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PHYSICAL REVIEW C VOLUME 3, NUMBER 2 FEBRUARY 1971

Coulomb Excitation of the First 2^+ State of ^{24}Mg†

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Coulomb excitation of the first excited state of ^{24}Mg has been investigated by means of a coincidence experiment using a position-sensitive detector. Interpreting the data according to the semiclassical theory and correcting for quantal effects, we obtained a reduced transition probability of $B(E2;\ 0^+ \rightarrow 2^+) = 0.042 \pm 0.002\ e^2\mathrm{b}^2$ and a static quadrupole moment of $Q_{2^+} = -0.305 \pm 0.064\ e\,\mathrm{b}$.

I. INTRODUCTION

In recent years, higher-order effects in Coulomb excitation (including the so-called reorientation effect) have been used extensively to determine spectroscopic quadrupole moments of excited nuclear states.[1] A large number of experiments have been performed on medium-heavy and heavy nuclei. It was of interest to extend those measurements to light nuclei, in particular to ^{24}Mg, whose excitation spectrum displays quasirotational features. In this region, the standard experimental techniques used in heavier nuclei present some technical difficulties, however, and various new methods have been developed. Bamberger, Bizetti, and Povh[2] have measured the quadrupole moment of the first excited state of ^{24}Mg by looking at the line shape of the 1.37-MeV γ rays emitted at 0°.

From this line shape it is possible to deduce the angular distribution of the inelastically scattered ions and hence the quadrupole moment. Häusser *et al.*[3] also measured the quadrupole moment of this state using a particle-γ-coincidence method.

A direct way to obtain the static quadrupole moment is to measure the ratio $R = d\sigma(2^+)/d\sigma(\text{g.s.})$ of the inelastic cross section to the elastic cross section. By using a coincidence method between the recoil nuclei and the scattered ions, we achieved the separation of elastic from inelastic events and were thus able to determine this ratio directly.

Since there has been considerable theoretical interest in ^{24}Mg,[4-6] it seemed desirable to verify previous results by means of our independent measurement.

II. EXPERIMENTAL PROCEDURE

The experiment was carried out with 20- and 22-MeV ^{16}O ions from the Pittsburgh tandem Van de Graaff. Isotopically enriched magnesium targets (99.96%) of about 5- to 15-μg/cm^2 thickness on 5-μg/cm^2 carbon backings were used. Target thicknesses were determined during vacuum evaporation by a crystal oscillator microbalance, and, later by Rutherford scattering. The values thus obtained are believed to be accurate to within 30%. Spot targets of 2 mm$\times$4 mm were employed in order to avoid the use of defining slits which cause slit-edge scattering. The scattered oxygen ions were detected in coincidence with the recoil magnesium ions.

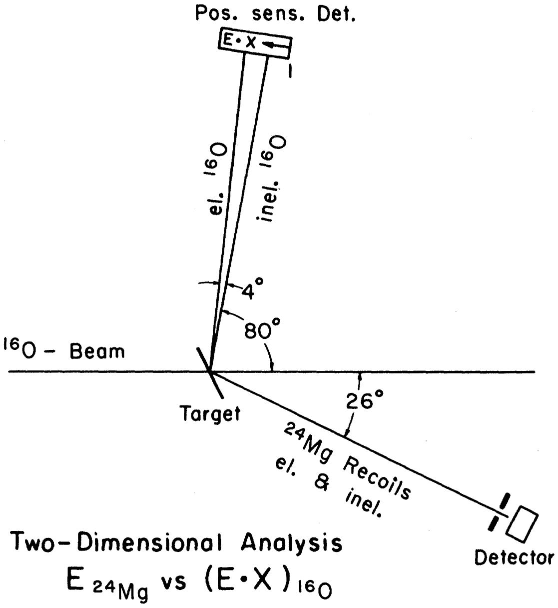

FIG. 1. Schematic representation of the experimental setup.

