$E_p = 1.118$ MeV resonance in the $^{27}Al(p, \gamma)^{28}Si$ reaction

J. Dalmas, F. Leccia, and M. M. Aléonard
Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33170 Gradignan, France
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The 12.664-MeV level in ^{28}Si has been populated by resonant proton capture at 1.118 MeV in the $^{27}Al(p, \gamma)^{28}Si$ reaction. γ-ray angular distributions have been measured with a 80-cm^3 Ge(Li) detector. The spin of the 11.432-MeV level is most probably 4 with $T=0$; for the 8.413-MeV level, the assignment $J^\pi=4^-$ is in agreement with the present data. Mixing ratios for γ-ray transitions have been extracted from the angular distributions. Lifetime and branching-ratio studies have been made at $E_p=1.118$, 1.724, and 2.876 MeV. Emphasis was given to measurements on levels at 8.413, 9.702, and 11.577 MeV, as possible candidates for the 4^-, 5^-, and 6^- states of a $K^\pi=3^-$ rotational band based on the 6.879-MeV level. The observed $E2$ transition strengths are not in agreement with the above assumption. A strength of 0.3 Weisskopf units is found for the 12.664→8.413-MeV $M1$ transition, which is in conformity with a $J^\pi \to J^\pi$, $\Delta T=1$ transition in a self-conjugate nucleus; this result may suggest the possibility of another interpretation of these negative-parity states, relied on one-particle – one-hole configurations.

NUCLEAR REACTION $^{27}Al(p, \gamma)^{28}Si$, $E_p=1.724$, 2.876 MeV; measured γ-ray branching ratios, Doppler-shift attenuation. $E_p=1.118$ MeV; measured resonance strength, γ-ray branching ratios, mixing ratios, Doppler-shift attenuation; deduced transition strengths. Natural targets, Ge(Li) detectors.

1. INTRODUCTION

The existence of a $K^\pi=3^-$ rotational band based on the first $J^\pi=3^-$, $E_x=6.879$ MeV level in ^{28}Si was postulated for the first time in 1964,[1] the $J^\pi=4^-$ and 5^- levels built on this band being the 8.413- and 9.702-MeV levels. Although the 8.413-MeV level was found to decay with a strong $E2$ transition to the 3^- level,[2] the long lifetime of the 9.702-MeV level ($\tau > 2.7$ ps)[3] seems to exclude this level from membership in the proposed band. Moreover previous lifetime determinations of the 8.413-MeV level differ by about a factor of 2 (see Table IV): It was important to eliminate this uncertainty when trying to measure the strength of the 8.413→6.879-MeV $E2$ transition. Finally, though the spin and parity of the 8.413-MeV level are very likely 4^-,[2] this has not been definitely established.

On the other hand, the decay scheme of the $E_p=2.876$ MeV, $E_x=14.360$ MeV resonance of the $^{27}Al(p, \gamma)^{28}Si$ reaction observed in this laboratory[4] and concurrently by Miehe *et al.* in Strasbourg[5] who established the $J^\pi=6^-$ value for the 11.577 MeV with a possible strongly enhanced $E2$ transition to the 5^- 9702-MeV level, led us to suggest that the members of this band might be found up to $J^\pi=6^-$: One can see that the excitation energies of the levels situated at $E_x=6.879$, 8.413, 9.702, and 11.577 MeV are roughly proportional to $J(J+1)$ if the spins J of these levels are, respectively, 3, 4, 5, and 6. More recently the $E_p=2.876$ MeV resonance was studied by Neal and Lam[6] who confirmed the $J^\pi=6^-$ value for the 11.577-MeV level and measured an $E2$ enhancement of 20 Weisskopf units (W.u.) for the 11.576 → 9.702 MeV transition.

The $E_p=1.118$ MeV resonance of the $^{27}Al(p, \gamma)^{28}Si$ reaction is known to feed strongly the 8.413-MeV level and a recent study[7] of proton elastic scattering from ^{27}Al definitively established the $J^\pi=4^-$ value for this resonant level and indicated that it is formed in the proton channel with $l=1$ and $s=3$. Then only one partial wave l and one channel spin s contribute to the formation of the compound state and the population parameters are uniquely determined[8] so that an interpretation of (p, γ) angular distributions is simplified.

Besides the 8.413-MeV level, the $E_p=1.118$ MeV resonance feeds a level situated at $E_x=11.432$ MeV which shows a strong decay to the 6.277-MeV 3^+ level.[9] Alexander *et al.*[10] suggested that the 6.277-MeV level may be the first member of a $K^\pi=3^+$ band. The spin value $J=(3, 4)$ $T=0$ of the 11.432-MeV level[5] makes it a possible 4^+ candidate for this band.

In this paper, we present the results of a detailed study of the γ rays arising from the $E_p=1.118$ MeV resonance. As an aid in the discussion, Fig. 1 also presents the γ-decay schemes that we obtained for the resonances at $E_p=2.876$ MeV ($E_x=14.360$ MeV, $J^\pi=6^-$) and at $E_p=1.724$ MeV ($E_x=13.246$ MeV, $J^\pi=5^-$), which were used

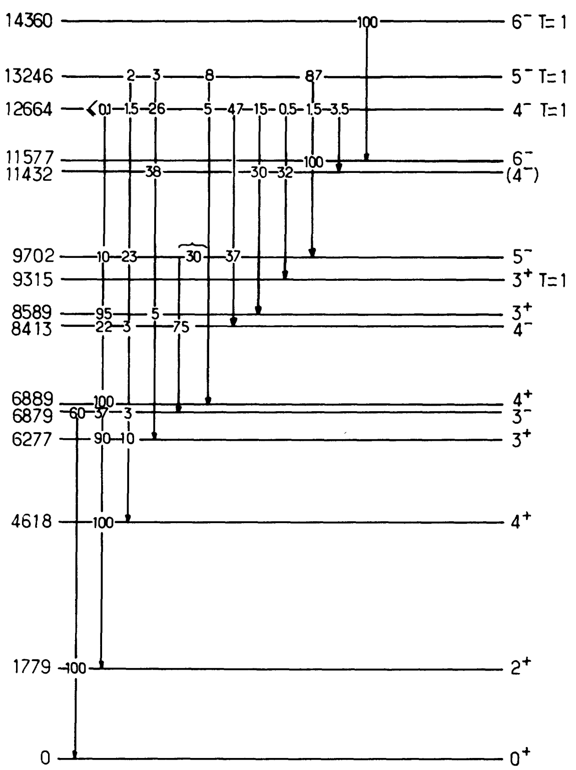

FIG. 1. Decay schemes of the resonances $E_p = 1.118$ MeV ($E_x = 12.664$ MeV), $E_p = 1.724$ MeV ($E_x = 13.246$ MeV), and $E_p = 2.876$ MeV ($E_x = 14.360$ MeV) from the $^{27}Al(p,\gamma)^{28}Si$ reaction. The branching ratios, in percentages, are from the present experiment.

