Marian Smoluchowski-Emil Warburg-Prize

# Heavy-Ion Atom Collisions

## Atomic Physics under Extreme Conditions

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**One of the actual frontiers in physics is the study of matter exposed to extremely strong electromagnetic fields. In particular, highly charged ions form unique laboratories where such conditions are largely fulfilled. These species can be stored in the form of intense beams and used in collision experiments. For such investigations, precise spectroscopy of photons emitted in collisions of heavy ions with atoms is required. This emission gives details of the specific electronic transition mechanisms operating in strong fields as well as information on electronic structure of the exotic atomic systems (e. g. H-like uranium). Among others, details concerning photoionization of very heavy atoms can be revealed in such experiments when observing radiative electron capture (REC). Moreover, accurate measurements of electron binding energies are very well suited to deduce characteristic quantum electrodynamics (QED) phenomena in strong fields. QED, the basis and cornerstone of all present field theories, is the best confirmed theory in physics, however, precise tests in the strong-field limit are still pending.**

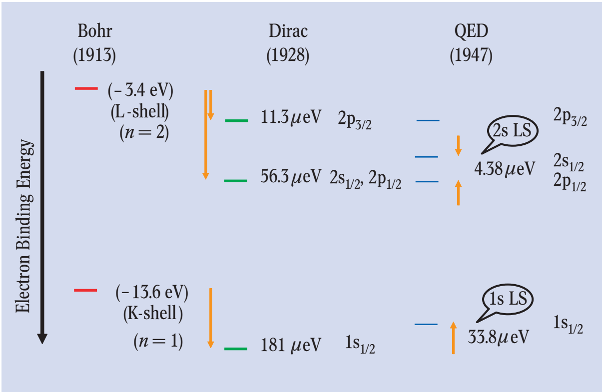


**Fig. 1:** Development of the description of the level structure in the hydrogen atom. The innermost levels, concerning L and K shell discussed in the text, are shown in the picture.

The simplest atom in nature, the hydrogen atom, played a crucial role in forming the base of our knowledge concerning quantum structure of matter. The first quasi-quantum model of the hydrogen atom, proposed by Bohr, was able to explain gross features of the atomic spectra only, and induced a rapid development of non-relativistic quantum mechanics. In the hydrogen atom an electron in the ground state probes a moderate electric Coulomb field of about $2\cdot 10^{10}$ V/cm with a classical orbital velocity of $c\cdot\alpha$ (c: velocity of light, $\alpha \approx 1/137$: fine structure constant) which appeared at first to be still beyond the relativistic regime. However, growing experimental accuracy triggered the next step of the development of the theory – the relativistic quantum mechanics of Dirac with the concept of spin included. Here, very tiny level shifts and splittings of the atomic levels (Fig. 1), caused by relativistic effects, were confirmed experimentally. In particular, it was observed that the spin-orbit interaction with its pure relativistic quantum-mechanical nature is responsible for the splitting of energy levels and for the degeneracy of the levels with the same total angular momentum quantum number $j$ (compare e. g. the L-shell structure shown in Fig. 1). Finally, observations done in 1947 by Lamb and Retherford of the $2s_{1/2}$ energy level shift – the so called Lamb shift (Fig. 1) – started the creation of quantum electrodynamics (QED), a joint work of Feynman, Schwinger and Tomonaga. According to QED, the main contributions to the Lamb shift are given by the electron self-energy (SE) and vacuum-polarization (VP) corrections.

Originally, the term *Lamb shift* was used for the $2s_{1/2} - 2p_{1/2}$ level splitting in atomic hydrogen only. Nowadays, this term is used for the energy shift of any level in atoms or ions, caused by QED effects. In particular, the Lamb shift for one-electron systems is defined as the difference between the experimental level energy and the energy eigenvalue calculated with the Dirac equation for a point nucleus, disregarding all the QED contributions and nuclear finite size (FS) corrections. So far, predictions of the bound-state QED in weak fields, e. g. in hydrogen, were confirmed with a very high accuracy. For example, the 1s Lamb shift in hydrogen (see Fig. 1) was measured with a precision close to $10^{-4}$ % which provides one of the rigorous verifications of QED [1].

However, the situation changes dramatically when matter (elec-

### Kompakt

- Highly charged (high-Z) ions form unique laboratories to study matter exposed to extremely strong electromagnetic fields.
- The innermost electrons in high-Z ions probe extremely strong fields thus giving rise to crucial tests of QED of bound states (Lamb shift).
- The investigation of relativistic effects in collisions of high-Z ions provides a deeper understanding of photoionization of the innermost shells close to the ionization limit.