A typical situation is represented in Fig. 1. A surface-barrier detector detected the elastic and the inelastic magnesium recoil ions at the same laboratory angle. A position-sensitive detector was used to detect the corresponding elastic and inelastic oxygen ions, which were separated by about 4°. For forward-angle data, we reversed the procedure to avoid exposing the position-sensitive detector to an excessive particle flux. In this case, the oxygen ions were detected by the surface-barrier detector at a forward angle and the recoils by the position-sensitive detector near 90°. To improve the coincidence timing and to decrease noise, both detectors were cooled to about −15°C.

Two-dimensional spectra were accumulated in the 64×64-channel mode of a pulse-height analyzer. The form of the display was E versus XE', where E is the energy spectrum from the surface-barrier detector and XE' is the position times energy output of the position-sensitive detector. A typical two-dimensional spectrum is represented in Fig. 2. A profile of this spectrum parallel to the E axis with XE' falling in channel 27, as indicated by the arrows in Fig. 2, is shown in Fig. 3. More details about the method will be given elsewhere.[7]

From these figures it is evident that the peak-to-valley ratio for the inelastic peak is ~40. The worst peak-to-valley ratio for any configuration was always better than 10. The peak labeled ^{19}F is due to elastic scattering of ^{16}O from a ^{19}F contaminant and appears only at forward-angle configurations.

III. ANALYSIS AND RESULTS

The quantity measured is the ratio

$$R_{\text{exp}} = d\sigma_{\text{inelastic}}(\theta_i)/d\sigma_{\text{elastic}}(\theta_e)$$

of the inelastic cross section to the elastic cross section, where θ_i and θ_e are the laboratory angles of the inelastically and elastically scattered oxygen ions. A least-squares fit to the experimental ratios was performed using the function

$$R_{\text{calc.}} = |M_{12}|^2[A + BM_{22} + C(M_{22})^2] .$$

The coefficients A, B, and C were calculated by means of the coupled-channel code of Winter and de Boer.[8] The incident energy at which these coefficients were calculated was taken to be the mean energy of the ^{16}O beam as it passed through the ^{24}Mg target. The quantities M_{rs} represent the reduced quadrupole matrix elements as defined in Ref. 8 between states r and s. The $B(E2)$ and static quadrupole moment values were extracted from the fit using the relations

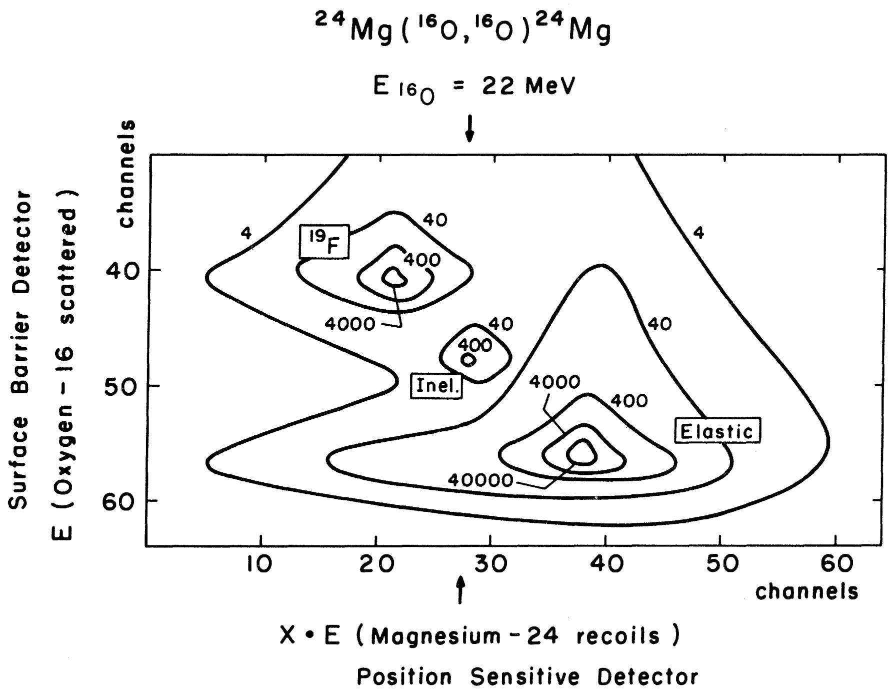

FIG. 2. Contour representation of a typical two-dimensional spectrum. The numbers indicate the number of counts per channel corresponding to a contour level.

