# 16th SPARC Workshop

Sunday 08 September 2019 - Friday 13 September 2019

Friedrich-Schiller-Universität Jena

# Book of Abstracts

# Contents

**Poster Session / 0**

## The Jena S-EBIT facility

**Author(s):** MORGENROTH, Tino[1]
**Co-author(s):** Dr. TROTSENKO, Sergiy [1] ; HERDRICH, Marc Oliver [1] ; VOROBYEV, Gleb [1] ; Dr. HERFURTH, Frank [1] ; Prof. SCHUCH, Reinhold [2] ; STÖHLKER, Thomas [1]

[1] *GSI, Darmstadt*

[2] *Stockholm university*

**Corresponding Author(s):** t.morgenroth@gsi.de

Studies at Electron Beam Ion Traps (EBIT) have gained large interest in particular in the domain of atomic physics and astrophysics. Here, the majority of experiments are based on x-ray spectroscopy of the trapped ions. Therefore, one can acquire detailed knowledge about transitions in partially ionized atomic systems and also gain information on the physical processes in EBITs to make statements particularly concerning the ion charge-state distributions. In such x-ray spectroscopic studies, the energy resolution plays particularly important role. The S-EBIT facility of the Helmholtz Institute Jena [1], apart from other activities, provides a tool for further steps in the improvement of x-ray spectroscopy in terms of resolving power and collection efficiency. In such types of experiments, magnetic metallic microcalorimeters possess new very promising x-ray detection technology that combines the excellent spectral resolution being typical for crystal spectrometers with the high stopping power of solid-state detectors. With this detector technology, the resolution for photon energies in keV range can be as good as a few eV [2]. Furthermore EBITs can be used as small standalone ion sources, as they are already used at GSI, for example at the HITRAP facility [3] and the HILITE experiment. The S-EBIT II is currently in commissioning on the HITRAP-platform and is planned as a standalone ion source for HITRAP or CRYRING [4]. This would increase the amount of usable ions in the event that the GSI ion facility is offline, which would increase the opportunities for local experiments, like the ARTEMIS g-factor [5] experiment.
[1] R. Schuch, S. Tashenov, I. Orban et al., JINST 5, C12018 (2010). [2] D. Hengstler, M. Keller, C. Schöly et al., Phys. Scripta T166, 014054 (2015). [3] Z. Andelkovic et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 795 (2015). [4] M. Lestinsky et al., Physics book: CRYRING@ESR, EPJ (2016). [5] M. Vogel et al., Annalen der Physik 531, 1800211 (2018)

**International Landscape: Atomic Physics Activities Related to SPARC / 1**

## Laboratory measurements at an electron beam ion trap: interpretation and astrophysical interest

Dr. AMARO, Pedro[1]

[1] *LIBPhys-UNL*

**Corresponding Author(s):** pdamaro@fct.unl.pt

Soft x-ray observations of astrophysical hot plasmas (few MK) are essential for understanding their physical conditions. L-shell spectra of metals recorded by space missions are widely used to diagnose temperature, electron and ion density, and x-ray opacity.
The x-ray emission from recombining Fe XVII has been measured in an electron beam ion trap with six-times reduced electron energy spread, enabling a clear identification and interpretation of the complex L-shell spectra. We observe a clear distinction between dielectronic recombination, resonant excitation, and direct collision excitation, leading to the formation of the 2p-3d and 2p-3s manifolds, and respective line satellites. A pronounced contribution of resonant excitation in the 2p-3d manifold is noticed, as well as a stepwise population of the upper levels of those transitions by cascades starting from forbidden states. Inconsistencies between measurements and state-of-the-art predictions have been confirmed for the 2p-3d manifold. Our measured cross-sections are of interest for opacity diagnostic of astrophysical plasmas.

We also provide an overview of previous related investigations with regards to relativistic and higher-order effects on dielectronic recombination, on which the interpretation of these new measurements is based.

**Poster Session / 2**

## A community approach to the computation of atomic structures, processes and cascades

Prof. FRITZSCHE, Stephan[1]

[1] *GSI, Darmstadt*

**Corresponding Author(s):** s.fritzsche@gsi.de

JAC, the Jena Atomic Calculator, has been developed for performing (relativistic) atomic structure calculations of different kind and complexity [1]. In particular, this code has been designed and worked out to compute not only atomic state functions and properties but also the (many-electron transition) 'amplitudes' for a large number of atomic processes, including the associated cross sections, rates, angular distributions and various other parameters. While the present focus in developing JAC has been placed upon the (automatic) generation of self-consistent fields, atomic properties and processes, this code will support with some further work also simulations of atomic cascades, the time-evolution of statistical tensors as well as a few semi-empirical estimates of selected atomic properties.
A primary guiding philosophy in designing JAC was to develop a general and easy-to-use toolbox for the atomic physics community, including an interface that is equally accessible for working spectroscopiest, theoreticians and code developers. In addition, I also wish to provide a modern code design, a reasonable detailed documentation of the code and features for integrated testing. In particular, most typical atomic calculations and the handling of (atomic) data should appear within the code similar to how they would occur in spoken or written language. Shortly speaking, therefore, JAC aims to provide a powerful platform for daily use and to extent atomic theory towards new applications. In this contribution, I shall explain by simple examples the use of JAC and how the code is distributed via Github [2].
[1] S. Fritzsche, Comp. Phys. Commun. 240 (2019) 1. [2] https://github.com/OpenJAC/JAC.jl (05/7/2019).

**Poster Session / 3**

## Isochronous mass measurement of neutron-rich nuclei using FRS-ESR facilities

**Author(s):** SIDHU, Ragandeep Singh[1]
**Co-author(s):** CHEN, Ruijiu ; Dr. LITVINOV, Yury [1] ; STÖHLKER, Thomas [1]

[1] *GSI, Darmstadt*

**Corresponding Author(s):** r.chen@gsi.de, y.litvinov@gsi.de

The storage of freshly produced secondary ions is the most efficient way to investigate the properties of such exotic particles, which production rates is inevitably small. This is used for precision experiments in the realm of atomic physics and nuclear structure and led to numerous studies at the intersection of both.
Precision mass and half-lifetime measurements of exotic nuclei have always been crucial for understanding nuclear structure properties of bound nuclei. Storage ring mass spectrometry [1, 2] is one of the direct methods by means of which the masses and half-lifetimes of very exotic nuclei can be measured. The combination of FRagment Separator (FRS) and Experimental Storage Ring (ESR) at GSI Helmholtz Centre for Heavy Ion Research, Darmstadt has been employed for past few decades for the purpose of mass measurements of exotic nuclei on both, neutron-rich and neutron-deficient sides of the nuclear chart.
With the motivation for the better understanding of the properties of short-lived exotic nuclei, an Isochronous Mass Spectrometry (IMS) experiment was performed using a 410-415 MeV/u 238U

projectile beam at GSI by M. Matos et al. [3] in 2002. Many neutron rich nuclides were produced via abrasion-fission of the projectile beam with isochronous settings on 130,133,135Sn50+ isotopes. However, except for the PhD thesis [3], the results of the experiment remained unpublished. We reanalyse the data by using improved analysis procedures developed at Institute of Modern Physics (IMP), Lanzhou. In this poster, we discuss some new and improved results from the revised data analysis of the above mentioned experiment.

[1] B. Franzke et al., Mass Spectrom. Rev. 27, 428 (2008).
[2] Yu. A. Litvinov et al., Nucl. Phys. A 756, 3 (2005).
[3] M. Matos, Ph. D. Thesis, Justus Liebig University Giessen, 2004.

**Poster Session / 4**

## Towards Background-Free Studies Of Capture Reactions

**Author(s):** VARGA, Laszlo[1]
**Co-author(s):** Prof. BLAUM, Klaus [2] ; STÖHLKER, Thomas [1] ; WOODS, Phil [3] ; XING, Yuanming [1] ; Dr. DAVINSON, Thomas [4] ; GLORIUS, Jan [1] ; Dr. JURADO, Beatriz [5] ; LANGER, Christoph [1] ; Prof. LEDERER-WOODS, Claudia [6] ; Dr. LITVINOV, Yury [1] ; Dr. REIFARTH, Rene [7] ; SLAVKOVSKA, Zuzana [8]

[1] *GSI, Darmstadt*

[2] *Max-Planck-Institut für Kernphysik*

[3] *University of Edinburgh(UE-SP)*

[4] *University of Edinburgh*

[5] *CENBG*

[6] *Edinburgh University*

[7] *University of Frankfurt*

[8] *Goethe-Universität Frankfurt(UFfm-IAP)*

**Corresponding Author(s):** t.stoehlker@gsi.de, j.glorius@gsi.de, y.litvinov@gsi.de

Stored and cooled highly-charged ions offer unprecedented capabilities for precision studies in the realm of atomic-, nuclear-structure and astrophysics [1].
After the successful investigation of the cross section of the 96Ru(p,γ)97Rh reaction in 2009 [2], the first measurement of the 124Xe(p,γ)125Cs reaction cross section was performed at the Experimental Storage Ring (ESR) of GSI [3] in 2016. Highly-charged 124Xe54+ were produced by accelerating primary beams to relativistic energies and stripping all electrons in a carbon foil. The ions were then injected and stored in the ESR. For the purpose of the experiment, the 124Xe54+ ions had to be decelerated. By using a Double Sided Silicon Strip Detector (DSSSD), the 125Cs proton-capture products have been successfully detected. The DSSSD was put directly into the Ultra-High-Vacuum environment of the ring, which sets severe constraints on the equipment. The cross sections were measured at 5 different energies between 5.5 AMeV and 8 AMeV. The energy range corresponds to the upper energy tail of the Gamow-window of the p-process expected in hot, explosive scenarios such as supernovae and X-ray binaries. The X-rays following the atomic radiative electron capture (REC) have been measured at several angles. The theoretical shape and the amplitude of the REC is well understood in our context. Therefore, the atomic REC cross section for 124Xe+H2 reaction is used for luminosity calibration.
Elastic scattering on the H gas jet target is the major source of background. Monte Carlo simulations show that an additional slit system in the ESR in combination with the energy information of the Si detector will make background free measurements of the proton-capture products possible. The corresponding hardware is being prepared. It will tremendously increase the sensitivity of the method.

