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Rotational states in ^{26}Mg

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Abstract. The decay properties of the levels at 3·941 (3^+), 5·476 (4^+) and 5·716 MeV (4^+) in ^{26}Mg have been investigated. Particle gamma-ray angular correlations were measured following the reactions ^{26}Mg(α, $\alpha'\gamma$)^{26}Mg and ^{26}Mg(p, p$'\gamma$)^{26}Mg enabling accurate branching ratios and E2/M1 mixing ratios to be determined. The lifetimes were obtained with the reaction ^{23}Na(α, pγ)^{26}Mg using the Doppler shift attenuation method.

The transition from the 5·476 (4^+) to the 3·941 MeV (3^+) state is shown to have an E2 strength of 12^{+9}_{-4} Weisskopf units whilst the transitions from the 3·941 MeV state itself are essentially dipole. The data together with the revised branching ratios result in a new assignment of states to the $K^\pi = 2^+$ and 3^+ rotational bands.

1. Introduction

The nucleus ^{26}Mg is in that part of the s–d shell where the sign of the deformation changes from prolate to oblate, and it is therefore of particular interest to study possible collective structure in this nucleus. The energies, spins and parities of excited states in ^{26}Mg are well known (Endt and van der Leun 1973), and four E2/M1 mixing ratios have been reported by Broude and Gove (1963) and Ferguson *et al* (1968). Lifetimes have been measured by Häusser *et al* (1968) and by Durell *et al* (1972) with the Doppler shift attenuation method and by Berant *et al* (1974) with the recoil distance method. Häusser *et al* (1968) have proposed a $K^\pi = 0^+$ ground-state band, which has been shown to have a strong prolate deformation from the measurement of the quadrupole moment of the 1·809 MeV (2^+) state by Schwalm *et al* (1972). Durell *et al* (1972) tentatively suggested two further rotational bands with the states at 2·938, 3·941 and 5·476 MeV being the members of a $K^\pi = 2^+$ band and the states at 4·350 and 5·716 MeV being the members of a $K^\pi = 3^+$ band. To obtain better evidence for this band structure we studied several of the states involved. If the 3·941 MeV state is the second member of a $K^\pi = 2^+$ band, the 1003 keV transition ($3^+ \rightarrow 2^+$) should have an enhanced E2 strength, which is not consistent with the small mixing ratio quoted by Ferguson *et al* (1968) for this transition. We therefore remeasured this mixing ratio together with the decay properties of the 4^+ states at 5·476 and 5·716 MeV including a determination of the lifetimes for which Durell *et al* (1972) only obtained limits.

2. Experimental arrangement

The experiments were carried out using the Liverpool EN tandem Van de Graaff accelerator. The particle gamma-ray angular correlations were measured following the

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reaction ^{26}Mg($\alpha, \alpha'\gamma$)^{26}Mg, in which a self-supporting target of 80 μg cm^{-2} thickness (isotopic enrichment 99·22 %) was bombarded at beam energies of 16·97 and 17·1 MeV. The scattered α particles were detected in a thin 100 μm annular surface barrier detector (resolution 60 keV FWHM) fixed at 180° with respect to the beam direction such that protons from the competing ^{26}Mg(α, p)^{29}Al reaction deposited less than 300 keV energy in the detector and hence did not mask any of the α peaks of interest. Gamma-ray angular distributions were measured in coincidence with the α particles using an array of five 5 in × 6 in NaI(Tl) crystals positioned in a horizontal plane at angles of 8°, 30°, 45°, 120° (60°) and 90°. In this geometry (method II of Litherland and Ferguson 1961) with the reaction ^{26}Mg($\alpha, \alpha'\gamma$)^{26}Mg the states are formed with maximum alignment; and as the spin values of each of the states were known, accurate values of the mixing ratio were easily obtained by fitting theoretical angular distributions to the experimental data as outlined by James *et al* (1974) using the sign convention of Rose and Brink (1967). Since only states of natural parity were excited with the (α, α') reaction, the 3^+ state at 3·941 MeV was populated via the ^{26}Mg(p, p$'\gamma$)^{26}Mg reaction at a proton energy of 7·6 MeV. In this case two substates could be excited and the population ratio of these was determined by the fit program as a free parameter. A further coincident gamma-ray spectrum was taken from a Ge(Li) detector (volume 50·2 cm^3) placed on top of the scattering chamber in order to obtain more detailed information about the decay modes of the different excited states. The apparatus and technique used in the experiment have been described in detail elsewhere (Twin *et al* 1974).

