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A study of the principal decay modes and lifetimes of levels in ^{29}Si below 7·2 MeV

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Abstract. The principal decay modes and lifetimes of levels populated in the reaction ^{26}Mg(α, n)^{29}Si have been studied. Lifetimes were measured by the Doppler shift attenuation method at beam energies of 5·0, 6·75, 8·0 and 9·25 MeV. There is good agreement with previous results and two new lifetimes of 20 ± 8 fs for the 5813 keV level and 47 ± 14 fs for the 7016 keV level have been measured. Thirteen new lifetime limits have also been obtained. The lifetime limit of the 5653 keV level restricts its spin to $9/2^+$. This level, and that at 7139 keV, are proposed as the $9/2^+$ and $11/2^+$ members of the $K^\pi = 3/2^+$ rotational band, and evidence is presented for the inclusion of the 6781 keV level in the $K^\pi = 7/2^-$ band.

1. Introduction

Attempts to describe ^{29}Si by shell model or vibration–particle coupling schemes (Baker and Segel 1968, Glaudemans *et al* 1964, Bailey and Choudhury 1970 and Castel *et al* 1970) have had poor results despite the fact that the nucleus consists of one neutron outside the closed $d_{5/2}$ subshell of ^{28}Si. The rotational model approach, initially employed by Bromley *et al* (1957), has had more success and is being increasingly used (Bardin *et al* 1970a, Main *et al* 1970, Pilt *et al* 1971 and Spear *et al* 1971) as a description of ^{29}Si. For the accuracy of these various models to be assessed, it is necessary to have more experimental information on the nuclear energy levels above 3·5 MeV. It was to this end that the present lifetime measurements were directed.

2. Experimental method

The main details of the experimental apparatus and the Doppler shift attenuation method used in the present experiment have been described elsewhere (Alderson and Dawson 1970, Durell *et al* 1972 and Sharpey-Schafer *et al* 1971). In the present experiment the target consisted of 1000 ± 100 μg cm^{-2} of magnesium evaporated onto a thick gold backing. The magnesium was enriched to 99·5% ^{26}Mg. States in ^{29}Si were populated by the reaction ^{26}Mg(α, n)^{29}Si ($Q = 0·033$ MeV) at beam energies between 4·5 and 9·5 MeV.

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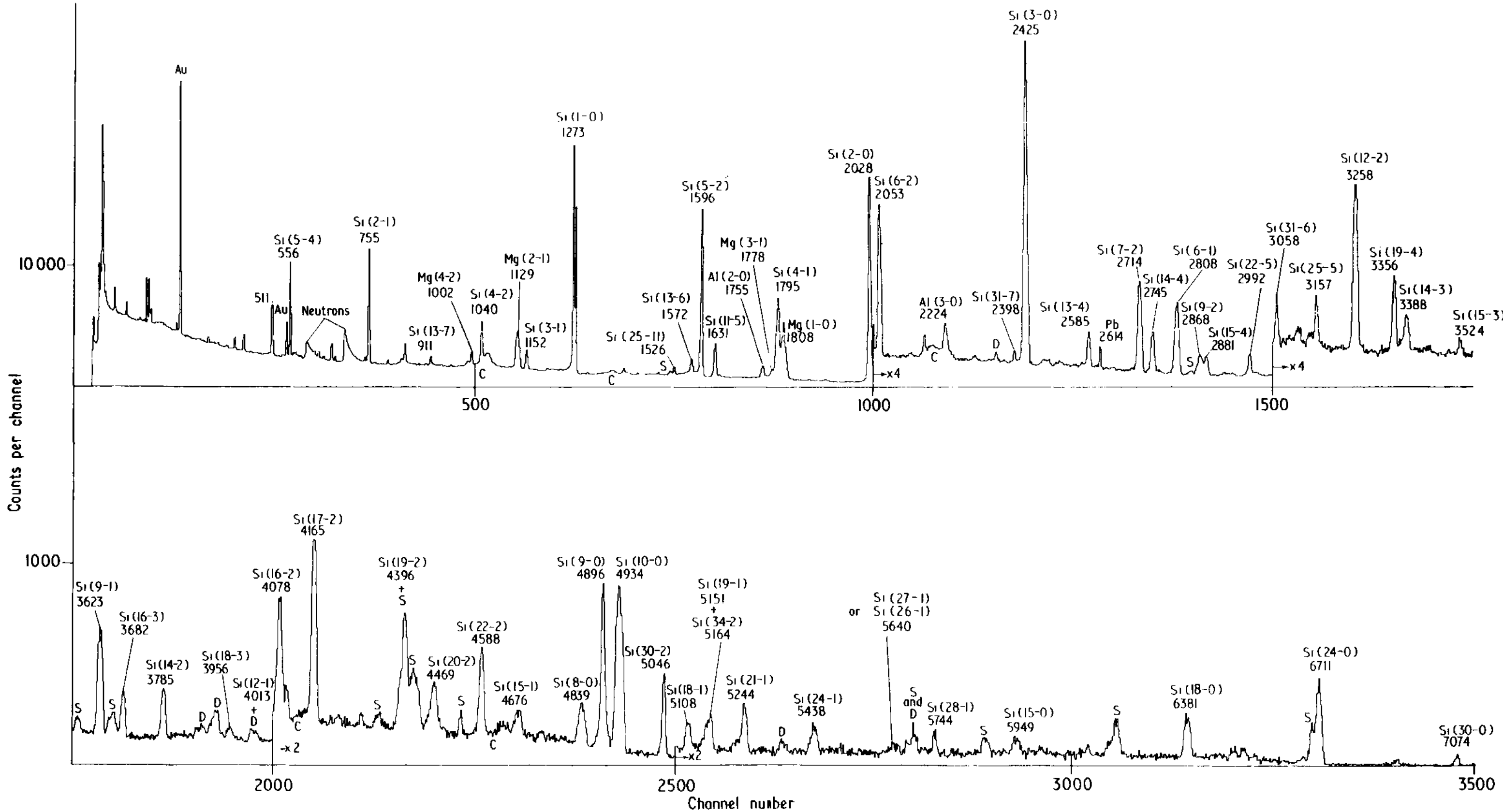