[1] F. Bosch et al., Prog. Part. Nucl. Phys.73, 84 (2013)
[2] B. Mei et al., Phys. Rev. C92 035803 (2015)
[3] J. Glorius et al., Phys. Rev. Lett. 122, 092701(2019)

**Poster Session / 5**

## Calculation of the 2D photoelectron momentum distribution for a hydrogen atom exposed to a strong laser field

**Author(s):** Mr. KOZIN, Nikita[1]
**Co-author(s):** Mr. TUMAKOV, Dmitry [2] ; Prof. SHABAEV, Vladimir [2]

[1] *St. Petersburg State University*

[2] *St Petersburg State University*

**Corresponding Author(s):** kozinnv96@gmail.com

The 2D photoelectron momentum distribution for a hydrogen atom exposed to a strong linearly polarized laser field is presented. Time-dependent Schrodinger equation is solved within the dipole approximation numerically using the generalized pseudospectral method. The photoelectron spectrum and angular distribution are obtained with the space partition technique, along with the analytical propagation of the ionized parts of the wave packet in the momentum space. Results are analyzed and compared with calculations in the literature.

**Poster Session / 6**

## Modeling of the prototype of the position-sensitive resonant Schottky cavity for FAIR facility

**Author(s):** DMYTRIIEV, Dmytro[1]
**Co-author(s):** Dr. SANJARI, Shahab [1] ; Dr. LITVINOV, Yury [1] ; STÖHLKER, Thomas [1]

[1] *GSI, Darmstadt*

**Corresponding Author(s):** y.litvinov@gsi.de, t.stoehlker@gsi.de

Storage of secondary highly-charged ions (HCI) in heavy-ion storage rings offers unparalleled opportunities for cross-discipline research comprising atomic physics, nuclear structure and astrophysics. Precision studies with HCIs require dedicated instrumentation.
For instance, studying the rapid neutron capture process (r-process) in stellar environments, that leads to the creation of elements heavier than 56-Fe, remains one of the fundamental questions of modern physics and therefore an active field of research within nuclear astrophysics [1]. Apart from other key measurables like neutron capture cross section and decay lifetimes, atomic masses are of outmost importance for pinpointing the r-process using theoretical and experimental approaches. Exotic nuclides which participate in the r-process due to their low production yield and short half-life can be efficiently investigated in storage rings [2, 3].
In such facilities non-destructive methods of particle detection are often used for in-flight measurements based on frequency analysis [4]. Due to the low signal level the detectors should be very sensitive and fast because of short lifetime of the particles. Resonant Schottky cavity pickups fulfill such requirements [5]. Apart from their applications in the measurements of beam parameters, they can be used in non-destructive in-ring decay studies of radioactive ion beams [4]. In addition, position sensitive Schottky pick-up cavities can enhance precision in the isochronous mass measurement technique. The goal of this work is to design such a position sensitive resonant Schottky cavity pickup based on theoretical calculations and simulations.
References [1] E. Margaret Burbidge et al. "Synthesis of the Elements in Stars". In: Rev. Mod. Phys. 29 (4 Oct. 1957), pp. 547– 650. doi: 10.1103/RevModPhys.29.547. url: https://link.aps.org/doi/10.1103/RevModPhys.29.547.
[2] Fritz Bosch, Yuri A. Litvinov, and Thomas St ¨ohlker. "Nuclear physics with unstable ions at storage rings". In: Progress in Particle and Nuclear Physics 73 (Nov. 2013), pp. 84–140. issn: 01466410. doi: 10.1016/j.ppnp. 2013.07.002. url: https://linkinghub.elsevier.com/retrieve/pii/S0146641013000744 (visited on 12/15/2018).
[3] J.X. Wu et al. "Performance of the resonant Schottky pickup at CSRe". In: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 317 (Dec. 2013), pp. 623–628. issn: 0168583X. doi: 10.1016/j.nimb.2013.08.017. url: https://linkinghub.elsevier.com/retrieve/pii/ S0168583X13008653 (visited on 12/15/2018).
[4] M. S. Sanjari et al. "A resonant Schottky pickup for the study of highly charged ions in storage rings". In: Physica Scripta 2013 (T156 2013), p. 014088. issn: 1402-4896. doi: 10.1088/0031-8949/2013/T156/014088. url: http://stacks.iop.org/1402-4896/2013/i=T156/a=014088.

[5] F. Nolden et al. "A fast and sensitive resonant Schottky pick-up for heavy ion storage rings". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 659.1 (Dec. 2011), pp. 69–77. issn: 01689002. doi: 10.1016/j.nima.2011.06.058. url: https: //linkinghub.elsevier.com/retrieve/pii/S016890021101182X (visited on 12/15/2018).

**Poster Session / 7**

# Monte Carlo simulation of an EDXRF setup with triaxial geometry: using Rayleigh to Compton ratio to evaluate the mean atomic number of unknown samples

**Author(s):** Prof. SANTOS, Jose Paulo[1] ; Mr. MARTINS, Luís Souto[1] ; Prof. CARVALHO, Maria Luísa[1]

**Co-author(s):** Dr. AMARO, Pedro [1] ; Dr. PESSANHA, Sofia [1]

[1] *LIBPhys / University NOVA of Lisbon*

**Corresponding Author(s):** jps@fct.unl.pt

Energy Dispersive X-ray Fluorescence spectrometry is a non-destructive analytical technique that allows multi-element analysis of a large variety of materials in a relatively fast and simple way. The analysis of the fluorescence peaks in the EDXRF spectrum allows elemental identification and quantification. Additional information can be obtained from analyzing the Compton and Rayleigh scattering peaks. Since Compton and Rayleigh scattering cross sections are both dependent on the atomic number Z, the Rayleigh-to-Compton intensity ratio, R_RC, can be used to evaluate the mean atomic number, Z_eff, of the matrix. The calibration curve, R_RC = f(Z_eff), can be obtained by measuring the Rayleigh-to-Compton intensity ratios of several reference materials with known composition and Z_eff, for a given experimental setup. This method permits the determination of the Z_eff of unknown samples [1, 2]. Due to high variation of Rayleigh scattering cross section in the low Z range, this method is highly sensitive for low Z_eff matrices and allows to perceive variations in the matrix that wouldn't be possible from the spectral lines. In a typical setup, where the sample is excited by polychromatic source, this method is affected mainly by the additional background under the scattering peaks and the additional Compton broadening, which may lead to high deviations.

In this work, it is employed an EDXRF spectrometer in a triaxial geometry between the X-ray source, a secondary target, the sample and the detector. Elemental quantification is obtained for standard reference materials of both light, medium and heavy matrices. Furthermore, a calibration curve, R_RC = f(Z_eff), ranging from 7.13 < Z_eff < 14.07, is obtained from measurement of the scattering peaks for a set of model samples consisting of different proportions of reference materials of Hydroxyapatite (HAp) and boric acid. In parallel, simulations for the same spectrometer and samples are performed using Geant4 toolkit [3]. The comparison of experimental and simulated spectra of standard reference materials present a good agreement (of better than 25%) regarding elemental quantification from the fluorescence lines of interest [4]. The comparison between the calibration curves, R_RC = f(Z_eff), obtained from experimental measurements and from the simulations present good agreement, with most of the simulated R_RC values being within the experimental value uncertainty.

The developed method and codes may be adapted to be applied to the analysis of spectra produced by other experimental setups.

This research was supported in part by research center Grant No. UID/FIS/04559/2013 (LIBPhys), from FCT/MCTES/PIDDAC, Portugal. L.SM. acknowledges support from FCT under Contracs PD/BD/105920/2014.

[1] V. Hodoroaba, V. Rackwitz, Analytical Chemistry, 2014, 6858{6864. [2] P. Duvauchelle, G. Peix, D. Babot, Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 1999, 221{228}. [3] Agostinelli, S., J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, et al., Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506, 250 (2003), arXiv:1005.0727v1. [4] P. Amaro, J. P. Santos, A. Samouco, R. Adão, L. S. Martins, S. Weber, S. Tashenov, M. L. Carvalho, and S. Pessanha, Spectrochimica Acta - Part B Atomic Spectroscopy 130, 60 (2017).