We measured the lifetimes in a separate experiment using the Doppler shift attenuation method. The 5·476 and 5·716 MeV states were populated with the reaction ^{23}Na(α, pγ)^{26}Mg at an α energy of 7·3 MeV. The target was 1·7 mg cm^{-2} metallic sodium evaporated on a thick gold backing, and to protect it against oxidation it was handled in an argon atmosphere before evacuation of the target chamber. The gamma-ray centroids were measured at eight angles between 0° and 124° with respect to the beam direction using a Ge(Li)–NaI(Tl) escape-suppressed spectrometer (Sharpey-Schafer *et al* 1971). The Doppler shift attenuation factors F were obtained by a least-squares fit to the data; and the method of Blaugrund (1966) was used to calculate F as a function of the mean nuclear lifetime τ. As the range of the recoiling nucleus was small compared with the target thickness only stopping in the ^{23}Na layer of the target was taken into account.

3. Results

The branching ratios for the 3·941, 5·476 and 5·716 MeV states compared with previous measurements are summarized in table 1 together with multipole mixing ratios, lifetimes and the resulting transition strengths. Table 2 contains the attenuation factors F, the derived mean lifetimes and the previous results of Durell *et al* (1972).

3.1. The 3·941 MeV state

An angular correlation experiment following the reaction ^{26}Mg(p, p$'\gamma$)^{26}Mg was used to measure the E2/M1 mixing ratio of the gamma rays depopulating the 3^+ state at 3·941 MeV. We found $\delta = 0{\cdot}04 \pm 0{\cdot}05$ and $\delta = 0{\cdot}00 \pm 0{\cdot}07$ for the 1003 and 2132 keV transitions respectively, indicating essentially pure dipole character in good agreement with the results reported by Ferguson *et al* (1968). The lifetime has recently been

Table 1. Summary of the experimental data obtained for the 3·941, 5·476 and 5·716 MeV states.

Initial state		Final state		Branching ratio (%)		Mixing ratio δ	Mean lifetime τ_m	$\|M(E2)\|^2$ (Wu)	$\|M(M1)\|^2$ (mWu)
E_x (MeV)	J^π	E_x (MeV)	J^π	present	previous†				
3·941	3^+	2·938	2^+	63±2	62±2	0·04±0·05	1·38±0·11 ps‡	<0·6	14±1
		1·809	2^+	37±2	38±2	0·00±0·07		<0·01	0·86±0·06
5·476	4^+	4·320	4^+	55±3	—	−0·05±0·19	35±15 fs		320±200
		3·941	3^+	30±3	14	0·27±0·04		12^{+9}_{-4}	69^{+50}_{-20}
		2·938	2^+	<3	76	E2		<2	
		1·809	2^+	15±3	10	E2		$1·1^{+0·8}_{-0·3}$	
5·716	4^+	4·350	3^+	30±4	66		125±35 fs		
		3·941	3^+	52±4	—				
		2·938	2^+	18±4	34	E2		1·5±0·5	

† Endt and van der Leun (1973).
‡ Berant *et al* (1974).

Table 2. The measured F factors and mean lifetimes of the 5·476 and 5·716 MeV levels. The results of Durell *et al* (1972) are given for comparison. The errors quoted for the mean lifetimes are experimental only and do not include systematic errors due to uncertainties in the slowing-down theory.

Level energy (MeV)	E_γ (keV)	F factor	F factor average	τ_m (fs) Present experiment	τ_m (fs) Durell *et al*
5·476	1156	0·977±0·027	0·980±0·010	35±15	<100
	1535	0·983±0·015			
	3667	0·979±0·015			
5·716	1366	0·92±0·02	0·93±0·02	125±35	<50
	1775	0·98±0·05			
	2778	0·94±0·02			

remeasured by Berant *et al* (1974) with the recoil distance method to be 1·38±0·11 ps. This value is about twice as large as the previous values obtained with the Doppler shift attenuation method by Häusser *et al* (1968) and Durell *et al* (1972) but in agreement with the DSAM result of de Kock *et al* (1970). The lifetime together with the errors on the mixing ratios yield upper limits of 0·6 Wu and 0·01 Wu for the experimental E2 strengths of the transitions to the second and first state respectively.