Figure 1. Escape suppressed spectrum of γ rays from the reaction $^{26}Mg(\alpha, n)^{29}Si$, E_α = 8·5 MeV, θ = 90°. The γ rays from ^{26}Mg, ^{29}Si and ^{29}Al are labelled with their corresponding transition and energy in keV. C, S and D indicate Compton edge, single escape and double escape peak respectively. All unlabelled peaks have been identified as contaminant γ rays arising from (α, α') and (n, n′) reactions in the chamber or detector assemblies.

The detector system was calibrated for energy and efficiency using γ rays from a ^{56}Co source, the energies and intensities being taken from the work of Scott and Van Patter (1969). The decay scheme of ^{29}Si was deduced from the γ ray energies and thresholds measured in a 0·5 MeV step excitation study. Data taken at angles of 55° and 125° to the beam direction were used to calculate branching ratios.

Centroid positions of γ ray lines were measured at angles (θ) of 0°, 55°, 70°, 90°, 110° and 125° and at beam energies of 5·0, 6·75, 8·0 and 9·25 MeV. F factors were obtained by linear least squares fits to these centroid positions against cos θ data.

3. Results

A typical escape suppressed spectrum, obtained at 90°, is reproduced in figure 1. Figure 2 shows the decay scheme of levels below 6·8 MeV deduced from present and previous work (Endt and van der Leun 1967, Meyer-Schützmeister *et al* 1969, Bardin *et al*

