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Angular correlation and gamma ray linear polarization measurements in ^{29}Al

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The decay scheme of ^{29}Al has been investigated with the ^{26}Mg$(\alpha, p)^{29}$Al reaction at $E_\alpha = 14.2$ MeV. Simultaneous measurements of p-γ angular correlations and p-γ linear polarizations, utilizing a three-detector Ge(Li) Compton polarimeter, have been accomplished. Spin-parity assignments of $7/2^+$, $3/2^+$, $5/2^+$, $9/2^+$, $5/2^+$, and $7/2^+$ are set forth, respectively, for the 1.75, 2.22, 3.18, 3.58, 4.22, and 5.99 MeV levels. The results suggest $J^\pi = 11/2^+$ for the 5.85 MeV level.

[NUCLEAR REACTIONS ^{26}Mg(α,p), E=14.2 MeV; measured $p\gamma$ coincidence, E_γ, $I_\gamma(\theta_\gamma)$, γ linear polarizations. ^{29}Al deduced levels, E_x, J, π, δ, branching ratios. Enriched target. Ge(Li) Compton polarimeter.]

I. INTRODUCTION

The measurements on ^{29}Al described here have been undertaken to supplement previous lifetime measurements done in this laboratory on the same nucleus.[1] Although the decay scheme of ^{29}Al has been studied by several authors,[2-6] the lack of unambiguous spin values and mixing ratios for most of the excited states has limited comparison with theoretical models such as the shell model calculations of De Voigt *et al.*[7] or such as the strong coupling model examined by several investigators.[2,4] This problem has led us to undertake experiments which can discriminate between the several allowed spins given for many low-lying excited states from previous p-γ angular correlation experiments, and also from particle studies in the ^{26}Mg$(\alpha, p)^{29}$Al,[3,4] ^{27}Al(t, p)-^{29}Al,[2,5] ^{30}Si$(t, \alpha)^{29}$Al,[2] and ^{30}Si$(d, {}^3$He$)^{29}$Al[6] reactions. Calculations show that simultaneous measurements of p-γ angular correlation and directional p-γ linear polarizations can lead to unambiguous values of the spins of low-lying excited states. Previous spin-parity restrictions for these states are: $E_x = 1.75$ $(\frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+)$, 2.22 $(\frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+)$, 3.18 $(\frac{3}{2}^+, \frac{5}{2}^+)$, and 3.58 MeV$(\leq \frac{9}{2}^+)$.

The present paper describes experiments done with the ^{26}Mg$(\alpha, p)^{29}$Al reaction using a Ge(Li) detector for the angular correlation measurements and a three Ge(Li) Compton polarimeter for the γ linear polarization measurements. Since this work was begun two new papers have appeared which further restricted the allowed spin values for some of the low-lying excited states. Williams *et al.*[8] have measured γ-ray linear polarizations with a classical NaI Compton polarimeter with results which fixed the spin of the 2.22 MeV level as $\frac{3}{2}^+$ and restricted the spin of the 1.75 MeV level to $\frac{7}{2}^+$ $(\frac{3}{2}^+)$, in agreement with the results we report. Ekström and Tillmann[9] have measured angular correlations with a Ge(Li) counter: their results show a transition from the 3.18 MeV level to the 1.40 MeV level $(\frac{1}{2}^+)$ with a large A_4 component which can only be explained by a $\frac{5}{2}^+$ spin value for the 3.18 MeV level. This result is also confirmed, as are their results for excitation energies, branching ratios, and mixing ratios, which values were deduced similarly from angular correlation-polarization measurements.

II. EXPERIMENTAL METHOD AND DATA ANALYSIS

The Compton polarimeter was constructed with three Ge(Li) detectors. A 69 cm^3 Ge(Li) detector (14% efficiency compared to a NaI 7.6 cm$\times$7.6 cm, and full width at half-maximum (FWHM) resolution of 2.6 keV for the 1.33 MeV γ-ray of ^{60}Co) was positioned in the horizontal plane at 90° to the beam direction. Compton-scattered γ-rays were detected by two Ge(Li) detectors (50 cm^3, efficiency 12%, energy resolution 2.4 keV) acting as polarization analyzers, one in the reaction plane and the other normal to it. The size of the scattering detector was appropriate for the detection of γ rays with an energy exceeding 0.9 MeV; for experiments involving lower-energy γ rays the scatterer can easily be replaced by a smaller Ge(Li) detector. The mechanical frame allowed the polarimeter to rotate about the target chamber with the relative crystal positions held fixed. The scatterer-analyzer distance and the scattering angle can also be changed: a scattering angle of 60° was used in the present experiment.

