15th Topical Workshop of the

Stored Particles Atomic Physics Research Collaboration

University NOVA of Lisbon, Portugal

LOCAL ORGANIZING COMMITTEE

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Workshop Program

Friday, September 7th

Time			Duration
Opening / Welcome and Status Session			
15h00	**Registration**		**30`**
15h30	**Welcome**	**Jose Paulo Santos** UNL	**10+5`**
15h45	**GSI/FAIR**	**Thomas Stöhlker** HI Jena, GSI, Univ. Jena	**15+5`**
16h05	**SPARC**	**Reinhold Schuch** Univ. Stockholm / GSI	**15+5`**
16h25	**Status of the ESR**	**Markus Steck** GSI	**20`+5`**
16h50	**Status of the CRYRING**	**Michael Lestinsky** GSI	**20`+5`**
17h15	**Status of the HITRAP**	**Wolfgang Quint** GSI	**20`+5`**
17h40	**Status of APPA-Cave**	**Angela Bräuning-Demian** GSI/FAIR, Darmstadt	**15`+5`**
18h00	**Reception**		

Saturday, September 8th

Time			Duration
Status of GSI and FAIR Facilities			
9h30	**Status of the SIS100 / Laser cooling**	**Danyal Winters** GSI, Darmstadt	15`+5`
9h50	**Status of the HESR**	**Anton Kalinin** GSI, Darmstadt	15`+5`
10h10	**Status of the EBITs**	**Serge Trotsenko** GSI /HI Jena	15`+5`
10h30	**APPA R&D – BMBF collaborative research in Germany**	**Stefan Schippers** Univ. Giessen	15`+5`
10h50	**Coffee Break**		
SPARC Instrumentation / recently submitted TDRs			
11h20	**CRYRING Internal Jet Target**	**Nikolaos Petridis** GSI Darmstadt	15'+5'
11h40	**In-ring Spectrometer for Nuclear Reaction Studies at CRYRING**	**Carlo Bruno** Univ. of Edinburgh	15'+5'
12h00	**Cold Target Recoil Ion Momentum Spectrometer for CRYRING**	**Markus Schöffler** Univ. of Frankfurt	15'+5'
12h20	**Lunch**		
International Landscape: Atomic Physics Activities Related to SPARC			
14h00	**Hyperfine splitting in simple ions for the search of the variation of fundamental constants**	**Natalia Oreshkina** MPI-K Heidelberg	15`+5'
14h20	**Hyperfine structure of doubly charged 229Th and the excitation of its nuclear clock isomer**	**Robert Müller** PTB	15`+5`
14h40	**Towards VUV optical clocks with highly charged ions**	**José Crespo López-Urrutia** MPI-K Heidelberg	15'+5'
15h00	**Results Of The Gamma Factory Test Runs With Highly Charged Xe And Pb Ions in the SPS and LHC Accelerator Rings At CERN**	**Simon Hirlander** CERN	15`+5`
15h20	**Coffee Break**		
International Landscape: Atomic Physics Activities Related to SPARC			
15h50	**Atomic physics at XFEL**	**Michael Meyer** European XFEL	15`+5`
16h10	**Results from the Heidelberg Cryogenic Storage Ring**	**Oldřich Novotný** MPI-K Heidelberg	15`+5
16h30	**Merged Ion Beams in Cryogenic Storage Rings**	**Henning Schmidt** Stockholm	15`+5
16h50	**Review of the recent AP activities at IMP**	**Xinwen Ma** IMP Lanzhou	15`+5

Collaboration Meeting			
17h10	**Topics: Funding Situation: International and National, Common Funds, Status Reports, "BMBF Verbundforschung"**	**Angela Bräuning-Demian Reinhold Schuch**	**80`**
18h30	**SPARC Board Meeting**		**60`**

Sunday, September 9^{th}

Free day

Excursion

Conference dinner

Monday, September 10th

Time			Duration
International Landscape: Atomic Physics Activities Related to SPARC			
9h30	**Towards an Optical Clock based on Quantum Logic Spectroscopy of Highly Charged Ions**	**Peter Micke** PTB	**15`+5`**
9h50	**Laboratory X-ray Astrophysics with Highly Charged Ions**	**Sven Bernitt** Univ. Jena	**15`+5`**
10h10	**Segmented-crystal von Hamos diffraction spectrometer for low-energy X-ray experiments at the electron cooler of CRYRING@FAIR**	**Pawel Jagodzinski** JKU, Kielce, Poland	**15`+5`**
10h30	**Coffee Break**		
SPARC experiments for FAIR Phase-0 and related theory			
11h00	**Calculations of the autoionization states of He- and Li-like ions**	**Ilya Tupitsyn** SPSU	**15’+5’**
11h20	**Bayesian data analysis tools for atomic physics**	**Martino Trassinelli** INSP	**15’+5’**
11h40	**Inner-shell transitions: fluorescence yields and auger electrons**	**José Marques** UNL	**15’+5’**
12h00	**The Ground-State Lamb Shift in the Heaviest Hydrogen-like Ion (U^{91+}): High Resolution X-ray Spectroscopy at the CRYRING electron cooler**	**Günter Weber** HI Jena	**15’+5’**
12h20	**Two-Quantum Annihilation of Positrons with K-shell Electrons**	**V.A. Zaytsev** SPSU	**15’+5’**
12h40	**Photoionization of C+ ions at CRYRING**	**Jan Rothhardt** HI Jena	**15’+5’**
13h00	**Lunch**		
SPARC experiments for FAIR Phase-0 and related theory			
14h30	**Nuclear recoil effect on the g factor of few-electron ions**	**Dmitry Glazov** SPSU	**15’+5’**
14h50	**Cooling and precision spectroscopy of $^{209}Bi^{82+}$ ion ensembles with the ARTEMIS and SPECTRAP experiments at the HITRAP facility**	**Wolfgang Quint** GSI, Darmstadt	**15’+5’**
15h10	**Dielectronic Recombination-assisted laser spectroscopy: A new tool to investigate the hyperfine puzzle in Bi$^{80+, 82+}$**	**Rodolfo Sanchez** GSI, Darmstadt	**15’+5’**

15h30	**MCDF calculations**	**Jorge Sampaio** UL/LIP	**15'+5'**
15h50	**Coffee Break**		
16h20	**Precision collision spectroscopy of Be-like ions at the CRYRING@ESR electron cooler**	**Carsten Brandau** Univ. of Giessen	**15'+5'**
16h40	**Binding energies of diatomic molecular ions**	**Daria Mironova** SPSU	**15'+5'**
17h00	**Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions**	**Siegbert Hagmann** GSI, Darmstadt	**15'+5'**
17h30	**Poster session (1.5 hours)**		

Tuesday, September 11th

Time			Duration
SPARC PhD-Prize			
9h30	**PhD-Prize talk**		**15'+5'**
SPARC experiments for FAIR Phase-0 and related theory			
9h50	**Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process**	**René Reifarth** Univ. of Frankfurt	**15'+5'**
10h10	**Measurement of the bound-state beta decay of bare ^{205}Tl ions**	**RuiJiu Chen** GSI, Darmstadt	**15'+5'**
10h30	**Coffee Break**		
International Landscape: Atomic Physics Activities Related to SPARC			
11h00	**DR measurements for astrophysics**	**Mike Fogle** Auburn University	**15'+5'**
11h20	**Dielectronic Recombination of Be-Like $^{40}Ar^{14+}$ at the CSRm**	**Zhongkui Huang** IMP Lanzhou	**15'+5'**
11h40	**A fresh computational approach to atomic structures, properties and processes relevant for basic research and applications**	**Stephan Fritzsche** HI-Jena	**15'+5'**
12h00	**Theoretical Description of the K-shell Ionization in Heavy Ion Collisions**	**Oleksandr Novak** Sumy, Ukraine	**15'+5'**
12h20	**Discussion concerning the Physics Book for the HESR**		**15`+5`**
12h40	**Closing speech and End of the Workshop**	**Reinhold Schuch** Univ. Stockholm	**10'**

Abstracts

TEOP Transitions In He-Like Highly Charged Ions

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We present a theoretical study of TEOP transitions in He-like uranium within the framework of QED. The TEOP transitions from the doubly excited states are considered. We performed a QED calculation of the TEOP transition probabilities. The line-profile approach was employed [1,2].

We also performed a calculation of the dielectronic recombination (DR) cross section with H-like uranium. The main attention was paid to the TEOP transitions. In particular, we have considered the cross section for the emission of a single photon with an energy of about $E = E(2s,2p)-E(1s,1s)$. This corresponds to DR by forming *(2s,2p)* states with further one-photon decay to the ground state. We studied the possibility of an experimental study of this process with local IMP (Lanzhou, China) facilities. We found that the most promising way is to measure the differential cross section with an angle of about 180 degrees, the backward radiation. The reason for this is that in the process under consideration, the direct radiative recombination channel strongly dominates for the total cross section, but the direct channel is sufficiently suppressed for back radiation, so that the resonance DR channel is dominant for the back radiation. We found that the TEOP transitions considered are very sensitive to Breit interaction.

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The role of He-like mixed ($1s^2\ ^1S$, $1s2s\ ^{1,3}S$) ionic states in the investigation of population mechanisms of He-like and Li-like excited states

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Fundamental collision mechanisms such as single electron transfer (T), single electron excitation (E), double electron excitation (DE), transfer Loss (TL), resonant transfer and excitation (RTE), and non-resonant transfer and excitation (NTE), mediated by electron-nucleus or electron-electron interactions, occasionally followed by spin exchange mechanisms, are readily accessible in collisions of few MeV/u low Z ions with gaseous targets. Customarily, low-Z He-like ion beams provided by tandem accelerators are delivered in the ground ($1s^2\ ^1S$) ionic state, but also in a mixed ($1s^2\ ^1S$, $1s2s\ ^{3,1}S$) ionic state depending on the ion stripping method. This turns out to be a unique advantage as it offers a way to separate the excitation channels corresponding to the ground and metastable state ionic beams, respectively. Indeed, recently we have published a new method for separating the contributions from the $1s^2$ and $1s2s\ ^3S$ components of the mixed ($1s^2$, $1s2s\ ^3S$) beam [1] that allowed us to investigate selective cascade feeding mechanisms in single electron transfer to the $C^{4+}(1s2s\ ^3S)$ state [2-4]. Here we extend our study to include results on separated contributions from both the ground state and the metastable $1s2s\ ^{3,1}S$ states on (a) Li-like KLL and KLn states (with n going all the way out to the series limit) and (b) He-like $2s2p\ ^{3,1}P$ hollow ionic states. Our experimental results are compared to state-of-the-art three-electron Atomic Orbital Coupled Channel (AOCC) calculations using the semi-classical close-coupling approach [5]. This is a work in progress and results to date will be presented.

