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LIFETIME MEASUREMENTS IN sd SHELL NUCLEI (VII). Mean lives of ^{27}Si and ^{27}Al levels

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Abstract: The mean lives and excitation energies of the lowest six levels of ^{27}Si were measured by means of the ^{28}Si(τ, $\alpha\gamma$)^{27}Si reaction. Coincidence Doppler-shift attenuation measurements lead to mean lives of $\tau_m = 2200 \pm 400$, 56 ± 12, 16 ± 8, < 10 and 79 ± 11 fs for the ^{27}Si levels at $E_x = 0.96$, 2.17, 2.65, 2.87 and 2.91 MeV, respectively. With the recoil-distance method applied to the ^{24}Mg(α, n)^{27}Si and ^{24}Mg(α, p)^{27}Al reactions, the mean lives of the 0.78 MeV level in ^{27}Si and the 0.84 MeV level in ^{27}Al were measured to be $\tau_m = 50 \pm 6$ ps and 48 ± 3 ps, respectively. Branchings were measured for the states at $E_x = 2.17$, 2.65, 2.87 and 2.91 MeV in ^{27}Si. From the presently known information it is possible to assign positive parity to the level at 2.17 MeV. The spectroscopic data on the $A = 27$ mirror nuclei are compared with the results of many-particle shell-model calculations.

E | NUCLEAR REACTIONS ^{28}Si(^{3}He, $\alpha\gamma$), $E = 8.2$ and 8.4 MeV; measured Doppler-shift attenuation. ^{27}Si deduced levels, $T_{\frac{1}{2}}$, J, π, γ-branchings. Natural target. ^{24}Mg(α, nγ), ^{24}Mg(α, pγ), $E = 10.4$ MeV; measured Doppler shift, recoil distance. ^{27}Si and ^{27}Al levels deduced $T_{\frac{1}{2}}$. Natural target.

1. Introduction

Presently, calculations of electromagnetic transition rates based on many-particle shell-model wave functions are carried out for the $A = 27$ nuclei [1]). Much spectroscopic information is available for ^{27}Al [refs. [2-7])]. For ^{27}Si, angular correlation measurements leading to spin assignments have been performed [8-11]), but the lifetimes of ^{27}Si levels were not known. The present work was undertaken to measure these lifetimes in order to compare corresponding γ-ray transition rates in the mirror nuclei ^{27}Al and ^{27}Si, and to relate them to corresponding β-transition strengths. Further, the experimental transition strengths can be used to check the above-mentioned many-particle shell-model calculations.

2. Experimental methods

2.1. THE DSA AND BRANCHING-RATIO MEASUREMENTS

The experimental set-up used for the DSA measurements has been described elsewhere [12]). Some details relevant to the present experiment are given here. The

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^{28}Si(τ, α)^{27}Si reaction was used to populate states of ^{27}Si. The τ-particles were accelerated with the Utrecht 6 MV tandem Van de Graaff generator. Two DSA experiments, each of 3.5 d, were performed with different targets and at different bombarding energies.

In the first experiment the τ-particles were accelerated to an energy of $E_\tau = 8.4$ MeV; the beam current was kept between 50 and 60 nA. The target consisted of 340 $\mu g \cdot cm^{-2}$ natural SiO_2 evaporated under vacuum onto a 200 $\mu g \cdot cm^{-2}$ C-foil. A 36 cm^3 Ge(Li) detector was located at $\theta_\gamma = 90°$ at a distance of 65 mm from the target. In the second experiment a target was used consisting of 100 $\mu g \cdot cm^{-2}$ natural Si evaporated onto a 200 $\mu g \cdot cm^{-2}$ C-foil. Gamma rays were detected with a 60 cm^3 Ge(Li) detector. The τ-particles were accelerated to an energy of $E_\tau = 8.2$ MeV; the beam current was 50 nA.

Alpha particles were detected with two 100 μm thick Si surface-barrier detectors at $\theta_\alpha = 70°$ and $-70°$ with respect to the beam. The γ-ray energy calibration was obtained with standard radioactive sources.

Branching ratios were measured by recording α-γ coincidences between an annular Si surface-barrier detector at $\theta_\alpha = 180°$ and a 60 cm^3 Ge(Li) detector at $\theta_\gamma = 125°$. The target consisted of 90 $\mu g \cdot cm^{-2}$ natural Si on a 20 $\mu g \cdot cm^{-2}$ C-backing.

