Lifetime for Li-like Ti $1s2s2p\ ^4P^o_{5/2}$ level using a mode of beam–two-foil experiments

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The option of varying thickness of the fixed foil in the beam–two-foil technique has been incorporated in our experimental setup. It gives an opportunity to explore a new mode of this technique. In the current study, we have investigated the lifetime of the $1s2s2p\ ^4P^o_{5/2}$ level in Li-like titanium using this technique. The data showed a dependence of foil thickness of the fixed foil on the interactions of levels produced in the first foil. Average lifetime obtained for the Li-like titanium $1s2s2p\ ^4P^o_{5/2}$ level (200 ± 12 ps) is compared very well with the earlier theoretical and experimental values.

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I. INTRODUCTION

The beam-foil time of flight technique is a unique method for measuring lifetimes in highly charged ions [1]. This technique however often suffers from cascade and blending problems which alter considerably the lifetimes under investigation. The use of different beam energies and careful analysis however may resolve these problems to a certain extent [1]. Special care is needed in cases for which both satellite line and the line of interest arise together in the measurement. The analysis of such cases within the framework of standard beam-foil approaches is not at all straightforward. The use of beams of higher energy in the measurement of the $1s2p\ ^3P^o_2$ level lifetime in ions in the regime $Z=20-50$, increases blending from the hydrogenlike $M1$ line and lowers blending from satellite lines. Satellite lines are not resolved by the energy dispersive solid state x-ray detectors commonly used in beam-foil experiments (for example [2,3]) for ions up to $Z\approx50$. The upper level of any satellite is partially autoionizing, and decay through both autoionization and radiative channels is possible. Our recent work [4] shows that use of the the beam-foil technique [1] coupled with the use of the two-foil technique [5], enables the resolution of the satellite blending problem in lifetime measurements in He-like vanadium [4]. It was subsequently shown in our laboratory that the contribution of the hydrogenlike $M1$ line may also be corrected within the beam-two-foil approach as shown in the study of the $1s2p\ ^3P^o_2$ level lifetime in He-like nickel [6]. Recent measurements in our laboratory have not only resolved satellite blending arising from the $M2$ $1s^22s\ ^2S_{1/2}-1s2s2p\ ^4P^o_{5/2}$ line but have also led to the measurement of the lifetime of the partially autoionizing satellite level $1s2s2p\ ^4P^o_{5/2}$ in Li-like vanadium. In the present study, we address the issue of the lifetime of the partially autoionizing satellite $1s2s2p\ ^4P^o_{5/2}$ level in Li-like Ti using beam single-foil and two-foil technique in a new mode. Here the foil thickness of the second or fixed foil is varied for a certain beam energy. We report the results obtained for the lifetime of the $1s2p2s\ ^4P^o_{5/2}$ level in Li-like Ti using the present novel technique. We also discuss the interaction mechanism between excited states, generated as $^{48}_{22}$Ti beams passing through the first foil, and thin carbon foils of variable thickness used as fixed foil.

II. EXPERIMENT

The ^{48}Ti ion beam used in the experiment was obtained from the 15 MV Pelletron accelerator at the Nuclear Science Centre, New Delhi. A collimated Ti beam of 3 mm diameter was excited by passage through a 60 $\mu g/cm^2$ carbon target movable along the beam. In the two-foil experiment, the beam then passes through a second, fixed carbon foil whose thickness was varied to 4, 8, 12, and 20 $\mu g/cm^2$. The experiment was performed with 90, 130, and 145 MeV ^{48}Ti beams in a setup similar to one used in [4,6]. Germanium ultra low energy detector from Canberra, model GUL 0035 with a resolution of 160 eV at 5.9 keV line of ^{55}Fe source was used for x-ray detection. The peak width increases up to 220 eV for the observed peak at 4.78 keV due to Doppler broadening and blending contribution from number of levels. Details may be found elsewhere [7].