to measure the lifetimes of the 9.702-MeV ($J^\pi = 5^-$) level and of the 11.577-MeV ($J^\pi = 6^-$) level.

2. EXPERIMENTAL METHOD

A proton beam was obtained from the 4-MV Van de Graaff accelerator of the Centre d'Etudes Nucléaires de Bordeaux-Gradignan. The targets were ^{27}Al deposited onto gold backings which were cooled with water so that a beam of 15 μA could be tolerated without observable deterioration. A cooled trap, placed close to the target, prevented buildup of carbon and fluorine deposits.

A. Measurement of the resonance strength

The resonance strength $\omega_\gamma = (2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ of the $E_p = 1.118$ MeV resonance was measured relative to that of the $E_p = 0.992$ MeV resonance, by measuring the excitation function of the 1.779-MeV γ ray with the help of a 80-cm^3 Ge(Li) detector at 55° to the proton beam and at a distance of 6 cm from the target. Refinements stemming from decay schemes were taken into account. At each proton energy setting the intensity of the 1.779-MeV γ ray was determined by measuring the area under this γ-ray line in the spectrum as obtained from a 4096 channel analyzer. The yields were corrected for variations in the analyzer dead time by feeding constant amplitude pulses into the detector system and simultaneously recording the pulsers total counting rate in a scaler.

B. Decay scheme

The γ-ray transitions from the $^{27}Al(p,\gamma)^{28}Si$ reaction were observed by the use of a 60-cm^3 coaxial Ge(Li) detector associated with a 4096 channel analyzer. The detector was placed at 55° to the proton beam direction and 7 cm distant from the target center. The energy scale was calibrated by use of several conventional radioactive sources and also with the aid of internal consistency checks using the known decay schemes. More precise corrections to this scale were obtained by aid of a special study[11] of the nonlinearity of the response curve of the system. Efficiency curves were determined by using radioactive sources and (p,γ) resonances of well-known decay schemes.[12]

C. Lifetime measurements

Mean lifetimes of bound levels in ^{28}Si were determined by the Doppler-shift attenuation method. The target thickness was such that the recoiling $^{28}Si^*$ nuclei came to rest in the Al layer. Shifts of the γ-ray lines were determined from a set of six measurements at 0 and 132° with respect to the direction of the proton beam. An 80-cm^3 Ge(Li) detector was used and its distance to the target center was 10 cm. The mean lifetimes were computed as described elsewhere[13] by applying the slowing-down theory developed by Lindhard, Scharff, and Schiøtt[14] and the large-angle-nuclear-scattering treatment due to Blaugrund.[15]

D. Angular-distribution measurements

The 80-cm^3 Ge(Li) counter was used to measure the angular distributions of the γ-ray transitions from the $E_p = 1.118$ MeV resonance in ^{28}Si. The distance between the target center and the front facr of the counter was 6 cm. The 60-cm^3 Ge(Li) was used as a monitor for the purpose of normalizing the angular distributions. Each counter was associated with a 4096 channel analyzer. In order to improve the accuracy, the five angle γ-ray angular distributions were measured five times. The $E_p = 1.519$ MeV resonance of the $^{27}Al(p,p'_1\gamma)$-^{27}Al reaction, leading to the $J^\pi = \frac{1}{2}^+$ first level of ^{27}Al, was used to check the experimental arrange-

TABLE I. Mixing ratios and transition strengths for the γ radiations from the 12.664-MeV resonant level in the $^{27}Al(p,\gamma)^{28}Si$ at $E_p = 1.118$ MeV. Branching ratios from Fig. 1 are used.

Final level (MeV)	J^π	δ	$\lvert M\rvert^{2\,a}$ (W.u.)
11.432	4^-	0.03 ± 0.03	$M1 = 0.9$
			$E2 \leq 8.5$
	4^+		$E1 = 2.9 \times 10^{-2}$
			$M2 \leq 9.0$
9.702	5^-		$M1 = 2.3 \times 10^{-2}$
			$E2 = 15$
9.315	3^+		$E1 = 2.1 \times 10^{-4}$
			$M2 = 82$
8.589	3^+	-0.05 ± 0.01	$E1 = 3.5 \times 10^{-3}$
			$M2 \leq 2.9$
8.413	4^-	0.09 ± 0.01	$M1 = 0.3$
			$E2 \leq 0.2$
6.889	4^+		$E1 = 4.2 \times 10^{-4}$
			$M2 = 54$
6.277	3^+	0.01 ± 0.01	$E1 = 1.5 \times 10^{-3}$
			$M2 \leq 6.0 \times 10^{-2}$
4.618	4^+		$E1 = 1.4 \times 10^{-4}$
			$M2 = 10$
1.779	2^+		$M2 \leq 4.7 \times 10^{-2}$

[a] When δ is unknown, pure transitions are assumed.

ment which was found to be isotropic within 1%. A spectrum was recorded below the resonance energy to assess the background γ rays. A computer program which calculates the χ^2 for different multipolarity mixing ratios with a given spin combination of initial and final levels was used.[16] The attenuation coefficients Q_2, Q_4[17] were calculated for the present geometry as a function of E_γ.[12]

