Radiative Electron Capture into the K- and L-shell of H-, He-, and Li-Like Uranium Ions at Relativistic Energies

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Radiative electron capture (REC) is the most important channel for charge exchange in collisions of highly charged ions with light target atoms. As, in addition, the process is the time reversal of photoionization, its investigation opened new possibilities for advanced studies of radiation-matter interaction [1]. In particular, angular distribution of REC photons is a very sensitive probe of relativistic effects in strong fields of heavy ions. Here, magnetic spin-flip transitions were observed, for the first time, in fast collisions of bare U-ions [2] with low Z-ions. Even, at very low projectile velocities, corresponding to photoionization close to the threshold, the presence of these transitions was confirmed as well [3].

We report the experimental study of the angular distributions of photons for REC into the K-shell of H-like and into the L-shell of H-, He- and Li-like uranium ions. The main goal was to observe the role of spectator electrons in the heavy projectile in order to reveal possible electron-electron correlations.

The experiment was performed at the ESR storage ring at GSI-Darmstadt. The U^{91+}- , U^{90+}- and U^{89+}-ions at an energy of 216 MeV/u colliding with N_2-target were used. X-rays emitted from the active target area were detected simultaneously at 13°, 35°, 60°, 90°, 120° and 150° with respect to the beam axis. At all the angles Ge(i) detectors equipped with x-ray collimator slits (except for 13°) were used. The collimator dimensions allowed us to resolve the splitting of the $K\alpha$ transitions into the $K\alpha_1$ and $K\alpha_2$ components. At 13°, a Ge(i) detector with four independent segments, each furnished with an individual readout, was installed on a moveable support. After passing through the target the beam was charge state analysed in the next dipole magnet. Down- and up-charged U-ions were registered (for the study of capture and ionisation processes) with position-sensitive particle detectors located in the inner and outer part of the storage ring. In the following, preliminary results concerning electron capture are presented and discussed only.

Fig.1 shows a typical x-ray spectrum observed at 90° for U^{91+}-ions associated with capture of one electron. The broad structures arise from REC into the projectile K-, L- and M-shells. The line-widths are dominated by the Compton profile of the target electrons. Electron capture into excited states (L, M and higher shells) leads, via cascades, to the characteristic $K\alpha$- and $K\beta$ -transitions, clearly seen in the spectra.

All the x-ray spectra were first energy calibrated and corrected for random events and for detection efficiency. Then, the yields of K- and L-REC photons were determined via special fits to the experimental spectra. Simultaneously, the intensities of $K\alpha_2$-lines ($U^{91+} \rightarrow N_2$) were extracted. Assuming, that the $K\alpha_2$-line (similar to the $Ly\alpha_2$-line) is isotropic in the emitter system, all the angular distributions (U^{91+}, U^{90+}, $U^{89+} \rightarrow N_2$) for K- and L-REC were normalised relative to its intensity pattern in the laboratory frame.

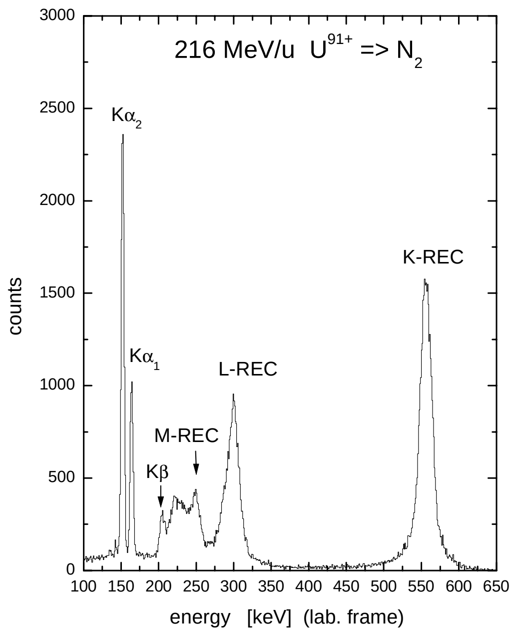


Fig.1 X-ray spectrum associated with one-electron capture (corrected for random events and detection efficiency) observed at an observation angle of 90°.

In Fig.2, the measured differential cross section for REC into the K-shell of 216 MeV/u U^{91+}-ions (present experiment) and 310 MeV/u U^{92+}-ions [2] are plotted as a function of the laboratory observation angle and compared with predictions (for $U^{92+} \rightarrow N_2$) based on rigorous relativistic calculations [4]. (The data obtained in the present experiment for 120° are still under evaluation and are therefore not displayed.) All the experimental and theoretical cross sections were normalised to an arbitrary value at 90°. Fig.2 shows that the shape of the angular distribution is almost unchanged when comparing the results for bare and H-like U-ions. The experimental data are in accordance with a fully relativistic theoretical description (solid line). The REC emission pattern deviates considerably from symmetry around 90° (compare dashed-line displaying a $sin^2\theta_{lab}$ distribution). Nonvanishing cross sections close to 0° point to the occurrence of magnetic (spin-flip) transitions for REC into high-Z projectiles.