3.2. The 5·476 MeV state

The Ge(Li) spectrum of gamma rays in coincidence with the α group from the 4^+ state at 5·476 MeV following the (α, α') reaction is shown in figure 1(*a*). This spectrum indicates that the major decay mode is by a 1156 keV gamma ray to the 4·320 MeV (4^+) state (followed by a 2511 keV gamma ray) with smaller branches to the 3·941 (3^+) and 1·809 MeV (2^+) states. This is in disagreement with the previously reported branching

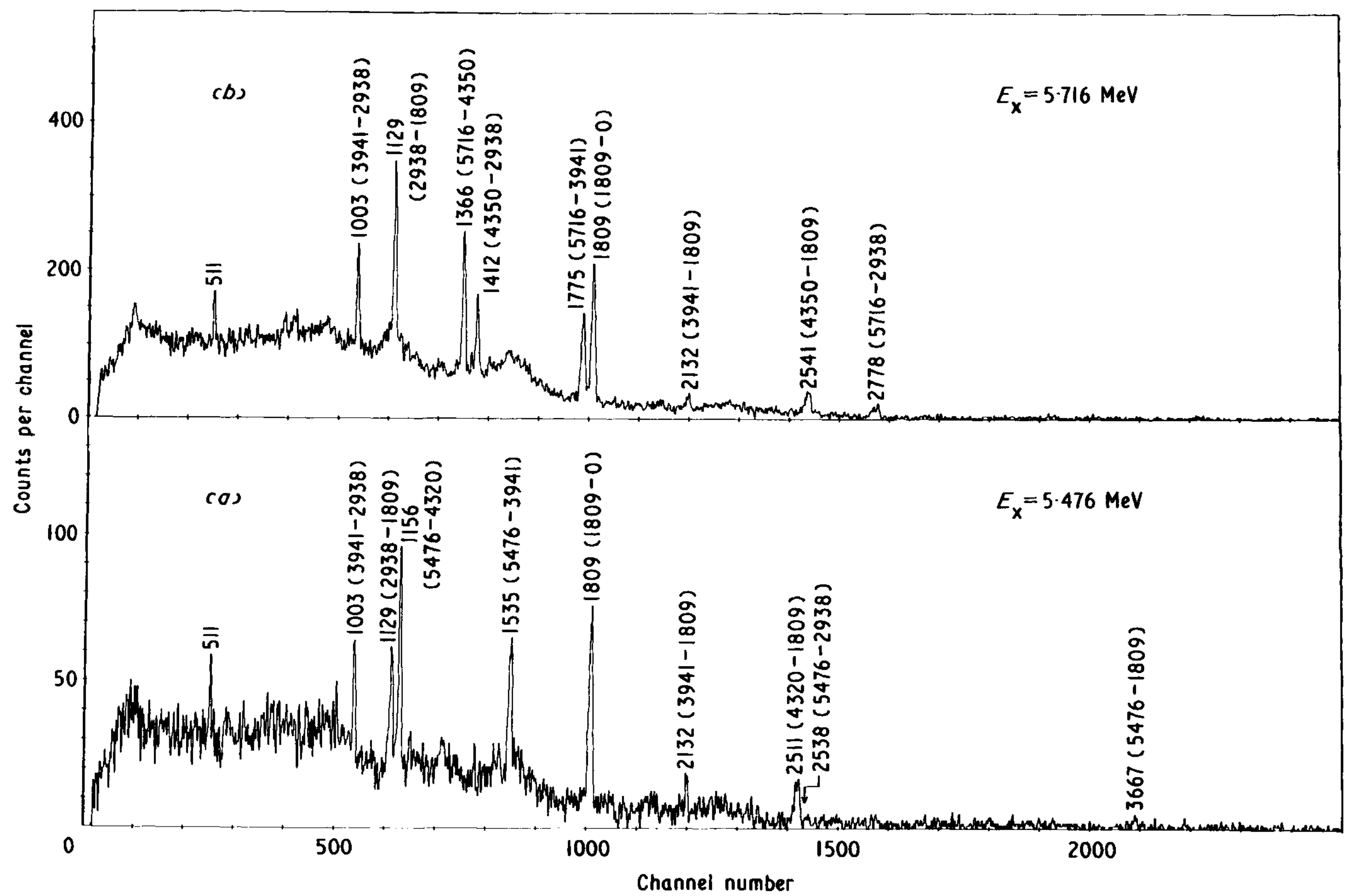

Figure 1. Ge(Li) spectra taken at $\theta = 90°$ in coincidence with the α group from (*a*) the 5·476 MeV (4^+) state and (*b*) the 5·716 MeV state following the reaction $^{26}Mg(\alpha, \alpha'\gamma)^{26}Mg$.

