Beam-single and beam-two-foil experimental facility to study physics of highly charged ions

Nissar Ahmad, A. A. Wani, R. Ram, S. R. Abhilash, Rakesh Kumar, J. K. Patnaik, Sankar De, R. K. Karn, and T. Nandi

Citation: Review of Scientific Instruments **77**, 033107 (2006); doi: 10.1063/1.2186212
View online: http://dx.doi.org/10.1063/1.2186212
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/77/3?ver=pdfcov
Published by the AIP Publishing

Beam-single and beam-two-foil experimental facility to study physics of highly charged ions

Nissar Ahmad
Department of Physics, Aligarh Muslim University, Aligarh-202 002, India and Inter University Accelerator Center (IUAC), Aruna Asaf Ali Marg, New Delhi-110 067, India

A. A. Wani
Department of Physics, Aligarh Muslim University, Aligarh-202 002, India

R. Ram, S. R. Abhilash, and Rakesh Kumar
Inter University Accelerator Centre (IUAC), Aruna Asaf Ali Marg, New Delhi-110 067, India

J. K. Patnaik
Pondicherry University, Pondicherry-605 014, India and Inter University Accelerator Centre (IUAC), Aruna Asaf Ali Marg, New Delhi-110 067, India

Sankar De
Department of Physics, University of Calcutta, 92, Acharya Prafulla Chandra Road, Kolkata-700 009, India and Inter University Accelerator Center (IUAC), Aruna Asaf Ali Marg, New Delhi-110 067, India

R. K. Karn and T. Nandi[a)]
Inter University Accelerator Centre (IUAC), Aruna Asaf Ali Marg, New Delhi-110 067, India

(Received 25 October 2005; accepted 17 February 2006; published online 31 March 2006)

A facility for lifetime measurement of metastable states in highly charged ions using the beam-foil technique with a single-foil and a two-foil target has been developed. In the two-foil technique, one foil moves with respect to the other and the option of varying the thickness of the fixed foil online has been implemented. A holder with multiple foils is used as a fixed target, and moved along x, y, and θ, the angle of rotation with respect to beam direction along the z axis. Using this facility, the He-like $1s2p\ ^3P_2^o$ and Li-like $1s2s2p\ ^4P_{5/2}^o$ titanium lifetimes have been measured and compared with earlier values. In addition to this, the processes which occur when excited states collide with carbon foils of different thicknesses have also been investigated. Preliminary results suggest the scope of studying intrashell transitions during ion-solid collision using this setup. In this article, the setup is described in detail and representative results are briefly discussed. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2186212]

I. INTRODUCTION

The beam-foil spectroscopic technique is an important tool to study the physics of highly charged ions.[1] Beam-foil interactions produce various excited states in several charge states of the ions in the postfoil beam which lead to very complicated spectral features. In order to detect the lines belonging to long lived levels, the detector is kept at some distance away from the target foil to detect only delayed spectra. In this case the spectra are much cleaner, because short lived lines will not appear in them. Still some problems remain due to the presence of satellite lines, i.e., the lines emanating from neighboring charge states. High resolution spectroscopic measurements are required to resolve these lines. Although crystal spectrometers may well resolve the closely spaced lines in x-ray region, low efficiency makes the lifetime measurements difficult. The beam-foil time of flight technique using energy dispersive solid state detectors suffers from blending problems along with cascading effects. However, the cascading is independent of spectral resolution. Satellite blending may be avoided to a great extent at high beam energy such that the charge state of interest in the postfoil beam is well below the mean charge state $\bar{q}$.[2] On the other hand one has to opt for low beam energy to reduce the cascade contribution.[3] Therefore, it is difficult to meet both the conditions, i.e., reduction of cascading and reduction in satellite line blending, simultaneously. Since most of the cascading levels decay to the metastable states through short lived $E1$ transitions, cascading does not impose much problem for the study of metastable states. Therefore, for lifetime measurement of satellite levels one can make use of the charge states well above $\bar{q}$ also.

