5.4 ATOMIC PHYSICS RESEARCH

T. Nandi

Beam-single-foil and beam-two-foil experiments are being carried out in collaboration with several universities. This year a more versatile set up has been developed in the LIBR line (see section 4.5). Results obtained from an experiment using Ti-beam has given us another mode of lifetime studies. Further results encourage us to investigate in greater detail the mechanism of an excited state interacting with a thin carbon foil. Besides some activity on inner shell ionization of rare earth atoms by fast ion impact is also going on.

i.Novel analysis of beam-foil and beam-two foil data from He-like V

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The study of hyperfine quenching effect on the life time of $1s2p^3P^0_2$ level in He-like Vanadium ions was carried out for 100 and 158 MeV ^{51}V beams using beam foil experimental setup at NSC. We observed very different type of decay for the 5.17 keV vanadium line at different energies, as reported in NSC Annual Report 2001-2002. The data have been re-analyzed for understanding the origin of the energy dependence of the lifetime of the 5.17 keV state.

The line observed at 5.17 keV in the delayed spectroscopy mode originates from several forbidden lines in He-and Li-like Vanadium. A careful look to the level scheme (not shown) suggests that there are six time components in the decay which need to be included in a full fit. These are listed below with the theoretical lifetimes [1,4] : (1) 91 ps (quenched He-like 1s2p $^3P_0{}^o$),(2) 157 ps (Li-Like 1s2p2s $^4P^o{}_{5/2}$), (3) 203 ps (quenched He-like 1s2p $^3P^o{}_2$ F= 7/2, 9/2 hyperfine levels), (4) 239 ps (quenched He-like 1s2p $^3P^o{}_2$ F= 5/2), (5) 313 ps (unquenched He-like a12p $^3P^o{}_2$, F=3/2 and F=11/2, hyperfine levels), and (6) 16.9 ns (He-like 1s2s $^3S_1$). We have considered all these levels and invoked some excitation mechanism in determining the lifetime values for Li-Like V 1s2p2s $^4P^o{}_{5/2}$ and He-like V 1s2p $^3P^o{}_2$ from beam-foil and beam-two foil data at different beam energies. Finally we have proved the interaction mechanism that considered for the analysis.

In the two-foil situation total traverse of the foil excited beam can be divided in two parts (i) at the foil separation (x) between two foils and (ii) at the distance between the second foil and the detector slit (d). The phenomena at x is the same as the case in the single foil condition. But due to interaction with the second foil the relative intensity of each time component may be altered, as a result the effective lifetime may differ considerably. We have included these facts in formulating the equation that could fit well the data as under

$$I(x) = I_1 e^{-x/vt1} + I_2(1-e^{-x/vt2}) + I_3(1-e^{-x/vt3}) + I_4(1-e^{-x/vt4}) + I_5$$

There are total three growing components viz., 1s2p2s $^4P^o_{5/2}$ (t1), 1s2p $^3P^o_2$ (t2), and 1s2s $^3S_1$(t3) having theoretical lifetimes of 157ps [4], 313ps (without hyperfine quenching) or 258ps (with hyperfine quenching)[1], 16.9ns [5], respectively. The measured effective lifetime from beam-foil experiment is 242ps. Now a growing trend of the two-foil data at 158MeV from beginning gives an indication that the major growing component is faster than 242ps. Therefore, growing component of 157ps may play major role. Third and fourth term of equation (1) may be dropped.

In the least square fitting, the effective lifetime t1 was fixed to the value (242ps) obtained from the single foil measurement. The lifetime of the pure 1s2p2s $^4P^o_{5/2}$ level responsible for the growth is then determined to be 125±18ps. In order to eliminate the contribution of the 1s2p2s $^4P^o_{5/2}$ level from the effective lifetime determined from the decay of the 5.17keV line in the single-foil situation, we refitted the single-foil decay curve at 158 MeV with two, rather than one, exponents.

$$I(x) = I_1 e^{-x/vt1} + I_2 e^{-x/vt2}$$

In this procedure, the lifetime of the component associated with the satellite line, t1, has been fixed to 125±18ps. The lifetime of the second component, t2, is determined in this manner as 322±28ps and it may be attributed to both 1s2p $^3P^o_{2,0}$ as our analysis is unable to eliminate the contribution of 1s2p $^3P^o_0$. However, the time components of 313ps and 91ps can only lead a time component of 322±28ps if the contribution of 1s2p $^3P^o_2$ and 1s2p $^3P^o_0$ are close to 100 and 0%, respectively.

