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LETTER TO THE EDITOR

Beam–foil mean-life measurements of the 3d4p ^{1}P and ^{3}F levels in Sc II

H P Palenius, L J Curtis and L Lundin
Research Institute of Physics, S-104 05 Stockholm, Sweden

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Abstract. Beam-foil mean-life measurements have been made for two levels in Sc II in an attempt to resolve a discrepancy between earlier beam-foil and beam-laser measurements. Our measurements yield the mean-lives $\tau(3d4p\ ^1P) = 8{\cdot}6 \pm 0{\cdot}6$ ns and $\tau(3d4p\ ^3F) = 6{\cdot}5 \pm 0{\cdot}4$ ns. The discrepancy between the beam-foil measurement of Buchta and colleagues, and the beam-laser measurement of Stoner and colleagues for the ^{1}P mean-life is explained as a result of a blend between Sc II and Sc III.

Recently measurements of the mean-lives of two levels in Sc II have been made using resonant in-flight laser excitation of a fast ion beam, which provide a useful check of the earlier and more extensive beam-foil measurements in Sc I, II and III by Buchta *et al* (1971). Thus while the result of 5·6 ± 0·6 ns for the 3d4p ^{3}F level by Buchta *et al* is in good agreement with the 6·2 ± 0·2 ns beam-laser result of Arnesen *et al* (1976), the result of 5·5 ± 0·5 ns for the 3d4p ^{1}P level by Buchta *et al* is in clear disagreement with the 9·2 ± 0·5 ns beam-laser result of Stoner *et al* (1976). The main advantage of a beam-laser measurement over a beam-foil measurement lies in the selectivity of the excitation, which avoids both the effects of cascade repopulation from higher-lying levels and of spectral line blending. Since the beam-foil results of Buchta *et al* are in excellent agreement with recent theoretical calculations for Sc III (Biémont 1976, Warner 1972, Wiese and Fuhr 1975), which should be reasonably reliable for this potassium-like sequence, it seems probable that the decay curve analysis techniques used by Buchta *et al* satisfactorily accounted for cascade repopulation effects. A more likely source of error in beam-foil work involves blending between close-lying spectral lines due to the Doppler broadening of the spectra. Subsequent to the publication of the work of Buchta *et al* a term analysis for Sc III has been completed by Holmström (1972) and Van Deurzen *et al* (1973) which has revealed that the Sc III 5p $^2P_{3/2}$–5d $^2D_{5/2}$ transition occurs at λ5032 Å (rather than 5020 Å, as earlier isoelectronic extrapolations had indicated) and therefore could have been strongly blended with the Sc II 3d^2 ^{1}D–3d4p ^{1}P transition at λ5031 Å in the beam-foil spectra. This possibility is easily tested by beam-foil methods, since the Sc II 3d4p ^{1}P level possesses another strong decay channel not investigated by Buchta *et al*, the 3d^2 ^{1}D–3d4p ^{1}P at λ3535 Å which should be free of close-lying blends. We have therefore restudied the 3d4p ^{3}F and ^{1}P levels in Sc II by beam-foil methods, remeasuring the relative spectral intensitites and decay curves of their transitions over a wide range of beam energies with spectral resolutions of high precision automated beam-foil instrumentation, and have compared our results with the original primary data of Buchta *et al* in an attempt to resolve this discrepancy.

