Photoionization Studies for H-like High-Z Ions at Low Energies

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The potential of Radiative Electron Capture for precision studies of the photoionization process in the high-Z domain has recently been demonstrated in a first angular-distribution experiment performed at the ESR jet-target for bare uranium ions [1]. This study allowed an unambiguous identification of spin-flip contributions to the differential cross-sections, an effect predicted recently [2,3,4]. Compared to direct photoionization experiments (for a review compare Ref. [5,6]), the observed spin-flip transitions are found at a lower energy since in our experiment this effect appears to be enhanced by the Lorentz transformation. In particular, due to the inverse kinematics, it reveals the origin of the observed spin-flip transitions as events related to large angle backward scattering in photoionization. For large backward angles close to 180^o, spin-flip effects have never been directly observed before. Besides this unique aspect of the time-reversed situation which can be exploited at the ESR jet-target, further peculiarities must be mentioned. By means of REC, photoionization can be studied even for excited states in high-Z H-like ions. Most important, no corrections due to electron scattering occurring in solid targets are required [5], leading in conventional photoionization studies for high-Z elements to a considerable broadening of the electron emission angle. Therefore in the high-Z regime, almost none of the few fine structure resolved photoionization data can be compared with theory since no corrections due to multiple scattering were performed. The absence of these deficiencies in REC experiments allows one to extend photoionization studies to much lower photon energies than available for the direct channel.

In order to elucidate the potential of the ESR for precise photoionization studies in more detail, a further angular-differential study of the time-reversed process was conducted at the jet-target for bare uranium ions [7]. In this experiment we were aiming to extend our knowledge of the photoionization process to the low-energy domain. For this purpose, bare uranium ions were actively decelerated in the ESR to an energy of 88 MeV/u. For the direct channel this corresponds to an photoelectron energy of 48 keV which must be compared to the ground state ionization potential of H-like uranium of close to 132 keV.

The data were taken during a parasitic beam time for bare U^{92+} projectiles in collision with a N_2 target and enabled us to measure at the same time REC into the ground state as well as into j-sublevels of the L-shell. A sample x-ray spectrum (recorded at 150^o) is depicted in Fig. 1. In the spectrum the REC lines of interest show up as broad structures whereas the characteristic Lyman transitions are the most intense features of the spectrum. The simultaneous observation of **Ly**α_2**+M1** radiation greatly facilitated the derivation of the electron angular distribution of the REC transitions as these transitions are isotropic in the emitter frame. This technique of normalization has already been successfully introduced in the former angular distribution study at the higher energy of 310 MeV/u [1]. In particular, it allows us to obtain directly angular-differential cross-sections for the emitter frame. In Fig. 2 the experimental results for K-REC are given as a function of the photon emission-angle in the emitter frame (solid circles).

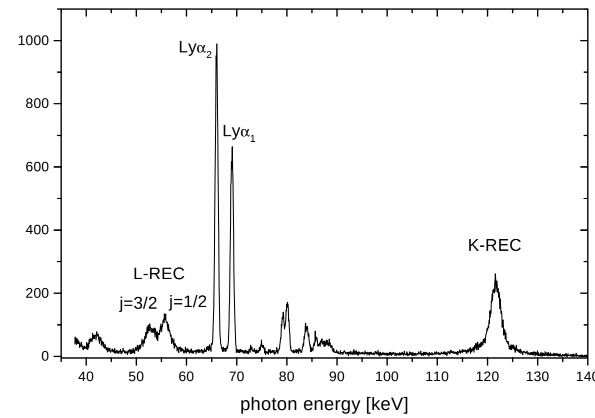

Figure 1: Sample x-ray spectrum recorded at 150^o for $U^{92+} \rightarrow N_2$ collisions at 88 MeV/u.

Although we are dealing with the low-energy domain, the distribution still shows a considerable backward peaking corresponding to a strong forward peaking of the electron emission for photoionization (compare upper x-axis in Fig. 2). This points out the importance of strong retardation corrections and to the presence of strong higher-order multipole contributions. Therefore the data support theoretical predictions for the high-Z regime that the relevance of higher-multipole contributions even persist close to the threshold for photoionization [3]. Indeed, the data are in good agreement with rigorous relativistic calculations [2] (see full line in Fig. 2). Most remarkably, both theory and experiment show a non-vanishing cross-section close to 0^o which proofs 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 amounts to only 3%. To facilitate a comparison with an angular distribution for high-energies, the results obtained recently for 310 MeV/u for $U^{92+} \rightarrow N_2$ collisions are displayed in addition. This comparison illustrates the enhanced importance of higher multipole contributions (retardation) with