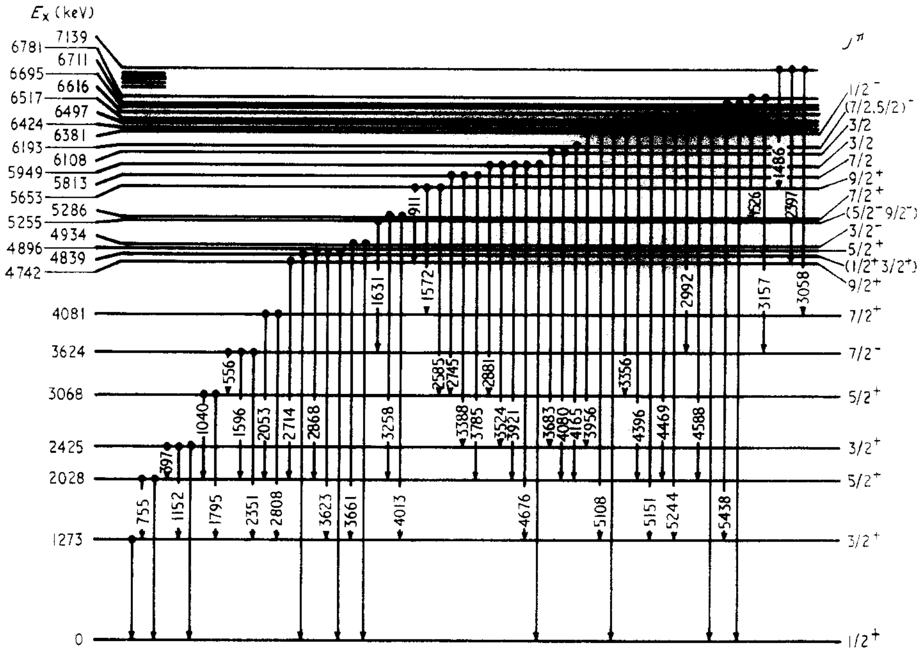

Figure 2. Decay scheme of levels in ^{29}Si observed in the present work, with additional data from references (Endt and van der Leun 1967, Meyer-Schützmeister *et al* 1969, Bardin *et al* 1970b, Dehnhard and Yntema 1970 and Main *et al* 1970).

1970b, Dehnhard and Yntema 1970 and Main *et al* 1970), and figure 3 comprises a representative selection of centroid against cos θ plots. Table 1 lists the level energies, branching ratios, F factors and lifetimes measured in the present experiment. The errors on the lifetimes quoted in column 7 of table 1 represent only those errors associated with the measurement of the F factors. There is an additional uncertainty in the conversion of F factors into lifetimes due to lack of full knowledge of the stopping theory involved. This uncertainty is taken as $\pm 25\%$ and is quoted separately.

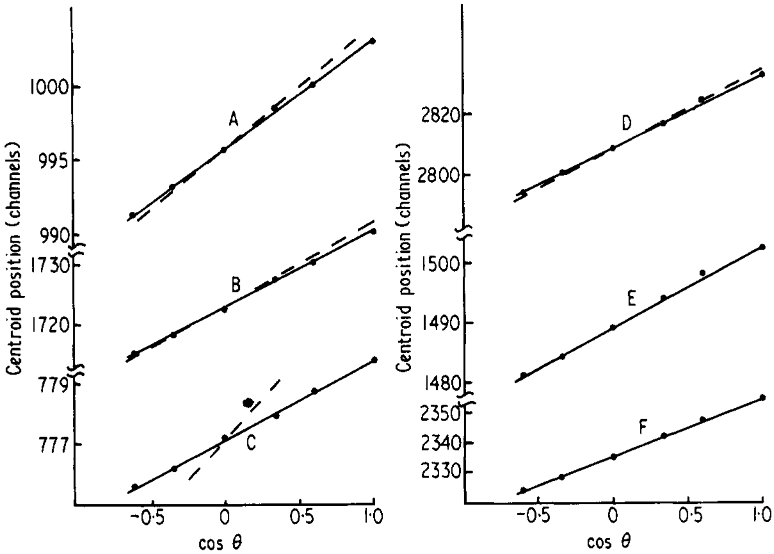

Figure 3. Centroid position against $\cos\theta$ plots of some γ rays from ^{29}Si. Least squares fits to the data are shown as full lines. Broken lines represent theoretical full shifts. The dispersion for the data taken at beam energies 5·0, 6·75 and 8·0 MeV is 1·61 keV per channel, while for the 9·25 MeV data it is 2·04 keV per channel. A 5255 keV state, E_γ = 1631 keV, F = 0·888 ± 0·013, E_α = 8·0 MeV; B 4081 keV state, E_γ = 2808 keV, F = 0·936 ± 0·019, E_α = 6·75 MeV; C 1273 keV state, E_γ = 1273 keV, F = 0·493 ± 0·016, E_α = 5·0 MeV; D 7016 keV state, E_γ = 5743 keV, F = 0·941 ± 0·016, E_α = 9·25 MeV; E 7139 keV state, E_γ = 3058 keV, F = 0·977 ± 0·024, E_α = 9·25 MeV; F 5813 keV state, E_γ = 3785 keV, F = 0·964 ± 0·012, E_α = 8·0 MeV.

Lifetimes of the first eleven levels have been measured previously by many authors (Booth and Wright 1962, Retz-Schmidt *et al* 1964, Baker and Segel 1968, Wozniak *et al* 1969, DeKock *et al* 1970, Fisher *et al* 1970 and McDonald *et al* 1970). In general these results, listed in table 2, agree well with the present experiment. Beyond level 11, two lifetimes have been obtained in the present work, the other thirteen measurements yielding lifetime limits.

