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Lifetimes and decay modes of energy levels in ^{23}Na, ^{26}Mg and ^{26}Al†

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Abstract. The mean lifetimes of levels in ^{23}Na, ^{26}Mg and ^{26}Al have been determined by the Doppler shift attenuation method. The levels were populated by the reactions ^{23}Na (p, p') ^{23}Na, ^{23}Na (α, p) ^{26}Mg and ^{23}Na (α, n) ^{26}Al at proton bombarding energies between 3·6 and 7·0 MeV and α particle energies between 4·6 and 7·5 MeV. The γ rays were detected using a Ge(Li)–NaI(Tl) anti-Compton and pair spectrometer. A discussion of the rotational band structure of the levels in ^{23}Na below 5 MeV is given. The results for ^{26}Mg and ^{26}Al are compared with other recent determinations.

1. Introduction

There is now substantial evidence that the nuclei of the 2s–1d shell divide into two distinct regions. The nuclei with $A = 18$–25 exhibit characteristics explicable in terms of a stable prolate deformation of the nuclear core (Bhatt 1962). Agreement with experimental data on the nuclei ^{24,25}Mg, ^{25}Al can be achieved with a relatively simple application of the rotational model (Branford and Wright 1971, private communication, Sharpey-Schafer *et al* 1968, Ollerhead *et al* 1968, Röpke *et al* 1968). In Coulomb excitation experiments Häusser *et al* (1969, 1970) have shown that the nuclear deformation changes sign from ^{24}Mg to ^{28}Si. Nuclei with $A > 28$ seem to be close to spherical in shape, and the levels of these nuclei have been described by Thankappan and Pandya (1962) in terms of the weak coupling of shell model states to surface vibrations of a spherical core. The structure of the nuclei with $A = 26, 27$ is not well defined, as there exists the possibility of either permanent deformation or sphericity for these nuclei.

It is of interest to provide more data on these systematic trends. To this end we have studied the nuclei ^{23}Na, ^{26}Mg and ^{26}Al, using the Doppler shift attenuation method (DSAM) to determine lifetimes of levels in these nuclei.

2. Experimental technique and data analysis

The excited states of ^{23}Na were populated using the ^{23}Na (p, p') reaction at incident proton energies from 3·6 to 7·0 MeV, and the levels of ^{26}Mg and ^{26}Al by the ^{23}Na (α, p)

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^{26}Mg (Q = 1·822 MeV) and ^{23}Na (α, n) ^{26}Al (Q = −2·964 MeV) reactions at α particle bombarding energies between 4·6 and 7·5 MeV. The ^{23}Na targets of thickness 1 to 1·3 mg cm^{-2} were metallic sodium evaporated on to gold, and were transferred to the target chamber under vacuum to prevent oxidation of the target. The target chamber and beam line were maintained at a vacuum of less than 10^{-6} Torr by triode ion pumps. A large cold trap separated this clean system from the accelerator diffusion pump system, eliminating carbon build-up on the target.

The γ rays produced in the inelastic proton scattering experiments were detected using both a 30 cm^3 Ge(Li) detector and a Ge(Li)–NaI(Tl) anti-Compton and pair spectrometer (Sharpey-Schafer *et al* 1971). In the case of the α particle induced reactions all data were collected using the spectrometer. The spectrometer was used in two simultaneous modes of operation. The NaI(Tl) annulus either provided an anticoincidence shield to suppress Compton scattering and escape events, or two opposite quadrants could be used in coincidence with the Ge(Li) detector to provide a spectrum containing double escape events only. The data from the spectrometer were accumulated on-line by a PDP-7 computer.

The outgoing reaction products were not detected. The measurement of lifetimes by this singles technique requires the assumption that the average initial velocity of the recoiling nuclei is the velocity of the centre of mass (CM) of the system comprising the incident particle and target nucleus. To ensure that this assumption is valid it is necessary to populate the excited states of the final nucleus as near to threshold as possible so that the light reaction product emerges with low momentum. The energy of a γ ray detected at an angle θ with respect to the incident beam direction will then be given by

$$E_\gamma(\theta) = E_\gamma(90°)\left(1 + F\frac{v_{cm}}{c}\cos\theta\right) \tag{1}$$

where v_{cm} is the CM velocity and F is the attenuation factor. The factor F can be evaluated experimentally by measuring the energy of the γ ray as a function of θ and performing a least squares fit to the data with the expression given in equation (1). The quantity v_{cm} is determined from the mean energy of the incident particles in the target.

The lifetimes were evaluated by comparing the experimental attenuation factors with theoretical calculations of F as a function of lifetime. These theoretical values of F were determined by a computer program based on the stopping power theory of Lindhard *et al* (1963) as developed by Blaugrund (1966). The total specific energy loss is

$$\frac{d\epsilon}{d\rho} = \left(\frac{d\epsilon}{d\rho}\right)_{\text{electronic}} + \left(\frac{d\epsilon}{d\rho}\right)_{\text{atomic}} \tag{2}$$

the electronic specific energy loss being given analytically, whilst the atomic specific energy loss is given as a numerical function. In computing the attenuation factors $(d\epsilon/d\rho)$ atomic has been represented (Broude 1968, private communication) by

$$\left(\frac{d\epsilon}{d\rho}\right)_{\text{atomic}} = \begin{cases} 1{\cdot}14\epsilon^{0{\cdot}35} - 0{\cdot}45\epsilon^{0{\cdot}7} - 0{\cdot}5\epsilon & \epsilon \leqslant 0{\cdot}2 \\ 0{\cdot}611\left\{1 - \exp\left(\dfrac{-\sqrt{\epsilon}}{0{\cdot}2406}\right)\right\}\exp\left(\dfrac{-\sqrt{\epsilon}}{1{\cdot}919}\right) & 0{\cdot}2 < \epsilon \leqslant 4{\cdot}0 \\ (2\epsilon)^{-1}\left\{0{\cdot}3 + \ln\left(\dfrac{0{\cdot}6+\epsilon^2}{\epsilon}\right)\right\} & \epsilon > 4{\cdot}0. \end{cases}$$

It is well known that the expression for electronic stopping power can be in error by as much as 20% compared to experimental data. There are also doubts concerning the atomic stopping power. It has therefore become the custom to replace equation (2) by

$$\frac{d\epsilon}{d\rho} = f_e\left(\frac{d\epsilon}{d\rho}\right)_{\text{electronic}} + f_n\left(\frac{d\epsilon}{d\rho}\right)_{\text{atomic}}$$

where f_e and f_n are numerical factors designed to make the theoretical expressions agree with experimental data. Electronic stopping powers for ^{23}Na ions in carbon and aluminium have been measured by Ormrod *et al* (1963, 1965) and Fastrup *et al* (1966) and there is approximately a 10% disagreement between the theoretical predictions of Lindhard *et al* (1963) and the experimental data in the energy range 20–400 keV. In the present experiments the initial recoil energy has a maximum value of 280 keV for 7·0 MeV incident protons. Within this energy range the atomic stopping power is expected to be comparable to the electronic stopping power. The effect of this 10% deviation will therefore be negligible compared to the remaining uncertainties in the atomic stopping power.