The γ-ray spectra from the scatterer and from the analyzer detectors were digitally summed after conversion by the analog-to-digital converters (ADC); this system allows for easy gain adjustment between the three counters. An anticoinci-

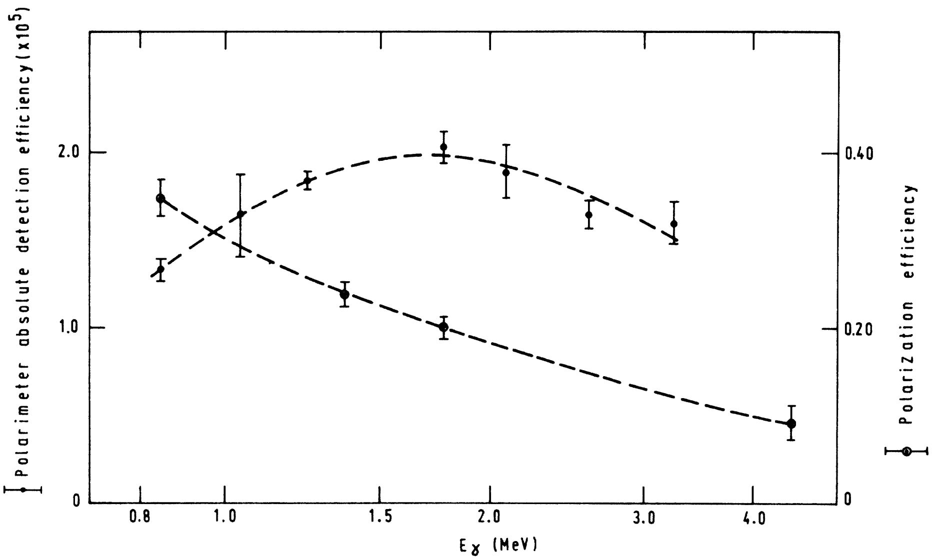

FIG. 1. Absolute detection efficiency and polarization efficiency of the "3 Ge(Li)" Compton polarimeter as a function of incident γ-ray energy. (The lines are drawn as visual guides.)

dence system allows for rejection of the 511 keV γ ray in the analyzers which could result from pair production in the scatterer. Shielding of 7.5 cm lead was placed between the target chamber and the polarimeter with a conic hole allowing the γ rays to reach the scatterer.

The polarimeter was calibrated from simultaneous[10] angular distribution and polarization measurements of well known $E2$ transitions emitted by nuclear levels strongly aligned in (p,p') reactions. The reactions were ^{56}Fe$(p,p')^{56}$Fe ($E_\gamma = 0.85$ MeV), ^{24}Mg$(p,p')^{24}$Mg($E_\gamma = 1.37$ MeV), ^{28}Si(p,p') ($E_\gamma = 1.78$ MeV), and ^{12}C$(p,p')^{12}$C ($E_\gamma = 4.43$ MeV). In Fig. 1 are shown the values obtained for the polarization efficiency $Q(E)$ defined by

$$Q(E) = \frac{1}{p(\theta)} \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}.$$

$N_\parallel$ and $N_\perp$ are the counting rates measured into and perpendicular to the reaction plane, respectively, and $p(\theta)$ is the linear polarization defined as follows:

$$p(\theta) = \frac{J(\theta, \psi = 0°) - J(\theta, \psi = 90°)}{J(\theta, \psi = 0°) + J(\theta, \psi = 90°)},$$

where θ is the angle of the direction of propagation of the γ radiation to the direction of the beam. $J(\theta, \psi)$ is the intensity of the γ radiation with its electric vector lying in a plane at an angle ψ to the plane containing θ so the expected theoretical polarization $p(\theta)$ can be calculated[10] from the measured angular correlation for pure E_L or M_L transitions.

The quantities $N_\parallel$ and $N_\perp$ were normalized by measuring possible asymmetries with a ^{56}Co source placed at the site of the target before and after each run. These values were also checked by measuring the polarization (which should be zero) of γ rays emitted by levels with spin $\frac{1}{2}$ in the ^{27}Al$(p,p')^{27}$Al ($E_\gamma = 0.84$ MeV) and ^{11}B$(p,p')^{11}$B ($E_\gamma = 2.13$ MeV) reactions.

Also shown in Fig. 1 is the variation of the absolute efficiency of the polarimeter $(N_\parallel + N_\perp)/N_0(\gamma)$ as a function of the γ ray energy; $N_0(\gamma)$ is the source activity.

The bombarding energy in the ^{26}Mg$(\alpha,p)^{29}$Al reaction was chosen so as to favor the population of the levels at 1.75, 3.18, and 3.58 MeV. The 14.25 MeV α-particle beam was provided by the Strasbourg MP tandem Van de Graaff accelerator. The rolled self-supporting ^{26}Mg targets enriched to 99.6% had a thickness of 170 μg/cm^2.

The protons were detected with an annular Si(Li) detector of 2 mm depth, positioned to allow detection of protons in the angular range between $\theta = 166°$ and 174°. In front of this detector an aluminium absorber 50 μm thick was placed to stop α particles elastically scattered by the target. The beam itself was stopped in a beam catcher located 50 cm behind the target chamber, with lead walls shielding the γ ray detectors. The diameter of the target chamber was 7.6 cm, allowing a target-polarimeter scatterer distance of 13 cm. The angular correlation detector was a 130 cm^3 Ge(Li) detector, with an efficiency of 21% and energy resolution 3.0 keV.