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trons) is exposed to an extremely strong Coulomb field. Few-electron ions with $Z{\cdot}\alpha \to 1$ ($Z$: atomic number of a highly charged ion) form unique laboratories where such conditions are largely fulfilled. For example, in an H-like uranium ion ($U^{91+}$) with $Z = 92$, the K-shell electron probes an electric Coulomb field of about $2{\cdot}10^{16}$ V/cm which is roughly six orders of magnitude larger than in the hydrogen atom. This strong field provides an exceptional opportunity to test QED in a regime where an ordinary perturbation treatment of QED, with $Z{\cdot}\alpha$ as the expansion parameter, is no longer a suitable tool. Instead, for high-$Z$ systems, where $Z{\cdot}\alpha$ approaches unity, the calculations have to be performed by taking into account all orders of $Z{\cdot}\alpha$. Thus, in very heavy atomic systems, higher order QED contributions to the Lamb shift can be effectively tested. The Lamb shift is largest for the ground state and strongly increases with $Z$ ($\sim Z^4$). Therefore, the ground state (1s) Lamb shift in $U^{91+}$ is the best experimental target. The structure of $U^{91+}$ is shown in Fig. 2. The 1s Lamb shift can be obtained by subtracting the calculated Dirac energy value from the precisely measured energy of the Ly-$\alpha_1$ transition (comp. Fig. 2). One has to note that the p states are practically not affected by the Lamb shift.

In recent years, considerable progress has been made in the precision X-ray spectroscopy of highly charged, few-electron ions, giving access to the subtle atomic structure contributions induced by QED. The aim of the present paper is to review the experimental achievements in the field and to compare the results with theoretical predictions. In particular, Lamb-shift measurements, exploiting different spectroscopy techniques in one- and two-electron ions, will be discussed.

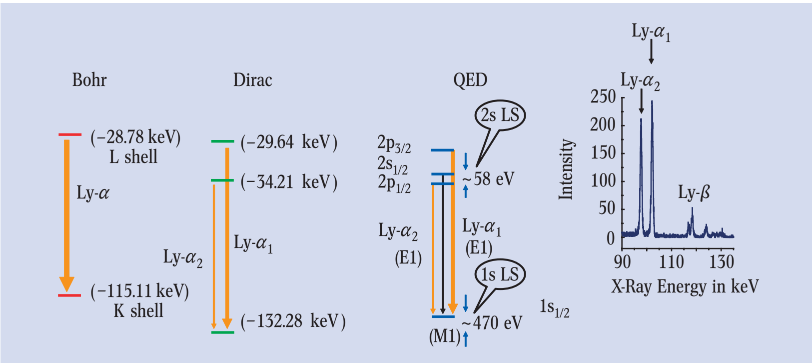


**Fig. 2:**
**Inner shell structure of H-like uranium ($U^{91+}$). Characteristic X-ray transitions discussed in the text are marked. The right part of the picture shows a fragment of the typical spectrum observed in experiments at the ESR storage ring [7]. This spectrum is taken with a standard Ge(i) detector, so the M1 transition marked in the picture is practically a part of the Ly-$\alpha_2$ line.**

Besides the pure QED aspects, relativistic effects are strongly present in high-$Z$ ions and have to be considered as well. They influence both the atomic structure and the dynamics of atomic processes observed in experiments. In order to show the influence of relativistic effects on the collision dynamics, a prominent example – radiative electron capture (REC) – will be presented, including the most recent experimental results. Moreover, manifestation of relativistic effects in the polarization of REC lines, measured recently for the first time, will be presented. In addition, relativistic effects in the formation and alignment of the excited states will be discussed. The decay of these excited states is characterized by a strong enhancement of higher multipole transitions.

## Lamb-shift measurements

As mentioned above, the QED corrections to the electron binding energy in atomic systems vary approximately proportional to $Z^4/n^3$, where $n$ is the principal quantum number. Since the level energies scale with $Z^2/n^2$, the relative level shift due to QED effects is largest for the ground-state electrons in high-$Z$ atoms or ions. Therefore, H-like heavy ions form the best and simplest objects for corresponding QED tests in strong fields. Experimentally, the Lamb shift of the ground state in high-Z, H-like ions is mostly inferred from measurements of the energy of the Ly-$\alpha_1$ line ($2p_{3/2} \to 1s_{1/2}$ transition, Fig. 2).

