IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Target Dependent X-Ray study of 100-170 MeV $^{56}Fe^{q+(q=10,11,13)}$ Ions with Interaction of C-foil

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Abstract: The charge-state evolution of energetic Fe ions interacting with thin carbon foils has been investigated using X-ray spectroscopic techniques at the Atomic Physics Beam Line of IUAC, New Delhi. Carbon targets with thicknesses of 8, 16, and 60 μg/cm² were employed to examine the influence of target thickness on ion–atom collision dynamics across a beam-energy range of 100–170 MeV. The recorded X-ray spectra exhibit distinct K_α, Fe^{25+} (H-like Fe), and K_β emission lines, which were analysed through spectral fitting to extract charge-state fractions and evaluate the contributions of different ionisation processes. The yields are found to increase with foil thickness, reflecting greater contributions from ionisation and multiple-collision processes. There are oscillatory features in the K_α and K_β intensities as a function of beam energy, with sudden changes in profile at specific energies, which correspond to discrete variations owed to the beam-energy dependence of the electron-loss, electron-capture and inner shell-vacancy cross sections. These observations highlight the strong interplay between projectile energy and target thickness in governing charge-state formation. The study provides deeper insight into the mechanisms of heavy-ion interactions with thin solid targets. It demonstrates the effectiveness of X-ray emission analysis for probing ion–atom collision processes.

***Index Terms* -** Ion-Solid Collision, highly charged ions, X-ray Spectroscopy, charge state distribution, Electron capture.

I. Introduction

A large share of the universe exists in a highly ionised form [1]. Because such extreme conditions are rarely found on Earth and since our atmosphere absorbs most incoming X-rays from distant astrophysical objects, opportunities to study this type of matter have historically been limited. As a result, early progress in atomic physics and ion-beam science occurred without routine laboratory access to highly charged ions.

In recent decades, this situation has changed significantly. Modern experimental facilities can now generate almost any ionisation state of naturally occurring elements whenever required. Compact sources are available that can fit on a standard laboratory bench [2]. At the same time, large accelerator complexes are capable of creating ions that travel at velocities close to the speed of light [3,4]. Although these instruments vary widely in scale and design, they share a common purpose: providing direct access to an environment that mirrors highly ionised cosmic conditions, an area of physics that remains uncharted mainly and of great importance to multiple scientific disciplines. Among the experimental methods developed, beam-foil spectroscopy [5] has become a compelling technique for studying highly charged ions. In this method, an ion beam in a chosen charge state passes through a thin foil, enabling detailed observation of the radiation emitted as ions rapidly capture or lose electrons and adopt new electronic configurations. In the interaction of highly charged ions with atomic targets, electrons in the target's inner shells can be excited or removed. The radiative part of these processes is known to provide a sensitive tool to study charge-exchange dynamics, elastic scattering, as well as inelastic energy transfer processes [6–8]. Moreover, the photon and secondary ion intensity and energy distribution are information on the internal electronic structure of both colliders as well as about some basic processes governing the collisions. Because of this, ion–solid collisions have attracted sustained scientific interest since the mid-20th century. Hagstrom [9] first introduced the Auger-type electron transfer that occurs when ions interact with metal surfaces. Later, Datz [10] classified the interaction of highly charged ions with solids into resonant electron capture, Auger neutralisation, and radiative de-excitation. Briand et al. [11] reported that, under such conditions, projectile ions may form highly excited multi-vacancy configurations known as hollow atoms. Burgdörfer et al. [12] subsequently formulated the classical over-the-barrier (COB) model to explain these processes. Experimental measurements by Köhrbrück et al. [13] of LMM and KLL Auger emissions from $Ar^{q+ (q = 9, 16)}$, Ne^{9+}, and O^{7+} ions striking a copper surface further supported the COB framework. As theoretical understanding improved, researchers were able to describe collision processes with greater precision. Nevertheless, these interactions remain complex many-body problems, and exact analytical solutions are often not feasible. For this reason, several approximate models and computational formalisms have been developed to interpret experimental observations. Many studies have shown that when light ions collide with a target, or when the projectile atomic number (Z_1) is much lower than the target atomic number (Z_2), inner-shell ionisation is dominated by direct Coulomb scattering. The binary encounter approximation (BEA) provides a useful classical description of this behaviour [14]. Quantum approaches, such as the plane-wave Born approximation (PWBA) and the improved ECPSSR model—which includes corrections for energy loss, Coulomb deflection, perturbed stationary states, and relativistic effects-also offer reliable predictions for such collisions [15,16]. In near-symmetric systems, electron transfer plays a significant role in generating inner-shell vacancies, and this process is often analysed using the quasi-molecular orbital (MO) model [17]. In recent years, the study of multi-charged ions interacting with matter at intermediate energies has become an active research area. This has led to a growing demand for accurate X-ray production cross-section data for various projectile–target combinations [18–22]. High-resolution measurements of X-rays emitted in ion–atom collisions constitute indispensable tests for theoretical models developed to interpret the sources of such radiation from astrophysical objects (e.g., comets) and from laboratory and fusion plasmas [23,24]. Iron ions, particularly in high charge states, are abundant in many astrophysical plasmas. Their K X-ray lines serve as a necessary diagnostic for plasma conditions, charge-state distributions, and atomic form factors. Therefore, this work aims to investigate the K-shell X-ray intensity of highly charged iron ions. To obtain accurate data for both astrophysical and laboratory plasmas, we measured the X-ray emission ssfrom Fe^{q+} ions (q = 10, 11, 13) impacting a carbon film. The experiment was conducted at projectile energies of 100, 110, 115, 120, 125, 130, 135, 140, 160, and 170 MeV using the 15 UD Pelletron accelerator at IUAC, New Delhi.

