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Impact parameter sensitive study of inner-shell atomic processes in the experimental storage ring

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In this work, we present a pilot experiment in the experimental storage ring (ESR) at GSI devoted to impact parameter sensitive studies of inner shell atomic processes for low-energy (heavy-) ion-atom collisions. The experiment was performed with bare and He-like xenon ions (Xe^{54+}, Xe^{52+}) colliding with neutral xenon gas atoms, resulting in a symmetric collision system. This choice of the projectile charge states was made in order to compare the effect of a filled K-shell with the empty one. The projectile and target X-rays have been measured at different observation angles for all impact parameters as well as for the impact parameter range of ∼35–70 fm.

1. Introduction

Ion-atom collisions offer a great venue for investigation of different fundamental atomic processes such as; ionization, excitation, electron capture, electron–positron pair production, etc. [1]. The advent of heavy ion accelerators and later of storage rings have extended the early investigations to heavy systems (high-Z ions) and explored a wide collision energy range from few MeV/u up to few GeV/u [2–8]. At GSI in Darmstadt, in particular, adiabatic heavy ion-atom collisions have been extensively investigated at the UNILAC [9–13] addressing in great detail quasi-molecular effects. In the following decades relativistic collisions of the heaviest one- and few-electron ions with light gas targets have been addressed extensively at the Experimental Storage Ring (ESR) [2,3,14].

We have recently initiated efforts to address relatively slow, (quasi-) symmetric collisions at the ESR [15]. Here, in contrast to the earlier investigations at the UNILAC, the heavy projectile ions can be prepared in any charge-state (up to bare), the beam energy can be varied over a broad range using the deceleration capability of the ESR, and single collision conditions can be ensured by using relatively thin gas targets. In particular, we concentrate on inner-

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shell atomic processes such as ionization, excitation, and electron transfer, at small impact parameters (i.e. smaller than the K-shell radius of the system) which are especially important for two-center (or quasi-molecular) effects. In this paper, first results from this experimental campaign are presented.

2. The experiment

The experiment was performed with bare and helium-like xenon ions (Xe^{54+}, Xe^{52+}) colliding with neutral xenon gas atoms, resulting in a symmetric collision system. This choice of the projectile charge states allows us to compare the effect of a filled K-shell with an empty one. The final beam energy (for both charge states) after deceleration was 50.5 MeV/u. Although the energy is not very low, one can still expect significant non-perturbative effects due to the heavy target. In order to obtain information concerning the impact parameter and, in particular to pick out close collisions which are especially important for observing quasi-molecular effects, scattered projectile ions which had undergone close collisions with the target atoms were detected by a particle detector (plastic scintillator) mounted in a specially constructed movable Roman pot/pocket (for details on the pockets used in the ESR we refer to [16]) ~3.5 m downstream from the target. In this configuration, the particle detector was sensitive to projectile scattering angles from ~0.5–1.0° (with an effective solid angle of approximately 10%) which, for the present collision system, corresponds to the impact parameter range of ~35–70 fm. In addition to the detector for the scattered projectiles, the X-rays emitted from the interaction zone were observed by an array of Ge(i) detectors mounted at different angles with respect to the ion beam direction. For the particles as well as the X-rays the time information was recorded allowing for reconstruction of coincident events. The scheme of the experimental setup is shown in Fig. 1.

3. Results and discussion

In Fig. 2, we present X-ray spectra for bare and helium-like xenon projectiles recorded by the detector mounted at 35° with respect to beam direction. For this spectra no coincidence condition with the particle detector is applied. In the spectra, projectile and target K- and L-shell lines are clearly visible/resolved. Due to the relativistic Doppler shift, the projectile lines are shifted to higher energies by a factor of 1.28. For the bare projectiles (Xe^{54+}), the $L \rightarrow K$ transitions originate mainly from capturing one electron from the target, thus forming a H-like ion. The corresponding $L \rightarrow K$ transition energies are: $2s_{1/2} \rightarrow 1s_{1/2}$: 30864.4 eV, $2p_{1/2} \rightarrow 1s_{1/2}$: 30857.3 eV and $2p_{3/2} \rightarrow 1s_{1/2}$: 31291.8 eV [17]. Note, that this fine structure can not be resolved in the present experiment and thus appears as a single peak at around 39.6 keV as expected from the above transition energies boosted by the factor of 1.28 due to the Relativistic Doppler shift. For He-like projectiles (Xe^{52+}), the different $L \rightarrow K$ transitions are also not resolved and appear as a single peak at a somewhat lower energy of around 38.8 keV (in accordance with the calculated transition energy values [18] taking into account the Doppler boost).

