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Radiative Electron Capture Studied for Bare, Decelerated Uranium Ions

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Abstract

By applying the deceleration technique for bare uranium ions at the ESR storage ring we studied the Radiative Electron Capture process in collisions with low-Z target atoms. This allowed us to extend the current information about the time-reversed photoionization process of highly-charged heavy ions to much lower energies than those accessible for neutral heavy elements in the direct reaction channel. The angular differential data obtained prove theoretical predictions that at high-Z higher-order multipole contributions and magnetic corrections play an important role even at energies close to the threshold.

1. Introduction

Detailed information about the elementary photoionization process can be derived via a study of its inverse reaction occurring in ion-atom collisions, i.e. Radiative Electron Capture (REC) [1–5]. This is in particular true for the high-Z regime where the photon-atom interaction is strongly influenced by relativistic effects. At high-Z the full retarded multipole expansion of the photon field must be considered and the strength of relativistic effects may lead to considerable corrections of the angular distribution. These contributions are difficult to disentangle in direct photoionization experiments, since retardation leads to a strong forward peaking of the photoelectron angular distribution (for a review of photoionization at high-Z see e.g. Refs. [6–8]). For REC, however, a cancellation between retardation and Lorentz transformation occurs for the angular distribution of REC into the K shell of bare ions [9]. As a consequence, the $\sin^2\theta$ distribution of the simple non-relativistic dipole-approximation is restored. Indeed a complete cancellation occurs as long as retardation is considered in all orders in a non-relativistic treatment. Therefore, deviations from the symmetric $\sin^2$ distribution provide a direct measure of relativistic corrections.

Here we discuss photon angular distribution studies for the time-reversed photoionization process occurring in collisions of bare uranium ions with light target atoms at low beam energies. This allows us to extend our knowledge for the photoionization process of high-Z elements to the low (near-threshold) and intermediate energy domain. At such energies, even no experimental data are available for the direct photoionization of neutral high-Z elements. For this purpose, bare uranium ions were actively decelerated in the ESR to an energy of 88 MeV/u [10]. For the direct channel this corresponds to an photoelectron energy of 48 keV. This has to be compared with the ground ionization potential in H-like uranium ($1s_{1/2}$: $\approx$ 132 keV).

2. Experimental technique

For the experiment, bare uranium ions where injected at the initial energy of 310 MeV/u into the ring. In the electron cooler device the ions were cooled by an electron beam of 200 mA providing U^{92+} ions with a longitudinal momentum spread of about 5×10^{-5}. Up to 10^8 bare uranium ions were stored and cooled, forming a beam with a diameter (full width half maximum) of 2 mm [11]. After the initial accumulation and cooling, the ions were decelerated to the beam energy of 88 MeV/u. At the end of the deceleration procedure, a N_2 supersonic-jet target with an effective area density of $\approx 10^{12}$ particles/cm^2 and a diameter of 5 mm (FWHM) was switched on.

To register X-ray emission, the atomic physics photon detection chamber at the internal jet target of ring has been used [5]. This environment allows us to view the beam/jet target interaction zone at a multitude of different observation angles with respect to the beam axis. For our current investigation an array of planar germanium detectors, covering observation angles in the range from $\approx 0^\circ$ to 150° was used. The projectile X-rays where registered in coincidence with down charge U^{91+} by using a plastic scintillator installed down-stream of the reaction chamber behind the next dipole magnet. For the case of the N_2 target, a sample coincident X-ray spectrum (recorded at 150°) is depicted in Fig. 1. In the spectrum, the Lyman-series transitions located at energies between 65 and 90 keV constitutes the most intense source of X-ray emission. Transitions due to radiative capture to the ground state show up at the