The data were collected by a Hewlett Packard

TABLE I. Excitations energies of ^{29}Al levels determined in the present work, and comparison to other measurements and to calculations done in the shell model framework.

E_x (keV)		Lifetimes (fs)		
Present work	Ref. 9	Exp.[a]	Theor.[b]	Theor.[c]
1397.6± 0.4	1398.2± 0.3	6500± 500	6000	10 000
1753.7± 0.4	1754.5± 0.3	32± 12	26	60
2224.5± 0.6	2223.9± 0.4	110± 30	180	110
2865.4± 0.8	2865.7± 0.6	100± 30	130	90
3060.8± 0.7	3062.0± 0.5	80± 30	72	20
3185.0± 0.8	3184.4± 0.5	180± 40	164	160
3432.3± 1.2	3433.1± 0.7		11	200
3577.3± 0.8	3577.8± 0.6	36± 10	12	
3641.8± 1.0	3641.3± 0.9	< 100	12	
3671.5± 0.9	3672.2± 1.3	< 100	15	
3935.4± 0.8	3934.6± 1.4	130± 30	145	
3986.9± 1.5	3985 ± 2	<40		
4058.8± 2.0	4056.8± 0.7	120± 70		
4219.4± 0.9	4219.8± 0.7	60± 20		
4402.8± 1.0	4403.3± 1.0	60± 30		
4715.8± 1.2	4715.2± 1.4			
4826.6± 1.5	4828.9± 1.3	60± 30		
	4940.8± 1.0	42± 12		
	5023 ± 3	< 120		
5182.2± 2.0	5181 ± 2			
	5248.3± 1.7	< 130		
5263.8± 1.2	5263 ± 3	110± 70		
	5392 ± 3			
	5433 ± 4			
	5733 ± 4			
5854.8± 1.2	5855.5± 1.0	42± 19	69	
	5993.6± 1.0	<90		

[a] Average from Ref. 1 and Ref. 9.
[b] Shell model calculations from Ref. 16.
[c] Shell model calculations with a truncated space from Ref. 7.

2100 (24 000 word) computer. Six ADCs were used to analyze the energy spectra of the five counters: annular detector, angular correlation detector, scatterer (twice analyzed, one for the normalization of the angular correlation, one for the sum spectra of the polarimeter), and the horizontal and vertical polarimeter analyzer detectors; two other ADCs were used to collect the time spectra of the angular correlation and of the polarization measurements, in order to allow random coincidence corrections. All data were recorded event by event on magnetic tape.

III. EXPERIMENTAL RESULTS

A. Excitation energies and branching ratios

The values of excitation energies and branching ratios determined here are reported in Table I and Table II and compared to previous measurements. These results agree quite well with recent values obtained by Ekström and Tillmann,[9] who also used Ge(Li) detectors; some disagreement with other previous work, especially for the transition from the 3.18 MeV level to the 1.40 MeV level, can be attributed to problems arising from the use of NaI detectors by these authors.[2,3]

B. Angular correlations

Some χ^2 fits are given in Fig. 2. Generally these fits do not allow unambiguous spin assignments except for the confirmation of the spin of the 2.87 MeV level (Fig. 3). The mixing ratios deduced from these fits are reported in Table III for the spin values determined in the polarization measurements. These results are in agreement with the previous values also reported in Table III except for the transition from the 2.87 MeV level to the 1.40 MeV level. In this case the disagreement between the Ge(Li) angular correlation experiments (this work and Ekström and Tillmann[9]) and the NaI angular correlation experiments[2-4] can be partially attributed to the fact that the Ge(Li) detectors were able to discriminate between the 1.47 and 1.40 MeV transitions deexciting the 2.87 MeV level.

The γ-ray strengths can be calculated from the mixing ratios and from the previous lifetime measurements (see Table I) for the different spins values allowed by the χ^2 fit. If one compares them to the recommended upper limits for γ-ray strengths defined by Endt and van der Leun,[11] and utilizes the fact that the 3.58 MeV level has positive parity, as established by particle measurements in the ^{27}Al$(t,p)^{29}$Al reaction,[12] then one deduces positive parities also for the excited levels at 1.75, 2.22, and 3.18 MeV. This has been discussed in detail in Ref. 9.

C. Polarization measurements

Various typical γ-polarization spectra obtained in coincidence with several proton groups are shown in Fig. 4. The counting rate obtained in such experiments (γ-ray polarization measured with Ge(Li) detectors in coincidence with particles) is poor, but the high energy resolution compensates to a large degree. However, only the strong transitions emitted by the levels populated at the $E_\alpha = 14.2$ MeV bombarding energy could be analyzed.

The experimental results of these polarization measurements, corrected for detection efficiency and for polarization sensitivity, are reported in Table IV. These values are compared in this table to those predicted from the angular correlation measurements for the different possible spin

TABLE II. Branching ratios of ^{29}Al levels.