**Poster Session / 8**

## Electron Capture to Continuum in 0.5-4.5 MeV/u Collisions of Protons and Deuterons with Gas Targets

**Author(s):** Mr. NANOS, Stefanos[1]
**Co-author(s):** Mr. LAOUTARIS, Angelos [2] ; Mr. MADESIS, Ioannis [3] ; Prof. ZOUROS, Theo [3] ; Prof. BENIS, Emmanouil [4]

[1] *Tandem Accelerator Laboratory, INPP, NCSR Demokritos, GR 15310 Ag. Paraskevi, Greece*

[2] *Department of Physics, University of Crete, Herakleio, Greece & Tandem Accelerator Laboratory, INPP, NCSR Demokritos, GR 15310 Ag. Paraskevi, Greece*

[3] *Department of Physics, University of Crete, Herakleio, Greece & Tandem Accelerator Laboratory, INPP, NCSR Demokritos, GR 15310 Ag. Paraskevi, Greece*

[4] *Department of Physics, University of Ioannina, GR 45110 Ioannina, Greece*

**Corresponding Author(s):** mbenis@uoi.gr

A systematic study of the production of electron capture to continuum (ECC) cusp shape peak in collisions of 0.5-4.5 MeV/u protons and deuterons with He, Ne and Ar gas targets is reported. The measurements were obtained at zero degrees with respect to the ion beam using our electron spectroscopy setup operating at the 5.5MV TANDEM accelerator laboratory of the NCSR "Demokritos" in Athens [1]. Double differential cross sections were obtained after normalizing the measured electron yields to the binary encounter electron peak, recorded in the same spectrum as the cusp peak. The many electrons contribution of the atomic shells to the ECC is provided by the Ne and Ar targets measurements, where a crossing of the energy dependence of the ECC cross sections around the energy of 0.75 MeV/u for the deuterons was observed. Our measurements are accompanied by standard calculations based on the continuum distorted wave eikonal initial state approximation [2] performed with the Ion-Atom/Argon Program [3], showing a reasonable overall agreement, but calling for more elaborate theories to reach a better agreement. Our goal is to provide a complete set of data for the above energy collision systems that can provide a stringent test of more sophisticated theories like the recent four-body distorted wave approximation [4].

1. I. Madesis *et al.*, J. Phys: Conf. Ser. **583**, 012014 (2015).
2. Dž. Belkic, J. Phys. B: At. Mol. Phys. **11**, 3529 (1978).
3. D. M. McSherry *et al.*, Comp. Phys. Com. **155**, 144-155 (2003).
4. J. Monti *et al.*, J. Phys. B: At. Mol. Phys. **42**, 19 (2009).

*We acknowledge support of this work by the project "Cluster of Accelerator Laboratories for Ion-Beam Research and Applications - CALIBRA" (MIS 5002799) implemented under the Action "Reinforcement of the Research and Innovation Infrastructure", funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund).*

**Poster Session / 9**

## g factor of highly charged boronlike ions

**Author(s):** ZINENKO, Dmitrii[1]
**Co-author(s):** AGABABAEV, Valentin [2] ; Mr. GLAZOV, Dmitry [1] ; VOLOTKA, Andrey [3] ; SHABAEV, Vladimir [3] ; Dr. PLUNIEN, Guenter [4]

[1] *Saint Petersburg State University*

[2] *Saint-Petersburg State University*

[3] *GSI, Darmstadt*

[4] *Technische Universitaet Dresden*

**Corresponding Author(s):** z-witcher@mail.ru

Significant progress in the g–factor studies in highly charged ions has been achieved in the last two decades [1,2]. Contemporary experiments have reached the precision of 10ˆ−9 — 10ˆ−11 for hydrogenlike and lithiumlike ions [3-6]. In particular, these studies have lead to the most precise up-to-date determination of the electron mass [7]. Furthermore, it was proposed to determine the fine structure constant alpha from the g factors of light [8] and heavy [9] few-electron ions. The ground-state g factor of boronlike argon has been measured recently with ppb precision within the ALPHATRAP project at the Max-Planck Institut fur Kernphysik [6]. The experimental value is in perfect agreement with the theoretical one [6]. The ARTEMIS project at GSI implements the laser-microwave double-resonance spectroscopy of the Zeeman splitting in both ground and first excited states of middle-Z boronlike ions [10,11]. This work presents theoretical g-factor calculations of the ground and first excited states of boronlike ions in the range Z=10 — 92. The first-order interelectronic-interaction corrections are evaluated within the rigorous QED approach in various effective screening potentials. The second-order interelectronic-interaction is considered within the Breit approximation. The QED, nuclear recoil and nuclear size corrections are also taken into account. The results middle-Z boronlike ions in the range Z=10 — 20 have been presented already in Refs [12,13].
References

1. S. Sturm *et al.*, Atoms **5**, 4 (2017).
2. V. M. Shabaev *et al.*, J. Phys. Chem. Ref. Data **44**, 031205(2015).
3. S. Sturm *et al.*, Phys. Rev. Lett. **107**, 023002 (2011).
4. A. Wagner *et al.*, Phys. Rev. Lett. **110**, 033003 (2013).
5. F. Köhler *et al.*, Nat. Commun. **7**, 10246 (2016).
6. I. Arapoglou *et al.*, Phys. Rev. Lett. **122**, 253001 (2019).
7. S. Sturm *et al.*, Nature **506**, 467 (2014).
8. V. A. Yerokhin *et al.*, Phys. Rev. Lett. **116**, 100801 (2016).
9. V. M. Shabaev *et al.*, Phys. Rev. Lett. **96**, 253002 (2006).
10. D. von Lindenfels *et al.*, Phys. Rev. A **87**, 023412 (2013).
11. M. Vogel *et al.*, Ann. Phys. (Berlin) **531**, 1800211 (2019).
12. V. A. Agababaev *et al.*, J. Phys. Conf. Ser. **1138**, 012003 (2018).
13. V. A. Agababaev *et al.*, X-Ray Spectrometry, 1-6 (2019).

**Poster Session / 10**

## Nuclear magnetic shielding in highly charged ions

**Author(s):** VOLCHKOVA, Anna[1]
**Co-author(s):** AGABABAEV, Valentin [2] ; Mr. GLAZOV, Dmitry [3] ; VOLOTKA, Andrey [4] ; ZINENKO, Dmitrii [3] ; SHABAEV, Vladimir [4] ; Dr. PLUNIEN, Guenter [5]

[1] *St. Petersburg State University*

[2] *Saint-Petersburg State University*

[3] *Saint Petersburg State University*

[4] *GSI, Darmstadt*

[5] *Technische Universitaet Dresden*

**Corresponding Author(s):** volchania@gmail.com

Investigations of the Zeeman splitting of the hyperfine-structure levels in few-electron ions can serve for precise determination of the nuclear magnetic moments. This problem has become particularly relevant in view of the recently established “Hyperfine Puzzle” [Ullmann et al.,

Nat. Commun. 8, 15484 (2017)]. Detailed investigations have shown that the uncertainty of the magnetic moment values determined by the nuclear magnetic resonance method can be significantly underestimated [Skripnikov et al., Phys. Rev. Lett. 120, 093001 (2018)]. The g-factor of highly charged ions allows one to determine the magnetic moments of nuclei with better accuracy than other available methods. The scheme of the corresponding experiment was presented in [Quint et al., Phys. Rev. A 78, 032517 (2008)]. To implement this method, theoretical calculations are necessary for both the electron g-factor and the hyperfine-interaction correction, which is also termed as the nuclear magnetic shielding constant. This constant was calculated in [Moskovkin et al., PRA 70, 032105 (2004), Yerokhin et al., Phys. Rev. Lett. 107, 043004 (2011); Yerokhin et al., Phys. Rev. A 85, 022512 (2012)] for hydrogen-like and in [Moskovkin et al., Opt. Spectrosc. 104, 637 (2008)] for lithium-like ions. The nuclear magnetic shielding constant for boron-like ions has been calculated recently to the leading order in effective screening potential by our group [Volchkova et al., Nucl. Instum. Methods Phys. Res. B 408, 89 (2017)]. In this work, we present improved results for boron-like ions, including the rigorous evaluation of the first-order electron-electron-interaction effects. As in our previous calculations, we use the non-perturbative A-DKB method (dual kinetic balance method for axially symmetric systems) [Rozenbaum et al., Phys. Rev. A 89, 012514 (2014)]. Within this method an axially symmetric field is included in the Dirac Hamiltonian. Thus, we can obtain solutions of the Dirac equation (energies and wave functions), which include magnetic and hyperfine interactions to all orders. The nuclear magnetic shielding constant is found as a derivative with respect to the field strengths.

