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Lifetimes in some even nuclei in the s–d shell

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Abstract. Mean lifetimes have been measured by the Doppler shift attenuation method for several nuclei in the s–d shell. Both Ge(Li) and NaI(Tl) detectors were used. The results (in ps) for the energy levels indicated in parenthesis (MeV) were: ^{24}Mg (1·37) 2·07 ± 0·34, (4·23) 0·110 ± 0·026; ^{30}Si (2·23) 0·332 ± 0·021, (3·51) 0·063 ± 0·015; ^{34}S (2·13) 0·467 ± 0·090, (3·30) 0·144 ± 0·028; ^{38}Ar (2·17) $0{\cdot}473^{+0{\cdot}145}_{-0{\cdot}110}$, (3·38) 25^{+8}_{-12}; ^{40}Ar (1·46) $2{\cdot}45^{+18}_{-1{\cdot}30}$.

1. Introduction

We report some results of a programme of lifetime measurements by the Doppler shift attenuation method (DSAM) in several even nuclei. Although measurements on most of the levels have already been reported, these also have generally been obtained by the DSAM (see table 2), and in view of the systematic uncertainties involved in this method and the advantages of our twin target coincidence technique (see Currie *et al.* 1969 for a full discussion), it is desirable that the results be corroborated. The levels involved are the two lowest 2^+ states in ^{24}Mg, ^{30}Si and ^{34}S, the first 2^+ and 0^+ excited states in ^{38}Ar and the first 2^+ state in ^{40}Ar.

2. Experimental procedure and results

The experimental procedure and apparatus have already been described (Currie and Johnson 1968). Briefly the method was as follows. The majority of the levels were populated by the (α, p) reaction. Two targets were placed simultaneously in the beam. The first was thin and unbacked and the beam passed through it with little energy loss. The second was on a thick backing. Each target was associated with an annular surface barrier detector in which protons near 180° were detected. The γ rays were detected at 0° in coincidence with these protons and in this way we were able to observe the full shift and the attenuated shift simultaneously. The earlier measurements were made by a 7·6 × 7·6 cm NaI (Tl) crystal but latterly great improvements were obtained by using a 50 cm^3 Ge (Li) detector.

The analysis procedures have also been described elsewhere (Currie *et al.* 1969). For the NaI data, attenuation coefficients ($F(\tau)$ values) were calculated from the centroid shifts, while the Ge (Li) data were treated by a full line-shaped fitting analysis in addition to the centroid shift treatment. The stopping powers used were the theoretical ones of Lindhard *et al.* (1963) and atomic scattering was taken into account by the method of Blaugrund (1966).

Figure 1 shows samples of the spectra obtained and table 1 gives the relevant data. The $F(\tau)$ values quoted are corrected for the effects of geometry and target thickness and the results ($F(\tau)$ and τ) for individual runs are given to illustrate the reproducibility. With improved stopping powers these $F(\tau)$ values could be used to obtain revised lifetimes. The errors quoted in table 1 are purely statistical. Some allowances must also be made for errors in the stopping powers. On the basis of our previous

