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The 4·510 MeV level in ^{27}Al

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Abstract. The 4·510 MeV level in ^{27}Al has been conclusively shown to have a J^π assignment of $\frac{11}{2}^+$. The branching ratio was measured to be $77 \pm 2\%$ to the 2·211 MeV $\frac{7}{2}^+$ state and $23 \pm 2\%$ to the 3·004 MeV $\frac{9}{2}^+$ state, the multipole mixing ratio for the latter transition being $-1{\cdot}16 \pm 0{\cdot}11$. It is suggested that the 4·510 MeV $\frac{11}{2}^+$ and the 3·004 MeV $\frac{9}{2}^+$ levels are possibly members of $K^\pi = \frac{11}{2}^+$ and $K^\pi = \frac{9}{2}^+$ bands respectively obtained by coupling an $\Omega = \frac{1}{2}$ (Nilsson orbit 9) neutron to the 5^+ ground-state configuration of ^{26}Al.

1. Introduction

The 4·510 MeV state in ^{27}Al has been firmly regarded as having a J^π assignment of $\frac{11}{2}^+$. However the data (Carter *et al* 1969) from which this assignment was made are by no means indisputable as indicated by Carter *et al* in their paper. The assignment of $\frac{11}{2}^+$ to this level has important experimental and theoretical consequences. Several (α, γ) resonances γ decay through it and the spins of other states in ^{27}Al are based on the $\frac{11}{2}^+$ assignment for the 4·510 MeV level (de Voigt *et al* 1971). This level is the lowest $\frac{11}{2}^+$ state in ^{27}Al and its prediction provides a useful test to possible models of this nucleus. For these reasons the spin of this state should be based on stronger evidence and we have studied this level by measuring the angular distributions and linear polarizations of its γ decays. As opposed to previous measurements the results conclusively prove the level to have a spin of $\frac{11}{2}^+$. Possible structures of the 4·510 MeV and 3·004 ($\frac{9}{2}^+$) MeV levels, in terms of the Nilsson model, are put forward.

2. Experimental results

The level was populated with the ^{24}Mg $(\alpha, p)^{27}$Al reaction 1·6 MeV above threshold using a 9·0 MeV He^{++} beam from the Liverpool EN tandem. The target was 1·5 mg cm^{-2} magnesium, enriched to 99·8% ^{24}Mg, on a thick gold foil. The γ rays were detected with an anti-Compton spectrometer and a linear polarimeter consisting of three Ge(Li) detectors. The linear polarimeter has been described in detail elsewhere (Butler *et al* 1973).

The 4·510 MeV level decays through the 2·211 MeV ($\frac{7}{2}^+$) and 3·004 MeV ($\frac{9}{2}^+$) states (see figure 2). The branching ratio was measured to be $77 \pm 2\%$ and $23 \pm 2\%$ respectively. The angular distribution and polarization of both γ rays were fitted with all possible spin hypotheses for the primary level. The substate populations were estimated by the statistical model program MANDY (Sheldon and Van Patter 1966). Only the $\frac{1}{2}$ and $\frac{3}{2}$ substates were predicted to be populated because of the very low penetrabilities of the outgoing protons with $l > 1$. The population of the $\frac{3}{2}$ substate was calculated to be 0·3 and an error of 50% was set on this value. In fact since the level undoubtedly has a high spin the fits would be highly insensitive to the population ratio of the first and second substates. The fitting was carried out according to the procedure set out by James *et al* (1974). The results are shown in figure 1 which indicates the quality of the data and the goodness of the fits. A unique spin assignment of $\frac{11}{2}^+$ is obtained for the level. To ensure that the results would in fact be insensitive to the statistical model predictions both γ-ray angular distributions and polarizations were also fitted simultaneously allowing the relative population of the $\frac{3}{2}$ and $\frac{1}{2}$ substates to vary freely, the only reaction model assumption then being made is that the populations of the $\frac{7}{2}$, $\frac{9}{2}$ and $\frac{11}{2}$ substates are less than a few per cent of the total (James *et al* 1974). The minimum χ^2 for the $\frac{11}{2}^+$ possibility was 9·3 corresponding to a 23% confidence level for 7 degrees of freedom. The mixing ratios were measured to be 0·00 ± 0·03 for the transition to the 2·211 MeV $\frac{7}{2}^+$ level, which is compatible with pure E2 radiation and $-1{\cdot}16 \pm 0{\cdot}11$ for the transition to the 3·004 MeV $\frac{9}{2}^+$ level. The mixing ratios were defined according to