**Poster Session / 11**

## Multiconfiguration Dirac-Fock calculations of Zn K-shell radiative and nonradiative transitions

**Author(s):** Prof. SANTOS, Jose Paulo[1] ; Mr. MARTINS, Luís Souto[1] ; Prof. CARVALHO, Maria Luísa[1]

**Co-author(s):** Dr. AMARO, Pedro [1] ; Dr. GUERRA, Mauro Guerra [2] ; Dr. JORGE, Machado [1] ; Dr. PESSANHA, Sofia [1] ; Prof. INDELICATO, Paul [3]

[1] *LIBPhys / University NOVA of Lisbon*

[2] *Universidade Nova de Lisboa*

[3] *CNRS/Laboratoire Kastler Brossel*

**Corresponding Author(s):** jps@fct.unl.pt

We present accurate multiconfiguration Dirac-Fock (MCDF) calculations of Zn K-shell radiative and nonradiative transition rates, which were calculated using the MCDFGME code [1], developed by J.P. Desclaux and P. Indelicato. The energy and wave function for the initial configuration of Zn consisted of a hole in the K-shell (1s^1 2s^2 2p^6 3s^2 3p^6 4s^2 3d^10) as well as the energies and wave functions of all possible final configurations attained through radiative or radiationless transitions were calculated independently, including in most cases all possible extra correlation states up to the 4p orbital. Having obtained accurate energies and wavefunctions, the radiative and radiationless transitions rates for all possible radiative and radiationless transitions are calculated. From the calculated transition rates, partial transition yields, transition intensity ratios, and the shell fluorescence yield are obtained.

We observe good agreement with radiative transition rates and partial fluorescence yields of Scofield's Dirac-Fock calculations [2]. Most radiative transition intensity ratios are also in good agreement with empirical values from NIST Fundamental Parameters Database [3]. The calculated radiationless K-LL total transition rate is lower than Chen et al. Dirac-Fock value [4] and higher than Safronova et al. Dirac-Fock value [5]. K-LX and K-XY calculated total rates are higher than those of Chen et al. and Safronova et al [5]. Calculated nonradiative transition intensities relative to the K-L2(1D2) transition, are in most cases in good agreement with the experimental results from Freedman et al. [6]. The K-shell fluorescence yield calculated in the present work is higher than all experimental and theoretical values compared, likely due to the fact that the calculated total radiationless transition rate is lower than those of other theoretical calculations.
This research was supported in part by research center Grant No. UID/FIS/04559/2013 (LIBPhys), from FCT/MCTES/PIDDAC, Portugal. L.SM. acknowledges support from FCT under Contracs PD/BD/105920/2014.

[1] Desclaux, J. P., Computer Physics Communications 9, 31 (1975). [2] J. Scofield, Physical Review A 9, 1041 (1974). [3] W. T. Elam, B. D. Ravel, and J. R. Sieber, Radiation Physics and Chemistry 63, 121 (2002). [4] M. H. Chen, B. Crasemann, and H. Mark, Atomic Data and Nuclear Data Tables 24, 13 (1979). [5] U. Safronova, W. Johnson, and J. Albritton, Atomic Data and Nuclear Data Tables 77, 215 (2001). [6] M. S. Freedman, F. T. Porter, and F. Wagner, Physical Review 151, 886 (1966).

**Poster Session / 13**

## Ground-State Energies of Heavy Diatomic Homonuclear Quasi-molecules

Mr. KOTOV, Artem[1] ; Mr. GLAZOV, Dmitry[1] ; Mr. MALYSHEV, Aleksei[1] ; Ms. VLADIMIROVA, Anastasia[1] ; Dr. SHABAEV, Vladimir[1] ; Dr. PLUNIEN, Günter[2]

[1] *Department of Physics, St. Petersburg State University*

[2] *Institut für Theoretische Physik, Technische Universität Dresden*

**Corresponding Author(s):** breengles@gmail.com

Few-electron diatomic quasimolecules represent the simplest molecular systems. One of the most interesting cases is heavy quasimolecules in which the total nuclear charge $Z$ is comparable to the critical charge $Z_c = 173$. Such systems can be observed during the heavy-ion collisions planned to be investigated at the GSI and FAIR facilities [1]. The electromagnetic field strength in such systems can be high enough to approach the critical field strength in the Schwinger mechanism $E_c = m^2c^3/(\hbar e) \approx 1.3 \cdot 10^{16}$ V/cm, i.e. spontaneous electron-positron pair production becomes possible [2]. In other words, the lowest-lying electronic state is close to "dive" into the Dirac negative-energy continuum at small enough internuclear distance [3, 4]. In this case the parameter $\alpha Z$ is not small ($\alpha$ is the fine-structure constant) so calculation should be done to all orders in $\alpha Z$.
We present relativistic calculation of the ground-state energy of one- and two-electron diatomic heavy quasimolecules valid to all orders in $\alpha Z$. The Dirac equation with the two-center potential is solved numerically using the dual-kinetic-balanced finite basis set [5]. The obtained results are compared with the results of the previous calculations [6–8]. In addition, we evaluate the one-electron one-loop QED contributions, i.e. self-energy and vacuum-polarization, to the ground-state energy in the monopole approximation of the two-center potential within the rigorous bound-state QED approach.
In case of the two-electron system we also take into account the interelectronic interaction effect to all orders in $\alpha Z$. The one-photon exchange is calculated for the two-center potential. For the two-photon exchange correction, we use the monopole approximation of the potential. To the best of our knowledge, this is the most accurate up-to-date evaluation of the two-electron quasimolecular binding energies.

---

[1] Conceptual Design Report: An International Accelerator Facility for Beams of Ions and Antiprotons, edited by W. Henning (GSI, Darmstadt, 2001).
[2] J. S. Schwinger, Phys. Rev. 82 664 (1951).
[3] Ya. B. Zeldovich and V. S. Popov, Sov. Phys. Usp. 14, 673 (1972).
[4] W. Greiner, B. Müller and J. Rafelski, Quantum Electrodynamics of Strong Fields (Springer-Verlang, Berlin, 1985).
[5] E. B. Rozenbaum et al., Phys. Rev. A 89, 012514 (2014).
[6] I. I. Tupitsyn and D. V. Mironova, Opt. Spectrosc. 117, 351 (2014).
[7] D. V. Mironova et al., Chem. Phys. 449, 10 (2015).
[8] A. N. Artemyev and A. Surzhykov, Phys. Rev. Lett. 114, 243004 (2015).

**Poster Session / 14**

## Bremsstrahlung from twisted electrons in the field of bare heavy nuclei

**Author(s):** Mr. GROSHEV, Maksim[1]
**Co-author(s):** Mr. ZAYTSEV, Vladimir [2] ; Dr. YEROKHIN, Vladimir [3] ; SHABAEV, Vladimir [4]

[1] *St. Petersburg State University*

[2] *Department of Physics, St. Petersburg State University, Ulianovskaya 1, Petrodvorets, 198504 St. Petersburg, Russia*

[3] *Peter the Great St. Petersburg Polytechnic University*

[4] *GSI, Darmstadt*

**Corresponding Author(s):** m.e.groshev@gmail.com

Twisted (or vortex) electrons attract tremendous interest from both experimental and theoretical sides (see Refs. [1-3] for a review and relevant references). The growing interest is mainly caused by the fact that these particles possess a well-defined total angular momentum (TAM) projection $m\hbar$ onto the propagation direction. Currently, the experimental techniques of producing a vortex beam with $m \sim 1000$ are well established [4]. The magnetic moment of the twisted electrons with such a high $m$ is three orders of magnitudes larger than the one of the conventional (plane-wave) electrons. This fact makes vortex beams a powerful tool for studying the magnetic properties of different materials [5-7]. For all these studies, a theoretical description of basic atomic processes is highly required.
In the framework of the present investigation, we present such a description for bremsstrahlung from twisted electrons in the field of bare heavy nuclei. We expand the fully-relativistic plane-wave formalism [8] which takes into accounts the electron-nuclei interaction in all orders to the twisted case with the usage of the method worked out in Ref. [9]. The developed approach is applied for the evaluation of the triple and double differential cross-sections. In addition, the Stokes parameters of bremsstrahlung from twisted electrons are also calculated.
[1] K. Y. Bliokh et al., Phys. Rep. 690, 1 (2017).
[2] S. M. Lloyd et al., Rev. Mod. Phys. 89, 035004 (2017).
[3] H. Larocque et al., Contemp. Phys. 59, 126 (2018).
[4] E. Mafakheri et al., Appl. Phys. Lett. 110, 093113 (2017).
[5] J. Rusz and S. Bhowmick, Phys. Rev. Lett. 111, 105504 (2013).
[6] A. Béché et al., Nat. Phys. 10, 26 (2013).
[7] A. Edström et al., Phys. Rev. Lett. 116, 127203 (2016).
[8] V. A. Yerokhin and A. Surzhykov, Phys. Rev. A 82, 062702 (2010).
[9] V. A. Zaytsev et al., Phys. Rev. A 95, 012702 (2017).