$B(E2;\ 0^+ \to 2^+) = |M_{12}|^2,$

$Q_{2^+} = -0.758 M_{22}.$

It was verified that the function used above reproduces the computer calculations to better than 0.05%.

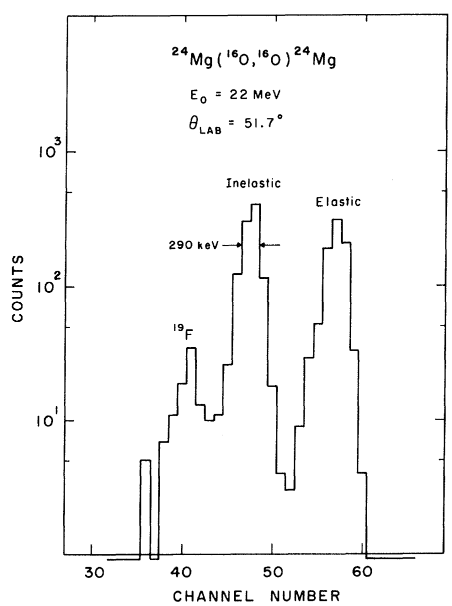

FIG. 3. Profile spectrum taken at the place indicated by the arrows on Fig. 2. The channel numbers correspond to the energy of the oxygen ions.

The experimental ratios are given in Table I. Column 2 gives the incident beam energy at the center of the target. Columns 3 and 4 give the laboratory angles of the oxygen ions. The ratios R_{exp} are given in column 5. The errors quoted include statistical errors, angle uncertainties which are believed to be ±0.15°, background subtraction, and the uncertainty in the mean energy at which the scattering took place. These data are represented in Fig. 4 as the ratio R_{exp}/R_0, where R_0 is calculated by means of the Winter-de Boer program setting $Q_{2^+}=0$ and $B(E2;\ 0^+\to 2^+)=0.042\ e^2 b^2$. For reasons discussed below, we believe the data points numbered 8-9-10, taken at 22 MeV, include nuclear effects. They have consequently been excluded from the evaluation of Q_{2^+} and the $B(E2;\ 0^+\to 2^+)$. Using only the two first levels (ground state and first 2^+ state), the least-squares analysis of the remaining data gives the following results:

$B(E2;\ 0^+ \to 2^+) = 0.042 \pm 0.002\ e^2 b^2,$

$Q_{2^+} = -0.338 \pm 0.070\ e\,b.$

The fit to the experimental points with these values is represented by the solid line in Fig. 4. Several corrections must yet be applied to these results.

It is well known that virtual excitation via higher excited states must be taken into account. In the present experiment virtual excitation via the 2^+

TABLE I. Experimental ratios.

Run No.	E_{lab} (MeV)	Laboratory angle Elastic (deg)	Laboratory angle Inelastic (deg)	R_{exp} ($\times 10^3$)
1	21.9	35.6	35.6	1.57 ± 0.05
2	21.9	42.9	42.9	2.78 ± 0.06
3	21.9	51.7	51.7	4.33 ± 0.09
4	19.9	51.7	51.7	1.98 ± 0.05
5	19.9	55.6	55.6	2.38 ± 0.07
6	19.9	87.1	82.5	3.80 ± 0.11
7	19.9	92.9	88.1	4.10 ± 0.10
8	21.9	91.2	86.9	6.83 ± 0.27
9	21.9	97.1	92.6	7.21 ± 0.16
10	21.9	97.9	93.4	7.47 ± 0.30

state at 4.232 MeV (Fig. 5) is expected to have the largest effect. Using the matrix elements given in Table II for either sign of M_{42}, we have calculated the effect on the quadrupole moment to be less than 2% (see Table III). For the highly excited 1^- states of the giant dipole resonance, estimates based on earlier works[1,9] indicate that this effect is negligible compared to the reorientation effect.

