Lifetimes of the First Excited States of Mg^{25} and Al^{25}†

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The lifetimes of the first excited states of Mg^{25} and Al^{25}, at 0.58 and 0.45 MeV, respectively, have been measured using a pulsed Van de Graaff beam technique. The mean lives were found to be (4.82±0.10) nsec for Mg^{25} and (3.33±0.07) nsec for Al^{25}.

I. INTRODUCTION

THE investigations of Litherland *et al.*[1] have shown that the Nilsson model[2] can give a generally satisfactory account of the mirror nuclei Mg^{25} and Al^{25}. In their work, a range of experimental data on the level structure, nucleon reduced widths, gamma transition widths, and branching and mixing ratios was compared with the model, and agreement was found for most of these properties for deformations in the region $\eta\sim4$. The work of Litherland *et al.* has stimulated further experimental work on Mg^{25} and Al^{25} and the present paper reports measurements of the lifetimes for the $E2$ gamma decay of the $\frac{1}{2}+$ first excited states of these nuclei to the $\frac{5}{2}+$ ground states. Both these lifetimes have been measured previously, and the present measurements were undertaken to confirm the published values and to improve their accuracy.

II. APPARATUS

Both lifetimes reported here were measured using the pulsed beam facility of the Brookhaven Van de Graaff. This system employs the slanted target time compression technique.[3] A detailed description of the apparatus has been published elsewhere[3–5]; only a brief account is given here.

The Van de Graaff beam is pulsed after acceleration to produce beam pulses of about 0.1-nsec duration on a target, with a spacing between pulses of 134 nsec. The beam accelerated in the Van de Graaff may be continuous in time, or may, if desired, be pulsed before acceleration in the terminal of the Van de Graaff. This terminal pulser produces beam pulses about 5 nsec wide. It can be synchronized with the external beam pulser which then further shortens the pulse to about 0.1 nsec. Operation with synchronized pulsers in this manner reduces substantially the background arising from beam swept onto beam pipes, collimators, and rf deflection plates.

Figure 1 shows a schematic diagram of the detector and associated electronic equipment, which have been described in detail elsewhere.[4,5] The photomultiplier was a RCA type C7260B. NaI(Tl) phosphors were used throughout the present experiments; a crystal 1 in. thick and $1\frac{1}{2}$ in. in diameter was used for the Al^{25} measurement and a 2 in.×2 in. crystal was used for Mg^{25}. The time resolution observed for prompt gammas from the reaction $C^{12}(d,p\gamma)C^{13}$ was 2.5 nsec (full width at half-maximum). This width arises mostly from the use of NaI(Tl) phosphors: With Pilot-B plastic scintillator, a width of less than 0.5 nsec is observed.

Time calibration of the apparatus is accomplished by insertion of varying lengths of RG63/U cable in the fast signal lead. The velocity of detector signals in this cable has been measured to an accuracy of 0.3%, and a description of these measurements, and of tests of

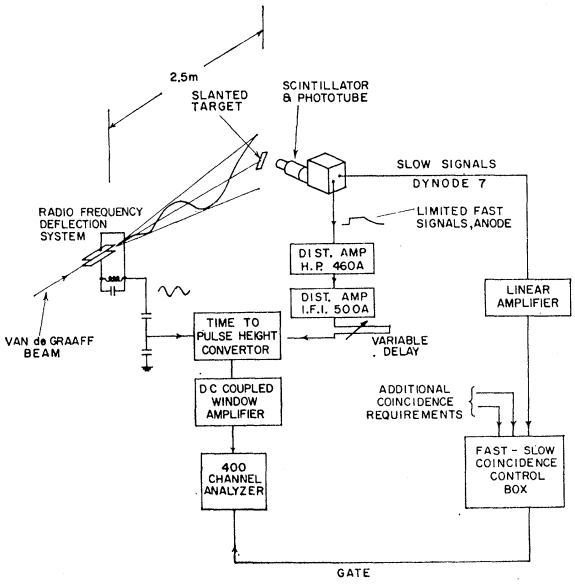

FIG. 1. Block diagram of the electronics.

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[1] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).

[2] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 16 (1955).

[3] J. V. Kane, M. A. El-Wahab, J. Lowe, and C. L. McClelland, in *Proceedings of the International Conference on Nuclear Electronics, Belgrade, May, 1961* (International Atomic Energy Agency, Vienna, 1962).