II. Experimental Details

The experiments were conducted using energetic ion beams of $^{56}Fe^{q+}$ (q = 10, 11, 13) with energies ranging from 100 to 170 MeV, produced by the 15 UD pelletron [25] accelerator at IUAC, New Delhi, India. A schematic of the experimental setup is shown in **Fig. 1**.

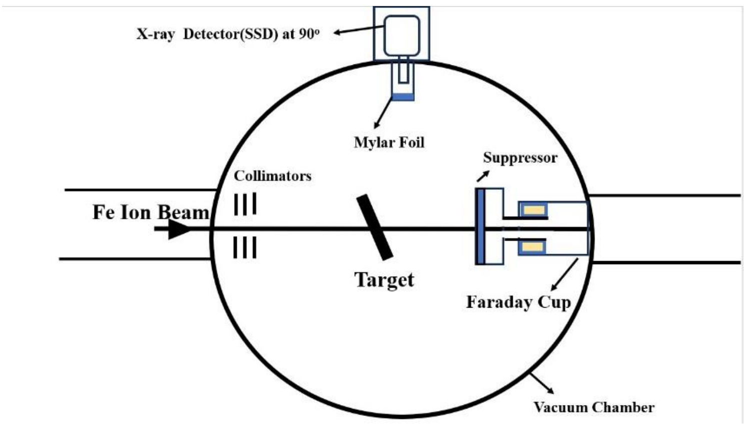

Fig. 1. Schematic diagram of experimental setup

In our experiment, a ^{56}Fe ion beam at energies of 100-170 MeV was passed through a carbon foil of thickness 8, 16, or 60 μg/cm^2, producing highly charged ions (HCI) in excited states. These HCIs are responsible for different charge states in excited states, which then relax to the ground state by emitting X-rays. A detector is positioned at 90° to the beam direction to record these X-rays. The vacuum of 10^{-6}-10^{-7} mbar was maintained during the experiment using a turbo molecular pump. The detector's energy calibration was performed before and after the experiment using ^{55}Fe and ^{241}Am radioactive sources. The resolution was approximately 130 eV at 5.9 keV under the experimental conditions in the beam hall. The beam halo was reduced by allowing the beam to pass through an empty target frame, thereby preventing its influence from distorting the peak structure produced by the projectile ions. The target surface may be positioned in front of the beam path, through a steeper motor attached to the target ladder. Data acquisition was performed using the PC-based software "root" [26].