The electronic stopping powers for ^{25}Mg and ^{27}Al ions have been measured by the same authors for energies below 1000 keV, and are found to agree within 10% with the predictions of Lindhard *et al* (1963) for ion energies above 200 keV. Although the discrepancy increases at low ion velocities, it is again to be expected that the uncertainties in the atomic contribution to the stopping powers will make the effect of the deviation of the electronic stopping power from theoretical predictions small.

No data are available on atomic stopping powers for Na, Mg or Al ions. We have therefore put $f_e = f_n = 1$ in the computation of the theoretical attenuation factors.

3. The nucleus ^{23}Na

The branching ratios and multipole mixing ratios of most of the levels of ^{23}Na below 5 MeV excitation have been measured by various reactions (Poletti *et al* 1969, 1970, da Silva 1968, 1971, Sowerby *et al* 1968) and are in reasonable agreement. However, until recently little was known of the lifetimes of these levels. The E2 width of the first excited state has been determined (see the compilation of Endt and van der Leun 1967) by Coulomb excitation experiments and its mean lifetime is given as $1{\cdot}60 \pm 0{\cdot}08$ ps. The lifetimes of the states at 2·98 and 4·43 MeV are found from resonance fluorescence experiments to be $4{\cdot}7 \pm 0{\cdot}7$ fs and $0{\cdot}29 \pm 0{\cdot}03$ fs respectively (Metzger 1964, Rasmussen and Khan 1966). DSAM measurements of the lifetimes of some levels in ^{23}Na have been reported by Poletti *et al* (1969) and Maier *et al* (1970) and comparison of our data with these results is made below. Since the preliminary results of the present experiment were reported (Durell *et al* 1969) more data have been analysed enabling a more accurate determination of some lifetimes to be made.

3.1. Experimental results

The decay scheme deduced for ^{23}Na is shown in figure 1 and the excitation energies of the levels measured in this work are given in table 1.

Particular attention had to be paid to the contamination of total capture γ ray peaks by the double escape peaks of higher energy γ rays. This was important in the case of the

2392 keV state, the two branches (E_γ = 1952, 2392 keV) of which contained contributions from the double escape peaks produced by the decay of the 2983 keV level to the ground state and by the 3409 keV γ ray from the decay of the 3850 keV level to the first excited state at 440 keV, at proton bombarding energies above 4 MeV. At E_p = 3·6 MeV the spectrum obtained using the pair spectrometer indicated no contribution of these double escape peaks to the 1952 and 2392 keV γ rays. Accordingly the data recorded at 3·6 MeV were used to determine the lifetime of this state.

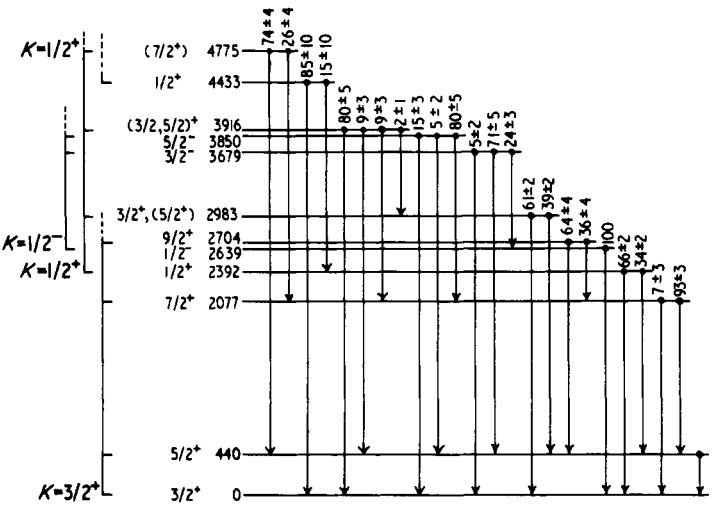

Figure 1. The levels of ^{23}Na showing the assignments to rotational bands. The decay scheme and branching ratios are those determined in the present experiment.

Levels in ^{20}Ne were populated by the ^{23}Na (p, α) ^{20}Ne reaction at all proton bombarding energies. The major branch of the 2077 keV, $J = 7/2^+$, level was obscured by the strong ^{20}Ne (1634 → 0) γ ray and therefore only the 7% 2077 → 0 branch could be used in the analysis. The lifetime of the state in ^{23}Na at 2639 keV, which decays 100% to the ground state, could only be determined at E_p = 3·6 MeV because of the contamination of the 2639 keV γ ray by the broadened 2620 keV ^{20}Ne (4253 → 1633) γ ray. Figure 2 shows the anti-Compton and pair escape spectra obtained by the bombardment of the ^{23}Na target by 6·5 MeV protons.

The efficiency of the spectrometer was determined up to a γ ray energy of 3·5 MeV with a ^{56}Co source, using the relative intensities given by Marion (1969).

Branching ratios determined in the present experiment (figure 1) were estimated from the 50° and 130° data, where the P_2 (cos θ) component of the γ ray angular distribution is minimized. Our measured branching ratios are in good agreement with previous data except for the decay of the 3850 keV level. We confirm the existence of a transition from the 3850 keV level to the first excited state. This transition has been reported previously by Wernbom-Selin and Arnell (1966) and by Greene (1965). This transition was only observed through its double escape peak in the pair spectra. The 3409 keV γ ray arising from this transition is obscured in the anti-Compton spectra by the double escape peak of the 4433 keV γ ray and the single escape peak of the 3916 keV γ ray.