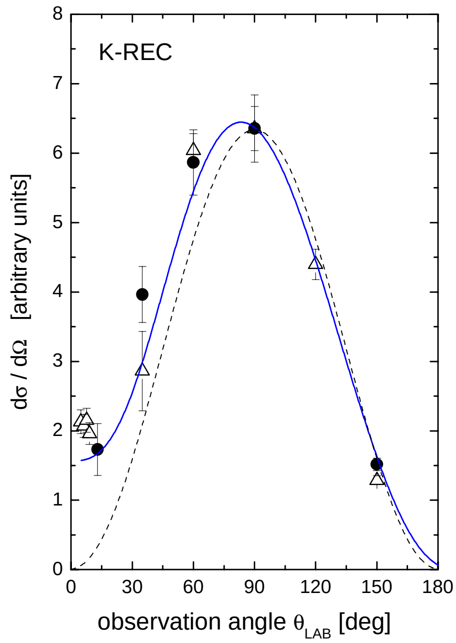
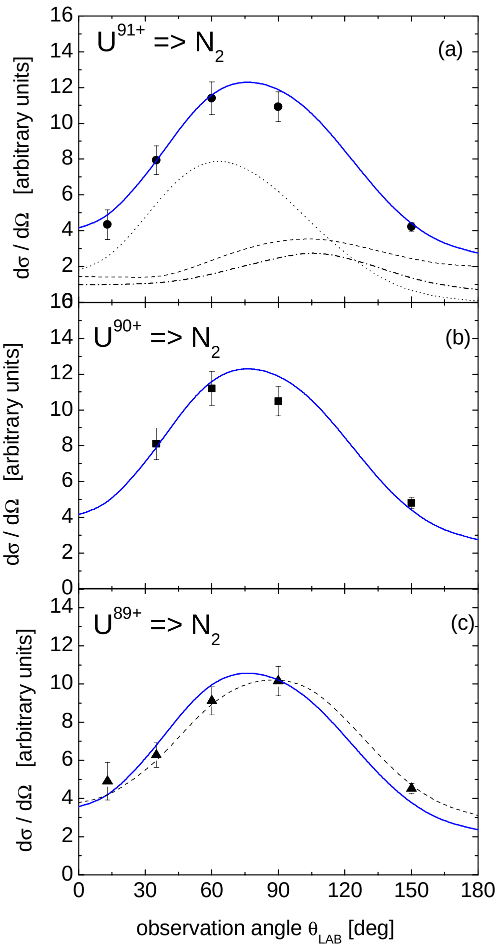


Fig.2 K-REC differential cross sections for 216 MeV/u $U^{91+} \rightarrow N_2$ (circles) and for 310 MeV/u $U^{92+} \rightarrow N_2$ (triangles); dashed-line – $sin^2\theta_{lab}$ distribution, solid-line – relativistic predictions for bare U-ions [4].

The differential cross sections for L-REC into U^{91+}-, U^{90+}- and U^{89+}-ions are presented in Fig.3a, 3b, 3c, respectively, along with theoretical calculations for the different subshells [4]. Similar to the K-REC, the photons observed at 0° and 180° angles present a clear signature of magnetic transitions. A basic feature of all the angular distributions displayed in Fig.3 is the asymmetry between the forward and the backward photon emission. The main contribution for H-like (Fig.3a) and He-like U-ions (Fig.3b) arises from the capture into the 2s-shell (dotted-line in Fig.3a) which has a pronounced maximum at the forward direction. Contributions from the 2p-shells (dashed-line: $2p_{1/2}$, dashed-dotted line: $2p_{3/2}$) reach their maximum at backward angles and do not compensate this forward peaking. In the case of $U^{89+} \rightarrow N_2$ system (Fig.3c) the emission pattern is shifted into backward direction due to the partially blocked contribution from the 2s-shell. Here, again the experimental data agree well with theoretical predictions taking into account only one electron present initially in the 2s-shell of U^{89+} (compare dashed-line in Fig. 3c. for one initial 2s vacancy and the full line for two initial 2s vacancies).

In summary, we measured the angular distributions of K- and L-REC into H-, He-, and Li-like U-ions at an energy of 216 MeV/u. They are found to be asymmetric and more pronounced at forward directions. The emission pattern for K-REC stays unchanged for bare and H-like U-ions. One electron present in the L-shell of the projectile (U^{89+}) shifts the photon emission into backward direction. The experimental data provide an excellent agreement with



rigorous relativistic predictions.

Fig.3 Differential cross sections for capture into the L-shell of U^{91+} (a) , U^{90+} (b) , U^{89+}(c) . (a) dotted-line: capture into the $2s_{1/2}$-shell, dashed-line: $2p_{1/2}$-shell, dot-dashed-line: $2p_{3/2}$-shell; (c) dashed-line – see text. All solid lines refer to the summed contributions for completely empty $2s_{1/2}$-, $2p_{1/2}$-, and $2p_{3/2}$ -subshells (relativistic predictions [4]).

References

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