References

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2 *D. Strohschein et al. Phys. Rev. A* **77** (2008) 022706.
3 *T. J. M. Zouros, B. Sulik, L. Gulyas, and K. Tökési, Phys. Rev. A* **77** (2008) 050701R.
4 *D. Rohrbein, T. Kirchner, and S. Fritzsche Phys. Rev. A* **81** (2010) 042701.
5 *J. W. Gao, Y. Wu, N. Sisourat, J.G. Wang and A. Dubois, Phys. Rev. A* **96** (2017) 052703.

Laboratory X-ray Astrophysics with Highly Charged Ions

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X-ray spectra measured with space observatories, like the satellites XMM-Newton and Chandra, provide insight into the state and dynamics of a variety of astrophysical plasmas. This is achieved by the comparison of observations with synthetic spectra, which are based on plasma models. Those models heavily depend on the accurate knowledge of the underlying atomic and molecular processes. Observations of the Perseus galaxy cluster with the Hitomi Soft X-ray Spectrometer (SXS) microcalorimeter recently provided the first high-resolution spectrum of such an object in the photon energy range from 0.1 to 12 keV. This spectrum contains well-resolved line features originating from highly charged ions of most astrophysically relevant elements from silicon (Z=14) to nickel (Z=28) [1]. Its analysis uncovered significant shortcomings of the commonly used spectral modelling software packages SPEX and AtomDB, namely inaccurate transition energies as well as atomic-scale processes completely missing from the models.

A weak line feature around 3.5 keV found in stacked spectra of 73 galaxy clusters sparked enormous interest in the scientific community, when it was attributed to a possible dark matter decay process [2]. Meanwhile, charge exchange between S^{16+} ions and hydrogen, a process not included in spectral models, was found to be a more likely explanation, which is supported by our experiments with electron beam ion traps [3]. This is one example of how our incomplete knowledge of atomic processes limits the amount of information that can be extracted from astrophysical X-ray spectra, not only from currently operating space observatories, but even more so the upcoming NASA/JAXA X-ray Astronomy Recovery Mission (XARM) and ESA's Athena.

We have used electron beam ion traps in combination with free-electron laser and synchrotron light sources to resonantly excite electronic transitions in highly charged ions, yielding, among others, accurate transition energies [4], oscillator strengths [5] and branching ratios [6]. These experiments allow to test atomic structure theory and improve plasma models. Furthermore, we have used highly charged ions to provide an accurate calibration of the photoabsorption spectra of various gases relevant for the interpretation of astrophysical X-ray spectra.

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Enhanced of hypersatellite Ar-K X-ray Emission Observed in EBIT at Electron Energies around 6500 eV

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In the advanced student laboratory, of the Institute of Physics of the Jagiellonian University, a compact commercial electron beam ion source (Dresden EBIT[1,2], DREEBIT Co.) was installed a few years ago for teaching purposes mainly. However, this compact room-temperature HCI-trap, equipped with an x-ray detector (XFlash 5030, Bruker Co.), opens a wide range of possibilities for studies of atomic processes associated with ion production and trapping in an EBIT[2]. Our starting experiments were focused on observation of radiative recombination (RR) and dielectronic recombination (DR). The emitted x-rays were registered, with the resolution of about 100 eV (FWHM), perpendicular to the electron-beam axis at the distance of about 10 mm from the trap centre. A very good resolution of the x-ray spectra for DR in argon encouraged a more detailed searching. This way, investigation of higher-order resonances, especially, of trielectronic radiative recombination (TR: KK-LLL, KK-LLM, …)[3, 4] in argon ions was initiated. The first attempt to observe this kind of TR in HCI's was presented for Kr^{+34}[4]. The present experiment was conducted with argon ions while scanning the electron beam energy of our EBIT in the region (5700-7200) eV. This electron energy region was expected to manifest a significant enhancement of hypersatellite Ar-K x-ray emission due to TR processes mentioned above (Figure 1b). Indeed, we observed a maximum-like behavior of the intensity of this radiation as presented in Figure 1c. Here, discussion of associated background effects is still required.

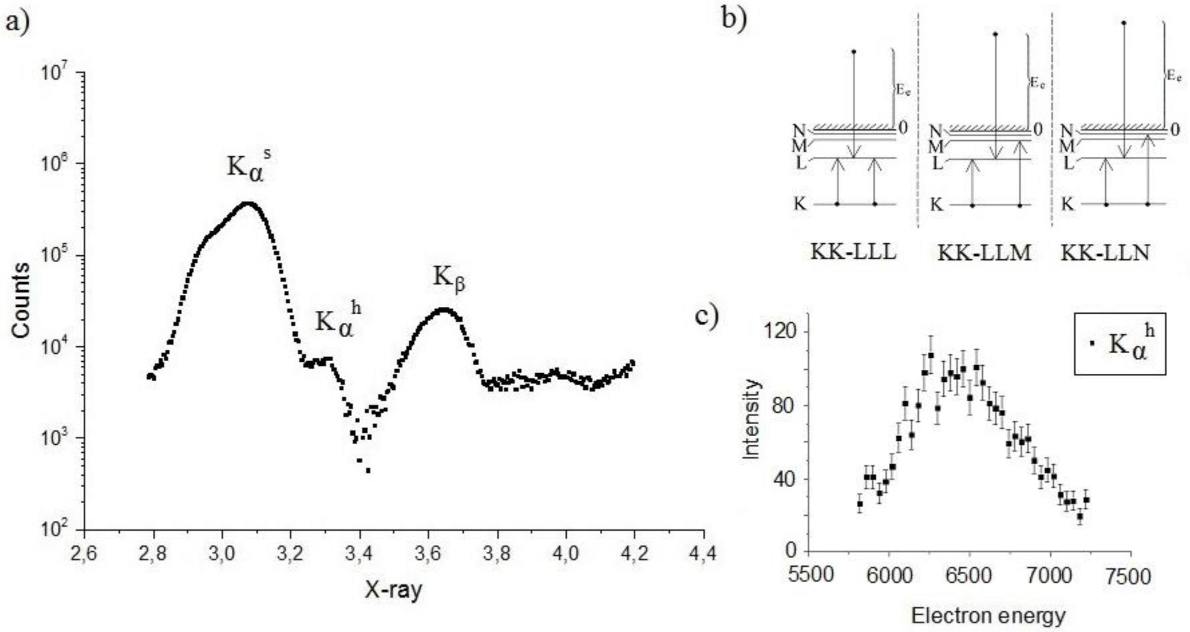

Figure 1: a) The Ar-K spectrum integrated in the investigated electron energy range (K_α^s –satellite of the K_α emission), b) a few examples of TR processes, c) intensity of hypersatellite Ar-K radiation (K_α^h) as function of the electron energy.

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Large-scale relativistic calculations of the $2s^2\ ^1S_0\ -\ 2s2p\ ^1P_1$ spin allowed transition in the Be-like ions

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Transition energies and transition rates are two fundamental properties of atomic states. Therefore, a detailed analysis and comparison of theoretical predictions with experimental observations may provide crucial insight into our basic understanding of the atomic structure. In particular, in the case of multi-charged ions, one can test a combination of the relativistic quantum mechanics and bound-state quantum electrodynamics (QED) at strong electric and magnetic fields [1,2]. For level energies, there exists a number of cases where very high accuracy has been achieved from both theory and experiment and has helped make QED and many-body relativistic effects visible. For the transition rates and line strengths, in contrast, the accuracy level is often not yet sufficient to test QED and many-body relativistic effects. This is partially due to theory and partially due to experiment.

To the experimental end, a high-precision experiment based on the pump-probe scheme has been proposed for the lifetimes of the excited states 2s(n)p 1P1 (with n = 2...5) in Be-like ions [3,4]. The lifetimes of these states are in few ps to few hundred ps ranges whereas the accuracy of the order femtoseconds is expected.

In order to achieve the high-precision ab initio prediction, we present large-scale calculations for the 2s2 1S0 − 2s2p 1P1 spin allowed transition for the Be-like carbon, argon and, iron ions. The many-electron wave functions of initial and final states are systematically enlarged by accounting valence valence, core-valence and core-core correlations using the multiconfiguration Dirac-Hartree-Fock method [5]. The wave functions are further improved by relativistic configuration interaction method where Breit interaction, radiative corrections and finite nuclear mass effects are added to the Dirac Coulomb Hamiltonian. The accuracy of the wave functions obtained is critically examined by the agreement of the computed energies with experiment and the agreement between length and velocity form of the line strength. Transition rate computed from the line strength and transition energy results in a theoretical lifetime of the 2s2p 1P1 state. Our improved lifetime is hopeful to provide a benchmark value in the prospect of the future high precision experiment. The results will be presented in the form of the poster in the workshop.

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Precision Collision Spectroscopy of Be-Like Ions at the CRYRING@ESR Electron Cooler

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As one of the first experiments that exploits the dual-storage-ring arrangement ESR and CRYRING at FAIR it is planned to perform high-resolution dielectronic recombination (DR) collision spectroscopy of heavy Be-like ions with $Z \geq 54$ at CRYRING@ESR. The ultra-cold beam of the CRYRING@ESR cooler promises very high experimental resolution and precision for DR collision spectroscopy that is unprecedented for such very heavy few-electron ions [1,2]. The very low temperature of the electron beam [3] allows one to measure DR resonances with a resolving power that is an order-of-magnitude higher as compared to the conditions at the ESR electron cooler [1, 3-5]. Such high-resolution studies have been performed at the CRYRING at its original installation at the Manne-Siegbahn-Laboratory in Stockholm [4,5] as well as at the TSR storage ring in Heidelberg [6] albeit with much lower-charged ions than available at GSI/FAIR.
With the proposed experiment we pursue several goals:

- Commissioning and performance tests of the new DR collision setup at the CRYRING@ESR cooler with few-electron heavy ions from the ESR.
- Precision spectroscopy of Be-like heavy ions as test of bound-state strong-field QED and relativistic atomic theories.
- Preexaminations and development towards a measurement of the two-photon E1M1-lifetime associated with the $1s^2\,2s\,2p\,^3P_0 \rightarrow 1s^2\,2s^2\,^1S_0$ transition [7-9]

This work is supported by the German Ministry Education and Research (BMBF, contract 05P15RGFAA), and the Helmholtz International Center for FAIR, a Hessian state funded Center of Excellence

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Status of the Transverse Free-Electron Target for the Heavy-Ion Storage Ring CRYRING@ESR

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A high-density free-electron target is planned to be installed in the experimental section YR09 ofthe CRYRING@ESR storage ring in the frame of the upcoming Facility for Anti-proton and Ion Research (FAIR) [1-5]. The target has been designed to produce intense ribbon-shaped electron beams for interaction with a stored ion beam at an angle of 90°. Electron beams can be produced at energies up to 12.5 keV employing various operation modes that are optimized for the requirements of specific experiments with an emphasis on photon-spectroscopy studies in a storage-ring environment.
The present contribution reports on the project status and highlights the experimental opportunities of employing such a free-electron target at a heavy-ion storage ring.