It has been pointed out by Smilansky[10] as well as Alder and Pauli[11] that quantum mechanical corrections to the semiclassical calculation may become important. Alder and Pauli showed that these corrections are inversely proportional to the parameter η which is defined as the ratio $a/\lambdabar$ of half the distance of closest approach in a head-on collision to $1/2\pi$ times the de Brogle wavelength of the projectile at infinity. If z_1 and z_2 are the charge numbers of projectile and target, respectively, and v the relative velocity between the two, then

$$\eta = \frac{a}{\lambdabar} = \frac{z_1 z_2 e^2}{\hbar v}.$$

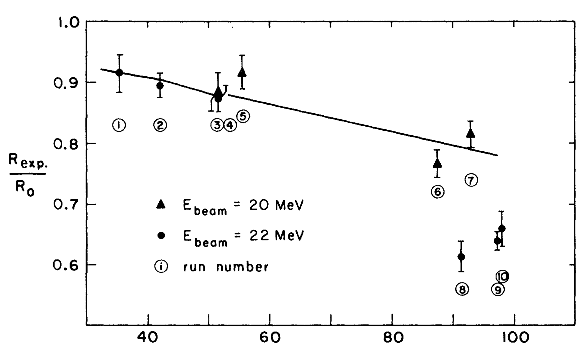

FIG. 4. Experimental data represented as the experimental ratio R_{exp} divided by the calculated ratio R_0. R_0 is evaluated with a zero quadrupole moment. The solid line represents the values of $R_{calc.}/R_0$ obtained from the fit.

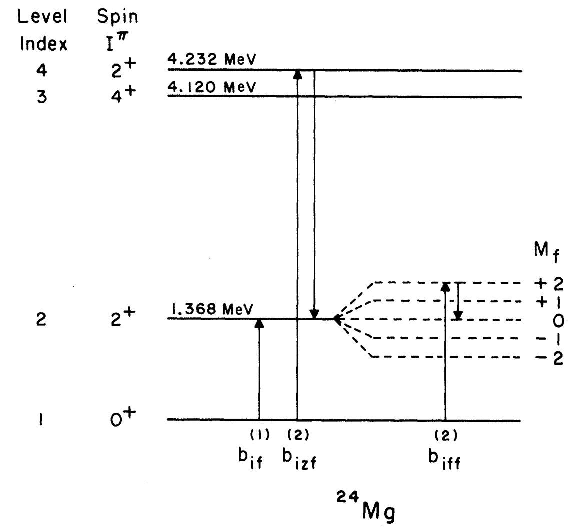

FIG. 5. Magnesium-24 level scheme. The arrows represent possible $E2$ transitions.

In the present experiment $\eta = 14$. Using the results of Ref. 11 one finds a correction of 0.8% for the $B(E2)$ and −11% for the quadrupole moment.

The effect due to atomic scareening was estimated in a manner similar to that given by Saladin, Glenn, and Pryor[12] and found to be negligible.

The final value for the reduced transition probability $B(E2; 0^+ \rightarrow 2^+)$ and Q_{2^+} are given in the last column of Table III. In Fig. 6 the present values are compared with those of other groups. The value for $B(E2; 0^+ \rightarrow 2^+)$ is in good agreement with those of Pelte *et al.*[13] and Ref. 3, but it disagrees with a recent measurement of Herrman and Kalus[14] who performed a resonance-fluoresence experiment. We have no explanation for this discrepancy. The value for the static quadrupole moment is consistent with the results of previous measurements.

IV. NUCLEAR EFFECTS

Recent experiments with α particles[15-17] have shown that deviations from pure Coulomb excitation occur at lower energies than previously

TABLE II. Summary of input information for the computer calculation. The matrix elements M_{12} and M_{22} are extracted from the data, the other matrix elements are from S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data A2, 347 (1966).

Level index n	Excitation energy (MeV)	Spin and parity	Matrix elements (eb) M_{n1}	M_{n2}	M_{n3}	M_{n4}
1	0.0	0^+	0.0	M_{12}	0.0	0.0475
2	1.3686	2^+	M_{21}	M_{22}	0.258	± 0.0686
3	4.1227	4^+	0.0	0.258	0.0	0.0
4	4.2330	2^+	0.0475	± 0.0686	0.0	0.0

TABLE III. Corrections to the experimental data.

