Eur. Phys. J. D **2**, 125–129 (1998)

THE EUROPEAN PHYSICAL JOURNAL D

Lifetime measurements for some n = 2 levels in Be-like Cl XIV and S XIII

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Received: 29 October 1997 / Revised: 10 February 1998 / Accepted: 5 March 1998

Abstract. Lifetime measurements have been carried out for some low lying ($n = 2$) levels in the four-electron ions Cl XIV and S XIII using the beam-foil technique. Accurate oscillator strengths for the $2s^2\ ^1S - 2s2p\ ^1P^o$ transition have been determined by the inclusion of prominent cascades in the analysis. Lifetimes of the levels of the $2p^2\ ^3P_j$ multiplet have also been measured for both ions. The results are compared with theoretical predictions and earlier measurements.

PACS. 32.70.Cs Oscillator strengths, lifetimes, transition moments

1 Introduction

Beryllium-like ions have been of considerable theoretical interest in recent times [1–4] as these are the simplest ions with a complete core plus a many-electron valence shell. In these isoelectronic ions the polarization of the $1s^2$ core by the valence electrons modifies the effective potential experienced by the valence electrons themselves. Thus atomic structure calculations have to include the core–valence and core–core effects, which in the configuration interaction approach lead to very large basis sets for the wavefunctions [1]. On the other hand, these four electron ions having the simplest core and only two electrons outside the $1s^2$ core should be more easily and precisely calculable than other more complicated species. It is therefore an important testing ground for the development of theoretical methods which attempt to calculate atomic structure of many-electron systems. In addition, the beryllium-like ions are of astrophysical interest for photo-ionisation modelling of elemental abundances in cosmic objects. Transitions in these ions are also observed in the solar corona.

Efforts towards data-based systematization of transition probabilities [5] also need reliable measurements of lifetimes for greater accuracy and better predictive power. Lifetime measurements of the $2s2p\ ^1P^o$ level by time-resolved observation of the resonance transition to the $2s^2\ ^1S$ level have been made for most ions of the Be isoelectronic sequence for $Z \leq 26$ and for $Z = 36$ [6]. Severe difficulties arise in the extraction of the $2s2p\ ^1P^o$ lifetime by evaluation of the decay curves due to the presence of extensive cascading from higher excited levels. Cascades generally cause overestimation of level lifetimes if not properly accounted for, and the various early measurements of the $2s2p\ ^1P^o$ level seem to suffer from this problem, as can be seen from the deviation of some (but not all) results from isoelectronic trends established later [6,7]. The experimentally determined oscillator strength f of the $2s^2\ ^1S - 2s2p\ ^1P^o$ transition in Cl XIV from previous measurements [8–10] has been found to be lower than the predictions [3,6,7].

The present work is aimed at more accurate experimental f values by way of improved measurements of the lifetimes of the $2s2p\ ^1P^o$ level in Cl XIV and S XIII, taking into account the prominent cascades by the arbitarily normalised decay curves (ANDC [11]) analysis technique. Besides, the lifetimes of the $2p^2\ ^3P_j$ levels have also been measured in both ions.

2 Experiment

The measurements were done using the beam–foil technique at the 14 MV tandem Pelletron accelerator facility at TIFR. This setup has been developed recently and the details will be discussed elsewhere [12]. Figure 1 is a schematic of the setup. Beams of Cl^{7+} at 71 MeV, Cl^{9+} at 120 MeV and S^{9+} at 72 MeV were incident on carbon foils of approximately 20 μg/cm^2 thickness such that the dominant post-foil ions were the four-electron Be-like species [13]. Five-, three-, and two-electron species were also present but in less significant quantities. The beam currents were typically 100–150 nA. Photon spectra of the foil-excited ions were collected perpendicular to the beam direction using a 1 m grazing incidence spectrometer, McPherson model 310G. A platinum-coated grating with 1200 lines/mm, blazed at 654 Å, was used to disperse the spectra. The photons were detected using a CsI coated channeltron, Minuteman model 425. An electron suppressor was placed in front of the entrance slit of the spectrometer to prevent δ-electrons from reaching the grating and