**Table 1: Recent values of the ground state Lamb shift in H-like uranium (in eV). The numbers in parentheses give the corresponding accuracy (in eV).**

| Experiment | Theory |
|---|---|
| 470 (16); [6] | **463.95 (0.50);** [5] |
| 468 (13); [7] | accuracy stable since about 5 years |
| **459.8 (4.8);** [8] | |

For ions that have more than one electron, screening effects and electron-electron correlations have to be considered. However, due to the strong central force, the influence of the electron-electron interaction on the atomic structure gets weaker with increasing $Z$. Hence, the structure of very heavy He-like ions reminds – beyond the level doubling – of that for H-like ions.

### *Ground state Lamb shift in heavy H-like ions*

A considerable improvement in the accuracy of measurements concerning the ground state Lamb shift (in the heaviest H-like elements) was introduced at the beginning of the last decade by the era of heavy-ion storage rings, in particular, by the ESR storage ring of the GSI in Darmstadt [2]. At the beginning of the previous decade, only two experiments on H-like, high-$Z$ ions were reported. In those experiments, the corresponding X-rays were registered with standard Ge(i) detectors. The 1s Lamb shift was measured only to a precision of 18 % for xenon and of 25 % for uranium. Thus, those results were not able to provide a stringent test of QED calculations in strong fields which, nowadays, have an accuracy in the range of 0.2 % – 0.5 % for $U^{91+}$ [3–5].

Recent progress in the production and cooling of intense beams of fully-stripped uranium at the synchrotron/storage ring facility (SIS/ESR) at GSI in Darmstadt, allows for an excellent precision in the spectroscopy of these ions after catching an electron from the electron cooler [6] or from the gas-jet target [7] (Fig. 3). Although the ESR provides brilliant, mono-energetic beams, the main problem encountered is still caused by the uncertainties introduced by the Doppler shift, because the X-rays are emitted by ions moving with relativistic velocities. Besides statistics, uncertainties due to Doppler shift corrections limit the final accuracy of the X-ray energy in the emitter frame. However, a significant reduction of these uncertainties can be achieved by exploiting 0° observation geometry (measurements at the electron cooler) and/or a deceleration of the ion beam. Very recently, these two techniques were combined at the ESR and a new, more precise value of the 1s Lamb shift was determined [8]. In Table 1, results of the ESR measurements are compared with theoretical predictions. These measurements of the ground state Lamb shift established a new accuracy standard, which is about one order of magnitude better than the one obtained previously. The last experiment achieved an accuracy of about 5 eV [8]. This gives a modest improvement by a factor of about two over the first ESR result (see Table 1), obtained in the electron-cooler experiment [6]. However, the significance of this measurement is that it demonstrates a procedure for handling the problems with Doppler corrections via active deceleration of the ion beam in the storage ring. This procedure will ultimately allow for experiments with a precision at the level of about 1 eV, which is already very close to the precision of the corresponding calculations, i. e., on the level of the second-order QED corrections [5]. Simultaneously, work is in progress, that should significantly improve the accuracy of the future experiments (see conclusions).

### *Two-electron contributions to the ground-state energy in He-like ions*

Helium-like ions are the simplest multi-electron systems. Therefore, they are most suitable objects for testing the two-electron contribution to the ground-state binding energy. This contribution includes, in addition to the dominant Coulomb term, effects from electron correlation, the Breit interaction, screening of the Lamb shift, and higher-order radiative corrections. Recent progress in the theory of heavy two-electron ions [9] has been a challenge for experiments. In particular, these two-electron contributions were studied in the first experiment at the Super-Electron-Beam-Ion-Trap (Super-EBIT) in Livermore [10]. There, radiative transitions of free and fast-moving electrons into the vacant K-shell of bare and H-like ions (radiative recombination, RR) have been exploited. A schematic explanation of this experiment is shown in Fig. 4. Since both the bare and the H-like ions are simultaneously trapped in the EBIT and interact with the same electron beam, the difference in the photon energies, $\Delta E$ (Fig. 4), between the energy of radiative transitions into bare and H-like ions does not depend on the electron beam energy. This difference gives exactly the two-electron contribution to the ground-state binding energy in He-like ions. This way, even contributions related to the nuclear structure are canceled out.