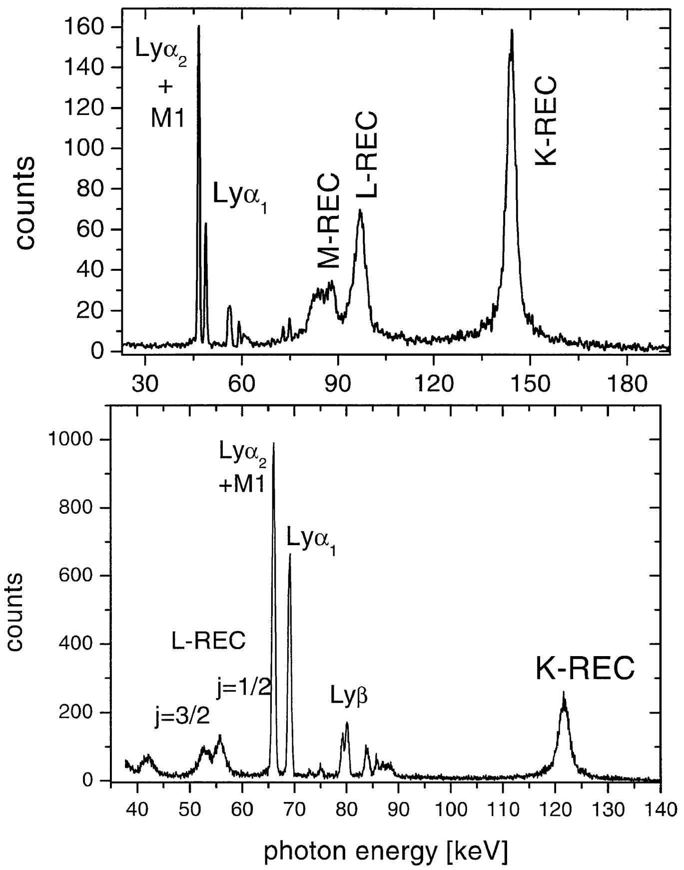

Fig. 1. Sample X-ray spectrum recorded at 150° for $U^{92+} \rightarrow N_2$ collisions at 88 MeV/u (bottom part) and for 310 MeV/u (top part) of the figure.

high-energy part of the spectrum. Also, REC into the L-shell of the projectile located at energies just below the Lyman-α ground state transition energies is well distinguishable. Note, that the low velocity of the decelerated ions results in a only moderate broadening of the REC lines due to the target electron momentum distribution (Compton profile). As a consequence the L-REC X-ray line splits into the two j fine-structure components $j = 1/2$ and $j = 3/2$ which are energetically separated by 4.5 keV in the projectile frame (see also the Lyman-α fine structure splitting observed in the spectrum). For comparison, the corresponding X-ray spectrum measured for the same collision system at the higher energy of 310 MeV/u is given in addition in the figure.

3. Data analysis and results

For data evaluation we adopted the technique as discussed in detail elsewhere [10]. Here, all characteristic Lyman ground state transitions as well as the REC lines for capture into K-shell and the L-shell sub-levels were considered by appropriate fitting routines. In the particular case of the REC transitions, line-profiles were described by using a theoretical line shape based on the double differential cross sections [2] which incorporates the correct Compton profiles of the target electrons. In the following we concentrate on the radiative transitions to the ground state.

In order to derive precise angular emission patterns for the radiative electron capture transitions we exploit the simultaneously observed Ly-α_2+M1 radiation. Since we are dealing with spin-less ^{238}U nuclei, no hyperfine coupling is present for the H-like projectiles formed by electron capture. Consequently, the Ly-α_2+M1 radiation stemming from the decay of the $2p_{1/2}$ and the $2s_{1/2}$ state is known to be isotropic in the emitter frame. As a consequence, its distribution in the laboratory frame is precisely known and is used in our data analysis for normalization purposes.

