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L shell x ray production in high-Z elements using 4–6 MeV/u fluorine ions

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ABSTRACT

L shell line and total x ray production cross sections in $_{78}$Pt, $_{79}$Au, $_{82}$Pb, $_{83}$Bi, $_{90}$Th, and $_{92}$U targets ionized by 4–6 MeV/u fluorine ions were measured. These cross sections are compared with available theories for L shell ionization using single- and multiple-hole fluorescence and the Coster-Kronig yields. The ECPSSR and the ECUSAR theories exhibit good agreement with the measured data, whereas, the FBA theory overestimates them by a factor of two. Although for the F ion charge states q = 6–8 the multiple-hole atomic parameters do not significantly differ from the single-hole values, after an account for the multiple-holes, our data are better in agreement with the ECUSAR than the ECPSSR theory.

1. Introduction

The measurement of emitted x rays from targets has resulted in major advances in radiation [1], plasma [2], atomic and nuclear physics [3], and in particle induced x ray emission (PIXE) technique [4,5]. While PIXE originated and continues using light ions such as protons or alphas [6–16], there is an increasing interest to use heavy ions for PIXE analysis due to higher cross sections and thereby better sensitivity [17]. While discrepancies between theories and experiment were attributed to multiple ionization even with protons[18], multiple-ionization effect has been known for decades in L-shell ionization by heavier ions [19–34]. However this effect is still rarely addressed for the x ray emission elemental analysis in the aftermath of ionization by such ions.

The sum of electron capture (EC) from a projectile with the atomic number Z_P and direct ionization (DI) of a target with the atomic number Z_T results in ionization of the target atom's inner shells. In asymmetric collisions, i.e., $Z_P/Z_T \ll 1$, the DI is dominant, whereas, for symmetric collisions, i.e., with Z_P/Z_T approaching 1, the EC process becomes increasingly important. As presented in Section 2, the L shell x ray production cross sections have been measured in high Z_T-targets ionized by the 76–114 MeV ^{19}F ions. With $Z_P = 9$, $0.10 \leqslant Z_P/Z_T \leqslant 0.12$ and the ratio of the projectile velocity $v_p = 6.351\ [E_P(\mathrm{MeV})/A_P(u)]^{1/2}$ to the orbital velocity of the L-shell electrons $v_T = (Z_T - 4.15)/2$ less than 1 i.e., $0.029 \leqslant v_P/v_T \leqslant 0.042$, the present data are in the asymmetric and slow collision regime.

While expanding on the existing data base with ionization by heavy ions as desired for PIXE analysis, the collision regime of the present data allows for a meaningful comparison with existing ionization theories as discussed in Section 3. Section 4 addresses effects of the single- and multiple-hole atomic parameters required for conversion of ionization to x ray production cross sections, and Section 5 summarizes our findings.

2. Experimental details and data analysis

The L shell x ray production cross sections in the elements with $78 \leqslant Z_T \leqslant 92$ elements using the ^{19}F ions (charge states q = 6^+, 7^+, 8^+) in the 76-114 MeV energy range had been measured. Heavy ions of F^{6+} (76 and 84 MeV), F^{7+} (90 MeV) and F^{8+} (98, 106 and 114 MeV) were obtained from the 15 UD Pelletron accelerator at Inter-University Accelerator Centre, New Delhi. Two silicon surface barrier detectors at ±7.5° to the beam direction were used to monitor the projectile ions. The chamber was evacuated to about 10^{-6} Torr and equipped with a 5 mm diameter collimator and 6 μm Mylar window in front of the Si(Li) detector. In the energy range

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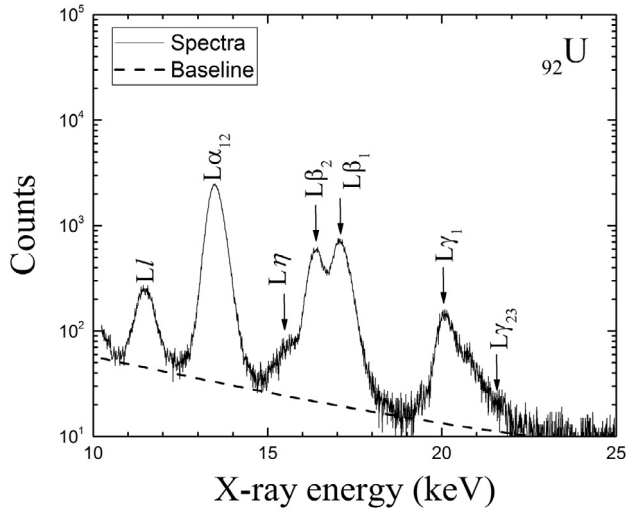

Fig. 1. L X ray spectrum of UF_4 bombarded with the 98 MeV ^{19}F ions. The dashed curve delimits the net counts in the x ray line peaks from the background due to the Compton scattering in the relatively thick (5 mm) detector. As addressed in Section 2, except for the *Ll* line, this background amount to less than 11% of extracted net x ray counts.