3. RESULTS

A. Resonance strength

Two competitive values differing roughly by a factor of 2 may be used for the strength of the $E_p = 0.992$ MeV resonance used as a reference point. The older, from the compilation of Endt and Van der Leun,[18] gives $\omega_\gamma = 40$ eV while Lyons, Toews, and Sargood[19] give $\omega_\gamma = 22.0 \pm 2.4$ eV. In a previous experiment,[20] we used the $E_p = 2.678$ MeV resonance as reference point in a measurement of strengths of (p,γ) resonances in the energy range $E_p = 1.9$–3.1 MeV. This $E_p = 2.678$ MeV resonance, when compared to the $E_p = 0.992$ MeV resonance, was found to give $\omega_\gamma = 13.8$ eV or $\omega_\gamma = 7.6$ eV according to whether Ref. 18 or Ref. 19 were used. We performed an absolute measurement of this resonance with a thick target[21] and using a 12.7 $\times$ 12.7-cm NaI(Tl) detector for the determination of radiative capture processes proceeding through the resonance. The result was $\omega_\gamma = 8 \pm 3$ eV. Moreover, if the value deduced from Lyons measurement was used a strength of 3.2 ± 0.6 eV was found[20] for the $E_p = 2.876$ MeV resonance in agreement

TABLE II. Branching ratios, mixing ratios, and transition strengths for γ radiations originating from the 6.277-, 8.413-, 8589-, and 11.432-MeV levels in ^{28}Si. These levels were excited in the decay of the resonant level of the $E_p = 1.118$ MeV resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction. When possible (see text) only the preferred solutions for mixing ratios are reported.

Initial level (MeV)	Final level (MeV)	Branching ratio (%)	Mixing ratio	$\lvert M\rvert^2$ (W.u.)
3^+, 6.277	2^+, 1.779	90 ± 5	-0.14 ± 0.02	$M1 = (2.5 \pm 0.2) \times 10^{-4}$
				$E2 = (1.3 \pm 0.3) \times 10^{-3}$
4^-, 8.413	2^+, 1.779	22 ± 2	2.5 ± 0.2	$M2 = (2.1 \pm 0.6) \times 10^{-2}$
				$E3 = 25 \pm 8$
	3^-, 6.879	75 ± 3	-0.17 ± 0.01	$M1 = (1.3 \pm 0.3) \times 10^{-2}$
				$E2 = 0.9 \pm 0.2$
3^+, 8.589	2^+, 1.779	86 ± 6	0.38 ± 0.03	$M1 = (6.5 \pm 1.5) \times 10^{-3}$
				$E2 = 0.10 \pm 0.05$
			1.5 ± 0.1	$M1 = (2.4 \pm 0.7) \times 10^{-1}$
				$E2 = 0.5 \pm 0.1$
4^+, 11.432	3^+, 9.315	32 ± 3	0	$M1 = (4.7 \pm 1.1) \times 10^{-2}$
	3^+, 6.277	20 ± 3	0.1 ± 0.08	$M1 = (2.0 \pm 0.6) \times 10^{-3}$
				$E2 = (9.4 \pm 6.6) \times 10^{-3}$
			$3.7^{+1.16}_{-0.7}$	$M1 = 0.8 \times 10^{-4}$ to 3.6×10^{-4}
				$E2 = 0.2$ to 0.5
4^-, 11.432	3^+, 9.315	32 ± 3	0	$E1 = (1.6 \pm 0.4) \times 10^{-3}$
	3^+, 6.277	20 ± 3	0.1 ± 0.08	$E1 = (7 \pm 2) \times 10^{-5}$
				$M2 = 0.3 \pm 0.1$
			$3.7^{+1.16}_{-0.7}$	$E1 = 0.3 \times 10^{-5}$ to 1.2×10^{-5}
				$M2 = 7.7$ to 14.3

TABLE III. Lifetimes of five levels in ^{28}Si measured with the Doppler-shift attenuation method. γ rays from resonances of the $^{27}Al(p,\gamma)^{28}Si$ were observed, and the recoils were stopped in aluminum.

$E_i \rightarrow E_f$ (MeV)		$F(\tau)$	Doppler shift determined at E_p (MeV)	Mean lifetime τ (fs)
8.413	6.879	0.15 ± 0.02	1.118	490 ± 110
	1.779	0.12 ± 0.04		
8.589	1.779	0.89 ± 0.03	1.118	13 ± 4
9.702	8.413	0.024 ± 0.004	1.724	4800 ± 1400
	1.779	0.019 ± 0.005		
11.432	9.315	0.84 ± 0.04	1.118	20 ± 5
11.577	9.702	0.37 ± 0.06	2.876	220 ± 70

with Miehe *et al.*[5] who found $\omega_\gamma = 3 \pm 1$ eV. For these reasons we prefered the measurement of Lyons, Toews, and Sargood.[19] Assuming this value, the ω_γ of the 1.118-MeV resonance was found to be 8.5 ± 0.9 eV. It must be noticed that the values reported in Table 28.10 of Ref. 18 are from measurements all matched directly or indirectly to $\omega_\gamma = 10.2$ eV at $E_p = 0.774$ MeV, while if the value $\omega_\gamma = 4.7 \pm 1.5$ eV for this latter resonance had been used,[22] a reasonable agreement with our measurements would have resulted. As a consequence, all the ω_γ values of Table 28.10 in Ref. 18 may be too large by a factor of approximately 2.

B. Decay scheme

The measured branching ratios for the resonant and bound levels are shown in Fig. 1, as well as in Tables I and II. A reasonable agreement is observed with previous results, though a few comments may be added. According to Meyer, Wolmarans, and Reitmann[9] the 6.879-MeV level is populated 6% at the 1.118-MeV resonance while according to Tweter and Nordhagen[7,23] the 6.889 MeV is populated 6%. Our energy measurements of the primary transition at 0, 90, and 132°, as well as energy measurements of secondary transitions together with the very different lifetime of the two members of the 6.88-6.89 doublet led us to support the second conclusion.

The decay scheme of the 11.432-MeV level is difficult to establish because the 11.432→8.589-MeV transition is superimposed on the 4.618 → 1.779-MeV transition, so that the intensity of the γ-ray peak at $E_\gamma = 2.839$ MeV is not fully accounted for by the 4.618→1.779-MeV transition. This fact was previously reported by Meyer, Wolmarans, and Reitmann[9] and is confirmed. In addition a previously unreported 11.432→9.315-MeV transition was observed.

