Aust. J. Phys., 1982, **35**, 371–6

Recoil-distance Lifetime Measurements of ^{47}Sc Levels

H. Ohnuma,[A,B] *P. B. Foot,*[A] *T. Aoki,*[A,C] *C. G. Ryan*[A] *and H. H. Bolotin*[A]

[A] School of Physics, University of Melbourne, Parkville, Vic. 3052.
[B] Permanent address: Physics Department, Tokyo Institute of Technology, Oh-Okayama, Meguro, Tokyo, Japan.
[C] Present address: Radioisotope Centre, Tsukuba University, Sakura-mura, Ibaraki-ken, 303, Japan.

Abstract

The mean lives of the first excited $\frac{3}{2}^-$ and $\frac{1}{2}^+$ states at 808 and 1391 keV excitation energy in ^{47}Sc were measured using the recoil-distance method (RDM). The levels of interest were populated in the ^{44}Ca(α, pγ) reaction using 9 MeV α beams. The mean lives extracted from the p–γ coincidence data were $\tau(808\,\text{keV}, \frac{3}{2}^-) = 22 \pm 5$ ps and $\tau(1391\,\text{keV}, \frac{1}{2}^+) = 13 \pm 4$ ps. These results are compared with similar prior measurements on other levels of interest in ^{47}Sc as well as with those in the other Sc isotopes, and are discussed in the light of the systematics displayed.

1. Introduction

It is surprising that despite growing interest in $f_{7/2}$ nuclei and the many prior extensive studies of their level properties, the lifetimes of two crucial states in ^{47}Sc have not as yet been experimentally determined. They are the $\frac{3}{2}{}_1^-$ and $\frac{1}{2}{}_1^+$ states at 808 and 1391 keV excitation energy, respectively.

Low-lying $\frac{3}{2}^-$ states in $f_{7/2}$ nuclei are usually not well accounted for by the $(f_{7/2}^n)$ model, but show complicated aspects (Kutchera *et al.* 1978; Poves and Zucker 1981). Roughly speaking, they can be grouped into three categories: those that have near-single-particle-like properties; those that decay strongly to the (usually ground) $\frac{7}{2}{}_1^-$ states; and those for which the decays to the $\frac{7}{2}{}_1^-$ states are severely hindered. It is an intriguing question why and how this behaviour arises. Typical examples of the first, second and third categories respectively are the $\frac{3}{2}{}_1^-$ states of ^{41}Ca, ^{45}Sc and ^{51}Cr. In ^{51}Cr (and also in ^{53}Fe) the $\frac{3}{2}{}_1^-$ state can even be regarded as a member of a $K^\pi = \frac{1}{2}^-$ rotational band (Kasagi and Ohnuma 1978; Kasagi and Ohnuma 1980). A lifetime determination of the $\frac{3}{2}{}_1^-$ level in ^{47}Sc will hopefully allow an overview of the properties of those levels in Sc isotopes.

Positive-parity levels in $f_{7/2}$ nuclei have been known to show band-like structure, presumably as a result of one-hole states arising from the $\frac{1}{2}$[200] and $\frac{3}{2}$[202] orbitals. It has been found recently (Ohnuma and Kasagi 1981) that the B(M1) value for the $\frac{1}{2}{}_1^+ \rightarrow \frac{3}{2}{}_1^+$ transition in ^{49}V is smaller, by factors of ~ 30 to ~ 50, than those of other M1 transitions between the positive-parity levels. Such a degree of hindrance cannot be explained in a simple-minded way, but is reproduced by a band-mixing calculation with all the s–d orbits included. It has been shown by Ohnuma and Kasagi (1981) that the calculated B(M1) value for the $\frac{1}{2}{}_1^+ \rightarrow \frac{3}{2}{}_1^+$ transition is sensitive to the deformation, and that strong cancellation of the M1 matrix elements takes place at $\beta \approx 0{\cdot}2$. The inclusion of the $d_{5/2}$ orbit, as well as the $d_{3/2}$, is essential for such a cancellation.

A natural question then would be whether or not this is a special phenomenon of rare occurrence; a question that can be answered, at least partially, by a knowledge of the lifetime of the $\frac{1}{2}^{+}_{1}$ level in ^{47}Sc.

In this paper we report the results of the lifetime determinations of the $\frac{3}{2}^{-}_{1}$ and $\frac{1}{2}^{+}_{1}$ states in ^{47}Sc. We made use of the Doppler-shift RDM, since the lifetimes of both of these levels are known to be long from limits set by previous workers (Halbert 1977). The results are discussed along the lines described above.