The gain of the electronic system was monitored throughout the experiment and gain shifts were found to be small enough to neglect. The effect of the small gain shifts

Table 1. A summary of the attenuation factors F and mean lifetimes τ obtained in the ^{23}Na (p, p'γ) experiment

E_x (keV)	Transition†	E_p (MeV)	F	F average	τ (fs)	τ average‡ (fs ± 25 %)
2076·7 ± 0·5	2 → 0	3·6	0·792 ± 0·028	0·777 ± 0·033	210 ± 35	210 ± 35
	2 → 0	3·6	0·717 ± 0·055			
2391·7 ± 0·7	3 → 0	3·6	0·281 ± 0·012	0·267 ± 0·012	1550 ± 90	1550 ± 90
	3 → 1		0·238 ± 0·018			
	3 → 0	3·6	0·273 ± 0·033			
	3 → 1		0·245 ± 0·034			
2639·4 ± 0·74	4 → 0	3·6	0·713 ± 0·028	0·645 ± 0·021	365 ± 40	365 ± 40
	4 → 0	3·6	0·615 ± 0·018			
2704·4 ± 0·7	5 → 1	4·6	0·921 ± 0·023	0·921 ± 0·032	80 ± 30	100 ± 20
	5 → 1	6·5	0·906 ± 0·015	0·906 ± 0·025	115 ± 30	
	5 → 1	7·0	0·931 ± 0·020	0·920 ± 0·023	100 ± 30	
	5 → 1 D	7·0	0·909 ± 0·023			
	5 → 2	7·0	0·940 ± 0·080			
2983·0 ± 0·5	6 → 1	4·6	1·030 ± 0·021	1·030 ± 0·031	< 10	< 25
	6 → 0	6·5	0·984 ± 0·011	0·985 ± 0·020	< 40	
	6 → 1	6·5	0·988 ± 0·027			
	6 → 0	7·0	0·981 ± 0·028	1·004 ± 0·025	< 25	
	6 → 0 D	7·0	0·979 ± 0·017			
	6 → 1	7·0	1·054 ± 0·028			
	6 → 1 D	7·0	1·004 ± 0·026			
3678·9 ± 0·7	7 → 1	6·5	0·897 ± 0·031	0·897 ± 0·040	120 ± 60	70 ± 40
	7 → 1	7·0	0·966 ± 0·021	0·966 ± 0·031	45 ± 40	
3849·5 ± 0·7	8 → 2	6·5	0·901 ± 0·050	0·901 ± 0·059	120 ± 70	170 ± 40
	8 → 2	7·0	0·849 ± 0·034	0·849 ± 0·042	190 ± 50	
3915·6 ± 0·7	9 → 0	6·5	0·970 ± 0·015	0·947 ± 0·014	64 ± 17	60 ± 15
	9 → 0 D	6·5	0·944 ± 0·005			
	9 → 0	7·0	1·002 ± 0·028	0·966 ± 0·026	45 ± 30	
	9 → 0 D	7·0	0·950 ± 0·020			
	9 → 2	7·0	0·962 ± 0·080			
4432·7 ± 0·7	10 → 0	6·5	1·071 ± 0·021	1·071 ± 0·032	< 10	< 45
	10 → 0	7·0	1·001 ± 0·027	1·001 ± 0·037	< 45	
4776·2 ± 0·7	11 → 1	6·5	1·014 ± 0·045	1·014 ± 0·055	< 50	
	11 → 1	7·0	1·004 ± 0·025	1·000 ± 0·030	< 35	< 35
	11 → 1 D	7·0	0·997 ± 0·031			

† Data from double escape peaks in the pair escape spectra are denoted by D.

‡ The errors in τ do not include any systematic uncertainty in the conversion of the attenuation factors to lifetimes due to uncertainties in the slowing down theory. These uncertainties are shown as a 25 % error in the timescale.

were minimized by randomizing the order of the angles at which the data were recorded. Table 1 summarizes the results obtained from the experimental data at all proton energies. The errors shown on the attenuation factors in column 4 of table 1 are errors associated with the goodness of the least-squares fit only. The lifetimes given in the final column are weighted averages of the separate lifetime determinations. The errors on the lifetimes contain an estimate of the uncertainty in determining the mean proton energy in the target, but do not include errors in the stopping theory. This error is taken to be ± 25 % and is shown as an error in the timescale of the last column of table 1. The results of the present experiment are compared with those of Poletti *et al* (1969) and Maier *et al* (1970)