Our results concerning the γ decay of the 9.702-MeV level are in good agreement with those of Lam, Litherland, and Azuma,[2] although we could not adequately resolve the two transitions to the 6.88-6.89 doublet and thus were unable to measure their relative intensity.

C. Lifetime measurements

Lifetimes of the levels at 8.413, 8.589, and 11.432 MeV were measured at the $E_p = 1.118$ MeV resonance. For the 9.702-MeV level this measurement was made using the $E_p = 1.724$-MeV resonance and for the 11.577-MeV level the $E_p = 2.876$ MeV resonance was used. Sets of six 0 and 132° Doppler-shift measurements were made during each of two separate runs. Our results are shown in Table III and compared with previous determinations in Table IV. The present determination specifies the long lifetime of the 9.702-MeV level, and supports the previous determinations leading to the longer value of the mean lifetime of the 8.413-MeV level.[9,28] For the 11.577-MeV level, the present determination is in agreement with that of Neal and Lam[6] and specifies the lifetime.

TABLE IV. Comparison of ^{28}Si lifetime measurements. The determinations of Refs. 9, 28, 24, 25, and 26 are based on the Doppler-shift attenuation method (DSAM). The states were excited in the $^{27}Al(p,\gamma)^{28}Si$ reaction except in Ref. 26 where $^{27}Al(^3He,d)^{28}Si$ reaction was used. The two values in Ref. 27 refer to results obtained with a delayed coincidence method for the first one and with the DSAM for the second one.

E_x (MeV)	Present experiment (fs)	Other lifetime results (fs) Ref. 6	Ref. 3	Ref. 9	Ref. 28	Ref. 24	Ref. 25	Ref. 26	Ref. 27
8.413	490 ± 110			560 ± 150	580 ± 400	280^{+100}_{-60}	230 ± 50		
8.589	13 ± 4			<6	10 ± 3	25 ± 2		<25	
9.700	4800 ± 1400		>2700	>1000					8000 ± 4000
									3300 ± 800
11.432	20 ± 5								
11.577	220 ± 70	340 ± 100							

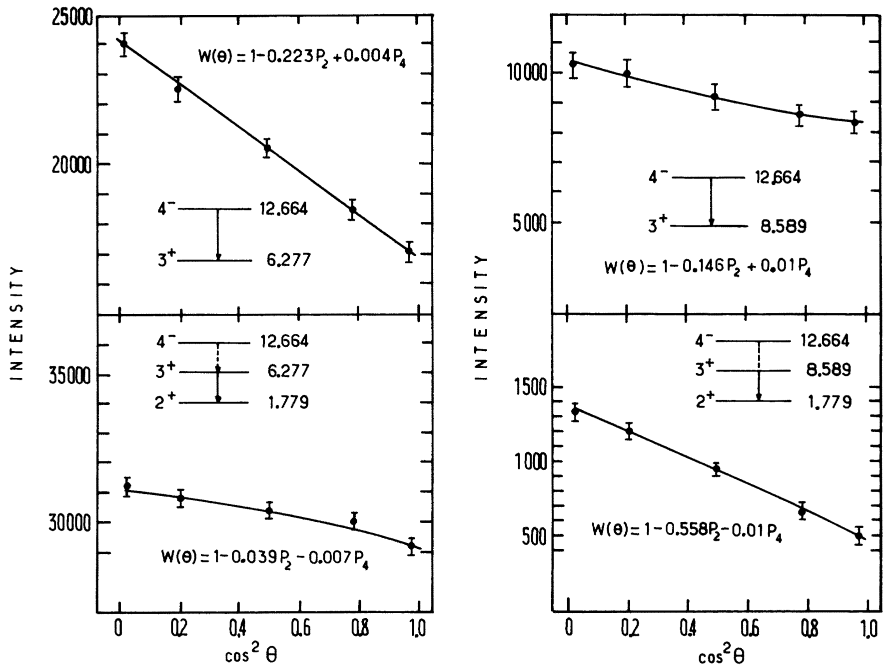

FIG. 2. Legendre polynomials fits to the angular distributions relative to the direction of the proton beam of γ rays observed in the $^{27}Al(p, \gamma)^{28}Si$ reaction. The level situated at 12.664 MeV is the resonant level. The transition observed is represented with full arrow; for the secondary transition the dotted arrow refers to the corresponding primary transition.

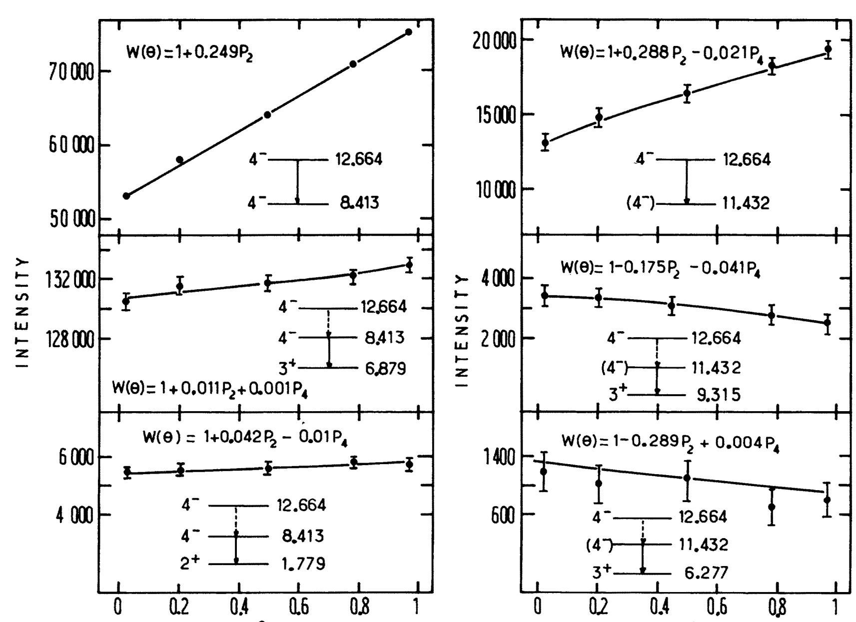

FIG. 3. Legendre polynomials fits to the angular distributions relative to the direction of the proton beam of γ rays observed in the $^{27}Al(p, \gamma)^{28}Si$ reaction. The level situated at 12.664 MeV is the resonant level. The transition observed is represented with full arrow; for the secondary transition the dotted arrow refers to the corresponding primary transition.

