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Effect of Foil Thickness on Excited States in the Beam-foil Interactions

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The present communication reports experimental studies on the interaction mechanism of excited states produced by fast heavy ions passing through carbon foil with a thin carbon foil. Oscillatory structure of the lifetime spectrum of the combined peak of M1 and M2 decays in He-like Ti-ions gives a direct evidence of the transitions between 1s2p $^3P_2$ and 1s2s $^3S_1$ states on every collision.

Key Words: Beam-foil excitations, Beam-two-foil experiment, Lifetime spectra, Intrashell transitions.

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 post-foil beam that 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 won't appear in them. Still some problems remain due to the presence of satellite lines i.e. the lines emanating from neighboring charge states. In order to eradicate the blending problem, a new method to analyze the lifetime spectra 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[2,3] and is called the iterative multi-component exponential growth and decay analysis. The present facility keeps an option of varying the thicknesses of the second foil for each beam energy used. This helps us to study the interaction mechanism of the excited states, generated during passage of the beam through the first foil, interacting with the thin carbon foils (second foil) of different thickness.

The charge state distribution of any ion beam with certain kinetic energy colliding with a solid foil varies with the thickness and the incident charge states. It is supposed to be so for the formation of excited states too. The K-X-ray fluorescence yield for H-like ions vary significantly on the charge state of the incident ions during the collision of H-like Si beam with He gas target[4]. If the probability for excitation within an atomic shell is large, then electrons may jump back and forth rapidly between the sub-levels (2s-2p) during collisions between a target atom and a proton[5] as predicted theoretically in late seventies. However, no experimental effort was made to verify this prediction till date, an attempt has been made to see how does intra-shell transition alter the data on collisions using the beam-single-foil and beam-two-foil experiments[6] and above mentioned novel method of data analysis[2].

EXPERIMENTAL

A beam of 143 MeV Ti from Pelletron accelerator at IUAC, New Delhi was passed through 90 $\mu g/cm^2$ carbon foil (first foil) loaded in a dedicated experimental set up[6] shown in Fig. 1 to produce He-like Ti 1s2s $^3S_1$ and 1s2p $^3P^0_2$ states. As these excited states decay to ground states, via M1 and M2 transition lines, which are close lying (Fig.2) and not resolved with the X-ray semiconductor detector, appearing at 4.78 keV as a composite peak as shown in Fig. 3. The concerned transition

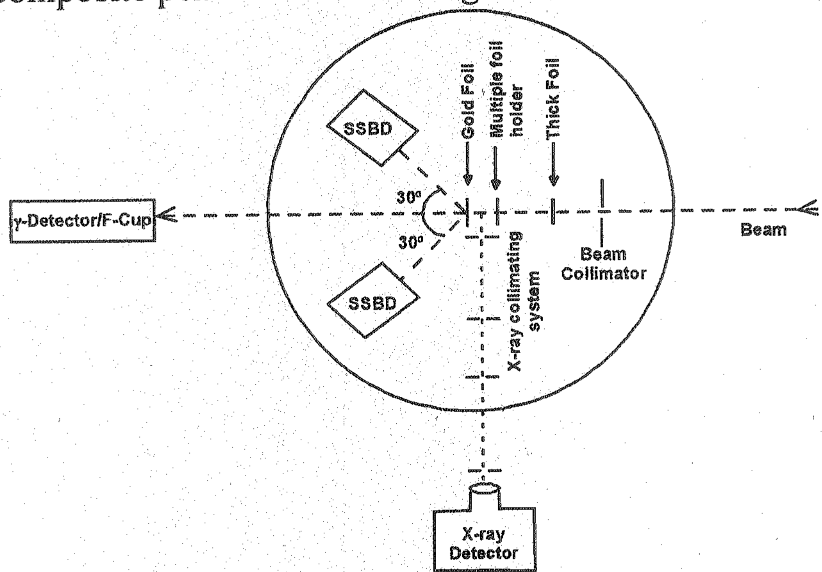

Fig.1. Schematic of the experimental arrangement

rates are 1.66 x 10^9 and 3.76 x 10^7/s, respectively. The excited states are made to undergo a collision with a 4 $\mu g/cm^2$ thin foil (second foil) in which He-like Ti 1s2p $^3P^0_2$ state may convert to He-like Ti 1s2s $^3S_1$ state and vice versa. If the abundance of these two states are unequal, the normalized intensity would either increase or decrease. The reduced intensity on single collision with the second carbon foil implies that 1s2p

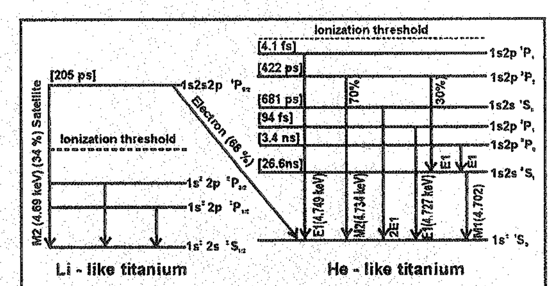

Fig.2. Theoretical transition energies (not to scale) and lifetimes for Li-like and He-like titanium levels

state is more abundant than the 1s2s $^3S_1$ state as produced from the first foil. Further, measurements were done with two (8 μg/cm^2), three (12 μg/cm^2) and five (20 μg/cm^2) collisions in the second foil also to show