Doppler shifts and branching ratios were measured simultaneously for all relevant levels by means of a CDC 1700 on-line computer system [13]).

2.2. THE RECOIL-DISTANCE MEASUREMENT

The mean lives of the first excited states of ^{27}Si and ^{27}Al were measured with the recoil-distance method at the Laboratori Nazionali di Legnaro (Padova, Italy). The experimental set-up has been described elsewhere [14]). The 0.78 MeV level in ^{27}Si and the 0.84 MeV level in ^{27}Al were populated with the ^{24}Mg(α, n)^{27}Si and ^{24}Mg(α, p)^{27}Al reactions, respectively. In both experiments doubly charged ^{4}He ions were accelerated to $E_\alpha = 10.4$ MeV by the Padova 5.5 MV Van de Graaff generator. The target consisted of 100 $\mu g \cdot cm^{-2}$ natural Mg on 2.5 $mg \cdot cm^{-2}$ Au. Gamma-rays were detected with a 40 cm^3 Ge(Li) detector at 4 cm distance from the target.

The γ-rays from the 0.78 MeV level of ^{27}Si were measured in a direct spectrum. Taking into account the energy loss in the Au foil one can calculate that the α-particles had an energy of 700 keV above the threshold for the 0.78 MeV level. Since the experimental full shift was 6.5 keV and the resolution of the detector was 3 keV FWHM, the shifted and unshifted peaks were well separated. The value of v/c was determined as $(8.5 \pm 0.4) \times 10^{-3}$ from the difference of the two peak positions measured with the Ge(Li) detector at 8 cm distance from the target. The γ-rays de-exciting the 0.84 MeV level of ^{27}Al were measured in a p-γ coincidence experiment. Protons were detected with an annular Si surface-barrier detector at 180° at 2 cm distance from the target. The value of v/c was determined in the same way as for ^{27}Si as $(13.1 \pm 0.3) \times 10^{-3}$. Since the experimental full shift was 11 keV and the resolution in the coincidence spectrum was about 5.5 keV FWHM also in this measurement the peaks were well separated.

3. Analyses of the data

3.1. THE DSA AND BRANCHING-RATIO DATA

The Doppler shifts were deduced from the peak centroids in the γ-ray spectra coincident with selected parts of the two α-particle spectra. The Compton continuum due to higher-energy γ-rays was subtracted. The $F(\tau_m)$ values defined as the ratio of the measured shift to the full shift are given in table 1. The $F(\tau_m)$ values have been corrected for the finite size of the detectors.

TABLE 1

Results of the DSA lifetime measurements in ^{27}Si

E_{xi} (keV)	E_{xf} (keV)	Target material	$F(\tau_m)$	τ_m(fs) this work	ref. [18]	ref. [19]
781±2	0	SiO_2	0.005±0.014	>12000	>8800	>5000
		Si	0.019±0.016			
958±2	0	SiO_2	0.169±0.018	2200±400	1760±200	2000±300
		Si	0.172±0.014			
2166±3	0	SiO_2	0.92 ±0.02	56± 12	53± 9	40± 20
		Si	0.917±0.015			
2650±3	0	Si	0.98 ±0.03	16± 8	37± 16	
	958	SiO_2	0.97 ±0.02			
		Si	0.974±0.012			
2869±3	0	SiO_2	0.98 ±0.04	<10	<15	
		Si	1.002±0.015			
2913±3	0	SiO_2	0.86 ±0.02	79± 11	75± 14	
		Si	0.893±0.015			

The attenuation curve was computed as described in ref. [15]. The quantity [15,16] ξ_e, extracted from experimental data on slowing-down of various ions in carbon [17], was found to be $\xi_e = 1.294+54\ v/c$; in the present experiments v/c was 0.010 to 0.011.

The uncertainty in the electronic stopping power was estimated to amount to 20 %. The influence of this uncertainty on the mean lives was evaluated by calculating attenuation curves for values of the electronic stopping power which were varied by ±20 %. The resulting error was added quadratically to the statistical error.

In the branching ratio measurement peak areas were computed as described in ref. [15]. A 10 % uncertainty in the relative efficiency of the detector was added quadratically to the statistical error.