III. RESULTS AND DISCUSSION

Figure 1 shows the partial level diagram of He-like and Li-like ^{48}Ti within the level energy range of interest to this work and corresponding lifetimes and decay modes. Our analysis focuses mainly on the Li-like $1s2s2p\ ^4P^o_{5/2}$ level, that partly decays (34%) [8] through a magnetic quadrupole ($M2$) transition to the ground state. A substantial decay through an autoionization channel (66%) is also possible. Since the He-like $1s2p\ ^1P^o_0$ and $1s2p\ ^3P^o_1$ level lifetimes are of the order of femtosecond, the lines that contribute to the 4.78 keV peak are due to the transitions $1s^2\ 2s\ ^2S_{1/2}-1s2s2p\ ^4P^o_{5/2}$ (4.687 keV), $1s^2\ ^1S_0-1s2p\ ^3P^o_2$ (4.734 keV) and $1s^2\ ^1S_0-1s2s\ ^3S_1$ (4.702 keV). These three lines lie within 50 eV and cannot be resolved by the detector that was used in our experiment. Since theoretical lifetimes for the corresponding upper levels are 205 ps [8], 422 ps [10], and 26.6 ns [10], respectively, the He-like $1s2p\ ^3P^o_2$ and $1s2s\ ^3S_1$ levels must be considered, in principle, in the analy-

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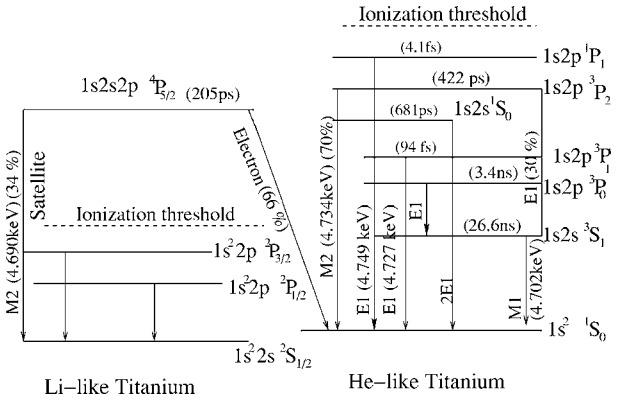

FIG. 1. Transition energies and lifetimes for Li-like and He-like titanium levels of interest to this work [8–12].

sis of our 4.78 keV data in addition to the Li-like $1s2s2p\ ^4P^o_{5/2}$ level.

The spectrum, calibrated using a standard ^{241}Am radiation source exhibits a prominent peak at 4.78 keV (Fig. 2). The intensity of this peak was measured as a function of the detector to foil distance in the single-foil experiment at three beam energies (90, 130, and 145 MeV) and normalized count rates vs distance are plotted in Fig. 3. When the curves are fitted with a single exponential, the lifetimes obtained are 209±5, 386±11, and 482±13 ps, respectively. The variation of the apparent lifetimes with beam energy shown in Table I may be attributed to the difference in the relative intensities of the lines that contribute to the peak (Table II, code ETACHA [15]).

It is interesting to note (Table I) that the single-exponent fit to the 90 MeV data yields a lifetime (209±5 ps) which is close to theoretical predictions [8,16,17] for the $1s2s2p\ ^4P^o_{5/2}$ lifetime. This suggests that, at this beam energy, contributions to the peak from the H-like and the He-like lines are

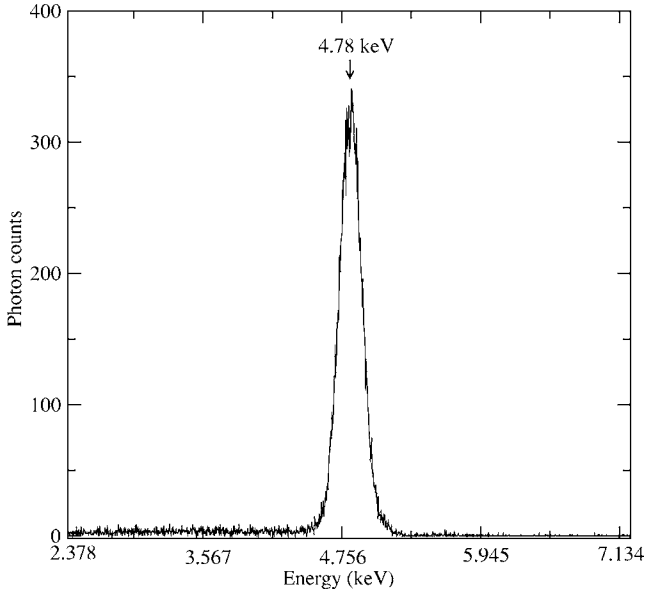

FIG. 2. Energy spectrum using ultra-low-energy germanium detector (90 MeV titanium beam incident on the 60 μg/cm^2 carbon foil).