**Poster Session / 15**

## How to observe the vacuum decay in heavy-ion collisions

**Author(s):** Mr. MALTSEV, Ilia[1]
**Co-author(s):** SHABAEV, Vladimir [2] ; KOZHEDUB, Yury [2] ; Mr. POPOV, Roman [3] ; Dr. PLUNIEN, Guenter [4] ; STÖHLKER, Thomas [2]

[1] *St. Petersburg State University*

[2] *GSI, Darmstadt*

[3] *Saint Petersburg State University*

[4] *TU Dresden*

**Corresponding Author(s):** ilia.alexm@gmail.com

In low-energy collisions of heavy ions with the total nuclear charge larger than $Z_{\mathrm{cr}} \approx 173$, the QED vacuum can spontaneously decay via production of electron-positron pairs. Detection of the emitted particles would be the direct evidence of this fundamental phenomenon. However, the spontaneously produced particles are indistinguishable from the dynamical background in the positron spectra. In the present talk, it is shown that the vacuum decay can nevertheless be detected via impact-sensitive measurements of pair-production probabilities. Possibility of such detection is demonstrated using numerical calculations of pair production in slow collisions of heavy bare nuclei.

**Poster Session / 16**

## Magnetic effects in the elastic scattering of twisted electrons by bare nuclei

**Author(s):** Ms. KOSHELEVA, Valeriia[1]
**Co-author(s):** Dr. ZAYTSEV, Vladimir [2] ; Prof. SURZHYKOV, Andrey [3] ; Prof. SHABAEV, Vladimir [2] ; STÖHLKER, Thomas [4]

[1] *Department of Physics, St. Petersburg State University, 7/9 Universitetskaya naberezhnaya, St. Petersburg 199034, Russia; Helmholtz-Institut Jena, D-07743 Jena, Germany; GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*

[2] *Department of Physics, St. Petersburg State University, 7/9 Universitetskaya naberezhnaya, St. Petersburg 199034, Russia*

[3] *Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany; Technische Universit¨t Braunschweig, D-38106 Braunschweig, Germany*

[4] *GSI, Darmstadt*

**Corresponding Author(s):** shvartzz@yandex.ru

The twisted (or vortex) electrons, whose existence was theoretically predicted in Ref. [1], nowadays are widely explored in various fields of physics (see, e.g., [2-4] and references therein). These electrons can carry a total angular momentum (TAM) projection onto the propagation direction, which can be as high as 1000 [5]. For the twisted beams with such large TAM projection determining the magnitude of the magnetic moment of the electron, one can expect the significant enhancement of the subtle magnetic effects [6-12].
Here we investigate the elastic (Mott) scattering of the twisted electrons by bare nuclei with nonzero nuclear spin. Let us note that the case of zero nuclear spin was studied in Refs. [13] and [14] within the first Born approximation and all-order treatment, respectively. In the framework of the present investigation, we analyze the influence of nuclear properties such as the nuclear spin and the nuclear magnetic dipole moment on the angular distribution of the outgoing electron.

[1] K. Y. Bliokh et al., Phys. Rev. Lett. 99, 190404 (2007).
[2] K. Y. Bliokh et al., Phys. Rep. 690, 1 (2017).
[3] S. M. Lloyd et al., Rev. Mod. Phys. 89, 035004 (2017).
[4] H. Larocque et al., Contemp. Phys. 59, 126 (2018).
[5] E. Mafakheri et al., Appl. Phys. Lett. 110, 093113 (2017).
[6] K. Y. Bliokh et al., Phys. Rev. Lett. 107, 174802 (2011).
[7] S. Lloyd et al., Phys. Rev. Lett. 108, 074802 (2012).
[8] G. M. Gallatin and B. McMorran, Phys. Rev. A 86, 012701 (2012).
[9] I. P. Ivanov and D. V. Karlovets, Phys. Rev. Lett. 110, 264801 (2013).
[10] J. Rusz and S. Bhowmick, Phys. Rev. Lett. 111, 105504 (2013).
[11] A. Be´che´ et al., Nat. Phys. 10, 26 (2013).
[12] A. Edstro¨m et al., Phys. Rev. Lett. 116, 127203 (2016).
[13] V. G. Serbo et al., Phys. Rev. A 92, 012705 (2015).
[14] V. P. Kosheleva et al., Phys. Rev. A 98, 022706 (2018).

**Poster Session / 17**

## Reference-free measurements of x-ray transitions in lithium-like sulfur and argon ions

**Author(s):** Dr. PAUL, Nancy[1]
**Co-author(s):** Dr. MACHADO, Jorge [2] ; BIAN, Guojie [1] ; Dr. TRASSINELLI, Martino [3] ; Dr. AMARO, Pedro [4] ; Dr. GUERRA, Mauro Guerra [5] ; Dr. SZABO, Csilla [6] ; GUMBERIDZE, Alexandre [7] ; ISAC, Jean-Michel [8] ; Prof. SANTOS, Jose Paulo [9] ; Prof. DESCLAUX, Jean-Paul [1] ; Prof. INDELICATO, Paul [10]

[1] *Laboratoire Kastler Brossel*

[2] *FCT, Universidade Nova de Lisboa*

[3] *Insitut des NanoSciences de Paris*

[4] *LIBPhys-UNL*

[5] *Universidade Nova de Lisboa*

[6] *Theiss Research, NIST*

[7] *GSI, Darmstadt*

[8] *Laboratoire Kastler Brossel, Ecole Normale Supérieure*

[9] *FCT, Universidade Nova Lisboa*

[10] *CNRS/Laboratoire Kastler Brossel*

**Corresponding Author(s):** nancy.paul@lkb.upmc.fr

We have used the Paris double-flat crystal spectrometer and high intensity ECRIS source to make reference-free measurements of the 1s 2s 2p2 P1/2,3/2 –> 1s2 2s2 S1/2 transitions in lithiumlike sulfur and argon, as well as the forbidden 1s 2s 2p4 P5/2 –> 1s2 2s2 S1/2 M2 transition in both elements. Transition energies are extracted with accuracies ranging from 2.9 ppm to 6.4 ppm, and represent the most accurate measurements ever of transition energies from core-excited three-electron ions. Widths and intensity ratios of the 1s 2s 2p2 P1/2,3/2 –> 1s2 2s2 S1/2 doublets have also been measured. The energies, widths, and intensity ratios are compared with advanced Multi-configuration Dirac Fock calculations. Bayesian techniques using NestedFit sampling are applied to test for the presence of hidden satellite lines, and an extensive comparison is performed between existing experimental and theoretical results.

**Poster Session / 19**

## Third-order diagrams of interelectronic interaction in bound-state QED

**Author(s):** VLADIMIROVA, Anastasia[1]
**Co-author(s):** Mr. GLAZOV, Dmitry [2] ; SHABAEV, Vladimir [3]

[1] *St. Petersburg State University*

[2] *Saint Petersburg State University*

[3] *GSI, Darmstadt*

**Corresponding Author(s):** kaktys171819@yandex.ru

Modern experiments with highly charged ions have reached a level of precision where the third-order multielectron QED effects come into play. In particular, the 2p_1/2 - 2s transition energy in lithium-like uranium was measured with an uncertainty of 0.015 eV [1], while the unknown QED contribution of three-photon-exchange estimated as 0.07 eV largely determines the theoretical uncertainty [2]. Similar situation takes place for the ground-state g-factor values of lithium-like silicon and calcium [3,4,5] and for the hyperfine splitting in lithium-like bismuth [6,7,8]. At the same time, this investigation provides independent determination of the fundamental constants and stringent tests of bound-state QED [9,10,11].
This context highly motivates theoretical investigations of the third-order interelectronic-interaction contributions within the rigorous QED approach. Using the two-time Green's function method [12,13], we derive the complete set of formulas for the energy shift from the two-electron three-photon-exchange Feynman diagrams. These diagrams possess two loops, which leads to double integration over intermediate energies. Contributions of the individual diagrams may contain infrared divergences, which cancel altogether. We analyze these divergences for the case of the ground state of a helium-like atom.
References:
[1] P. Beiersdorfer, H. Chen, D.B. Thorn, and E. Traebert, Phys. Rev. Lett. 95, 233003 (2005).
[2] Y.S. Kozhedub et al., Phys. Rev. A 77, 032501 (2008).
[3] A. Wagner et al., Phys. Rev. Lett. 110, 033003 (2013).
[4] F. Koehler et al., Nat. Commun. 7, 10246 (2016).
[5] D.A. Glazov et al., arXiv:1903.11609.
[6] A.V. Volotka et al., Phys. Rev. Lett. 108, 073001 (2012).
[7] J. Ullmann et al., Nat. Commun. 8, 15484 (2017).
[8] L.V. Skripnikov et al., Phys. Rev. Lett. 120, 093001 (2018).

[9] A.V. Volotka, D.A. Glazov, G. Plunien, and V.M. Shabaev, Ann. Phys. (Berlin) 525, 636 (2013).
[10] M.G. Kozlov, M.S. Safronova, J.R. Crespo Lopez-Urrutia, and P.O. Schmidt, Rev. Mod. Phys. 90, 045005 (2018).
[11] V.M. Shabaev et al., Hyperfine Interact. 239, 60 (2018).
[12] V.M. Shabaev, Phys. Rev. 356, 119 (2002).
[13] V.M. Shabaev, I.G. Fokeeva, Phys. Rev. A 49, 4489 (1994).

