Quantum Electrodynamics in Extreme Fields: Precision Spectroscopy of High-Z H-like Systems

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Abstract. In this review we address the topic of X-ray spectroscopic investigations of the ground-state transitions in the heaviest one-electron systems by using the intense beams of cooled heavy ions provided by the Experimental Storage Ring (ESR) at GSI Darmstadt. Such experiments on high-Z ions open up unique possibilities for the investigation of the quantum electrodynamical (QED) effects in the nonperturbative domain of extremely strong electromagnetic fields. Particular emphasis is given to the developments as well as to the current progress for the future experiments aiming for the sensitive tests of the higher-order bound-state QED effects. These include novel high-resolution detection systems: crystal spectrometers in combination with position-sensitive solid-state detectors and bolometers.

1 The Current Status of the Experimental and Theoretical Investigations

Hydrogen-like ions traditionally serve as an important testing ground for fundamental atomic structure theories and for investigation of relativistic and QED effects. Atomic hydrogen has provided the unique venue for the development, testing and establishment of the quantum mechanical and relativistic theories. Furthermore, the discovery by Lamb and Rutherford [1] of a small difference between the binding energies of the $2s_{1/2}$ and $2p_{1/2}$ states, known as the Lamb shift, has triggered the decisive developments in the formulation of the QED theory. For the light one-electron systems such as atomic hydrogen, the QED predictions are now well confirmed with extraordinary precision [2, 3]. On the other hand, the developments in efficient production and storing of the heaviest one- and few-electron systems provide a complementary way for testing our understanding of relativistic and quantum electrodynamic effects in the formerly not accessible domain of extremely strong fields. Furthermore, during the last few years significant progress took place in the theoretical studies of these systems, resulting in nonperturbative (without expansion in αZ,

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in contrast to the methods applied for the low-Z ions) calculations for high-Z hydrogen-like systems which do now comprise all second-order (in α) corrections [4, 5]. For such ions, the most direct experimental approach for the investigation of the effects of quantum electrodynamics in strong Coulomb fields is a precise determination of X-ray energies for transitions into the ground state of the ion. In particular, the Lyman-α transitions are used as they appear most intense and well resolved in the X-ray spectra. In these experiments the Lamb shift value is deduced from the measured transition energy by comparison with the Dirac energy eigenvalue for the 1s ground state of a point-like nucleus and the additional assumption that the binding energies of the excited states involved are known to high accuracy.

The Experimental Storage Ring (ESR) at GSI with its brilliant beams of cooled heavy ions has proven to provide unique conditions for precision investigations of high-Z fundamental atomic systems. Experimental studies at the ESR devoted to precise spectroscopy of X-ray transitions from bound or continuum states into the ground state of the heavy ion-electron systems have provided substantial improvements in accuracy over the last decade. In Fig. 1, this is shown for the example of the 1s Lamb shift in H-like uranium (U^{91+}). Here, an increase of precision by more than an order of magnitude over the last decade has been achieved. The most recent value (from 2005) has been obtained at the electron cooler device of the ESR by utilizing the deceleration capability of the ring in combination with the 0° geometry [6].