E_i (MeV)	E_f (MeV)	Present work	Branching ratios (%) Ref. 9	Ref. 4	Ref. 2	Ref. 3	Adopted [a]	Theor. [b]	Theor. [c]
1.40	0	100	100	100	100	100	100	100	100
1.75	0	100	100	100	100		100	100	100
2.22	0	100	100	100	100	99 ± 1	100	98	95
	1.40	< 2	< 2	< 2	< 1	1 ± 1	< 1	2	5
2.87	0	53 ± 4	52 ± 4	58 ± 2	56 ± 2	67 ± 2 [a]	56 ± 2	84	85
	1.40	47 ± 4	48 ± 4	42 ± 2	44 ± 2	33 ± 1 [a]	44 ± 2	15	3
	2.22	< 4	< 4	< 2	< 2	< 2	< 2	1	12
3.06	0	23 ± 7	27 ± 3	33 ± 4	29 ± 2	40 ± 2 [a]	29 ± 2	43	58
	1.75	77 ± 8	73 ± 3	67 ± 4	71 ± 2	58 ± 2 [a]	71 ± 2	55	42
	2.22	< 8	< 3			2 ± 2	< 3	2	
3.18	0	7 ± 2	7 ± 1	6 ± 2	10 ± 3 [a]	15 ± 2 [a]	7 ± 1	27	44
	1.40	13 ± 1	14 ± 1	9 ± 6	< 10 [a]	< 33 ± 2 [a]	13 ± 1	20	23
	1.75	23 ± 2	24 ± 2	29 ± 3	25 ± 7 [a]	< 33 ± 2 [a]	24 ± 2	14	1
	2.22	57 ± 2	55 ± 2	56 ± 5	65 ± 7 [a]	52 ± 1 [a]	56 ± 2	35	32
	2.87	< 2	< 2		< 5	< 10	< 2	4	
3.43	0		< 8	< 15 [a]	6 ± 2 [a]	16 ± 4 [a]	< 8	12	4
	1.40		83 ± 3	71 ± 5 [a]	74 ± 3 [a]	69 ± 3 [a]	83 ± 3	82	87
	2.22		17 ± 3	29 ± 5 [a]	20 ± 3 [a]	15 ± 2 [a]	17 ± 3	6	9
3.58	0	7 ± 2	9 ± 1	14 ± 4 [a]	14 ± 2 [a]	21 ± 2 [a]	9 ± 1	10	
	1.75	93 ± 2	91 ± 1	86 ± 4 [a]	86 ± 2 [a]	79 ± 3 [a]	91 ± 1	90	
3.64	0		91 ± 2	83 ± 12	56 ± 3 [a]		91 ± 2	61	
	1.75		9 ± 2	17 ± 12	44 ± 3 [a]		9 ± 2	39	
3.67	0	100	100	100	100		100	71	
	1.40	< 15	< 12		< 15		< 12	0	
	1.75	< 10	< 9		< 4		< 9	26	
	2.22	< 15	< 15		< 15		< 15	2	
	2.87	< 10	< 8		< 5		< 8	1	
3.93	0		87 ± 3	84 ± 6			86 ± 3	70	
	1.75		< 9	< 12			< 9	8	
	2.22		13 ± 3	16 ± 6			14 ± 3	22	
3.99	0		100				100		
4.06	1.40		54 ± 4	45 ± 5			50 ± 4		
	2.22		46 ± 4	55 ± 5			50 ± 4		
4.22	1.75	100	100	100			100		
4.40	0	31 ± 8	42 ± 4	55 ± 5			47 ± 6		
	1.75	69 ± 8	58 ± 4	45 ± 5			53 ± 6		
4.72	0	100	100				100		
4.83	0		75 ± 10				75 ± 10		
	3.18		25 ± 10				25 ± 10		
4.94	0		100				100		
5.02	0		100				100		
5.18	0		100				100		
5.25	1.40		100				100		
5.26	1.75		100				100		
5.39	0		100				100		
5.43	0		100				100		
5.73	1.75		100				100		
5.85	1.75	35 ± 2	35 ± 3				35 ± 2		
	3.58	65 ± 2	65 ± 3				65 ± 2	88	
5.99	3.58		34 ± 5				34 ± 5	12	
	3.64		14 ± 3				14 ± 3		
	4.22		52 ± 5				52 ± 5		

[a] The adopted values are the average except in the cases where the values obtained with NaI (Refs. 2–4) are too diferenent from the more recent Ge(Li) works (Ref. 9, present work).
[b] Shell model calculation from Ref. 16.
[c] Shell model calculations in a truncated space from Ref. 7.