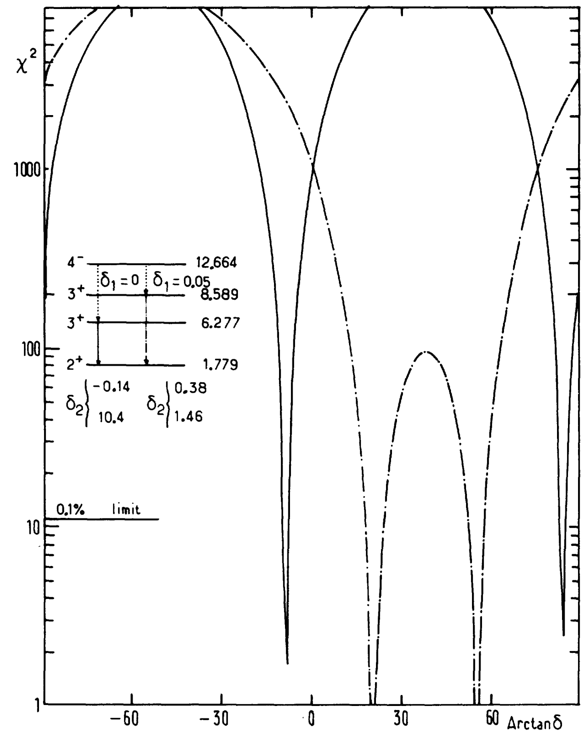

FIG. 4. A plot of χ^2 against mixing ratios for the two transitions 8.589→1.779 and 6.277→1.779 MeV as observed in the $E_p = 1.118$ MeV resonance of the $^{27}Al(p,\gamma)$-^{28}Si reaction. The solid curve refers to the second transition. The 12.664-MeV level is the resonant level and the indicated δ_1 values were obtained in a fitting procedure of the primary corresponding γ rays. The δ_2 values are the mixing ratios indicated by the relative minima in χ^2 within a 0.1% confidence limit; two solutions are observed for each transition.

D. Angular distributions

The angular distributions relative to the direction of the proton beam, and Legendre polynomial fits to them of the transition from the 12.664-, 11.432-, 8.589-, 8.413-, and 6.277-MeV levels, are shown in Figs. 2 and 3. Using the results of Tweter,[7] the population parameters of the resonant level were calculated from[8]

$$P(m) = (sJm - m \mid l0)^2$$

and the deduced statistical tensors[29] were introduced as known values. The result $\Gamma_p/\Gamma = 0.99 \pm 0.01$[7] was used in the calculations of the primary transition strengths.

1. *6.277- and 8.589-MeV levels*

Because the spin values of these levels are well established, the only free parameter in the fitting procedure for the primary γ ray is the multipolarity mixing ratio. The values resulting from this fitting have been introduced as input data in the subsequent fitting procedure for the secondary transitions shown in Fig. 4. For each transition two relative minima in χ^2 are obtained within the 0.1% confidence limit value. For the 6.277→1.779 MeV transition the deduced value $\delta_2 = -0.14 \pm 0.02$ is in excellent agreement with the known previously determined value $\delta_2 = -0.12 \pm 0.05$[30] and is therefore unambiguously the prefered value. It is not possible to choose between the two δ_2 solutions for the 8.589→1.779-MeV transition, because when used in the calculations of the transition strengths, both lead to values situated within the limits given by Endt and Van der Leun.[31]

2. *8.413-MeV level*

All the spin possibilities were tested using the fitting procedure for the primary transition leading to the 8.413-MeV level. A plot of the χ^2 versus mixing ratio is shown in Fig. 5. One can reject the

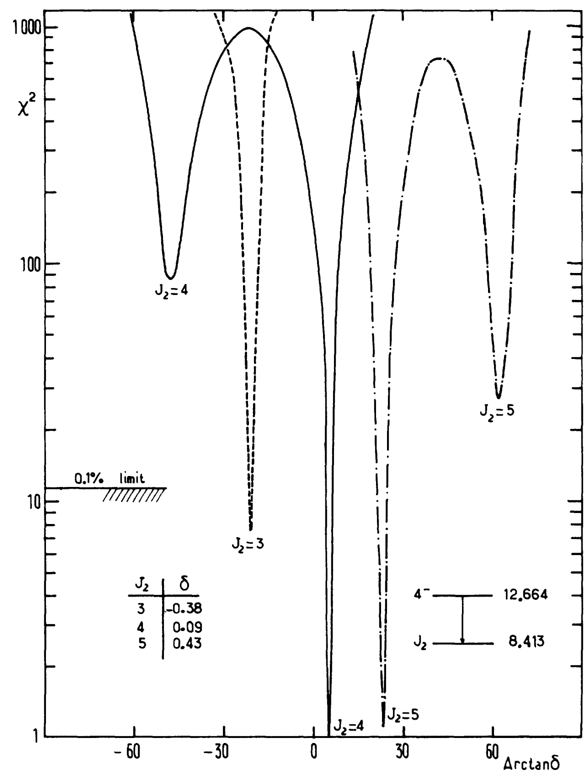

FIG. 5. A plot of χ^2 against mixing ratios for the $r \to 8.413$ MeV primary transition in the $^{27}Al(p,\gamma)^{28}Si$ reaction. One solution corresponding to a relative minimum in χ^2 within the 0.1% confidence limit is observed for each spin possibility $J = 3$, 4, or 5 for the 8.413-MeV level. The indicated δ values are the corresponding solutions for the mixing ratios. The consequences resulting from these values are discussed in Sec. 3D1.