In Fig. 2 the experimental results for K-REC are given as a function of the photon emission-angle in the laboratory frame (solid triangles). In addition the data are compared with predictions based on rigorous relativistic calculations (solid line) [2,3]. For comparison, the measured angular distribution is normalized to the theoretical prediction at 90°. Also we display in Fig. 2 the $\sin^2\theta$ distribution of the non-relativistic theory (dotted line). As observed in the figure, the complete relativistic calculations lead to deviations from the non-relativistic theory which are largest for the forward hemisphere. The apparent asymmetry of the complete relativistic prediction with respect to 90° seems to be in accordance with the experimental findings. Most

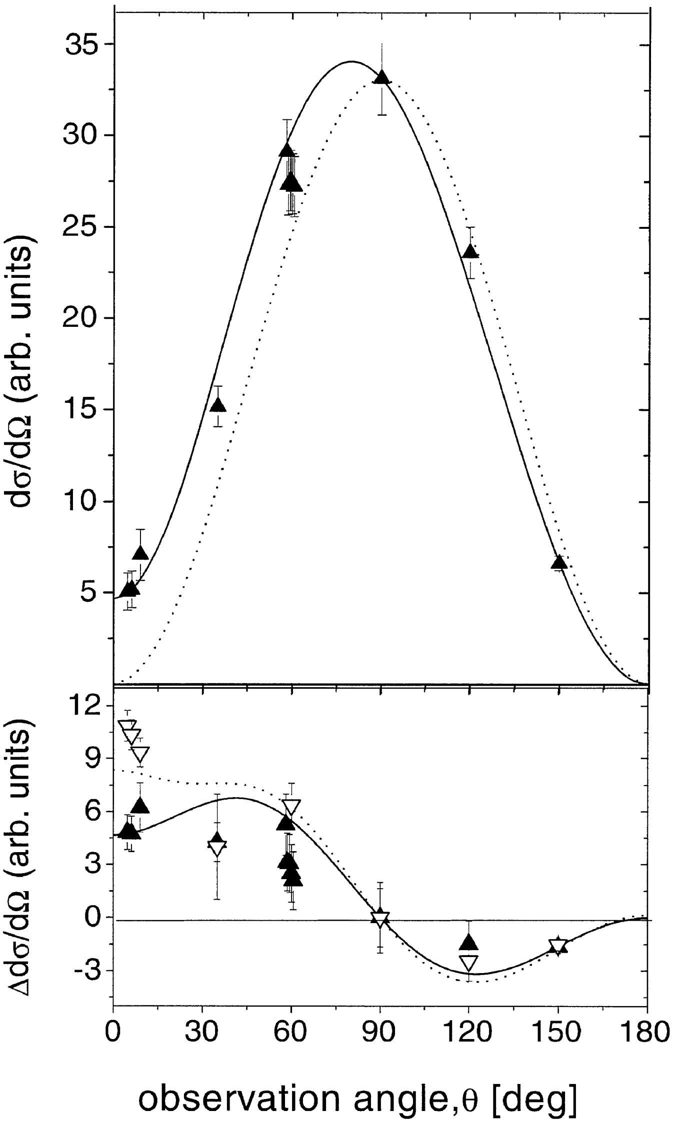

Fig. 2. Top part: Experimental K-REC angular distribution (88 MeV/u, solid triangles) in comparison with complete relativistic calculations (solid line) and the $\sin^2\theta$ distribution of the non-relativistic theory (laboratory frame, compare text). Bottom part: Deviations from the $\sin^2\theta$ distribution. Solid triangles: 88 MeV/u $U^{92} \rightarrow N_2$ [1]; open triangles: 310 MeV/u $U^{92} \rightarrow N_2$ [1]; dashed and solid line: corresponding relativistic predictions.

remarkably, the non-vanishing cross-section close to 0° proves that magnetic contributions are still present in the low-energy domain. This also emphasizes the sensitivity of the applied method, since magnetic transitions contribute to the total K-REC cross-section to only 3%. Therefore, our data support theoretical predictions that for high-Z systems relativistic corrections and higher multipole contributions persist to play a significant role even when approaching the photoionization threshold [7].