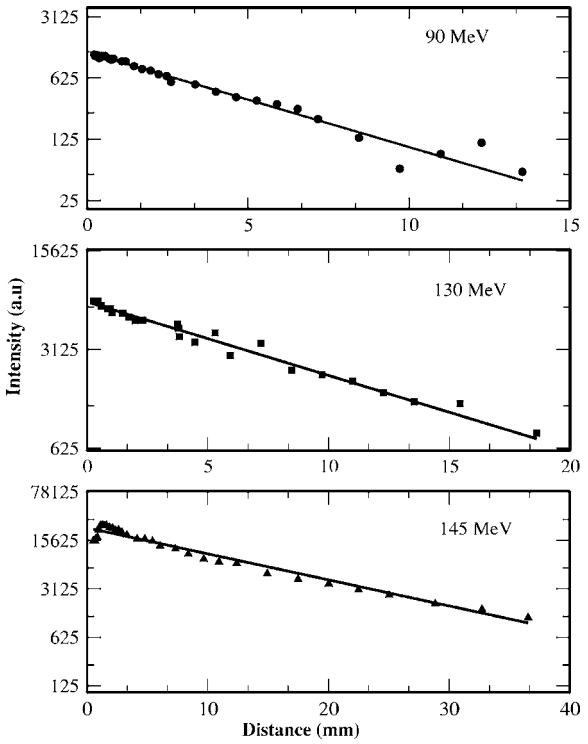

FIG. 3. Normalized count rate for the 4.78 keV titanium peak as a function of the distance between the foil and the detector in the single-foil experiment with different beam energies. Foil thickness was 60 μg/cm^2.

negligible. The apparent decay time at 130 MeV (386±11 ps) lies in-between the lifetimes of the $1s2s2p\ ^4P^o_{5/2}$ (198 [17], 205 [8], or 212 [16] ps) and $1s2p\ ^3P^o_2$ (422 ps) levels, whereas the value at 145 MeV (482±13 ps) is slightly larger than the $1s2p\ ^3P^o_2$ lifetime (Table II), suggesting that the contribution from the H-like $M1$ line may no longer be neglected. Such variations are due to changes in the charge state fractions as well as in the excitation cross sections. These observations are consistent with the results reported in Table II of [18] for Li-like and Be-like Mg levels which suggest that, as the beam energy decreases, the satellite contribution increases. Our results so far are consistent with the observation that low beam energies are more appropriate for the investigation of the lifetime of the $1s2s2p\ ^4P^o_{5/2}$ level. In order to disentangle the contributions of the blending lines from the $1s2s2p\ ^4P^o_{5/2}$ lifetime measurement we have kept the beam energy fixed at 90 MeV and employed the beam-two-foil technique, this time varying the thickness

TABLE I. Effective decay times obtained from single-exponent fits to the 4.78 keV ^{48}Ti single-foil experiment data at various energies.

Incident ion beam	Energy (MeV)	Lifetime(ps) This work
Ti^{8+}	90	209±5
Ti^{10+}	130	386±11
Ti^{11+}	145	482±13

TABLE II. Theoretical charge state fractions (code ETACHA [15]) for titanium beams of different incident energies and charge states Q_{in} emerging from the 60 $\mu g/cm^2$ carbon foil.

Ion beam		Charge state fraction (%)			
Energy (MeV)	Q_{in}	H-like	He-like	Li-like	Be-like
90	8	0.2077	5.57	18.82	28.60
130	11	1.872	19.80	34.31	27.06
145	12	3.21	26.48	36.55	22.95

of the second (fixed) foil to 4, 8, 12, and 20 $\mu g/cm^2$.

The radiative decay of He-like $1s2p\ ^3P^o_2$ and $1s2s\ ^3S_1$ excited states, and the autoionization of Li-like $1s2s2p\ ^4P^o_{5/2}$ excited states may generate He-like $1s^2\ ^1S_0$ ground state during the flight between the first and the second foil. As a result of collisions within the second foil, He-like ground state $1s^2\ ^1S_0$ may be reexcited to $1s2s\ ^3S_1/1s2p\ ^3P_{2,1,0}$. Further, more ions in the He-like ground state may undergo dielectronic capture to produce Li-like $1s2s2p\ ^4P_{5/2}$ level. $1s2s$ and $1s2p$ levels may capture an electron in the $2p$ or the $2s$ shell as they exit the foil, thus forming $1s2s2p\ ^4P^o_{5/2}$. Li-like $1s^22s$ ground state levels may also be reexcited to $1s2s2p\ ^4P^o_{5/2}$ as a result of collisions in the second foil, whereas the long-lived $1s2s\ ^3S_1$ may be reexcited to $1s2p\ ^3P^o_2$ [5] or vice versa. The thicker the foil, the larger the probability for excitation of $1s2s\ ^3S_1$ and $1s2p^3P_{2,1,0}$ from $1s^2\ ^1S_0$ similarly $1s2s2p\ ^4P^o_{5/2}$ from $1s^2\,2s\ ^2S_{1/2}$ as well as from $1s2s\ ^3S_1$ and $1s2p\ ^3P^o_{2,1,0}$. However the dielectronic process of producing $1s2s2p\ ^4P^o_{5/2}$ will be reduced as more number of collisions will decrease the ions in the $1s^2\ ^1S_0$ state. As a result, a certain number of collisions in the second foil will lead to an equilibrium among various excited states. For the titanium beam used in this work, we have estimated the mean free path for the intrashell transition $2s$-$2p$ and vice versa to be about 4 $\mu g/cm^2$ using Eq. (A17) of [19]. Mean free paths for such processes that may take place when ionic levels pass through a foil have been discussed in [5]. Data from two-foil experiments, coupled to theoretical considerations, may therefore be used for a quantitative investigation of such processes.