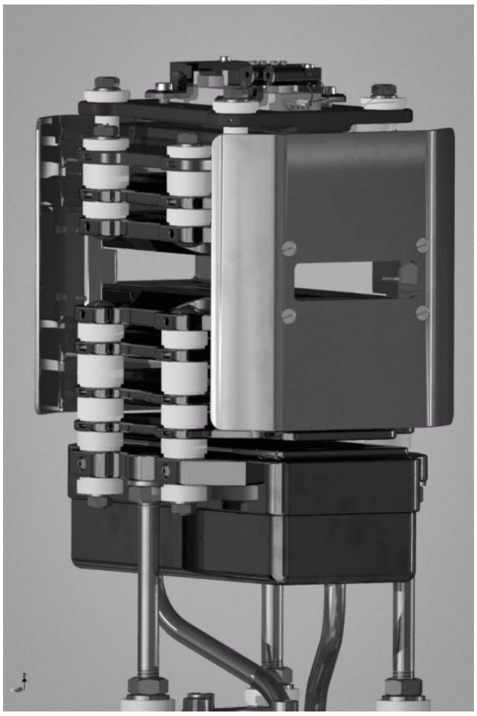

Figure 1.The CAD model of the present electron target. The electron beam is directed from top to bottom. The ion beam passes the gun through the shielding apertures at the front and at the back. The interaction volume, open from both sides, provides a large solid angle for photon spectroscopy.

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Resonant propagation of polarized photon in a strong magnetic field

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In this work, the resonant process propagation of polarized photon in a strong magnetic field is studied using diagram technique. The Feynman diagram of the process is shown in figure 1. Magnetic field is considered to be comparable with the critical Schwinger one. Subcritical magnetic field can be generated in heavy ion collisions with impact parameter comparable to the Compton wavelength of an electron [1]. Such fields are also believed to exist in neutron stars [2].

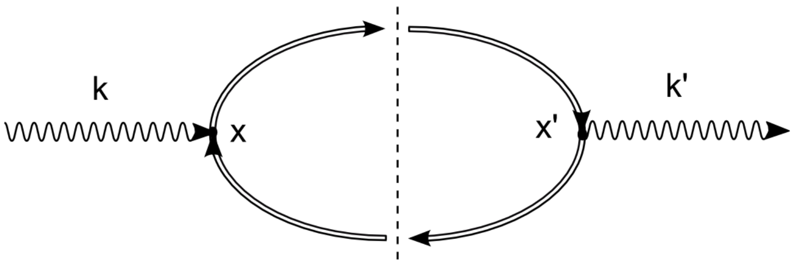

Figure 1. Feynman diagram of the resonant process of photon propagation in a magnetic field with production and annihilation of a virtual electron–positron pair.

The process of photon propagation in a strong external electromagnetic field remains topical, despite an extensive literature on this subject. The first theory of this process has been developed in [3] using polarization operator methods, and the refractive index of polarized vacuum has been found. In an external electromagnetic field, vacuum becomes an optically active medium, and an effect similar to light birefringence can be observed. In works [4, 5] considerable attention was paid to vacuum polarization and the singularity of the polarization operator in a constant magnetic field. It should be emphasized that in the resonant case the intermediate electron-positron pair can still annihilate to the final photon instead of producing a real electron-positron pair. However, the divergence of the polarization operator is usually associated only with one-photon pair creation. The cascade process of pair production with subsequent annihilation requires more detailed study.

In this work, the probability of the resonant process of photon propagation in the low Landau levels approximation has been found. It has been shown that the polarization of the final photon is independent on the polarization of the initial photon, except for the case when the initial photon is normally linearly polarized.

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A fresh computational approach to atomic structures, processes and cascades for multiply and highly-charge ions

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The recent years have seen an increasing demand for accurate atomic computations. Apart from the traditional fields of astro- and plasma physics, accurate atomic data are needed today in various emerging areas, such as laser spectroscopy, quantum optics and metrology, x-ray lithography, or even in material science, to name just a few. In order to fulfill these demands, the multiconfiguration Dirac-Fock (MCDF) method has been found a very versatile tool and has been implemented [1] for calculating a variety of atomic properties and processes. – Despite of its successes, however, difficulties often arise from the (open) shell structure and the large number of different processes that (may) occur in Nature, including excitation, ionization, capture of electrons as well as all the subsequent decay processes and cascades [2,3].

In this contribution, I report about a new (Julia) code for modeling atomic properties and processes. To this end, a high-level toolbox has been designed (and already implemented to a sizable extent) for dealing more efficiently with complex systems. Here, I shall introduce these tools and explain by simple examples how they help provide theoretical predictions and may serve for (requests from) the spectroscopy of multiply- and highly-charged ion or in astro and plasma physics.

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Nuclear Excitation In The Two-Photon Decay Of Highly Charged Ions

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A new mechanism for nuclear excitation by atomic transition is suggested and explored theoretically by studying the two-photon decay of highly charged ions [1]. This mechanism can be seen as a two-photon transition in the presence of an intermediate cascade state, which is given by the electron-nucleus state with the electrons in its ground level and the nucleus in an excited level. Similarly to the pure electronic two-photon decay, the presence of such a cascade leaves a clear footprint in the photon emission spectrum as sharp peaks in the energy regions when one of the photons has a frequency close to the nuclear excitation energy. Detailed calculations are performed for the E1E1 decay 1s2s $2^1S_0 \rightarrow 1s^2$ 1^1S_0 in helium-like $^{225}Ac^{87+}$ ion and for the resonant excitation of the known nuclear level at 40.09(5) keV above the nuclear ground state. The probability that such two-photon decay occurs via the nuclear excitation is found to be 3.5×10^{-9} and is, thus, similar to the corresponding values as obtained for the nuclear excitation by electron transition. The experimental observation of the proposed mechanism is discussed thoroughly as well as its possible applications for the search of low-lying isomeric states, energy storing, and controlled triggering.

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Negative Ions Studies in the Frankfurt Low Energy Storage Ring (FLSR)

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In order to allow for studies of the electronic structure of negative atomic and molecular ions by laser photodetachment, a commercial rf charge exchange ion source for negative ions (Alphatross®, National Electrostatic Corporation [1]) has been installed at the injection terminal of the Frankfurt Low Energy Storage Ring (FLSR) facility [2]. First tests with negative ions stored in FLSR at 20 keV have successfully been conducted. So far, the storage times of 50 nA He^-, 260 nA O^- and 110 nA OH^- have been measured (see Figure 1). They are in good agreement with the theoretical predicted storage times based on the residual gas pressure ($p_{FLSR} \approx 1{,}0 - 2{,}0 \times 10^{-10}$ mbar, corrected for H_2 as residual gas). Also, the lifetime of the metastable He^- is in good agreement with previous measurements [3].

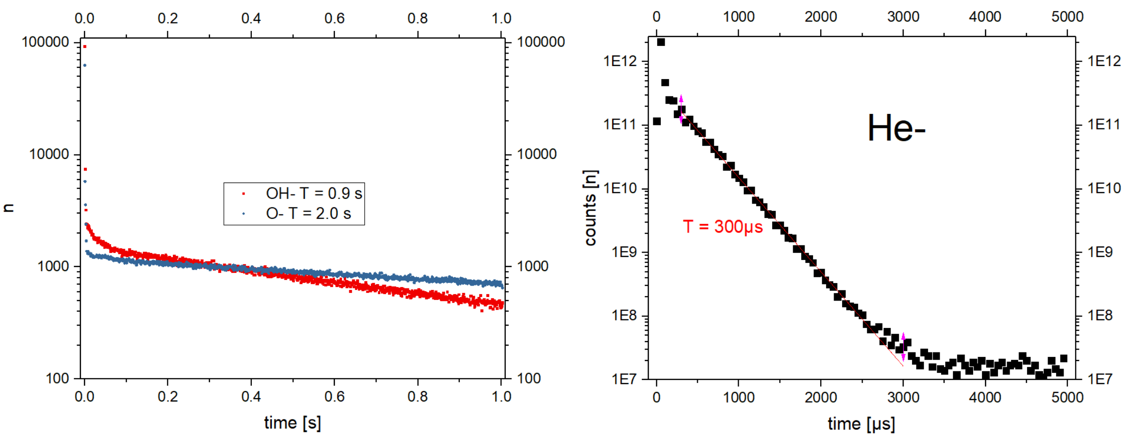

Figure 1. Decay of the neutral particle rates at the 180°-detector of the FLSR for He^-, O^- and OH^-.

The injection of laser pulses into FLSR is presently discussed. There are three possibilities:
1. Injection perpendicular (or with grazing incidence) at interaction point (IP) 2 or 3.
2. Injection parallel to the stored beam in the 0° beam line. Outlet and control of the laser at the 0° port of the injection chamber of the FLSR facility.
3. Injection parallel to the stored beam in the short section of the ring. In this section two points of high ion density exist [2]. Outlet and control of the laser beam via a mirror at the upstream CD-chamber.

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Nuclear recoil effect on the *g* factor of few-electron ions

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Experimental and theoretical investigations of the *g* factor of highly charged ions provided the stringent tests of the bound-state QED effects [1,2] and the most accurate up-to-date determination of the electron mass [3]. Recent *g*-factor measurement for the two isotopes in lithiumlike calcium allows one to test the relativistic theory of the nuclear recoil effect [4]. We present the rigorous evaluation of this effect for lithiumlike and boronlike ions. The first calculation of the nuclear recoil correction to the ground-state *g* factor of hydrogenlike ions complete to all orders in αZ in the first order in m/M was performed in [5] within the theoretical framework developed in [6]. We extend these calculations to the $2s$ and $2p_{1/2}$ states. We also evaluate the many-electron contributions for three- and five-electron systems to all orders in $1/Z$ within the relativistic approach. For lithiumlike ions, a disagreement is found with the previous calculations [7] based on the effective two-component Hamiltonian [8] due to the terms mistakenly neglected in [8]. As a result, we have obtained the most accurate up-to-date values of the nuclear recoil correction to the *g* factor of lithiumlike [9,10] and boronlike [11] ions in the wide range of the nuclear charge. In particular, the new value of the isotopic shift for lithiumlike calcium is presented [9], which is significantly closer to the experimental one [4]. Moreover, we have shown that the non-trivial QED part of the nuclear recoil effect can be probed on a few-percent level in the specific difference of the *g* factors of heavy hydrogen- and lithiumlike ions [12]. This opens a unique scenario for testing the bound-state QED effects beyond the Furry picture in the strong-coupling regime.