	Value corrected for energy loss in target	Quantal correct.	Higher states	Giant dipole	Atomic screening	Final value
			(Corrections in percent)			
$B(E2;\ 0^+ \rightarrow 2^+)$ $(e^2 b^2)$	0.042 ± 0.002	+0.8	~−0.2	<0.1	−0.3	0.042 ± 0.002
Q_2^+ $(e\,b)$	-0.338 ± 0.070	−11	−2 [a] +0.5 [b]	±1	...	-0.305 ± 0.064

[a] For $M_{12} M_{14} M_{24} > 0$.
[b] For $M_{12} M_{14} M_{24} < 0$.

thought. It was furthermore shown that these deviations are consistent with the results of distorted-wave Born-approximation (DWBA) calculations. Coupled channels as well as DWBA calculations are in progress to investigate the interference behavior between Coulomb and nuclear excitation in the present experiment. Standard DWBA codes are unfortunately too limited in the number of partial waves included in the calculation as well as in the range of integration of the radial equations to give reliable results.

It has been suggested,[18] that an empirical guide for "safe" bombarding energies is given by the requirement that the separation between the *surfaces* of projectile and target be larger than or equal to 5 F (defining the nuclear radius by $R = 1.25 \times A^{1/3}$ F). We investigated this question experimentally by means of an excitation function at a laboratory angle of 51.7°. The results are presented in Fig. 7 and show that deviations from the pure Coulomb-excitation prediction occur at ~24 MeV. This corresponds to a separation distance of 5 fm, and thus corroborates the empirical rule mentioned above. Applied to the backward-angle measurements the rule implies bombarding energies below or equal to 20 MeV. This is the reason for omitting the backward-angle data of 22 MeV (runs No. 8–10), which correspond