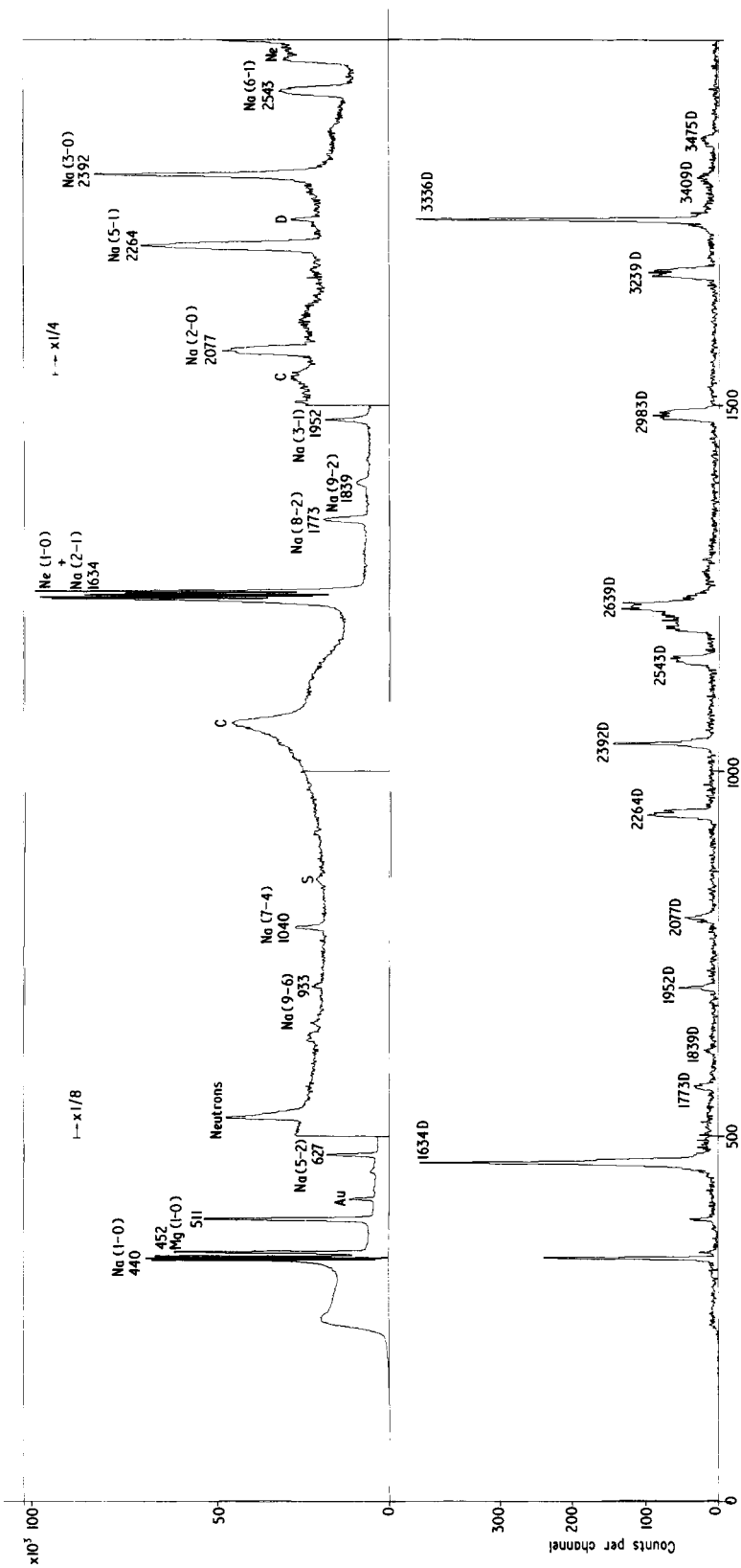

Figure 2. A spectrum obtained with the anti-Compton and pair spectrometer for the bombardment of ^{23}Na with 6·5 MeV protons. The peaks in the Compton suppressed spectrum are labelled by their energy in keV and the transition from which they arise. The labels C, S and D indicate Compton edges, single escape peaks and double escape peaks respectively. In the pair spectrum each peak is labelled with the energy of its corresponding total capture peak.

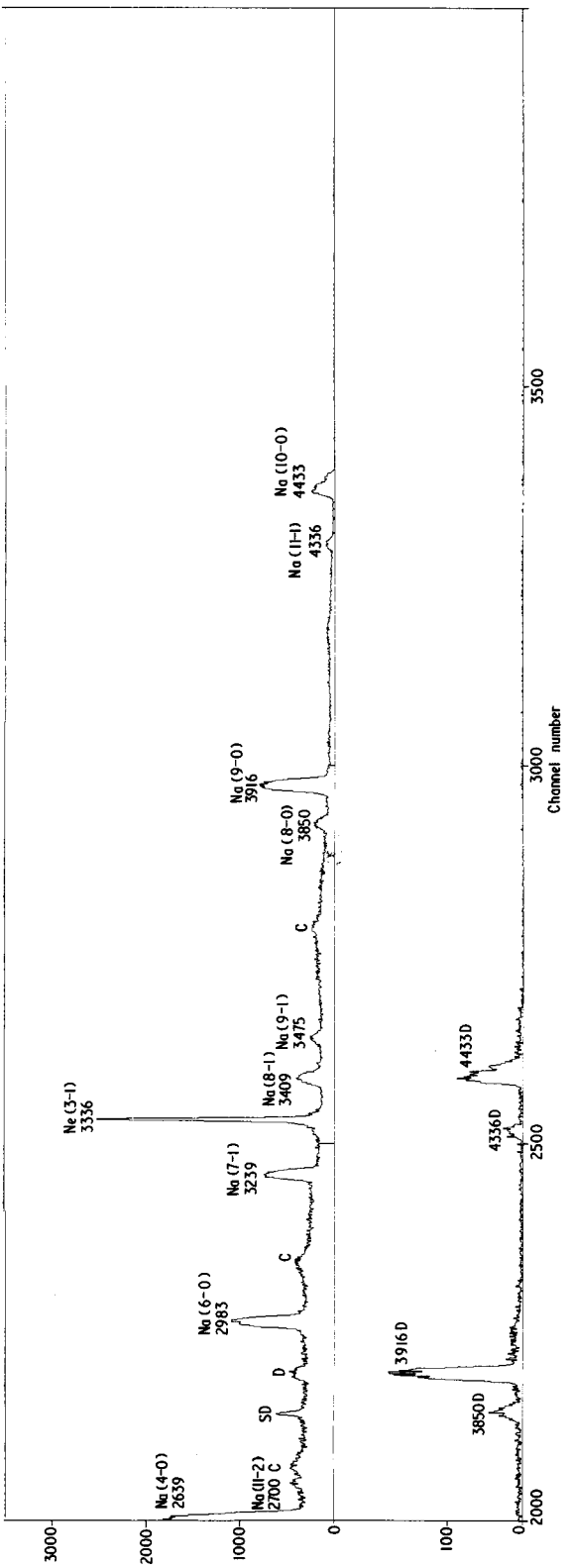

Figure 2. (continued)

in table 2. The agreement is reasonably satisfactory except in the case of the 2392 keV state. In the present work it was discovered that the attenuation factors determined for γ rays from this state were very sensitive to proton bombarding energy because of the contaminating double escape peaks. The lifetime of the 2392 keV state was measured at $E_p = 3{\cdot}6$ MeV in the present work, where no contaminating γ rays were present. The results of Poletti *et al* (1969) and Maier *et al* (1970) were obtained at $E_p = 3{\cdot}75$ MeV and $E_p = 4{\cdot}12$ MeV.

Table 2. Comparison of the lifetimes of levels in ^{23}Na determined in the present work with other results

E_x (keV)	Lifetime (fs)			
	Present	Poletti *et al* (1969)	Maier *et al* (1970)	Other
400				1600 ± 80†
2077	210 ± 60	<230	<300	
2392	1550 ± 400	950 ± 200	700^{+300}_{-200}	
2639	370 ± 90	200 ± 80		
2704	100 ± 25	200 ± 100	100^{+80}_{-40}	
2983	<25	<70	<100	$4{\cdot}7 \pm 0{\cdot}7$‡
3679	70 ± 40	<170	<100	
3850	170 ± 50			
3916	60 ± 15			
4433	<45			$0{\cdot}29 \pm 0{\cdot}03$§
3776	<35			

† An average value cited by Endt and van der Leun (1967)
‡ Value from Metzger (1964)
§ Value from Rasmussen and Kahn (1966)