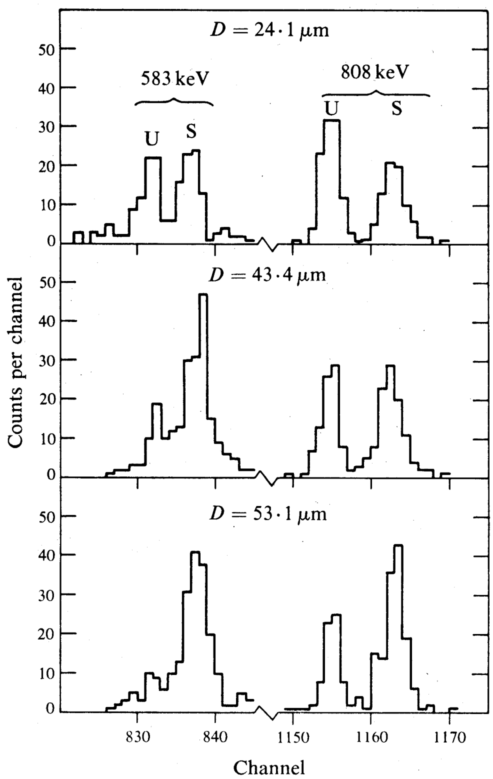

Fig. 1. Sample γ-ray spectra in coincidence with proton groups of interest. Unshifted and shifted peaks are labelled U and S respectively; D denotes the target–stopper distance.

2. Experimental Procedure and Results

A 9 MeV $^{4}He^{++}$ beam from the University of Melbourne 5U Pelletron accelerator was used to excite levels in ^{47}Sc via the ^{44}Ca(α, p)^{47}Sc reaction. The target was metallic calcium 120 μg cm^{-2} thick, enriched to 98·6% in ^{44}Ca, reduced from $CaCO_3$ by Ta powder, and evaporated onto a stretched Ag foil 1·3 mg cm^{-2} thick. The target assembly was set normal to the beam with the silver side to the beam. The energy loss of the beam in the silver foil was 250 keV. Another parallel silver foil 1·6 mg cm^{-2} thick downstream from the target was used as a recoil-nucleus stopper. The beam was stopped by a thick tantalum plate placed beyond the second foil. A micrometer set-up served to change, as well as to specify, the target–stopper distance.

Outgoing protons were detected by an Si surface-barrier annular detector 1000 μm thick, which was covered by a copper foil 25 μm thick to stop scattered α particles. Gamma rays were detected by a 60 cm^3 high purity (HP) Ge detector at 0°. Another HP Ge detector of the same size at 90° served as a monitor. Both sets of p–γ coincidence energy and timing signals from these detectors were stored event-by-event on magnetic tape and were also partially analysed on-line to monitor the experiment.

Relevant portions of representative γ-ray spectra gated by the proton groups directly populating the levels around 800 and 1400 keV are shown in Fig. 1. The 583 keV γ ray corresponds to the transition between the 1391 and 808 keV levels, and the 808 keV γ ray to the ground state transition from the 808 keV state. Fig. 2 shows the decay curves for the 808 and 583 keV γ rays obtained from these spectra. Here we define the ratio $R = I_U/(I_U+I_S)$, where I_U and I_S are the intensities of the unshifted and shifted component peaks respectively. The solid lines are the results of least-squares fits to the data. The mean lives extracted are $\tau(808\,\text{keV}, \frac{3}{2}^-) = 22\pm5$ ps and $\tau(1391\,\text{keV}, \frac{1}{2}^+) = 13\pm4$ ps.

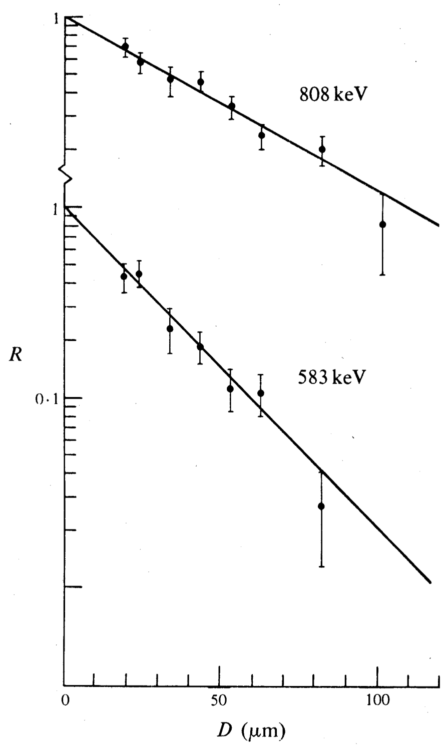

Fig. 2. Measured ratio R of the unshifted to the sum of the unshifted and shifted component intensities plotted as a function of target–stopper distance D for the 808 and 583 keV γ rays. The solid lines represent least-squares fits to the data.