The heaviest system investigated at the Super-EBIT was Bi ($Z=83$). That experiment provided results with an accuracy at the threshold of sensitivity to higher-order QED effects (two-electron Lamb shift) [10]. However, more accurate EBIT experiments, with even higher-$Z$ ions, suffered from counting statistics, because the production efficiency of bare high-$Z$ ions in the EBIT is rather low.

Very recently, this technique was applied at the electron cooler device of the ESR storage ring at the GSI in Darmstadt for He-like and H-like U-ions [11]. In this case, $E_{\text{Kin}} \approx 0$ (comp. Fig. 4). The key advantage of this experiment is a relative measurement of radiative recombination (RR) into the K shell of initially bare and H-like uranium. Therefore, during the experiment, several changes between the two charge states were executed. Decelerated ions with an energy of 43 MeV/u were used, which helped to keep all the uncertainties associated with Doppler corrections as low as possible. Moreover, at this low beam energy, the

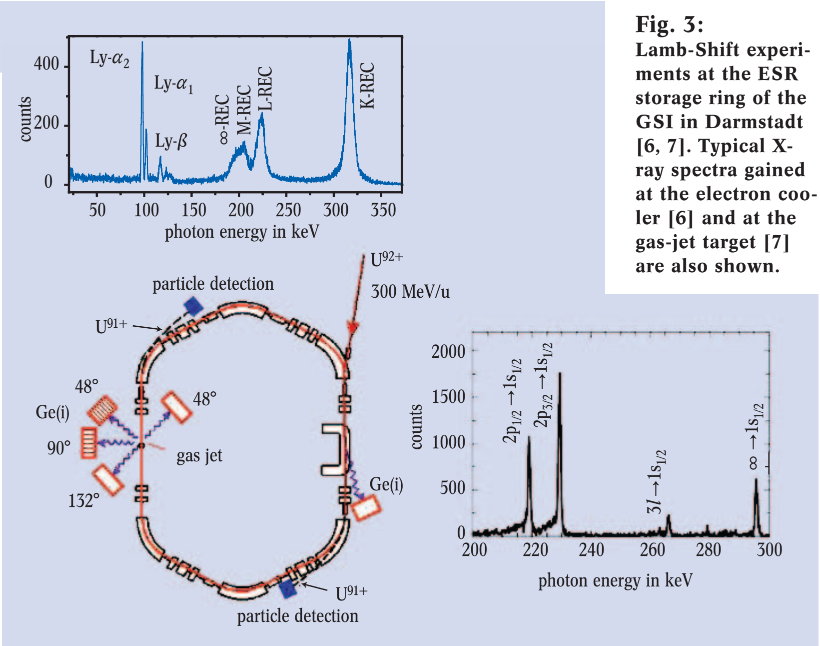


**Fig. 3: Lamb-Shift experiments at the ESR storage ring of the GSI in Darmstadt [6, 7]. Typical X-ray spectra gained at the electron cooler [6] and at the gas-jet target [7] are also shown.**

bremsstrahlung intensity caused by the cooler electrons was strongly reduced due to the relatively small cooler voltage of 27 kV. As mentioned above, the goal of the experiment was to measure, as precisely as possible, the energy separation between the two K-RR lines (see Fig. 5). Although the intrinsic resolution of the Ge(i) detector, for the energy range of relevance, was about 750 eV, a small energy difference between two close-spaced lines can be determined with a high accuracy. In order to take advantage of that, a projectile energy of exactly 43.59 MeV/u was chosen. At this particular beam energy, the Doppler shift for the lines registered at 0° observation angle, allowed the 177.2 keV $\gamma$-line of $^{169}$Yb (calibration line) to be positioned just between the K-RR lines for He-like and H-like U-ions (Fig. 5). During the experiment, the calibration source was regularly placed in front of the detector in order to gain control over possible energy drifts. Finally, for $\Delta E$, a value of 2248 ± 9 eV was obtained (Table 2). The estimated accuracy of about 9 eV is on the level of the radiative two-electron QED corrections (7.1 eV, [9]).

