Study of the Two-Electron Lamb Shift in High-Z Helium-Like Ions

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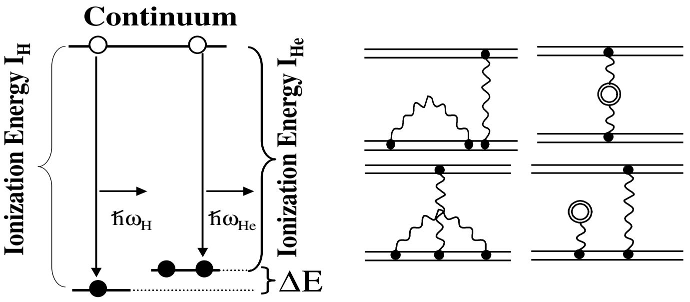

Figure 1: Left side: Schematic presentation of the RR process of free electrons into the initially bare and H-like ions. The energy difference $\Delta E = \hbar\omega_H - \hbar\omega_{He}$ gives exactly the two-electron contribution to the ionization potential in He-like ions. Right side: Feynman diagrams for the two-electron self energy and vacuum polarization.

Helium-like ions are the simplest atomic multi-body systems. Very recently the theoretical as well as the experimental investigations of these fundamental systems gained a considerable improved precision [1, 2]. The experimental progress manifests itself in a novel approach and exploits Radiative Recombination (RR) transitions into the vacant 1s shell of bare and H-like ions [2]. In this process an electron may undergo a direct transition into a bound state of the stationary ion via the emission of a photon carrying away the energy difference between the initial and final electron state, i.e. $\hbar\omega = E_{kin} + E_B$ (compare Fig. 1). The difference in the centroid energies for such radiative recombination transitions into the vacant K-shell of bare and H-like high-Z ions is equal to the difference in the ionization potential between the hydrogen-like and the heliumlike ions formed by the recombination process. It gives exactly the two-electron contribution to the ground-state energy of the heliumlike ions. Most important, all one-electron contributions to the binding energy such as the finite-nuclear size corrections and the one-electron self-energy cancel out completely in this type of experiment [1]. These first experiments on the ground-state of He-like ions conducted at Super-EBIT were very successful and provided to the very first time results which are at the threshold to become sensitive to higher order QED effects [2, 3]. However, at high nuclear charges such as Z = 83 or even Z = 92 it turned out that the production efficiency for bare ions is not sufficient and the results suffered by counting statistics. Very recently we applied this technique at the electron cooler device at the ESR storage ring for the case of He-like uranium. The aim of this experiment is to measure precisely the two-electron contribution to the ionization potential in He-like uranium of 2.2 keV with an accuracy better than 5 eV. Since two-electron QED effects are calculated to contribute 7 eV [1], such an experimental study would therefore provide the very first test of higher-order QED corrections (higher order in α) in the domain of high-Z ions (some of the relevant Feynman diagrams are displayed in Fig. 1).

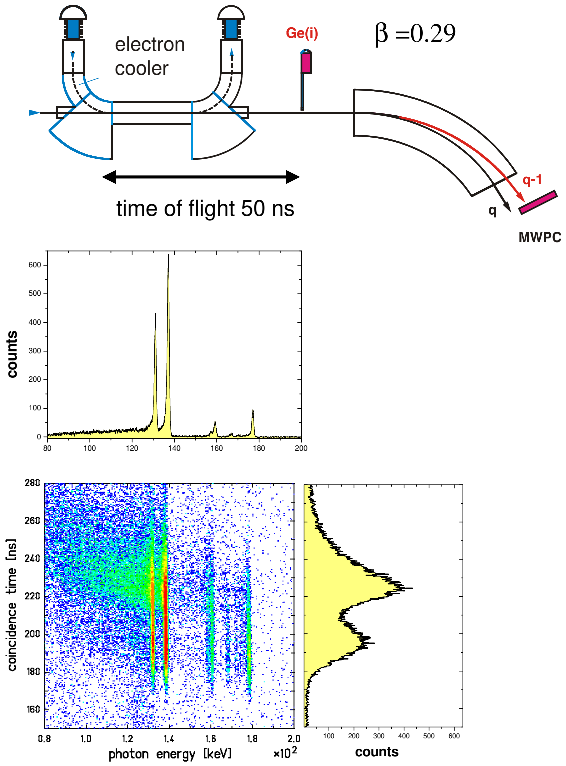

Figure 2: Sketch of the experimental setup (top) and two dimensional scatter plot of the observed x-ray emission versus the coincidence time. The latter refers to the time difference between photon and particle detection. The pronounced structure observed in the time spectrum (right side) allows us to disentangle between photon emission which has occurred inside the electron cooler section and such events where the emission takes place just in front of the x-ray detector.

For the experiment, the setup available at the electron cooler section was used (cf. top of Fig. 2). There, the x-rays emitted via RR of the cooler electrons into the ground state of the bare- or H-like ions can be detected by a solid state detector which views the interaction region at an observation angle close to 0° [4]. Because the key feature of the experiment is a relative measurement of RR into the K-shell of initially bare and H-like uranium, we changed during the experiment three times between the two charge states. Compared to a simultaneous storage of both charge states, also possible at the ESR, this applied method has the advantage to allow us to measure the x-ray emission in coincidence with the down-charged ions by using a particle detector located behind the next dipole magnet (compare scheme of the experimental set-up displayed in Fig. 2).

