Strong Evidence of Plasma-like Behaviour for Ion-Solid Collisions

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Charge state distributions of various projectile ions passing through thin carbon foils have been studied in the energy range of 0.7-3.0 MeV/u using x-ray spectroscopy. This technique is found to be appropriate to segregate the charge state distribution in the bulk from that of the surface by measuring the charge changing phenomena right at the interaction zone i.e. at t=0. This observation has been confirmed by different theoretical approaches. Surprisingly, it is found that the charge state distribution measured in the bulk, exhibits Lorentzian profile which is an important characteristic of any plasma. The occurrence of such behaviour suggests that ion-solid collisions constitute tenuous plasma in the bulk of the solid target. Thus, this work is expected to have practical implications in various fields, in particular, plasma physics and astrophysics.

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Atomic phenomena such as electron-capture and -loss processes [1-3] are the key factors for any collisions of swift ions with atoms, ions or molecules that cause a change in charge state of the ions traversing a medium. Even though a monochromatic ion beam with a fixed charge state is passed through the medium, several charge states emerge out of the target irrespective of its thickness [4]. However, after a large number of collisions, equilibrium in charge state distribution (CSD) as well as mean charge state (q_m) is established, when certain balance in electron-capture and -loss processes is attained. The number of collisions or thickness required to arrive at the equilibrium depends on the ion species, its velocity and characteristics of the target including atomic number, density, phase, structure etc. Experimental techniques involved in measuring CSD and q_m are mainly electromagnetic in origin, thereby accounting for the total charge of the ion in the detectors placed at the focal plane, a few meters away from the target. This implies that these techniques give an integral measure of electron-capture and -loss processes at bulk as well as surface of the foil and cannot allow one to segregate the charge changing phenomenon in the bulk from that of the surface. This difficulty can be circumvented using charge less observables in the experiments. In the present work, we intend to study the ion-solid interactions only in the bulk. With this motivation, we confine the work to study the CSD and other relevant parameters right at the interaction zone or at t=0 using the x-ray spectroscopy technique.

Experiments were performed with the energetic ion beams of ^{58}\text{Ni} and ^{56}\text{Fe} using 15 UD Pelletron [5] accelerator at IUAC, New Delhi. Well-collimated ion beam of energies 0.7-3.0 MeV/u were bombarded on 80 μg/cm^2 thick natural carbon target foils. The target was placed at 45° to the beam axis so that we can measure the x-ray spectra right from the ion-solid interaction zone. 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, with constant quantum efficiency in the range of 3-20 keV) at 90° to the beam axis. The detector was kept outside the chamber at 65 cm away from the target with a thin mylar window of 6 μm at the interface. The beam was dumped in a Faraday cage. Two solid surface barrier detectors were used at ±10° to monitor the beam direction. Vacuum chamber was maintained at a pressure around 1×10^{-6} Torr. 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}\text{Co} and ^{241}\text{Am} standard sources. The resolution was found to be about 200 eV at 6.41 keV with the experimental conditions.

The primary motivation of this work is to determine the charge state distribution of projectile ions at t=0 along with q_m from measured x-ray spectra. It is important to note that the parameters obtained at different energies for the particular ion can be compared without normalizing the x-ray spectra. Hence, complexity of normalization is avoided in this work like any electromagnetic method coupled with position sensitive detectors [6].

It is clear from the spectrum of 126 MeV Ni on C as shown in Fig. 2 that it contains mainly three structures. First one is due to the projectile ion x-ray, whereas second and third are due to different nuclear reactions [7]. It is worth mentioning here that the second and third structures are of no relevance in this work, hence they will not be covered in further discussion. From the Fig. 1 it is discernible that as the beam energy increases, centroid of the projectile x-ray peak starts shifting towards higher energy side. Since the x-ray spectroscopy is a reliable method to find the charge state origin during atomic collisions [8-12], we are encouraged to utilize this method to measure the charge state of projectile ions right at the ion-atom collision or at t=0. Further, it is well known that the passage of a monochromatic ion beam through any medium produces a number of charge states, which results in CSD [4]. The fact is that in every charge state, there is a certain probability of creating a single K-shell
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 as shown on third axis of the figure.