[4] J. Lowe, C. L. McClelland, and J. V. Kane, Phys. Rev. **126**, 1811 (1962).

[5] J. Lowe, Brookhaven National Laboratory Report BNL-6140, 1962 (unpublished).

the over-all calibration of the system is given in reference 4.

III. EXPERIMENTAL PROCEDURE

Mg^{25}

The first excited state[6] of Mg^{25} can be excited in the $Mg^{25}(p,p')$ reaction. In the present experiments a thick natural Mg target (10% Mg^{25}) was bombarded with 2.7-MeV protons. Figure 2 shows a gamma pulse-height spectrum from the NaI(Tl) scintillation detector, which was situated about 10 cm from the target. The terminal pulser in the Van de Graaff was not used. The single-channel discriminator was channeled as shown on the 580-keV gamma. This channel also contains contributions from the Compton distributions of the 980-keV gamma from the second excited state of Mg^{25} and the 1.37-MeV gamma from the first excited state of Mg^{24}. Both these gammas are known to be fast[6]; they, therefore, contribute a prompt component to the time spectrum.

The time spectrum of 580-keV gammas, after subtraction of background, is shown in Fig. 3. The prompt comparison curve was obtained using 0.84- and 1.01-MeV gammas from $Al^{27}(p,p'\gamma)Al^{27}$, with the channel set at 580 keV as before. To avoid errors due to gradual drift of the centroid position the Mg and Al targets were bombarded alternately; the data of Fig. 3 are the sum of 20 short runs on each target.

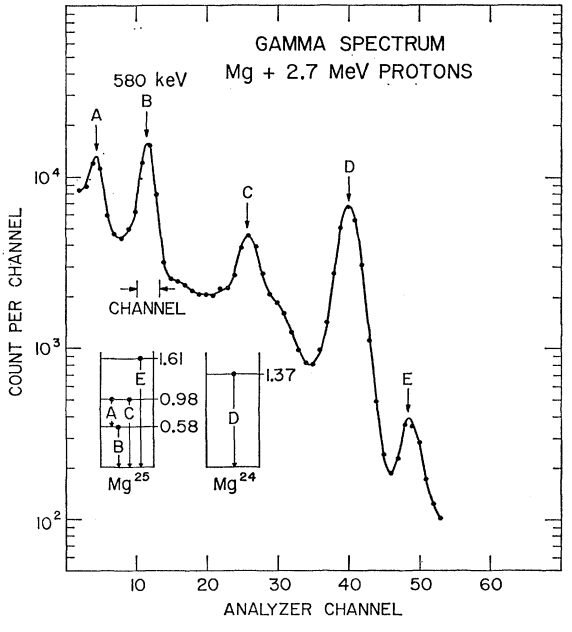

FIG. 2. Gamma pulse-height spectrum for the NaI(Tl) scintillation detector during the proton bombardment of magnesium. The single-channel discriminator was channeled on the 580-keV gamma photopeak as shown.

[6] P. M. Endt and C. Van der Leun, Nucl. Phys. 34, 1 (1962).

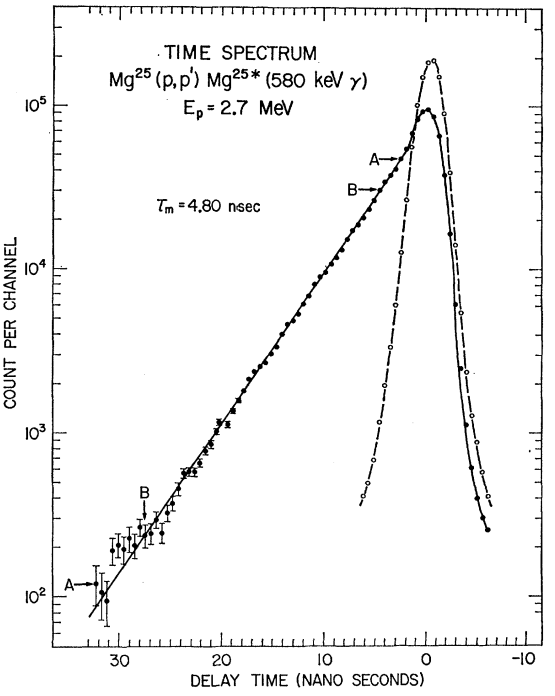

FIG. 3. Time spectrum of 580-keV gammas from the proton bombardment of magnesium. The exponential part of the decay is a least-squares fit to the region A-A. A prompt comparison curve using gammas from the reaction $Al^{27}(p,p'\gamma)Al^{27}$ is also shown.

