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# Radiative resonant energy transfer process in projectile-like ion formed in beam-foil interaction

Adya P. Mishra [a,*], T. Nandi [b], B.N. Jagatap [a]

[a] Atomic and Molecular Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
[b] Inter-University Accelerator Center, JNU New Campus, Aruna Asaf Ali Marg, New Delhi 110 067, India

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ABSTRACT

The formation of projectile-like $^{55}_{25}$Mn ion during bombardment of a thin carbon foil by $^{51}_{23}V^{12+}$ ion beam of energies above the Coulomb barrier is inferred through the observation of unresolved $1s2p^3P_2^o \rightarrow 1s^2{}^1S_0$ and $1s2p^3P_0^o \rightarrow 1s^2{}^1S_0$ transitions of He-like Mn at 6.14 keV. From the decay of intensity of this line the measured radiative lifetime of the upper state is found to be $78.7 \pm 11.6$ ps which is close to the theoretical lifetime of the $1s2p^3P_0^o$ state (86.18 ps), but substantially lower than that of $1s2p^3P_2^o$ state (147.1 ps). This suggests that the $1s2p^3P_0^o$ state is populated more than the $1s2p^3P_2^o$ state when He-like Mn exits the carbon foil. This behavior is explained on the basis of radiative resonant energy transfer process in beam-foil excitation as reported recently (Nandi T, et al. J Quant Spectrosc Radiat Transfer 2012;113:783–8).



A beam of ions directed through a thin foil target emerges in a range of ionized states and in a variety of electronically excited states. The underlying mechanisms for production of various ionized states during ion–solid collisions are well understood and sophisticated models considering various processes have been developed to predict the measured charge state distributions accurately [1]. However, the mechanisms that govern the production and evolution of different excited states are less well understood and it is not always possible to predict the degree of excitation. Although the beam-foil interaction is a highly non-selective excitation process, the interaction favors the production of a certain class of states. For example, beam-foil excitation is usually very efficient in populating multiply-excited states. The interaction also favors formation of very high orbital angular momentum ($l$) Rydberg states. There are also reported observations of selective excitation at the back surface of the foil [2–6] as well as in its bulk [7]. A considerable amount of theoretical and experimental work has been done to understand the distribution of Rydberg states populated by beam-foil excitation [2–6,8–13]. However the information on the population of low-lying states is still very limited. In order to explain the selective population of the $1s2p^3P_2^o$ state in He-like Ti ions with a carbon target, recently Nandi et al. [7] suggested a new plasmon driven excitation mechanism, called radiative resonant energy transfer (RRET), which mainly contributes to excitation of low-lying levels. In this letter we provide further evidence to RRET process in beam-foil excitation. It is shown here that the bulk plasmon energy of carbon foil is transferred to He-like Mn ions in the $1s2s^3S_1$ level, which is produced by bombarding a thin carbon foil with a $^{51}_{23}V^{12+}$ ion beam of energy higher than the Coulomb barrier to excite to the $1s2p^3P_0^o$ state resonantly.

The experiments are performed at 15 UD tandem Pelletron accelerator laboratories at IUAC, New Delhi. The details of the beam-foil and beam-two-foil experimental setups are

* Corresponding author. Tel.: +91 22 25595082; fax: +91 22 25519613.
*E-mail addresses:* amishra@barc.gov.in, amishram@yahoo.com (A.P. Mishra), nanditapan@gmail.com (T. Nandi), bnj@barc.gov.in (B.N. Jagatap).

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described in earlier papers [7,14–16]. Briefly, an ion beam of $^{51}_{23}V^{12+}$ from the accelerator, at a required energy, is passed through 50 μg/cm$^2$ thick carbon foil. In case of two-foil experiment, a second thin carbon foil (4-μg/cm$^2$) is placed at 1.2 mm upstream from the detector. This foil and the detector are held fixed while the first foil is moved to record the x-ray spectra at different delay times by monitoring the distance between the two foils with high precision ($<1$ μm). A germanium ultralow energy detector (GUL0035, Canberra Inc.), which has a resolution of 150 eV at 5.9 keV and a 25 μm thick Be entrance window, is used to record the x-ray spectra in the direction perpendicular to the beam-axis. A collimating system consisting of three slits is used to ensure that the detector views a $\sim$2 mm length of the beam. Two silicon surface barrier detectors are used to monitor the incident ion beam by detecting the elastically scattered projectiles from a 120 μg/cm$^2$ gold foil which is fixed 20 mm downstream from the detector window. Intensities are normalized using this method, which agrees to within 3–5% with the charge normalization method using a deep Faraday cup. Vacuum inside the chamber is maintained at better than $1\times10^{-6}$ Torr. The x-ray spectrum is calibrated with a $^{241}$Am source.