3.2. THE RECOIL-DISTANCE DATA

The experimental results of the recoil-distance measurements are shown in fig. 1. The mean lives of the first excited states of ^{27}Si and ^{27}Al were deduced from least-squares fits of the data to the formula $I_s/(I_s+I_f) = \exp(-D/v\tau_m)$. Here I_s and I_f are the intensities of the γ-ray peaks emitted by nuclei decaying in the stopper and in flight, respectively, and D is the distance between target and stopper. Calculations yield $\tau_m = 50 \pm 6$ ps and 48 ± 3 ps for the 0.78 MeV level in ^{27}Si and the 0.84 MeV level in ^{27}Al, respectively. The loss of energy due to finite target thickness was accounted for by measuring v/c experimentally.

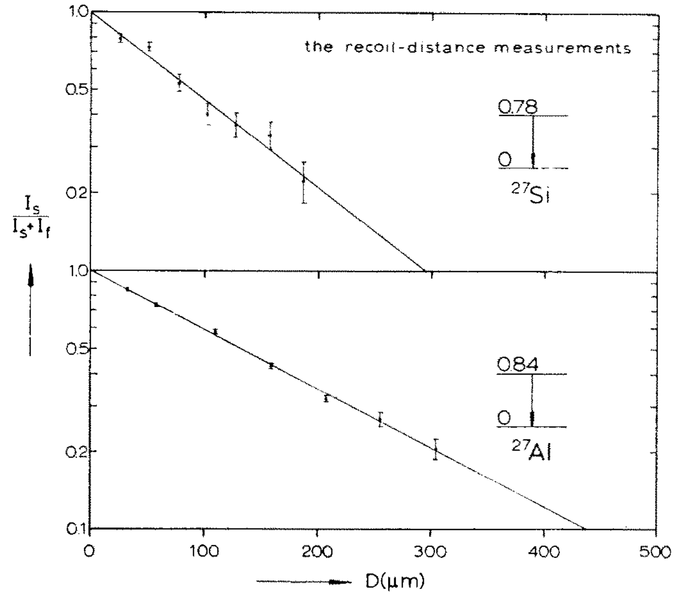

Fig. 1. The fraction of the shifted-peak intensity to the total peak intensity in the recoil-distance measurements as a function of the distance D.

4. Experimental results

4.1. EXCITATION ENERGIES, LIFETIMES AND BRANCHING RATIOS

The ^{27}Si excitation energies given in table 1 follow from the average of γ-ray energies measured in the DSA experiment. Fig. 2 shows parts of some γ-ray spectra measured in coincidence with α-particles. The result of the DSA lifetime measurements are summarized in table 1.

The measured branching ratios are shown in fig. 3. The branchings of the $0.96 \rightarrow 0.78$ and $2.65 \rightarrow 2.17$ MeV transitions were accidentally not measured. In fig. 3 is shown the limit of 1.5 % from ref. [9]) for the $0.96 \rightarrow 0.78$ MeV transition, but a value of 2 % is reported in ref. [18]).

4.2. SPIN AND PARITY ASSIGNMENTS

Spins and limits for spins of the lowest six levels in ^{27}Si have been determined previously from angular correlation measurements [8-11]).

The 2.17 MeV level has $J = \frac{7}{2}$ and the mixing ratio of the ground state transition is $\delta = 0.43 \pm 0.03$ [ref. [8])]. If the parity of this level were odd this transition would have an unreasonably strong M2 component of 280 ± 80 W.u., such that even parity can be assigned to this level.