ratios of Häusser *et al* (1968) and Durell *et al* (1972) of a major 76% branch via a 2538 keV gamma ray to the 2·938 MeV (2^+) state (followed by a 1129 keV gamma ray) with similar smaller branches as reported above. We note that Häusser *et al* (1968) used the $^{26}Mg(p, p'\gamma)^{26}Mg$ reaction in a singles experiment so that the 2511 and 2538 keV gamma rays were completely masked by the decay of the triplet at 4·3 MeV to the 1·809 MeV state, and they assigned the 1156 keV transition to ^{26}Al as a decay of the 2·915 MeV state. However, Bissinger *et al* (1969) found no evidence for this transition in ^{26}Al and restricted the branching ratio to less than 2%. From the coincidence spectrum in figure 1(*a*), which was at $\theta = 90°$, we can restrict the fraction to the 2·938 MeV (2^+) state to be less than 20% of that to the 1·809 MeV (2^+) state as both transitions have identical angular distributions. The branching ratios quoted in table 1 have been determined from the angular distributions of the singles Ge(Li) spectrum following the $^{23}Na(\alpha, p\gamma)^{26}Mg$ reaction and show the branch to the 1·809 MeV state to be 15 ± 3% and hence we conclude the branch to the 2·938 MeV state is less than 3%.

In the NaI(Tl) spectra taken in coincidence with the α group from the 5·476 MeV state the 1156 and 1129 keV peaks were not resolved. However, an angular distribution was extracted by the subtraction of 1129 keV gamma-ray intensities calculated from the branching ratios and the angular distribution of the 1129 keV gamma ray from the 2·938 MeV state. The resultant E2/M1 mixing ratio $\delta = -0{\cdot}05 \pm 0{\cdot}19$ is small with the error including zero, whereas the E2/M1 mixing ratio $\delta = 0{\cdot}27 \pm 0{\cdot}04$ of the 1535 keV transition to the 3·941 MeV (3^+) state is significantly nonzero (figure 2).

The Doppler shift attenuation factors quoted in table 2 give consistent values for all three primary gamma rays resulting in a mean lifetime of 35 ± 15 fs. The E2 strengths