The x-ray spectra of one-foil-excited V at five incident energies are shown in Fig. 1. These spectra are recorded at delay times larger than $\sim$60 ps (corresponding to minimum distance between first foil and detector), so that the transitions from short lived (lifetime $<1$ ps) excited states do not show up. Besides the prominent line at 5.17 keV (assigned to four unresolved lines: three transitions $1s2p^3P^o_2\rightarrow1s^21S_0$ and $1s2s^3S_1\rightarrow1s^21S_0$ of He-like V and one transition $1s2s2p^4P^o_{5/2}\rightarrow1s^22s^2S_{1/2}$ of Li-like V), a low intensity broad peak at 6.14 keV is observed for all incident beam energies except for 100 MeV. The position of this line may suggest that it can be assigned to $1s3p^1P^o_1\rightarrow1s^21S_0$ and $1s3p^3P^o_{1,2}\rightarrow1s^21S_0$ transitions of He-like V. However, since the lifetimes of $3^1P^o_1$ and $3^3P^o_{1,2}$ states are $<0.1$ ps [17], these transitions are unlikely to be seen at delay times of the order of 100 ps. Also, the satellites of the lines $1s3p$–$1s^2$ created from $1s2l3l'$ autoionization states cannot be observed at such long delay times as the lifetimes of these states are $<1$ ps [18]. No other transition of highly ionized V (for our experimental conditions more than 99% of ions formed at the exit of the foil are in the charge state $V^{17+}$–$V^{22+}$ [1]) is known at 6.14 keV energy [17]. Further, this line is not observed at an incident beam energy of 100 MeV, which is below the Coulomb barrier for V+C system (134 MeV). These observations lead us to think of the possibility of projectile-like ions produced by nuclear transfer reaction and we assign the line at 6.14 keV to $1s2p^3P^o_2\rightarrow1s^21S_0$ and $1s2p^3P^o_0\rightarrow1s^21S_0$ transitions of He-like Mn [17]. It is important to note here that if the energy of the projectile ions in the beam-foil experiments is above the Coulomb barrier, the projectile-like ions can be produced by nuclear transfer reactions. The interaction of such ions with the foil, both in its bulk as well as at its exit surface, generates various excited states of the projectile-like ions. Consequently, the projectile-like ions produced from the foil act as a secondary beam in beam-foil spectroscopy experiments. The x-ray emission from projectile-like ions have been observed earlier in several beam-foil spectra (for example see [19]) and the x-ray lines from target-like atoms as well as from nuclear reaction products have been used to study nuclear reactions [20] and atomic phenomena [15,21].

Nuclear reaction products at the exit of the solid target can be obtained by considering multi-nucleon transfer processes as discussed by Alhassid et al. [22] and Nandi [15]. Accordingly the most probable nuclear products in the present case for incident energies above Coulomb barrier are due to an alpha transfer from the carbon foil to an incident vanadium ion:

$$^{51}_{23}V+^{12}_{06}C\rightarrow^{55}_{25}Mn+^{8}_{4}Be+0.57\ \text{MeV},$$

which is an exothermic reaction. For all other possible exit channels the ground state reaction $Q$-value is negative [23]. Note that in similar experiments with Fe+C and Ni+C [15], breaking up of $^8_4$Be into two α-particles has been observed in coincidence [24], which confirms the alpha transfer reaction. It is also important to mention that predictions of residual nuclei by PACE4 [25] are quite different. For incident energies of V in the range 150–180 MeV, the percentage yields of Mn is only 1–2% and (fusion) cross section varies from 8 to 20 MB. We have not seen any other nuclear product predicted by PACE4, which is not surprising as PACE4 is based on formation of a compound nucleus due to fusion and followed by evaporation. The nucleon transfer process is once again seen to be the dominant mechanism for the nuclear reaction products when fast moving heavy ions penetrate a solid target.

In the next step we measure the decay of the line (shown in Fig. 2) at 6.14 keV for incident beam energies of 150 and 160 MeV. The time axis of Fig. 2 is determined by dividing the distance between the first carbon foil and the detector by velocity of the post foil projectile-like ion (Mn), which is quite different from velocity of the projectile ion (V). A simple kinematic calculation [26] provides us with a wide range of projectile-like ion energies and the scattering angles of the projectile-like ions with respect to the beam axis. For an impact of 160 MeV V ion beam on C the energy of projectile-like $^{55}_{25}$Mn ions can be 157–123 MeV at 0–10° angles, while that at 150 MeV can be 147–116 MeV [26]. The geometry used for the present experiment can accept a full range of angles; hence we take the mean projectile-like ion energy while estimating the velocity of Mn ions. It is important to note here that the error in delay time measurements ($\pm5$ ps) is mainly due to the uncertainty in determining the distance ($\pm0.1$ mm [14–16]) between the first carbon foil and the detector. The error in time measurements due to velocity spread is only $\pm1$ ps. A large spread in both velocity and scattering angle of Mn ions results in broadening of the line at 6.14 keV. From the decay curves corresponding to 160 and 150 MeV incident beams, the measured mean lifetime for the upper state is $74.2\pm6.5$ and $83.2\pm9.6$ ps respectively. Thus the average value of lifetime for the upper state of blended $1s2p^3P^o_2\rightarrow1s^21S_0$ and $1s2p^3P^o_0\rightarrow1s^21S_0$ transitions of He-like Mn is $78.7\pm11.6$ ps, which agrees well with the theoretical lifetime of the $1s2p^3P^o_0$ state (86.18 ps), and it is substantially lower