Recent Developments for the Investigation of Ground-State Transitions in Heavy One-Electron Ions

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Abstract. Accurate investigations of the structure of one- and few-electron ions in the high-Z regime provide unique possibilities for testing fundamental theories underlying our present understanding of the physics of extremely electromagnetic strong fields. In this review, we concentrate on x-ray spectroscopic investigations of the ground-state transition energies in H-like uranium (heaviest stable element available) by using the intense beams of cooled heavy ions provided by the storage ring ESR at GSI. Such experiments allow for a precise study of the ground-state binding-energies in high-Z H-like ions where relativistic and QED effects are strongest. The most recent experiment is presented where the deceleration capability of the ESR storage ring was exploited for x-ray spectroscopy at the ESR electron cooler. In addition, we discuss the ongoing developments for a new generation of ground-state Lamb shift experiments aiming on a precision of 1 eV or even better. In particular, emphasis will be given to the dedicated crystal spectrometer (FOCAL) in combination with state of the art 2D position-sensitive solid state detectors, allowing for energy and time resolved x-ray imaging.

Recent progress in the developments of heavy-ion storage-rings equipped with electron coolers and internal targets provided a new access for precision studies of the atomic structure in the regime of high-Z one- and few-electron ions. In this domain, in contrast to low-Z (ordinary) ions relativistic and quantum electrodynamical effects start to play a key role, making experimental as well as theoretical studies of such systems very challenging. In particular, high-Z H-like ions are of interest since they represent the most fundamental and simple atomic systems where the bound electron is exposed to the extremely strong Coulomb field of the nucleus. Here the field strength approaches already the critical value for spontaneous pair production. Precision measurements of x-ray transitions from bound or continuum states into the ground state of the heavy bare ion-electron systems are best suited to deduce characteristic QED phenomena in intense fields and a comparison of predicted with experimentally determined level energies provides a critical test of theory in this regime \cite{1, 2, 3, 4}. In theory, a significant progress was achieved during the last few years. For the case of H-like uranium the theoretical uncertainties...
are now reduced to a value of 0.5 eV by evaluating higher order QED contributions \[3, 5\].

The ESR storage ring with its brilliant beams of cooled heavy-ions has proven to provide unique conditions for this kind of precision investigations \[6, 1, 2\]. Within the last years there has been a constant improvement in beam handling and the maximum possible number of stored ions has improved significantly (see Fig. 1).

All of these features are important prerequisites for precise experimental investigations in the domain of high-Z systems. In the following section we will concentrate on the dedicated experiment, we have recently carried out at the ESR storage ring at GSI, aiming on a precise determination of the ground-state Lamb shift in H-like uranium \[7\]. Here, a combination of excellent beam quality (properties) provided by the ESR and the \(0^\circ\) observation geometry, allowed us to determine the ground-state Lamb shift in hydrogen-like uranium (U\(^{91+}\)) from the observed x-ray lines with an accuracy of 1%.

1. The ground-state Lamb shift in H-like uranium: experiment at the ESR electron cooler

For the experiment bare uranium ions extracted out of the SIS (Schwerionen Synchrotron) were injected into the ESR at an energy of 360 MeV/u and subsequently decelerated down to 43.59 MeV/u. Directly after the injection from the SIS (before the deceleration) the ions were first cooled at the high energy, then electron cooling was switched off, the coasting beam was bunched and the deceleration mode was applied. At the low energy the electron cooling was turned on again and the measurement cycle started. As it was already mentioned above, electron cooling guarantees a well defined constant beam velocity, generally of the order of \(\Delta \beta/\beta \approx 10^{-5}\) as well as a low beam emittance. The accumulated ion currents in the ESR were about 3-4 mA and 550-600 \(\mu\)A before and after the deceleration, respectively.

X-rays emitted via radiative recombination in the cooler were detected by a segmented germanium detector consisting of four individual strips (for details about the setup please refer to \[8, 7\]). The detector was mounted 4.1 m downstream of the midpoint of the 2.5 m long straight cooling section and could be moved vertically by means of a stepping motor. During the measurement the detector was placed close to the ion beam so that the observation angles of the ion-beam/electron-beam interaction zone were 0.35°, 0.53° and 0.71° for strip number 1, strip number 2 and strip number 3 respectively. The shift of the observed photon energy between two neighboring strips due to the Doppler effect amounted to about 1 eV. The Doppler...
broadening was negligible due to the observation angle of close to 0°. The x-rays were recorded in coincidence with down-charged uranium ions, as produced by the capture of one electron in the cooler. The down-charged ions were registered by a particle detector installed in a pocket behind the first dipole magnet downstream from the electron cooler.