At 100 MeV beam energy effective lifetime of 161±5ps as measured with the single-foil target and appearance of a constant in the two-foil situation after a while implies that growing component must be slower than 161ps component. Among the lines involved in 5.17 keV, major candidates may be 1s2p $^3P^o_2$ (200 to 313ps including all Fs) and 1s2s $^3S_1$. Therefore, in the analysis the equation the second term of equation (1) can be ignored.

We have assumed two different processes in determining the mean lives of 1s2p $^3P^o_2$ and 1s2p2s $^4P^o_{5/2}$ from the single-and two-foil data at two different beam energies. If the assumptions are reasonable then the relative intensity of 1s2p $^3P^o_2$ (I_{He}) and 1s2p2s $^4P^o_{5/2}$ (I_{Li}) in single-foil situation must agree well with the two-foil case. Obviously, the excitation cross section is hidden in the intensity. As per the assumptions made on the excitation mechanism with the thin second foil at 158 MeV the observed intensities from the fitting of two-foil data using equation (1) can be equated approximately by involving the measured time components and the branching ratios [2,5] as under

$$(0.74 * I_{He} e^{-d/vt1} + 0.37 * I_{Li} e^{-d/vt2}) / (0.63 * I_{Li} e^{-d/vt2}) = I_1 / I_2$$

to obtain I_{li} / I_{He} ratio. Similarly the equation used for the evaluating the I_{li} / I_{He} in the single-foil case as

$0.37*I_{Li}\, e^{-d/vt2} / 0.74*I_{He}\, e^{-d/vt1} = I_1 / I_2$

In this case the observed intensities (I_1 & I_2) are obtained from equation (2). Further the observed intensities with two-foil data at 100MeV was equated to equation

$$(0.74*I_{He}\, e^{-d/vt1} + 0.37*I_{Li}\, e^{-d/vt2}) / (0.26*I_{He}\, e^{-d/vt1}) = I_l / I_2$$

and the observed intensity ratio with single-foil data with equation (1). The intensity ratio of I_{li} / I_{He} obtained (Table 1) shows a very good agreement which in turn proves the assumptions on the excitation mechanism. For details one may see our recent article [6].

Table 1 : The relative level population of 1s2p2s $^4P^o_{5/2}$ to 1s2p $^3P^o_2$ is compared at different beam energies in the single-foil as well as the two-foil experiment.

Beam Energy (MeV)	*Intensity Ratio single foil experiment*	*Intensity ratio two-foil experiment*
100	11.67 [2], 12.7 [3]	11.67 [2], 11.28 [3]
158	5.89 [2], 6.4 [3]	6.45 [2], 5.97[3]

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5.4.2 Lifetime of 1s2p2s $^4P_{5/2}$ level in Li-like ^{48}Ti using Beam Two-foil Experiment

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Satellite lines originating from a doubly excited level of given charge state of an ion are very close to the singly excited line in the next higher charge state. These lines for ions up to Z ≈ 50 are not resolved in the solid state x-ray detectors commonly used in the beam single-foil experiment (for example [1,2]). The upper level of any satellite is partially autoionizing and decay through both autoionization and radiative channels. Our recent work [3] shows that this property, in conjunction with the beam single-foil technique [4] and beam two-foil technique [5], enables the resolution of the satellite blending problem in the lifetime measurements of helium like vanadium [3] and nickel [6] ions. These measurements in our laboratory has confirmed the satellite blending problem of the M2 line $1s^2\ ^1S_0$- $1s2p\ ^3P_2$ as well as led to the mean lifetime measurement of the partially autoionizing satellite level of $1s2s2p\ ^4P_{5/2}$ in lithium like ions.