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Measuring The Electron Magnetic Moment In Highly Charged Ions Via Laser-Microwave Double-Resonance Spectroscopy And Studying The Behaviour Of Ion Ensembles In A Penning Trap

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The ARTEMIS experiment in GSI Darmstadt aims to precisely measure the magnetic moment of the electron in highly charged ions with laser-microwave double-resonance spectroscopy as the method of choice. The first major phase of the experiment is a proof of principle to be performed on boron-like Ar^{13+} ions stored in a Penning trap at pressures estimated to be as low as 10^{-16} mbar within a 7-Tesla magnetic field. In the first of two connected Penning traps, ion charge-states up to Ar^{16+} are produced via electron impact ionisation. Subsequently, the ion cloud is cleaned to attain a high relative concentration of Ar^{13+} ions, which are then transported to a second Penning trap dedicated to storing the ions for spectroscopy. Storage times of more than 2 weeks are easily achievable, enabling prolonged studies of ion ensemble properties such as cooling behaviour, ion density and ensemble temperature. The results point towards fluid-like behaviour of the ion ensembles.

Measurements are projected to be performed on much heavier ions, such as hydrogen-like Bi^{82+}, extracted from the HITRAP facility at GSI eventually. Results herein would enable fine assessments of the theoretical propositions of bound-state quantum electrodynamics.

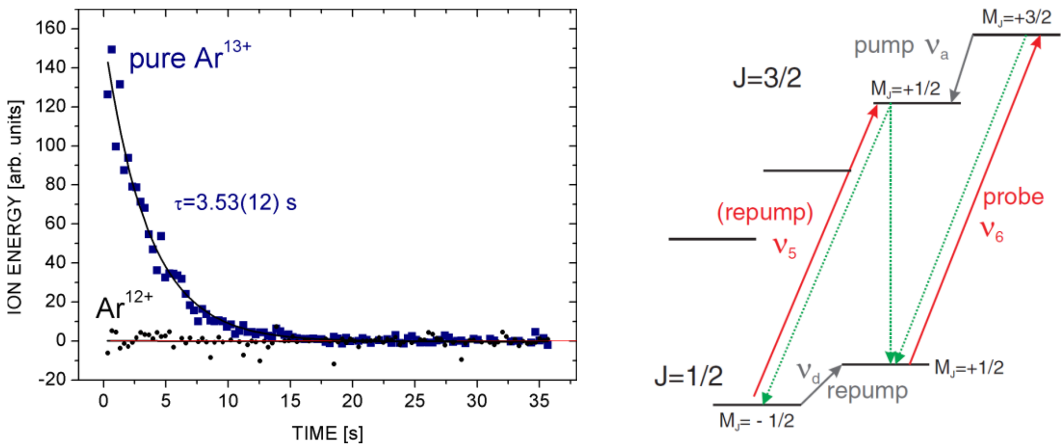

Figure 1. (left) Analysis of the cooling behaviour of a pure Ar^{13+} cloud yields a cooling time constant of 3.53 s. [1] (right) Spectroscopy scheme in the Zeeman-split fine-structure doublet; solid ν_6 arrow indicates saturated probing (and ν_5 optional laser pumping), dotted arrows are spontaneous decays, and the ν_a and ν_d transitions are microwave-stimulated. [2]

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Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions

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We will present an experiment planned at the storage ring ESR which shall study the dynamics of excitation and ionization of electrons in innermost molecular orbitals in very heavy symmetric and highly adiabatic collisions by measuring the impact parameter (b) dependence of combined i) projectile electron continua and ii) target K-Auger electron emission and target K-x ray emission following K- shell to K- shell charge transfer, for the first time for H-like and bare projectiles like $Xe^{53+, 54+}$ in collision systems with $Z_{UA}>100$, $Z_{UA}= Z_{proj}+Z_{target}$. This powerful technique, where differential transfer cross sections are even comparable to the elastic cross sections, is highly attractive as it can be applied to observe indirectly supercritical fields in transient superheavy quasimolecules. We show how the strong oscillations observed in the impact parameter dependent K-vacancy production probability P(b) are related to the energy difference $E_{1s\sigma}(R)-E_{2p\sigma}(R)$, R=internuclear separation, for innermost molecular orbitals $|1s\sigma>$ and $|2p\sigma>$ during the collisions.

Single-Particle Detectors For CRYRING@ESR

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The novel FAIR accelerator and storage ring complex, currently under construction at the site of the GSI Helmholtz Center for Heavy Ion Research near Darmstadt, Germany, achieved a major milestone with the commissioning of the CRYRING storage ring facility in late 2017. To fully exploit the multifaceted field of research thus made accessible, robust and reliable single-particle detectors (SPDs) are of fundamental importance [1,2]. These sensors will be exposed to MHz count rates of charged and neutral particles with energies ranging from sub-MeV/u to 15 MeV/u, and have to withstand the radiation damage imparted by impinging ions.

A variety of sensor concepts have been proposed, and will be presented in this contribution. This includes a detector system based on secondary electron emission whose performance and durability were boosted by the implementation of Extended Dynamic Range (EDR) channel electron multipliers. In addition, a detector based on the YAP:Ce crystal scintillator was designed and is currently awaiting installation at the ring, utilizing a material both comparatively affordable as well as endowed with a significant degree of radiation hardness [3]. The contribution details the detector designs and outlines the results of characterization measurements.

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Dielectronic Recombination of Be-Like $^{40}Ar^{14+}$ at the CSRm

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Electron-ion recombination of Be-like $^{40}Ar^{14+}$ has been measured by employing the electron-ion merged-beams method at the cooler storage ring CSRm [1]. The measured absolute recombination rate coefficients for collision energies from 0 to 60 eV are presented, covering all dielectronic recombination (DR) resonances associated with $2s^2 \rightarrow 2s2p$ core transitions. In addition, strong trielectronic recombination (TR) resonances associated with $2s^2 \rightarrow 2p^2$ core transitions were observed. Theoretical calculations were performed by using multi-configuration Breit-Pauli (MCBP) atomic structure code AUTOSTRUCTURE to compare with the experimental results. The plasma rate coefficients for DR+TR of Ar^{14+} in the temperature range from 10^3 to 10^7 K were deduced from the measured electron-ion recombination rate coefficients and compared with calculated data from the literature. We will present the current results and progress of the preparation of the DR experiments at the CSRe on the conference.

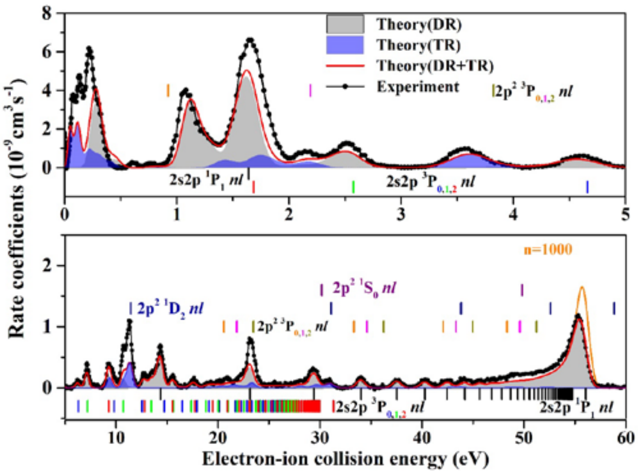

Figure 1. Electron-ion recombination rate coefficients of Be-like argon as a function of relative collision energy. Four $\Delta n = 0$ DR series associate with 2s2→2s2p, $^1P_1$, $^3P_{0,1,2}$ core excitations and parts of five $\Delta n = 0$ TR series (2s2→2p2, $^1S_0$, $^1D_2$, $^3P_{0,1,2}$) can be observed. The corresponding resonance positions are indicated by short bars in different colors. The calculated DR and TR rate coefficients are shown by the gray area and the blue area, respectively. The sum of the theoretical DR and TR contribution is shown as a solid red line.

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Approximate Scaling of the Dirac Equation for Hydrogen-like Ions Exposed to Intense Electromagnetic Pulses

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Nowadays, laser technologies are being rapidly developed. Free-electron lasers are able to produce fields with the peak intensities up to 10^{25} W/cm^2 and wavelengths down to 0.05 nm. The X-ray Free Electron Laser (XFEL) at Hamburg and Linear Coherent Light Source (LCLS) at Stanford are the new generation light sources which will provide opportunities to carry out experiments with heavy highly charged ions interacting with extremely intense laser fields.

In this work, we address the problem of approximate scaling of the time-dependent Dirac equation (TDDE) for hydrogen-like ions exposed to intense electromagnetic pulses with respect to the nuclear charge. In the non-relativistic regime, exact scaling laws for Coulomb systems interacting with laser fields and described by the time-dependent Schrödinger equation (TDSE) are known for years; in particular, the scaling relations and their application to positronium were studied in Ref. [1]. The non-relativistic exact scaling relations are analytically derived within the dipole approximation for the interaction of the Coulomb systems with electromagnetic fields. However, they cannot be extended to the relativistic regime described by the TDDE, and no other exact scaling relations can be found. Nonetheless, in Ref. [2] an approximate scaling law was proposed that matches non-relativistic solutions of the TDSE and relativistic solutions of the TDDE.

Based on the scaling laws from Refs. [1, 2], we derive a new, though approximate, scaling relation for the TDDE describing hydrogen-like ions exposed to intense laser fields. In particular, the scaling relations for the laser wavelengths and peak intensities are suggested in our work. Applicability of this scaling law is illustrated by calculations of multiphoton ionization of various hydrogen-like ions exposed to very short and intense laser pulses. We study the ions with the nuclear charges from 1 to 92 and solve the TDDE numerically using the dipole approximation and length gauge for the interaction with the electromagnetic field. Good agreement between the fully numerical results obtained with the properly scaled laser wavelengths and peak intensities for various nuclear charges is achieved.

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Segmented-crystal von Hamos diffraction spectrometer for low-energy X-ray experiments at the electron cooler of CRYRING@FAIR

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The high resolution measurements of the X-rays emitted in radiative recombination (RR) of ions with electrons in the electron cooler of ion storage ring give precise information on the structure of few-electrons heavy ions and the dynamics of the collision. For this reason a diffraction X-ray crystal spectrometer is needed to achieve the accuracy required to study the subtle QED and relativistic effects [1]. In the electron cooler the RR X-rays are emitted from a long linear source, defined by an overlap of ion and electron beams, having typically m x mm dimensions. This geometry sets severe restrictions on crystal spectrometer geometry to be used in such measurements. Here, we report on the design of a high-resolution von Hamos spectrometer equipped with a segmented-type crystal, optimized to detect the X-rays emitted from long linear source (see Fig. 1 left). This spectrometer is dedicated for low-energy (1-10 keV) X-ray measurements at the electron cooler of the CRYRING@FAIR ion storage ring. The performed X-ray tracing simulations show that the energy profile of X-rays to be measured by a dedicated von Hamos spectrometer for a linear X-ray source exhibits a pronounced symmetry with a wide plateau. The full width at half maximum (FWHM) of this profile, interpreted as the energy resolution of a spectrometer, was simulated to be 1.9 eV for 9 keV photons measured with Si(111) crystal with third order of reflection for ion beam diameter of 1 mm (see Fig. 1 right). However, due to expected symmetric and smooth line profile the energy of X-rays can be fitted with a factor of ten times better accuracy resulting to about 200 meV precision of energy determination of photons.