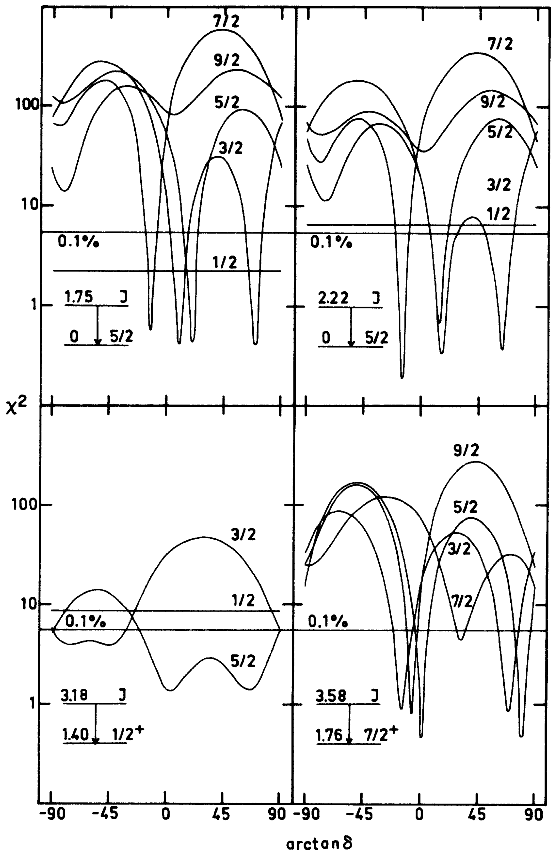

FIG. 2. The χ^2 fits of the angular correlation data for different transitions from the 1.75, 2.22, 3.18, and 3.58 MeV levels.

values. Accepted solutions are within two standard deviations of the experimental results.

1.75 MeV level

In Fig. 3 are shown the spectra obtained in coincidence with proton groups feeding the three first excited states. At the $E_\alpha = 14.25$ MeV bombarding energy only the state of 1.75 MeV is fed sufficiently to allow polarization measurements. Previous measurements[2-4] concluded in possible $J = \frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ spin values for this level. During completion of the present work new limitations to $\frac{7}{2}^+$ or $\frac{3}{2}^+$ appeared.[8,9] The present result, $J^\pi = \frac{7}{2}^+$, is thus in agreement with previous conclusions.

2.22 and 3.18 MeV levels

The bombarding energy was chosen in order to provide a good yield for the 1.75 and 3.58 MeV states and also to favor the excitation of the 3.18 MeV level over that of the nearby 3.07 MeV level. The γ-ray lines occurring in Fig. 3 in coincidence with protons arise from the 3.18 MeV level. The

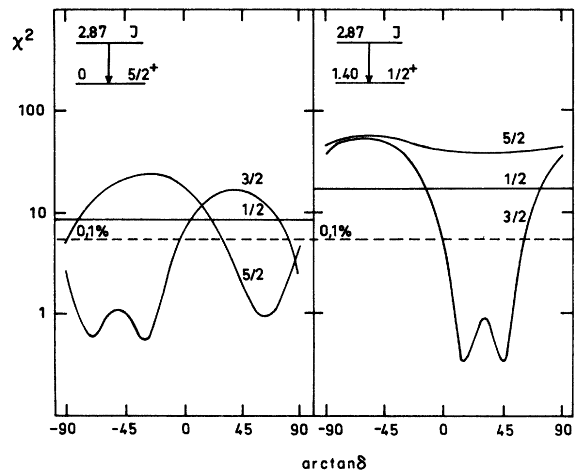

FIG. 3. The χ^2 fits of the angular correlations for the γ rays of 2.87 and 1.47 MeV emitted by the 2.87 MeV level.

measured linear polarization of the 0.96 MeV γ-ray line connecting the 3.18 MeV level to the 2.22 MeV level determines the spin values which were previously reported as $\frac{5}{2}$ or $\frac{3}{2}$ and $\frac{7}{2}$, $\frac{5}{2}$, or $\frac{3}{2}$, respectively. The deduced values $J^\pi = \frac{5}{2}^+$ for the 3.18 MeV level and $\frac{3}{2}^+$ for the 2.22 MeV level are in agreement with the recent measurements.[8,9]

3.58 MeV level

The spin value of the 1.75 MeV level (determined here as $\frac{7}{2}^+$) restricted the possible spin values of the 3.58 MeV level, which has positive parity, to $\frac{5}{2}^+$, $\frac{7}{2}^+$, or $\frac{9}{2}^+$ because a quadrupole transition would require an $E2$ enhancement of 190. The value of the linear polarization measured for the transition of 1.83 MeV deexciting this level to the 1.75 MeV excited state then leads to an assignment of $J^\pi = \frac{9}{2}^+$ for this level.

4.22 MeV level

Spin values of $\frac{3}{2}^+$ or $\frac{5}{2}^+$ have been assigned to this level.[2] This level decays 100% to the 1.75 MeV level whose spin has been determined here to be $\frac{7}{2}^+$. A $\frac{3}{2}^+$ spin assignment would require an improbably strong $M3$ component[9] and thus $J^\pi = \frac{5}{2}^+$ can be assigned to the 4.22 MeV level.

5.85 MeV level

This level decays 65% to the 3.58 MeV level and 35% to the 1.75 MeV level. The assignments $\frac{7}{2}^+$ and $\frac{9}{2}^+$, respectively, attributed to the 1.75 and 3.58 MeV excited states and the angular correlation results limit the possible spin value of the 5.85 MeV level to $\frac{7}{2}$, $\frac{9}{2}$, or $\frac{11}{2}$. The value $J^\pi = \frac{9}{2}^-$

TABLE III. Mixing ratios of transitions from ^{29}Al levels.

