unable to account for the energy levels. Thus comparisons of the Bohr-Mottelson and Davydov nuclear models in this transition region have often indicated a decided preference for the model of Davydov. Furthermore, the careful experimental work of Scharff-Goldhaber and collaborators[1–5] and others[6–11] has led to a large amount of information on Os^{186}, Os^{188}, and Os^{190}. Recently, Lark, Morinaga, and Gugelot[12] have been able to measure the energies of the ground-state rotational bands of deformed nuclei up to very high spins. We shall compare the energies of, and the transition probabilities involving, the ground-state bands in the three mass nuclei Os^{186}, Os^{188}, and Os^{190} with the rotation vibration model (RV model)[13–15] and the model of Davydov[16] with rotation-vibration interaction of the beta vibrations carefully considered. These comparisons indicate advantages for the RV model relative to the

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