The points discussed so far can only reduce but cannot eliminate the blending problem. In order to eradicate the blending problem, a new method to analyze the data obtained from beam-foil time of flight technique with a single-foil as well as a two-foil target has been introduced in our laboratory[4,5] and is called the iterative multicomponent exponential growth and decay analysis. This technique does not restrict the measurement at any particular charge state of the postfoil beam, as it is well suited even at $\bar{q}$. Recent measure-

[a)]Author to whom correspondence should be addressed; electronic mail: nandi@nsc.ernet.in

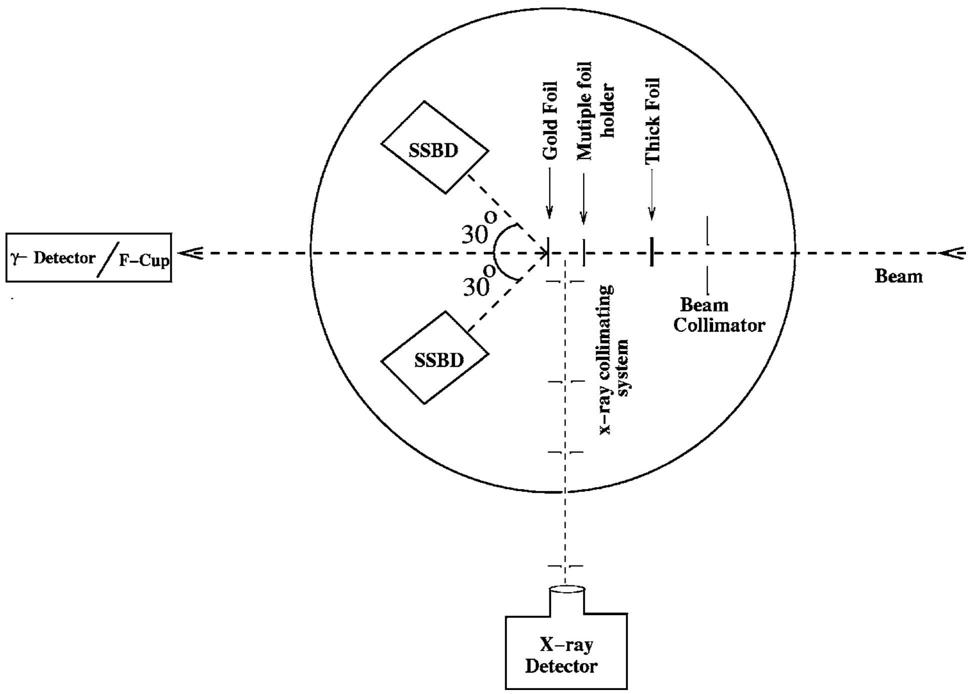

FIG. 1. Schematic of the experimental arrangement.

ments using this method not only have resolved the satellite blending arising from the $M2$ $1s^22s\ ^2S_{1/2}-1s2s2p\ ^4P^o_{5/2}$ line but also measured the lifetime of the partially autoionizing satellite level $1s2s2p\ ^4P^o_{5/2}$ in Li-like vanadium.[4] The facility used for the earlier experiments[4,5] had a small flight length ($\leqslant$12 mm). Recently, we have developed a dedicated setup having a larger flight path of about 90 mm. In this article, we report the salient features of the experimental setup in detail and the results obtained for the lifetime measurement of the Li-like titanium $1s2s2p\ ^4P^o_{5/2}$ and the He-like titanium $1s2p\ ^3P^o_2$ levels. The present facility keeps an option of varying the thicknesses of the second foil for each beam energy used. We also discuss the interaction mechanism of the excited states generated during passage of the beam through the first foil, as well as through the thin carbon foils (second foil) of different thicknesses.