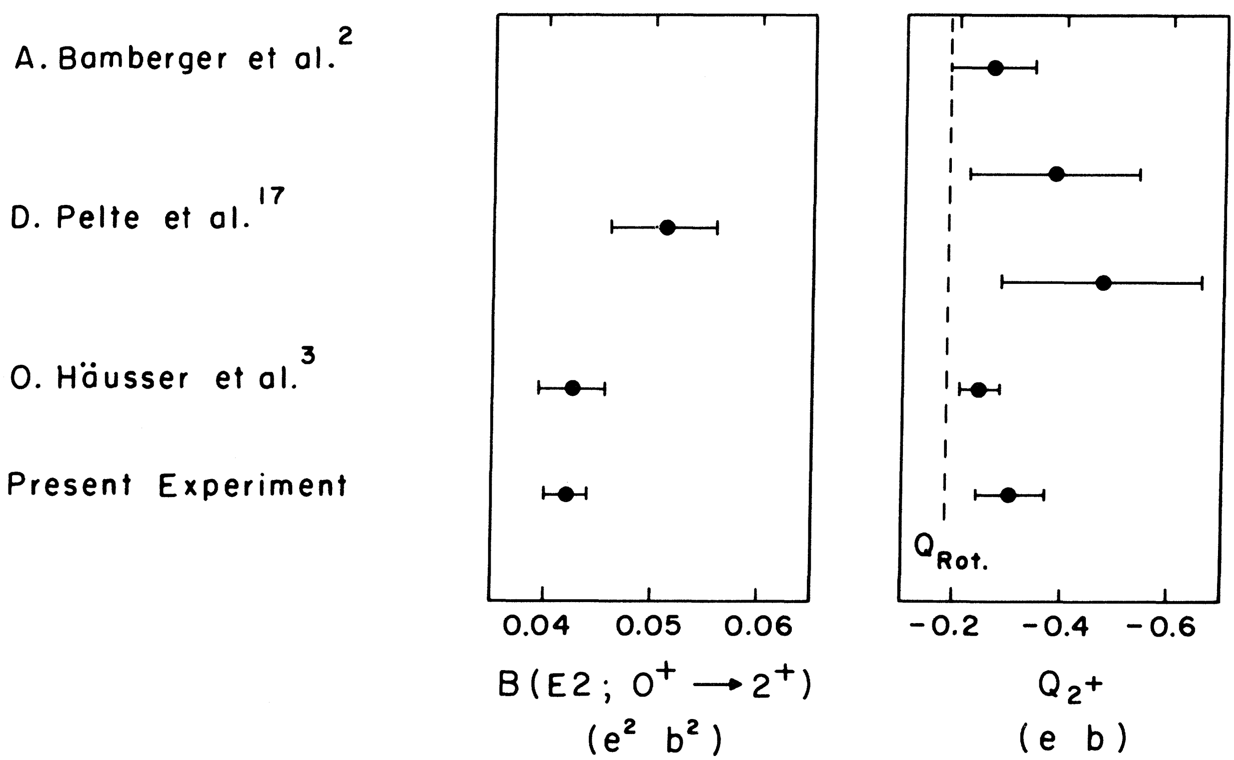

FIG. 6. Experimental $B(E2;\ 0^+ \rightarrow 2^+)$ and Q_{2^+} values for magnesium-24. The indicated Q_{Rot} is calculated from our $B(E2)$ value according to the adiabatic rotation model.

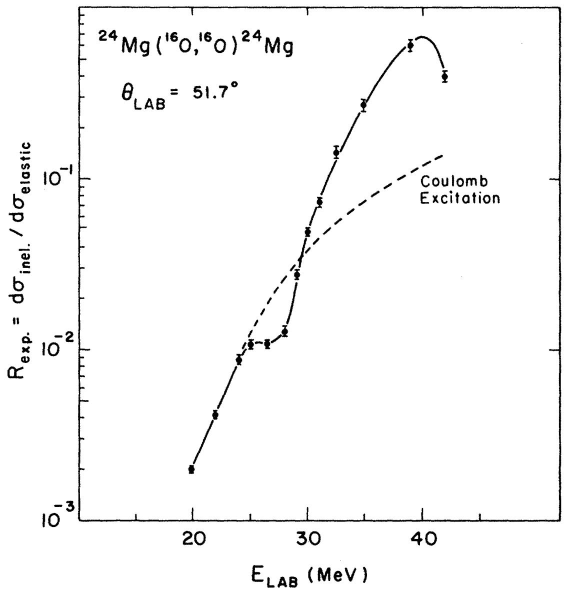

FIG. 7. Experimental ratio $R_{exp} = d\sigma_{inel.}/d\sigma_{elastic}$ as a function of the incident beam energy E. The solid line is drawn as a guide to the eye. The dashed line is the Coulomb-excitation prediction.

to a separation of only 3.7 F in the evaluation of Q_{2^+} and $B(E2;\ 0^+ \rightarrow 2^+)$. It is in fact evident from Fig. 3, when one compares the backward-angle data points at 20 MeV with those at 22 MeV, that non-Coulombic contributions are present in the latter. It should be noted that the presence of nuclear excitation would simulate a quadrupole moment which is too large in magnitude.

Due to the rapid decrease in the excitation cross section it was not possible to extend the measurements to energies below 20 MeV. On the basis of the above discussion it seems, however, reasonable to assume that the data used in determining the quantities Q_{2^+} and $B(E2;\ 0^+ \rightarrow 2^+)$ are free from nuclear excitation, but we cannot entirely exclude the possibility of such contributions.

V. DISCUSSION

Even though the various results for the quadrupole moment of the first 2^+ state in ^{24}Mg are associated with quite large uncertainties, it is conspicuous that all measurements yield a value which is significantly larger in magnitude than the value given by the symmetric rotator model.[19]

Certain refinements of this rotational model also appear not to be able to account for this measured quadrupole moment. The asymmetric rotator model of Davydov and Filippov,[20] for example, predicts a quadrupole moment very close to that of the symmetric rotator model. Another variation, the variable moment-of-inertia model of Mariscotti, Scharff-Goldhaber, and Buck[21] also predicts a very similar quadrupole moment when the parameters of the model are chosen to fit the level spectrum and the $B(E2;0^+ \rightarrow 2^+)$ of ^{24}Mg. In Ref. 21 it is suggested that the reduced transition probability $B(E2;\ 0^+ \rightarrow 2^+)$ is proportional to the moment of inertia. It may be significant that in the present case of ^{24}Mg the proportionality constant assumes the value $k = 13.6 \times 10^{-24}$ cm^{2}keV$^{1/2}$ which is very different from the value $k = 39.4 \times 10^{24}$ cm^2 keV$^{1/2}$ found in Ref. 21 for nuclei between $A = 126$ and 240.