(MeV)	(MeV)	J_i^π	J_f^π	Present work	Ref. 9	Ref. 2-4 [a]	Mixing ratios Average	Theor. [b]	Theor. [c]
1.75	0	$\frac{7}{2}^+$	$\frac{5}{2}^+$	-0.21 ± 0.03	-0.15 ± 0.02	-0.23 ± 0.03	-0.18 ± 0.03	-0.18	-0.26
2.22	0	$\frac{3}{2}^+$	$\frac{5}{2}^+$	0.27 ± 0.08	0.15 ± 0.04	$0.14<\delta<0.53$	0.18 ± 0.04	0.39	0.42
				$2.0\ \pm0.5$	$2.7\ \pm0.3$	$1.2\ <\delta<2.6$	$2.4\ \pm0.3$		
2.87	0	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$-8.1<\delta<0.14$		-0.47 ± 0.17	-0.47 ± 0.17	-1.4	0.71
				χ^2min at $=-0.36$		$-4.1\ \pm2.2$	$-4.1\ \pm2.2$		
				or -3.08					
	1.40		$\frac{1}{2}^+$	$0.09<\delta<1.38$	$0.09<\delta<1.6$	0.02 ± 0.09	$0.09<\delta<1.4$ [d]	0.04	-0.34
				χ^2min at $\delta=0.27$	χ^2min at $\delta=0.28$	$1.7\ \pm0.4$	χ^2min at $\delta=0.27$		
				or 1.00	or 1.10		or 1.05		
3.06	0	$\frac{5}{2}^+$	$\frac{5}{2}^+$			0.41 ± 0.25	0.41 ± 0.25	0.12	0.19
						$\delta<-1.9$	-1.9		
	1.75		$\frac{7}{2}^+$		-0.08 ± 0.04	-0.05 ± 0.13	-0.08 ± 0.04	-0.07	-0.05
3.18	1.40	$\frac{5}{2}^+$	$\frac{1}{2}^+$	0.08 ± 0.30	0.07 ± 0.08		0.07 ± 0.08		
	1.75		$\frac{7}{2}^+$	-0.36 ± 0.14	-0.23 ± 0.07	-0.14 ± 0.40	-0.25 ± 0.06	-0.28	0.72
	2.22		$\frac{3}{2}^+$	-0.04 ± 0.02	-0.02 ± 0.02	-0.07 ± 0.06	-0.03 ± 0.02	-0.09	-0.11
3.58	0	$\frac{9}{2}^+$	$\frac{5}{2}^+$	0.15 ± 0.30	0.03 ± 0.09		0.03 ± 0.09		
	1.75		$\frac{7}{2}^+$	-0.09 ± 0.02	-0.10 ± 0.02		-0.10 ± 0.02	-0.14	
3.64	0	$(\frac{5}{2}^+)^e$	$\frac{5}{2}^+$		0.10 ± 0.08		0.10 ± 0.08	-0.02	
					$-2.3\ \pm0.9$		$-2.3\ \pm0.9$		
3.93	0	$(\frac{7}{2}^+)^e$	$\frac{5}{2}^+$		0.23 ± 0.09	0.31 ± 0.07	0.28 ± 0.06	0.76	
					$2.2\ \pm0.6$		$2.2\ \pm0.6$		
4.06	1.40	$(\frac{3}{2}^+)^f$	$\frac{1}{2}^+$		-0.16 ± 0.06	-0.34 ± 0.20	-0.17 ± 0.06		
					$2.6\ \pm0.5$		$2.6\ \pm0.5$		
	2.22		$\frac{3}{2}^+$		0.37 ± 0.10		0.37 ± 0.10		
					$\lvert\delta\rvert>4$		$\lvert\delta\rvert>4$		
4.22	1.75	$\frac{5}{2}^+$	$\frac{7}{2}^+$	0.01 ± 0.09	0.02 ± 0.02		0.02 ± 0.02		
				$5.6\ \pm2.0$	$6.0\ \pm1.0$		$5.9\ \pm0.9$		
5.85	1.75	$(\frac{11}{2}^+)^g$	$\frac{7}{2}^+$	0.00 ± 0.20	0.03 ± 0.10		0.02 ± 0.09		
	3.58		$\frac{9}{2}^+$	-0.10 ± 0.04	-0.08 ± 0.03		-0.09 ± 0.03		0.70
5.99	3.58	$\frac{7}{2}^+$	$\frac{9}{2}^+$		-0.02 ± 0.12		-0.02 ± 0.12		
					$\lvert\delta\rvert>3$		$\lvert\delta\rvert>3$		
	4.22		$\frac{5}{2}^+$		-0.14 ± 0.04		-0.14 ± 0.04		
					$\lvert\delta\rvert>13$		$\lvert\delta\rvert>13$		