II. EXPERIMENTAL SETUP

The schematic of the experimental setup as shown in Fig. 1 was used at the Inter University Accelerator Centre (IUAC), New Delhi, India for the lifetime measurement of the metastable states of highly charged ions. Figure 2(a) shows the cross-sectional view of the experimental chamber which is 356 mm in diameter and 316 mm in height with the following features: (a) an arrangement to load the single carbon (first) foil on a stand mounted in the horizontal rail enabling movement in the beam direction, and (b) an arrangement to load a number of thin (second) foils having different thicknesses on a multifoil holder capable of moving in the vertical direction. The beam collimator, the first carbon foil, and the gold foil were placed on the horizontal rail track. Optical alignment of the beam collimator and the first, sec-

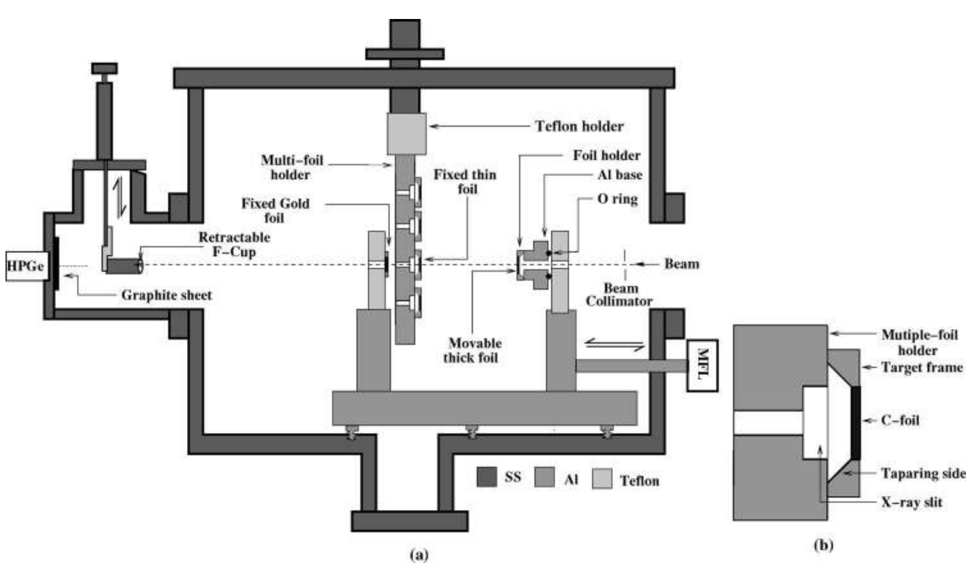

FIG. 2. (a) Cross-sectional view of the experimental chamber (not to scale); (b) enlarged view of a fixed thin foil frame in the multiple-foil holder.

ond, and gold foil holder along the beam direction was carried out using a theodolite. The vacuum in the chamber was maintained at 1×10^{-6} Torr throughout the experiment, with the help of a 250 l/s turbo molecular pump. The x rays, emerging from the foil-excited beam, were passed through a collimating system consisting of three slits in the direction perpendicular to the beam axis, and detected by a germanium ultralow energy detector from Canberra, model GUL 0035, with energy resolution [full width at half maximum (FWHM)] of 160 eV at 5.9 keV line of an ^{55}Fe source. Resolution of the detector worsens up to 220 eV for the observed peak at 4.78 keV due to Doppler broadening and blending contributions from a number of levels.

During the lifetime measurement the exciter or the first foil moves upstream to the beam, which makes it difficult to normalize the photon counts. A photon detector moving along with the exciter foil would have been a good choice. We have used the elastically scattered projectile ions from a fixed gold foil for normalization of the x-ray photons during the experiments with the single- as well as the two-foil target. The gold foil was mounted on a target holder similar to the first foil holder adjacent to the second foil and kept stationary throughout the experiment. The particle flux was measured by two silicon surface barrier detectors (SSBDs) mounted independently and anchored to the chamber base plate at ±30° to the beam axis, as shown in Fig. 1. A tantalum collimator of 1 mm diameter was placed in front of each SSBD and two such detectors were used in order to take care of the minor deflection of the beam in either direction. Intensity decay curves were normalized using this method, which agree to within 3%–5% with the charge normalization method using a deep Faraday cup.