3. Discussion

(*a*) *808 keV Level*

A summary of the experimental data on the $\frac{3}{2}{}_1^- \to \frac{7}{2}{}_1^-$ transitions in odd-mass Sc isotopes is given in Table 1. The excitation energy of the $\frac{3}{2}{}_1^-$ level initially decreases as the neutron number increases, reaches a minimum at $N = 24$, and then rises again as $N \to 28$. The spectroscopic factors previously reported from studies of proton transfer reactions to these levels display a similar behaviour, as indicated in the second last column of Table 1. The B(E2) values for the $\frac{3}{2}{}_1^- \to \frac{7}{2}{}_1^-$ transitions, being largest in the middle of the $f_{7/2}$ shell and tapering off towards both ends, are well correlated with the excitation energies and the spectroscopic factors. The B(E2) value for ^{47}Sc, obtained from the present lifetime measurement, is also consistent with this systematic behaviour.

Table 1. Properties of lowest $\frac{3}{2}^-$ states in Sc isotopes

Nucleus	E_x (keV)	τ_m (ps)	$BR(\frac{3}{2}{}_1^- \to \frac{7}{2}{}_1^-)$ (%)	$B(E2; \frac{3}{2}{}_1^- \to \frac{7}{2}{}_1^-)$ ($e^2 fm^4$)	c^2S	Comprehensive reference to prior work
^{41}Sc	1718	$0 \cdot 9^A$	$(100)^A$	60	2·7–3·6	Endt & van der Leun (1978)
^{43}Sc	472	226 ± 15	96	150 ± 10	0·38–0·72	Endt & van der Leun (1978)
^{45}Sc	377	61 ± 5	8·1	144 ± 12	$0 \cdot 56^C$	Beene (1977)
^{47}Sc	808	22 ± 5^B	100	108^{+32}_{-20}	$0 \cdot 57^D$	Halbert (1977)
^{49}Sc	3085	$0 \cdot 07^{+0 \cdot 04}_{-0 \cdot 03}$	92	40^{+25}_{-15}	$2 \cdot 51^E$	Halbert (1978)

[A] Partial lifetime calculated from $(2J+1)\Gamma_p \Gamma_{\gamma_0}/\Gamma = 3$ meV, assuming $\Gamma_p = \Gamma$. [B] Obtained in present work.
[C] Schwartz and Alford (1966). [D] Schwartz *et al.* (1967). [E] Britten and Watson (1976).

Table 2. Properties of electromagnetic transitions between positive-parity levels in ^{47}Sc

Details from prior experimental work are from Toulemonde *et al.* (1974) and Halbert (1977)

$E_i \to E_f$ (keV)	$J_i^\pi \to J_f^\pi$	τ_m (ps)	BR (%)	δ	$B(M1)^A$ (μ_N^2)	$B(E2)^B$ ($e^2 fm^4$)
1404 → 767	$\frac{5}{2}{}_1^+ \to \frac{3}{2}{}_1^+$	$1 \cdot 4 \pm 0 \cdot 4$	23	$0 \cdot 72 \pm 0 \cdot 28$	$(2 \cdot 4^{+1 \cdot 8}_{-1 \cdot 0}) \times 10^{-2}$	440^{+460}_{-280}
1857 → 767	$(\frac{7}{2}{}_1^+) \to \frac{3}{2}{}_1^+$	$0 \cdot 45 \pm 0 \cdot 09$	9	∞		107^{+26}_{-18}
→ 1404	$\to \frac{5}{2}{}_1^+$		2		$< 3 \cdot 4 \times 10^{-2}$	< 2400
1391 → 767	$\frac{1}{2}{}_1^+ \to \frac{3}{2}{}_1^+$	13 ± 4^C	14		$< 4 \times 10^{-3}$	< 140
2002 → 1404	$\frac{3}{2}{}_2^+ \to \frac{5}{2}{}_1^+$	$0 \cdot 58 \pm 0 \cdot 11$	15		$< 8 \cdot 5 \times 10^{-2}$	< 3400
2381 → 767	$\frac{5}{2}{}_2^+ \to \frac{3}{2}{}_1^+$	$< 0 \cdot 25$	44		$< 2 \cdot 4 \times 10^{-2}$	< 130

[A] Upper limits obtained assuming transitions with unknown mixing ratios to be pure M1.
[B] Upper limits obtained assuming transitions with unknown mixing ratios to be pure E2.
[C] Obtained in present work.

The $\frac{3}{2}{}_1^-$ levels in ^{43,45,47}Sc cannot be reproduced in the pure $(f^n_{7/2})$ model, the model predictions being too high in excitation energy (Kutchera *et al.* 1978). The inclusion of the one-particle jump to the $p_{3/2}$ orbit tends to ameliorate the situation (Oda *et al.* 1977; Yokoyama *et al.* 1978; Horie *et al.* 1978; Poves and Zuker 1981), but not without some trouble (Poves and Zuker 1981).