The deviations of the experimental data from the $\sin^2\theta$ distribution is illustrated in more detail in the bottom part of Fig. 2 where the difference $\Delta(d\sigma/\omega)$ is plotted as a function of the observation angle. The solid line refers to the deviation of the complete relativistic theory (solid line) from the non-relativistic prediction. For comparison, the corresponding variance is given for the result of the former experiment conducted at the 310 MeV/u (open triangles) and for the outcome of the relativistic theory for this higher energy (dashed line). As can be observed in the figure, the data sets for both energies are indistinguishable within the error bars, except close to 0°. For angles larger than 40° the same holds true for the corresponding fully relativistic descriptions where only small energy dependent variations are observed. Consequently, for the energy regime under consideration, the deviations from the non-relativistic appears to a large amount energy insensitive and caused by the relativistic wave functions of the high-Z system. Only the spin-flip transitions appear to be strongly velocity dependent which are mediated by the magnetic field produced by the moving projectile (compare region close to 0° in the figure). Note, these considerations are a specific feature of our reference system due to the partial cancellation of retardation and Lorentz transformation as already predicted by the non-relativistic theory. However, in the emitter frame a strong variation of the angular distribution as function of energy is present. This is depicted in Fig. 3 where the angular distributions measured for 88 MeV/u and 310 MeV/u are given in the emitter frame (Fig. 3(a)). Note, that the corresponding electron angular distributions for photoionization are simply obtained by interchanging θ' by $\pi - \theta'$.

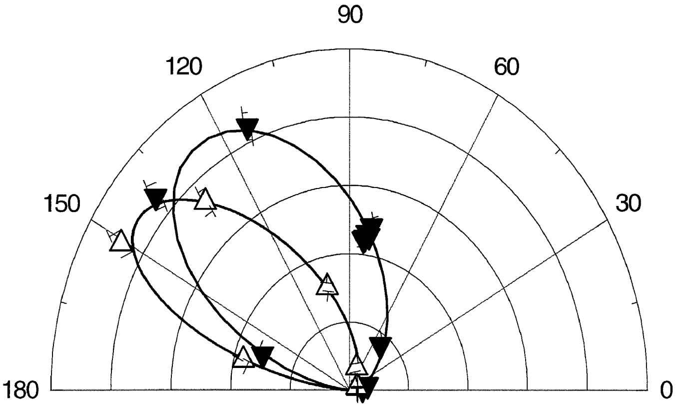

Fig. 3. Polar representation of the K-REC angular distributions (projectile frame, solid circles) measured at 88 MeV/u (solid triangles) and 310 MeV/u (open triangles) as a function of the emission angle. The full lines give the corresponding distributions as obtained from complete relativistic calculations.

4. Summary

In summary, we introduced the deceleration technique for angular-distributions studies of radiative electron capture into the bare uranium ions, i.e. at energies far below the energy required for the production of such high projectile charges. This allowed us to obtain for the first time differential data for photoionization of a high-Z hydrogen-like system in the low-energy regime. Our results clearly point out, that for high-Z elements retardation effects and magnetic corrections are still of importance even at low and intermediate energies. The comparison between our current data and the results obtained in a former experiment at the higher energy of 310 MeV/u is of particular importance. It allows us to distinguish between relativistic wave function effects and dynamically induced corrections. For the latter, the observed spin-flip transitions turn out to be most sensitive.

Currently, experiments are under preparation which will utilize the deceleration technique for the study of to high-Z multi-electron systems where the electron-electron interaction is expected to play a considerable role. This can be tested by comparing the angular-differential cross-sections for initially bare and H-like ions. Therefore our goal is to extend our previous REC studies to strongly decelerated bare and H-like uranium ions by exploiting the deceleration capability of the ESR storage ring. At the ESR we intend to focus on ion beams at energies between 10 to 20 MeV/u, energies which are meanwhile accessible. In the time-reversed situation they correspond to photoelectron energies of 5.5 keV and 11 keV. The ionization potentials of H- and He-like uranium are close to 130 keV, so this experiment will indeed allow us to perform the very first study of photoionization for H- and He-like high-Z systems very close to the threshold, an experimental study only possible at the ESR storage ring.

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