**Table 2: Two-electron contribution to the ground state energy in the He-like uranium (in eV). The number in parentheses gives the corresponding experimental accuracy (see text).**

| Experiment [11] | Theory [9] | | | | |
|---|---|---|---|---|---|
| | Total | QED | | | non QED |
| | | non radiative QED | radiative QED | | |
| | | | 2e SE | 2e VP | |
| **2248 (9)** | **2246.0** | 1.3 | – 9.7 | 2.6 | 2251.8 |

## Relativistic collisions

In fast (relativistic) collisions of highly charged heavy ions with atoms, i. e., in the presence of strong fields, both the fully relativistic wavefunctions and the full, relativistic interaction between the collision partners have to be taken into account. In particular, this means that, instead of the Coulomb interaction, the full Liénard-Wiechert potential and the full multipole expansion of the matrix elements involved have to be applied [12]. In many cases, experimental studies of relativistic atomic collisions reveal completely new effects, never observed in the non-relativistic collision regime, which go beyond the commonly used standard description - the ordinary dipole approximation.

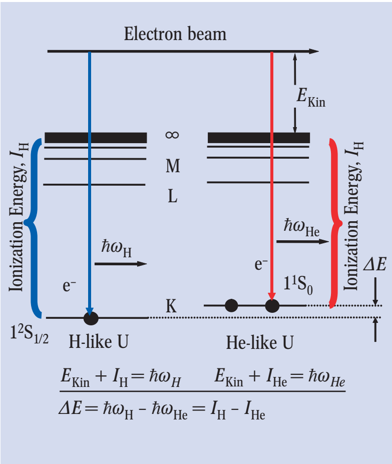


**Fig. 4:**
**The concept of applying radiative recombination (RR) of heavy ions with electron beams for measurements of the two-electron QED contribution at Super-EBIT [10] and at the storage ring cooler device [11].**

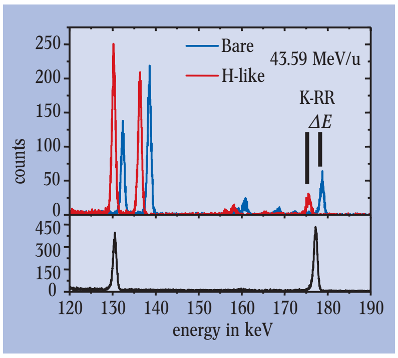


**Fig. 5:**
**Measurement of the two-electron contribution ($\Delta E$) to the ground-state energy in He-like ions. Spectra of H- and He-like uranium, after electron capture into bare and H-like ions, respectively, obtained at the electron cooler of the ESR, are shown close to 0° observation angle, [11]. Below, the crucial calibration lines of $^{169}$Yb at 130.5 keV and 177.2 keV (discussed in the text) are displayed.**

### *Radiative electron capture – the time reversal of photoionization*

Radiative electron capture (REC) is the only relevant charge-changing process in fast collisions of bare high-$Z$ projectiles with low-$Z$ target atoms. There, within the impulse approximation, a quasi-free target electron is captured into the projectile and the released energy is emitted as a photon (Fig. 6). First observations of REC were made in the early seventies. A survey on the field can be found in [12].

As, in addition, REC can be considered as the time-reversed atomic photoeffect – one of the most fundamental effects in quantum physics – it has been proposed to apply REC to the investigation of the photoeffect in the domain of high-$Z$ ions (Fig. 6) [13]. Significant progress in understanding the process was made in the nineties with the introduction of storage rings. Here, the leading role of the ESR storage ring of the GSI in Darmstadt, the only storage ring equipped with a gas-jet target, should be emphasized. At the gas-jet target, photoionization can be studied, by means of REC, under clean single-collision conditions. In this case, no corrections due to photoelectron scattering occurring in solid targets are required, in contrast to direct photoionization measurements. Experiments, in accordance with theory, show unambiguously that even at moderately relativistic collision velocities (up to about 1 GeV/u), total K-REC cross sections are still well described by a simple non-relativistic dipole approximation [14] (Fig. 6). This uniqueness of all the REC transitions into s states is mostly due to an accidental cancellation among the various manifestations of relativistic, retardation, and multipole effects. Strong departure from this behavior, predicted by theory [12], was only observed in the highly relativistic collision regime [15] (Fig. 6).

More detailed information on REC was obtained from differential cross sections. In particular, studies of the angular distribution of the REC radiation revealed, for the first time, the importance of spin-flip transitions caused by the magnetic interaction. This interaction produces a forward-backward asymmetry of the REC emission pattern in the laboratory frame, manifested by the enhanced photon emission at 0° [13]. Moreover, these measurements established that, even for the highest nuclear charges, a cancellation between retardation and Lorentz transformation occurs, known from the measurements with lighter projectiles.