The processes listed above enhance the x-ray intensity at 4.78 keV as observed in the two-foil experiments. It may be noted (Fig. 4) that a drastic change, as far as trend of the curves is concerned, takes place as we move from the 4 $\mu g/cm^2$ to the 8 $\mu g/cm^2$ foil. This observation indicates that, at 90 MeV, a foil thickness of 8 $\mu g/cm^2$, corresponding to two mean free paths for the $2s$-$2p$ transition [19], is almost adequate in establishing an equilibrium amoung the excited state, as far as the x-ray intensity at 4.78 keV is concerned, between deexcitation processes, occurring as ions in different electronic states travel between the two foils, and excitation, electron capture and stripping processes occurring at the second foil.

We have made use of the prescription given by Nandi *et al.* [4,6] in the determination of lifetimes. In this procedure, 4.78 keV x-ray intensity as a function of distance between the foil and the detector window were obtained with

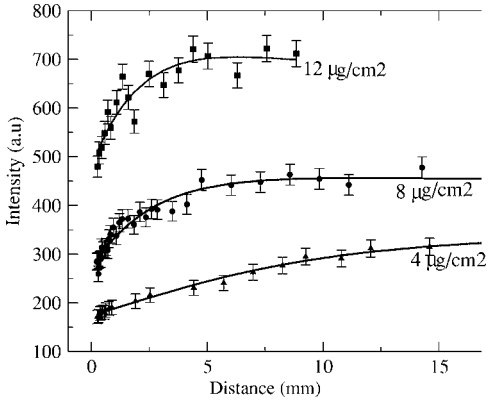

FIG. 4. Normalized count rate for the 4.78 keV titanium peak as a function of the distance between the two foils (normalization varies with the foil thickness) in the two-foil experiment. Beam energy 90 MeV; second foil-detector distance 2.5 mm; thickness of the first foil 60 $\mu g/cm^2$.

single-foil experiment (Fig. 3). Single exponential curve fitting led to determination of the effective lifetime of all the levels involved in the peak as given in Table I. In the next experiment with two-foil target, normalized x-ray intensities were plotted as a function of the separation between the two foils (x) (Fig. 4). Data so obtained were fitted with the following equation:

$$I(x) = I_1 e^{-x/v\tau_1} + I_2(1 - e^{-x/v\tau_2}). \quad (1)$$

Here $I(x)$ is the intensity as a function of x. First term represents the decay of the level associated with 4.78 keV peak. τ_1 was set to a fixed value as obtained from the fit of the single foil data as given in Table I. The repopulation of the $1s2s2p\ ^4P^o_{5/2}$ level from other levels interacting with the second foil which leads to growing structure, represented by second term in Eq. (1). τ_2 is the lifetime of the $1s2s2p\ ^4P^o_{5/2}$ level. Same procedure was applied to all the fixed foils (4, 8, 12, and 20 $\mu g/cm^2$). Lifetimes obtained together with previous theoretical and experimental results are presented in Table III. The scatter in the lifetime values at different thickness of the second foil lie within two standard deviations, so the average value quoted include two standard deviations of error. Further, intensity ratio I_2/I_1 is also given in Table III. This ratio approaches equillibrium with increasing foil thickness.