In Fig. 2 calibrated x-ray spectrum is displayed as observed for initially bare uranium ions at an energy of 43.59 MeV/u. The spectrum is almost background free, since was recorded in coincidence with down-charged ions. The most intense lines observed can be attributed to direct transition of electrons into the K-shell of the projectile ions (K-RR) and to characteristic \( L \rightarrow K \) (Lyman α) transitions. Assuming that the energies of the \( L \)-shell levels are precisely known from the theory [9], the ground state Lamb shift can be deduced by comparison with the Dirac energy eigenvalue for the 1s-ground state of a point like nucleus. However, it should be noted that only the Lyα\(_1\) centroid energy allows a direct comparison with the ground state Lamb shift prediction where only the \( 2p_{3/2} \rightarrow 1s_{1/2} \) transition contributes to the observed line. In contrast, the Lyα\(_2\) line consists out of two transitions which cannot be resolved experimentally (the \( 2p_{1/2} \rightarrow 1s_{1/2} \) and the \( 2s_{1/2} \rightarrow 1s_{1/2} \), respectively). In total, six independent values for the 1s binding energy were obtained, three from the Ly-α\(_1\) transitions and three from the K-RR lines [7]. The relativistic Doppler transformation into the emitter frame gives an error resulting from an imprecision in the beam velocity determination of \( \Delta \beta = 2.9 \cdot 10^{-5} \) which implies a relative uncertainty for the Doppler correction of \( \Delta E/E = 3.16 \times 10^{-5} \) corresponding in turn to a 3.5 eV error for the ground-state binding energy in hydrogen-like uranium. Finally, taking a weighted average of the above results we obtain a value of 460.2 ± 2.3 ± 3.5 eV for the ground state Lamb shift in H-like uranium. The uncertainty of 2.3 eV is entirely statistical whereas the one of 3.5 eV stems from the imprecision of the beam velocity determination (see above). In addition, we estimate an uncertainty of 2 eV to account for possible systematic errors introduced by the line-shape analysis. Adding quadratically these various contributions results in an uncertainty of 4.6 eV for the experimental 1s Lamb shift value.

In table 1 we compare our experimental result for the 1s Lamb shift with the newest theoretical value [3, 5]. In order to emphasize the achieved experimental precision, several individual contributions to the total theoretical Lamb shift including the recently calculated 2-nd order QED corrections are listed separately as well. The comparison shows that our result is sensitive to the QED contributions of the first order (in \( \alpha \)) at the 2% level and thus, represents the most precise test of the bound-state QED in high-Z one-electron systems.
In Fig. 3, our experimental result for the ground-state Lamb shift in hydrogen-like uranium is presented together with available results from other experiments [6, 2, 1, 10, 11] and compared with different theoretical predictions [12, 3, 13, 14, 15] (solid line). The figure demonstrates the substantial improvement which took place at the ESR storage ring within the past ten years. Note, that the theoretical predictions are also changing in time.

|              |       |
|--------------|-------|
| Finite nuclear size | 198.81 |
| 1-st order QED   | 266.45 |
| 2-nd order QED   | -1.26(33) |
| **Total theory [3, 5]** | **464.26±0.5** |
| This work       | 460.2±4.6 |

**Table 1.** The Ground-state Lamb shift for H-like uranium in eV.

2. **Towards an accuracy of 1 eV: The FOCAL Spectrometer for precision x-ray spectroscopy of fast heavy ions**

In the most recent 1s lamb shift experiment for $U^{91+}$ discussed in the previous section a ground state Lamb shift of 460.2 ± 4.6 eV was obtained which is already at the threshold of a meaningful test of higher-order QED contributions [7]. By using decelerated beams along with an improved detector setup further progress in improving an absolute accuracy may be anticipated. However, in order to obtain a significantly improved precision, future experiments will focus in addition on decelerated ions combined with high-resolution crystal spectrometers or micro-calorimeters which are presently under construction [16, 18, 17]. At GSI, a system of two crystal spectrometers for accurate wavelength measurements of hard x-rays emitted by heavy ions in flight is presently being completed (see Fig. 4).

