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X-ray spectroscopy: An experimental technique to measure charge state distribution during ion–solid interaction

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ABSTRACT

Charge state distributions of ^{56}Fe and ^{58}Ni projectile ions passing through thin carbon foils have been studied in the energy range of 1.65–2.69 MeV/u using a novel method involving the X-ray spectroscopy technique. Interestingly the charge state distribution in the bulk shows Lorentzian behavior instead of usual Gaussian distribution. Further, different parameters of charge state distribution like mean charge state, distribution width and asymmetric parameter are determined and compared with the empirical calculations and ETACHA predictions. It is found that the X-ray measurement technique is appropriate to determine the mean charge state during the ion–solid interaction or in the bulk. Interestingly, empirical formalism predicts much lower mean charge states of the projectile ions compared to X-ray measurements which clearly indicate multi-electron capture from the target surface. The ETACHA predictions and experimental results are found to be comparable for the present energy regime.

1. Introduction

When an ion beam passes through the target, different atomic phenomena, e.g. electron capture and loss processes, inner-shell ionization, etc., occurring both in the bulk and at the target surfaces introduce fluctuations in charge state of the ion. In general, final charge state of the ion depends not only on the parameters associated with incident ion (initial ion velocity, charge and atomic number) but also on target characteristics (atomic number and density). Even though a monochromatic ion beam with a fixed charge state is passed through the medium, several charge states emerge out of the target [1]. However, after a large number of collisions, an equilibrium in charge state distribution (CSD) is established, where certain balance in electron capture and loss processes are attained. The study of equilibrium conditions where charge state fractions (CSF) as well as mean charge state (q_m) attains a certain stability is very crucial and has plenty of applications in various fields including atomic physics [2], nuclear physics [3], astrophysics [4], biophysics [5], energy loss experiments [6], accelerator designs [7], detectors [8]. Many experimental and theoretical groups have worked in these fields of research since 1950s [9] and therefore many reviews or collection of data can be found in the literature based on electromagnetic methods and empirical formalisms (e.g. Allison [10], Betz [11], Wittkower [12], and Shima [1,13]).

Worth to mention that there are many experimental techniques like CRBS [14], recoil separator [15,16], TOF [17], electromagnetic methods [18], etc., which can be used to separate adjacent charge states and to study the charge state distribution of the respective atomic systems. These techniques account for the total charge of the concerning ion. This implies that these techniques give a measure of electron-capture and -loss processes occurring in bulk as well as at surface of the foil and cannot segregate the charge changing phenomenon occurring only in the bulk or at the surface. Therefore, these techniques are not appropriate to measure the charge state distribution during the ion–solid interaction. This difficulty can be avoided by using charge less observables in the experiments to measure the charge states during the ion–solid interaction. Interestingly, in the past several measurements have been carried out using X-ray spectroscopy to study various plasmas [19,20]. Nevertheless, the measurements with X-ray photon detection have not yet been employed to study the CSD and other relevant parameters like q_m, distribution width and asymmetric parameter of the projectile ions during passage from any solid/gas targets. With this motivation, we confine the work to study the CSD and its parameters during the ion–solid interaction using the X-ray spectroscopy technique.

2. Experiments

The experiments were performed with the energetic ion beams of ^{56}Fe and ^{58}Ni using 15 UD Pelletron [21] accelerator at IUAC, New Delhi, India. Well-collimated ion beam in the energy range of

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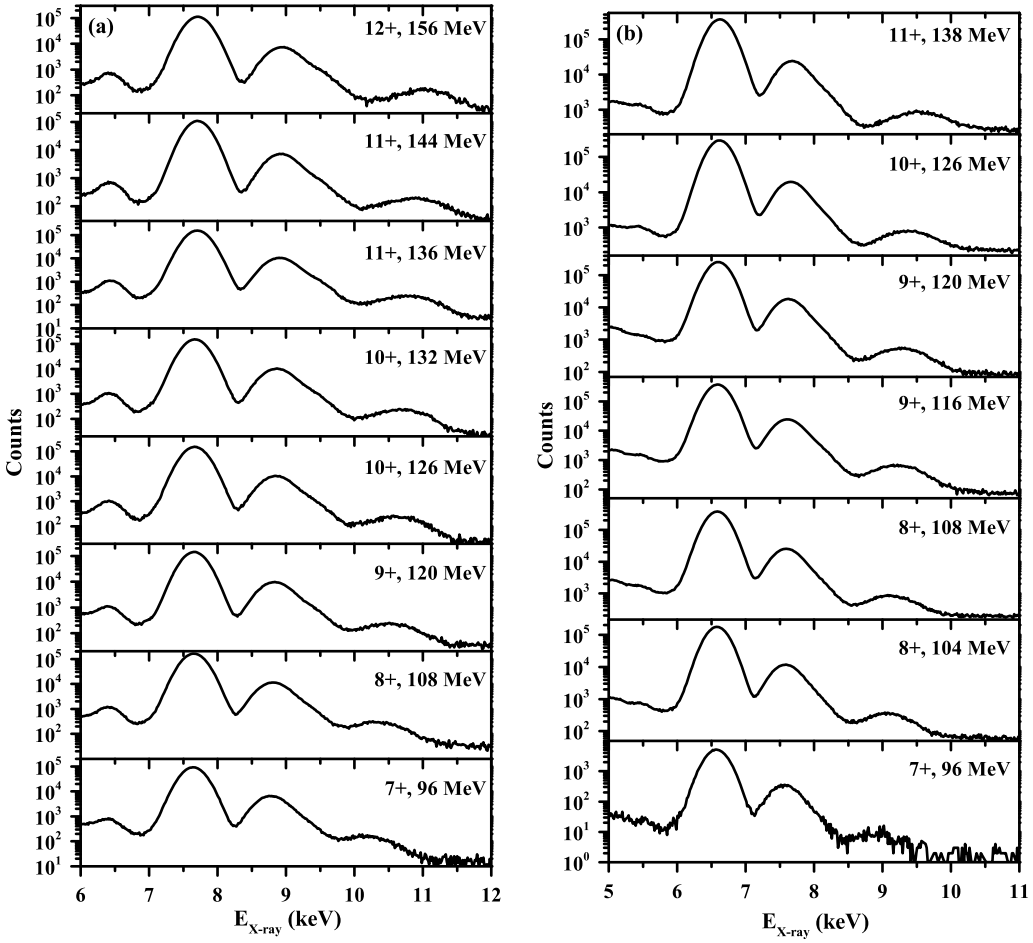