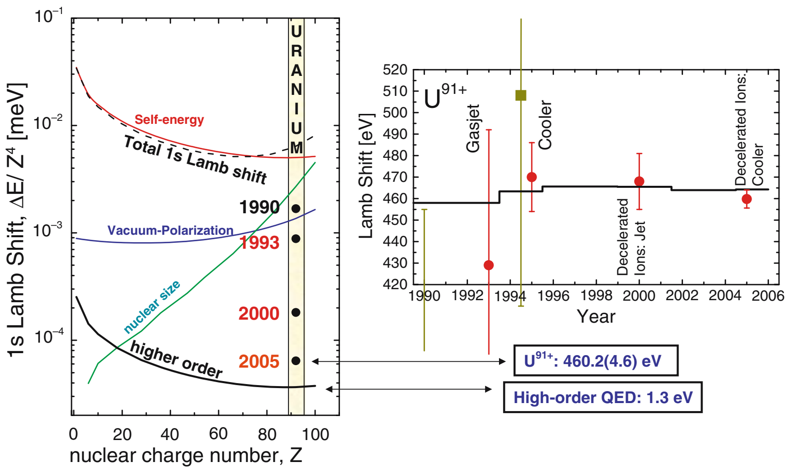

Fig. 1. Left side: Various individual contributions to the ground-state Lamb shift in H-like uranium together with the experimental accuracies achieved so far [6, 7, 8, 9]; **Right side**: Comparison between theoretical and experimental values for the 1s Lamb shift in H-like uranium. *Squares* show results obtained at the BEVALAC accelerator. *Circles* depict the values obtained at the ESR. The theory is represented by the *line*

Table 1. The ground-state Lamb shift for H-like uranium. All values are given in eV

Finite nuclear size	198.81
First order QED	266.45
Second order QED	–1.26(33)
Total theory [4, 5]	464.26±0.5
Experiment	460.2±4.6

The latest experimental result is presented in Table 1 in comparison with the most recent theoretical value. The latter includes all of the second-order (α^2) QED contributions whose evaluations have been completed very recently, following the work during the last decade (see [4, 5] and references therein). From the comparison, a good agreement between the theoretical prediction and the experimental value can be stated whereby the experimental result provides a test of the leading QED effects at the percent level.

2 Next Generation Spectroscopic Experiments on High-Z H-like Ions

The recent achievement of complete evaluation of all the second-order (α^2) QED effects opens up unique opportunities for probing higher-order QED effects in the most fundamental atomic system in the presence of strongest electromagnetic fields. Accordingly, the goal of the experiments is to achieve a precision which not only tests the higher-order contributions in αZ but also probes QED corrections which are beyond the one-photon exchange corrections, such as the two-photon exchange diagrams, i.e., α^2 contributions. These effects contribute on the level of about 1 eV (see Table 1). Therefore, for the next generation experiments devoted to the ground-state Lamb shift in high-Z H-like systems, a dedicated high-resolution X-ray crystal spectrometer (FOCAL) has been developed at GSI [10, 11, 12]. This development is complemented by progress in production of semi-conductor position-sensitive (two-dimensional) detectors [13] which are indispensable for the crystal-spectrometer-based precision X-ray spectroscopy. In addition, a different kind of high-resolution X-ray detection system, a X-ray calorimeter, has been developed at GSI and will be exploited in the future Lamb shift studies [14].

Very recently, a first experiment utilizing these devices has been conducted at the gasjet target of the ESR devoted to a measurement of the ground-state Lamb shift in H-like Pb. The setup used in the experiment is shown in Fig. 2. The bare Pb ions injected from the SIS into the ESR were brought to interact with a supersonic jet of krypton atoms. Here, the ions may capture an electron thus populating bound states of a hydrogen-like lead ion (Pb^{81+}). The ground-state binding energy and thus the Lamb shift can be directly derived from the centroid energy of the Lyman α_1 X-rays which can be obtained with high

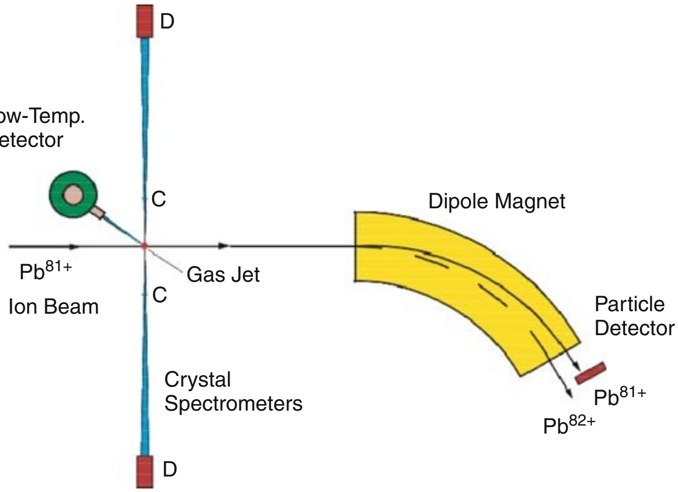

Fig. 2. The experimental arrangement used in the first beam-time dedicated to measure ground-state Lamb shift in H-like Pb exploiting high-resolution X-ray spectrometers in combination with position-sensitive Ge(i) detectors as well as the specially developed low-temperature microcalorimeter