The major components are described below in detail. A stepper motor was fitted to the upper lid of the chamber for the vertical movement of the multiple-foil holding ladder. Its shaft coincides with the central axis of the chamber. The rotational movement of the shaft helped in making the two foils parallel to each other. A multiple-foil holder $(170\times20\times10\ \mathrm{mm}^3)$ made of aluminum was fixed to the motor shaft by means of a thick teflon piece which provides an appropriate mechanical guide as well as electrical insulation required for the capacitance measurement (discussed later). Slots of $8\times1.4\ \mathrm{mm}^2$ were made along the breadth of this holder at each foil position. When the foil frame is fixed in front of this slot, it behaves like a slit for the emerging x rays. Three carbon foils having thicknesses of 4, 8, and 12 μg/cm^2 were fixed on the multiple-foil holder with one position kept blank for the conventional beam-single-foil experiments. The rail track arrangement was placed horizontally at the required height by means of three pivots fixed on the base plate of the chamber as shown in Fig. 2(a). It is an aluminum piece $(240\times60\times30\ \mathrm{mm}^3)$ having a tapering slot at a certain angle and a rectangular slot at the bottom to guide the foil movement along the beam direction. The base of the stand holding the first foil fits into the groove and moves freely. A Teflon piece was fixed on this stand to ensure electrical insulation required for measuring the minimum distance using the capacitance measurement method. A hole of 10 mm diameter at the appropriate height in the Teflon piece allows the incident beam to pass through it. An Al base for the target holder, having a 10 mm diameter hole, was fixed in front of the Teflon piece, as shown in Fig. 2(a). A viton O-ring was also placed in between the Teflon piece and the Al base of the foil holder to ease the alignment between the two foils. A 90 μg/cm^2 carbon foil, lifted on a foil holder, was fixed to the base using a thin layer of adhesive.

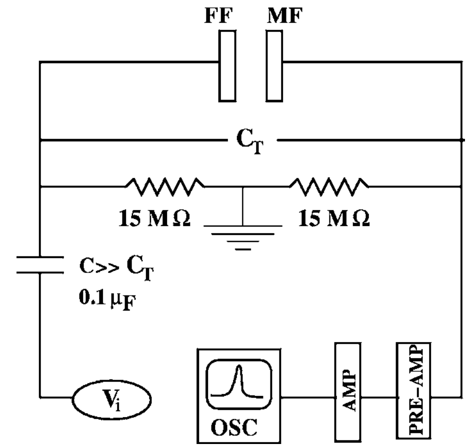

FIG. 3. Arrangement for the measurement of the minimum distance between the two foils. FF indicates the fixed foil, MF the movable foil, C_T the capacitance due to the two foils, and C the capacitance of the dc filtering capacitor.

To achieve fine horizontal movement, a motorized linear motion feedthrough (model MFL-275-4) and a programable motor logic controller (model MLC-1, programable indexer/driver) were procured from Huntington Laboratories Inc. The linear motion feedthrough (LMF) had the following features: linear travel of 4 in., shaft pitch of 0.125 in., and motorized accuracy of 25 000 microsteps/revolution. The LMF was connected to the base of the first carbon foil holder. The distance traveled in a single step is 0.127 μm. A computer program developed in house was used to control and read back its movement through a PC.

For precise lifetime measurement, it is essential to make the foils flat which may not be achieved by stretching the carbon foils mechanically. A method was developed to ensure that the carbon foils remain stretched while being lifted on the target frame. Figure 2(b) shows the Al target frame $(2\times20\ \mathrm{mm}^2$ diameter) having a 6 mm hole in the center with tapering on one side. Further it was well polished using powders of different grades so that the polished conical surface allows the water to slide down through the rear side of the foil when the foil is lifted out of water. Carbon film deposited on the surfactant coated glass plate was floated on 25% alcohol-water mixture. This reduces the surface tension of water, which in turn decreases the tension on the foil and hence results in a wrinkle-free foil. The success rate for making thin, stretched carbon foils was high using this method.