The configuration is working in the FOcusing Compensated Asymmetric Laue (FOCAL) mode (for details see [16]) along with high performance two-dimensional position sensitive
micro-strip Ge detectors. The FOCAL x-ray optics has been designed for high systematic wavelength accuracy with an efficiency, large in comparison with previous crystal-spectrometers for that wavelength range. The spectrometer along with position-sensitive detectors enables us to perform precision spectroscopy of fast heavy ions available in accelerator-based experiments with limited source strength. To a large extent, resolution and detection efficiency can be adapted to the requirements of a given fast moving x-ray source. FOCAL comprises a large useful energy range (30-120 keV), corresponding to the wavelength range of 40-10 pm), high linearity, self alignment through double spectra, zero Doppler broadening and easy adaption to a fast moving source. Combining with a position-sensitive detector permits the measurement of an energy spectrum wide enough to investigate the interesting energy regime simultaneously. In addition, the good energy resolution enables discrimination against background events of the recorded spectra arising from various sources. Recently such a micro-strip detector system, developed at the Forschungszentrum Jülich [20], with a position resolution of close to 200 μm has become available and has been tested in combination with the FOCAL spectrometer using an intense radioactive $^{169}$Yb source. Even without any strict conditions on the photon energies for the individual strips, the intensity pattern observed with the microstrip detector as function of the position (i.e. strip number) identifies clearly the two x-ray lines of the Kα-doublet from Tm and Yb (Fig. 2) which are separated by approximately 970 eV and 1030 eV, respectively [22]. We like to emphasis that the spectral line shapes can not be described with Gaussian function as it is obvious from the Fig. 5. A Voigt profile (convolution of Lorentzian and Gaussian) should be used instead do to the natural line width of the x-ray transitions of interest of about 30 eV. This means that the FOCAL spectrometer in combination with the micro-strip germanium detector allows us to achieve an energy resolution of better than 100 eV along with high detection efficiency.

The FOCAL spectrometer was tested addition during a beam time at the ESR storage ring. At the ESR a beam of completely stripped Au$^{79+}$ ions was stored at a velocity $\beta=0.4433$. Lyman-α lines of hydrogen-like Au$^{78+}$ were produced by electron capture in collisions with a low-dense argon supersonic jet target. X rays were measured in coincidence with those particles that have lost one unit of charge and that are registered in a particle detector after the next dipole magnet of the storage ring. After setting suitable time and energy windows in the data acquisition software, the spectrum of Fig. 6 was obtained showing clearly the Lyman-α doublet.
Figure 5. Result obtained with the germanium microstrip detector mounted at the FOCAL spectrometer [19]. The intensity pattern as function of the position (energy) identifies well resolved the two components of the Kα-doublet of Tm as well as those of Yb [22]. The dashed line refers to a Gaussian profile and the full line to a Voigt profile, respectively.

of one electron Au$^{78+}$. Also shown in the figure is an overlaid calibration spectrum with the 63.121-keV gamma-ray line, scaled down by a factor of 140. Although the number of collected Lyman photons was low in this first test, it was demonstrated that it is feasible to record useful x-ray spectra with FOCAL in an accelerator environment with its limited source strength. The favorably low background level observed is attributed to the efficient shielding and suppression methods. The somewhat increased width seen in the Lyman lines is fully consistent with the expected slanting of the lines due to the Doppler effect [19].

This slight broadening can be eliminated in case of two-dimensional germanium strip-detector. Very recently such a microstrip detector has been developed for Lamb shift experiments at GSI [21]. A 128-strip structure on an area of 32 x 56 mm$^2$ with a pitch of 250 µm on the front contact (implanted) and a 48-strip structure with a pitch of 1167 µm on the rear contact (amorphous Ge) are realized with the help of plasma etching. The detector is mounted on a cryostat, which will enable any orientation of the detector with respect to a photon source. The energy resolution [FWHM] was measured with 60 keV photons at a bias voltage of 1300 V with all the preamplifiers operating to be close to 2.3 keV at 60 keV. In addition, a time resolution [FWHM] of 50 ns at 60 keV can be anticipated. Both time and energy resolution will help to further reduce the x-ray background by setting suitable energy and time windows.