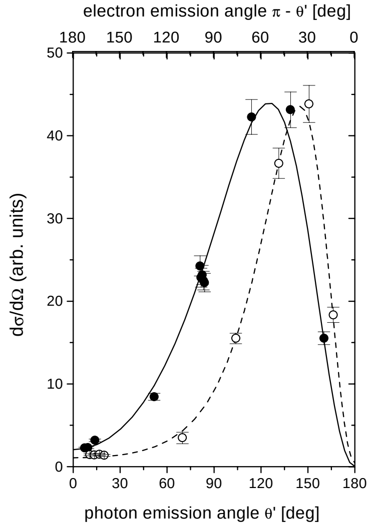

Figure 2: K-REC angular distribution (solid circles) as a function of the emission angle θ' (bottom x-axis) in the projectile frame. The data were obtained for $U^{92+} \rightarrow N_2$ collisions at 88 MeV/u. The x-axis at the top refers to the corresponding electron angular distribution for photoionization of H-like uranium (photon electron energy 48 keV). The full line gives the photoionization distribution as obtained from complete relativistic calculation. In addition, the results of a former experiment conducted at the high-energy of 310 MeV/u (photon energy of 170 keV)are shown for comparison (open circles and dashed line) [1].

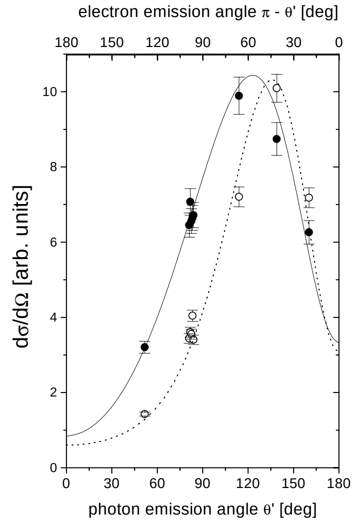

Figure 3: Experimental angular distribution for REC into the first excited states of H-like uranium as measured for $U^{92+} \rightarrow N_2$ collisions at 88 MeV/u (solid points: $2s_{1/2}$ and $2p_{1/2}$; open circles: $2p_{3/2}$) state. The lower x-axis refers to the emitter frame whereas the upper scale refers to the electron emission angle for photoionization with an kinetic photoelectron energy of 48 keV. The lines depict the result of rigorous relativistic calculations. Note that in the case of the $2p_{3/2}$ state, the experimental and theoretical results were multiplied by a factor of 1.6.

increasing energy leading to a very strong backward peaking of the distribution.

A very important aspect of the current investigation is that the enhanced experimental resolution due to the narrow Compton profiles at low beam energies allowed us to derive even j-subshell selective differential cross-sections for photoionization of the first excited states in hydrogen-like uranium. These data are given in Fig. 3. There, the solid points refer to capture into the two j=1/2 fine structure components of the L-shell ($2s_{1/2}$ and $2p_{1/2}$) and the open circles give the data obtained for the $2p_{3/2}$ state. The corresponding result of rigorous relativistic calculations are displayed in addition in the figure (full line: $2s_{1/2}$ and $2p_{1/2}$; dotted line: $2p_{3/2}$). Note, that for comparison of the angular distributions for the different j-fine structure components, the $2p_{3/2}$ distribution was multiplied by a factor of 1.6. For the case of the j=1/2 distribution, the $2s_{1/2}$ gives the strongest contribution and the final shape is quite similar to the one observed for the ground state. In contrast, the differential cross-section observed for the experimentally isolated $2p_{3/2}$ level exhibits a much more pronounced backward shift. Its maximum shows up at angles quite similar as it is observed for the K-REC distribution measured at the much higher energy of 310 MeV/u. This illustrates that retardation corrections depend crucially on the angular momentum of the final state and that they are much more pronounced for p than for s-states.

In summary, we measured the angular-distributions for REC into the ground state and the first excited states of decelerated bare uranium ions. This allowed us to obtain for the very first time differential data for photoionization of an high-Z element in the low-energy regime. The results demonstrate that the applied method is a powerful tool for the study of photon matter interaction in regimes not accessible in direct photoionization experiments.

In the near future we will extend our investigations to high-Z multi-electron systems in the low-energy domain where the electron-electron interaction is expected to play a considerable role. In order to perform such experiments at even lower beam-energies (e.g. 10 to 20 MeV/u), a H_2-cluster target has been developed for the ESR which was commissioned very recently [8].

References

[1] Th. Stöhlker et al. *Phys. Rev. Lett.* **82** (1999) 3232; *Phys. Rev. Lett.* **84** (2000) 1360;

[2] A. Ichihara et al. *Phys. Rev. A* **49** (1994) 1875 .

[3] J. Eichler et al. *Phys. Rev.A* **51** (1995) 3027 .

[4] A. Ichihara et al. *Phys. Rev. A* **54** (1996) 4954 .

[5] H. K. Tseng, R.H. Pratt, S. Yu, and A. Ron, *Phys. Rev.A* **17** (1978) 1061 .

[6] R.H. Pratt, A. Ron, and H.K. Tseng, *Revs. Mod. Phys.* **45** (1973) 273 .

[7] Th. Stöhlker et al. to be published

[8] A. Krämer, contribution to this report