[a] Average values from values determined with NaI counters in Refs. 2–4.
[b] Shell model calculations from Ref. 16.
[c] Shell model calculations with a truncated space from Ref. 7.
[d] For the choice of the average see text.
[e] Also possible $J^\pi=\frac{3}{2}^+$.
[f] Also possible $J=\frac{1}{2}$.
[g] Also possible $J^\pi=\frac{9}{2}^+, \frac{7}{2}^+, \frac{7}{2}^-$.

is very improbable[11] because the transition to the 3.58 MeV level ($\delta=0.70\pm0.19$) would require an $M2$ enhancement of 390 ± 130. The polarization measurement, which rejected the $J^\pi=\frac{11}{2}^-$ value, is not able to discriminate unambiguously between the remaining J^π values, but the value is in good agreement with $J^\pi=\frac{11}{2}^+$ suggested by the decay mode of this level. Another argument for this J^π value can be found in the fact that this level is seen strongly in the ^{26}Mg$(\alpha,p)^{29}$Al reaction at 14.2 MeV, as are the 1.75 MeV ($J^\pi=\frac{7}{2}^+$) and the 3.58 MeV ($J^\pi=\frac{9}{2}^+$) levels which can all be attributed to the ground state rotational band.

5.99 MeV level

The decay of this level has been studied by Ekström and Tillmann,[9] who concluded $J^\pi=\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$. They show also that an assumption $J^\pi(3.58)=\frac{9}{2}^+$ requires $J^\pi(5.99)=\frac{7}{2}^+$. The spin of

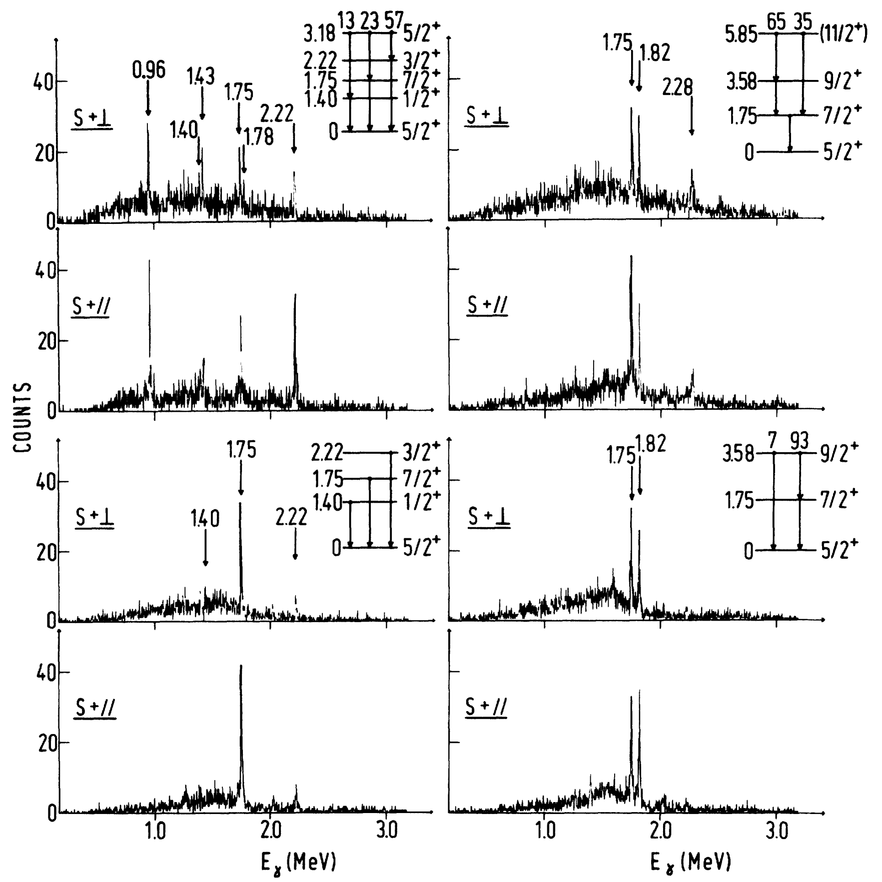

FIG. 4. Spectra of the summed scatterer-plus-horizontal and scatterer-plus-vertical detectors of the polarimeter measured in coincidence with several proton groups feeding ^{29}Al excited states through the ^{26}Mg$(\alpha,p)^{29}$Al reaction.

the 3.58 MeV having been fixed here as $\frac{9}{2}^+$, then a value $J^\pi = \frac{7}{2}^+$ can be assigned to the 5.99 MeV level.

IV. SUMMARY AND DISCUSSION

The simultaneous measurement of angular correlations and γ polarizations with Ge(Li) detectors has been able to fix the spins of the 1.75, 2.22, 3.18, and 3.58 MeV levels which were not known at the beginning of this work. During the analysis two papers have appeared[8,9] which assign spins for the 2.22 and 3.18 MeV levels in agreement with our results. Our results for the 1.75 and 3.58 MeV levels, in conjunction with the data reported by Ekström and Tillmann,[9] determine the spins of the 4.22 and 5.99 MeV levels to be $\frac{5}{2}^+$ and $\frac{7}{2}^+$, respectively.