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Table 1. New Data

Nuclide	Level (MeV) ($J\pi$)	Detector	Backing	E_{beam} (MeV)	$F(\tau)$	τ† (ps)
^{24}Mg	1·37	Ge(Li)	Al	25	0·203 ± 0·008	$2{\cdot}22^{+0{\cdot}23}_{-0{\cdot}19}$
	(2^+)	Ge(Li)	Mg	25	0·266 ± 0·013	$2{\cdot}18^{+0{\cdot}30}_{-0{\cdot}26}$
^{30}Si	2·23	NaI	Ni	4·5	0·471 ± 0·067	0·254 ± 0·063
	(2^+)	NaI	Ni	8·0	0·419 ± 0·084	0·348 ± 0·080
		NaI	Ni	4·5	0·419 ± 0·095	0·293 ± 0·090
		NaI	Mg	4·5	0·648 ± 0·065	0·427 ± 0·066
		NaI	Mg	4·5	0·719 ± 0·095	0·317 ± 0·098
		NaI	Mg	7·0	0·808 ± 0·110	0·200 ± 0·110
		NaI	Mg	7·0	0·707 ± 0·102	0·363 ± 0·100
^{30}Si	3·51	Ge(Li)	Sn	7·0	0·905 ± 0·025	0·053 ± 0·012
	(2^+)	NaI	Ni	8·2	0·832 ± 0·072‡	0·077 ± 0·034
		NaI	Ni	8·2	0·784 ± 0·077§	0·096 ± 0·037
		NaI	Ni	8·2	0·861 ± 0·079‡	0·064 ± 0·033
		NaI	Ni	8·2	0·753 ± 0·075§	0·110 ± 0·036
^{34}S	2·13	NaI	Ni	8·00	0·317 ± 0·038	0·445 ± 0·065
	(2^+)	NaI	Ni	8·30	0·275 ± 0·040	0·540 ± 0·119
^{34}S	3·30	NaI	Ni	8·35	0·638 ± 0·052‡	0·135 ± 0·030
	(2^+)	NaI	Ni		0·429 ± 0·070§	0·290 ± 0·075
		NaI	Ni	8·14	0·552 ± 0·120‡	0·185 ± 0·082
		NaI	Ni		0·720 ± 0·110§	0·095 ± 0·048
		NaI	Ni	8·05	0·642 ± 0·080‡	0·125 ± 0·040
		NaI	Ni		0·597 ± 0·070§	0·160 ± 0·040
^{38}Ar	2·17 (2^+)	NaI	Ni	8·10	0·288 ± 0·041	$0{\cdot}473^{+0{\cdot}127}_{-0{\cdot}085}$
^{38}Ar	3·38 (2^+)	NaI	Ni	8·10	0·029 ± 0·101	$25^{+\infty}_{-12}$
^{40}Ar	1·46 (2^+)	NaI	Au	8·40	0·068 ± 0·058	$2{\cdot}45^{+18{\cdot}0}_{-1{\cdot}30}$

† Statistical errors only.
‡ Ground state transition.
§ Cascade transition.

findings (Currie *et al.* 1969) we adopt the compromise figure of 15% for the additional uncertainty. In the subsequent discussion this has been added in quadrature to the figures derived from table 1. The only exception is the first excited state of ^{30}Si which has already been discussed by Currie *et al.* (1969).

2.1. *The* 1·37 *and* 4·23 *MeV levels in* ^{24}*Mg*

The first excited state of ^{24}Mg has been studied extensively and its lifetime measured by different methods. In the first instance it was selected as a convenient case for testing our technique and some results have already been published (Currie and Johnson 1968). There is, however, a further interest in this level. Until recently there has been some inconsistency in the measured values for $B(\mathrm{E2})\uparrow$ and $B(\mathrm{E2})\downarrow$, the latter being greater by 35% on average. We have therefore made more accurate measurements of the lifetime using the 50 cm^3 Ge (Li) detector. The state was populated by the reaction (^{16}O, α) on ^{12}C, the alphas being detected at about 15° in annular counters. This resulted in a full shift of approximately 2% and as can be seen in figure 1 the full shift was considerably greater than the resolution so that detailed line-shape fitting was possible. Backings of Mg and Al were employed, and both gave the same