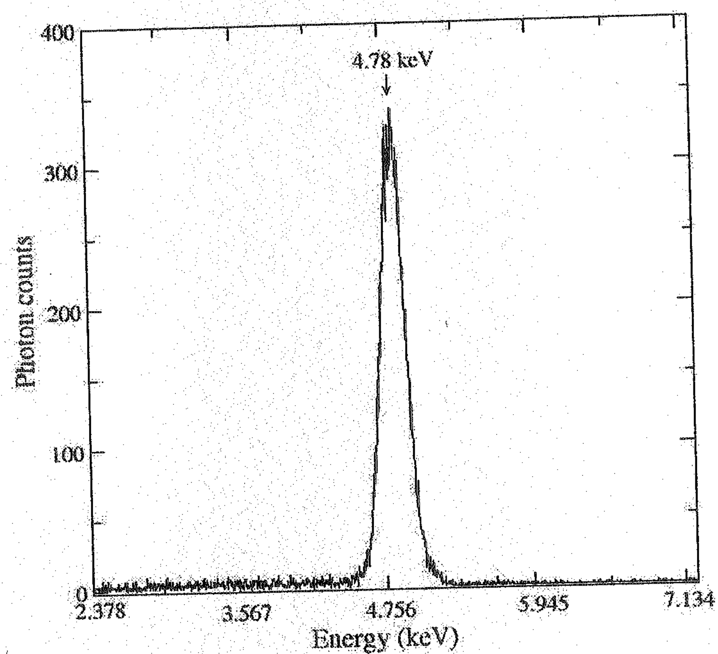

Fig.3. A delayed X-ray spectrum for 143 MeV titanium beam incident on the 90 μg/cm^2 carbon foil

the effect of intra-shell transitions in subsequent collisions. Such effect can be revealed from the change in intensity ratios of M1 and M2 lines of He-like Ti in the 4.78 keV peak with the thickness of the second foil. Number of collision was estimated from carbon foil thickness using the prescription given by Doyle *et al*[4]. Details of the experimental set up is given elsewhere[6]. The 4.78 keV peak contains also Li-like M2 line (1s2s2p $^4P^{0}_{5/2}$ - $1s^22s^2S_{1/2}$), however it remains unaltered due to 2s-2p transitions.

RESULTS AND DISCUSSION

The probabilities for 2s-2p transition and vice versa are often large compared to those for excitation from one shell to another (including the continuum), since the 2s-2p energy difference is relatively small. If the probability for excitation within an atomic shell is large, then the electron may jump back and forth rapidly between the sub-levels 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.*[5] estimated the 2s-2p excitation probabilities for collisions with the high-velocity heavy projectiles. Using these probabilities mean free path is calculated. If the thickness of the fixed carbon foil is chosen to be about one mean free path then on the average 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. The intensity decay is observed as shown in Fig. 4.

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 compared to previous set of such observations imply that the electron predominantly present in the 1s2p $^3P^0_2$ state jumps with a high probability to the 1s2s $^3S_1$ state on first collision; in the next collision it returns to the 1s2p $^3P^0_2$ state, and in the third collision it again goes back to 1s2s $^3S_1$ state. Hence, the oscillation in the population of 1s2p $^3P^0_2$ and 1s2s $^3S_1$ states leads to an oscillatory structure of the total intensity observed with the number of

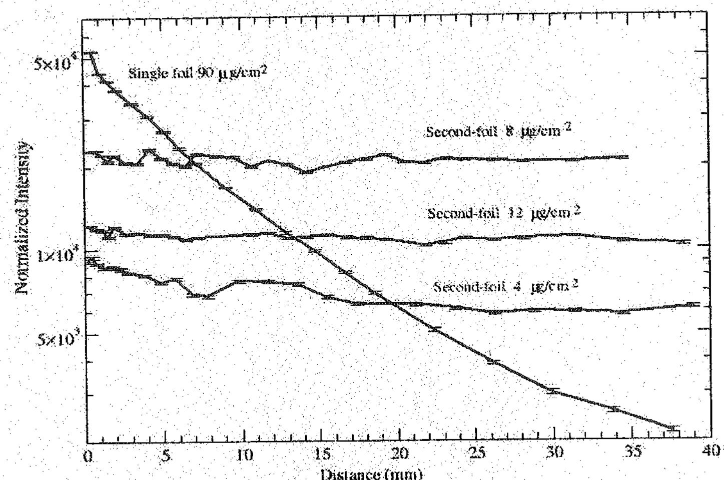

Fig.4. X-ray intensity as a function of the distance between the two foils

data collisions. It has been found that five to six collisions in the second foil are sufficient to reach equilibrium. Such a process of electron changing its position within a shell has been observed for the first time. 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[7].

Various carbon foils of thickness 0, 4, 8 and 12 mg/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 0 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 curve had been curtailed at 40 mm as the two foil experiments were not extended up to that. Here distance 0 mm implied that the minimum distance between the second foil and detector was about 2.5 mm. Solid lines are to guide the eyes only.

Conclusions

Present studies on interaction mechanism on excited states with thin carbon foil hint on population transfers from one state to another within a shell during a collision. Data indicate that after few more collisions, two states will be totally indistinguishable. Accordingly a simple calculation shows that six collisions are sufficient to admix two states completely. This experiment gives the researchers an opportunity to make invaluable contributions on the interaction mechanism between the excited states and thin solid foils.

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