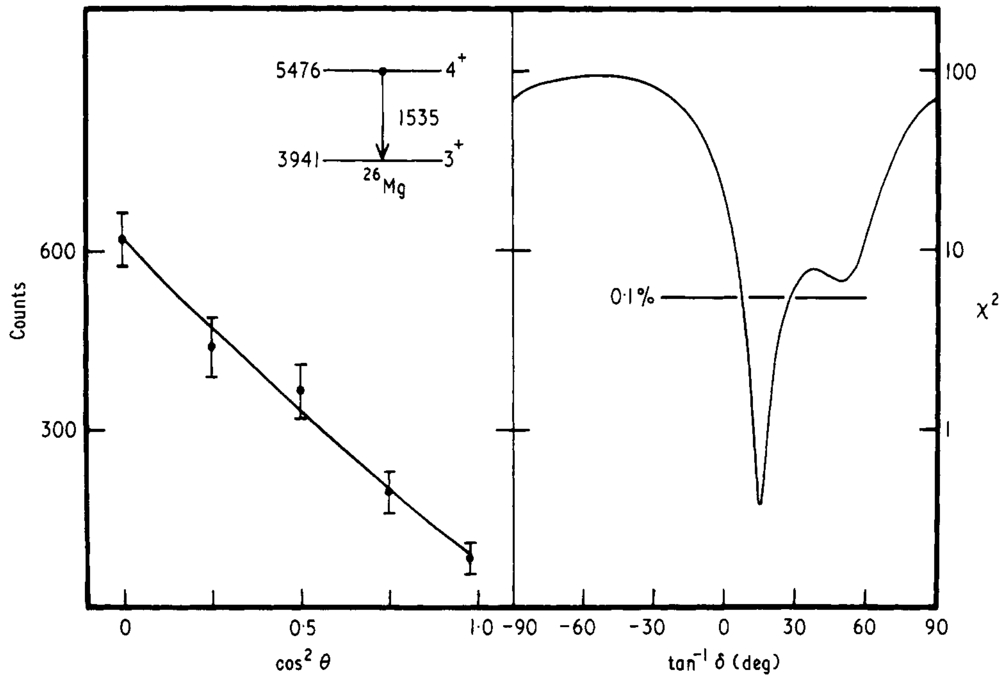

Figure 2. Angular distribution and plot of χ^2 against $\tan^{-1}\delta$ for the 1535 keV gamma ray from the 5·476 MeV (4^+) state indicating an E2/M1 mixing ratio $\delta = 0{\cdot}27 \pm 0{\cdot}04$.

obtained from the above data are listed in table 1 and show that the 1535 keV transition is enhanced with a strength of 12^{+9}_{-4} Wu.

3.3. The 5·716 MeV state

A spin assignment of $J^{\pi} = 4^{+}$ has been made to the level at 5·716 MeV from electron scattering work by Lees *et al* (1974) in agreement with an α-scattering experiment of Blair and Naqib (1970). The Ge(Li) spectrum (figure 1(*b*)) taken in coincidence with the α group from this level shows the major branch is to the state at 3·941 MeV and two further branches to the states at 2·938 and 4·350 MeV. The major branch via a 1775 keV gamma ray has not been reported previously since in the singles experiment of Häusser *et al* (1968) and Durell *et al* (1972) it is masked at angles near 90° by the 1779 keV transition from the 3·588 to the 1·809 MeV state. However, as this latter gamma ray is not shifted due to the long lifetime of the 3·588 MeV (0^{+}) state the two peaks were separated in the singles experiment at angles other than 60°, 75° and 90° and areas and centroids were calculated by a least-squares fit assuming gaussian shape. The 1775 keV gamma ray could further be contaminated in the singles spectra by a 1777 keV transition from the 6·127 MeV state which might be excited. However, the branching ratios obtained from the Ge(Li) coincidence and the singles experiment were similar indicating the 6·127 keV state is definitely only weakly excited. Hence the branching ratios quoted in table 1 were determined from the singles angular distributions.

The *F* factors for the two well resolved primary gamma rays are in good agreement and yield a lifetime of 125 ± 35 fs (table 2). This value is much larger than the limit of Durell *et al* (1972) of less than 50 fs obtained from the 1366 keV transition.

Unfortunately, the mixing ratios of both the $4^{+} \rightarrow 3^{+}$ transitions from the 5·716 MeV state could not be determined from the angular correlation experiment as the resolution of the NaI(Tl) crystals was not sufficient to separate the 1366–1412 and 1775–1809 keV doublets.

4. Discussion

The band structure of ^{26}Mg proposed by Durell *et al* (1972) is indicated in the decay scheme shown in figure 3. In addition to the $K^{\pi} = 0^{+}$ ground-state band they suggest two further bands with $K^{\pi} = 2^{+}$ and 3^{+} based upon the levels at 2·938 and 4·350 MeV, for which they assume configurations described by antiparallel and parallel coupling of the last two nucleons in Nilsson orbits 5 ($\Omega = \frac{5}{2}^{+}$) and 9 ($\Omega = \frac{1}{2}^{+}$). However the present data confirm the dipole character of both $3^{+} \rightarrow 2^{+}$ transitions from the 3·941 MeV state. In particular the 1003 keV transition to the second excited state, which should be an in-band transition, has an E2 strength of less than 0·6 Wu and therefore the 3·941 MeV state cannot belong to the $K^{\pi} = 2^{+}$ band.