We now proceed to discuss on the results obtained in more detail. The $1s2s2p\ ^4P^o_{5/2}$ lifetime, determined from our single foil measurement as 209 ± 5 ps, might possibly suffer from blending due to $1s2p\ ^3P^o_2$ and $1s2s\ ^3S_1$ levels. Since the lifetimes of these levels are higher than the $1s2s2p\ ^4P^o_{5/2}$ lifetime, our 209 ± 5 ps value provides an upper limit for the $1s2s2p\ ^4P^o_{5/2}$ lifetime. In principle, two-foil measurements should result in $1s2s2p\ ^4P^o_{5/2}$ lifetimes lower than the value 209 ± 5 ps, irrespective of the thickness of the second foil. Varying the thickness of the second foil gives rise to changes in the relative intensities of the lines originating from the three levels $1s2s2p\ ^4P^o_{5/2}$, $1s2p\ ^3P^o_2$, and $1s2s\ ^3S_1$. Total effect for every foil is accounted by the intensity parameter I_2 in the above equation. Thus, each two-foil measurement in

TABLE III. Lifetime of the $1s2s2p\ ^4P^o_{5/2}$ level in Li-like titanium obtained from beam single-foil and beam two-foil experiments at 90 MeV (4.78 keV peak). The thickness of the second (fixed) foil was varied.

Foil thickness (μg/cm^2)	Lifetime(ps)	I_2/I_1
4	215±16	0.145
8	195±13	0.596
12	183±15	0.706
20	207±14	0.793
Average	200±12	
Other work	236±12,[a] 210.5±13.5[b] 198,[c] 212,[d] 205[e]	

[a]Experiment [21].
[b]Experiment [20].
[c]Theory [17].
[d]Theory [16].
[e]Theory [8].

the current study ought to give the actual $1s2s2p\ ^4P^o_{5/2}$ lifetime, irrespective of the thickness of the second foil. In addition, the $1s2s2p\ ^4P^o_{5/2}$ lifetimes, derived from two-foil measurements, should not exceed the value 209±5 ps. Average lifetime (200±12 ps) obtained from one beam energy and several fixed foil of different thickness agree well with lifetime (210.5±13.5 ps) measure with one fixed foil and two different beam energies (95 and 143 MeV) [20]. Present experimental $1s2s2p\ ^4P_{5/2}$ level lifetime agrees well with theoretical values [8,17]. Our average lifetime is significantly lower than the value 236±12 ps reported in an earlier experimental study [21], in which an electrostatic cylindrical mirror analyzer was used for the detection of electrons generated through the autoionizing channel. As it is discussed in [21] that the influence of cascades as big as 30% requires further work for resolving the issue. Thus the technique introduced in the current study is capable of disentangling both cascade and blending effects.

In the present experiment, the distance between the two foils in the two-foil experiments did not exceed 18 mm. As a result it was not possible to obtain lifetime for the $1s2p\ ^3P^o_2$ level from the 130 and 145 MeV data. As discussed above, the apparent decay time obtained from the single-foil measurement at 145 MeV may well suffer from contributions arising from the $1s2s\ ^3S_1$ level (lifetime 1.014 ns). A longer travel between the two foils is therefore required in order to disentangle the effect of the H-like $M1$ line from the $1s2p\ ^3P^o_2$ lifetime measurement. This shortcoming of our experimental setup is now being rectified in an effort to obtain a reliable measurement for the $1s2p\ ^3P^o_2$ lifetime.

At present, variants of beam-foil method such as beam-foil technique using two-foil target (beam–two-foil technique) [5], combininig beam-single and beam–two-foil technique [4,6] and the present technique varying the thickness of the second foil in the beam–two-foil technique exist. Beam–two-foil technique [5] was introduced to measure as small as 1 ps lifetime that was not possible with convensional beam-foil method. Major advantage of the use of beam-single and beam–two-foil technique [4,6] over the convensional beam–two-foil technique [5] was to resolve the effect of the Li-like $M2$ satellite line on the He-like $M2$ line to maximum extent and to determine the lifetime of the upper level of the satellite line too. Merits of the present method over the earlier [4,6] are mainly to get rid of the iterative analysis procedure required to disentangle the He-like $M2$ level lifetime from the Li-like $M2$ level lifetime which undoubtedly introduces a major fitting error in the analysis. Use of different beam energy in the beam-foil experiments is essential to get a reliable lifetime. In the present method foils of different thickness are used for a single beam energy. The reason is the same as to produce excited states with different relative population. This fact is obvious from I_2/I_1 ratio for different foils as given in Table III.

IV. CONCLUSION

A variant of the beam-single and beam–two-foil technique [4] has been developed and tested in our laboratory. Our beam–two-foil experimental setup in which the thickness of the second, fixed foil, was varied that has been applied to the measurement of the $1s2s2p\ ^4P^o_{5/2}$ level lifetime in Li-like Ti. Lifetime obtained shows excellent agreement with the earlier measurement [20] and theoretical results [8,16,17].

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