One striking feature seen from the spectra is the large difference in the relative strength of the L-radiation with respect to the K-radiation for bare and Helium-like projectiles. This difference is present both for the projectile as well as the target radiation. For the projectile radiation this can be explained by electron capture from the neutral xenon atoms into excited projectile states which then via cascades lead to the strong projectile K-radiation for the initially bare ions. This process is impossible for the helium-like ones due to the closed K-shell where the K-radiation can be produced only by excitation or ionization of the K-shell electrons. The large difference in the relative strength of L- and K-radiation of the target (for bare and He-like projectiles) is also remarkable. This can definitely not be explained by a simple Z_p^2 scaling well-known from perturbative approaches. Hence, here non-perturbative two-center calculations are needed to clarify the effect.

As a demonstration of the fact that we are able to pick out X-rays stemming only from the close-collisions (i.e. impact parameter range of ~35–70 fm) we display in Fig. 3 (inset) the time difference between the scattered projectiles and X-rays recorded by the detector at 90° observation angle for bare projectiles. A coincidence peak is clearly visible in the spectrum. Applying the proper condition on this time spectrum we get the X-ray energy spectrum containing only the events stemming out of the close collisions. The

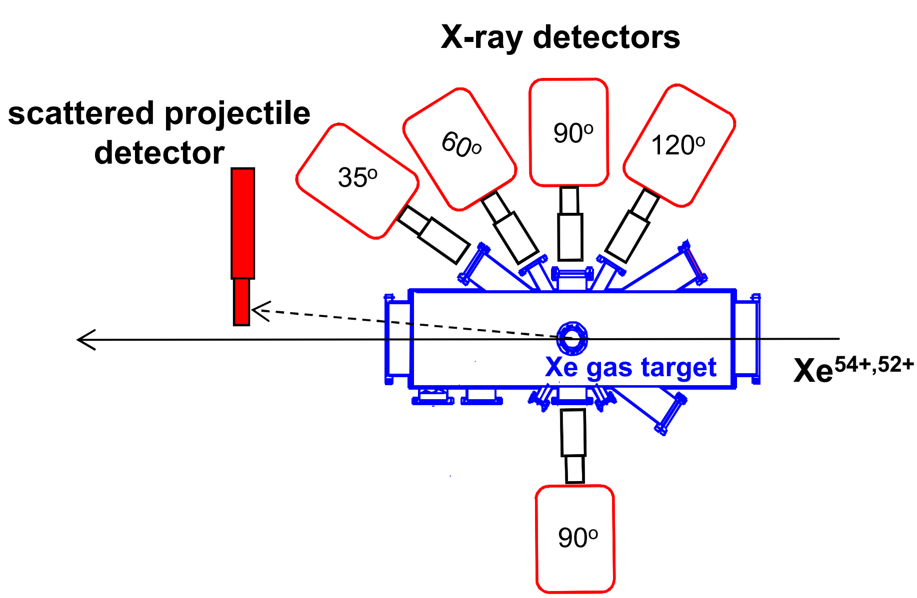

Fig. 1. The scheme of the experimental setup at the gas jet target of the ESR. The solid arrow depicts the ESR beam, and the dashed arrow shows the ions which have undergone a close collision with the xenon target and have been deflected onto the particle detector. In the measurement position, the particle detector was sensitive to projectile scattering angles from ~0.5–1.0°.

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