FIG. 2. X-ray spectrum of $^{58}$Ni on C at 126 MeV (a) Fitting shows only broad features of the spectrum (b) Projectile x-ray peak is fitted into nine peaks corresponding to x-ray lines appearing from H-like to F-like Ni. (c) The residuals of fitting is shown in (b).

vacancy owing to ion impact on the target with a certain energy that gives rise to a characteristic x-ray emission for that particular charge state. Therefore, we expect many x-ray lines emanating from the projectile ions. Though detector resolution in the experiment restricts us to resolve individual x-ray lines; the well-defined centroid gives a correct measure of the mean charge state.

In order to get a right correspondence between the centroid and the mean charge state, we have adopted a special analysis method as follows: in first step, we have plotted the standard $K_{α}$ x-ray energies from NIST database [13] for H-like to F-like Fe ions. It should be noted here that $K_{α}$ x-ray energies for Ni are available only for H-like to Li-like Ni [13]. The rest of the energies for Be-like to F-like Ni are scaled from corresponding Fe data. Next, in order to know the correct $q_m$ for any x-ray energy, we have fitted the data with a special multi-parameter function given below

$$q = A_1 + \frac{A_2 - A_1}{1 + e^{p(x_0 - x)}}$$ (1)

The parameters are given in Table I. Interestingly, the parameter $A_1$ fairly matches with the average of the effective nuclear charge of all the electrons; whereas $A_2$ shows a correspondence between the effective nuclear charge for 1s electrons [14].

Afterwards, projectile x-ray peak is fitted with a Gaussian function to find the centroid and corresponding
TABLE I. Parameters obtained from the fitted spectra with a special multi-parameter function

| Parameters | Ni ion          | Fe ion          |
|------------|----------------|----------------|
| A_1        | 16.9206±1.6708 | 15.7315±1.2956 |
| A_2        | 27.122±0.3311  | 25.1441±0.365  |
| p          | 9.8403±2.4045  | 13.0308±3.2178 |
| x_0        | 7.5994±0.0366  | 6.5682±0.0251  |

A special multi-parameter function

charge state is computed from eqn. (1) with above mentioned set of parameters. The charge state so obtained represents the value of q_m. This procedure is repeated for both the ion species of all beam energies. In next step, for validating that our measurements represent bulk effect only, we choose two different approaches for comparison. First, ETACHA code [15] which takes account of ionization and capture processes theoretically and ought to represent the measurements in bulk or at t=0, is used to get q_m for Ni and Fe ions on 113 µg/cm² thick C target at different beam energies. It is important to note that empirical formalisms which are tuned on the basis of the measured data taken from the electromagnetic methods represent the integral role of the bulk and the surface of the foil. Thus, in the midst of available empirical formalisms we choose Schwietz formalism [16] because of its vast and updated dataset [17] to calculate q_m for a combined role of bulk and surface effect or at t=t'.

The experimentally measured values of q_m are compared with ETACHA predictions and Schwietz formalism as shown in Fig. 3. As expected, Schwietz calculations [16] are found to be much lower than both ETACHA predictions [15] and experimental results, showing a clear indication of dominant multi-electron capture from the surface of the foil. In contrast, ETACHA predictions show quite good agreement with experimentally measured values of q_m. However, for Ni case, experimental q_m are little greater than the ETACHA predicted values for < 2MeV/u. Whereas for Fe case, experimentally measured q_m are found little lesser in the same energy range. Interestingly, for both cases q_m start merging at ≥ 2 MeV/u. Thus, the comparison not only fairly validates the surface effect removal in the x-ray spectroscopy technique, but also reveals that ETACHA predictions [15] better represent the data obtained at t=0 and approached to the measured data for energies ≥ 2 MeV/u. Hence, our work also establishes that ETACHA [15] does not only represent data beyond 10 MeV/u as one of our earlier studies revealed [18], but also the lower energy side too. Surprisingly, at the low beam energies (~0.6-1.0 MeV/u); ETACHA predictions much underestimate the experimental observations in case of both Ni and Fe. Ionization due to shaking process [19,20] can probably be responsible for such happening. In addition to this, one can notice that in both cases, around the Coulomb barrier unusual enhancement in ionization is observed, which results a kink in experimentally measured q_m, as shown in Fig. 3. The Coulomb barrier energy in the lab frame for ⁵⁸Ni and ⁵⁶Fe on ¹²C are 2.313 and 2.167

FIG. 3. Mean charge states versus the beam energies for (a) ⁵⁸Ni beam and (b) ⁵⁶Fe beam on 80 µg/cm² C-foil. Solid lines are to guide eye only. Error bars are smeared with the symbol size.