Al^{25}

The first excited state[6] of Al^{25} at 450 keV can be produced in the reaction $Mg^{24}(d,n\gamma)Al^{25}$. In the present experiment a natural Mg target (79% Mg^{24}) was bombarded with 2.7-MeV deuterons. The gamma pulse-height spectrum from the NaI(Tl) scintillator is shown in Fig. 4. The channel shown also contains contributions from the Compton distributions of 840-, 980-, and 950-keV gammas from Al^{27}, Mg^{25}, and Al^{25}, respectively (see Fig. 4). The first two of these are known to be fast,[6] and the last is expected to be, because of the known speed[6] of the corresponding transition in the mirror nucleus, Mg^{25}. The channel also contains a contribution produced by the 580-keV gamma from Mg^{25}; the effect of this delayed gamma on the measurement will be discussed below.

The time spectrum of 450-keV gammas, after subtraction of background, is shown in Fig. 5. In obtaining these data, the beam was pulsed before acceleration in the Van de Graaff terminal, and the terminal pulser was synchronized with the post-acceleration pulser as described in Sec. II. The detector was heavily shielded[4] and was placed about 120 cm from the target. With this geometry, the flight time of the highest energy neutron group from the target is long enough to permit the observation of 3 decades of exponential decay followed by about 15 nsec of time-independent background, free of neutron groups. Prompt comparison

runs were taken using gammas from $C^{12}(d,p\gamma)C^{13}$ with the same gamma channel as in the Al^{25} runs. The Mg and C targets were alternated 4 times during the run.

Al^{25} can also be produced in the $Mg^{24}(p,\gamma)Al^{25}$ reaction. A run using this reaction was attempted, with a target of 99.96% $Mg^{24}O$, bombarded with 1.6-MeV protons. Synchronized beam pulsing was again employed, and the detector, a 2-in.×2-in. NaI(Tl) crystal, was placed about 10 cm from the target. Prompt comparison gammas were provided by the reaction $O^{16}(p,\gamma)F^{17}$ on a quartz target; the lifetime of the first excited state of F^{17} is short compared with that of Al^{25}.

IV. RESULTS

Mg^{25}

After subtraction of background, the data (shown in Fig. 3) were analyzed carrying out a least-squares fit to the region of the exponential decay clear of the influence of the prompt peak, the region *A-A* in Fig. 3. The mean life corresponding to this slope is 4.80 nsec; the narrower region *B-B* yields a mean life within 0.4% of this value. A similar run of comparable statistical accuracy but with a smaller channel on the single-channel discriminator yielded a mean life of 4.84 nsec. The two runs, therefore, agree to about 0.7%, and the external error in each is about 0.5%. However, the dominant source of error is the uncertainty of 2% in the time calibration (discussed in reference 4). Thus, the final result for the mean life is

$$\tau_m = (4.82 \pm 0.10) \text{ nsec.}$$

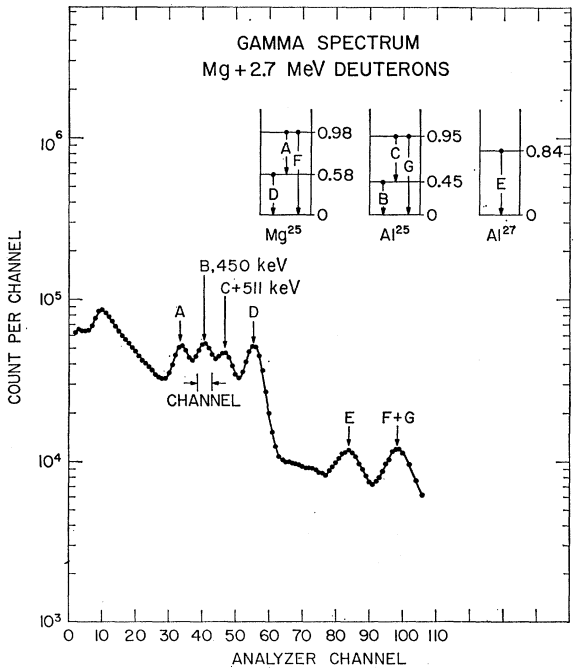

FIG. 4. Gamma pulse-height spectrum from the deuteron bombardment of magnesium. The single-channel discriminator was channeled on the 450-keV gamma photopeak as shown.