Figure 3 shows the capacitance measuring arrangement, inside the chamber, for determination of the minimum distance between the two foils to make them parallel[6] and to calibrate the motorized LMF. In this method a small, fixed voltage pulse V_i from a pulse generator was applied to one of the foils in such a way that the output, V_0, is less than 10 V. The output signal was taken to an amplifier through a charge

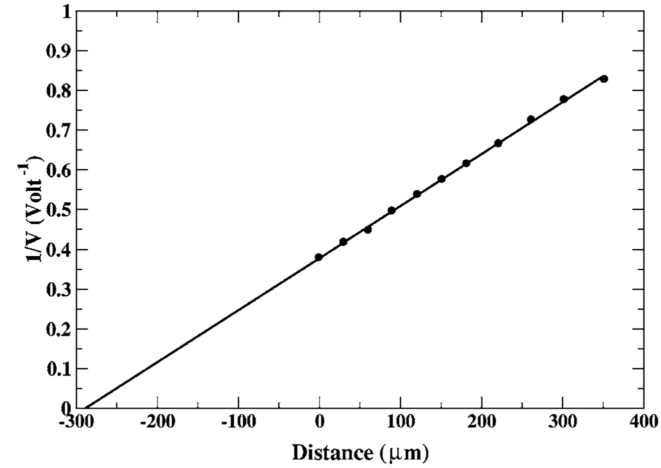

FIG. 4. Graph of V^{-1} vs the distance between the two foils.

sensitive preamplifier and finally read on an oscilloscope/ MCA. V_0 is proportional to $C_T V_i$ and thus it is inversely proportional to distance d. Variation of V_0 becomes nonlinear or discontinuous when the two foils touch each other. Beyond this, the variation is linear as shown in Fig. 4. This method is applied until V_0 drops to 0.5 V, though for larger distances calibrated LMF is used. In the experiment, the minimum distance of separation between the two foils was measured up to 83 ± 1 μm.

Besides the beam-foil x-ray spectroscopy, the present setup had also been used to study K-shell and L-subshell ionization cross section of solid as well as gas targets by high-velocity, heavy ion impact.[7] During the beam-foil experiments, passage of high energy (150–170 MeV) heavy ion beams (Z=20–28) through carbon foil causes nuclear reaction. For online studies on such nuclear products, a provision of placing a HPGe detector at the beam dump for γ spectroscopy is provided. This in turn will help us in studying atomic physics aspects involving the nuclear products.

III. RESULTS AND DISCUSSION

The results of an experiment using the above experimental facility are presented here. Figure 5 shows the partial level diagram of He-like and Li-like ^{48}Ti levels of our interest with the corresponding lifetimes and decay modes. Our analysis focuses on the Li-like $1s2s2p\ ^4P^o_{5/2}$ and He-like $1s2p\ ^3P^o_2$ levels. The former state partly decays (34%) (Ref. 8) through a magnetic quadrupole ($M2$) transition to the ground level and through an autoionization channel (66%) to the He-like ground state. Since the He-like $1s2p\ ^1P^o_1$ and $1s2p\ ^3P^o_1$ level lifetimes are of the order of femtoseconds, the lines that contribute to the 4.78 keV peak (Fig. 6), as calibrated using a ^{241}Am radiation source, are due to the $1s^22s\ ^2S_{1/2}-1s2s2p\ ^4P^o_{5/2}$ (4.69 keV), $1s^2\ ^1S_0-1s2p\ ^3P^o_2$ (4.734 keV), and $1s^2\ ^1S_0-1s2s\ ^3S_1$ (4.702 keV) transitions. The observed peak agrees within ±80 eV of the theoretical estimate of about 4.78 keV. These three lines lie within 47 eV (Fig. 5) and cannot be resolved spectrally by the detector used in our experiment for x-ray spectroscopy. Theoretical lifetimes for the corresponding upper levels are 205, ps[10] 422 ps,[8] and 26.6 ns,[11] respectively.