FIG. 4. Comparison of the CSDs from reported experimental data using electromagnetic method (t=t') [26], ETACHA predictions [15] and the present data with x-ray spectroscopy method (t=0) for ⁵⁶Fe on C for different beam energies. Figure shows Lorentzian fit to present work and Gaussian fit to ETACHA [15] and experimental work [26]. Errors are embedded in symbol itself.
MeV/u respectively [21]. The possible reason of such occurrence is beyond the scope of this paper.

It is noteworthy to mention that there are certain atomic processes like formation of long lived Rydberg states occurring at the exit surface of the foil [22-25] which can introduce another CSD on each charge state produced in bulk of the foil. Thus in the next step, we have attempted to measure the CSD in bulk for each beam energy by limiting the measurements right at the ion-atom collisions. Since, low resolution of solid state x-ray detector used in this experiment gives a broad single peak accounting for the x-ray emissions from projectile ions of several charge states, shown in Fig. 2(a); we have adopted a method to deconvolute individual x-ray intensities corresponding to each charge state. Each peak has been fitted with many Gaussian functions by fixing the centroid of the peaks to H-like to F-like ion x-ray as shown in Fig. 2(b). One can note that number of allowed transitions increases with number of electrons available to fill in the K vacancy. As a result the energy level diagram becomes more and more complex as it goes from higher to lower ionic state. Hence, full width at half maximum of the Kα x-ray lines were fixed in ascending order from H-like to F-like ions.

The residuals of the fitting shown in Fig. 2(c) validate the fitting performed. In this way we have obtained the distribution of charge state fractions \( F_q \) directly from the measured distribution of intensities as follows

\[
F_q = \frac{I_q}{\sum_q I_q}
\]  

Here, \( I_q \) is the intensity corresponding to the charge state \( q \). To include other sources of errors besides the statistical error, we have added an error equal to two times the statistical error in every \( F_q \). Two representative CSD using electromagnetic techniques [26] along with a typical CSD from this work and ETACHA predicted values are displayed in Fig. 4. The CSD predicted by ETACHA as well as the measured data at \( t=t' \) follows the Gaussian shape, however, present dataset depicts a different pattern, which is fitted well with a Lorentzian function. Interestingly, deviation from the Gaussian distribution can be observed in various plasmas, for example, Voigt distribution has been found in Ar plasma produced in electron cyclotron resonance ion source [11] and Lorentzian distribution for z-pinch plasma [27]. The CSD of gold ions in EBIT plasma shows also Lorentzian distribution [28] that has also been theoretically reproduced [29]. Further, besides the laboratory plasma, astrophysical plasma exhibiting the same distribution is popularly known as Lorentzian astrophysical plasma [30-32]. Thus this work reveals that interactions due to ion beam passing through solid thin foil replicate the typical plasma behaviour. Such plasma can be considered as beam-foil plasma having very high density, but extremely small volume. Tenuous plasma is also produced during laser-solid interaction [33] in the laboratory. Similar high density plasma is prevalent in stellar interiors [34] in large vol-

FIG. 5. Measured CSD with Lorentzian fitting for (a) \(^{58}\)Ni on C and (b) \(^{56}\)Fe on C for various beam energies.
ume. Thus, this work can provide useful informations to understand high density plasma where ion-ion interactions dominate.

To conclude, the charge state distribution of the projectile ions during ion-solid collisions can only be carried out at $t=0$ by charge-less observables, as is done here using x-ray spectroscopy. This approach succeeds in observing the CSD only at the bulk of the foil unlike the electromagnetic techniques, which give an integrated contribution from both the bulk as well as the exit surface. Large difference between the measured $q_{cm}$ in this measurement and the calculated CSD from empirical formalism confirms multi-electron capture from the exit surface. Further, it is shown that ETACHA code [15] represents well the measurements at $t=0$ for the energy $\geq 2$ MeV/u. An unusual charge state distribution in the form of Lorentzian distribution is observed in contrast to the ETACHA predictions [15] and experimental results using electromagnetic methods [26] of the Gaussian distribution. Appearance of Lorentzian distribution for the CSD is analogous to the CSD in any plasma. Thus, ion-solid collisions in the bulk of a solid target can simulate the characteristics of high density plasma as seen in stellar interior [34]. We believe that the studies using such beam-foil plasma will open up new opportunities to the researchers.

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