In the case of two-foil target the first-foil on which the beam falls first is moved upstream relative to the second foil (static). The x-ray detector is kept fixed at right angles to the incident beam, and the distance between x-ray collimator and static foil is remained fixed through out the experiment. X-ray emerging from the foil excited beam was passed through a collimating system consisting of three slits in a direction perpendicular to the beam axis, to detect them in a low energy germanium detector. Normalization was achieved with the elastically scattered ions from the gold foil and detected them in two surface barrier detectors plaed at 30^0 to the incident beam. Two surface barrier detectors were used in order to take care of the minor deflection that may take place in either directions. In the experiment the minimum distance of separation between the two foils was found to be 83µm. The capacitance measuring arrangement made inside the chamber was used to measure the minimum distance, and calibrated linear motion drives readings [7].

Provision of loading a two-foil target system makes it possible to measure the lifetime as short as picoseconds by using a beam-foil technique [8]. The two plots show the trend in the normalised intensity variation of the 4.78 keV peak with distance for the single-foil (Fig. 1a) and the two-foil experiment (Fig. 1b). The negative expontional decay trend in case of single-foil target is natural. In two-foil target the trend is totally different as it is obvious from the plot that the intensity of 4.78 keV peak grows with separation up to a certain distance then shows a saturation. Now the lifetime analysis from the single-foil data as well as two-foil data for a particular foil was done by the prescription given in Nandi et al. [3,6].

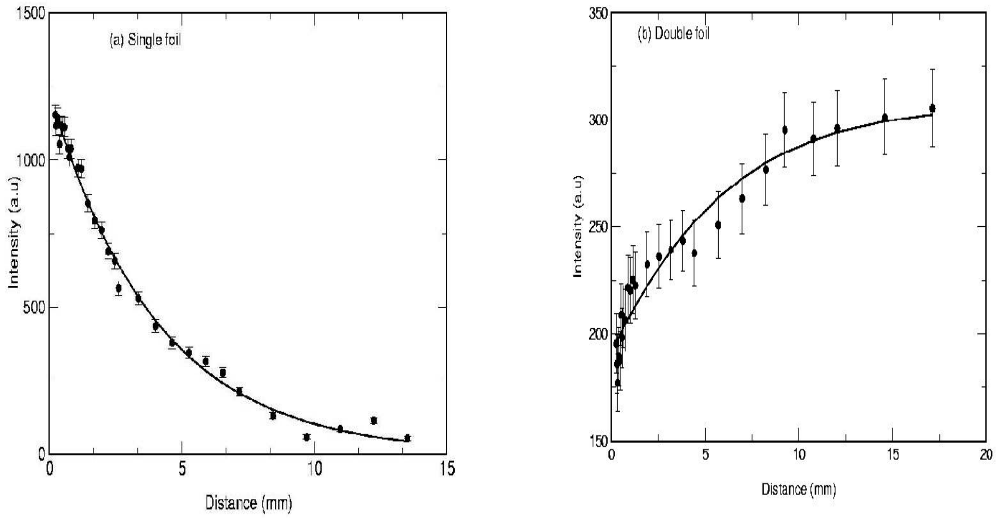

Fig. 1 : Normalized count rate as a function of the separation between the foil and detector in the (a) single foil (b) double foil experiment at 90 MeV.

The lifetime of 1s2p2s $^4P_{5/2}$ state in $^{48}Ti^{19+}$ is found to be 197.5± 3ps. This value is very close to the theoretical value (201 ps) [9] which was obtained relativistically in the intermediate coupling scheme, using Dirac- Hartree-Slater wave functions and the Moller two-electron operator. However the value is lower than another theoretical value of Bhalla and Tunnel (212 ps) [10] which was obtained using relativistic Hartree-Fock model and the earlier experiment using a flat crystal spectrometer and an electrostatic cylindrical mirror analyzer found also a higher value (236 ± 12 ps) [11].

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5.4.3 L X-ray production cross-sections for $_{57}La$, $_{58}Ce$, $_{60}Nd$ and $_{62}Sm$ by 30-60 MeV C^{4+} and O^{5+} ions

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The experimental and theoretical understanding of inner shell ionization by charged particles has been studied extensively over the past decades. A review of the tabulated data reveals extensive study of K and L shell ionization for incident proton and light ions [1]. The experimental data is scarce for heavy ions. The direct ionization (DI) mechanism is dominant when $Z_1 << Z_2$ and $v_1 >> v_{2s}$ while the electron capture (EC) process dominates if ion velocities $v_1 \leq v_{2s}$ and $Z_1 \leq Z_2$, where Z_1 and Z_2 are the atomic numbers of the projectile and the target atom, and v_1 and v_{2s} are the velocities of the projectile and the target inner-shell (s = K-, L-shell) electron, respectively.