**Facilities relevant for SPARC / 20**

## Nuclear orbiting resonances in atomic phenomena

Dr. NANDI, Tapan[1]

[1] *Inter-University Accelerator Centre, JNU Campus, New Delhi 110067, India.*

**Corresponding Author(s):** nanditapan@gmail.com

T. Nandi1, Yash Kumar2, Prashant Sharma3, A.P. Mishra4, D. Mitra5, G. Singh6, N. Dwivedi7, S.R. Jain7, and A. Khiefets8
1Inter-University Accelerator Centre, JNU Campus, New Delhi 110067, India. 2Dipartimento di Fisica "Galileo Galilei", Universita di Padova, I-35131 Padova, Italy. 3Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel. 4Atomic & Molecular Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400 085, India. 5Department of Physics, Kalyani University, Kalyani, Nadia, West Bengal-741235, India. 6USICT, GGSIPU, New Delhi - 110078, India. 7Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai - 400 085, India. 8Research School of Physics, The Australian National University, Canberra, ACT 0200, Australia.
Resonances in nuclear orbiting have been studied in the past for various nuclear reactions [1]. Present work demonstrates that the nuclear orbiting can occur even at the sub-barrier energies. Even though the dinuclear orbiting cross section at these energies is up to two orders of magnitude higher than the Coulomb excitation cross sections, no study for nuclear orbiting at sub barrier energies has yet been conducted using any nuclear techniques. The target and projectile nuclei in the dinuclear complex are so close that higher nuclear charge is felt by the orbital electrons. By incorporating this fact into a simple model, we have determined the orbiting duration for the dinuclear complex. Interestingly, these values are found to be within a factor of three larger than that of the predictions made by the nucleon exchange code HICOL [2]. Nuclear recoil induced shake off ionization explains well only the enhanced ionization [3] whereas the present mechanism of dinuclear orbiting explains both the enhanced ionization and anomalously large angle scattering [4]. A very significant point is to note that the experimentally observed resonance energies are reproduced by a scattering theory [5]. Another interesting fact is that the difference between the resonance energy and interaction barrier gives us the orbiting energy. It means the interaction barrier is revealed to be the point from where the nuclear force starts acting. Hence, interaction barrier radius can be a good measure of the range of the nuclear force. We have also tried to unravel the possible origin of the short time scale of the orbiting complex. It is the Coulomb excitation process, which diminishes the orbiting energy considerably within a few zs so that the orbiting complex breaks into the incoming channels. We have proposed the multi photon exchange as a single virtual photon, which is responsible not only for the Coulomb excitation, but also for the atomic excitation. The excitation in an atomic system with a vacancy in the K-shell can lead to autoionization, which does not occur instantly, rather it goes through Wigner-Smith time delay [6] of the order of a few hundreds of as. Hence, the orbiting induced ionization triggered in nuclear time scale (zs) transfers the phenomenon occurring in atomic time scale (as) so that one can measure the x-ray emissions. This process enables us to explain the longstanding discrepancy between the measured values of fission time scales by the nuclear and atomic techniques. Formation of the dinuclear orbiting complexes at sub-barrier energies thus exhibits an intriguing research area in the interface of atomic and nuclear physics. This area of research can be explored in GSI, especially for heavier systems, what is not possible at our place.

[1] A. Ray, Nucl. Phys. A787, 499 (2007) and references therein. [2] H. Feldmeier, Rept. Prog. Phys. 50, 915 (1987). [3] P. Sharma and T Nandi, Phys. Rev. Lett. 119, 203401 (2017). [4] P. Braun-Munzinger et al., Phys. Rev. Lett. 38, 944 (1977). [5] H.J. Korsch and K.E. Thylwe, J. Phys. B16, 793 (1983). [6] A. Kheifets et al., Phys. Rev. A 92, 063422 (2015).

**Poster Session / 21**

# A free-electron target for the heavy-ion storage rings at FAIR

**Author(s):** BRANDAU, Carsten[1]
**Co-author(s):** Dr. BOROVIK, Alexander [2] ; Mr. DÖHRING, Michel [3] ; Mr. EBINGER, Benjamin [4] ; Dr. LESTINSKY, Michael [1] ; Prof. MÜLLER, Alfred [5] ; Prof. SCHIPPERS, Stefan [5]

[1] *GSI, Darmstadt*

[2] *Justus-Liebig Universität Gießen*

[3] *Justus-Liebig-Universität, FB07, AG für Atom- und Molekülphysik*

[4] *Justus-Liebig-Universität Gießen*

[5] *JLU Giessen*

**Corresponding Author(s):** michel.doehring@physik.uni-giessen.de

At present a free-electron target is being built that delivers a ribbon-shaped electron beam and operates in transverse collision geometry, i.e., with an interaction angle of 90° between ion and electron beams. The target is optimized for applications in the heavy-ion storage rings of the international Facility for Antiproton and Ion Research (FAIR) and will initially be installed at the low-energy ring CRYRING@ESR.
[1] Lestinsky M et al 2016 Eur. Phys. J. ST 225 797
[2] Lestinsky M et al 2015 Phys. Scr. T166 014075
[3] Brandau C et al 2016 GSI Scientifc Report, p 240
[4] Brandau C et al 2017 GSI Scientifc Report, p 179
[5] Brandau C et al 2017 J. Phys. CS 875 052040
[6] Ebinger B et al 2017 Nucl. Instrum. Meth. B 408 317

**Poster Session / 22**

# First experimental results from a new high-power electron gun: Electron-impact ionisation of multiply charged xenon ions

**Author(s):** Mr. DÖHRING, Michel[1]
**Co-author(s):** Mr. EBINGER, Benjamin [2] ; Dr. BOROVIK, Alexander [3] ; Dr. HUBER, Kurt [4] ; Dr. JIN, Fentao [5] ; Prof. MÜLLER, Alfred [6] ; Prof. SCHIPPERS, Stefan [6]

[1] *Justus-Liebig-Universität, FB07, AG für Atom- und Molekülphysik*

[2] *Justus-Liebig-Universität Gießen*

[3] *Justus-Liebig Universität Gießen*

[4] *JLU Gießen*

[5] *Department of Physics, National University of Defense Technology*

[6] *JLU Giessen*

**Corresponding Author(s):** michel.doehring@physik.uni-giessen.de

During recent years we have developed a new high-current electron gun for the Giessen electron-ion crossed-beams experiment aiming at an extension of the previously available collision-energy range of 1–1000˜eV to 3500˜eV. Here, we report on the first measurements of absolute cross sections for electron-impact ionisation of multiply charged xenon ions employing the new electron gun. Comparisons with available experimental and theoretical data from the literature provide

convincing evidence that the new electron gun can be operated reliably over the entire design energy-range.

[1] Borovik A et al 2015 J. Phys. B 48 035203
[2] Borovik A et al 2013 J. Phys. B 46 175201
[3] Ebinger B et al 2017 Nucl. Instrum. Meth. B 408 317
[4] Lestinsky M et al 2016 Eur. Phys. J. ST 225 797

**Poster Session / 23**

## The low energy beamline of the FISIC experiment: current status of construction and performance

**Author(s):** Dr. SCHURY, Daniel[1]
**Co-author(s):** Dr. MÉRY, Alain [2] ; Mr. STEYDLI, Sebastien [3] ; Dr. TRASSINELLI, Martino [4] ; Prof. VERNHET, Dominique [5] ; GUMBERIDZE, Alexandre [6] ; STÖHLKER, Thomas [6] ; Dr. BRÄUNING-DEMIAN, Angela [6] ; Mr. HAHN, Christoph [6] ; SPILLMANN, Uwe [6] ; Prof. LAMOUR, Emily [7] ; Mr. RAMILLON, Jean-Marc [2] ; Prof. ADOUI, Lamri [2] ; Prof. CHESNEL, Jean-Yves [2] ; Dr. LÉVY, Anna [8] ; Mr. MACÉ, Stephane [8] ; Dr. PRIGENT, Christophe [9] ; Dr. RANGAMA, Jimmy [2] ; Dr. ROUSSEAU, Patrick [2]

[1] *INSP, Sorbonne Université, Paris*

[2] *CIMAP, CEA/CNRS/ENSICAEN/Université de Caen Normandie*

[3] *UPMC / INSP*

[4] *Insitut des NanoSciences de Paris*

[5] *INSP- UMR CNRS 7588- UPMC- Sorbonne Universités*

[6] *GSI, Darmstadt*

[7] *Institut des NanoSciences de Paris - UPMC*

[8] *INSP, Sorbonne Université*

[9] *INSP/UPMC*

**Corresponding Author(s):** daniel.schury@insp.upmc.fr

So far, ion-ion collisions in atomic physics were performed mainly in the context of magnetically confined plasmas using crossed beam devices in the low-energy domain where electron capture is the dominant process or fast-ion/plasma-discharge experiments with a charge state distribution as target. Up to today no reliable experimental data exists for fast (MeV/u) and slow (keV/u) ion collisions in the regime where the ion stopping power (energy transfer) is maximum. There all the primary electronic processes (electron capture, -loss and -excitation) reach their maximum and therefore the role of the individual processes on the collision is almost impossible to disentangle, while being of high importance in ion-matter interaction, including biological materials. To fill in the blanks we are designing a new ion-ion collision experiment, the FISIC project (\textbf{F}ast \textbf{I}on \textbf{S}low \textbf{I}on \textbf{C}ollisions), a mobile experimental set-up, although being quite complex, being able to conduct crossed beam ion-ion collisions at different high energy ion beam facilities. Today we present the current status of the set-up and performance of the low-energy branch of FISIC, which will deliver a medially- to highly-charged pure low-energy ion beam which will then be crossed with high energy ions. Test results, mainly on the charge state purification, carried out at the ARIBE beam-line at the GANIL facility in Caen and at Sorbonne Universit\'e in Paris, utilizing the SIMPA ion source, will be presented. The obtained experimental data can be favourably compared with numerical simulation. Proposed experiments at different facilities such as CRYRING@ESR or S3/Spiral2/GANIL and the status of the integration of our beam-line into the existing infrastructure will be discussed.