Numerous instrumental improvements have been made in the beam-foil equipment at the Research Institute of Physics since the measurement of Buchta *et al* in 1971. A wider range of accelerator energies is available with the 380 keV heavy-ion accelerator than was possible with the 80 kV isotope separator; sub-millimetre positional accuracy has been achieved in foil positioning and optical detection, and the operation has been automated through a programmable on-line control and data collection system. Details of this apparatus have been given elsewhere (Astner *et al* 1976). In this measurement Sc^+ ions were accelerated to energies of 75–380 keV and directed through 5–10 $\mu g\, cm^{-2}$ carbon foils. The light emitted by the foil-excited ions was focused by a lens onto the slit of the monochromator and detected as single photons by a low noise photomultiplier tube. Decay curves were recorded by successively stepping the carriage-mounted foil turret in 0·25 mm or 0·50 mm increments. To compensate for small fluctuations in the beam current, data were accumulated for a preset number of counts from a monitor phototube which viewed the beam at a fixed distance from the foil through a fibre-optics link. The beam current was quite steady, however, and the accumulation time rarely deviated by more than 10% among the channels unless major foil damage had occurred during the run. A systematic increase in accumulation time over a run thus signalled foil damage, and both the foil and the run were then discarded. The decay curves and the accumulation times were recorded in a multichannel analyser operated in the multiscaling mode, and punched onto paper tape after each complete data set which consisted of 100–200 steps. The velocities of the ions emerging from the foil were measured after each data set using a 50 cm Danfysik electrostatic analyser which was calibrated using beam-foil excited quantum beat signals of known frequency (Astner *et al* 1976). This repeated velocity measurement allowed a second monitoring of foil characteristics, which were found not to change measurably over the course of a single decay curve measurement (~300 s) unless a major foil failure occurred. Decay curves were then analysed using standard multi-exponential non-linear least squares fitting programs.

Figure 1 compares a spectral scan taken at 75 keV beam energy with one taken at 275 keV in the region λ4600–5200 Å. Classified lines of Sc I, II and III are indicated by vertical lines of lengths proportional to their reported emission intensities (Meggers *et al* 1975, Van Deurzen *et al* 1973). No Sc IV lines (Smitt 1973) have been found in our beam-foil spectra. Notice the fact that at 75 keV the lines at the wavelengths 4670 Å and 5031 Å are about equally strong, these lines presumably arising from the Sc II $3d^2\ ^1D$–$3d4p\ ^1F$ and $3d^2\ ^1D$–$3d4p\ ^1P$ transitions respectively. At 275 keV the trend of the relative intensities of these two lines has changed so that the line at λ5031 Å is much stronger than that at λ4670 Å. Although it is difficult to deduce relative excitation functions from beam-foil spectra without a careful evaluation of the effects of lifetimes and beam velocities upon detection efficiencies, it can be inferred with reasonable certainty from this figure that blending from the Sc III $5p\ ^2P_{3/2}$–$5d\ ^2D_{5/2}$ transition at λ5032 Å increases sharply with beam energy and poses severe problems for lifetime measurements with these excitation conditions. The Sc III 5d ^2D lifetime has been measured previously in another branch (Buchta *et al* 1971) to be 2·4 ns, and theoretically calculated (Wiese and Fuhr 1975) to be 2·3 ns, which could be difficult to separate from the 9·2 ns value reported for the Sc II 3d4p ^1P lifetime by Stoner *et al* if the two transitions contributed about equally. To test this we measured the decay curve of the 5031 Å line at foil-emergent beam energies of 75, 150, 275 and 330 keV, which, when analysed, gave lifetimes of 8,

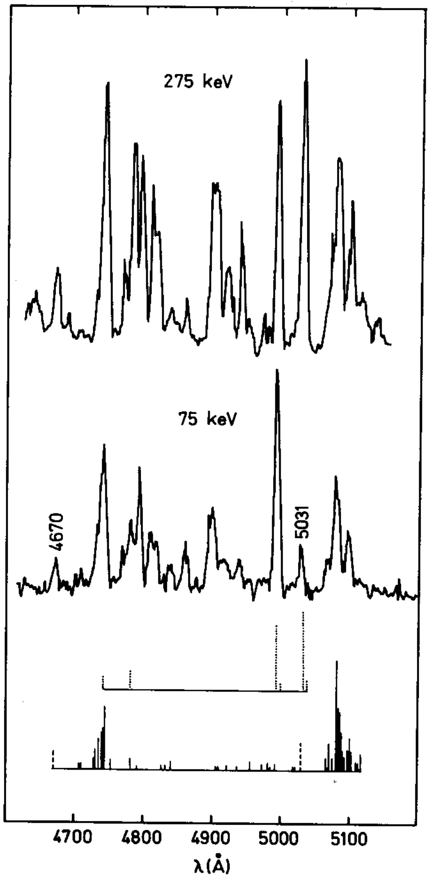

Figure 1. Spectral scans at 75 and 275 keV beam energies. Strong transitions are indicated by vertical lines of length proportional to the emission intensities reported for Sc I (full lines) and Sc II (broken lines) by Meggers *et al* (1975) and for Sc III (broken lines) by Van Deurzen *et al* (1973). Some intensity peaks on the scans in the wavelength region 4790–5000 Å cannot be identified with the help of these reports.