(b) 1391 keV Level

The properties of electromagnetic transitions between the positive-parity levels in ^{47}Sc are summarized in Table 2. Further experimental information is clearly needed, especially on mixing ratios. Nevertheless, the upper limit of $4\times10^{-3}\ \mu_N^2$ (or $4\cdot4\times10^{-5}$ $e^2\,\mathrm{fm}^2$) set for the B(M1) value of the $\frac{1}{2}{}_1^+ \to \frac{3}{2}{}_1^+$ transition from the present lifetime measurement unambiguously establishes this M1 transition to be severely hindered.

The upper limits of the B(E2) values for the $\frac{3}{2}{}_2^+ \to \frac{5}{2}{}_1^+$ and $(\frac{7}{2}{}_1^+) \to \frac{5}{2}{}_1^+$ transitions (inferred assuming these transitions to be pure E2) suggest that the mixing ratios of these transitions cannot be large; thus, both are predominantly of M1 character. Therefore, although the mixing ratios of these transitions are not known, the B(M1) values for these transitions should not be expected to be much smaller than the upper limits (obtained assuming pure M1) given in Table 2; both are about an order of magnitude larger than that of the $\frac{1}{2}{}_1^+ \to \frac{3}{2}{}_1^+$ transition.

Ohnuma and Kasagi (1981) found the B(M1) value for the $\frac{1}{2}{}_1^+ \to \frac{3}{2}{}_1^+$ transition in ^{49}V to be from one-thirtieth to one-fiftieth of those of other M1 transitions between the positive-parity levels. Such a degree of hindrance has been explained within the framework of the strong-coupling model by the cancellation of the M1 matrix elements. The results given in Table 2 suggest that there is a remarkable similarity between the intraband M1 transitions in ^{49}V and ^{47}Sc. Furthermore, one can deduce from the available data that the $B(\mathrm{M1};\ \frac{1}{2}{}_1^+ \to \frac{3}{2}{}_1^+)$ values in ^{43}Sc and ^{45}Sc are $<5\times10^{-3}\ \mu_N^2$ and $<6\times10^{-3}\ \mu_N^2$ respectively, and that the B(M1) values for the $\frac{3}{2}{}_2^+ \to \frac{3}{2}{}_1^+$ transitions are also hindered in these nuclei. Certainly this behaviour cannot be considered accidental, but must reflect similarities in the structure of 'hole' states in these nuclei. Further experimental data, for example on positive-parity levels in ^{45}Ti and ^{47}Ti, and large-space shell-model calculations could shed light on the evolution of 'collectivity' in core-excited states of nuclei in this mass region.

Acknowledgments

The authors appreciate the technical aid provided by B. Szymanski and R. Szymanski. One of the authors (H.O.) wishes to thank the staff of the School of Physics of the University of Melbourne for their kind hospitality and acknowledges receipt of a Sir Thomas Lyle Fellowship which made his stay there possible.

References

Beene, J. R. (1977). *Nucl. Data Sheets* **22**, 1.
Britten, R. M., and Watson, D. L. (1976). *Nucl. Phys.* A **272**, 91.
Endt, P. M., and van der Leun, C. (1978). *Nucl. Phys.* A **310**, 1.
Halbert, M. L. (1977). *Nucl. Data Sheets* **22**, 59.
Halbert, M. L. (1978). *Nucl. Data Sheets* **24**, 175.
Horie, H., Muto, K., and Yokoyama, A. (1978). *J. Phys. Soc. Jpn Suppl.* **44**, 329.
Kasagi, J., and Ohnuma, H. (1978). *J. Phys. Soc. Jpn* **45**, 1099.
Kasagi, J., and Ohnuma, H. (1980). *J. Phys. Soc. Jpn* **48**, 351.

Kutchera, W., Brown, B. A., and Ogawa, K. (1978). *Rev. Nuovo Cimento* **3**, Vol. 1, 1.
Oda, T., Muto, K., and Horie, H. (1977). *Lett. Nuovo Cimento* **18**, 549.
Ohnuma, H., and Kasagi, J. (1981). *J. Phys.* G **7**, 1691.
Poves, A., and Zuker, A. (1981). *Phys. Rep.* **70**, 235.
Schwartz, J. J., and Alford, W. P. (1966). *Phys. Rev.* **149**, 820.
Schwartz, J. J., Alford, W. P., and Marinov, A. (1967). *Phys. Rev.* **153**, 1248.
Toulemonde, M., Deschenes, L., Jamshidi, A., and Schulz, N. (1974). *Nucl. Phys.* A **227**, 309.
Yokoyama, A., Oda, T., and Horie, H. (1978). *Prog. Theor. Phys. Jpn* **60**, 427.

Manuscript received 19 April, accepted 10 May 1982