III. Results and Discussion

When energetic Fe ions traverse these foils (8, 16, or 60 μg/cm^2), they gradually lose kinetic energy due to collision with electrons and nuclei. Therefore, a series of electron-loss, electron-capture, and excitation processes occur, ultimately leading to X-ray emission. The recorded spectra for the three target thicknesses are presented in **Fig. 2**, where distinct peaks associated with various ionic states of Fe ions are clearly visible. These features reflect the complex balance of charge-changing processes occurring during the collision.

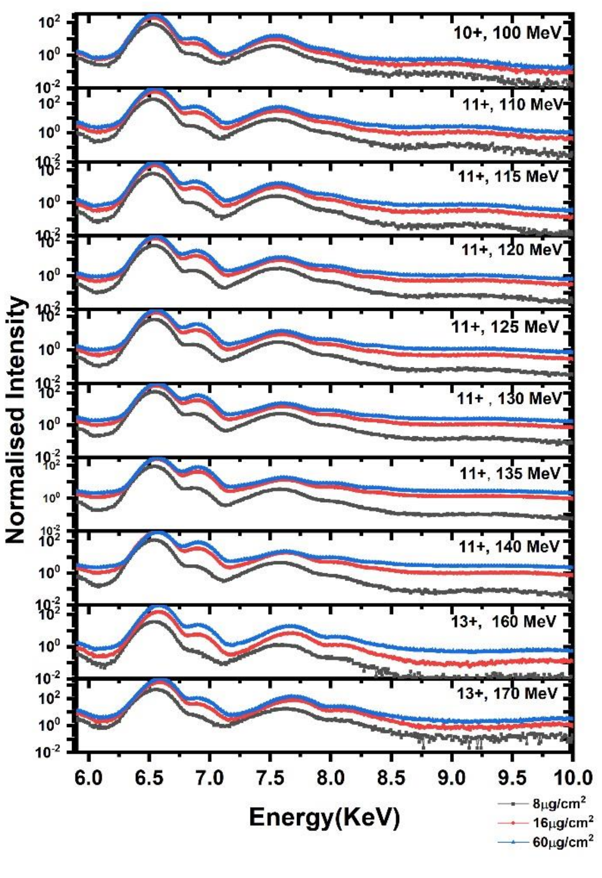

Fig. 2: X-ray spectra for ^{56}Fe beam on 60 μg/cm^2 C-foil at different beam energies (from 100 -170 MeV/u) and initial charge states q+ (q = 10,11,13).

To interpret the spectral structure in detail, the experimental spectra were fitted, as shown in **Fig. 3**. Deconvolution of the spectra enables separation of the individual contributions of different charge states. This study has been published by Prasant et al. [27]. This is particularly important in ion-atom collisions, where the population of each charge state depends sensitively on the projectile's energy, the target thickness, and the competition between electron-capture and electron-loss probabilities. The differences observed among the three thicknesses illustrate how increasing the target foil increases the likelihood of multiple collisions, thereby enhancing ionisation and modifying the charge-state distribution at the foil exit.

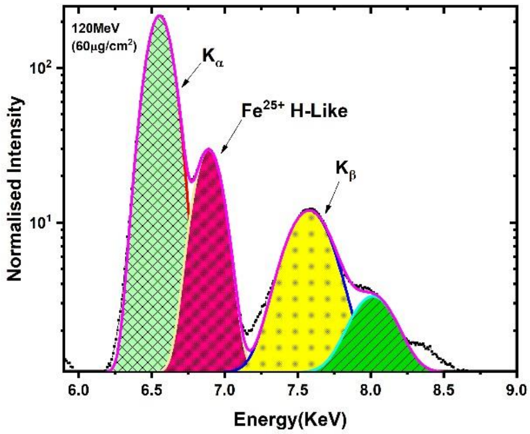

Fig. 3: X-ray spectra of ^{56}Fe on C at 120 MeV (Fitting shows only broad features of the spectrum)

Before the interaction takes place, the target atoms have fully occupied electronic shells; therefore, any change in the K-shell X-ray energy is influenced by vacancies generated in the K, L, or M shells during the ion-solid collision. For projectile ions, however, many of the outer electrons are removed during their passage through the target (depending on the incident energy) [29], so the observed x-ray line-energy shift arises mainly from vacancies in the K and L shells, as electrons in higher shells such as M or N are largely absent [28]. As the projectile's charge state increases, the X-ray centroid shifts to higher energies with increasing beam energy.