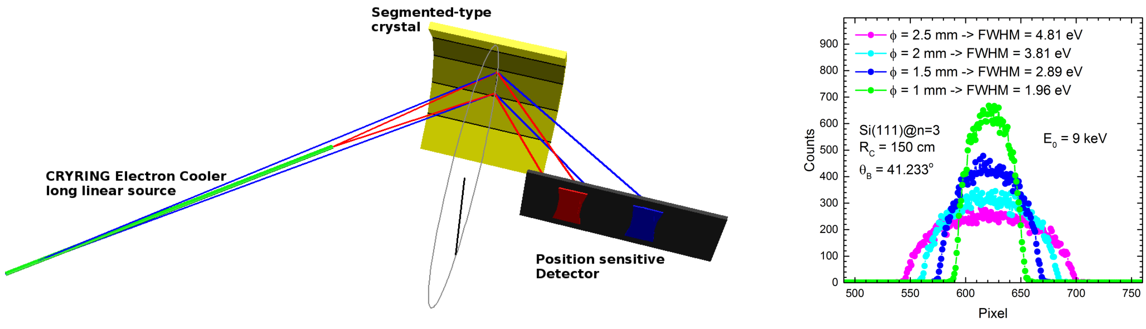

Figure 1. Scheme of the segmented-type crystal von Hamos spectrometer for a long linear X-ray source configuration (left). Simulated X-ray line profiles for 9 keV photons expected for segmented-type crystal von Hamos spectrometer for different of ion beam diameter with estimated energy resolution (right).

Finally, more detailed discussion of Monte-Carlo ray-tracing simulations [2] as well as the main factors influencing the energy resolution and detection efficiency of the von Hamos spectrometer, with estimated count rates, will be presented.

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Comparison Between Anion and Cation Emission from Methane Molecules Colliding with 10.5-keV Singly Charged C Cations

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We show that both cations (H^+, C^+, CH_x^+) and anions (H^-, C^-) are emitted from methane molecules after collisions with positive ions at an impact energy of a few keV. The experiment was performed at GANIL in Caen, France. Figure 1 shows the energy distribution of the anions and cations in 10.5-keV $C^+ + CH_4$ collisions. Each spectrum shows a broad structure, slowly decreasing with energy, resulting from soft many-body processes involving large impact parameters. Pronounced peaks are observed at higher emission energies. As observed for other systems [1-3], these peaks are due to recoil ions formed in hard binary collisions occurring at small impact parameters. For both binary and many-body processes, the anion yield is relatively large, as it represents more than 3% of the cation yield.

The most striking feature is that the kinetic energy distribution of the ejected anions shows strong similarities with the cation one. This finding suggests a statistical picture in which the final charge state distribution of the emitted centers barely depends on how close the atomic centers approach each other during the collision. However, in the particular case of the light H fragments, the binary peak due to H^- ions is centered at a significantly lower energy than the peak due to H^+ ions (energy difference of 20–30 eV in the 40°–70° angular range), suggesting that the post-collisional interaction has equal but opposite effects on the anions and cations.

This work was supported by the Hungarian National Science Foundation OTKA (K109440), the French-Hungarian Cooperation Program PHC Balaton (38620NH / TÉT_16-1-2016-0126) and the International Scientific Cooperation Project (PICS-CNRS No. 7739 / NKM-115/2017)

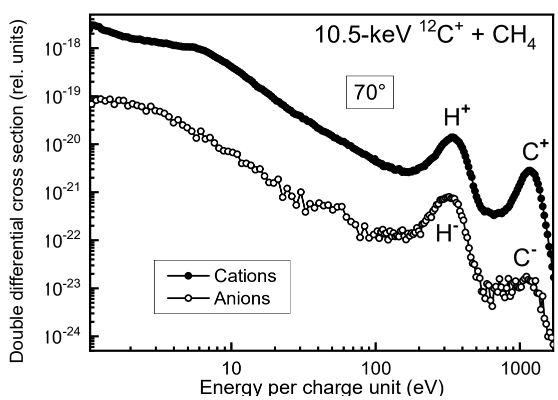

Figure 1. Energy distribution of the fragments in in 10.5-keV $C^+ + CH_4$ collisions at 70° observation angle.

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Status of the HESR, SPARC-setup and infrastructure

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The High Energy Storage Ring (HESR) synchrotron [1] is a part of the new international accelerator facility FAIR. An important feature of the new facility is the combination of phase space cooled beams with internal targets, which opens new capabilities for high precision experiments. The SPARC collaboration benefits from the possibility to perform experiments with highly-charged heavy-ions at relativistic energies in the HESR; the main focus lay on the exploration of the physics at strong, ultra-short electromagnetic fields including the fundamental interactions between electrons and heavy nuclei as well as on the experiments at the border between nuclear and atomic physics [2].
State-of-the-art experiments need close cooperation between accelerator operators and experimentalists, and both areas are being merging. Integration of the experimental setup into the accelerator and the necessary buildings and infrastructure designs are important tasks, which need careful planning. Effects of the targets (objects that particle beam hits) on the accelerator need to be minimized. The space for the detectors, setup, electronic needs to be reserved. Specific experimental requirements and the possibility to fulfill them are only possible if considered already during the planning stage.
We would like to present actual design of the HESR with the SPARC experimental setups integration and corresponding infrastructure.

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Relativistic configuration-interaction calculation of relativistic recoil effect for the ground and singly excited energy levels in berylliumlike ions

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Nowadays highly charged ions (HCI) provide one of the most unique scenario for probing quantum electrodynamics (QED) effects in the strongest field of nucleus. Moreover HCI are important for diagnostics of hot laboratory plasma, notably in magnetic nuclear fusion and tokamaks, study of nearly all classes of cosmic x-ray sources and etc. In view of this importance, accurate theoretical predictions are needed for the reliable identification and interpretation of experimental spectral data.

Evaluation of electron-electron correlation effects is one of the most challenging problem for theoretical description of HCI, with the leading sources of theoretical uncertainty being originated from the relativistic recoil and higher-order screened QED corrections. The full relativistic theory of the nuclear recoil effect can be formulated only in the framework of QED [1]. In order to evaluate the recoil effect within the lowest-order relativistic approximation one can use the relativistic recoil operator. Within this approximation the recoil correction is calculated with many-electron wave functions in order to take into account the electron-correlation effect. The one- and two-electron contributions to the recoil effect are evaluated to all orders in αZ.

In present work we focused on relativistic calculations of recoil correction to the first order in m/M for the ground and singly excited energy levels in berylliumlike ions exploiting the large-scale perturbation theory and configuration-interaction approaches with Dirac-Fock-Sturm basis functions [2]. The interelectronic-interaction corrections are taken into account within the Breit approximation. The evaluations are carried out using one-particle basis set obtained as for Coulomb as well for clear-defined screened potentials, which allow ones easily to add QED correlation corrections, as soon as they will be available. The results obtained are supplemented by a systematical estimations of calculation errors and omitted effects. The results are compared with previous theoretical calculations including high-precision non-relativistic methods for low-Z ions.

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High Power UV Laser Systems for Spectroscopy and Cooling of Highly Charged Relativistic Ion Beams

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Laser spectroscopy and laser cooling of highly charged ion beams are effective tools in accelerator facilities. Despite the large Doppler shift, the high energies of the transitions in for example Lithium-like ions require laser wavelengths in the ultraviolet [1].
We present a narrow linewidth high power CW system as well as a pulsed system capable of delivering transform limited pulses with high average power and adjustable pulse widths.
In the past a CW laser system at 257 nm with a wide mode hop free scanning range was developed and used for spectroscopy and cooling of C^{3+} [2]. In standard commercial and non-commerical CW systems the nonlinear BBO crystal used for the conversion to the ultraviolet undergoes degradation which limits the output power and the operation hours. Our system was not immune to this effect either. Recently, however, we succeeded in overcoming the degradation effect by a novel elliptical focusing enhancement cavity design. By this we are able to produce long term stable 600 mW CW narrow linewidth laser light at 257 nm (cf. figure 1). This measurement was performed with the same standard crystal which degrades within our previous standard focussing enhancement cavity to below 5 mW within minutes.
The pulsed system is based on waveguided interferometric pulse generation and fiber amplifiers. The system benefits from this specific pulse generation with transform limited spectral widths in the low GHz range with pulse lengths between 70 and 740 ps. The repetition rate can be adjusted freely between 1 and 10 MHz.
We will present both the CW and the pulse laser system as well as possible applications.

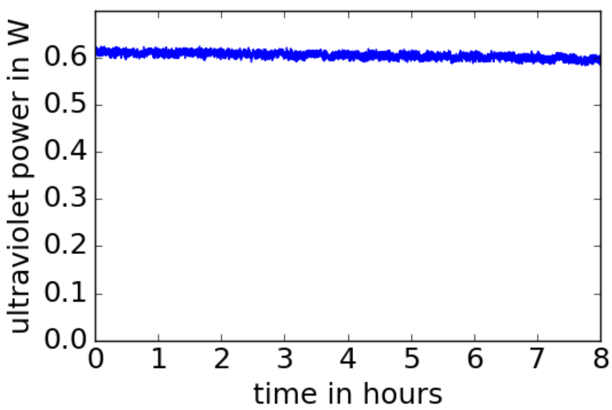

Figure 1. An 8-hour measurement of more than 600 mW CW output power at 257 nm.

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HILITE – Ion Deceleration and Non-Destructive Ion Detection

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The HILITE Penning Trap Experiment [1] will provide the opportunity to investigate laser-matter interactions in both the high-intensity and high-energy regime. The experimental setup includes an Electron Beam Ion Source (EBIS) to create highly-charged ions, in order to be independent from external sources. Amongst others, for ion detection and analyzation, we use non-destructive single-pass charge counting devices [2]. For initial ion deceleration to kinetic energies below 400eV/q a pulsed drift tube is used, which is integrated into the setup.

We implemented two distinct non-destructive charge counters, one on each side of the trap. This configuration allows time-of-flight measurements and thereby we can determine the initial kinetic energy. Furthermore, we are able to assess the number of elementary charges and the total ion number within each bunch. In addition, one can estimate parameters like the bunch length from the charge counter signals. We use these results to find parameters for efficient ion deceleration and dynamic ion capture.