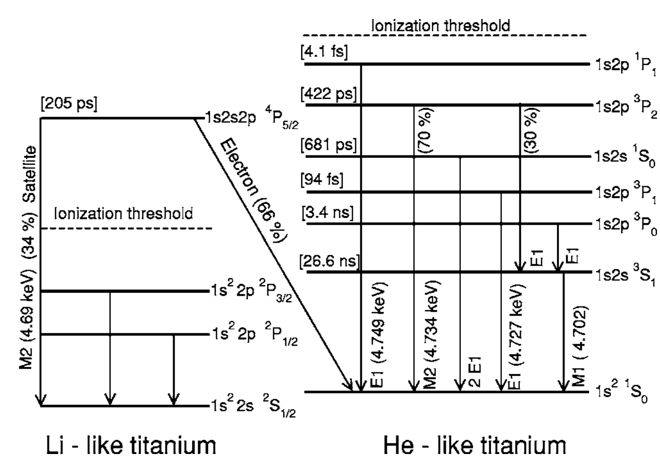

FIG. 5. Theoretical transition energies (not to scale) and lifetimes (Refs. 8–10) for Li-like and He-like titanium levels of interest to this work.

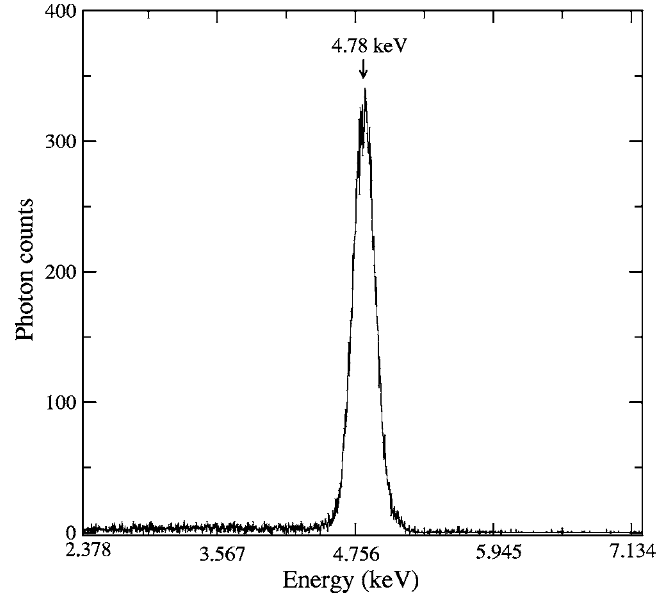

FIG. 6. A delayed x-ray spectrum for 143 MeV titanium beam incident on the 90 μg/cm^2 carbon foil.

The intensity of the 4.78 keV peak was measured as a function of the detector to foil distance in the single-foil experiment and as a function of the distance between the two foils in the case of the two-foil experiment. For every beam energy used, the single-foil data showed a multiexponential decay curve but the two-foil data contain an exponential decay due to the $1s2s2p\ ^4P^o_{5/2}$ level along with a growing component due to the electron capture to He-like $1s2p\ ^3P^o_2$ and $1s2s\ ^3S_1$ levels from the repopulated $1s2s2p\ ^4P^o_{5/2}$ level during the collision with the second foil. Analysis gives an impression that the He-like $1s2p\ ^3P^o_2$ level contributes in a strong way to the growing component while the contribution from the $1s2s\ ^3S_1$ level was negligible. Feeding now this He-like $1s2p\ ^3P^o_2$ level lifetime component in the single-foil data we can disentangle the effect of two levels, He-like $1s2p\ ^3P^o_2$ and Li-like $1s2s2p\ ^4P^o_{5/2}$, and find out the Li-like $1s2s2p\ ^4P^o_{5/2}$ level lifetime. In this way from the growing component of the two-foil data, He-like $1s2p\ ^3P^o_2$ level lifetime was determined. This method of data analysis involves both single-foil as well as two-foil data iteratively, which in

TABLE I. Comparison of lifetimes (ps) for the He-like $1s2p\ ^3P_2^o$ and Li-like $1s2s2p\ ^4P_{5/2}^o$ ^{48}Ti levels obtained from combined beam-single-foil and beam-two-foil experiments.

	Lifetime		
Upper level	Present	Previous	Theory
$1s2s2p\ ^4P_{5/2}^o$	210.5 ± 13.5	236 ± 12[a]	212[b]
		200 ± 12[c]	205[d]
$1s2p\ ^3P_2^o$	404 ± 19	404 ± 40[a]	422[e]

[a]Reference 16.
[b]Reference 17.
[c]Reference 13.
[d]Reference 18.
[e]Reference 8.