The excitation energies, branching ratios, and mixing ratios measured here are compared to previous measurements and are found to be in good agreement with recent data[9] also measured with Ge(Li) detectors.

The decay scheme of ^{29}Al has been discussed previously in terms of the Nilsson model[2,4] and of a shell model calculation in a truncated $1d_{5/2}2s_{1/2}1d_{3/2}$ configuration space.[7,10] We notice that with a phenomenological model, such as the Nilsson model, the authors of previous works[2,4] have been able to successfully predict the spins of the 1.75, 2.22, 3.18, and 3.58 MeV levels.

Energy spectra and mixing ratios, especially for the ground state rotational band $[E_x = 0(\frac{5}{2}^+)$, $1.76(\frac{7}{2}^+)$, $3.58(\frac{9}{2}^+)$ and perhaps $5.85(\frac{11}{2}^+)]$, seem to be best fitted by a prolate deformation of ^{29}Al, whereas ^{29}Si and ^{29}P have an oblate deformation.[13,14] In this framework a reasonable similarity is seen between ^{25}Al and ^{29}Al as concerns the properties of the ground state rotational band ($\hbar^2/2J \sim 0.38$ MeV in both cases, with a small contribution from the vibrational rotational interaction, in contrast to ^{27}Al), and also for the $|M(E2)|^2$ value [4 W.u. (Weisskopf units)] of the $E2$ transition from the first $J^\pi = \frac{1}{2}^+$, $K = \frac{1}{2}^+$ state to the ground state $J^\pi = \frac{5}{2}^+$, $K = \frac{5}{2}^+$.[1]

TABLE IV. The measured polarizations as compared to the polarizations calculated from the measured angular correlations and the deduced ^{29}Al level spin values.

E_{xi} (MeV)	E_{xf} (MeV)	A_2 (Measured)	J_i^π	J_f^π	Polarization ($\theta=90°$) Predicted	Measured	Deduced
1.75	0	0.07 ± 0.03	$\frac{7}{2}^+$	$\frac{5}{2}^+$	-0.71 ± 0.03	-0.63 ± 0.15	$J_i^\pi=\frac{7}{2}^+$
			$\frac{5}{2}^+$	$\frac{5}{2}^+$	$+0.76\pm 0.03$		
			$\frac{3}{2}^+$	$\frac{5}{2}^+$	-0.26 ± 0.03		
3.18	2.22	-0.32 ± 0.05	$\frac{5}{2}^+$	$\frac{3}{2}^+$	-0.54 ± 0.03	-0.56 ± 0.25	$J_i^\pi=\frac{5}{2}^+$
				$\frac{5}{2}^+$	$+0.42\pm 0.05$		$J_f^\pi=\frac{3}{2}^+$
				$\frac{7}{2}^+$	-0.11 ± 0.03		
			$\frac{3}{2}^+$	$\frac{3}{2}^+$	$+0.68\pm 0.02$		
				$\frac{5}{2}^+$	-0.04 ± 0.02		
3.58	1.75	-0.12 ± 0.04	$\frac{9}{2}^+$	$\frac{7}{2}^+$	-0.55 ± 0.03	-0.61 ± 0.20	$J_i^\pi=\frac{9}{2}^+$
			$\frac{7}{2}^+$	$\frac{7}{2}^+$	$+0.47\pm 0.05$		
			$\frac{5}{2}^+$	$\frac{7}{2}^+$	-0.21 ± 0.03		
5.85	3.58	-0.09 ± 0.07	$\frac{11}{2}^+$	$\frac{9}{2}^+$	-0.54 ± 0.03	-0.58 ± 0.60	$J_i^\pi=\frac{11}{2}^+$,
			$\frac{11}{2}^-$	$\frac{9}{2}^+$	$+0.54\pm 0.03$		$(\frac{9}{2}^+, \frac{7}{2})$
			$\frac{9}{2}^+$	$\frac{9}{2}^+$	$+0.35\pm 0.09$		
			$\frac{7}{2}^+$	$\frac{9}{2}^+$	-0.26 ± 0.03		
			$\frac{7}{2}^-$	$\frac{9}{2}^+$	$+0.26\pm 0.03$		

The comparison of the decay scheme of ^{29}Al to the shell model calculation of de Voigt *et al.*[7] is discussed in detail elsewhere.[9] We still notice difficulties similar to those we had in ^{29}P (Ref. 14) in attempting an explanation of the energy spectra and the values of some branching and mixing ratios.

More recently, Cole, Watt, and Whitehead[15] calculated the even parity spectrum by use of the Preedom-Wildenthal interaction in the full *s-d* basis. Their results seem to agree quite well with the present results, especially for the spins of the 1.76 and 2.22 MeV levels for which the truncated shell model predicts an inversion in the order of spin values. For the higher excited states the order of the levels seems to be well reproduced, although the calculated energy scale seems to be systematically a little too large. In proof these authors have published another paper[16] which gives the lifetimes, branching ratios and mixing ratios calculated with this model. These data have been included in Tables II–IV for comparison with the experimental results; in general the agreement is very good.

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