4. Discussion

4.1. The $K^\pi = 3/2^+$ band

Two new rotational band members are proposed on the basis of their energies, decay modes and transition strengths. The level at 5653 keV excitation has been observed (Dawson *et al* 1970, private communication) to decay to levels at 4081 keV and 3068 keV and to have a spin of 5/2 or 9/2. In the present work a decay (E_γ = 911 keV) to the 4742 keV level ($J^\pi = 9/2^+$) was also seen. The lifetime limit for the 5653 keV level of less than 20 fs enables the spin of this level to be restricted to $9/2^+$ on the grounds of the large transition strengths implied by the other three spin and parity possibilities. An assignment of $J^\pi = 5/2^+$ requires the 911 keV transition to have an E2 strength of greater than 1475 Weisskopf single particle units (Wu). The pure E3 or M2 strengths for the same transition, assuming $J^\pi = 5/2^-$, are $>4\times10^8$ Wu and $>4{\cdot}5\times10^4$ Wu

Table 1. Energies, branching ratios, F factors and lifetimes of levels in ^{29}Si measured in the present experiment

Level	E_x (keV)	Transition	Branching ratio† (%)	E_α (MeV)	F	τ_{mean}‡ (fs)
1	1273·2 ± 0·2	1–0	100	5·0	0·493 ± 0·016	470 ± 35§
2	2028·2 ± 0·2	2–0	95 ± 1	5·0	0·479 ± 0·018	490 ± 40§
		2–1	5 ± 1		0·625 ± 0·109	
3	2425·5 ± 0·3	3–0	87 ± 1	5·0	0·943 ± 0·033	29 ± 11
		3–1	13 ± 1		1·019 ± 0·080	
		3–2	*			
		3–0		6·75	0·957 ± 0·026	
		3–1			0·953 ± 0·023	
4	3067·5 ± 0·6	4–1	87 ± 2	5·0	0·922 ± 0·032	20^{+25}_{-10}§
		4–2	13 ± 2		‖	
5	3624·2 ± 0·4	5–1	2 ± 1	5·0	‖	4200 ± 500§
		5–2	90 ± 1		0·109 ± 0·023	
		5–4	8 ± 1		0·154 ± 0·287	
		5–2		6·75	0·085 ± 0·016	
		5–4			0·125 ± 0·021	
6	4081·3 ± 0·5	6–1	73 ± 2	5·0	0·892 ± 0·069	40 ± 8
		6–2	27 ± 2		1·014 ± 0·073	
		6–1		6·75	0·936 ± 0·019	
		6–2			0·940 ± 0·016	
		6–1		8·0	0·930 ± 0·017	
		6–2			0·981 ± 0·025	
7	4741·9 ± 0·5	7–2	100	6·75	0·953 ± 0·018	33 ± 10
		7–2		8·0	0·950 ± 0·018	
8	4839 ± 2	8–0	100	6·75	1·066 ± 0·030	< 10
		8–0		8·0	0·980 ± 0·016	
9	4896·1 ± 0·7	9–0	25 ± 3	6·75	1·008 ± 0·024	< 10
		9–1	42 ± 4		1·011 ± 0·020	
		9–2	33 ± 3		1·010 ± 0·020	
		9–0		8·0	0·997 ± 0·029	
		9–1			0·972 ± 0·016	
		9–2			¶	
10	4933·9 ± 1·0	10–0		6·75	1·036 ± 0·023	< 10
		10–1	¶		¶	
		10–0		8·0	0·997 ± 0·020	
11	5255·1 ± 0·5	11–5	100	6·75	0·917 ± 0·022	80 ± 10
		11–5		8·0	0·888 ± 0·013	
12	5286·0 ± 0·5	12–1	19 ± 4	6·75	1·023 ± 0·027	< 10
		12–2	81 ± 4		1·010 ± 0·019	
13	5652·9 ± 0·7	13–4	41 ± 2	6·75	0·985 ± 0·020	< 20
		13–6	47 ± 2		0·948 ± 0·018	
		13–7	12 ± 2		1·002 ± 0·063	
		13–4		8·0	1·027 ± 0·031	
		13–6			0·973 ± 0·026	
		13–7			1·031 ± 0·055	
14	5813·3 ± 0·5	14–2	28 ± 3	8·0	0·964 ± 0·012	20 ± 8
		14–3	30 ± 3		0·960 ± 0·019	
		14–4	42 ± 4		0·995 ± 0·018	
15	5949·2 ± 0·7	15–0		8·0	1·013 ± 0·030	< 15
		15–1			1·000 ± 0·026	
		15–2	¶		¶	
		15–3			0·954 ± 0·047	
		15–4	¶		¶	