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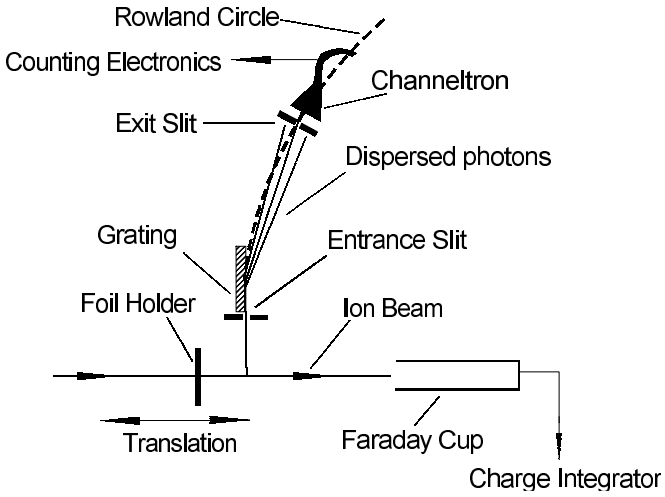

Fig. 1. Schematic of the experimental setup.

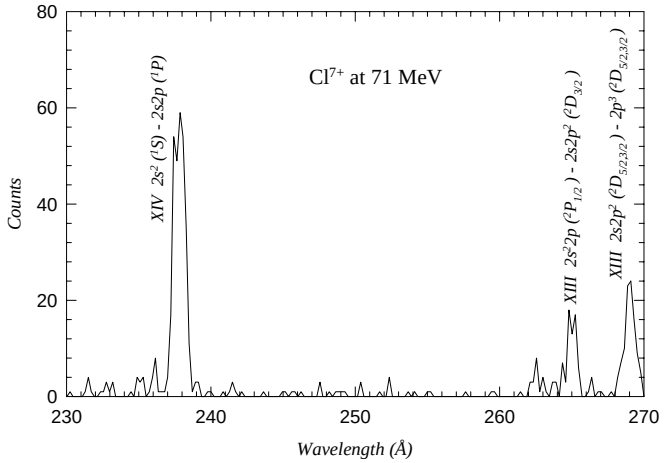

Fig. 2. Post-foil photon spectrum of a 71 MeV Cl^{7+} ion beam impinging on a 20 μg/cm^2 carbon foil. The dominant post-foil ion species at this energy and charge state is Cl XIV. The resonance transition $2s^2\ ^1S - 2s2p\ ^1P^o$ in Cl XIV which has been studied is indicated.

the channeltron. The photon signal was normalized to the total charge deposited by the ion beam in a deep shielded Faraday cup. An electron suppressor was placed upstream of the Faraday cup to prevent the escape of secondary electrons. Lifetime measurements were done by translating the exciter foil upstream along the beam path using a micrometer screwhead (Mitutoyo). The accuracy of the distance measurement is 10 μm and the total translation is 30 mm.

3 Results and discussion

Spectra were collected for Cl XIV and S XIII in the 50–340 Å range, and the spectral lines were assigned using the wavelength tables given by Fawcett [14], the NIST

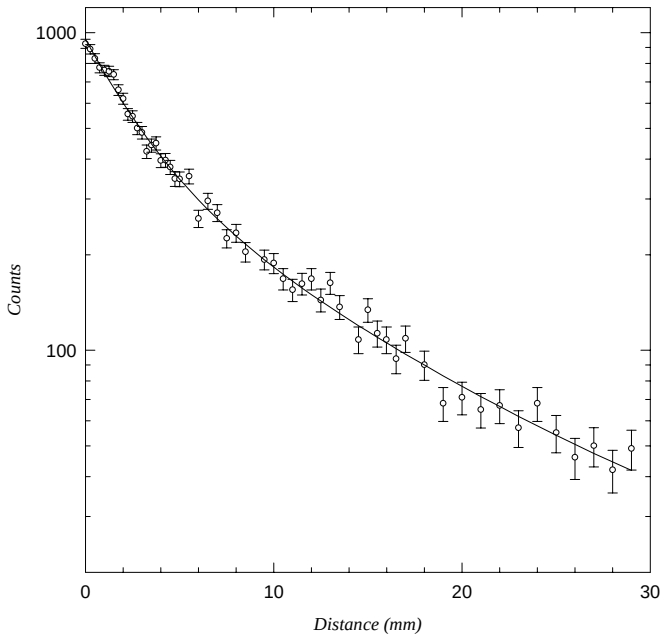

Fig. 3. Decay curve of the $2s^2\ ^1S - 2s2p\ ^1P^o$ in Cl XIV measured at 237.8 Å. The beam energy was 71 MeV corresponding to a post foil velocity of 19.7 mm/ns.

on-line data base [15] and the Kelly and Palumbo wavelength tables [16]. A typical spectrum collected is shown in Figure 2. The spectrometer slit-widths were adjusted to give a spectral resolution of 1 Å. Even though the signal level was low in individual spectra due to low beam current, each spectral feature was reproducible scan-to-scan. Preliminary analysis of the decay curves was done with a multiexponential function using the Levenberg-Marquardt method for non-linear least squares fitting. Each data set was fitted to different background levels to verify the stability of the fits against uncertainty in the background. To eliminate the possibility of foil holder vignetting, the data sets were analysed with and without truncation of data points from the begining of the decay curves. The decay curve for the $2s^2\ ^1S - 2s2p\ ^1P^o$ transition in Cl XIV is shown in Figure 3.