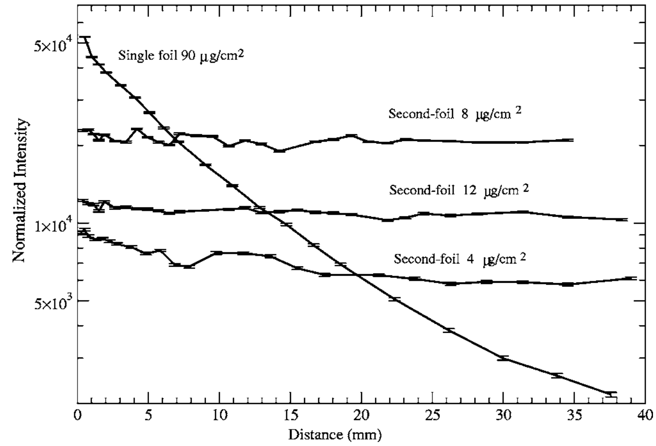

FIG. 7. X-ray intensity as a function of the distance between the two foils. Various carbon foils of thicknesses of 0, 4, 8, and 12 μg/cm^2 were used as second foils. These foils correspond to 0, 1, 2, or 3 collisions in the second foil with 143 MeV ^{48}Ti beam. Foil thickness of 0 μg/cm^2 implies that the experiment was done with single-foil target only (i.e., no second foil). Lifetime measurements performed with the single foil up to 80 mm showed clearly two exponents. But the curve had been curtailed at 40 mm as the two-foil experiments were not extended up to that. Here the distance of 0 mm implies that the minimum distance between the second foil and detector was about 2.5 mm. The solid lines are to guide the eyes only.

turn help us to separate out the contributions from transitions in the other charge states that cannot be spectrally resolved. Measurements are carried out at 95 and 143 MeV to obtain the mean values for He-like $1s2p\ ^3P_2^o$ and Li-like $1s2s2p\ ^4P_{5/2}^o$ level lifetimes, which are compared with earlier values in Table I. Further details can be seen elsewhere.[12]

Another variant of the beam-two-foil experiment has also been used. Here the option of varying the thickness of the fixed foil in the beam-two-foil technique has revealed a new way to measure the lifetime of the $1s2s2p\ ^4P_{5/2}^o$ level in Li-like titanium. In this method, instead of different beam energies, various foils of different thicknesses at the second foil position were used to obtain the lifetimes of He-like $1s2p\ ^3P_2^o$ and Li-like $1s2s2p\ ^4P_{5/2}^o$ levels[13] at 90 MeV beam energy. Results obtained compare very well with the above mentioned experimental values, as well as with the theoretical values, as shown in Table I.

Now we will discuss the interaction mechanism of the excited states with thin foils. The probabilities for $2s-2p$ excitation and vice versa are often large compared with those for excitation from one shell to another (including the continuum), since the $2s-2p$ energy difference is relatively small.[14] If the probability for excitation within an atomic shell is large, then the electron may jump back and forth rapidly between the sublevels during the collisions. The probability for $2s-2p$ excitation is required in some cases to compute effective fluorescence yields used to relate x-ray rates to the collision rates. McGuire *et al.*[14] estimated the $2s-2p$ excitation probabilities for collisions with the high-velocity heavy projectiles. Using these probabilities a mean free path is calculated. If the thickness of the fixed carbon foil is chosen to be about one mean free path then predominantly only one collision may take place between the ions and the carbon atoms. Appropriate thickness of the second foil was chosen so that on the average one, two, and three collisions probably take place in the second foil. This enables us to study the interaction mechanism of an excited state on one, two, or three collisions in the second foil. We observed the intensity decay as shown in Fig. 7. The normalized x-ray intensity observed with the single foil reduces by about a factor of 6 due to a single collision at the second foil. However, on the next collision the intensity increases by about a factor of 2.5. One additional collision brings the intensity to half. Such observations imply that the electron predominantly present in the $1s2p\ ^3P_2^o$ subshell jumps with a high probability to the $1s2s\ ^3S_1$ subshell on first collision; in the next collision it returns to the $1s2p\ ^3P_2^o$ subshell, and in the third collision it again goes back to the $1s2s\ ^3S_1$ subshell. Hence, the oscillation in the population of $1s2s\ ^3P_2^o$ and $1s2p\ ^3S_1$ levels leads to an oscillatory structure of the total intensity observed with the number of collisions. It has been found that five to six collisions in the second foil are sufficient to reach an equilibrium. Such a process of electron changing its position within a shell has been observed for the first time (Fig. 7). Detailed analysis, including the oscillation mechanism, theoretical simulations and fitting of the data to find the probability for 2s–2p excitation, will be published elsewhere.[15]