accuracy from one hand by the spectrometer and the 2D-detector setup and from the other hand by the microcalorimeter. In the present experiment, two of the crystal spectrometers were aligned at 90° with respect to the beam direction in order to reduce uncertainties stemming from the relativistic Doppler transformation due to possible ion beam misalignment. Position-sensitive Germanium detectors were mounted behind both of the spectrometers for energy and time-resolved detection of Lyman X-rays deflected by the spectrometers.

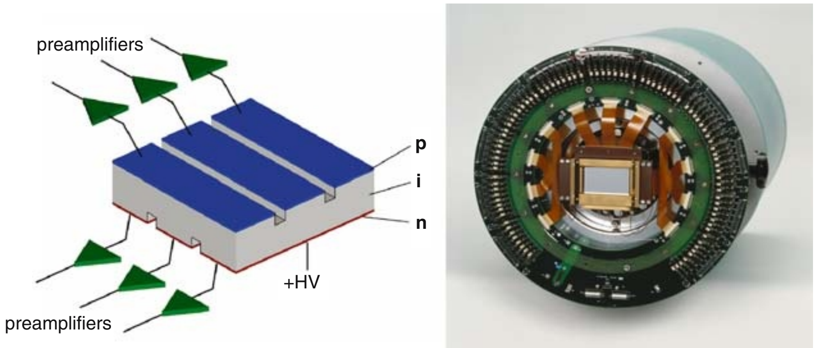

Fig. 3. Two-dimensional germanium X-ray detector developed at FZ Jülich [13]. The front contact (128 strips and a pitch of 250 m) and the rear contact (48 strips and a pitch of 1167 m) are realized by means of plasma etching

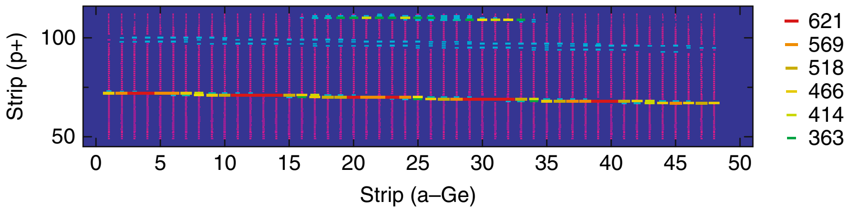

Fig. 4. Calibration line of the ^{169}Yb source projected on the position-sensitive detector mounted behind one of the spectrometers. For details see text

One of the detectors exploited in the experiment is shown in Fig. 3. The calorimeter was mounted at 145° with respect to the beam direction.

In Fig. 4 we show an X-ray image of the ^{169}Yb source as recorded by a 2D position-sensitive Germanium detector mounted behind one of the spectrometers. The intense line corresponds to the ^{169}Yb γ photons with an energy of 63.121 keV. This line is used for calibration purposes, and energies of the Lyman X-rays expected at about 60.98 and 63.13 keV in the laboratory frame will be determined relative to it. In addition, in Fig. 5 we present a preliminary X-ray spectrum recorded by the calorimeter for a run with H-like uranium. Here, the Lyman α_1, Lyman α_2 as well as Lyman β lines are clearly identified along with 59.8 keV γ-line of the ^{241}Am source used for calibration. The data analysis is currently being conducted.