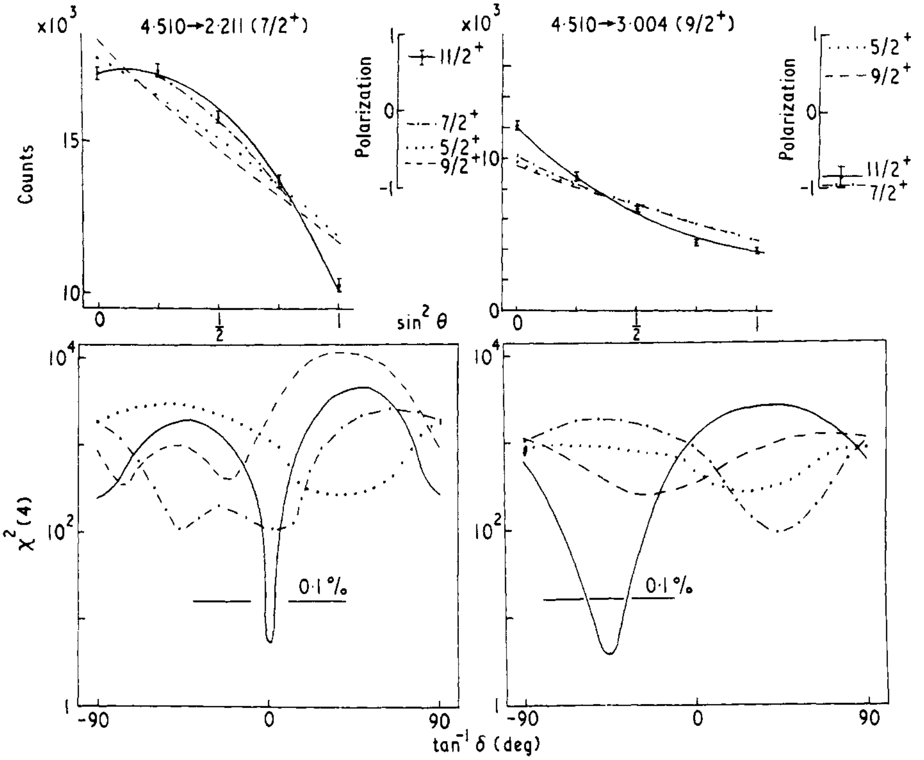

Figure 1. A plot of $\chi^2(4)$ against $\tan^{-1}\delta$ for various spin hypotheses for the 4·510 MeV level for the transitions to the 2·212 MeV $(\frac{7}{2}^+)$ level and the 3·004 MeV $(\frac{9}{2}^+)$ level. Here $\chi^2(4)$ means χ^2 for 4 degrees of freedom. The experimental linear polarizations of these transitions have been included in the χ^2 test. For the 4·510 → 3·004 MeV transitions the theoretical fits of the angular distribution for spin possibilities $\frac{5}{2}^+$, $\frac{7}{2}^+$ and $\frac{9}{2}^+$ are almost indistinguishable for angles between 30° and 90°. The fits to the polarizations are those having a minimum χ^2.

the phase convention of Rose and Brink (1967). The results are essentially the same as those obtained from the data shown in figure 1 corresponding to the independent fitting of both γ rays using the statistical model predictions. The mixing ratio of the transition to the 3·004 MeV $\frac{9}{2}^+$ level compares with $-0{\cdot}60 \pm 0{\cdot}15$ measured by Carter *et al* (1969), $-1{\cdot}14^{+0{\cdot}38}_{-0{\cdot}98}$ measured by Röpke and Lam (1968) and $-0{\cdot}58 \pm 0{\cdot}08$ measured by Hausser *et al* (1968). The results of Carter *et al* and Hausser *et al* differ by about three standard deviations from the present result. As has already been pointed out this difference cannot be caused by any error in the substate populations used in the present analysis, the results depend solely on the experimental data points. It is worthwhile pointing out that Hausser *et al* used an *ad hoc* renormalization of their errors whilst Carter *et al* in their fitting of the cascade γ rays from the 4·510 MeV level used fixed mixing ratios for the secondary γ rays and did not allow for any errors on these mixing ratios. The results are summarized in table 1.

Table 1. A summary of the present experimental results. The a_2 and a_4 coefficients have been corrected for solid angle effects.