Very recently, a deceleration technique was introduced into REC study to investigate, for the first time, angular distributions of photoelectrons from a high-$Z$ ion in the low-energy regime, i. e. close to the ionization threshold. This measurement revealed the persistence of spin-flip transitions, which continue to be important in the vicinity of the ionization threshold, in a way similar to the high-energy regime. In addition, it has been shown that, by means of L-REC, the photoionization can be studied even for the excited states in high-$Z$ H-like ions. In this case, the fine-structure components of the L-REC line can be resolved, which illustrates an additional benefit of the deceleration technique.

### *Angular distribution of the* Ly-$\alpha_1$ *radiation – alignment of the* $2p_{3/2}$ *state populated via L-REC.*

The angular distribution of the Ly-$\alpha_1$ radiation, following radiative electron capture from a gaseous target into the $2p_{3/2}$ level of H-like uranium, allows us, under clean experimental conditions, to obtain magnetic-substate sensitive information on the REC process (alignment). The first experiments concerning angular distribution of Ly-$\alpha_1$ radiation, obtained in relativistic collisions of high-$Z$ ions with light target atoms, show strong emission anisotropy [16]. The angular emission characteristics of this radiation is simply given by $W(\theta) \propto 1 + \beta_A[1 + 3/2 \sin^2\theta]$, where $\theta$ denotes the emission angle in the emitter frame and $\beta_A$ is the anisotropy coefficient. For the considered Ly-$\alpha_1$ transition, $\beta_A = 1/2\, A_2$, where $A_2$ describes alignment, i. e., the non-statistical population of $|m_j| = 1/2$ and $|m_j| = 3/2$ magnetic substates of the $2p_{3/2}$ level. The emission characteristics, given above, includes the contribution from the

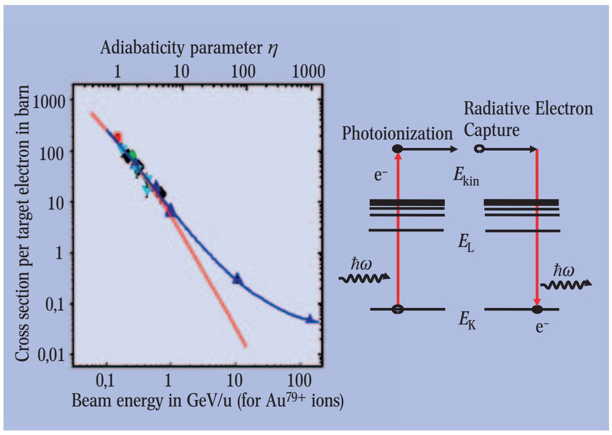


**Fig. 6:**
**Photoionization and REC are time-inversed processes (right part of the picture). Total K-REC cross-section scales, within a simple dipole approximation [14], with the adiabaticity parameter $\eta$ [13, 14] even at relativistic velocities. Departure from this behavior was observed at ultra-relativistic energies [15] in accordance with theory (for $\eta > 100$) [12].**

electric-dipole (E1) transition, whereas the weak magnetic-quadrupole component (M2) is neglected.

Note, that the Ly-$\alpha_2$ radiation must follow an isotropic emission pattern in the emitter frame. Therefore, in order to obtain alignment of the $2p_{3/2}$ level, which would be almost unaffected by systematic experimental uncertainties, one has to normalize the Ly-$\alpha_1$ line intensity to the intensity of the Ly-$\alpha_2$ transition. An example of the Ly-$\alpha_1$ and Ly-$\alpha_2$ intensity ratio is plotted in Fig. 7 as a function of the observation angle in the laboratory frame.