6, 4 and 3 ns, respectively. The energy dependence indicates that the Sc II transition dominates at the lower energies, the Sc III transition dominates at higher energies, but at intermediate energies (Buchta *et al* used 168 keV) blending is too strong for a reliable analysis. Thus it is clear that the Sc II 3d4p ^{1}P lifetime, measured by Buchta *et al* by the decay branch at λ5031 Å is unreliable. Furthermore, the Sc I 3d^{2}4p ^{2}D and ^{4}D lifetimes, measured by the decay branches at λ4992 Å (although the multiplet centroid at λ5007 Å is listed as the nominal wavelength for this transition in their table 1) and at λ4737 Å, respectively, are also unreliable due to blending from Sc III transitions. In addition, the measurement by Buchta *et al* of the Sc II 3d4p ^{3}D lifetime by the decay branch at λ3575 Å should be used rather than the measurement by the decay branch at λ4318 Å, since the latter might have been affected by the close Sc III transition at λ4309 Å. Since the λ5031 Å transition is not suitable for measurement of the Sc II 3d4p ^{1}P lifetime, we next made decay curve measurements of its 3d^2 ^{1}D$_2$–3d4p ^{1}P$_1$ branch at λ3535 Å. In this case we found that, provided the spectral resolution used was sufficient to neglect the effect of a weaker (and unknown) transition at λ3530 Å, a lifetime of 8·6 ± 0·6 ns was extracted regardless

Table 1.

Level	Mean-life (ns)				
	This work	Earlier beam-foil	Beam-laser	Emission	Theory
3d4p z $^1P^o$	8·6 ± 0·6	5·5 ± 0·5[a]	9·2 ± 0·5[b]	7·0[d], 6·1[e]	6·6[f], 8·0[g]
3d4p z $^3F^o$	6·5 ± 0·4	5·6 ± 0·6[a]	6·2 ± 0·2[c]	5·8[d], 6·6[e]	5·2[f], 5·5[g]

a, Buchta *et al* (1971); b, Stoner *et al* (1976); c, Arnesen *et al* (1976); d, Warner (1967); e, Corliss and Bozman (1962); f, Wiese and Fuhr (1974); g, Victor *et al* (1976).

of the beam energy, in agreement with the beam-laser measurement of Stoner *et al* (1976). Similar decay curve measurements were made for the Sc II 3d4s $^3D_1$–3d4p $^3F_2$ transition at λ3642 Å which yielded a value of 6·5 ± 0·4 ns, also the same value regardless of beam energy, which is in agreement both with the beam-foil measurement of Buchta *et al* (1971) and with the beam-laser measurement of Arnesen *et al* (1976). These results are compared with each other and with emission measurements and theoretical calculations in table 1.

In conclusion, our results support the beam-laser measurement of Stoner *et al* (1976) of the Sc II 3d4p ^1P lifetime, and both the beam-laser measurement of Arnesen *et al* (1976) and the beam-foil measurement of Buchta *et al* (1971) for the Sc II 3d4p ^3F. Further, we have found evidence to indicate that the beam-foil measurements by Buchta *et al* of the Sc II 3d4p ^1P and Sc I 3d^{2}4p ^2D and ^4D lifetimes were seriously affected by blends from Sc III transitions. However, a comparison of the wavelengths measured by Buchta *et al* with recent Sc III classifications (Holmström 1972, Van Deurzen *et al* 1973) indicates that of the 22 lifetimes reported by Buchta *et al*, only these three would be expected to be troubled by blends from Sc III.

It is interesting to note that the Sc II lifetimes calculated by Victor *et al* (1976) agree within the combined error limits with beam-foil and beam-laser results, although the calculated values are systematically around 15% shorter.

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