**International Landscape: Atomic Physics Activities Related to SPARC / 24**

## FISIC Experiment at CRYRING

**Author(s):** Mr. SCHURY, Daniel[1]
**Co-author(s):** Dr. MÉRY, Alain [2] ; Dr. BRÄUNING-DEMIAN, Angela [1] ; Mr. HAHN, Christoph [1] ; SPILLMANN, Uwe [1] ; Prof. LAMOUR, Emily [3] ; Mr. RAMILLON, Jean-Marc [2] ; Mr. MACÉ,

Stéphane [4] ; Dr. PRIGENT, Christophe [5] ; Dr. RANGAMA, Jimmy [2] ; Mr. STEYDLI, Sebastien [6] ; Prof. VERNHET, Dominique [7] ; GUMBERIDZE, Alexandre [1] ; STÖHLKER, Thomas [1]

[1] *GSI, Darmstadt*

[2] *CIMAP, CEA/CNRS/ENSICAEN/Université de Caen Normandie*

[3] *Institut des NanoSciences de Paris - UPMC*

[4] *INSP, Sorbonne Université, Paris*

[5] *INSP/UPMC*

[6] *UPMC / INSP*

[7] *INSP- UMR CNRS 7588- UPMC- Sorbonne Universités*

**Corresponding Author(s):** d.schury@gsi.de

So far, ion-ion collisions in atomic physics were performed mainly in the context of magnetically confined plasmas using crossed beam devices in the low-energy domain where electron capture is the dominant process or fast-ion/plasma-discharge experiments with a charge state distribution as target. Up to today no reliable experimental data exists for fast (MeV/u) and slow (keV/u) ion collisions in the regime where the ion stopping power (energy transfer) is maximum. There all the primary electronic processes (electron capture, -loss and -excitation) reach their maximum and therefore the role of the individual processes on the collision is almost impossible to disentangle, while being of high importance in ion-matter interaction, including biological materials. To fill in the blanks we are designing a new ion-ion collision experiment, the FISIC project (\textbf{F}ast \textbf{I}on \textbf{S}low \textbf{I}on \textbf{C}ollisions), a mobile experimental set-up, although being quite complex, being able to conduct crossed beam ion-ion collisions at different high energy ion beam facilities. Today we present the current status of the set-up and performance of the low-energy branch of FISIC, which will deliver a medially- to highly-charged pure low-energy ion beam which will then be crossed with high energy ions. We will focus on the status and challenges on integrating the set-up into the CRYRING facility and propose experiment cases.

**Poster Session / 25**

## Bound Electron g-factor Measurements at ARTEMIS

**Author(s):** KLIMES, Jeffrey William[1] ; KANIKA, Kanika[None]
**Co-author(s):** GUO, Zhexi ; Dr. QUINT, Wolfgang [1] ; VOGEL, Manuel [1] ; Prof. BIRKL, Gerhard [2] ; Mr. BAUS, Patrick [2] ; SHAABAN, Mouwafak [1]

[1] *GSI, Darmstadt*

[2] *Technische Universität Darmstadt*

**Corresponding Author(s):** j.klimes@gsi.de, k.kanika@gsi.de

The ARTEMIS experiment is designed for high precision measurements of the g-factor of electrons bound in heavy, highly charged, atomic systems using laser-microwave double-resonance spectroscopy. Such g-factor measurements are tests of calculations in the realm of bound-state QED in strong fields. To study such highly charged ions (HCIs), they are confined to a small volume inside a Penning trap, where they can be resistively cooled via their image current such that their trajectories are well-defined, and they can be stored for weeks. These long storage times indicate a residual gas pressure inside the trap chamber of less than $10^{-15}$ $mbar$. Production and capture of such HCIs is possible in situ of the experiment by way of a mini-EBIT integrated into the trap design. It has been shown to produce highly charged Ar atoms up to charge state 16+. Future ions will be delivered to the experiment from the HITRAP facility via a specialized injection beamline. The second stage of ARTEMIS is a half-open Penning trap design with large optical access for laser-microwave spectroscopy and a nearly homogeneous magnetic field. This stage is used to obtain g-factor measurements with the highest achievable precision.

**26**

## Registration

**Opening / Welcome and Status / 27**

## Registration

**Opening / Welcome and Status / 28**

## Welcome

**Corresponding Author(s):** t.stoehlker@gsi.de

**Opening / Welcome and Status / 29**

## Status SPARC

**Corresponding Author(s):** schuch@fysik.su.se

**Opening / Welcome and Status / 30**

## The Helmholtz Institute Jena

**Corresponding Author(s):** t.stoehlker@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 31**

## QED With Heavy Ions: On the Way From Strong to Supercritical Fields

**Corresponding Author(s):** v.shabaev@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 32**

## Status of μ-Calorimeter Detector Development for 1s Lamb Shift in U91+@CRYRING

**International Landscape: Atomic Physics Activities Related to SPARC / 33**

## Status Report: Towards first Experiments at CRYRING

**Corresponding Author(s):** m.lestinsky@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 34**

## Status of the Hyperfine Puzzle and Preparation of Upcoming Experiments for Bi80+,82+

**Corresponding Author(s):** r.sanchez@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 35**

## Status of the ESR

**Corresponding Author(s):** m.steck@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 36**

## Precision Collision Spectroscopy of Be-like Ions at the CRYRING@ESR Cooler

**Corresponding Author(s):** schippers@jlug.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 37**

## Laser Spectroscopy on Be-like Kr at ESR

**Corresponding Author(s):** d.winters@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 38**

## COLTRIMS at HESR

**Corresponding Author(s):**

**International Landscape: Atomic Physics Activities Related to SPARC / 39**

## Relativistic Calculations of the Binding Energies in Few-Electron Diatomic Quasimolecules

**Corresponding Author(s):** glazov.d.a@gmail.com

**International Landscape: Atomic Physics Activities Related to SPARC / 40**

## Polarization Effects in Bound-Free Pair Production in Light-Ion Interaction

**Corresponding Author(s):** j.sommerfeldt@tu-bs.de

**International Landscape: Atomic Physics Activities Related to SPARC / 41**

## Status of the HITRAP Facility

**Corresponding Author(s):** z.andjelkovic@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 42**

## Status of the ARTEMIS Experiment at HITRAP

**Corresponding Author(s):** w.quint@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 43**

## Status GSI/FAIR

**Corresponding Author(s):** p.giubellino@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 44**

## Gamma Factory at CERN: Overview

**Corresponding Author(s):**

**International Landscape: Atomic Physics Activities Related to SPARC / 45**

## Atomic Physics Program at Gamma Factory

**Corresponding Author(s):** budker@uni-mainz.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 46**

## Charge State Tailoring for Gamma Factory

**Corresponding Author(s):** felixkr1990@yahoo.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 47**

## High Precision Tests of Strong-Field QED in He-like Uranium

**Corresponding Author(s):** martino.trassinelli@insp.jussieu.fr

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 48**

## Laser-Assisted Nuclear Physics Experiments in Traps and Storage Rings

**Corresponding Author(s):** fkarpeshin@gmail.com

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 49**

## Measurement of Bound-State Beta Decay of 205Tl Ions

**Corresponding Author(s):** r.chen@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 50**

## Status of Internal Gas Targets (ESR, CRYRING, HESR)

**Corresponding Author(s):** n.petridis@gsi.de

**Poster Session / 51**

## Electron-loss-to-continuum cusp in relativistic collisions of uranium ions with gaseous targets

**Author(s):** Dr. BONDAREV, Andrey[1]
**Co-author(s):** KOZHEDUB, Yury [2] ; SHABAEV, Vladimir [2]

[1] *St. Petersburg State University*

[2] *GSI, Darmstadt*

**Corresponding Author(s):** a.bondarev@spbu.ru

Collisions of highly charged ions with atoms and molecules represent a unique tool for investigating the electron dynamics and testing various theoretical approaches. With the implementation of storage rings, the process of electron loss to continuum (ELC) became accessible for experimental study. In this process, the projectile (heavy ion) is ionized in a collision with a gas target. Due to kinematical conditions the electron emission in the laboratory frame occurs mainly in a narrow cone around the ion direction of motion with a velocity close to the ion velocity. Herewith in the energy distribution of the emitted electrons a specific cusp at the energy corresponding to zero emission energy in the projectile reference frame is observed. Although for some systems this process has been investigated since a long time theoretically [1, 2], as well as experimentally [3], its detailed experimental study was hampered by the need to use the coincidence technique. Along with the detection of the emitted electron, it is necessary to detect the change of charge state of the projectile after the collision. This allows one to distinguish between electrons ionized from the projectile and target. Thus, the first experiments exploiting the coincidence technique to measure the spectrum of electrons emitted by heavy ions in collisions with gas targets were carried out only quite recently [4, 5]. The theoretical description of these experiments was performed within the framework of first-order perturbation methods. For the 90 MeV/u U88+-N2 collision the theoretical results are in good agreement with the experimental data [4]. However, for the 50 MeV/u U28+-H2, 30 MeV/u U28+-N2 and 50 MeV/u U28+-Xe collisions the agreement is quite poor: the experiment shows strong asymmetry of the cusp, while the theory predicts an almost symmetric cusp [5]. Possible reasons for this discrepancy are due to the use of a too simple model for the multielectron structure of the uranium ion and the use of first-order perturbation-theory methods. In this contribution, we report a recent progress in extension of our relativistic approach to calculation cross sections for ionization in ionatom collisions [6, 7] towards description of the aforementioned experiments.