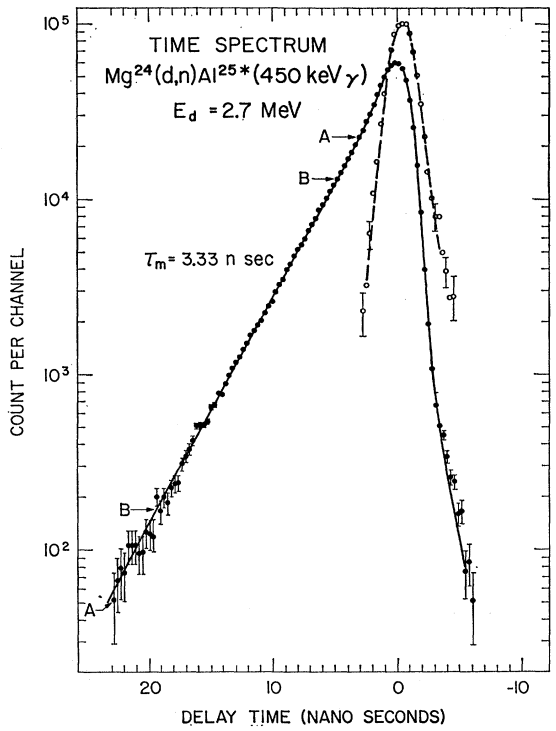

FIG. 5. Time spectrum of 450-keV gammas from the $Mg^{24}(d,n\gamma)Al^{25}$ reaction. The exponential part of the decay is a least-squares fit to the region *A-A*. A prompt comparison curve using gammas from the reaction $C^{12}(d,p\gamma)C^{13}$ is also shown.

Al^{25}

The data of Fig. 4 were analyzed by a least-squares technique in the same way as the Mg^{25} data. The region *A-A* in Fig. 4 corresponds to a mean life of 3.33 nsec. The region *B-B* yields a value within 0.5% of this, as also does the upper, statistically most significant, section of the data when analyzed separately. The possibility exists of distortion of the exponential decay by the presence in the channel of 580-keV gammas from $Mg^{24}(d,p\gamma)Mg^{25}$ (τ_m=4.82 nsec) or of 420-keV gammas from $Mg^{25}(d,n\gamma)Al^{26}$ (τ_m=1.23 nsec[7]). The absence of any significant distortion is confirmed by the agreement between lifetime values determined from least-squares fits to different regions of the exponential decay, and also by the closeness of the external and internal errors of these fits, the ratio of which is 1.06 for the region *A-A* and 1.02 for the region *B-B*. The slope of the lowest decade of the region *A-A* yields a lifetime of (3.54±0.42) nsec. The fact that this is longer than the mean slope of the entire region *A-A* (though equal to it within its error) presumably reflects the presence of distortion by 580-keV gammas from Mg^{25}. However, the agreement to within 0.5% between the mean slope of the whole region with that of the *upper* decade indicates that the distortion does

[7] S. Gorodetzky, R. Richert, R. Manquenouille, and A. Knipper, J. Phys. Radium **22**, 690 (1961).

not affect the lifetime determined to within this accuracy.

The $Mg^{24}(p,\gamma)Al^{25}$ reaction was used to establish further the absence of distortion of the Al^{25} decay by Mg^{25} and Al^{26}, since these nuclei are not produced in the proton bombardment of $Mg^{24}O$. The lower yield to background ratio for this experiment produced a value for the lifetime of the 450-keV level in Al^{25} substantially less accurate ($\pm 10\%$) than that from the $Mg^{24}(d,n\gamma)Al^{25}$ measurement, but the two values agreed within the error. Thus, the $Mg^{24}(p,\gamma)Al^{25}$ run supports, but cannot confirm in detail, the result from the $Mg^{24}(d,n\gamma)Al^{25}$ runs.