$J^\pi = 3^+$, 4^+, and 5^+ solutions leading to $M2$ components of 310, 24, and 380 W.u., respectively. If the solutions $J^\pi = 3^-$ or 5^- are used, $E2$ components of 10 and 13 W.u. will result, which are both compatible with a T-allowed $E2$ transition. Actually, the resonant level can with high probability be classified as a $T=1$ state.[7] Then these values are difficult to reconcile with the recommended upper limit of 3 W.u. for an $E2$ T-forbidden transition.[31] However, if $J^\pi = 4^-$ is used an $M1$ transition streng strength of 0.3 W.u. will result, which is in conformity with a $J^\pi \rightarrow J^\pi$ $\Delta T = 1$ $M1$ transition in a self-conjugate nucleus. Furthermore, the 4^- value is in better agreement with the unnatural parity of this 8.413-MeV level which is suggested by the α-particle spectrum at 0° in the $^{16}O(^{16}O, \alpha)^{28}Si$ reaction.[10] All these reasons strongly support the

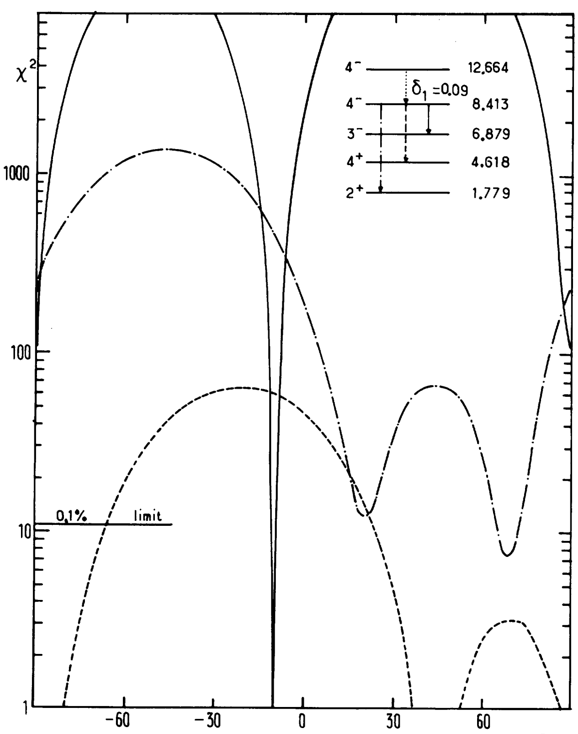

FIG. 6. A plot of χ^2 against mixing ratios for the transitions issued from the 8.413-MeV level, fed in the $E_p = 1.118$ MeV ($E_x = 12.664$ MeV) resonance of the $^{27}Al(p, \gamma)^{28}Si$ reaction. The value $\delta_1 = 0.09$ was obtained in the fitting procedure of the primary γ ray assuming $J=4$ for the 8.413-MeV level. The solid curve refers to the 8.413→6.879-MeV transition. It shows only one well-defined relative minimum is χ^2 within a 0.1% confidence limit; the deduced mixing ratio $\delta_2 = -0.17$ leads to an $E2$ component much weaker than previously thought (see Ref. 2). The 8.413→1.779-MeV transition shows only one clearly well-defined solution within the 0.1% confidence limit while nothing can be said for the 8.413→4.613-MeV transition represented in dotted line.

$J^\pi = 4^-$ value for the 8.413-MeV level.

The χ^2 versus mixing ratio for the three transitions originating from the 8.413-MeV level, presented in Fig. 6, shows only one well-defined solution within a 0.1% confidence limit for the 8.413 → 6.879-MeV transition. The corresponding mixing ratio $\delta = -0.17$ is in reasonable agreement with the value $\delta = -0.27$ obtained by Lam, Litherland, and Azuma.[2] But these authors on the basis of linear-polarization measurement preferred their second solution leading to a pure $E2$ transition. This choice results in a strongly enhanced $E2$ transition, even with the larger τ value supported by our work. The absence of this second solution in our results leads us to keep the first solution. This choice, as shown in Sec. 4, eliminates the enhanced character of the $E2$ 8.413→6.879-MeV transition.

For the 8.413→1.779-MeV transition two χ^2 minima are observed. Only one of them (corresponding to the larger value of $E3/M2$ mixing ratio) clearly lies within the 0.1% confidence limit. This solution results in an $E3$ transition of 25 W.u. It seems well established[10,32] that the 1.779-MeV level is the 2^+ level of a $K^\pi = 0^+$ band based on the ground state. If, in addition, the 8.413-MeV level is a member of a $K^\pi = 3^-$ band, this enhanced $E3$ transition strength is satisfactory interpreted since the $M2$ decay would be K forbidden.

Due to the larger statistical errors, no firm conclusions concerning the 8.413→4.618-MeV transition (3% of total decay of the 8.413-MeV level) can be obtained from the present data.

3. 11.432-MeV level

The plot of χ^2 versus mixing ratios for the transition from the resonant level to the 11.432-MeV level (Fig. 7) does not allow the exclusion of any of of the values $J = 2$ to 6, probably on account of the large statistical errors in the data for this transition. If the resulting mixing ratios are used in the calculated transition strengths, the only reasonable possibility is $J^\pi = 4^\pm$ with $\delta_1 = 0.03$. The $J^\pi = 4^-$ value leads to a 0.9-W.u. $M1$ component in conformity with a $M1$ $\Delta T = 1$ transition in this self-conjugate nucleus, suggesting the value $T=0$ for the 11.432-MeV level. If the $J^\pi = 4^+$ value is used, an $E1$ component of 2.8×10^{-2} W.u. will result and this choice allows the two possibilities $\Delta T = 0, 1$. However the $J^\pi = 4^+$ $T=1$ solution can be ruled out because the decay of the 11.432-MeV level feeds both the $J^\pi = 3^+$ $T=1$ 9.315 MeV level and the $J^\pi = 3^+$ $T=0$ 6.277-MeV level. In consequence the first $M1$ transition would be T forbidden and the second would be T favored, which conclusion is in disagreement with our experimental results. In con-