3.2. Discussion

The states at 440, 2077 and 2704 keV form with the ground state a $K = 3/2^+$ rotational band (Dubois 1967). The transitions connecting these states are expected to exhibit enhanced E2 characteristics. If this rotational band is pure $K = 3/2^+$ then the E2 transition strengths should be in the ratios of the squares of Clebsch–Gordan coefficients. In table 3 the experimentally determined E2 strengths are compared to the model predictions which have been normalized to the E2 transition strength of the decay of the first excited state. It is evident that the E2 transitions within the ground state band are not even in qualitative agreement with the predictions of the Nilsson model, where no mixing between bands is considered. The most interesting features of these transition strengths are the anomalously low E2 transitions from the $J = 7/2^+$ member of the band at 2077 keV. The transition strength of the $9/2^+$ to $7/2^+$ decay is very dependent upon the measured mixing ratio which has not been determined accurately. Walsh (1970) has calculated the transition strengths within the ground state band using deformed Saxon–Woods wavefunctions assuming an inert core so that only bands based on particle intrinsic states are mixed with the ground state $K = 3/2^+$ band. The results of these calculations are also compared to the experimental values in table 3. The band mixing in this calculation does not account for the weak transition strengths from the $7/2^+$ member of the band. It seems that one must include core excitation states in any mixing calculation before the experimentally determined transition strengths can be reproduced.

Table 3. The experimentally determined E2 transitions within the ground state band of ^{23}Na compared with the pure band Clebsch–Gordan coefficient ratios and the band mixing calculation of Walsh (1970)

$J_i \rightarrow J_f$	δ	$\lvert M(E2)\rvert^2$(Wu)		
		experimental	pure band	mixed band†
$5/2^+ \rightarrow 3/2^+$		24 ± 2‡	24	26
$7/2^+ \rightarrow 3/2^+$	$0{\cdot}18 \pm 0{\cdot}02$§	$2{\cdot}2 \pm 0{\cdot}9$	10	12
$5/2^+$		$2{\cdot}2 \pm 0{\cdot}5$	15	19
$9/2^+ \rightarrow 5/2^+$	$0{\cdot}10 \pm 0{\cdot}04$§	25 ± 5	15	16
$7/2^+$		80 ± 60	10	9

† Walsh (1970).
‡ Average Endt and van der Leun (1967) partial E2 strength from Coulomb excitation.
§ Weighted averages from Poletti *et al* (1966, 1970), da Silva (1968), Sowerby *et al* (1968) and Maier *et al* (1970).

The level in ^{23}Na at 2392 keV has been assigned as the $J = K = 1/2^+$ particle state based on Nilsson orbit 9. It has been known from the branching ratio of this state that the magnetic dipole transition to the ground state is inhibited. The lifetime determined in the present work gives an M1 strength for the decay to the ground state of 10^{-3} Wu, assuming that this transition is pure dipole. Pelte (1966) has shown that this inhibition may be accounted for by proper consideration of the wavefunction of this state. If isospin is a good quantum number this wavefunction will contain two components corresponding to either the odd proton or one of the neutrons in orbit 5 being promoted to Nilsson orbit 9. Using this wavefunction Pelte calculated an M1 retardation factor of 100 for the decay of the 2392 keV level. Walsh (1970) in his calculation predicts an M1 transition strength for this decay of 1·4 Wu. He did not include in this calculation the treatment of the 2392 keV level as proposed by Pelte. If one introduces the retardation factor of 100 predicted by Pelte, then the calculated M1 strength would be 14×10^{-3} Wu, compared with the experimental value of 10^{-3} Wu.

The states at 2983, 3916 and 4776 keV have been assigned as members of the $K = 1/2^+$ band based upon the 2392 keV level (Dubois 1967). As these higher members of the band have the same intrinsic structure as the $J = K = 1/2^+$ states it might be expected that they should exhibit the same inhibited M1 transitions to the ground state band. The $J = 5/2^+$ member of the band does indeed decay to the members of the ground state band by M1 strengths of the order of 10^{-3} Wu, but the $J = 3/2^+$ and $7/2^+$ members do not exhibit such inhibitions in their decay. The only transition connecting any of these states is the 2% branch from the 3916 keV state to the 2983 keV state. This transition is an E2/M1 mixture and the mixing ratio is not known.

The states at 2639, 3679 and 3850 keV have been identified as members of a negative parity band arising from a hole configuration. If this $K = 1/2^-$ band is based upon the configuration of a hole in Nilsson orbit 4 then it has the same configuration as the lowest negative parity band in ^{19}F. The states of ^{19}F have been treated successfully by Benson and Flowers (1969) by a model in which the negative parity states of ^{19}F are constructed by the coupling of a $p_{1/2}$ proton hole to the rotational bands of ^{20}Ne. An immediate consequence of this formulation is that El transitions to positive parity states based on the $(2s, 1d)^3$ configuration are forbidden if these positive parity states contain no contribution from core excitation. By analogy with ^{19}F the negative parity states of ^{23}Na

can be constructed by coupling a $p_{1/2}$ proton hole to the ground state band of ^{24}Mg, whereas the positive parity ground state band arises from the $(2s, 1d)^7$ configuration. The E1 strengths in such a band in ^{23}Na would therefore be expected to be characterized by inhibitions. The E1 strengths determined in the present work are of the order of 10^{-5} to 10^{-4} Wu. An exception to these inhibited E1 transitions is the $5/2^- \rightarrow 7/2^+$ transition which has a strength of 10^{-3} Wu. The anomalous E2 strengths of the decay of of the $J = 7/2^+$ member of the ground state band indicate that this state contains admixtures of configurations other than $K = 3/2^+$. This E1 strength suggests that the $J = 7/2^+$ state contains admixtures of core excitation configurations.

4. The nuclei ^{26}Mg and ^{26}Al

There have been several experiments (Youngblood *et al* 1967, Robinson and Bent 1968, Häuser *et al* 1968, Häusser and Anyas-Weiss 1968, de Kock *et al* 1970) using the DSAM to measure lifetimes in ^{26}Mg and ^{26}Al. The majority of these lifetimes have been determined using the ^{26}Mg (p, p') ^{26}Mg, ^{26}Mg (p, n) ^{26}Al and ^{25}Mg (p, γ) ^{26}Al reactions. We have measured the lifetimes of levels in these nuclei using α particle induced reactions on ^{23}Na, where the initial velocity of the recoiling ions is larger and the observed Doppler shifts correspondingly greater. The known decay schemes of ^{26}Mg and ^{26}Al are shown in figures 3 and 4 respectively.