The results of the lifetime measurements for Cl XIV and S XIII are listed in Tables 1 and 2 respectively, along with previous measurements, data based predictions and theoretical calculations. The measured lifetime values for S XIII have also been compared with the data generated by the Opacity Project (TOPbase) [17] using a new formalism of the equation of state [18] and the close-coupling approach [19–21]. The database (TOPbase) does not have data for the Cl XIV ion.

The levels cascading into the $2s2p\ ^1P^o$ level in Be-like systems are those belonging to the $2sns\ ^1S$ and $2snd\ ^1D$ level series besides the $2p^2\ ^1S$ and the $2p^2\ ^1D$ levels. The lifetimes of the levels belonging to the $2sns\ ^1S$ and $2snd\ ^1D$ series are much shorter than those in the $n = 2$ shell, because of the larger energy difference and the systematic rapid decrease with increasing Z [22]. The $2p^2\ ^1D$ level lifetime, being much longer than that of the $2s2p\ ^1P^o$

Table 1. Lifetimes (in 10^{-12} s) of several singly and doubly excited terms of Be-like Cl compared with earlier experimental data and calculated values. Wavelengths are in Å.

Cl XIV Transition	λ	τ (this work)	τ (prev.)	Theory	Data based prediction
$2s^2\ (^1S_0) - 2s2p\ (^1P^o_1)$	237.8	117 ± 10^{e}	140 ± 10^{c} 150 ± 30^{d}	117^{b}	114^{a}
$2s2p\ (^1P^o_1) - 2p^2\ (^1S_0)$	277.9	77±9	84 ± 5^{d} 67 ± 10^{d}	75^{b}	
$2s2p\ (^1P^o_1) - 2p^2\ (^1D_2)$	458.4^{f}	625 ± 25^{g}	630 ± 20^{c} 600 ± 60^{d}	621^{b}	
$2s2p\ (^3P^o_2) - 2p^2\ (^3P_2)$	286.2	160±10	169 ± 5^{c} 160 ± 10^{d}	147^{b}	
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_2)$	276.1		160 ± 10^{c}		
$2s2p\ (^3P^o_0) - 2p^2\ (^3P_1)$	279.72	165±15			
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_1)$	284.3		160 ± 10^{c}	150^{b}	
$2s2p\ (^3P^o_2) - 2p^2\ (^3P_1)$	294.9		170 ± 10^{c}		
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_0)$	290.5	170±9		155^{b}	

[a] Ref. [6]; [b] Ref. [3]; [c] Ref. [10]; [d] Ref. [8]; [e] Results from ANDC analysis;
[f] Wavelength value from previous measurements; [g] Lifetimes measured from direct cascades.

Table 2. Lifetimes (in 10^{-12} s) of several singly and doubly excited terms of Be-like S compared with earlier experimental data and calculated values. Wavelengths are in Å.

S XIII Transition	λ (obs)	λ (TOPbase)	τ (this work)	τ (prev.)	Theory	Data based prediction
$2s^2\ (^1S_0) - 2s2p\ (^1P^o_1)$	256.70	262.5	129 ± 6^{e}	130 ± 15^{d}	128^{b} 138^{c} (129^{f})	125^{a}
$2s2p\ (^1P^o_1) - 2p^2\ (^1S_0)$	301.04	307.8	84±10	81 ± 4^{d}	84^{b} 86.6^{c} (81^{f})	
$2s2p\ (^1P^o_1) - 2p^2\ (^1D_2)$	500.42^{g}	533.9	740 ± 45^{h}	700 ± 50^{d}	704^{b} 862^{c} (710^{f})	
$2s2p\ (^3P^o_2) - 2p^2\ (^3P_2)$	308.9				161^{b}	
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_2)$	299.9		173±20			
$2s2p\ (^3P^o_0) - 2p^2\ (^3P_1)$	303.3					
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_1)$	307.4				164^{b}	
$2s2p\ (^3P^o_2) - 2p^2\ (^3P_1)$	316.8		177±9			
$2s2p\ (^3P^o_1) - 2p^2\ (^3P_0)$	312.7		192±15		169^{b}	