Fig. 1. X-ray spectra for (a) ^{58}Ni beam and (b) ^{56}Fe beam on 80 μg/cm^2 C-foil at different beam energies and initial charge states.

1.65–2.69 MeV/u were bombarded on 80 μg/cm^2 (≈113 μg/cm^2 at 45°) thick amorphous carbon target foils to produce the equilibrium charge state distribution. The target was placed at 45° to the beam axis so that the X-ray spectra could be measured during the ion–solid interaction. The X-rays were detected in a Low Energy Germanium Detector (GUL0035, Canberra Inc., with 25 μm thick Be entrance window, resolution 150 eV at 5.9 keV) placed at 90° to the beam axis to avoid the Doppler shift. The X-ray produced during the ion–solid interactions were passed through two collimators of 3 mm diameter kept at 55 cm apart whereas the first collimator was placed at 10 cm away from the target. This configuration ensured that the X-rays were coming from a tiny section (±3–4 mm) of the ion–solid interaction zone. In the time scale, the X-ray detector could observe only atomic transitions of very short life-time (few tens of psec) with respect to the centre of the interaction zone. Hence, the X-ray spectroscopy technique could be considered as a measurement during the ion–solid interaction compared to the electromagnetic measurements taking place away from the interaction zone or at $t \approx$ a few μsec for MeV ions. The X-ray detector was placed outside the chamber at 65 cm away from the target separating a thin mylar window of 6 μm at the interface of detector and chamber. The beam was dumped in a Faraday cup. Two silicon surface barrier detectors were used at ±10° to monitor the beam direction. The X-ray spectra observed for all the beam energies are shown in Fig. 1. Calibrations were done for the X-ray detectors using ^{60}Co and ^{241}Am standard radioactive sources. The resolution was found to be about 200 eV at 6.41 keV with the experimental conditions in the beam hall. Further, the calibration was internally verified through Fe K_α and K_β peaks due to beam halo hitting the carbon foil holder made up of stainless steel in the case of ^{58}Ni projectile ions. However, in the case of ^{56}Fe-beam experiment, beam halo was minimized by passing the beam through a blank target frame so that its presence did not affect much the peak structure originated from the projectile ions. Vacuum chamber was maintained at a pressure around 1×10^{-6} Torr.

3. Data analysis, results and discussion

In this work we are intended to determine the charge state distribution of projectile ions during the ion–solid interaction along with q_m and other relevant parameters from the measured X-ray spectra. Accordingly we have developed a novel method to extract required information from the X-ray spectra observed. Worth mentioning here that the parameters like charge state fraction, mean charge state, etc., obtained at different energies for the particular ion can be compared without normalizing the X-ray spectra. Hence, normalization of X-ray spectra is not required in this work like any other electromagnetic methods coupled with position sensitive detectors [22]. It is clear from the spectrum of 136 MeV ^{58}Ni on C that it contains mainly three structures as shown in Figs. 1 and 2a. In our earlier work the first peak (7–8.4 keV) is recognized to have originated from the projectile ion X-ray, whereas second and third peak (8.4–11.5 keV) belong to the projectile-like fragment ions emanating from the nuclear reactions, respectively [23, 24]. It is worth mentioning here that we are only considering the charge changing phenomena in elastic events or in the projectile ions, thus the second and third structures are of no relevance in this work; hence they will not be brought in the further discussion. Another point is to be cleared at this stage that when the fast projectile ions incident on target atom, the collisions create vacan-