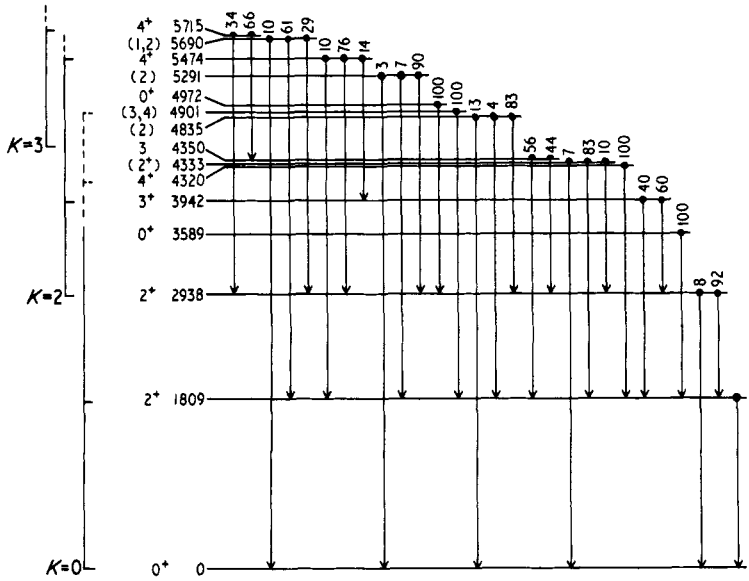

Figure 3. The levels of ^{26}Mg, showing the level energies and decay modes observed in the present work.

4.1. Results

Figure 5 shows the centroid shifts of some of the γ rays observed in the ^{23}Na + α reaction. The full lines are the least-squares fits to the data and broken lines indicate the expected full shift. The gain of the electronics was monitored by taking ^{56}Co source runs at each

angle. Gain shifts were observed and the centroids were corrected for these shifts before the least-squares fitting was carried out. The maximum gain shift observed in the experiment was 0·06 %.

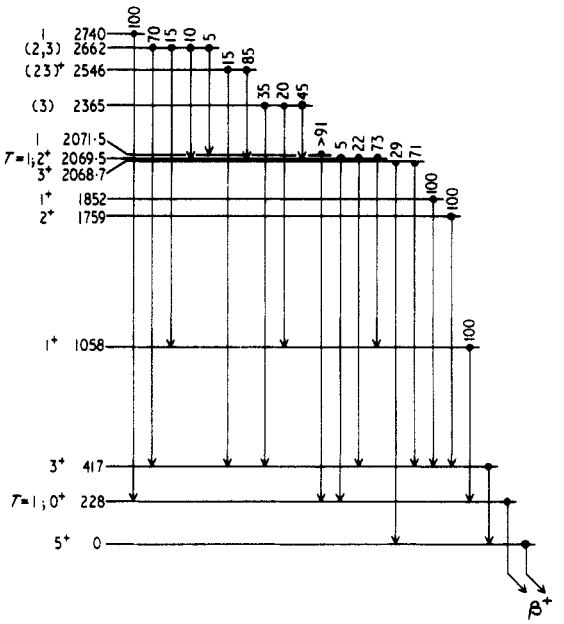

Figure 4. The levels of ^{26}Al, showing the level energies and decay modes observed in the present work.

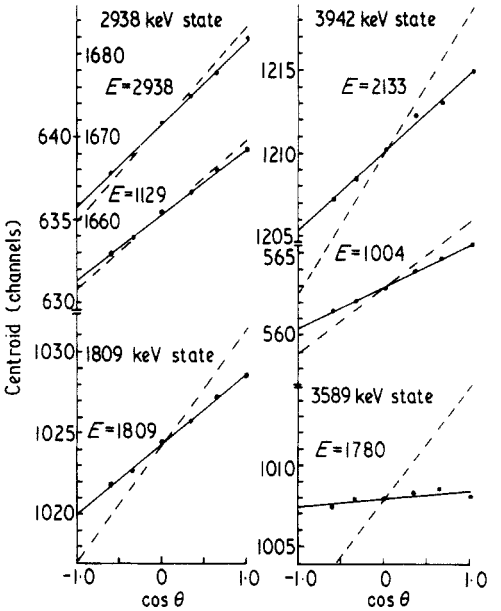

Figure 5. The centroid shifts of γ rays in ^{26}Mg observed in the ^{23}Na (α, p) ^{26}Mg reaction at an α particle bombarding energy of 4·6 MeV. The full lines are least squares fits to the data and broken lines indicate the expected full shift. The dispersion is 1·746 keV per channel.

Tables 4 and 5 summarize the results obtained in the present experiment for the ^{23}Na (α, p) ^{26}Mg and ^{23}Na (α, n) ^{26}Al reactions respectively. The first excited state of ^{26}Mg was fed by the decay of the second (37%), third (3%) and fourth (2%) excited states and the second excited state by the fourth (5%) excited state. The attenuation

Table 4. A summary of the attenuation factors F obtained in the ^{23}Na (α, pγ) ^{26}Mg experiment

E_x (keV)	Transition	E_α (MeV)	F	F average	τ (fs)	τ average† (fs ± 25%)
1808·9 ± 0·5	1 → 0	4·6	0·593 ± 0·018	0·67 ± 0·05‡	610 ± 100	610 ± 100
2938·2 ± 0·7	2 → 0	4·6	0·861 ± 0·017	0·895 ± 0·05‡	170 ± 100	170 ± 100
	2 → 1	4·6	0·890 ± 0·017			
3588·8 ± 0·7	3 → 1	4·6	0·072 ± 0·030	0·072 ± 0·031	12500^{+13000}_{-4000}	15000^{+10000}_{-5000}
	3 → 1	6·0	0·044 ± 0·025	0·044 ± 0·025	23000^{+30000}_{-10000}	
3941·5 ± 0·7	4 → 1	4·6	0·557 ± 0·022	0·593 ± 0·021	830 ± 100	965 ± 170
	4 → 2	4·6	0·630 ± 0·018			
	4 → 1	6·0	0·522 ± 0·007	0·525 ± 0·013	1100 ± 100	
	4 → 2	6·0	0·537 ± 0·016			
4332·7 ± 0·7	6 → 2	6·0	0·973 ± 0·034	> 0·93	< 100	< 100
	6 → 0	7·5	0·960 ± 0·026	> 0·92	< 125	
4349·9 ± 1·0	7 → 2	6·0	0·905 ± 0·013	0·905 ± 0·022	165 ± 40	180 ± 30
	7 → 2	7·5	0·894 ± 0·022	0·894 ± 0·031	200 ± 50	
4835·2 ± 1·0	8 → 2	6·0	0·975 ± 0·015	> 0·95	< 90	< 90
	8 → 0	7·5	0·973 ± 0·019			
	8 → 2	7·5	0·974 ± 0·026	> 0·94	< 100	
4901·0 ± 1·0	9 → 1	6·0	0·961 ± 0·015	0·961 ± 0·025	70 ± 35	85 ± 25
	9 → 1	7·5	0·940 ± 0·011	0·940 ± 0·021	110 ± 30	
4972·0 ± 1·0	10 → 2	6·0	0·639 ± 0·040	0·639 ± 0·046	760 ± 150	760 ± 150
5291·4 ± 1·0	11 → 2	6·0	1·025 ± 0·017	> 0·99	< 10	< 10
		7·5	1·006 ± 0·011	> 0·98	< 30	
5473·7 ± 1·0	12 → 1	7·5	0·981 ± 0·025	> 0·94	< 100	< 100
5689·8 ± 1·0	13 → 1	7·5	1·001 ± 0·021	> 0·97	< 50	< 50
5714·9 ± 1·0	14 → 7	7·5	1·001 ± 0·023	> 0·97	< 50	< 50