The simplest re-interpretation of the two 3^{+} states at 3·941 and 4·350 MeV is a complete reversal of that proposed by Durell *et al* (1972) with the 3·941 MeV state as the first member of a $K^{\pi} = 3^{+}$ band and the 4·350 MeV state as the second member of the $K^{\pi} = 2^{+}$ band. It is now the 41 % branch via a 1412 keV gamma ray from the 4·350 to the 2·938 MeV state which is an in-band transition and hence should have a large E2 strength. However, the mixing ratio of this decay has not been determined; but the lifetime measurement yields an E2 strength of less than 84 Wu. The other decay branch of the 4·350 MeV state to the 1·809 MeV (2^{+}) state has $\delta = 0{\cdot}11 \pm 0{\cdot}06$ (Ferguson

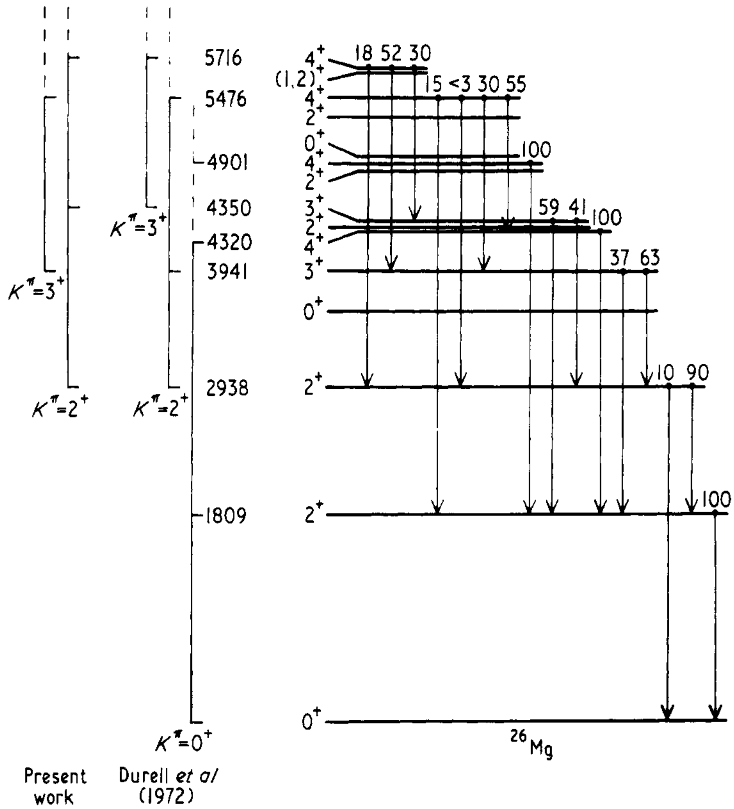

Figure 3. Partial decay scheme of ^{26}Mg showing the present branching ratios. The band structure proposed by Durell *et al* (1972) and a revised band configuration derived from the present data are indicated for comparison. Several spin assignments are taken from the work of Lees *et al* (1974), other data not obtained from the present work are quoted from Endt and van der Leun (1973).

et al 1968) and the resulting E2 strength of $0{\cdot}08 \pm 0{\cdot}06$ Wu is consistent with its interpretation as an out-of-band transition.

The candidates for the 4^+ members of the bands are the 5·476 and 5·716 MeV states, and the data on these states are shown in table 1. Only the 5·716 MeV state decays to the 4·350 MeV (3^+) state and therefore it is reasonable to assume this state is the third member of the $K^\pi = 2^+$ band. The mixing ratio of the $4^+ \to 3^+$ transition, however, is not known, as the gamma ray was unresolved in the NaI(Tl) coincidence spectra, but the lifetime limits the E2 strength to be less than 87 Wu, and the in-band crossover $4^+ \to 2^+$ transition has a weak E2 strength of $1{\cdot}5 \pm 0{\cdot}5$ Wu. The interpretation of the 5·476 MeV (4^+) state as the second member of the $K^\pi = 3^+$ band is confirmed by the strong in-band E2 strength of 12^{+9}_{-4} Wu obtained for the 1535 keV gamma ray to the 3·941 MeV (3^+) state, while the out-of-band $4^+ \to 2^+$ transition has an E2 strength of $1{\cdot}1^{+0{\cdot}8}_{-0{\cdot}3}$ Wu and the out-of-band $4^+ \to 4^+$ transition has essentially dipole character.

The revised assignment of states to the proposed $K^\pi = 2^+$ and 3^+ bands, shown in figure 3, is: $K^\pi = 2^+$: 2·938 MeV (2^+), 4·350 MeV (3^+), 5·716 MeV (4^+); and $K^\pi = 3^+$: 3·941 MeV (3^+), 5·476 MeV (4^+). Though the collective nature of the excited states in

^{26}Mg is not as striking as for most nuclei in the lower part of the s–d shell, the results obtained so far are consistent with the interpretation that ^{26}Mg is a prolate deformed nucleus.

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