Only a few measurements are available in the literature on the study of L shell by Carbon and Oxygen ions beam. For Carbon ions, Sarkadi and Mukoyama [2] reported L_i subshell ionization cross-sections for Au in the energy range between 0.4-3.4 MeV, Malhi and Gray [3] measured individual L X-ray cross-sections for Yb and Au energies ranging 6-36 MeV, and Mehta *et al*. [4] reported total L X-ray production cross-sections for different elements from Cu to Pb in the energy range 2-25 MeV. Semaniak *et al.* [5] measured L subshell ionization cross-sections of some heavy elements between Hf and Th by C^{3+} and O^{3+} ions in the energy range between 0.4-1.8 MeV/amu. M.C. Andrews *et al.* [6] have measured L X-ray production cross-sections of Nd, Gd, Ho, Yb, Au and Pb by 25 MeV Carbon and 32 MeV Oxygen ion beam at different projectile charge states. M.C. Andrews *et al.* [6] have shown that projectile with one K shell electron or bare projectile, without K shell electrons, the target X-rays production cross-section enhanced over those for projectile with two or more electrons. This result was inferred from the contribution of EC from target inner shell to projectile K shell vacancy.

In the present work, L X-ray production cross-sections have been measured for thin (~57 µg/cm^2) solid targets of $_{57}La$, $_{58}Ce$, $_{60}Nd$ and $_{62}Sm$ by 30-60 MeV C^{+4} and O^{+5} ions. The incident ions don't have any K shell vacancy. This will help in a reliable check of the theories of direct ionization with heavy projectile at high energies.

The present experiment was performed at Nuclear Science Centre (NSC), New Delhi. The targets were positioned at 45° to the beam direction as well as to the X-ray detector in the scattering chamber, under vacuum (~10^{-6} Torr). A LEGe detector (FWHM = 180 eV at 5.96 keV) was placed outside the target chamber in the side port with 20 µm thick mylar window at 90° to the beam direction. In order to avoid target damage, charge build up and to reduce the dead time correction, the current at the target was kept 5 nA. The total charge deposited on each target was measured using a charge integrator connected to the Faraday cup. All elemental targets were prepared by vacuum evaporation employing an electron gun. A quartz crystal was used to monitor the thickness of each target during evaporation. The accurate mass thickness was determined using the Energy Dispersive X-Ray Fluorescence (EDXRF) technique.