† The errors in τ do not include any systematic uncertainty in the conversion of the attenuation factors to lifetimes due to uncertainties in the slowing down theory. These uncertainties are shown as a 25% error in the timescale.

‡ In these cases F average has been corrected for feeding from higher levels.

Table 5. Summary of the attenuation factors F obtained in the ^{23}Na (α, n)^{26}Al reaction

Level	Transition	E_α	F	τ_m (fs ± 25%)
1057·5	3 → 1	6·0	1·007 ± 0·017	< 35
1759·2	4 → 2	6·0	0·282 ± 0·002	2750 ± 200
		7·5	0·228 ± 0·008	3900 ± 200
2068·7	6 → 0	7·5	0·801 ± 0·027	375 ± 60
2071·5	8 → 1	7·5	0·763 ± 0·011	460 ± 40
2365·9	9 → 2	7·5	0·379 ± 0·014	2000 ± 200
2546·2	10 → 7	7·5	0·507 ± 0·010	1250 ± 200
2913·9	13 → 4	7·5	0·996 ± 0·008	< 40

factors measured for these levels were corrected for this feeding using the method described by Bell *et al* (1969). Comparison of the lifetimes determined in this work with previous determinations of the lifetimes of levels in ^{26}Mg and ^{26}Al is made in table 6. As can be seen the lifetimes of ^{26}Mg levels determined in the present work are consistently longer than those determined by Häusser *et al* (1968) but the lifetimes of ^{26}Al levels are in reasonable agreement with each other. These discrepancies may be caused by the different stopping media used in the experiments.

Table 6. Comparison of the lifetime measurements in ^{26}Mg and ^{26}Al of the present work with that of previous authors

^{26}Mg			^{26}Al		
	τ† (fs)			τ† (fs)	
E_x (keV)	present work	Hausser *et al* (1968)	E_x (keV)	present work	Hausser *et al* (1968) Hausser and Anyas-Weiss (1968)
1809	610 ± 100	530 ± 100‡	1058	<35	<80
2938	170 ± 100	50^{+30}_{-20}§	1759	3300 ± 200	>3400
3589	15000^{+10000}_{-5000}	3000^{+2500}_{-1200}	1852		16 ± 7
3942	970 ± 170	550^{+150}_{-110}	2068·7	380 ± 60	380^{+150}_{-100}
4320		300^{+80}_{-100}	2069·5		13 ± 5
4333	<100	<70	2071·5	460 ± 40	560^{+350}_{-200}
4350	180 ± 30	90^{+40}_{-30}	2365	2000 ± 200	1400^{+500}_{-350}
4835	<90	<50	2546	1250 ± 200	
4901	85 ± 25	50^{+40}_{-30}	2662		>2000
4972	760^{+170}_{-120}	540^{+300}_{-200}	2740		
5291	<10	<50	2914	<40	75^{+40}_{-30}
5474	<100				
5690	<50	70^{+50}_{-40}			
5715	<50				

† None of the lifetimes in this table include any allowance for uncertainties in the stopping theory. In this way differences in the lifetimes due to inadequacies in the theory are not disguised.

‡ This lifetime is measured as 570 ± 140, 700 ± 300, 370 ± 150, 570 ± 40 and 300^{+100}_{-60} fs by Andreev *et al* (1961), Rasmussen *et al* (1961), Booth *et al* (1964), Robinson and Bent (1968) and de Kock *et al* (1970) respectively.

§ This lifetime is measured as 48 ± 25, 176 ± 17 and 95 ± 25 fs by Youngblood *et al* (1967), Robinson and Bent (1968) and de Kock *et al* (1970) respectively.

4.2. The levels of ^{26}Mg

Only one multipole mixing ratio for a transition in ^{26}Mg has been published. This is the E2/M1 mixing ratio for the decay of the 2938 keV level to the first excited state given by Broude and Gove (1963) as $\delta = 0{\cdot}12 \pm 0{\cdot}02$. Spin and parity assignments have been made to the levels of ^{26}Mg by stripping reactions (Hinds *et al* 1965, Cujec 1964) inelastic α particle scattering (Naqib and Blair 1969, private communication) and a correlation experiment (Ferguson *et al* 1967). However, there are still uncertainties in the spins and

parities of several of the levels of ^{26}Mg below 6 MeV in excitation. This lack of information on level quantum numbers and quadrupole–dipole transitions makes detailed comparisons with model predictions difficult. A discussion of the structure of the levels of ^{26}Mg is given below assuming that the nucleus may be understood in terms of the strong coupling collective model.