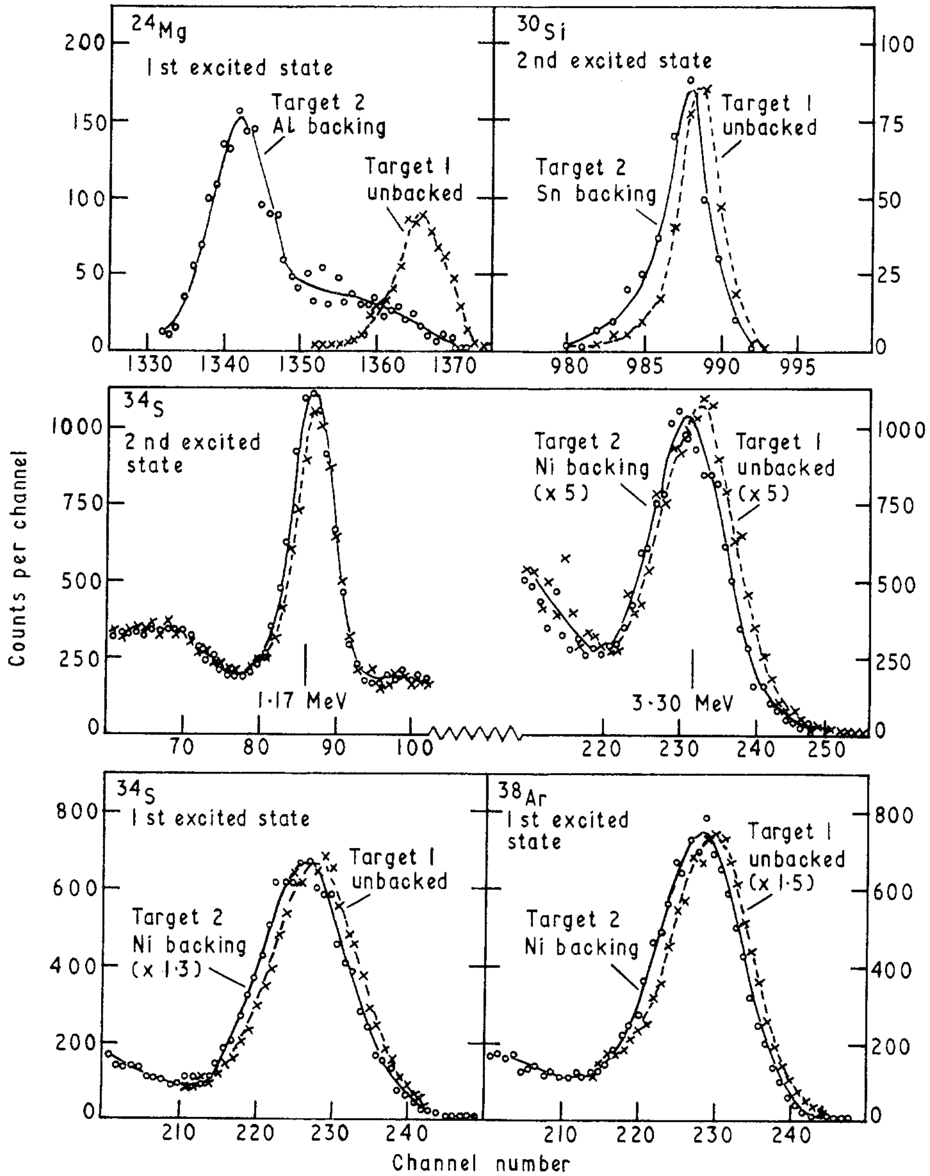

Figure 1. Some examples of the photopeaks recorded. Those for ^{24}Mg and ^{30}Si were taken with a 50 cm^3 Ge(Li) detector, the rest were taken with a NaI(Tl) detector. In all cases the broken curve is the fully shifted peak (unbacked target) while the full curve gives the attenuated peak (backed target). In the top two spectra the full curve was obtained by a computer calculation.

result for τ, but this result is considerably higher than that reported previously by one of us (Currie and Johnson 1968). We have therefore re-analysed the earlier data, taking into account target thickness effects, with the result that the original figure of 1·51 ps is now corrected to 1·60 ± 0·20 ps. This still disagrees with the new results given in table 1. We cannot account for this difference, and in the absence of any known systematic effects which would justify the rejection of the earlier measurement we adopt the weighted mean of the three results as our revised figure.

A detailed study of this level has also been carried out at Chalk River (Pelte *et al.* 1969). From a DSAM line-shape analysis the $B(\mathrm{E2})\downarrow$ was determined to be 24·5 ± 2·0 Weisskopf units. Coulomb excitation was used to investigate the $B(\mathrm{E2})\uparrow$ and a result equivalent to 22·8 ± 2·5 Wu extracted. Our revised result corresponds to 21·2 ± 3·8 Wu.

We have also re-analysed our data for the 2^+ state at 4·23 MeV correcting fully for the decay of recoils in the target layer. Since this state has a short lifetime the effects are significant and the original figure of 0·082 ± 0·015 ps is raised to 0·110 ± 0·026 ps.