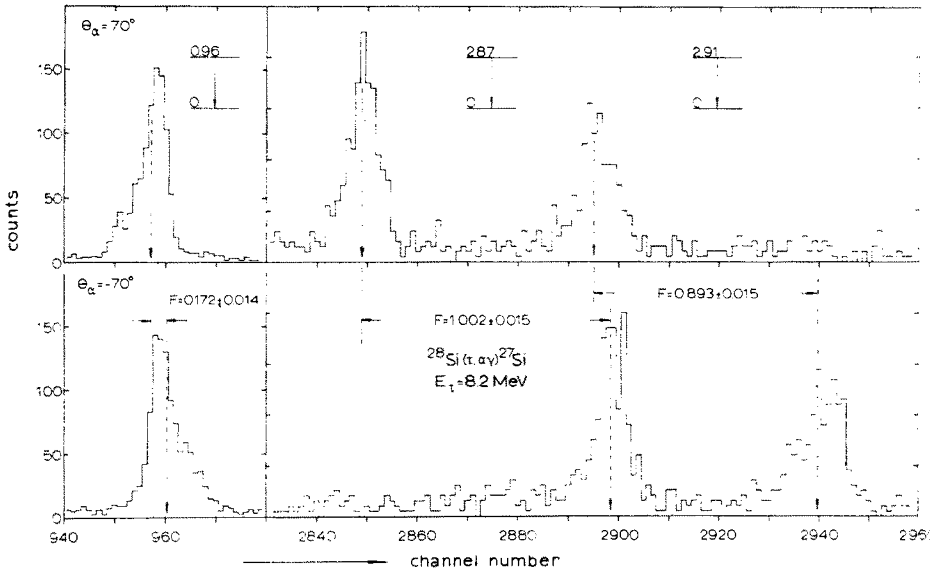

Fig. 2. The full-energy peaks of the $0.96 \to 0$, $2.87 \to 0$ and $2.91 \to 0$ MeV γ-ray transitions detected at $\theta_\gamma = 90°$ in coincidence with α-particles detected at $\theta_\alpha = +70°$ and $-70°$. The energy dispersion is 1.00 keV/channel.

The 2.87 MeV level has $J = (\frac{3}{2}-\frac{7}{2})$ [ref. [11])]. The (6 ± 3) % branch to the $J^\pi = \frac{1}{2}^+$ level at 0.78 MeV excludes $J^\pi = \frac{5}{2}^-$ because the M2 transition would have a strength of > 400 W.u. Similarly, $J = \frac{7}{2}$ is excluded by the measured mean life such that the 2.87 MeV level has $J^\pi = (\frac{3}{2}, \frac{5}{2}^+)$.

The 2.91 MeV level has $J = (\frac{3}{2}, \frac{5}{2}, \frac{9}{2})$ [ref. [11])]. The (7 ± 2) % branch to the $J^\pi = \frac{7}{2}^+$ state at 2.17 MeV excludes spin values below $\frac{5}{2}$. The ground state transition excludes $J^\pi = \frac{9}{2}^-$ because an M2 transition would have a strength of 280 ± 40 W.u., so the 2.91 MeV level has $J^\pi = (\frac{5}{2}, \frac{9}{2}^+)$.

The J^π assignment for the 2.87 MeV level is consistent with $^{28}Si(p, d)^{27}Si$ measurements by Jones *et al.* [20]), who found an $l_n = 2$ component for the (unresolved) transition to the 2.87 and 2.91 MeV doublet.

5. Discussion

5.1. THE DSA LIFETIME MEASUREMENT

The results of the DSA lifetime measurement are in good agreement with results of recent measurements by Weaver *et al.* [18]) and Hagen *et al.* [19]), which are given in table 1. The largest difference in lifetimes exists for the $E_x = 2.65$ MeV level but the values differ less than the combined errors.

5.2. COMPARISON OF β- AND γ-RAY MATRIX ELEMENTS IN $A = 27$ NUCLEI

All available spectroscopic information on ^{27}Si and ^{27}Al relevant to the present discussion is shown in fig. 3. The level schemes are very similar if one makes the