Table 1.—continued

Level	E_x (keV)	Transition	Branching ratio† (%)	E_α (MeV)	F	τ_{mean}‡ (fs)
16	6107·6 ± 0·8	16–2	79 ± 1	8·0	0·985 ± 0·015	< 20
		16–3	21 ± 1		0·981 ± 0·017	
17	6193 ± 2	17–2	100	8·0	0·984 ± 0·013	< 20
18	6381 ± 2	18–0	30 ± 10	8·0	1·019 ± 0·036	< 10
		18–1	45 ± 10		1·025 ± 0·086	
		18–3	25 ± 10		‖	
19	6424·0 ± 0·5	19–1		8·0	‖	< 20
		19–2	¶		¶	
		19–4			0·997 ± 0·024	
20	6496·7 ± 0·6	20–2	100	8·0	0·987 ± 0·033	< 35
		20–2		9·25	0·965 ± 0·072	
21	6517 ± 4	21–1	100	8·0	1·002 ± 0·028	< 15
		21–1		9·25	1·013 ± 0·036	
22	6616·2 ± 0·7	22–2	73 ± 2	8·0	0·975 ± 0·020	< 35
		22–5	27 ± 2		0·979 ± 0·041	
24	6711 ± 2	24–0	¶	9·25	¶	< 90
		24–1			0·937 ± 0·046	
25	6781·4 ± 0·7	25–5	40 ± 5	9·25	1·004 ± 0·044	< 10
		25–11	60 ± 5		1·038 ± 0·046	
28	7016 ± 3	28–0	14 ± 10	9·25	0·846 ± 0·082	47 ± 14
		28–1	86 ± 10		0·941 ± 0·016	
31	7139·3 ± 0·8	31–6	60 ± 10	9·25	0·977 ± 0·024	< 40
		31–7	20 ± 10		0·996 ± 0·040	
		31–13	20 ± 10		0·905 ± 0·040	

† Branching ratio results are averages of data taken at the beam energies listed.
‡ The lifetimes quoted in this column are weighted averages of the lifetimes measured at the beam energies listed. The errors quoted do not contain any estimate of the systematic uncertainty in the conversion of F factors to lifetimes due to uncertainties in the slowing down theory. This uncertainty is taken as ±25 %.
§ Lifetimes corrected for feeding from higher excited states.
* The transition 3–2, not observed in the present work, was seen by Harris *et al* (1969) as a 0·4 % branch.
‖ γ ray was too weak for measurement to be made.
¶ Measurements are unreliable because γ rays were not resolved.

respectively. Finally, for $J^\pi = 9/2^-$, the decay to the 3068 keV level ($J^\pi = 5/2^+$) would have pure E3 and M2 strengths of $> 9 \times 10^5$ Wu and > 840 Wu respectively.

The 5653 keV level is a good candidate for the $9/2^+$ member of the $K^\pi = 3/2^+$ rotational band based on Nilsson orbit configuration $[1234567]^4$ [8]. The major part of its decay (see table 1) is to the $7/2^+$ and $5/2^+$ band members identified by Main *et al* (1970) and Pilt *et al* (1971).

Present work has also revealed a possible $11/2^+$ band member at 7139 keV. This level was observed to decay to the 5653 keV and 4081 keV levels and also to the $9/2^+$ member of the ground state ($K^\pi = 1/2^+$) band at 4742 keV. The plot of excitation energy against $J(J+1)$ (figure 4) for the $K^\pi = 3/2^+$ band strengthens the case for these two new assignments. Together with the three confirmed band members, they are fitted approximately by a straight line. This also tends to support the preliminary results of the calculations of Pilt *et al* (1971) which predict fairly weak Coriolis coupling