Transition (MeV)	J_i^π	J_f^π	a_2	a_4	Polarization	Mixing ratio	Branching ratio (%)
4·510 → 2·211	$\frac{11}{2}^+$	$\frac{7}{2}^+$	$0{\cdot}40 \pm 0{\cdot}02$	$-0{\cdot}15 \pm 0{\cdot}01$	$0{\cdot}70 \pm 0{\cdot}09$	$0{\cdot}00 \pm 0{\cdot}03$	77 ± 2
4·510 → 3·004	$\frac{11}{2}^+$	$\frac{9}{2}^+$	$0{\cdot}86 \pm 0{\cdot}04$	$0{\cdot}25 \pm 0{\cdot}04$	$-0{\cdot}83 \pm 0{\cdot}13$	$-1{\cdot}16 \pm 0{\cdot}11$	23 ± 2

3. Discussion

The ^{27}Al level scheme is summarized in figure 2. In the simple Nilsson model picture of ^{27}Al (Smulders *et al* 1968), which describes the nucleus as a particle outside a deformed mass 26 core, the low-lying states are explained as being members of a $K^\pi = \frac{5}{2}^+$ and a $K^\pi = \frac{1}{2}^+$ band corresponding to the odd particle being in Nilsson orbits 5 and 9 respectively. Thus the $\frac{9}{2}^+$ level at 3·004 MeV and the $\frac{11}{2}^+$ level at 4·510 MeV are described as members of the $K^\pi = \frac{5}{2}^+$ ground-state band.

An alternative description, suggested by Röpke *et al* (1970), is that in addition to the $K^\pi = \frac{5}{2}^+$ ground-state band, $K^\pi = \frac{1}{2}^+$ and $K^\pi = \frac{9}{2}^+$ bands are generated by coupling an $\Omega = \frac{5}{2}$ particle to a 2^+ γ-vibrational state in ^{26}Mg. The $\frac{9}{2}^+$ and $\frac{11}{2}^+$ levels are then described as members of the $K^\pi = \frac{9}{2}^+$ γ-vibrational band while the $\frac{1}{2}^+$, $K^\pi = \frac{1}{2}^+$ γ-vibrational level corresponds to the first excited state.

In this discussion we suggest another possible interpretation of the $\frac{9}{2}^+$ and $\frac{11}{2}^+$ levels in terms of the Nilsson model. The levels may be described as the band heads of $K^\pi = \frac{9}{2}^+$ and $K^\pi = \frac{11}{2}^+$ bands obtained by coupling an $\Omega = \frac{1}{2}$ neutron to the parallel coupled configuration of two $\Omega = \frac{5}{2}$ particles, ie an $\Omega = \frac{1}{2}$ neutron coupled to the 5^+ ground-state configuration of ^{26}Al. In addition to these two states one also generates three $K^\pi = \frac{1}{2}^+$ states corresponding to the coupling of the $\Omega = \frac{1}{2}$ particle to the anti-parallel coupled configuration of the $\Omega = \frac{5}{2}$ particles. These are $T = \frac{3}{2}$ and $T = \frac{1}{2}$, $K^\pi = \frac{1}{2}^+$ bands obtained from coupling an $\Omega = \frac{1}{2}$ particle to a $K^\pi = 0^+$, $T = 1$ pair and a $T = \frac{1}{2}$, $K^\pi = \frac{1}{2}^+$ band obtained from coupling the $\Omega = \frac{1}{2}$ particle to a $K^\pi = 0^+$, $T = 0$ pair. These types of states have already been considered by Brink and Kerman (1959). From simple energy considerations one can make estimates of the relative positions of these states.