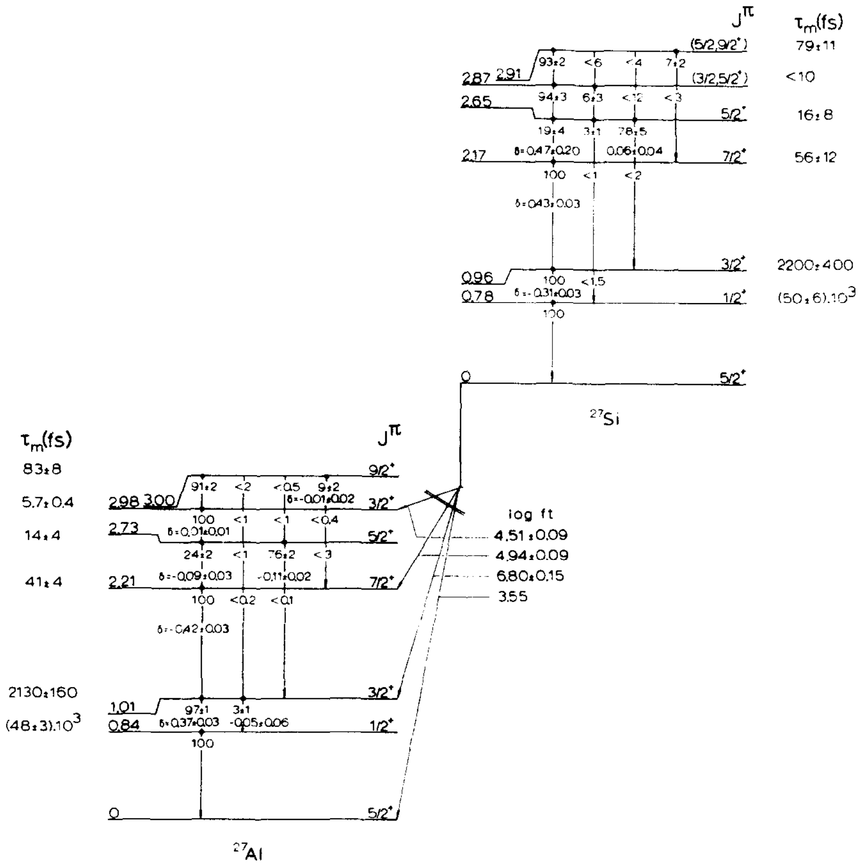

Fig. 3. Level schemes of ^{27}Al and ^{27}Si with the information relevant to the discussion. The lifetime of the first excited state in ^{27}Al is from the present work, all other ^{27}Al data are from refs. [2-7]). The log ft values of the β-decay are from refs. [23,24]). The mixing ratios for ^{27}Si are from refs. [7,8]), the limit on the branching ratio of the 0.96 MeV level in ^{27}Si is from ref. [9]), the J^{π} assignments not extracted from the present work are from ref. [2]).

plausible choices $J^{\pi} = \frac{3}{2}^+$ and $\frac{9}{2}^+$ for the ^{27}Si levels at $E_x = 2.87$ and 2.91 MeV, respectively. The M1 and E2 strengths of transitions between positive-parity states, calculated from the known mean lives, branching ratios and mixing ratios, are given in table 2.

As has been shown in ref. [21]), values for the matrix elements of the M1 operator can be deduced from the strengths of the M1 transitions and the corresponding β-decay. The formalism used in the following is described in ref. [21]).

TABLE 2

Survey of M1 and E2 strengths in ^{27}Al and ^{27}Si [a])

Transition	$\lvert M(\mathrm{M1})\rvert^2$ (10^{-2} W.u.)			$\lvert M(\mathrm{E2})\rvert^2$ (W.u.)		
	^{27}Al	^{27}Si	theor. [b])	^{27}Al	^{27}Si	theor. [b])
$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+(1)$				8.1 ± 0.5	11.4 ± 1.4	8.4
$\frac{3}{2}^+(1) \rightarrow \frac{5}{2}^+(1)$	1.21 ± 0.09	1.5 ± 0.3	7.6	8.5 ± 1.4	8 ± 2	9.3
$\frac{3}{2}^+(1) \rightarrow \frac{1}{2}^+$	9 ± 3	<4 [c])	9.1	<140		3.4
$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+(1)$	6.0 ± 0.6	4.6 ± 1.0		11.5 ± 1.8	10 ± 2	
$\frac{5}{2}^+(2) \rightarrow \frac{5}{2}^+(1)$	2.6 ± 0.7	1.6 ± 0.9	0.4	0.15 ± 0.11	$2.7^{+8.5}_{-2.2}$	3.1
$\frac{5}{2}^+(2) \rightarrow \frac{1}{2}^+$				<7	14 ± 8	3.5
$\frac{5}{2}^+(2) \rightarrow \frac{3}{2}^+(1)$	33 ± 10	31 ± 15	53	7 ± 3	$2.1^{+10.3}_{-1.9}$	3.5
$\frac{3}{2}^+(2) \rightarrow \frac{5}{2}^+(1)$	21 ± 2	>12 [c])	1.8	<0.03		0.8
$\frac{3}{2}^+(2) \rightarrow \frac{1}{2}^+$	<0.6 [c])	>1.0 [c])				
$\frac{9}{2}^+ \rightarrow \frac{5}{2}^+(1)$				7.5 ± 0.7	9.3 ± 1.3	
$\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$	6.9 ± 1.7	7 ± 2 [c])		<0.3		

[a]) Octupole transitions have not been considered.