[a] Ref. [6]; [b] Ref. [3]; [c] Ref. TOPbase; [d] Ref. [25]; [e] Results from ANDC analysis;
[f] Lifetime corrected as mentioned in text (Eq. 4); [g] Wavelength value from previous measurements;
[h] Lifetimes measured from direct cascades.

level, can be deconvoluted easily using a multiexponential fit. The lifetime of the $2p^2\ ^1S$ level, however, is very close to that of the $2s2p\ ^1P^o$ level, and it therefore is difficult to deconvolute in a multiexponential fit. As has been previously seen by Pegg *et. al.* [23] the ratio $\tau(^1P^o)/\tau(^1S)$ increases from 1.3 in N IV to only 1.6 in Cl XIV [22,23].

The results of the previously reported measurements of the lifetime of the $2s2p\ ^1P^o$ level in Cl XIV [8–10] have been consistently higher than the predicted values [6,7]. This may be due to insufficient cascade analysis, as suggested by Träbert [7]. We have measured and analysed the decay curves for the $2s2p\ ^1P^o$ level both for Cl XIV and S XIII using the ANDC technique [11] by means of the CANDY program [24]. For Cl XIV and S XIII the lifetimes of the $2sns\ ^1S$ and $2snd\ ^1D$ levels are ≤ 10 ps (TOPbase). It was thus reasonable to ignore the effects of these cascades in our analysis of the decay curves.

In the case of Cl XIV, the primary lifetime for the $2s2p\ ^1P^o$ level obtained by the multiexponential fit was 138 ± 10 ps, which is in very good agreement with the previously measured values [8–10] where the same type of analysis was done. For the ANDC analysis, the decay curve of the cascading $2p^2\ ^1S$ level was measured via the cascading transition to the $2s2p\ ^1P^o$ at 277.9 Å itself. For Cl ions at a beam energy of 71 MeV, this transition is heavily blended by the $2s^22p\ ^2P_{3/2} - 2s2p^2\ ^2D_{3/2,5/2}$

transitions at 277.4 Å and 277.0 Å, respectively, in Cl XIII, for which the post-foil charge state fraction is about 21% as opposed to 33% for Cl XIV [13]. For this reason the cascade transition was measured at the beam energy of 120 MeV, where the charge state fraction for Cl XIII is below 1% and that for Cl XIV is about 6% [13] so that the blending can be considered minimal. As a precautionary measure the spectrometer slits were narrowed to give a spectral resolution of about 0.5 Å. The long lived cascading transition from the $2p^2\ ^1D$ level at 458.4 Å was beyond our wavelength range. Hence the intensity and lifetime input required by CANDY for this cascade was taken from the result of the multiexponential fitting and from the previously reported results [8–10] and was analysed separately. The ANDC results in both cases *i.e.* from the multiexponential fitting and previous measurements agreed with each other within 3%. ANDC analysis of our data gave a lifetime of 117 ± 10 ps which is 18% lower than the result of the multiexponential fitting, but in good agreement with data-based predictions [6] and theoretical calculations [3].

The result of the measurement of the $2s2p\ ^1P^o$ level lifetime in S XIII agrees very well with that of Träbert and Heckmann, who take into account the cascading from the $2p^2\ ^1S$ level [25], though this is not true for the two cascading transitions, $2s2p\ ^1P^o - 2p^2\ ^1S$ and $2s2p\ ^1P^o - 2p^2\ ^1D$, which agree only within the experimental error limits. Here again, the lifetime obtained from the multiexponential fitting was 20% higher than that given by ANDC analysis. In this case the cascading transition $2s2p\ ^1P^o - 2p^2\ ^1S$ at 301 Å blends with the $2s2p\ ^3P_1 - 2p^2\ ^3P_2$ transition in S XIII at 299.9 Å. For a 72 MeV beam, blending from S XII ions can be considered negligible since the post-foil charge state fraction of S XII ions is 2% as opposed to 16% for the S XIII ions. The lifetime measurement was done at a higher spectrometer resolution resulting in lower intensity in the decay curve. For the cascade from the $2p^2\ ^1D$ level at 500.4 Å, a procedure similar to that followed for Cl XIV was employed.