In particular the experiment benefits from the recent established deceleration technique [5]. At low energies, all uncertainties associated with Doppler corrections are strongly reduced compared to high-energy beams. Also, for decelerated ions the bremsstrahlung intensity caused by the cooler electrons is strongly reduced (due to the comparably small cooler voltage of 27 kV and current of 100 mA). Consequently, very clean conditions for x-ray spectroscopy are present at the cooler section. This is depicted in Fig. 3 where a preliminary calibrated, coincident x-ray spectrum is plotted as observed for initially bare uranium ions at an energy of 43 MeV/u. Note, the strongly reduced bremsstrahlung intensity allowed us for the very first time to observe even RR transitions into the L-shell, located at the low-energy part of the spectrum. In the spectrum, the x-ray transitions for RR into the ground state show up in the high energy part of the spectrum which are of particular interest for the current study. Most important, the tails of the Lyman-α transition lines, caused by cascade feeding of the L-shell levels [4], are consequently not present in the case of the RR photon emission. A further important aspect of our study is that due the low β-value of 0.29 and the experimental time resolution of about 20 ns, photon events which occurred inside the cooler section can be distinguished from events where the emission took place just in front of the x-ray detector. For the latter x-ray events, the set-up possesses a comparably large solid angle and the photon energy appears markedly shifted leading to the low-energy tails of the Lyman radiation.

In Fig. 4 we depict the photon spectra which were accumulated by using a time condition (see Fig. 2) which excludes most of the cascade contributions leading to the low-energy tails. Indeed, as observed in Fig. 4, the time condition used eliminates almost completely the low energy tails and reduces also the intensity of the Lyman transitions but leads the K-RR lines practically unaffected. However, even the centroids of the K-RR lines might be affected by this time condition applied, because Lyman transition arising from high-n levels may contribute to the x-ray background located at the low-energy region of the K-RR lines. In the inset of Fig. 3 the energy regime relevant for K-RR transitions is displayed. There the line intensities as measured for initially bare- and H-like uranium are compared. From a first preliminary analysis, a statistical accuracy for the splitting close to 9 eV can already be stated. Keeping in mind that for collection of the data a total beam time of 4 days has been used, a second more extended run should provide us with the desired experimental accuracy of 4 eV or even below.

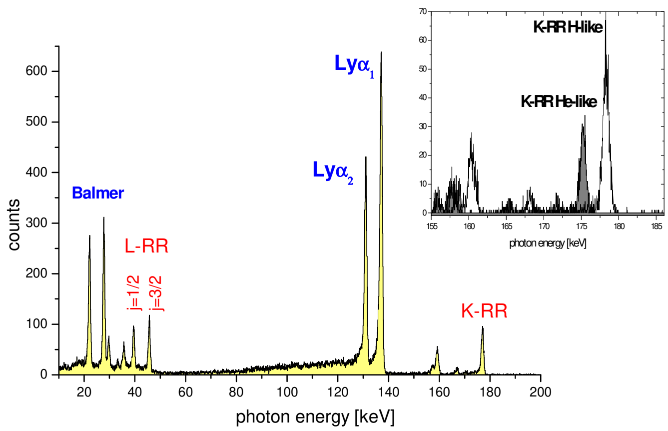

Figure 3: X-ray spectrum for H-like uranium as observed for decelerated ions at the electron cooler of the ESR storage ring. For details compare text. The inset compares H- and He-like spectra at the RR region.

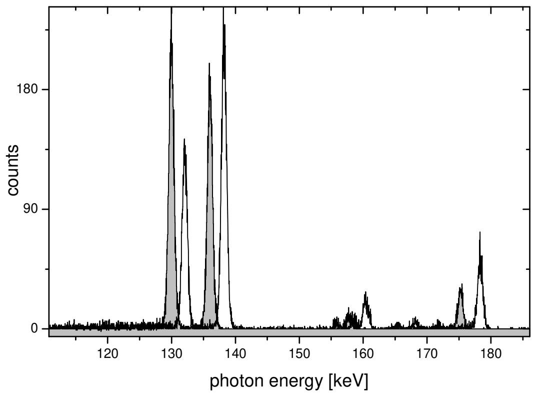

Figure 4: X-ray spectra of H- and He-like (filled) uranium as measured at the ESR cooler. For accumulation, a time condition (compare text) has been used.

Acknowledgements
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References

[1] H. Persson, S. Salomonson, P. Sunnergren, and I. Lindgren, Phys. Rev. Lett. **76** (1996) 204 .

[2] R.E. Marrs, S.R. Elliott, and Th. Stöhlker, Phys. Rev. **A52** (1995) 3577.

[3] Th. Stöhlker, S.R. Elliott, and R.E. Marrs, Hyperfine Interactions **99** (1996) 217.

[4] H.F. Beyer et al., Z. Phys. **D35** (1995) 169.

[5] Th. Stöhlker et al., Phys. Rev. **A58** (1998) 2043.