Table 2. Comparison of present lifetime results with previous work

Level (keV)	Lifetime measurements (fs)					
	Present	Previous				
		DSAM				Other methods
		Baker and Segel (1968)	Wozniak *et al* (1969)	Fisher *et al* (1970)	De Kock *et al* (1970)	
1273	470 ± 35	310^{+110}_{-80}	370^{+60}_{-50}	360 ± 70	560 ± 130	150 ± 50† 305 ± 105‡
2028	490 ± 40	370^{+90}_{-80}	370^{+70}_{-60}	360 ± 70	830 ± 260	
2425	29 ± 11	20 ± 7	$\leqslant 46$	20 ± 10	24 ± 14	20 ± 7†
3068	20^{+25}_{-10}	23 ± 11	$\leqslant 74$			
3624	4200 ± 500		4800^{+3000}_{-1500}	4000 ± 1000		3900 ± 500§
4081	40 ± 8		70 ± 20	45 ± 15		
4742	33 ± 10			45 ± 15		
4839	< 10		$\leqslant 13$	< 10		
4896	< 10			< 10		
4934	< 10			< 10		
5255	80 ± 10			100 ± 20		

† Resonance fluorescence method (Booth and Wright 1962).
‡ Resonance fluorescence method (Retz-Schmidt *et al* 1964).
§ Recoil distance method (McDonald *et al* 1970).

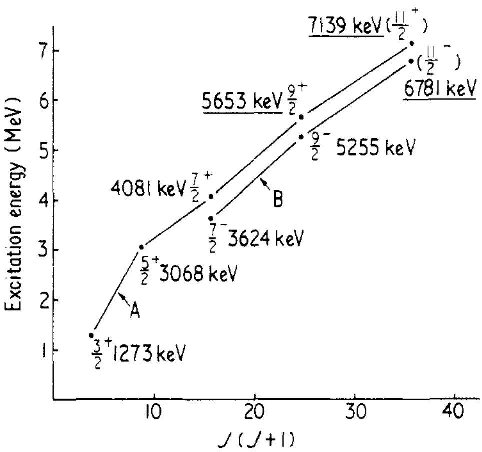

Figure 4. Plots of excitation energy against $J(J+1)$ for the (A) $K^\pi = 3/2^+$ and (B) $K^\pi = 7/2^-$ rotational bands in ^{29}Si. New band members, proposed in the present work, are underlined.

of this band with the ground state band. Transition strengths also indicate that the levels at 5653 keV and 7139 keV belong to the $K^\pi = 3/2^+$ band. The two pure E2 decays of these levels, with strengths of > 27 Wu and > 10 Wu respectively, are typical of the collective transitions found in this mass region.

4.2. *The* $K^\pi = 7/2^-$ *band*

Recently Bardin *et al* (1970a) measured the spin of the 5255 keV level to be $9/2^-$ and therefore proposed the states at 3624 keV ($7/2^-$) and 5255 keV as the first two members of the $K^\pi = 7/2^-$ band with Nilsson orbit configuration $[1234567]^4$ [10]. Main *et al* (1970) also obtained a spin of 9/2 for this level. Subsequently Spear *et al* (1971) remeasured the spin to be $5/2^-$ or $9/2^-$, and they throw doubt on the unique assignment of Bardin *et al.* Because of this confusion in the data interpretation it is important to try to establish the rotational nature of these levels by looking for higher band members.

The present experiment shows a state at 6781 keV which decays to those at 3624 and 5255 keV with branching ratios of $40 \pm 5\,\%$ and $60 \pm 5\,\%$ respectively. Assuming spins of $7/2^-$, $9/2^-$ and $11/2^-$ for these three states, a $J(J+1)$ plot (figure 4) produces an approximate linear relationship, and shows such a band to have a very similar moment of inertia to that of the $K^\pi = 3/2^+$ band. The assumption of a spin of $11/2^-$ for the 6781 keV level implies that the transition to the level at 3624 keV is pure E2 and has a strength of greater than 20 Wu. The other transition, to the 5255 keV level, is an unmeasured E2/M1 mixture. The pure E2 and M1 strengths of > 1120 Wu and $> 0{\cdot}54$ Wu respectively do not rule out the possibility of an enhanced E2 for this transition. Thus all the evidence so far supports the interpretation of the 5255 keV and 6781 keV levels as the second and third members of the $K^\pi = 7/2^-$ band.

5. Conclusions

This lifetime investigation has shown that most levels above 5 MeV decay too rapidly for DSAM measurement. However, the results obtained do support the description of ^{29}Si as a deformed rotator with a well developed band structure. It has been possible to produce evidence for the assignment of the 6781 keV and 7139 keV levels to rotational bands, but in order to obtain confirmation of this it will be necessary to measure the spins of these levels. Angular distribution data are at present being analysed in this laboratory with thc aim of measuring these two spins and checking the spin assignment of the 5653 keV level.

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