3. Summary
The status and prospects of x-ray experiments at the storage ring ESR are reviewed which are aiming at an accurate determination of the effect of QED in the strongest accessible electron-magnetic fields as they prevail for the ground state in hydrogenlike uranium. In particular, a very recent experiment was discussed where x-ray spectra following the radiative recombination of free electrons with bare uranium ions were measured at the ESR electron cooler. The experiment was carried out by utilizing the deceleration technique which leads to a considerable reduction of the uncertainties associated with Doppler corrections. This technique along with the substantial intensity increase for high-Z ions at the ESR allowed us to determine the ground-state Lamb shift in hydrogenlike uranium from the observed x-ray lines with an accuracy of 1%. The present result provides the most stringent test of the bound-state quantum electrodynamics for
one-electron systems in the strong field regime. As discussed, a further improvement by almost one order of magnitude is envisaged by the dedicated transmission x-ray spectrometer system FOCAL which has been developed recently. This progress is accompanied by the commissioning of position sensitive solid-state detectors, allowing for energy and time-resolved photon imaging, a prerequisite for an efficient operation of the FOCAL spectrometer. In addition, also microcalorimeters for the hard x-ray regime are currently developed and tested at the ESR for high-resolution spectroscopy of hard x-ray transitions. In a hybrid setup, combining both the transmission type spectrometers and micro-calorimeters, a breakthrough in testing QED in strong field regime might be expected soon.

[1] Th. Stöhlker et al., Phys. Rev. Lett. 85, 3109 (2000).
[2] H.F. Beyer et al., Z. Phys. D 35, 169 (1995).
[3] V. A. Yerokhin et al., Phys. Rev. A 64, 062507 (2001).
[4] S. Fritzsch, P. Indelicato, Th. Stöhlker, J. Phys. B: At. Mol. Opt. Phys. 38 No 9, S707 (2005).
[5] V. A. Yerokhin et al., Phys. Rev. Lett. 91, 073001 (2003).
[6] Th. Stöhlker, P.H. Mokler, K. Beckert, F. Bosch, H. Eickhoff, B. Franzke M. Jung, T.Kandler, O. Klepper, C. Kozhuhaov, R. Moshammer, F. Nodeln, H. Reich, P. Rymuza, P. Spädtke, and M. Steck, Phys. Lett. A 71 (1993), 2184.
[7] A. Gumberidze et al., Phys. Rev. Lett. 94, 223001 (2005).
[8] A. Gumberidze, PhD thesis, University of Frankfurt (2003).
[9] P. Indelicato, private communication (1998).
[10] J.P. Briand, P. Chevallier, P. Indelicato, K.P. Ziock, and D. Dietrich, Phys. Rev. Lett. 65, 2761 (1990).
[11] J.H. Lupton, D.D. Dietrich, C.J. Hailey, R.E. Stewart, K.P. Ziock, Phys. Rev. A 50, 2150 (1994).
[12] T. Beier et al., Phys. Lett. A 236, 329 (1997).
[13] W.R. Johnson and G. Soff, At. Data and Nucl. Data Tables 33, 405, (1985).
[14] H. Persson, S. Salomonson, P. Sunnergren, I. Lindgren, M.G.H. Gustavsson, Hyperfine Interaction 108, 3 (1997).
[15] P.J. Mohr, Nucl. Instrum. Methods in Phys. Res. B 87, 232 (1994).
[16] H.F. Beyer, Nucl. Instr. Meth., A 400, 137 (1997).
[17] E. Silver et al., Nuc. Instr. Meth. in Physics Research A 520, 60 (2004).
[18] P. Egelhofer et al., Nucl. Instr. Meth. A 370, 26(1996).
[19] H.F. Beyer, Spectrochimica Acta Part B 59, 1355 (2004).
[20] D. Protic et al., IEEE Trans. Nucl. Sci. Vol. 48, 1048 (2001).
[21] D. Protic et al., IEEE Trans. Nucl. Sci., in print (2005).
[22] Th. Stöhlker et al., Nucl. Instr. Meth. B 205, 210 (2003).