[b]) Only for ^{27}Si.

[c]) These transitions have been assumed to be unmixed.

TABLE 3

Results of the comparison of β- and γ-ray matrix elements in $A = 27$ nuclei

M1 $J_i^\pi \rightarrow J_f^\pi$	$\log ft$	$\lvert\langle\psi_f\lvert\lvert s\tau\rvert\rvert\psi_i\rangle\rvert$	R
$\frac{3}{2}^+(1) \rightarrow \frac{5}{2}^+$	6.80 ± 0.15 [a])	0.080 ± 0.014	3.1 ± 0.8 or -5.1 ± 0.8
$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	4.94 ± 0.09 [b])	0.68 ± 0.07	0.36 ± 0.16 or -2.36 ± 0.16
$\frac{3}{2}^+(2) \rightarrow \frac{5}{2}^+$	4.51 ± 0.09 [c])	1.11 ± 0.12	0.18 ± 0.14 or -2.18 ± 0.14

[a]) Ref. [23]).

[b]) Ref. [24]).

From the M1 strengths of the ground state transitions from the first $J^\pi = \frac{3}{2}^+$ state and the $J^\pi = \frac{7}{2}^+$ state it follows that the isoscalar parts of the M1 matrix elements are less than 11 and 13 %, respectively, of the isovector part. Because for the $J^\pi = \frac{3}{2}^+$ state at $E_x = 2.87$ MeV in ^{27}Si only a lifetime limit is known, it is not possible to derive the value of the isoscalar part, but is was assumed to be relatively small.

The results of the calculations are summarized in table 3. The values of the matrix elements $\lvert\langle\psi_f\lvert\lvert s\tau\rvert\rvert\psi_i\rangle\rvert$ follow from the $\log ft$ values of the ^{27}Si β^+ decay [21]). The value R is the ratio of the orbital and spin contributions to the isovector part of the M1 strength [22]). As is shown in ref. [25]) it is expected that the spin contribution dominates over the orbital contribution to the isovector part. This holds for the $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ and the $\frac{3}{2}^+(2) \rightarrow \frac{5}{2}^+$ transitions if R is assumed to be equal to the smaller of the two possible values. However, for the $\frac{3}{2}^+(1) \rightarrow \frac{5}{2}^+$ transition the orbital contribution is much larger than the spin contribution. It has been pointed out by Détraz *et al.* [23]) that the ^{27}Si β^+ decay to the first $J^\pi = \frac{3}{2}^+$ level in ^{27}Al is strongly retarded which also results in a small spin contribution to the M1 strength.

5.3. COMPARISON WITH MANY-PARTICLE SHELL-MODEL CALCULATIONS

The experimental transition probabilities given in table 2 can be compared with the results of many-particle shell-model calculations in ^{27}Si [ref. [1])], in which calculations the wave functions from ref. [26]) are used. The shell-model space comprises a closed ^{16}O core and particles in the $2s_{\frac{1}{2}}$ and $1d_{\frac{3}{2}}$ subshells and up to four holes in the $d_{\frac{5}{2}}$ subshell. The residual interaction is of the modified surface-delta type. For E2 strengths effective charges for the proton and the neutron were used of $e_p = 1.44\, e$ and $e_n = 0.68\, e$, as resulting from a least-squares fit to E2 transition probabilities in $A = 30$–34 nuclei [ref. [21])]. For the M1 transitions realistic g-factors were used.

The results of the calculations on ^{27}Si are included in table 2; theoretical estimates of transition strengths which involve the $J^\pi = \frac{7}{2}^+$ and $\frac{9}{2}^+$ states are not available at present. For the E2 strengths the agreement is fair, for the M1 transitions only the order of magnitude is correct. More detailed calculations on $A = 27$ nuclei are in progress [1]).

6. Conclusions

Combination of the present lifetime measurements summarized in table 1 and the branching ratios given in fig. 3 with the results of previously reported angular correlation measurements, leads to $J^\pi = \frac{7}{2}^+$, $(\frac{3}{2}, \frac{5}{2}^+)$ and $(\frac{5}{2}, \frac{9}{2}^+)$ assignments to the ^{27}Si levels at $E_x = 2.17$, 2.87 and 2.91 MeV, respectively. Recent shell-model calculations on ^{27}Si agree with the measured E2 strengths but for the M1 strengths an extended configuration space seems to be required.

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