The lifetimes of the $2s2p\ ^1P^o$ level listed in Tables 1 and 2 are the ANDC results with the input required for the $2p^2\ ^1D$ cascade taken from the result of our multiexponential fitting. Our lifetime analysis gives an oscillator strength of 0.217 ± 0.018 for Cl XIV and 0.229 ± 0.011 for S XIII for the $2s^2\ ^1S - 2s2p\ ^1P^o$ transition. The lifetimes for the $2p^2\ ^1D$ level in Cl XIV and S XIII reported in Tables 1 and 2 are the results of cascade analysis of the decay curve for the $2s^2\ ^1S - 2s2p\ ^1P^o$ transition and not direct measurements of the decay via the $2s2p\ ^1P^o - 2p^2\ ^1D$ transition. Generally lifetime values obtained by this method are less accurate as compared to direct measurements, since the cascades mostly add to the tail end of the decay curve where data statistics is poor, also deconvolution with the use of multiexponential fitting adds to error. The lifetime of the individual levels in the $2p^2\ ^3P_{2,1,0}$ level multiplet were also measured. Our results are in reasonable agreement with previous measurements but are consistently higher than the theoretically calculated values [3]. This may indicate that there may be higher lying levels cascading into the $2p^2\ ^3P_{2,1,0}$ multiplet which have lifetimes longer than what we can measure with our present setup; a longer foil translation and fine cascade analysis may be required for these levels. The error in foil positioning is less than 10 μm and the beam energy definition is better than $500q$ eV where q is the beam charge state. These errors are negligible compared to the statistical and fitting errors which are indicated in Tables 1 and 2.

The lifetimes calculated by the Opacity Project show better agreement with the measured values when the transition wavelengths generated by the calculations are replaced by the experimentally observed wavelengths by using the relations given below.

The probability for spontaneous emission [19,21] $b \to a$ is

$$A_a(b \to a) = \frac{\alpha^2}{2g_b} \left(\frac{hc}{\lambda}\right)^2 \frac{g_a f(b,a)}{\tau_0} \tag{1}$$

where α = fine structure constant, g_i = statistical weight factor of the level i, $\tau_0 = \dfrac{\hbar^3}{me^4}$ and $f(b,a)$ is the oscillator strength of the transition $b \to a$ which is proportional to $\dfrac{1}{\lambda}$. The total radiative probability is

$$A(b) = \Sigma_a A_a(b \to a) \tag{2}$$

with A_a summed over all lower states a and the lifetime of level b is

$$\tau_b = \frac{1}{A(b)}\,. \tag{3}$$

In the case that a transition probability $A_a(b \to a)$ of any one decay channel is at least one order of magnitude greater than all others, then the largest $A_a(b \to a)$ will be the main lifetime determining factor. In this particular case all the three level lifetimes corrected by this factor have only one allowed transition according to the LS coupling selection rules for electric dipole transitions, so only one wavelength can be considered. By replacing the calculated wavelength λ, by the observed wavelength λ_{obs}, in equation (1) we get the corrected lifetime of the level b as

$$\tau_b \sim \frac{1}{A(b)} \left(\frac{\lambda_{obs}}{\lambda}\right)^3. \tag{4}$$

The measured lifetime values show good agreement with the calculations after this correction, as can be seen in Table 2. TOPbase does not give the lifetimes of the individual levels in a multiplet. The uncorrected lifetime of the multiplet level $2p^2\ ^3P_j$, for S XIII, generated by TOPbase is 175 ps.

4 Conclusions

The lifetimes of ($n = 2$) levels have been measured in the four-electron Be-like ions Cl XIV and S XIII. We believe that the detailed cascade analysis done on the decay of

the $2s2p\ ^1P^o$ level in Cl XIV (by the resonance transition to the $2s^2\ ^1S$ level) has removed the discrepancy between predictions and the existing measurements. Our capability for wide-range energy variation helped reduce the systematic errors from unresolved spectral lines. Lifetimes of the levels of the $2p^2\ ^3P_{2,1,0}$ multiplet for both ions have also been determined, but further measurements with detailed cascade analysis may be required for more accurate values.

The authors would like to thank Prof. E. Träbert for many fruitful discussions and valuable suggestions. N.B. would also like to thank Prof. H. G. Berry for drawing her attention to reference [10]. We express sincere thanks to Mr. D. C. Ephraim and Mr. E. D. Dias for making the carbon foils and to the staff of the Pelletron accelerator for smooth running of the machine. We are grateful to Mr. W. A. Fernandes for help with electronics and automation. We thank Prof. Y. K. Agrawal, Dr. R. G. Pillay and Prof. M. B. Kurup for support and encouragement.

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