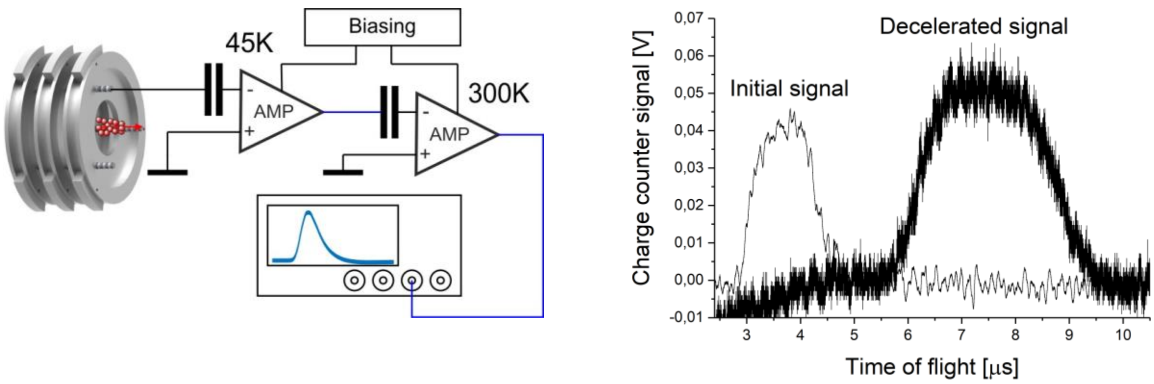

Figure 1: (left) Schematic drawing of a single-pass charge counter and (right) charge counter signal of an initially unperturbed and a decelerated ion bunch.

We will show a brief overview of the HILITE Experiment and present the implemented ion detection and deceleration techniques, including first characterizing results. Additionally, we will outline the further developments of ion deceleration and manipulation techniques to create a well-defined ion target.

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Elastic Scattering Of Twisted Electrons By Atomic Target: Going Beyond The Born Approximation

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Twisted (or vortex) electrons presently attract a lot of attention from both theoretical [1-3] and experimental [4-6] studies. These electrons can carry a nonzero projection of the orbital angular momentum (OAM) onto the propagation direction. This projection, which nowadays can be as high as $1000\hbar$ [7], determines the magnitude of the OAM induced magnetic moment. Due to such huge (in contrast to the plane-wave electrons) magnetic moment, the twisted electrons provide a unique possibility to get a deeper insight into the role of the spin-orbit interaction in different atomic processes.

In the present work, we study the Mott scattering of twisted electrons by neutral atoms. The electron-atom interaction is taken into account in all orders. Up to now, this process was considered only perturbatively in the framework of the first Born approximation [8]. This approximation stays valid only for light systems with relatively small nuclear charge Z. We perform detailed calculations of the total and differential cross sections as well as the degree of polarization of scattered electrons in order to illustrate effects beyond the first Born approximation. Also, we investigate the influence of the kinematic parameters of the incident twisted electrons on the angular and polarization properties of the scattered electrons.

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A FPGA/Labview-based Data Acquisition System for Voltage-Biased Silicon Microcalorimeters for X-ray Detection

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Within the SPARC collaboration, an array of 96 voltage-biased silicon microcalorimeters for high-precision X-ray spectroscopy on highly-charged heavy ions is currently under development. As part of this work, a new readout and data acquisition system is also developed. The detector array *SiM-X* will consist of 96 silicon thermistors with tin absorbers and an active area of approximately 30 mm². The micrcalorimeters are read out by cold JFETs and voltage-sensitive preamplifiers [1,2,3]. The preamplifier signals are then digitized by a 24-bit channel-to-channel-isolated Flash ADC with Anti-Aliasing Filter (National Instruments NI 9239) and a digitization rate of 50 kS/s. The FADC data are transferred to a CompactRIO FPGA Controller (NI PXI 7813R) with 40 MHz frequency and 216 kByte embedded block RAM. To read out 96 channels, six Flash ADCs and two CompactRIO controllers will be used.

To allow for flexible signal length as well as pretrigger and posttrigger sample numbers, a versatile algorithm was developed to digitize the signals and determine the trigger level, which means that every channel triggers and is read out independently. All parameters of the signals can be chosen freely up to the maximum digitization rate. Data processing includes a first stage digital Butterworth filter. The setup is modular and can, therefore, be extended to a larger number of channels easily. The poster will introduce the hardware and software and discuss the performance.

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Experimental Determination of Electron Capture Cross Sections into Excited States of Decelerated Xenon Projectiles

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Currently only very few data exists for electron-capture cross sections of highly-charged ions colliding with atoms/molecules at energies well below the respective projectile's ionization threshold. However, such conditions will be common for beams of decelerated highly-charged heavy ions in the recently commissioned CRYRING@ESR of GSI/FAIR, Darmstadt, where the capture rate with residual gas atoms/molecules will determine the ion beam lifetimes. Thus, the knowledge of electron capture cross sections is in particular of crucial importance for the future operation of CRYRING@ESR, as well as for the planning of experiments in this storage ring.

In this work experimental cross section data were evaluated for Xe^{54+} ions in collisions with H_2 molecules [1]. The experiment was performed with xenon projectiles at collision energies between 5.5 MeV/u and 30.93 MeV/u during a beam time in 2016 at the internal gas target of the ESR storage ring at GSI, Darmstadt. It allowed the determination of cross sections for electron capture into excited states of the decelerated xenon projectiles. Therewith a comparison of the commonly used empirical Schlachter formula [2] and of the eikonal theory [3], used for the prediction of non-radiative electron capture (NRC) cross sections, to the preliminary experimental data could be conducted. As was shown, the results of the Schlachter formula deviate markedly from the experimental data in contrast to the eikonal theory, which is in reasonable agreement with the experimental data.

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Charge State Tailoring of Relativistic Heavy Ion Beams for FAIR and CERN

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Upcoming heavy ion acceleration facilities will allow to extend the range of achievable beam intensities and energies. For experiments relying on intense, few-electron charge state ions, it is necessary to produce the required charge states with stripper foils optimized for the specific experimental parameters. However, corresponding data on the charge state distribution for the design of effective stripper foils is very rare in the relativistic regime. In addition widely used program codes to estimate the charge state distribution during the passage through matter are limited in the newly accessible high energy range.

Therefore the recently developed BREIT[†] code [1], has been verified and adapted to overcome this limitation. In contrast to codes like CHARGE [2], GLOBAL [2] and ETACHA [3] it has no built-in charge exchange cross sections, allowing the algorithm to be used for arbitrary beam energies and charge states as long as the relevant cross sections are provided by the user. For the production of these input cross sections different well-tested codes have been used. After first consistency checks at energies of several hundred MeV/u the BREIT code was used together with the aforementioned cross section codes for an exemplification study for the upcoming FAIR facility at GSI, and finally for a study for the planned Gamma Factory at CERN [4]. As a result of this study, stripper foils have been chosen that will be investigated at CERN during a test experiment scheduled in 2018.

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[†]Balance Rate Equations for Ion Transportation

[1] N. Winckler et al., NIM B **392**, 67-73 (2017).
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Charge State Tailoring of Relativistic Heavy Ion Beams for FAIR and CERN

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Study of Autoionizing States in Resonant Processes with HCI

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Processes of electron capture by ions [radiative electron capture (REC), dielectronic (DR) and trielectronic (TR) recombinations], processes of electron loss from ions [direct electron loss, excitation-autoionization (EA) and resonant excitation double autoionization (REDA)] and processes of electron scattering [elastic, inelastic, resonant] actively proceed in highly ionized laboratory and astrophysical plasmas. Many of these processes are resonant, and because of that they are very important and interesting subjects for investigation. In general, the autoionizing states determine the resonance structure of the collision processes and, therefore, they continue to trigger the interest of researchers working in different fields of physics from both experimental and theoretical points of view. The autoionizing states of HCI are very sensitive to relativistic and QED effects, accordingly the HCI should be described within the framework of QED.

We present a theoretical study of the autoionizing states in the DR processes with H- and He-like uranium ions initially being in the ground or metastable states. The resonance structure of the corresponding total and differential cross sections, as well as the energies and widths of the autoionizing states are calculated [1-3]. We show that the Breit interaction can play an important and even dominant role in such processes. We also investigated the two-electron one-photon (TEOP) transitions in the DR process with H-like ions.

Another process in which the autoionizing states can play an important role is the EA process. The corresponding differential cross sections were calculated for the electron loss from He-like calcium and zinc in their collisions with various atomic particles: photons, electrons, bare nuclei and light atoms [4].

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Signature of the diving phenomenon in low-energy heavy-ion collisions

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Low-energy collisions of heavy ions give an unique access to the domain of supercritical fields. In the presence of such fields the ground state of the quasimolecule formed by the colliding ions dives in the negative-energy Dirac continuum. After diving the ground state turns into the resonance which can decay spontaneously via emission of a positron. The detection of the emitted particles would be the direct evidence of the diving phenomenon and, therefore, confirm the predictions of QED theory in highly nonperturbative supercritical regime. However, it turns out that the spontaneous contribution to pair production is indistinguishable from the dynamical background induced by the time-dependent potential of the moving ions [1, 2]. This fact makes the direct detection impossible.

In the present talk, it is shown that there is a possibility of indirect observation of diving phenomenon. For this observation one can use the impact-sensitive measurements of pair-production probabilities. This conclusion follows from the numerical calculations of the pair production in low-energy collisions of heavy bare nuclei with different values of the charge and the impact parameter.

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QED Calculations of the Nuclear Recoil Corrections to the Energy Levels of Highly Charged Ions

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The full relativistic theory of the nuclear recoil effect to the first order in the electron-to-nucleus mass ratio m/M and to all orders in the nuclear strength parameter αZ can be formulated only in the framework of quantum electrodynamics (QED) [1-4]. To date, the QED contributions to the recoil effect were considered within the independent-electron approximation, i.e., to zeroth order in $1/Z$ [4-8]. The first and higher orders in $1/Z$ were treated within the lowest-order relativistic (Breit) approximation employing the effective two-electron recoil operator [1,2,9]. In view of high-precision experiments to measure isotope shifts of the energy levels in highly charged ions which are anticipated in the near future, the rigorous QED evaluation of the nuclear recoil effect beyond the independent-electron approximation is urgent. In this work we present the current progress of these calculations. The results obtained are compared with results of the Breit-approximation calculations.

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Inner-Shell Transitions: Fluorescence Yields and Auger Electrons

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The knowledge of accurate values of atomic inner-shell radiative and radiationless transition rates is essential in many branches of physics and technology such as spectroscopy, plasma physics, astrophysics, and more recently, in targeted cancer therapy. The fluorescence yield is one of the most important parameters that can be extracted from those transition rates.

Fluorescence yields are routinely used in applications ranging, for instance, from X-ray based analytical techniques, X-Ray fluorescence (XRF), particle-induced X-ray emission (PIXE), to electron probe micro-analysis.

Inner-shell transitions have been object of intense research, both theoretically and experimentally, since the second half of the 20th century, and several reviews can be found in the literature but, despite the increasing number of available theoretical and experimental works on this subject, available data are still scarce or outdated.

I review here recent work concerning the theoretical determination of radiative and radiationless transitions for the inner shells of several elements, using the multi-configuration Dirac-Fock (MCDF) method, outlining its importance in different fields with special emphasis in cancer targeted radiotherapy.