IV. DISCUSSION

A beam-two-foil experimental setup, having the provision to change the thickness of the second foil, has been developed and tested for lifetime measurements as well as for the investigation of the interaction mechanism of excited states with thin carbon foils. Using the present setup, the measured lifetimes show very good agreement with earlier measurements,[16–18] while interaction mechanism studies hint on population transfers from one state to another within a shell during a collision.

ACKNOWLEDGMENTS

The authors thank the Pelletron staff for providing the ion beam and Akhil Jinghan, P. Barua, and A. Kothari for their help during the experiment. The authors are also thankful to C. P. Safvan for the software support and G. K. Padmashree and Ram Janay for help during preparation of the manuscript.

[1] D. J. Pegg, in *Atomic Physics Accelerators*, edited by P. Richard (Academic, New York, 1980), Vol. 17, Chap. 10, and references therein.
[2] Y. Zou, R. Hutton, S. Huldt, I. Martinson, K. Ando, T. Kambara, H. Oyama, and Y. Awaya, Phys. Rev. A **60**, 982 (1999).
[3] T. Nandi, P. Marketos, N. Bhattacharya, and S. K. Mitra, J. Phys. B **32**, 769 (1999).
[4] T. Nandi *et al.*, Phys. Rev. A **66**, 052510 (2002).
[5] T. Nandi, A. A. Wani, N. Ahmad, P. Marketos, R. P. Singh, R. Ram, and S. Ahmad, J. Phys. B **37**, 703 (2004).
[6] T. K. Alexander and A. Bell, Nucl. Instrum. Methods **81**, 22 (1970).
[7] M. Hajivaliei *et al.*, Nucl. Instrum. Methods Phys. Res. B **105**, 645 (1999).
[8] C. D. Lin, W. R. Johnson, and A. Dalgarno, Phys. Rev. A **15**, 154 (1977).
[9] I. P. Grant, C. F. Fischer, and F. A. Parpia, GRASP-1992 (private communication).
[10] M. H. Chen, B. Crasemann, and H. Mark, Phys. Rev. A **24**, 1852 (1981).
[11] V. A. Boiko, V. G. Palchikov, I. Yu. Shobelev, and A. Ya. Faenov, *The Spectroscopic Constant of Multicharged Ions* (Standard, Moscow, 1988) (in Russian).
[12] T. Nandi, N. Ahmad, A. A. Wani, and P. Marketos, Phys. Rev. A (to be published).
[13] T. Nandi, N. Ahmad, and A. A. Wani, Phys. Rev. A **72**, 022711 (2005).
[14] J. H. McGuire, D. J. Land, J. G. Brennan, and G. Basbas, Phys. Rev. A **19**, 2180 (1979).
[15] T. K. Nandi, N. Ahmad, and A. Ahmad, NSC Annual Report, 2003–04 (unpublished), p. 179.
[16] H. D. Dohmann, R. Mann, and E. Pfeng, Z. Phys. A **309**, 101 (1982).
[17] C. P. Bhalla and T. W. Tunnel, Z. Phys. A **303**, 199 (1981).
[18] M. H. Chen, B. Crasemann, and H. Mark, Phys. Rev. A **24**, 1852 (1981).