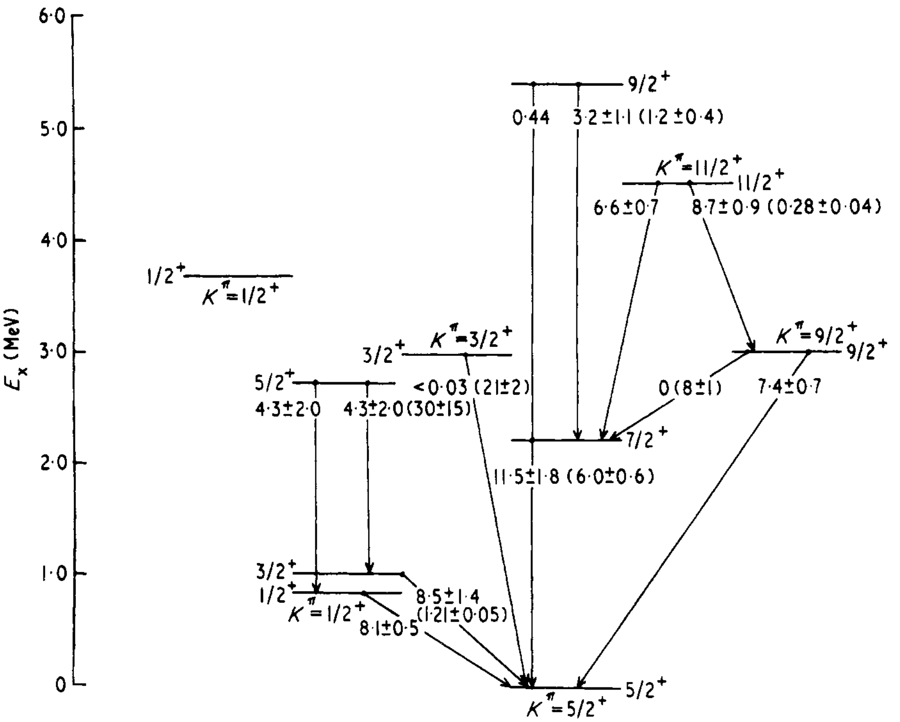

Figure 2. The low-lying level scheme of ^{27}Al showing the experimental E2 and M1 strengths and the proposed band structure. The E2 strengths are in Wu and the M1 strengths in Wu × 10^{-2}, the M1 strengths being in parenthesis. These strengths are obtained from Smulders *et al* (1968), Mauritzon *et al* (1971), de Voigt *et al* (1971) and the present work.

The $T = \frac{3}{2}$ and $T = \frac{1}{2}$, $K^\pi = \frac{1}{2}$ states obtained from coupling the $\Omega = \frac{1}{2}$ particle to the $K^\pi = 0^+$, $T = 1$ pair split as a result of the $\boldsymbol{T}.\boldsymbol{t}$ potential. The splitting will be equal to $3V$ where V is the strength of this potential. The $T = \frac{3}{2}$ state moves upwards in energy an amount V and the $T = \frac{1}{2}$ state downwards an amount $2V$. The $T = \frac{3}{2}$, $K^\pi = \frac{1}{2}^+$ state in ^{27}Al has been identified as the 6·815 MeV $\frac{1}{2}^+$ level (Endt and Van der Leun 1967) while the $T = \frac{1}{2}$, $K^\pi = \frac{1}{2}^+$ state is the 0·844 MeV $\frac{1}{2}^+$ first excited state. The unperturbed position of these states is 4·8 MeV. The $T = \frac{1}{2}$, $K^\pi = \frac{1}{2}^+$ state obtained from coupling the $\Omega = \frac{1}{2}$ particle to the $K^\pi = 0^+$, $T = 0$ pair would be expected at this approximate energy if one neglects the difference in pairing energy between the $K^\pi = 0^+$, $T = 0$ and $K^\pi = 0^+$, $T = 1$ pairs, ie the difference in band-head energies of the $K^\pi = 0^+$, $T = 1$ and $T = 0$ bands in ^{26}Al. A possible candidate for this state would be the 3·678 MeV $\frac{1}{2}^+$ level. Using this estimate of the unperturbed position of the $\frac{1}{2}^+$ levels the centre of gravity of the $K^\pi = \frac{9}{2}^+$ and $K^\pi = \frac{11}{2}^+$ states, obtained from coupling the $\Omega = \frac{1}{2}$ neutron to the 5^+ ground state configuration of ^{26}Al, can be deduced by subtracting the difference in pairing energy between the $K^\pi = 5^+$, $T = 0$ and $K^\pi = 0^+$, $T = 1$ pairs. This is the excitation energy of 0·2 MeV of the 0^+, $T = 1$ level in ^{26}Al, making the centre of gravity 4·6 MeV. Experimentally one finds that the $\frac{9}{2}^+$ and $\frac{11}{2}^+$ levels have a centre of gravity of 3·76 MeV. This is quite consistent with the above estimate especially as this was made on the assumption of no band mixing.

It is not suggested that these levels consist purely of the configurations already discussed since the E2 and M1 decays of the $K^\pi = \frac{9}{2}^+$ and $\frac{11}{2}^+$ levels shown in figure 2 indicate that considerable band mixing has occurred. However it is suggested that these configurations could be major components in the wavefunctions of the levels and that these levels can be obtained from the Nilsson model without resort to coupling a particle to a γ-vibrational level in ^{26}Mg. One of the advantages of the present description is the explanation of the strong stripping strength to the first $\frac{1}{2}^+$ state and the weak strength to the second $\frac{1}{2}^+$ state in the $^{26}\mathrm{Mg}(\tau, \mathrm{d})^{27}\mathrm{Al}$ reaction which is in disagreement with the predictions of the rotation–vibration interaction model (Röpke *et al* 1970). The proposed configuration for the $\frac{9}{2}^+$ level at 3·004 MeV is further supported by the recent shell-model calculations of Wildenthal and McGrory (1973) in which they find that a major fraction of the wavefunction of this level is a configuration of the form $[(\mathrm{d}\frac{5}{2})^{10}_{5^+}(\mathrm{s}\frac{1}{2})^{1}]_{\frac{9}{2}^+}$.

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