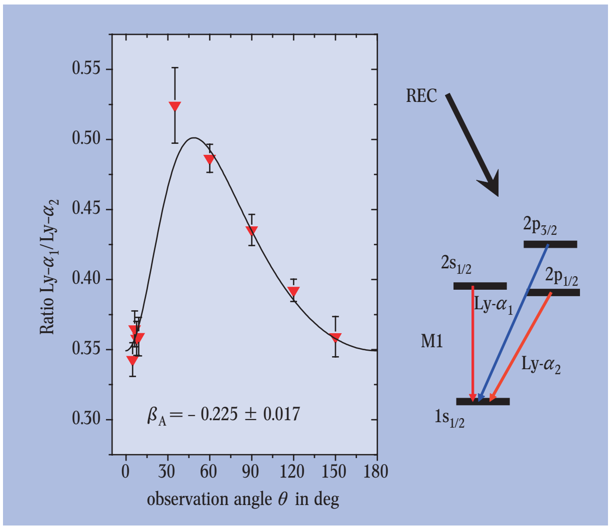


**Fig. 7:**
**Angular distribution of Ly-$\alpha_1$ due to alignment of $2p_{3/2}$ state populated by REC [16].**

The measured angular distribution of the Ly-$\alpha_1$ radiation yields significant negative values of the alignment parameter. A simple dipole approximation, including only the E1 transition between $2p_{3/2}$ and $1s_{1/2}$ levels, is not able to describe the experimental anisotropy values. In order to remove this variance, an interference between the E1 and M2 transition amplitudes was proposed. In this way, the much weaker M2 transition gives rise to a remarkable modification of the angular distribution of the photons emitted from the REC aligned levels in high-$Z$ ions.

***Polarization studies for Radiative Electron Capture into high-Z ions.***

Recently, polarization of photons produced by radiative electron capture has attracted particular interest [17]. However, up to now, no such data has been available for the high-$Z$ systems. This field can be addressed experimentally by a new generation of segmented germanium detectors which offer energy as well as position resolution. In such detectors, polarization measurements can be performed by exploiting the relation between the differential Compton scattering cross-section and the linear polarization of the primary photon as predicted by the Klein-Nishina formula. For bare uranium at an energy of 400 MeV/u a very first polarization study for REC into the K shell has recently been performed at the jet-target of the storage ring ESR [18]. For this purpose a planar germanium pixel detector was used, mounted at observation angles of 90° and 60°. In the experiment, the photon polarization was obtained by a coincident registration of events occurring simultaneously in two pixels. One pixel registered the Compton recoil electron and the other, the outgoing scattered photon, whereby the sum energy was constant and referred to the K-REC photon energy. The anisotropy observed in the angular distribution points to a strong polarization of the K-REC radiation in the reaction plane. As shown in Fig. 8, the final results are in good agreement with the fully-relativistic calculation given in [19].

## Conclusions

In high-$Z$ ions, the innermost electrons probe extremely strong fields, thus giving rise to crucial tests of QED of bound states. For one-electron systems the fundamental QED contributions can be tested, so far, on a 3 % level. In the near future, the development of crystal spectrometers and micro-strip germanium detectors [20] may improve the experimental uncertainty by an order of magnitude, which should be sufficient to compete with the accuracy of calculations.

Comparison of H-like and He-like systems gives direct access to the higher-order QED contributions to the ground state of He-like ions. Here, further progress is expected in the near future as well.

Relativistic effects in collisions of high-$Z$ ions have been discussed for a few selected cases. In particular, spin-flip transitions observed in REC form an essential part of the photon-electron interaction responsible for REC photon emission close to 0°. Application of decelerated beams will allow a deeper understanding of photoionization (time-inversed REC) of the innermost shells close to the ionization limit.

The measured angular distribution of the Ly-$\alpha_1$ radiation following REC into the $2p_{3/2}$ level of high-$Z$ projectiles at relativistic energies yields a significant negative value of the alignment parameter. In this case REC populates mostly the ±1/2 magnetic sublevels (by about 75 %), which implies that the Ly-$\alpha_1$ radiation is strongly linearly polarized (about 40 %). The corresponding direct polarization measurements, even for highly energetic K-REC photons, are already in progress at the ESR in Darmstadt.

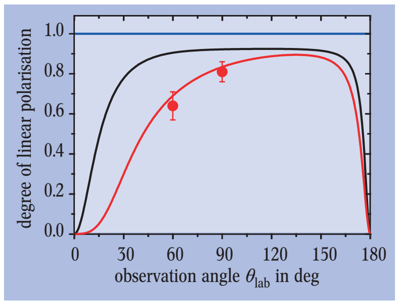


**Fig. 8:**
**Comparison of the measured polarization of K-REC photons [18] with calculations. Theoretical results, concerning exact relativistic treatment for 20 MeV/u (black) and 400 MeV/u (red), are plotted according to [19]. The blue line shows the result of the non-relativistic dipole approximation.**