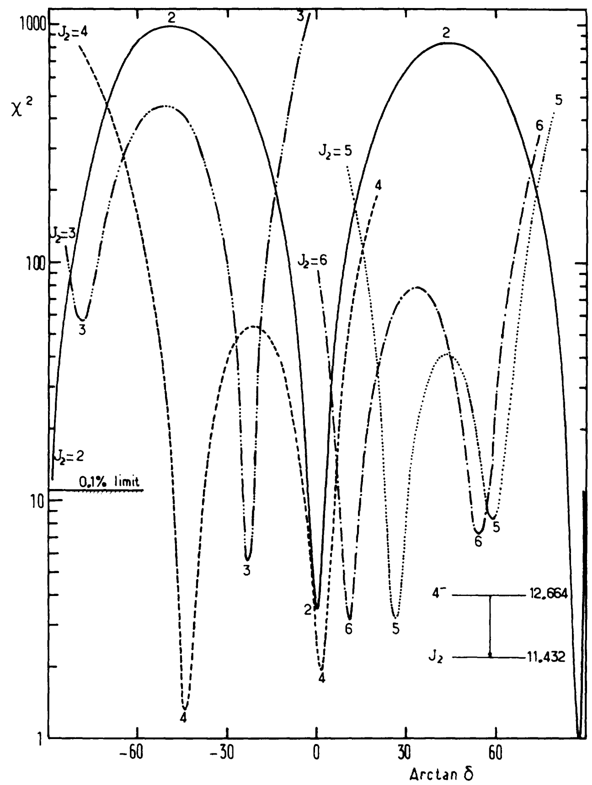

FIG. 7. A plot of χ^2 against mixing ratios for the 12.664→11.432-MeV transition observed in the $E_p = 1.118$ MeV ($E_x = 12.664$ MeV) resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction. The numbers of the curves refer to the various spin possibilities tested for the 11.432-MeV level.

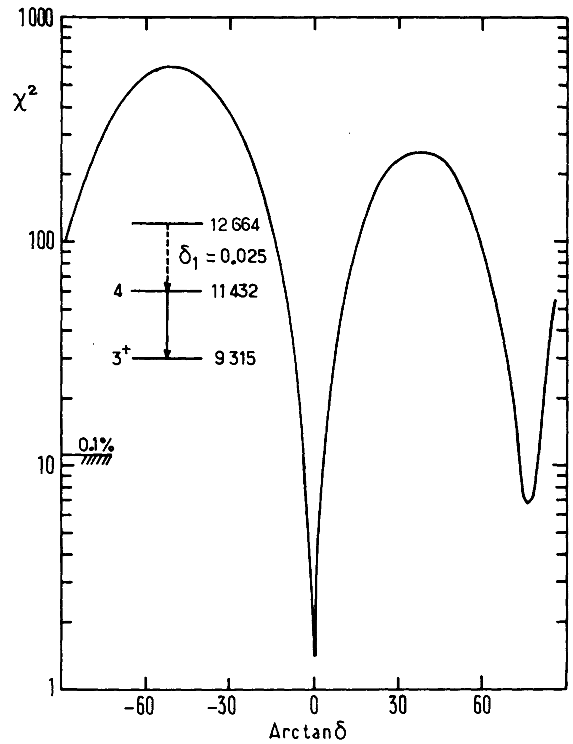

FIG. 8. A plot of χ^2 against mixing ratios for the 11.432→9.315-MeV transition observed in the $E_p = 1.118$ MeV ($E_x = 12.664$ MeV) resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction. The indicated δ_1 value was obtained in a fitting procedure of the primary γ ray, assuming $J = 4$ for the 11.432-MeV level. Two relative minima in χ^2 are observed within a 0.1% confidence limit, but as explained in Sec. 3D3, the one corresponding to a mixing ratio $\delta_2 = 0$ is preferred.

clusion, the two possibilities $J = 4^{\pm}$, $T = 0$ remain for the 11.432-MeV level.

In the 11.432→9.315-MeV transition (Fig. 8) the $\delta_2 = 0$ value of the mixing ratio is preferred since the larger one would lead to unreasonable strengths for the $E2$ or $M2$ components. This $\delta_2 = 0$ value involves an $M1$ strength of 4.7×10^{-2} W.u. if $J^\pi = 4^+$ and an $E1$ strength of 1.6×10^{-3} W.u. if $J^\pi = 4^-$. The results concerning the 11.432→6.277-MeV transition do not allow one to choose between the two possibilities.

4. DISCUSSION

A. Positive-parity levels

As previously reported,[33] if the 6.277-MeV level is to be associated with a $K = 3$ band, its $E2$ decay to $K = 0$ states must be forbidden. The present δ measurement of the 6.277→1.779-MeV transition, together with the mean lifetime $\tau = 1100 \pm 280$ fs previously measured in this laboratory,[34] leads to an $E2$ component of $(1.4 \pm 0.4) \times 10^{-3}$ W.u., which indicates that this $E2$ transition actually is inhibited. Other members of the suggested band are still to be found and a likely candidate is the 11.432 MeV level if it has $J^\pi = 4^+$. However, this possibility is not substantiated by our measurements which lead to an unenhanced $E2$ component $|M|^2(E2) \leq 0.4$ W.u. for the 11.432→6.277-MeV transition.

B. Negative-parity levels

Our lifetime measurement of the $J^\pi = 6^-$ 11.577-MeV level when used with the multipole mixing ratio $\delta_2 = \infty$ for the 11.577→9.702-MeV transition,[6] leads to an $E2$ strength of 32 W.u., and our lifetime measurement of the $J^\pi = 5^-$ 9.702-MeV level, when used with the multipole mixing ratio $\delta_2 = -10$ for the 9.702→8.413 MeV transition,[2] leads to an $E2$ strength of 4.5 W.u. These values lead to an experimental ratio

$$\frac{B(E2; 6 \to 5)}{B(E2; 5 \to 4)} = 7,$$

while the theoretical value on the basis of the collective model is 0.8.

For the $8.413 \to 6.879$ MeV transition, the $E2$ strength of 0.9 W.u. found in this work is much weaker than previously thought.[2] The deduced experimental ratio is

$$\frac{B(E2; 5 \to 4)}{B(E2; 4 \to 3)} = 5 ,$$

while the theoretical value on the basis of the collective model is 0.9

In conclusion the proposed $K^{\pi} = 3^-$ band is inconsistent with the observed transition strengths. The probable nonexistence of this band leaves one without an explanation for the enhanced $E3$ component which is observed in the $8.413 \to 1.779$ MeV transition.