2.2. *The 2·23 and 3·51 MeV levels in ^{30}Si*

The investigation of the first excited state of ^{30}Si made with the 50 cm^3 Ge(Li) detector and six different backing materials is described by Currie *et al.* (1969). The lifetime obtained was 0·336 ± 0·025 ps. Prior to the Ge study extensive measurements were also made with the NaI(Tl) detector and backings of Ni and Mg. The weighted means of the results given in table 1 are 0·291 ± 0·043 ps for the Ni backing and 0·356 ± 0·044 ps for Mg. It is noteworthy that, as with the Ge(Li) results, the lifetime for the Mg backing is higher than that for Ni, and the overall mean of 0·323 ± 0·031 ps is very close to the result obtained with the Ge(Li) detector. In this case, therefore, the Ge(Li) and NaI(Tl) give consistent results and these results are also consistent with two previous measurements (Broude *et al.* 1967, Lieb *et al.* 1967), (see table 2). The lifetime of the 2·23 MeV level would thus seem to be fairly well determined.

The lifetime of the second excited state is quite short and the Doppler shift method is therefore subject to larger uncertainties, firstly because of the small observed shift and secondly because of the significant amount of γ-ray emission in the target itself. Our twin target technique, with a Ge(Li) detector would seem to be the best method for such a case since it permits the accurate measurement of very small shifts, and the use of Sn as a backing material greatly reduces the differential effects between target and backing as the slowing down times in Al and Sn are very similar. Figure 1 shows the observed peaks for the cross-over transition, and table 1 gives the results. NaI(Tl) data were also taken, with a Ni backing. The results of four separate runs on both the cross-over and cascade transitions were consistent (table 1) but the mean of 0·087 ± 0·018 ps is not in very good agreement with the Ge(Li) result of 0·053 ± 0·012 ps. There is no evidence of any spurious effects in either of these results and so we adopt the weighted mean 0·063 ± 0·015 ps for the lifetime of this state.

Our result is in good agreement with the Freiburg result (Lieb *et al.* 1967) but not with the Chalk River result (Broude *et al.* 1967), (table 2). Also while these two earlier measurements give a consistent ratio of 3·0 between the first and second excited state lifetimes we obtain 4·8. This is of some importance since it is the ratio of the transition rates which is of most theoretical significance. In view of the extensive nature and general consistency of our own measurements on ^{30}Si and also because the Chalk River measurements were carried out with very thick Al targets on Au, we are inclined to attribute less weight to their results and to regard the Freiburg result and our own result as more reliable measurements of the second excited state lifetime.

Table 2. Summary of lifetimes and transition strengths

Element	Level (MeV) (J, π)	Previous results (ps)	This work (ps)	(Transition) (Multi-polarity)	Strength $\|M\|^2$ w.u.
^{24}Mg	1·37 (2⁺)	$1\cdot4 \pm 0\cdot3$(a) $1\cdot44^{+0\cdot24}_{-0\cdot20}$(b) $1\cdot67 \pm 0\cdot16$(c) $1\cdot91 \pm 0\cdot26$(c)	$2\cdot07 \pm 0\cdot34$	1·37 → 0 E2	$21\cdot2^{+4\cdot2}_{-3\cdot0}$
^{24}Mg	4·23 (2⁺)	$0\cdot101^{+0\cdot035}_{-0\cdot031}$(b) $0\cdot12 \pm 0\cdot03$(d)	$0\cdot110 \pm 0\cdot026$	4·23 → 0 E2	$0\cdot99^{+0\cdot31}_{-0\cdot19}$
				4·23 → 1·37 E2	$2\cdot33^{+0\cdot72}_{-0\cdot43}$
				M1	$(5\cdot8 \pm 4\cdot5) \times 10^{-6}$
^{30}Si	2·23 (2⁺)	$0\cdot26 \pm 0\cdot06$(e) $0\cdot47 \pm 0\cdot05$(g)	$0\cdot332 \pm 0\cdot021$(f)	2·23 → 0 E2	$8\cdot01^{+0\cdot53}_{-0\cdot47}$
^{30}Si	3·51 (2⁺)	$0\cdot086 \pm 0\cdot020$(e) $0\cdot15 \pm 0\cdot02$(g)	$0\cdot063 \pm 0\cdot015$	3·51 → 0 E2	$1\cdot97^{+0\cdot61}_{-0\cdot38}$
				3·15 → 2·23 E2	$11\cdot7 \pm 6\cdot4$
				M1	$0\cdot128^{+0\cdot040}_{-0\cdot025}$
^{34}S	2·13 (2⁺)	$0\cdot35 \pm 0\cdot06$(h)	$0\cdot467 \pm 0\cdot090$	2·13 → 0 E2	$6\cdot08^{+1\cdot45}_{-0\cdot98}$
^{34}S	3·30 (2⁺)	$0\cdot12 \pm 0\cdot03$(h)	$0\cdot144 \pm 0\cdot028$	3·30 → 0 E2	$1\cdot22^{+0\cdot30}_{-0\cdot20}$
				3·30 → 2·13 E2	$2\cdot0 \pm 0\cdot6$
				M1	$0\cdot061^{+0\cdot015}_{-0\cdot010}$
^{38}Ar	2·17 (2⁺)	$0\cdot59 \pm 0\cdot07$(h, i)	$0\cdot473^{+0\cdot145}_{-0\cdot110}$	2·17 → 0 E2	$4\cdot7^{+1\cdot4}_{-1\cdot1}$
^{38}Ar	3·38 (0⁺)		$25^{+\infty}_{-12}$	3·38 → 2·17 E2	$\leq 3\cdot5$
^{40}Ar	1·46 (2⁺)	$1\cdot2 \pm 0\cdot3$(j)	$2\cdot45^{+18}_{-1\cdot30}$	1·46 → 0	$6\cdot1^{+7\cdot0}_{-5\cdot4}$

