Two-electron processes in relativistic collisions of He-like uranium with gaseous targets

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Abstract

The simultaneous excitation-ionization and excitation-capture processes in collisions of 223 MeV/u He-like uranium ions with heavy target atoms are identified by measuring the x-ray (L$\rightarrow$K) transitions in coincidence with projectiles undergoing charge exchange. The state selective cross sections for the population of the L-shell sub-levels of the projectile are determined, and in the case of excitation-ionization data compared to the detailed relativistic calculations. It is emphasized that the experimental data can serve as an important benchmark of the independent particle approximation and fully relativistic perturbative models, for the domain of relativistic ion-atom collisions.

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1 Introduction

During the last few years the experimental investigations at the gas-jet target of the ESR Storage Ring at GSI-Darmstadt focused on the charge-exchange and projectile excitation phenomena. Particular attention was given to the spin-flip, retardation, and magnetic effects manifesting itself only at relativistic collision velocities. Basic understanding of these processes has been achieved [1]. The ESR facility, provides intense beams of cooled high-Z ions. Here also an internal gas-jet targets are routinely available for experiments, allowing us for the study of two-electron effects occurring in relativistic ion-atom collisions. Such effects have been studied extensively both experimentally and theoretically for strictly non-relativistic systems due to the fundamental question of the role of electron-electron interaction in the dynamics of ion-atom collisions. The interpretation of the experimental data in terms of the importance of electron correlation still remains controversial [2].

As it will be shown in this paper, multiple electron processes become observable at the relativistic collision velocities, when the perturbing potential is sufficiently large. Moreover, for low-density gaseous targets, as those used in this work, the probability of sequential processes involving two projectile electrons is negligible, allowing for the unambiguous identification of the two-electron transitions. For instance, the simultaneous excitation and ionization (EI) of the He-like projectile can be identified by measuring ground state x-rays of the projectile in coincidence with ions which lost one electron. Likewise, the measurement of projectile x-rays in coincidence with Li-like projectiles constitutes a direct signature of the excitation-capture (EC) events occurring in single ion-atom collision. We like to emphasize, that until now no such data are available for high-Z ions, since in standard single-pass experiments in which solid targets are used, effects due to multiple collisions cannot be excluded.

In the following we concentrate on the EI state selective cross sections, i.e. the case in which experimental data can be compared to the detailed relativistic calculations, although cross sections for the EC process are also given. Our theoretical description is based on the independent particle model (IPM) and semi-classical approximation (SCA) which allows us to express the impact parameter dependent probability for EI into the bound final n, l, j state of the projectile as a product of single electron transition probabilities:

$$p_{nlj}^{\mathrm{ion-exc}}(b) = 2\, p^{\mathrm{ion}}(b)\, p_{nlj}^{\mathrm{exc}}(b), \tag{1}$$

and the total cross sections for excitation-ionization as:

$$\sigma_{nlj}^{\mathrm{ion-exc}} = \int_0^\infty 2\pi\, b\, p_{nlj}^{\mathrm{ion-exc}}(b) db. \tag{2}$$

Consequently, we neglect correlation effects. The single electron excitation probabilities in Eq.(1) are calculated according to the first order perturbation theory in a rigorously relativistic manner i.e. incorporating both relativistic electron wave-functions and complete (Liénard-Wiechert) interaction potential [3]. A semi-relativistic model is used for the description of the ionization [4]. Since we use the first order perturbation theory to calculate single electron probabilities for excitation and ionization process and both scale with Z_{T}^2 (Z_{T} is the target atomic number) $\sigma_{nlj}^{\mathrm{ion-exc}}$ is within this approach proportional to Z_{T}^4.

2 Experiment and results

The experimental arrangement was similar to that described in [5]. The x-rays produced in collisions of 223 MeV/u He-like uranium with the Ar, Kr, and Xe were measured by three Ge(i) detectors placed at 48°, 90°, and 132° with respect to beam direction, in coincidence with down- and up-charged uranium ions. Simultaneously, the "single" (i.e. not associated with charge exchange in the gas-jet target) x-ray spectra were registered.

Figure 1 shows x-ray spectra recorded for U^{90+} impinging upon the Kr target. In the single, as well as in coincident spectra, well resolved L→K shell x-ray transitions associated with the single excitation (upper plot), EI (middle plot), and EC (lower plot) can be seen. The cross sections for the EI, and EC processes were put on the absolute scale by normalizing the observed (in the capture channel), radiative electron capture yields to the rigorous relativistic calculations [6]. Experimental cross sections for the EI into the final projectile L-shell sub-states with the total angular momentum $j = \frac{1}{2}$, and $j = \frac{3}{2}$, are shown along with the theoretical data in Fig. 2. The experimental data agree well with calculations for the Ar target, and stay in fair agreement for the Kr. It is worth noting that the EI process should occur preferably at small impact parameters where perturbing potential is the largest. For such near-central collisions excitation is dominated by the monopole part of the interaction potential [3]. While the calculations of EI cross sections based on the independent particle approximation, and the first order perturbation theory proved to be remarkably accurate for lighter targets, for the heaviest (Xe) target, a significant discrepancy for excitation into the j-sub-states of the L-shell is found. This points towards the invalidity of the peturbative treatment of the relativistic near-central collisions between heavy but asymmetric collision partners. For this strong interaction regime, presumably a unified coupled-channel formalism taking into account all of the possible collisional processes is required.