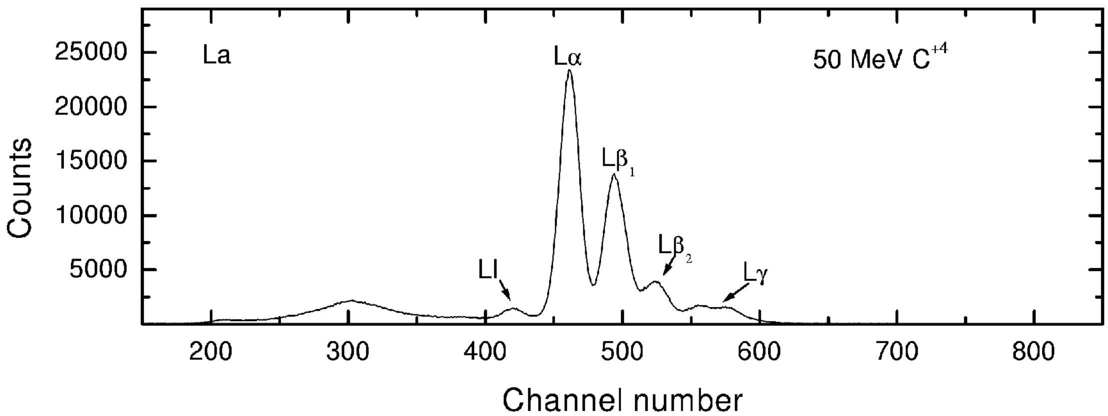

Fig. 1 : L X-ray spectrum of La target at 50 MeV C^{+4} beam

Typical L X-ray spectrum of La elemental target at 50 MeV C^{+4} beam is shown in Fig. 1. In this figure, the spectrum shows well-separated Ll, Lα, $L\beta_1$, $L\beta_2$ and Lγ X-ray peaks of La element. Present experimental L X-ray production cross-sections were evaluated using the method as described by M. Hajivaliei *et al.* [7]. The L X-ray production cross-sections are compared with those predicted by Plane Wave Born Approximation (PWBA) and ECPSSR [energy loss (E), Coulomb deflection effect (C), Perturbed Stationary State (PSS) approximation with relativistic correction] theories. The L X-ray production cross-sections for all the four targets as a function of Z_1/Z_2 are presented in Fig. 2 at different energies of O^{+5} ions.

Preliminary results reflect that at all the incident beam energies for C^{4+} and O^{5+} ions La and Ce L X-ray production cross-sections are higher than the theoretical values predicted by both PWBA and ECPSSR approximations. Further, critical evaluation of the present data is in progress.

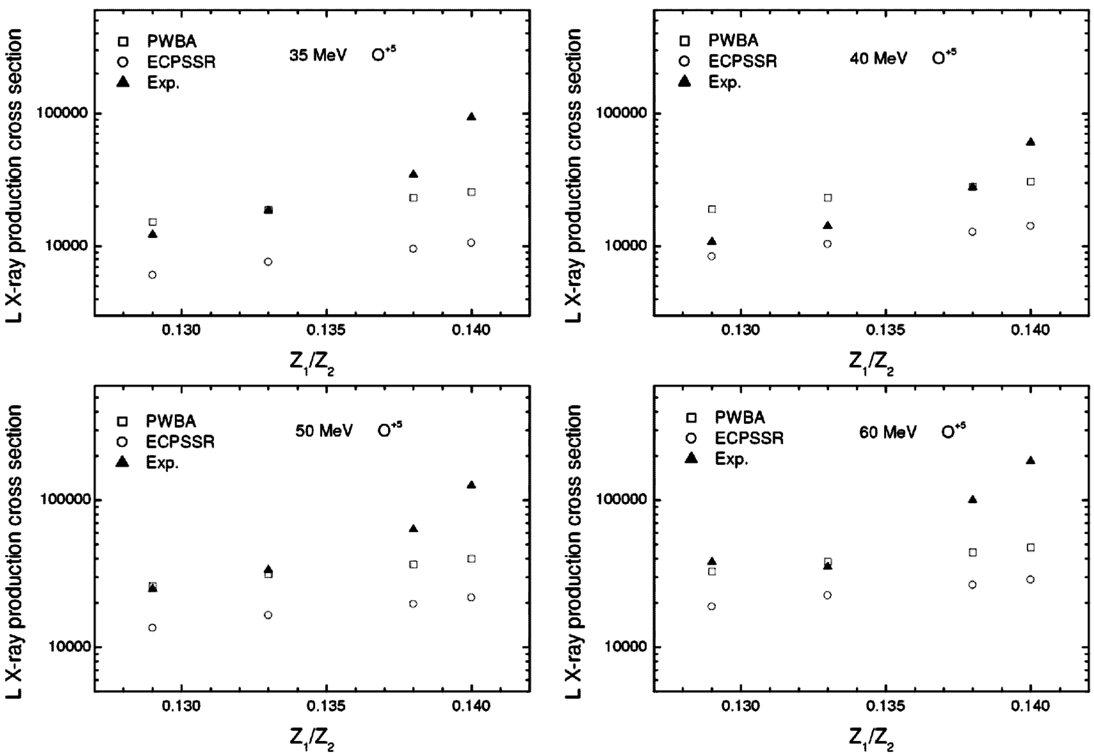

Fig. 2 : L X-ray production cross-sections for $_{57}La$, $_{58}Ce$, $_{60}Nd$ and $_{62}Sm$ by 30-60 O^{+5} ions as a function of Z_1/Z_2

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