(a) Endt and van der Leun 1967; (b) Robinson and Bent 1968; (c) Pelte 1969, private communication; (d) Alexander *et al.* 1966; (e) Lieb *et al.* 1967; (f) This value is the weighted mean of the results in table 1 with the accurate Ge(Li) result from Currie *et al.* (1969). In this case the additional 15% error for slowing down uncertainties has not been added; (g) Broude *et al.* 1967; (h) Grawe and Lieb 1969; (i) Grawe and Lieb 1968; (j) Kokame *et al.* 1966.

2.3. *The* 2·13 *and* 3·30 *MeV levels in* ^{34}S

For ^{34}S, all the measurements were made with NaI(Tl). The targets of red ^{31}P were prepared by a special evaporation technique (Hooton 1964) and the backing used was Ni. Table 1 gives details of the runs. The statistical errors are large for individual runs but within their limitations the agreement is good, thus showing consistency between the lifetimes determined from the two components in the decay of the second excited state and also between a normal and reversed target arrangement (normally the first target encountered by the beam was unbacked but in this case a reversed arrangement was also tried as a check on geometrical corrections). Furthermore both determinations are in excellent agreement with the results of Grawe and Lieb (1969).

2.4. *The* 2·17 *and* 3·38 *MeV levels in* ^{38}*Ar and the* 1·46 *MeV level in* ^{40}*Ar*

The spectra obtained for these levels were again taken with NaI(Tl) but were of poorer quality than in the foregoing cases, chiefly because of asymmetries in the intrinsic photopeak line shapes. In addition each lifetime was obtained with only one backing, and for the two relatively long lived levels, the backings used (Ni and Au) were not the most appropriate. The targets were AgCl.

The results 0·47 ± 0·13 ps for the first excited state of ^{38}Ar is consistent with the figure of 0·59 ± 0·07 ps published by Grawe and Lieb (1968) but the result for the second excited state gives little more than a lower limit for the lifetime. For ^{40}Ar both a lifetime measurement (Gusinkii *et al.* 1968) and a B(E2) from α scattering (Kokame *et al.* 1966) are available. While our figure of $2{\cdot}45^{+18{\cdot}0}_{-1{\cdot}30}$ ps is again not well determined, it does agree with both of these measurements.

3. Conclusion

The final results are compared with other recent results in table 2 where it is seen that the agreement is quite tolerable. The transition strengths derived from the present results also listed in table 2 illustrate the expected changes throughout the s–d shell. The ^{24}Mg nucleus is known to be strongly deformed, and the rotational band structure has been well established. In particular, the in-band E2 strength from the first excited state is greatly enhanced, while the interband strengths from the second 2^+ level are much weaker. We also note that the $\Delta T = 0$ selection rule and the interband nature of the cascade very strongly inhibit the M1 strength. The rest of the levels measured are away from the strong deformation region, and the strengths are about average. Very little more can be added at present to the previous theoretical implications of these transition rates, as for example discussed by Grawe and Lieb (1969) and Robinson and Bent (1968).

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