Influence of Nuclear Recoil on Atomic Ionization near Coulomb Barrier Energy

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Introduction

The well-known existing disparity between the interaction range and the coupling constants for the electromagnetic and the strong force suggests independent treatment of atomic and nuclear phenomena. However, the borderline between atomic and nuclear physics i.e. Coulomb barrier region provides an interesting playground for many basic nuclear and atomic processes which mutually influence each other [1]. It has been reported in various theoretical works that sudden nuclear recoil can play a vital role in the evolved ionic charge state [3]. Nevertheless, no direct experimental evidence is yet obtained on such nuclear influence during the ion-atom collisions. Noteworthy that the precise information of charge states of the resulting product of the nuclear reactions is important in various fields of science, for example, designing of accelerators & beam optics, identification of nuclear products with the use of electromagnetic techniques, etc. Further, in various studies, the increased charge of projectile/target like fragment ions has been reported, however, a clear description of the mechanism is still missing in the literature. The present work is intended to explore the interplay of charge changing processes around the Coulomb barrier using the X-ray spectroscopy technique and to provide the basic understanding of the phenomenon.

Experimental Setup

Well-collimated ion beams of ^{56}Fe and ^{63}Cu with the energies 1.51-2.69 MeV/u were bombarded on different thickness of the carbon target. The foil thickness and the target orientation (80 μg/cm^2 & 45° in the case of ^{56}Fe beam and 60 μg/cm^2 & 60° in the case of ^{63}Cu beam) was chosen such that even with the use of ion beam of highest energy, projectile ions attain equilibrium charge distribution. The Low Energy Germanium Detector (GUL0035, Canberra Inc., with 25 μm thick Be window, resolution 150 eV at 5.9 keV, with constant quantum efficiency in the range of 5-20 keV) was used to detect the X-rays from the back surface of the target at 90° to the beam axis for minimizing the Doppler shift. The energy calibrations were done for the X-ray detectors using ^{60}Co and ^{241}Am radioactive sources. A typical X-ray spectrum of the ^{58}Ni beam on ^{12}C target at 120 MeV is shown in the Fig. 1. The peak structure at 6.8 keV (shaded curve) corresponds to the X-rays emitted from the projectile ions, whereas the other structures refer to the inelastic nuclear reaction products [2]. Two silicon surface barrier detectors were used at ±10° to monitor the beam direction. The vacuum chamber was maintained at a pressure around 1×10^{-6} Torr.

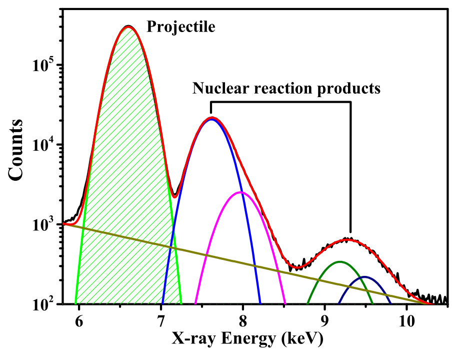

FIG. 1: Typical X-ray spectrum during the ion-atom collisions for 120 MeV $^{56}Fe^{12+}$ C-foil showing X-ray energy peaks from projectile and nuclear reaction products.

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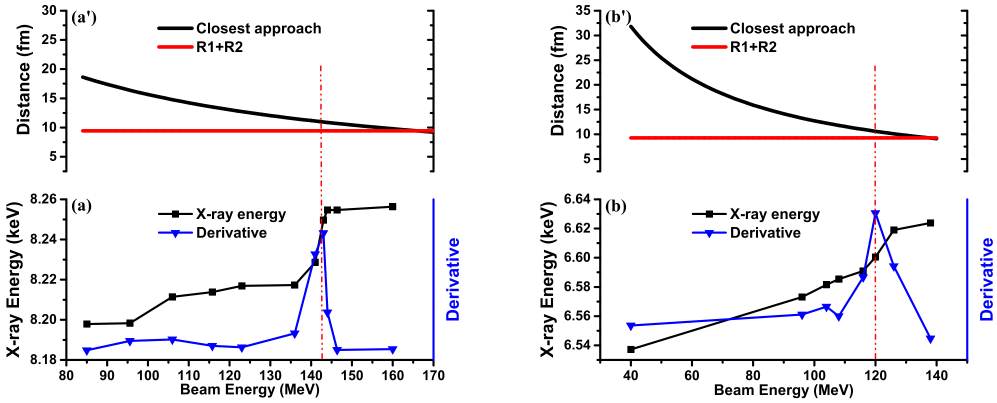

FIG. 2: The projectile X-ray energies versus beam energies in lab frame (a) ^{63}Cu beam and (b) ^{56}Fe beam on C-foil. Distance of closest approach and touching distance versus beam energy in lab frame for two body system of (a') ^{63}Cu beam and (b') ^{56}Fe beam on C-foil. Error bars are tiny and within the symbol size. All solid lines are only to guide the eye.

Results and Discussion

To study the charge changing processes, the emitted projectile ion X-rays have been measured as a function of the beam energies around the Coulomb barrier regime, shown in the Fig. 2. Interestingly, the variation of the X-ray centroid energies corresponding to the projectile ionization exhibits an unexpected enhancement below the Coulomb barrier. The sudden increment in the X-ray energy may be explained in terms of the interference effects between atomic and nuclear interactions, which occurs due to the recoil of respective nuclei. It results in the initiation of shaking processes [3] which consequently enhance the atomic ionization near the Coulomb barrier. Further, it has been observed that the sudden enhancement due to the nuclei-nuclei interactions occurs slightly below from the theoretical predictions of Coulomb barrier height. It clearly indicates the coupling of elastic channels at sub-barrier energies. The present findings have been validated with two asymmetric collision systems in inverse kinematics heavy ion reactions. Moreover, the work suggests further modifications in the theoretical atomic predictions by incorporating the influence of the nuclear effects during the heavy ion-atom collisions around the Coulomb barrier.

Conclusion

The experiments performed with X-rays emanating from the projectile ions have revealed an unusual jump in atomic ionization during its passage through a thin carbon target. The appearance of such kink near the Coulomb barrier is due to the inclusion of shaking process [3] in charge changing processes which correspond to the possible nuclear influence regarding the nuclear recoil at sub-barrier energies. This study may open up new channels for interdisciplinary research comprising of atomic and nuclear physics.

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References

[1] Y. A. Litvinov, F. Bosch *et al.*, Phys. Scr. **2011**, 14001 (2011).

[2] T. Nandi, J. Phys. B At. Mol. Opt. Phys. **42**, 61002 (2009).

[3] P. Sharma and T. Nandi, arXiv:1507.04171 (2015) and references therein.