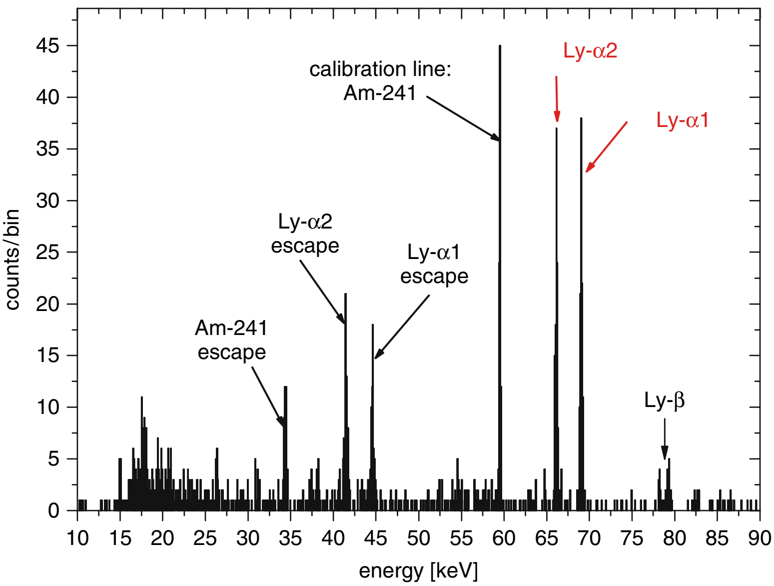

Fig. 5. The preliminary X-ray spectrum of the H-like uranium recorded by the calorimeter mounted at the 145° observation angle with respect to the beam axis

3 Conclusions

The current status and recent developments in experimental investigations of the strong field QED effects in heaviest hydrogen-like ions are reviewed. Comparison of the most recent experimental results with the state-of-the-art theoretical values shows a good agreement and provides test of the dominant QED contributions on a percent level. In order to reach the sensitivity needed for testing the higher-order QED contributions the next-generation spectroscopic experiments will exploit the high-resolution X-ray detection systems, the specially developed FOCAL crystal spectrometers in combination with the state-of-the-art position-sensitive germanium detectors and the low-temperature calorimeters. The beam-time utilizing both of these devices has already been conducted providing the first high-resolution spectra for ground-state transitions in hydrogen-like lead. From the current status of the data evaluation, we can conclude that the achievement of the envisioned accuracy will require improvements in the detection setup and thus reduction of various systematic uncertainties as well as developments for the digital signal processing which are currently being conducted [15].

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References

1. W. E. Lamb and R. C. Retherford: Phys. Rev. **72**, 241 (1947). 157
2. M. Niering et al.: Phys. Rev. Lett. **84**, 5496 (2000). 157
3. B. de Beauvoir et al.: European Physical Journal D**12**, 61 (2000). 157
4. V. A. Yerokhin et al.: Phys. Rev. A**64**, 062507 (2001). 158, 159
5. V. A. Yerokhin et al.: Phys. Rev. Lett. **91**, 073001, (2003). 158, 159
6. A. Gumberidze, Th. Stöhlker, D. Banas, K. Beckert, P. Beller, et al.: Phys. Rev. Lett. **94**, 223001, (2005). 158
7. Th. Stöhlker et al.: Phys. Rev. Lett. **71**, 2184 (1993). 158
8. H. F. Beyer et al.: Z. Phys. D**35**, 169 (1995). 158
9. Th. Stöhlker et al.: Phys. Rev. Lett. **85**, 3109 (2000). 158
10. H. F. Beyer et al.: NIM A**400**, 137, (1997). 159
11. H. F. Beyer, Th. Stöhlker, D. Banas, D. Liesen, D. Protic, K. Beckert, P. Beller, J. Bojowald, F. Bosch, E. Forster, B. Franzke, A. Gumberidze, S. Hagmann, J. Hoszowska, P. Indelicato, O. Klepper, H.-J. Kluge, S. König, C. Kozhuharov, X. Ma, B. Manil, I. Mohos, A. Orsic-Muthig, F. Nolden, U. Popp, A. Simionovici, D. Sierpowski, U. Spillmann, Z. Stachura, M. Steck, S. Tachenov, M. Trassinelli, A. Warczak, O. Wehrhan and E. Ziegler: Spectrochim. Acta, Part B **59**, 1535 (2004). 159

12. S. Chatterjee et al.: NIM B**245**, 67 (2006). 159
13. D. Protic et al.: IEEE Transactions on Nuclear Science **52**, 3194 (2005). 159, 160
14. A. Bleile et al.: NIM B**444**, 488 (2000). 159
15. M. Kajetanowicz, et al.: Radiation Physics and Chemistry **75**, 1972 (2006). 162