In Fig.3 we show cross sections for the EC into the $j = \frac{1}{2}$ and $j = \frac{3}{2}$ states of Li-like uranium. The experimental data rise steeper than EI cross sections and follow approximately Z_{T}^5 scaling law (see solid line). This reflects a different Z_{T} dependence of the single electron excitation and capture probabilities for collisions at small impact parameters. A comparison of the EC cross section data with theory requires an impact parameter formulation of non-radiative electron capture probabilities. For relativistic systems such calculations are not yet available.

3 Summary

By measuring the photon yields of the total angular momentum resolved L→K transitions in coincidence with projectile ions which captured or lost one electron, state selective cross sections for the two-electron (excitation-ionization and excitation-capture) processes were determined. The sensitivity of the state selective EI, and EC cross sections for the details of the excitation process at impact parameters close to the origin makes our experimental data a sensitive probe of our understanding of the relativistic collision dynamics. In the case of EI a simple independent electron approximation combined with strictly relativistic treatment of the individual single electron processes appears to be successful in predicting the measured cross sections for low-Z target atoms. The detailed discussion of this subject will be given in the forthcoming paper [7].

4 Acknowledgment

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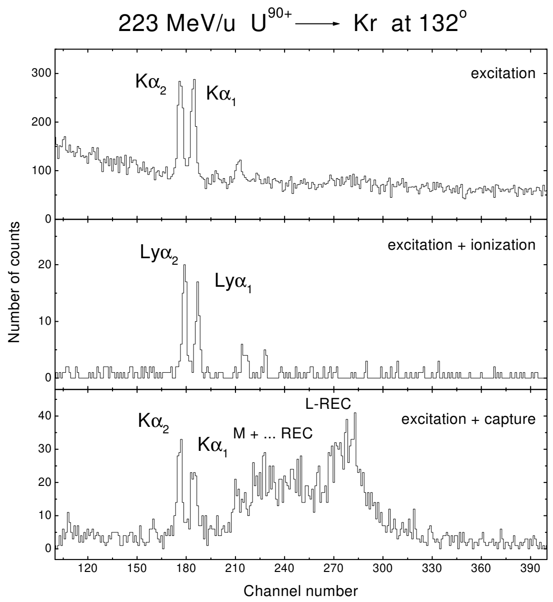

Figure 1: Sample x-ray spectra recorded at 132° for 223 MeV/u U^{90+} →Kr system. Upper plot – x-rays measured without coincidence conditions (single excitation), middle – projectile x-rays associated with EI, bottom – x-rays measured in coincidence with U^{89+} ions, representing REC into the unoccupied projectile states, and projectile x-rays associated with EC channel.

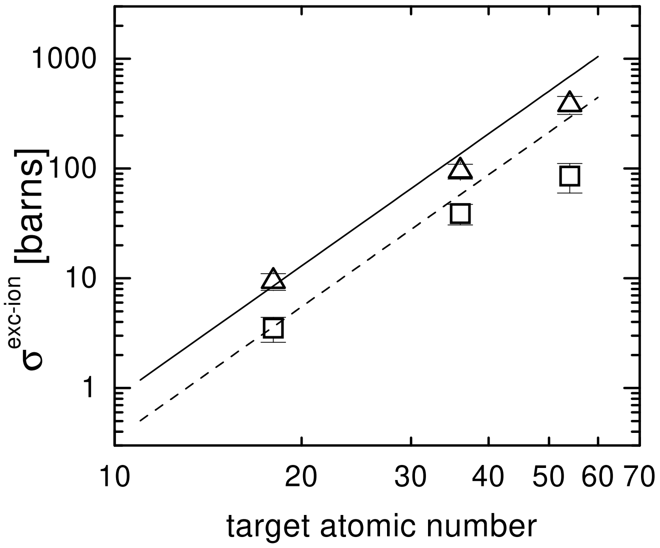

Figure 2: Excitation-ionization cross sections for 223 MeV/u U^{90+} ions colliding with the Ar, Kr and Xe targets; $\triangle$ - EI into the $j = \frac{1}{2}$ state, $\square$ - EI into the $j = \frac{3}{2}$ state of the projectile L-shell. The theoretical predictions are given by solid ($j = \frac{1}{2}$), and dashed ($j = \frac{3}{2}$) lines.

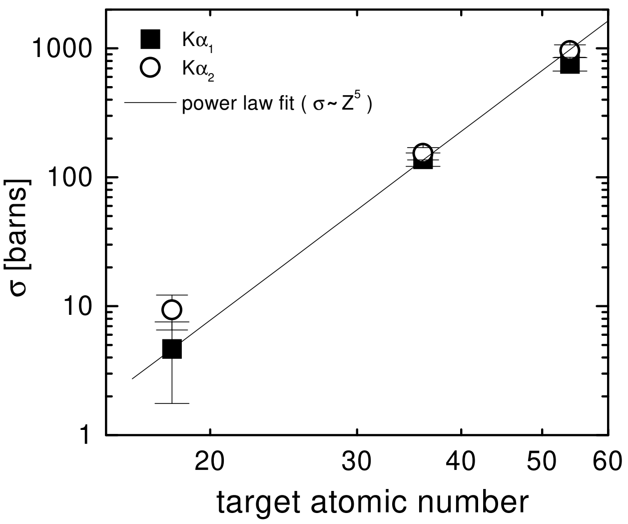

Figure 3: Excitation-capture cross sections for 223 MeV/u U^{90+} ions colliding with the Ar, Kr and Xe targets. Solid line shows the fitted power law dependence to the experimental data for capture and excitation into the $j = \frac{3}{2}$ states of the projectile.