4.2.1. $K = 0^+$ ground state band. The levels at 0, 1809 and 4320 keV in excitation may be assigned as the 0^+, 2^+ and 4^+ members of a ground state rotational band. The ratio of the E2 transition strength from the 4320 keV level to the E2 transition strength from the first excited state is $0{\cdot}35^{+0{\cdot}30}_{-0{\cdot}06}$ compared to the predicted value for an unmixed $K = 0$ band of 1·43. It seems therefore that either this state is not a member of the ground state band, or that there is some mixing. The situation regarding 4^+ states in ^{26}Mg is not clear, for it has been recently shown in the inelastic α particle scattering experiments of Naqib and Blair (1968, 1969, private communication) that there are several levels in ^{26}Mg below 6 MeV in excitation which share a $\lambda = 4$ excitation strength comparable to that of the single 4^+ level in ^{24}Mg at 6·005 MeV. It is possible that ^{26}Mg is similar (Durell and Symes 1970) to ^{30}Si in that the collective 4^+ strength is shared between two or more levels. There is a level at 4901 keV to which $J = (3, 4)$ has been assigned by Ferguson *et al* (1967). This level decays 100 % to the first excited state with an E2 transition strength of $9{\cdot}4^{+3{\cdot}8}_{-2{\cdot}1}$ Wu assuming a pure quadrupole transition. This state may well contain a large proportion of the ground state band 4^+ strength. If the 4901 keV level is the collective 4^+ state associated with the ground state band then the 4320 keV state could be an intrinsic state arising from the promotion of a proton from Nilsson orbit 7 to Nilsson orbit 5, and the parallel coupling of the $5/2^+$ proton to the $3/2^+$ proton hole.

4.2.2. $K = 2^+$ rotational band. The levels at 2938 ($J^\pi = 2^+$), 3942 (3^+) and 5474 (4^+) keV may be associated with a $K = 2^+$ rotational band. It should be expected that M1 transitions between the members of this band and members of the ground state band be inhibited. The strength ($0{\cdot}20 \pm 0{\cdot}06$ Wu) of the M1 transition between the 2938 keV level and the first excited state is not consistent with this description. However the stripping data of Hinds *et al* (1965) has shown that the first two 2^+ states have large $(s_{1/2}, d_{5/2})$ intrinsic state admixtures. The $l = 0$ population of the 2938 keV level in the (d, p) reaction and the strong excitation of this state by the (t, p) reaction suggests that this state is a particle intrinsic state based on the last two neutrons being in Nilsson orbits 9 and 5. This description accounts for there being a $K = 2^+$ band in ^{26}Mg at a lower excitation energy than in ^{24}Mg where the lowest $K = 2^+$ band is usually assumed to be a γ vibrational band. The large M1 and E2 transition strengths connecting the 2938 and 1809 keV states in ^{26}Mg ($0{\cdot}20 \pm 0{\cdot}06$ and $12{\cdot}4 \pm 6{\cdot}0$ Wu respectively) may then be measures of the intrinsic state admixture within these 2^+ states. Further support to this possibility is given by the shell model calculations of Bell *et al* (1969) who found that the decay modes of the second excited states of ^{26}Mg and ^{26}Si could be quite well explained on the basis of shell model admixtures.

The mixing ratios for the γ rays seen in decay of the 3^+ state at 3942 keV are not known, but if the decay to the first excited state was pure M1 the transition strength would be $(2{\cdot}0 \pm 0{\cdot}3) \times 10^{-3}$ Wu. The pure E2 strength would be $2{\cdot}3 \pm 0{\cdot}5$ Wu. The E2 strength to the 2938 keV level is less than 180 Wu.

Only a limit on the lifetime of the 5474 keV state was obtained, but the decay modes and transition strength limits obtained are consistent with it being the 4^+ member

of the $K = 2$ band. From the branching ratio for the decay of this state it can be deduced that the E2 transition from this 4^+ state to the 2938 keV level is a factor of 50^{+60}_{-20} stronger than that to the 1809 keV state. This ratio is consistent with the in-band and out-of-band description of these transitions.

4.2.3. $K = 3^+$ rotational band. If the band based upon the level at 2938 keV is described in terms of the coupling of the last two nucleons in Nilsson orbits 9 and 5, then one should also expect the existence of a $K = 3^+$ band based upon the same configuration. The level at 4350 keV has an unambiguous spin assignment (Ferguson *et al* 1967) of $J = 3$ and from the work of Hinds *et al* (1965) it probably has positive parity. The mixing ratios for the decays of this state to the first and second excited states are not known, but the transitions strengths calculated assuming pure M1 are $(9{\cdot}0 \pm 1{\cdot}5) \times 10^{-3}$ and $(4{\cdot}1 \pm 0{\cdot}7) \times 10^{-2}$ Wu respectively. The transition to the first excited state could contain a large quadrupole contribution. This state at 4350 keV is a candidate for the $J = K = 3^+$ intrinsic state. The level at 5715 keV has been found by Naqib and Blair (1969) to be $J^\pi = 4^+$ from the ^{26}Mg (α, α') reaction. It decays mainly to the 4350 keV state with its other branch being to the second excited state. This decay mode suggests that this level could be the $J^\pi = 4^+$ member of a $K = 3^+$ band based upon the 4350 keV state.

4.3. The levels of ^{26}Al

Information on the low-lying levels of ^{26}Al has been obtained in the present work, and previous lifetime determinations have been confirmed. In particular, the lifetime of the 2365 keV level has been determined. This level decays by a $\Delta T = 1$ M1 transition to the 2^+, $T = 1$ state at 2069·5 keV. The transition strength for this decay is $0{\cdot}28 \pm 0{\cdot}04$ Wu which is comparable with the other $\Delta T = 1$ M1 transitions in the nucleus. If the $J = 1$ state at 2071·5 keV in excitation has positive parity then the M1 strength for its decay to the $J = 0^+$, $T = 1$ state would be $0{\cdot}011 \pm 0{\cdot}001$ Wu. This would therefore be the only inhibited T favoured M1 transition in ^{26}Al. The 2071·5 keV state could have negative parity, decaying by an E1 transition strength of $(3{\cdot}7 \pm 0{\cdot}4) \times 10^{-4}$ Wu.

5. Conclusions

The present work has provided more data on the systematic trends within the 2s–1d shell. Although the $A = 24$ and 25 nuclei may be described quite well in terms of the rotational model, it seems that the neighbouring nuclei ^{23}Na, ^{26}Mg and ^{26}Al must be treated carefully because of the large number of intrinsic states available. The amount of configuration mixing between states in the nuclei considered in this report is considerable, but the electromagnetic transition strengths measured in this experiment lend support to the evidence for the existence of rotational bands in ^{26}Mg. In the case of ^{26}Al the spectroscopic data available on the low-lying levels do not provide enough information to test any specific model.

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Note added in proof. Recent work in this laboratory (Sharpey-Schafer *et al* 1971 *Phys. Rev. Lett.* **27** 1463–5) has shown that rotational bands also exist in ^{26}Al.

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