One must look for another interpretation of these negative-parity levels. The $E_p = 1.118$-MeV resonance is formed by $l = 1$ proton capture and can be considered to have a large component of the $(1d_{5/2}^{-1}, 2p)$ structure mixed in its wave function.[7] If the 12.664- and 8.413-MeV levels actually are, respectively, 4^- $T = 1$ and 4^- $T = 0$ levels, the strength $|M|^2(M1) = 0.3$ W.u. obtained for the $12.664 \to 8.413$ MeV level suggests an analog-antianalog state transition, and the configurations of the two states are expected to be similar. The same situation is observed at the $E_p = 1.724$ MeV resonance with the 13.246 (5^- $T = 1$)$\to$ 9.702 MeV (5^- $T = 0$), $|M|^2(M1) = 0.7$-W.u. transition and an expected $(d_{5/2}^{-1}, f_{5/2})$ configuration for the compound state.[2] Finally a similar situation probably occurs at the $E_p = 2.876$ MeV resonance with $(d_{5/2}^{-1}, f_{7/2})$ configuration for the compound state.[6] Hence simple one-particle–one-hole calculations may explain these negative-parity levels. The 6.879-MeV $J^{\pi} = 3^-$ level may be interpreted in a similar manner. We looked for a possible $T = 1$ level associated in the same way with this level. The desired characteristics may be presented by the level at $E_x = 12.802$ MeV and a study of the resonance at $E_p = 1.262$ MeV is planned.

Referring back to the $J^{\pi} = 4^-$ $T = 0$ possibility found for the 11.432-MeV level, a strength of 0.9 W.u. would result for the $12.664 \to 11.432$ MeV transition, suggesting a splitting of the antianalog state of the 12.664-MeV level, shared upon the 8.413- and the 11.432-MeV levels.

In conclusion, the existence of the suggested 3^- $4^-5^-6^-$ rotational band is not substantiated but simple one-particle–one-hole calculations may provide an explanation of these negative-parity states.

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[1]R. Nordhagen and A. Tweter, Nucl. Phys. 56, 337 (1964).
[2]S. T. Lam, A. E. Litherland, and R. E. Azuma, Can. J. Phys. 49, 685 (1971).
[3]N. Anyas-Weiss, A. M. Charlesworth, L. E. Carlson, K. P. Jackson, and R. E. Azuma, Can. J. Phys. 47, 1725 (1969).
[4]J. Dalmas and D. Bertault, J. Phys. (Paris) 34, 357 (1973).
[5]C. Miehe, J. P. Gonidec, A. Huck, and G. Walter, in Conference on Nuclear Structure and Nuclear Reactions, Birmingham, April, 1972 (unpublished) and private communications.
[6]G. F. Neal and S. T. Lam, Phys. Lett. 45B, 127 (1973).
[7]A. Tweter, Nucl. Phys. A185, 433 (1972).
[8]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).
[9]M. A. Meyer, N. S. Wolmarans, and D. Reitmann, Nucl. Phys. A144, 261 (1970).
[10]T. K. Alexander, C. Broude, A. J. Ferguson, J. A. Kuehner, A. E. Litherland, R. W. Ollerhead, and P. S. M. Smulders, Can. J. Phys. 47, 651 (1969).
[11]A. Lapierre, thesis (3rd cycle), University of Bordeaux, 1972 (unpublished).
[12]M. M. Aleonard, University of Bordeaux (unpublished).
[13]J. P. Thibaud, M. M. Aleonard, D. Castera, P. Hubert, F. Leccia, and P. Mennrath, Nucl. Phys. A135, 1272 (1969).
[14]J. Lindhard, M. Scharff, and E. Schiøtt, K. Dan. Vidensk. Selsk. Mat.–Fys. Medd. 33, No. 14 (1963).
[15]A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[16]F. Leccia, thesis, University of Bordeaux, 1973 (unpublished).
[17]P. B. Smith, *Nuclear Reactions*, edited by P. M. Endt and P. B. Smith (North-Holland, Amsterdam, 1962), Vol. II, Chap. V.
[18]P. M. Endt and C. Van der Leun, Nucl. Phys. A105, 1 (1967).
[19]P. B. Lyons, J. W. Toews, and D. G. Sargood, Nucl. Phys. A130, 1 (1969).
[20]J. Dalmas, C. R. Acad. Sci. 277, 237 (1973).
[21]H. E. Gove, *Nuclear Reactions* (see Ref. 17), Vol. I, Chap. VI.
[22]P. B. Smith and P. M. Endt, Phys. Rev. 110, 397 (1958).
[23]R. Nordhagen and A. Tweter, Nucl. Phys. 63, 529 (1965).
[24]E. F. Gibson, K. Battleson, and D. K. McDaniels, Phys. Rev. 172, 1004 (1968).
[25]L. E. Carlson and R. E. Azuma, Phys. Lett. B24, 462

(1967).
[26]J. H. Anderson and R. C. Ritter, Nucl. Phys. A128, 305 (1969).
[27]R. D. Barton, J. S. Wadden, A. L. Carter, and H. L. Pai, Can. J. Phys. 50, 1282 (1972).
[28]F. C. P. Huang, E. F. Gibson, and D. K. McDaniels, Phys. Rev. C 3, 1222 (1971).
[29]A. J. Ferguson, *Angular Correlation Methods in Gamma Ray Spectroscopy* (North-Holland, Amsterdam, 1965).
[30]C. Broude and H. E. Gove, Ann. Phys. (N. Y.) 23, 71 (1963).
[31]P. M. Endt and C. Van der Leun, report (unpublished).
[32]A. E. Litherland, P. J. M. Smulders, and T. K. Alexander, Can. J. Phys. 47, 639 (1969).
[33]S. Das Gupta and H. Harvey, Nucl. Phys. 47, 639 (1969).
[34]M. M. Aleonard, D. Castera, P. Hubert, F. Leccia, P. Mennrath, and J. P. Thibaud, Nucl. Phys. A146, 90 (1970).