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**References**

[1] *S. Bourzeix, B. de Beauvoir, F. Nez, M. D. Plimmer, F. de Tomasi, L. Julien*, and *F. Biraben*, Phys. Rev. Lett. **76**, 384 (1996)
[2] *P. H. Mokler* and *Th. Stoehlker*, Adv. Atom. Mol. Opt. Phys. **37**, 297 (1996)
[3] *T. Beier, P. J. Mohr, H. Persson, G. Plunien, M. Greiner*, and *G. Soff*, Phys. Lett. **A236**, 329 (1997)
[4] *I. Lindgren*, Phys. Scr. **T80**, 133 (1999)
[5] *V. A. Yerokhin* and *V. M. Shabayev*, Phys. Rev. **A64**, 062507 (2001)

[6] *H. F. Beyer, G. Menzel, D. Liesen, A. Gallus, F. Bosch, R. Deslattes, P. Indelicato, Th. Stoehlker, O. Klepper, R. Moshammer* et al., Z. Phys. **D35**, 169 (1995)

[7] *Th. Stoehlker, P. H. Mokler, F. Bosch, R. W. Dunford, F. Franzke, O. Klepper, C. Kozhuharov, T. Ludziejewski, F. Nolden, H. Reich* et al., Phys. Rev. Lett. **85**, 3109 (2000)

[8] *A. Gumberidze, Th. Stoehlker, D. Banaś, G. Bednarz, H.F. Beyer, F. Bosch, X. Cai, S. Hagmann, O. Klepper, C. Kozhuharov, D. Liesen, X. Ma, P.H. Mokler, A. Oršić-Muthig, D. Sierpowski, Z. Stachura, M. Steck, S. Tashenov, S. Toleikis, A. Warczak,* and *Y. Zou*, GSI Scientific Report 2003, p. 99

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

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

[11] *A. Gumberidze, Th. Stoehlker, D. Banaś, K. Beckert, P. Beller, H. F. Beyer, F. Bosch, X. Cai, S. Hagmann, C. Kozhuharov, D. Liesen, F. Nolden, X. Ma, P. H. Mokler, A. Oršić-Muthig, M. Steck, D. Sierpowski, S. Tashenov, A. Warczak*, and *Y. Zou*, Phys. Rev. Lett. **92**, 203004 (2004)

[12] *J. Eichler, W. E. Meyerhof*, Relativistic atomic collisions, Academic Press, San Diego (1995)

[13] *Th. Stoehlker, P. H. Mokler, C. Kozhuharov,* and *A. Warczak*, Comm. At. Mol. Phys. **33**, 271 (1997)

[14] *M. Stobbe*, Ann. Phys. (Leipzig) **7**, 661 (1930)

[15] *H. F. Krause, C. R. Vane, S. Datz, P. Grafstroem, H. Knudsen, C. Scheidenberger*, and *R. Schuch*, Phys. Rev. Lett. **80**, 1190 (1998)

[16] *Th. Stoehlker, F. Bosch, A. Gallus, C. Kozhuharov, G. Menzel, P. H. Mokler, H. T. Prinz, J. Eichler, A. Ichihara, T. Shirai* et al, Phys. Rev. Lett. **79**, 3270 (1997)

[17] *A. Surzhykov, S. Fritsche*, and *Th. Stoehlker*, Phys. Lett. **A289**, 213 ( 2001)

[18] *S. Tachenov, Th. Stoehlker, D. Banaś, H.F. Beyer, S. Fritsche, A. Gumberidze, S. Hagmann, C. Kozhuharov, Th. Krings, X. Ma, A. Oršić-Muthig, D. Protić, D. Sierpowski, U. Spilmann, A. Surzhykov,* and *A. Warczak*, GSI Scientific Report 2003, p. 107

[19] *A. Surzhykov, S. Fritzsche, Th. Stöhlker,* and *S. Tachenov*, Phys. Rev. **A68**, (2003)

[20] *H. F. Beyer, Th. Stöhlker, D. Banaś, D. Liesen, D. Protić, K. Beckert, P. Beller, J.Bojowald, F. Bosch, E. Förster* et al., Spectrochimica Acta Part **B59**, 1535 (2004)


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## The Author

**Andrzej Warczak** (right, with the president of the Polish Physical Society, Maciej Kolwas) studied Physics at the Jagiellonian University of Krakau where he also obtainded his Ph.D. in 1978 and his postdoctoral lecture qualification in 1986. Since 2000 he is extraordinary professor for physics at the University of Krakau. Over the years, Andrzej Warczak visited the Gesellschaft für Schwerionenforschung in Darmstadt for several research periods and established a close cooperation between Poland and Germany. His main concern is the physics of heavy ions, particularly the spectroscopy and dynamics of highly charged heavy ions.