As in the case of Mg^{25}, the external error in the $Mg^{24}(d,n\gamma)Al^{25}$ run is less than 0.5% and the 2% uncertainty in the time calibration is the dominant source of error. The result for Al^{25} is, therefore,

$$\tau_m = (3.33 \pm 0.07) \text{ nsec.}$$

As a check on the internal consistency of the measurements, a time spectrum was taken during deuteron bombardment, with the channel set on the photopeak of the 580-keV gamma from Mg^{25} (Fig. 4). The lifetime observed agreed with that observed for this same radiation in the $Mg^{25}(p,p'\gamma)Mg^{25}$ measurements.

V. DISCUSSION

The present result for Mg^{25} is in agreement with the only other published measurement of this lifetime, that of Ferguson, Grace, and Newton,[8] who found

$$\tau_m = (5.05 \pm 0.29) \text{ nsec.}$$

The present result for Al^{25} does not agree with that of Ferguson *et al.*, who obtained

$$\tau_m = (2.6 \pm 0.4) \text{ nsec.}$$

However, these authors did not observe the exponential decay directly, but analyzed the shape of their delayed time spectrum by a visual technique. Such a technique is not as accurate as direct measurement of the exponential decay, and the discrepancy is probably not significant. The present result for Al^{25} is also in disagreement with that of Gorodetzky *et al.*[9] who found $\tau_m = (2.72 \pm 0.14)$ nsec, using a delayed coincidence technique in the reaction $Mg^{24}(p,\gamma)Al^{25}$. Gorodetzky *et al.* obtained their value from the exponential decay of the level. The reason for this discrepancy is not known.

In the Nilsson model both these transitions are regarded as single-particle transitions, from orbit 9 to orbit 5, outside a deformed Mg^{24} core. There is no rotational contribution, even when first-order band mixing is included, since the states belong to bands for which K differs by 2. In calculating the Nilsson model estimate, two assumptions must be made concerning the parameters involved:

(a) The prediction is sensitive to the nuclear size assumed through the radial integrals for Al^{25}. Values for the integrals involved have been calculated by Arnurius, Buck, and Satchler[10] using wave functions computed in a well of Saxon-Woods form with realistic parameters which reproduce correctly the odd proton binding energy in Al^{25}. In the present calculation, the integrals computed by Arnurius *et al.* were used. The numerical values are 14.1×10^{-26} and 14.0×10^{-26} cm^2 for the $2s$-$1d$ and $1d$-$1d$ integrals, respectively.

(b) Polarization of the nuclear core by the last odd nucleon is conventionally allowed for by the assignment of an additional effective charge to the odd nucleon. Theory and experiment[4,11,12] indicate that effective charges of $0.2e$ to $0.5e$ are typical for light nuclei, and that the effective charge should be less[12] for a proton than for a neutron.

The present results are in agreement with these requirements on the effective charge for deformations in the range, $1.5 \lesssim \eta \lesssim 4$. For $\eta \lesssim 1.5$, the prediction for Al^{25} is too fast even with no additional effective charge on the odd proton. For $\eta \gtrsim 4$, the effective charge required to fit the results is greater for the odd proton in Al^{25} than for the odd neutron in Mg^{25}, and in any case seems unreasonably high ($>0.8e$) for light nuclei. The most reasonable region of deformation is: $2.0 < \eta < 3.5$, within which effective charges of $0.1e$–$0.6e$ for the proton and $0.5e$–$0.7e$ for the neutron are required to achieve agreement of the Nilsson model prediction with experiment. This is consistent with the analysis of Litherland *et al.*[1] who found, with deformations in the region: $3 < \eta < 4.5$, the Nilsson model can, in general, give a reasonably good account of these nuclei.

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[8] A. T. G. Ferguson, M. A. Grace, and J. O. Newton, Nucl. Phys. **17**, 1 (1960).

[9] S. Gorodetzky, R. Richert, R. Manquenouille, and A. Knipper, Compt. Rend. **251**, 944 (1960).

[10] D. E. Arnurius, B. Buck, and G. R. Satchler, *Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, Tennessee, October 5–7, 1961*, Nuclear Science Series Report No. 37, (National Academy of Science-National Research Council Publication 974, 28, 1962); and (private communication) from Dr. Satchler through Dr. B. J. Raz.

[11] B. J. Raz, Phys. Rev. **120**, 169 (1960).

[12] G. Barton, Nucl. Phys. **11**, 466 (1959); G. Barton, D. M. Brink and L. M. Delves, *ibid.* **14**, 256 (1959/60).