A recent shell-model calculation[22] for nuclei in the s-d shell predicts for ^{24}Mg $Q_{2^+} = -0.14\ e$ b and $B(E2;\ 0^+ \rightarrow 2^+) = 0.033\ e^2$b^2. Thus the predicted quadrupole moment is too small by about a factor of 2 while there is reasonable agreement with regard to the transition probability. The situation is very similar for ^{20}Ne and ^{22}Ne.[23,24]

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PHYSICAL REVIEW C VOLUME 3, NUMBER 2 FEBRUARY 1971

Study of the Low-Lying Excited States of ^{29}Al. III. Mean Lifetimes and Interpretation*

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Lifetimes or, alternatively, limits for lifetimes of low-lying levels in ^{29}Al have been obtained employing the Doppler-shift-attenuation method. The levels were excited by the ^{27}Al$(t,p)^{29}$Al reaction and measurements were made of the γ-ray spectrum in coincidence with reaction protons. Measured mean lifetimes, or limits, $[E_x(\tau_m)$, in MeV(psec)] for the first six levels of ^{29}Al are: 1.402$(3.3^{+2.2}_{-1.0})$, 1.762(<0.05), 2.228(<0.08), 2.875(<0.15), 3.071(<0.05), and 3.191(0.21 ± 0.10). A partial level scheme of ^{29}Al for excitation energy $E_x \leq 4.5$ MeV based on previously reported information is presented. Properties of these levels are interpreted according to the Nilsson model on the basis of (1) a direct-reaction investigation and (2) γ-ray angular-correlation investigations as previously reported. The properties of ^{29}Al are shown to be consistent with a prolate deformation characterized by $\eta \approx +3$.

I. INTRODUCTION

The present series of measurements to determine lifetimes of the excited states of ^{29}Al was undertaken to supplement previous work in this laboratory on the same nucleus.[1-3] This work consisted of (1) a direct-reaction investigation and subsequent interpretation of the differential cross-section measurements,[1] (2) γ-ray branching-ratio determinations and measurements of γ-ray angular correlations in a collinear geometry,[2] and (3) investigation of the delayed γ-rays following the β decay of ^{29}Al.[3] Since completion of the first phases of our investigation, three publications have appeared pertaining to the structure of the levels of this nucleus.[4,5] These are the work of Kean and his collaborators[4] and that of Hirko.[5] Both used the ^{26}Mg$(\alpha, p\gamma)^{29}$Al reaction and made measurements of γ-ray branchings and γ-ray angular correlations for the low-lying levels of ^{29}Al. Their results and those of Ref. 2 are essentially in agreement as regards spin assignments. However, the reported branchings of the 3.19- and 3.65-MeV levels disagree. Hirko[5] reports a (9 ± 6)% branch from the 3.19 → 1.40 transition. This branch is not seen in the other investigations. The branching of the 3.65-MeV level is reported by Hirko[5] as (83 ± 12)% to the ground state and (17 ± 12)% to the 1.76-MeV state. Jones, Becker, and McDonald[2] report these branches as (56 ± 3)% and (44 ± 3)%, respectively. The investigations of Kean *et al.*[4] did not include this level. No ready explanation for this discrepancy is available. Weighted averages of the branching-ratio determinations of Refs. 2, 4, and 5 are given in Fig. 1. To arrive at the quoted values, due allowance was made for a possible ±15% error in the results of Kean *et al.*[4] as quoted in their paper.

Kean *et al.*[4] speculate as to the applicability of an intermediate-coupling model and also a strong-coupling model to ^{29}Al and conclude that the information presently available on the nucleus does not warrant detailed comparison with nuclear models. The work of Hirko,[5] on the other hand, includes a Nilsson-model[6] description with assignment of low-lying levels to rotational bands based on this model. Hirko's assignments are, however, based entirely on level position, spin and parity values,