Binding Energies of Diatomic Molecular Ions

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During the last decades the experimental and theoretical accuracy of atomic and molecular spectroscopic data has increased significantly. As a result, consideration of many-electron relativistic contributions to the energy levels of heavy molecules and molecular ions becomes urgent. Moreover, the high-precision calculations of the adiabatic curves for heavy quasimolecules are also of interest for describing various processes in the collisions of highly charged ions. In this work we present the relativistic calculations of the binding energies of heavy diatomic molecular ions which represent the ideal grounds to test different theoretical approaches. To obtain the binding energy, the Dirac-Coulomb-Breit equation for a few-electron molecule is solved by means of the configuration-interaction method using the basis of two-centered atomic Dirac-Sturm (DS) orbitals [1,2]. Earlier the DS basis was successfully applied to the case of one-electron diatomic systems [3]. With the method developed, the adiabatic curves for different heavy few-electron diatomic molecules are rigorously evaluated taking into account many-electron relativistic effects for a wide range of the internuclear distances (from the chemical distances up to the critical ones). The results obtained are compared with the results of the previous calculations.

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A Reaction Microscope for the Frankfurt Low Energy Storage Ring (FLSR)

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In order to allow for high-resolution studies of atomic/molecular reactions in the Frankfurt Low Energy Storage Ring (FLSR) [1], the HITRAP-supersonic jet target [2], in combination with a COLTRIMS reaction microscope will be installed at FLSR. For this purpose, a new recoil ion spectrometer has been designed (see Figure 1) and is presently implemented at the supersonic gas target in the high-energy beam line of the Frankfurt 14Ghz-ECR-RFQ facility at IKF. At this position the gas target and the spectrometer will be calibrated, the Q-value resolution of the spectrometer for the reaction:

$$HeH^{+} + He \rightarrow He + H + He^{+} + KER,$$

will be determined and the above reaction will be investigated in detail to provide data for the population of vibrational levels in the excited (hot) molecule.

Figure 1. SIMION simulation for the recoil ion spectrometer.

As next step the set up will be mounted into the FLSR at interaction point 4, where previously measurements with a residual gas spectrometer were performed [3]. These measurements have shown that the distribution of the kinetic energy release (KER) changes with storage (cooling) time of the HeH^{+} ion beam. In order to investigate the population of vibrational energy levels as a function of the cooling time, a very good Q-value resolution is required.

In this contribution the measurements at the IKF 14GHz-ECR-RFQ facility and the details of the implementation of the set up into FLSR will be discussed.

[1] *K.E. Stiebing V.Alexandrov, R.Dörner, S.Enz, N.Yu.Kazarinov, T.Kruppi, A.Schempp,H. Schmidt-Böcking, M.Völp, P.Ziel, M.Dworak, W.Dilfer*; Nucl. Instr. and Methods in Physics Research A 614, 10 (2010).

[2] *D. Tiedemann et al., NIM **A764** (2014) 387-393.*

[3] J. C. Mueller, Journal of Physics Conference Series, 07/2017, 875(10)

Theoretical Description Of The *K*-shell Ionization In Heavy Ion Collisions

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A theoretical study of the K-shell ionization of hydrogenlike ions, colliding with bare nuclei, is performed within the framework of the time-dependent Dirac equation. The ionization probability is obtained within the first-order perturbation theory using adiabatic expansion of the time-dependent electronic wave function in terms of the stationary states. Numerical calculations of the matrix elements were carried out using two-center wave functions obtained within the approach developed in [1, 2].

The matrix elements of corresponding to K-shell ionization are parametrized with a simple expression containing three fitting parameters. This allowed us to derive an analytical expression for estimation of the probability of ionization from the 1σ state. In contrast to the previous studies [3], our formula is based on the full multipole expansion of the two-center potential and allows one to study collisions between nuclei with different atomic numbers $Z_1 \neq Z_2$ and non-zero asymmetry degree $A = (Z_1 - Z_2) / (Z_1 + Z_2)$.

The calculations performed for both symmetric and asymmetric collisions indicate that the ionization probability is reduced when the difference between the atomic numbers of ions increases.

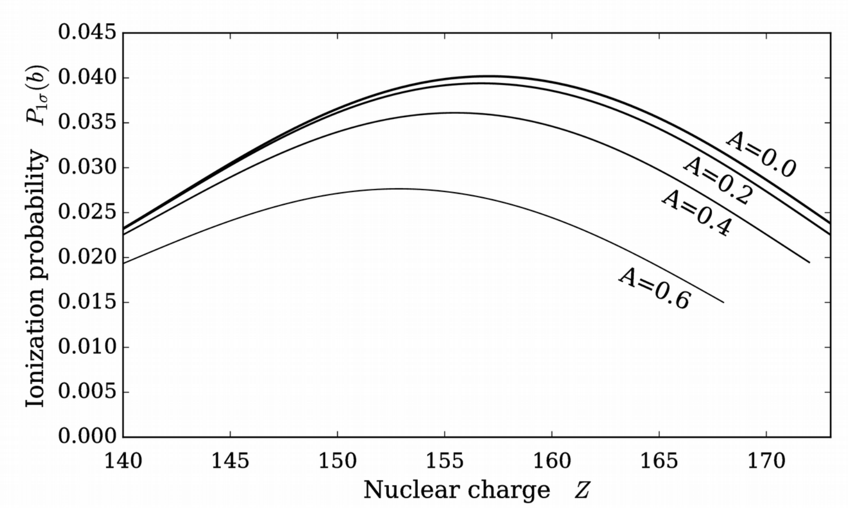

Figure 1. Ionization probability of the 1σ state of a hydrogenlike ion colliding with a bare nucleus. The probability is calculated for a zero impact parameter *b* and for the distance of the closest approach equal to 20 fm.

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Results from the Heidelberg Cryogenic Storage Ring

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The electrostatic Cryogenic Storage Ring (CSR) in Heidelberg, Germany, is designed to store ion beams at 300 keV per charge unit, independently of ion mass [1]. Cryogenic cooling of the whole beamline chamber leads to a low radiation field, allowing even molecular ions to relax to their rovibrational ground state. Additionally, at 6K wall temperature reached, the cryo-pumping on the walls results in low residual gas densities and ion beam storage times of several thousand of seconds. The various collision targets are designed to study the ion collisions with electrons, photons, and neutral atoms. In the talk we will present the results on the general ring performance, on the recently established electron cooling, as well as on the first molecular collision studies [2,3].

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[3] C. Meyer et al. 2017 Phys. Rev. Lett. 119 023202

HILITE – Current Status and Commissioning Results

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Detailed investigations of high-intensity and high-energy laser-matter interactions require well-defined ion targets and detection techniques for high-sensitivity measurements of reaction educts and products. Therefore, we have conceived, designed and built the HILITE Penning trap [1]. It employs various ion-target formation techniques as well as destructive and non-destructive techniques to analyze the stored species and charge states individually and simultaneously [2].
To be independent from external ion sources and to move the experimental setup to different laser facilities, we have combined the Penning trap setup with an Electron Beam Ion Source (EBIS), which delivers ion species up to He-like ions such as Ar^{16+}. Upon extraction from the source, ions have kinetic energies of around 3.5 keV per charge. To enable dynamic ion capture into the trap, the ions are decelerated by a baffle-structured pulsed drift tube down to several tens of electron-volts.

Figure 1. Photo of the ion trap setup with EBIS, Wien filter, laser beam dump, super-conducting magnet with Penning trap inside, and laser entrance windows (left to right).

We will present the current status of the HILITE experiment and the ion-detection techniques used. We will provide characterization data of the ion deceleration and ion capture, and we will give an outlook to upcoming experiments.

[1] M. Vogel, W. Quint, G.G. Paulus, Th. Stöhlker, Nucl. Inst. Meth. B **285** (2012) 65
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Recoil effect on the g factor of heavy ions: prospects for tests of QED at strong-coupling regime beyond the Furry picture

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The relativistic theory of the nuclear recoil effect on the g factor of H- and Li-like heavy ions is considered. The one-electron recoil contributions are calculated within the framework of the rigorous QED approach while the two-electron terms are evaluated within the framework of the Breit approximation using a four-component approach [1]. As the result, the second largest uncertainty of the g factors of Li-like lead and uranium is strongly reduced. Special attention is paid to tests of the QED recoil effect on the g factor in experiments with heavy ions. It is found that, while the QED recoil effect on the g-factor value is masked by the uncertainties of the nuclear size and nuclear polarization contributions, it can be probed on a few-percent level in a specific difference of the g factors of H- and Li-like heavy ions. This paves a way to test QED in a new region: strong-coupling regime beyond the Furry picture [2].

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SIM-X: Silicon Microcalorimeters For X-ray Spectroscopy At Storage Rings – Status And Perspectives

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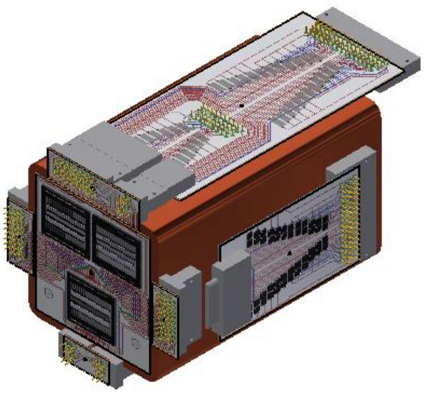
High-precision X-ray spectroscopy of hydrogen-like heavy ions provides a sensitive test of quantum electrodynamics in very strong Coulomb fields. However, one limitation of the current accuracy of such experiments is the energy resolution of available X-ray detectors [1]. To improve this accuracy the concept of “microcalorimeters” is exploited for such measurements. With this kind of detectors and affixed X-ray absorbers appropriate to the desired energy range, a relative energy resolution of about 1 per mille is obtained in the energy regime of 10 - 100 keV [2].
In order to reduce the statistical uncertainty and to improve the lateral sensitivity, a larger detector array with three times the active detector area in a new, cryogen-free cryostat is currently in preparation (Fig 1.). Our detector is based on a design by Bleile et al. [2] which, however, had to be considerably modified in order to accommodate the larger detection area within the rather restricted space available in the cryostat. This next generation detector was tested at the ESR storage ring of the GSI facility in 2016 [3]. After the test beamtime, several further optimizations and developments were carried out resulting in a much improved detector performance. For the 60-keV-gamma-line of ^{241}Am (Fig. 1) an experimental line width of 84 eV was achieved.



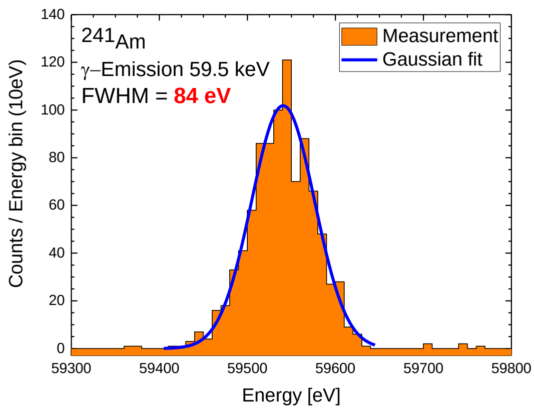


Figure 1: *left*: Design of the larger detector array with three times the active detector area. *right*: Measured X-ray spectrum from a ^{241}Am gamma emitter from one silicon microcalorimeter pixel. The data acquisition time was 12 h.