of the measured L x ray spectra, the energy resolution of the detector was ~200 eV for the Mn Kα x rays. A Si(Li) solid state detector (thickness = 5 mm, diameter = 10 mm, 25 μm Be window from ORTEC, Oak Ridge, Tennessee, USA) was placed in the horizontal ion beam plane configuration outside the vacuum chamber at an angle of 125° to the beam direction and a distance of 170 mm from the target. The targets were mounted on a steel ladder at a 90° angle to the beam direction. The ladder could accommodate up to 24 targets (8 rows and 3 columns) each of 11.7 mm diameter and the desired target was brought along the beam direction by the horizontal and the vertical movement of the target ladder using the stepper motor arrangement. The spot size of the ion beam at the target was ~2 mm diameter. The spectra were taken at different positions of each target by tiny steering the beam. The thickness and the uniformity of these targets were measured by the energy loss method using alpha particles from a radioactive decay of ^{241}Am. Targets of $_{78}Pt$, $_{79}Au$, $_{82}Pb$, and $_{83}Bi$ (thickness ~ 120 μg/cm^2) were prepared on the 20 μg/cm^2 carbon backing using the vacuum deposition technique [35]. Thinner and spectroscopically pure (99.999% pure) targets of ThF_4 (48.7 μg/cm^2) and UF_4 (48.6 μg/cm^2) on Mylar backing (thickness = 3 μm) procured from Micromatter, Deer Harbor, Washington, USA were also used in the present work. The target uniformity was verified to be better

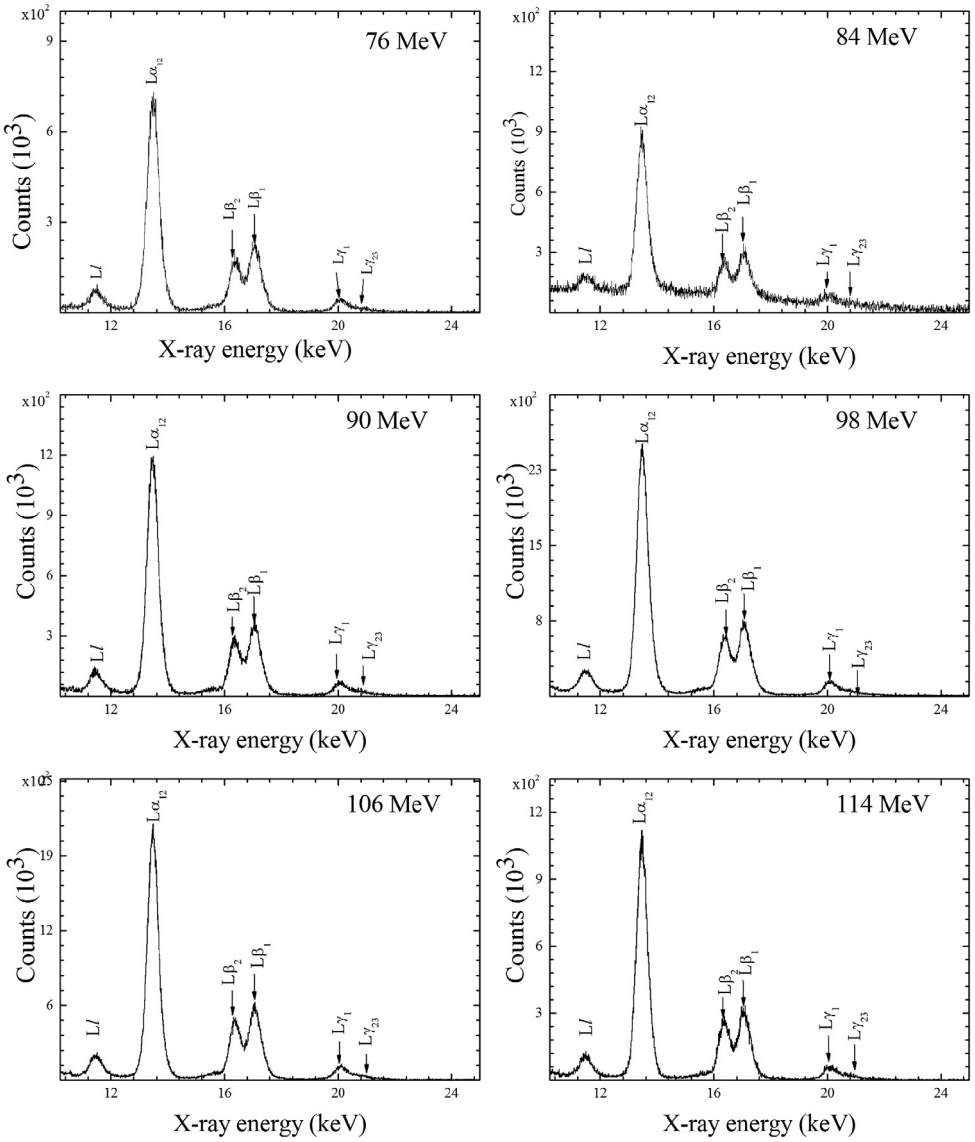

Fig. 2. L x ray spectra from $_{92}U$ (48.6 μg/cm^2 UF_4 target) bombarded with 76, 84, 90, 98, 106, and 114 MeV ^{19}F ions.