In the fitted spectra, the first dominant peak corresponds to the K_α transition, arising from inner-shell (1s) ionisation followed by radiative decay. The second peak corresponds to emission from Fe^{25+} (H-like Fe), indicating that the projectile has undergone extensive ionisation during its passage through the foil. The third peak corresponds to the K_β line. The relative intensities of these peaks can be used to correct the binding energy and fluorescence yield of the subshell layer, in order to obtain the theoretical production cross section of K-shell x-ray similarly it provide a direct measure of charge-state fractions and illustrate the degree of ion stripping experienced by the projectiles.

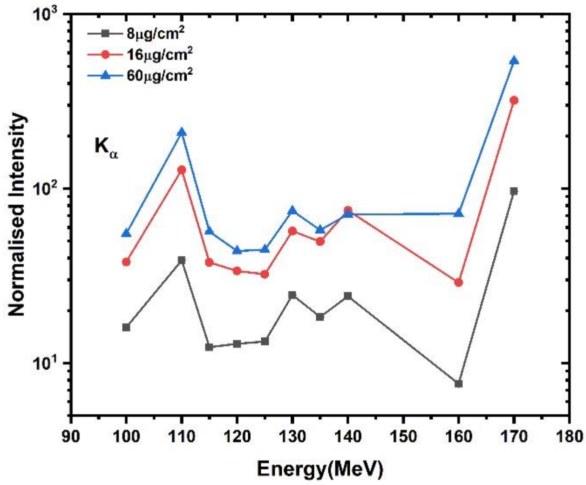

Fig. 4: Variation of K_α intensity as a function of beam energy (100–170 MeV) for carbon foils with thicknesses of 8, 16, and 60 μg/cm².

Fig. 4 shows the variation of K_α intensity on beam energy for all three foil thicknesses. The systematic increase in K_α intensity with increasing foil thickness is consistent with higher ionisation cross-sections resulting from more frequent ion-atom collisions. The oscillatory behaviour observed in the K_α intensity across the energy range suggests variations in the effective ionisation and excitation probabilities as the projectile velocity changes. Sudden enhancements around 110, 130, 140, and 170 MeV may correspond to conditions in which electron-loss and excitation cross-sections are maximised, whereas decreases near 115–125 MeV and around 135 and 160 MeV reflect regions where electron-capture or de-excitation becomes more competitive. Despite these fluctuations, all thicknesses follow a similar pattern, indicating that the fundamental collision mechanisms remain the same, although the number of collisions varies. **Fig. 5** shows the variation of Fe^{25+} (H-like Fe) intensity on beam energy for all three foil thicknesses.

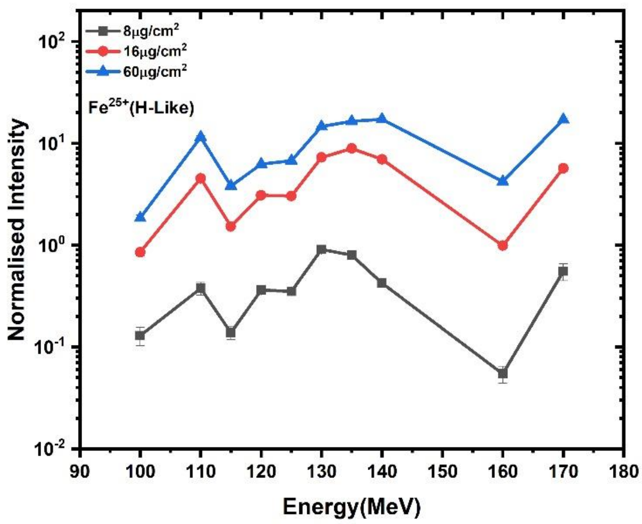

Fig. 5: The dependence of Fe^{25+} intensity on beam energy (100–170 MeV) for carbon foils with thicknesses of 8, 16, and 60 μg/cm².