In this contribution, we will briefly introduce the detection principle following the developments resulting from the test experiment. In addition to the status of the large detector array for experiments at the future FAIR facility, perspectives for other high-precision experiments will be discussed.

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[2] S. Kraft-Bermuth et al., J. Phys. B **50**, 055603 (2017). [3] P. Scholz et al., NIMB **408,** 323 (2017).

Calculations of the Autoionizing States of He- and Li-like Ions

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We report the results of calculations of the Auger widths, Auger shifts, and level energies of excited 2l2l' and 1s2l2l' autoionizing states of He-like and Li-like ions, respectively. The calculations are performed by the relativistic CI method using the complex-scale transformation of the Hamiltonian. The complex-scaling (CS) method is one of the most convenient ways to apply bound-state methods to study autoionizing states (see [1] and references therein). The Dirac-Fock-Sturm (DFS) orbitals are used as one-electron basis. To improve the convergence in the calculations of the bound state contributions, the DFS basis was also transformed by the CS method.

The energy levels of the excited states of Li-like ions in the range Z=6-36 were previously calculated in the works [2,3] by the relativistic CI method adapted to the treatment of autoionizing core-excited states. It is of interest to compare the level energies of autoionizing states obtained by two different methods. In addition to the energy levels, we also calculated the widths and shifts of Auger resonances in the He-like and Li-like ions and analyzed the dependence of these values on the nuclear charge.

The vacuum polarization part of the QED corrections was evaluated using the Uehling and Wichmann-Kroll potentials. The self-energy contribution was calculated using so-called model operator approach [4,5]. This model self-energy operator has been successfully used in earlier calculations of many-electron atoms and highly charged ions (see, e.g., Ref. [6]).

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Status of the ESR

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The operation of the Experimental Storage Ring (ESR) was stopped for two years (2016-2018) due to various activities which prepare the existing GSI accelerator facility for FAIR. The operation of the ESR will be continued this year as part of the FAIR-Phase 0 experimental program. During the shutdown period a new barrier bucket rf system and a second Schottky resonator was installed. Repair work on the drift tube system of the ESR electron cooler had to be stopped due to the discovery of hazardous bakeout equipment. The recommissioning of all ESR systems with the new accelerator control system is planned starting in August 2018. The presentation will focus on the recent modifications of the ESR and the progress of the recommissioning.

Measurement Of The Linear Polarization Of Radiative Electron Capture

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To improve the understanding of cosmic and laboratory plasmas with their high temperatures, charge states and field strengths, the determination of the linear polarization of the emitted photons is very important. Many Si(Li) and Ge(i) Compton polarimeters have been built and used within the SPARC collaboration for this purpose [1,2,3]. The development of these detector systems was accompanied by a significant increase of the energy resolution as well as an extension of the lowest accessible photon energy.

To make use of this improvement, the newest double-sided segmented Si(Li) detector with cryogenic preamplifiers was employed at an experiment at the internal gas target of the ESR storage ring of GSI, Darmstadt. The polarization of photons at the comparably low energy of 56 keV, arising from the radiative electron capture (REC) into the K shell of bare xenon ions interacting with the hydrogen gas target at an energy of 31 MeV/u, was measured. At such low-Z targets, the REC can be well approximated as the time-inversed process of photoionization. The dipole emission pattern of this process exhibits a next to full linear polarization [4].

A recorded spectrum of this measurement and a Compton scattering distribution of the K-REC photons can be seen in figure 1. The strong anisotropy of the 2D plot indicates the expected high degree of linear polarization. The preliminary results of this experiment will be shown in this contribution.

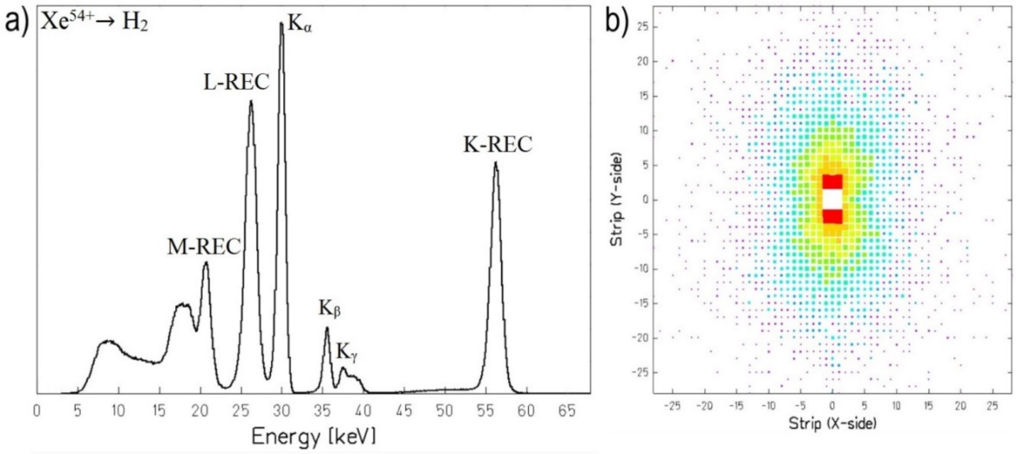

Figure 1: a) Recorded spectrum (preliminary) of a beam of bare xenon ions at 31 MeV/u colliding with a hydrogen gas target, observed at 90° with respect to the beam axis. b) Compton scattering distribution (preliminary) of the K-REC peak at 56 keV. The high anisotropy indicates a high degree of linear polarization.

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Laser cooling of relativistic lithium-like $^{16}O^{5+}$ ion beams at the CSRe

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Based on the success of laser cooling of $^{12}C^{3+}$ at the ESR [1,2], and the experience of test laser cooling experiments at the CSRe [3], laser cooling of lithium-like $^{16}O^{5+}$ ion beams with an relativistic energy of 275.7 MeV/u was achieved for the first time at the heavy-ion storage ring CSRe in Lanzhou, China. In the experiment, a CW laser system with a wavelength of 220 nm was used to match the optical transition of $2s_{1/2}$-$2p_{1/2}$ of $^{16}O^{5+}$ ions at this beam energy. In order to cool the relativistic ion beams with only one counter-propagating CW laser, the ion beams were bunched by applying a sinusoidal voltage to the RF-buncher system. Fig. 1 (a) shows the Schottky spectrum of laser-cooled bunched $^{16}O^{5+}$ ion beams with a fixed laser. The relative longitudinal momentum spread of laser-cooled ion beams reached dp/p less than 1×10^{-6} as shown in Fig. 1 (b) which is extracted from slice (1) in Fig. 1 (a). The successful laser cooling of $^{16}O^{5+}$ ion beam demonstrates the highest charge state and highest energy of ions that have been ever cooled by lasers. We will present the very recent experimental results on this SPARC workshop.

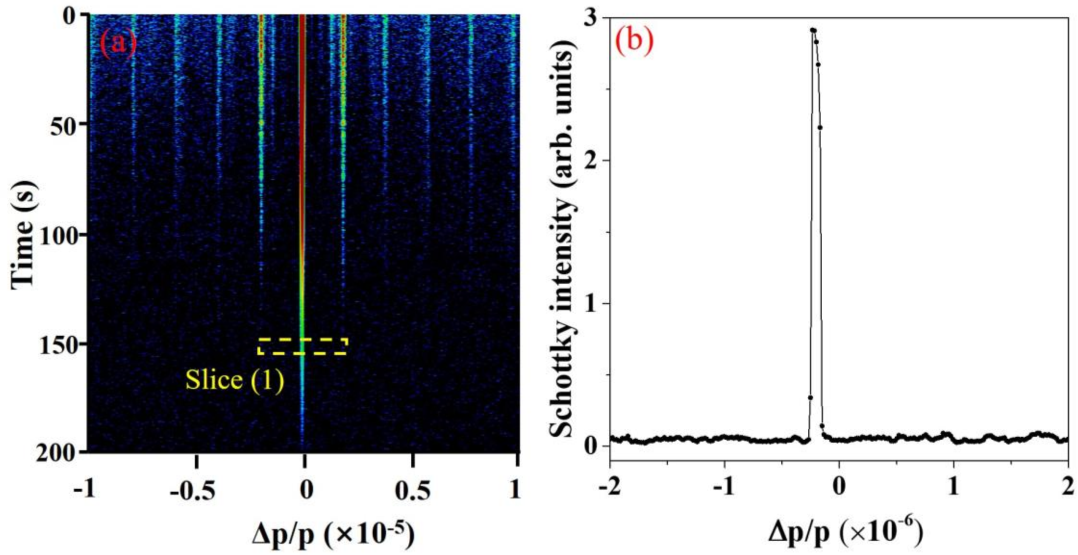

Figure 1. (a) Schottky spectrum of laser-cooled bunched $^{16}O^{5+}$ ion beams with a fixed laser. (b) The relative longitudinal momentum spread extracted from Slice (1) in figure (a).

Reference:
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Commissioning And Calibration Of The Precision High Voltage Divider For The Electron Cooler At CRYRING@ESR

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In high precision experiments at ion storage rings the velocity of the ions is a critical quantity. For measurements at CRYRING@ESR the electron cooler determines the ion velocity and momentum spread of the ions by superimposing the ion beam with a mono-energetic electron beam. Therefore a precise knowledge of the acceleration voltage of the electron beam is essential for the accuracy of the experiments. At the University of Münster we constructed a high-precision voltage divider for voltages up to 35 kV with a similar design as the ultrahigh-precision voltage dividers which also have been constructed in Münster in cooperation with PTB for use at the KATRIN experiment [1, 2].

We will present calibration and stability measurements that characterize the performance of the high voltage divider. With a novel absolute calibration method developed in Münster the voltage dependency of the dividers scale factors could be measured to the ppm-level. As a consequence it is possible to conduct ppm-precise voltage measurements over the whole 35 kV range of the divider.

Furthermore we will give an outlook on the future use of the HV divider since in July 2018 the divider has been delivered to and was integrated into the CRYRING@ESR facility.

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Relativistic calculations of X-Ray transition energies and isotope shifts in heavy atoms

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In present work we have evaluated the energies and the isotope shifts of the X-ray lines in neutral atoms using the configuration-interaction Dirac-Fock-Sturm method in approximation of the barycenter of valence nonrelativistic configuration. The obtained results are compared with the previous calculations [1, 2] and experiments [1, 3]. The comparison demonstrates good agreement of the obtained theoretical results for the K-lines and the related isotope shifts in uranium and mercury atoms. In case of the L-lines, there exist some discrepancies between theory and experiment [4] for the isotope shifts in uranium atoms. The discrepancy becomes especially large for the $L\beta_1$ lines.

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