The variation of K_β intensity with beam energy is shown in **Fig. 6** and exhibits a similar sensitivity to collision dynamics. A sharp rise at 110 MeV for all foils indicates an increase in L-shell vacancy production, attributable to increased direct ionisation probabilities at this energy. The behaviour between 115 and 125 MeV for 8 and 16 μg/cm² foils follows a similar trend. In contrast, the slight decrease for the 60 μg/cm² foil indicates increased multi-collision effects that may favour electron capture. In the 130–140 MeV region, the 16 and 60 μg/cm² foils show similar trends. In contrast, the 8 μg/cm² foil exhibits a small intensity drop near 135 MeV, reflecting reduced inner-shell ionisation probability at thinner targets. A pronounced decrease around 160 MeV for all foils suggests a temporary reduction in inner-shell ionisation efficiency at this beam velocity. In comparison, the substantial increase at 170 MeV implies a renewed rise in electron-loss and excitation processes.

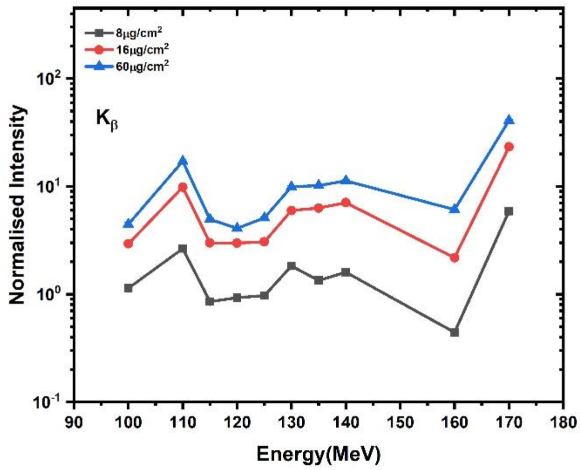

Fig. 6: The dependence of K_β intensity on beam energy (100–170 MeV) for carbon foils with thicknesses of 8, 16, and 60 μg/cm²

Overall, the observed variations in K_α and K_β emission intensities provide a clear signature of the underlying ion-atom collision physics. The combined influence of projectile energy and target thickness governs the probabilities of electron loss, electron capture, and inner-shell vacancy creation, thereby shaping the charge-state distribution and the resulting X-ray yields. These results highlight the complex interplay of multi-electron processes in heavy-ion collisions with thin solid targets.

IV. SUMMARY AND CONCLUSIONS

In this study, the x-ray emission from energetic $Fe^{q+\,(q = 10,\,11,\,13)}$ ions interacting with carbon foils of varying thickness was systematically investigated using X-ray spectroscopy. The recorded and fitted spectra clearly demonstrate the presence of K_α, Fe^{25+}, and K_β emission lines, as well as various iron charge states; each peak corresponds to a different stage of projectile ionisation during the collision process. Analysis of these spectra reveals that x-ray intensity is strongly influenced by both beam energy and target thickness, indicating the electron-loss, electron-capture, and excitation mechanisms within the foil.

The variations of K_α and K_β intensities across the 100-170 MeV energy range exhibit specific behaviour, corresponding to changes in ionisation and excitation cross-sections with projectile beam velocity. Thicker foils yield higher X-ray intensities, indicating greater ionisation and a higher probability of achieving highly charged states due to multiple collisions within the target. Sudden intensity variations at specific beam energies further underscore the sensitivity of inner-shell processes to changes in collision dynamics.

In general, these findings may provide important insights into the complex charge-changing process of heavy ions in thin solid targets and into the successful application of X-ray emission analysis for investigating the ion–atom collision mechanism. The discrepancy between the target thickness for both intensities may be attributable to cross-sectional X-ray production. These results shed light on charge-state generation in high-energy heavy-ion collisions. They are of significant importance for applications such as accelerator physics, atomic physics, radiation science, and materials modification.

V. ACKNOWLEDGMENT

We sincerely express our gratitude to the dedicated Pelletron accelerator staff for their consistent cooperation and technical support throughout this work. Their commitment was essential to the smooth operation of the experiments. We also warmly acknowledge the valuable assistance, insightful discussions, and continuous encouragement provided by our colleagues from the Atomic and Molecular Physics Group at IUAC, New Delhi. Their contributions significantly strengthened the quality and progress of this study.

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