References

[1] Briggs J S and Drepper F 1978 J. Phys. B 11 4033
[2] Burgdoerfer J et al. 1983 Phys. Rev. A 28 327
[3] Stolterfoht N et al. 1974 Phys. Rev. Lett. 33 59
[4] Hillenbrand P-M et al. 2014 Phys. Rev. A 90 042713
[5] Hillenbrand P-M et al. 2016 Phys. Rev. A 93 042709
[6] Bondarev A I et al. 2017 Phys. Rev. A 95 052709
[7] Bondarev A I et al. 2019 Eur. Phys. J. D 73 46

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 52**

## Cryogenic Current Comparators: Non-destructive Beam Diagnostics for FAIR

**Corresponding Author(s):**

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 53**

## Measurements of Proton-Induced Reaction Rates on Rare Isotopes for the Astrophysical p Process

**Corresponding Author(s):** j.glorius@gsi.de

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 54**

## Nuclear Astrophysical Reaction Studies Using the CRYRING Reaction Chamber System

**Corresponding Author(s):** carlo.bruno@ed.ac.uk

**CRYRING Session: Offline Operation, Local Injector / 55**

## Accurate Position Calibration of Beam Position Monitors in Storage Rings

**Corresponding Author(s):** t.wagner@fz-juelich.de

**CRYRING Session: Offline Operation, Local Injector / 56**

## Current Developments of XUV Light Sources for Storage Rings

**Corresponding Author(s):** j.rothhardt@gsi.de

**CRYRING Session: Offline Operation, Local Injector / 57**

## ECR Ion-Source as Local Injector at CRYRING

**Corresponding Author(s):** alexander.borovik@physik.uni-giessen.de

**CRYRING Session: Offline Operation, Local Injector / 58**

## Controls and DAQ for DR Experiments at the CRYRING Cooler

**Corresponding Author(s):** c.brandau@gsi.de

**Collaboration Meeting / 59**

## Topics: Funding Situation: International and National, Common Funds, Status Reports, APPA R&D "BMBF Verbundforschung"

**Corresponding Author(s):** a.braeuning-demian@gsi.de, schuch@fysik.su.se, schippers@jlug.de

**Collaboration Meeting / 60**

## SPARC Board Meeting (Closed Session)

**Corresponding Author(s):**

**SPARC PhD-Prize / 61**

## PhD-Prize Talk: High-Precision Measurement of the Proton's Atomic Mass

**Corresponding Author(s):** fabian.heisse@mpi-hd.mpg.de

**Interaction of Ions with Intense Laser Fields / 62**

## The HILITE Experiment: Status and Prospects

**Corresponding Author(s):** n.stallkamp@gsi.de

**Interaction of Ions with Intense Laser Fields / 63**

## Vacuum Photon Emission in Strong Space-Time-Dependent Electromagnetic Fields

**Corresponding Author(s):** i.aleksandrov@spbu.ru

**Interaction of Ions with Intense Laser Fields / 64**

## Anomalous Multiphoton Ionization of H-like Ions Exposed to few-cycle Laser Pulses

**Corresponding Author(s):** ira.ivanova.v@gmail.com

**Interaction of Ions with Intense Laser Fields / 65**

## Relativistic Calculations of the Photoelectron Angular Distributions for a H-like Ion Exposed to a Strong Laser Field

**Corresponding Author(s):** dm.tumakov@gmail.com

**International Landscape: Atomic Physics Activities Related to SPARC / 66**

## HIBEF Facility at XFEL

**Corresponding Author(s):** t.cowan@hzdr.de

**International Landscape: Atomic Physics Activities Related to SPARC / 67**

## QED in Strong Laser Fields

**Corresponding Author(s):** f.karbstein@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 68**

## High-Precision Polarimetry: Towards Observing Vacuum Birefringence at XFEL

**International Landscape: Atomic Physics Activities Related to SPARC / 69**

## The g-Factor of Bound Electrons

**Corresponding Author(s):** a.volotka@gsi.de

**70**

## Social Event

**Social Event / 71**

## Bus Trip to Leuchtenburg

**Social Event / 72**

## Walk to Leuchtenburg

**Social Event / 73**

## Guided Tour Leuchtenburg

**Social Event / 74**

## BBQ Dinner

**Social Event / 75**

## Walk to Bus Stop

**Social Event / 76**

## Bus Trip Back to Jena

**Facilities relevant for SPARC / 77**

## Current Status of the HIAF Project

**Corresponding Author(s):** x.ma@impcas.ac.cn

**Facilities relevant for SPARC / 78**

## Muonic Atom Experiment with Microcalorimeter at J-PARC

**Corresponding Author(s):** sokada@riken.jp

**Facilities relevant for SPARC / 79**

## ELENA at CERN

**Corresponding Author(s):** eberhard.widmann@oeaw.ac.at

**Facilities relevant for SPARC / 80**

## TO BE SELECTED

**International Landscape: Atomic Physics Activities Related to SPARC / 81**

## Experiments on Liquid Jets at XFEL

**Corresponding Author(s):** r.grisenti@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 82**

## 229Th Studies with Micro-Calorimeters

**Corresponding Author(s):** andreas.fleischmann@kip.uni-heidelberg.de

**International Landscape: Atomic Physics Activities Related to SPARC / 83**

## In-Ring Experiments on Nuclear Reactions

**Corresponding Author(s):** jurado@cenbg.in2p3.fr

**International Landscape: Atomic Physics Activities Related to SPARC / 84**

## Laboratory measurements at an electron beam ion trap: interpretation and astrophysical interest

**Corresponding Author(s):** pdamaro@fct.unl.pt

**International Landscape: Atomic Physics Activities Related to SPARC / 85**

## COLTRIMS at CRYRING

**Corresponding Author(s):** l.schmidt@em.uni-frankfurt.de

**International Landscape: Atomic Physics Activities Related to SPARC / 86**

## FISIC Experiment at CRYRING

**Corresponding Author(s):** d.schury@gsi.de

**International Landscape: Atomic Physics Activities Related to SPARC / 87**

## Ultrafast Relaxation of Hollow Rydberg Atoms in Solids

**Corresponding Author(s):**

**International Landscape: Atomic Physics Activities Related to SPARC / 88**

## Closing Speech

**Corresponding Author(s):** schuch@fysik.su.se

**Darmstadt Visit / 89**

## Bus Trip to Darmstadt

**Darmstadt Visit / 90**

## Tour GSI and FAIR Construction Site

**Darmstadt Visit / 91**

## Bus Trip back to Jena

**Poster Session / 92**

## Higher-order recombination processes in Argon ions observed via x-ray emission in an EBIT

**Author(s):** Ms. BIELA, Weronika[1]
**Co-author(s):** Mr. LA MANTIA, David [2] ; Prof. WARCZAK, Andrzej [3] ; Prof. TANIS, John [2]

[1] *Jagiellonian University*

[2] *Department of Physics, Western Michigan University, Kalamazoo, MI 49008 USA*

[3] *Jagiellonian University, Krakow*

**Corresponding Author(s):** weronika.biela@student.uj.edu.pl

The electron-electron interaction is a crucial aspect of atomic reactions involving electron-ion collisions. An effective way to investigate electron-electron interaction is to study the higher-order recombination processes. The most basic of those recombination processes is dielectronic recombination. DR is the time reversal to the Auger process and thus is well-known and investigated in many different highly-charged systems [1,2]. In this resonant process, a free electron is captured while another bound electron is excited due to the direct interaction between the two electrons. The recombination is completed through radiative stabilization of the excited ion. The research presented here was conducted the Jagiellonian University EBIT[3]. An XFlash SD x-ray detector was positioned perpendicular to the electron beam axis. The very good

resolution of the x-ray detector enabled the K-LL DR resonances to be distinguished for He- up to N-like Ar ions. In this region, in addition to the K-LL DR, one of the $2p_{1/2}$ subshell electrons can be excited to the $2p_{3/2}$ subshell state [2]. A significant influence of various intershell TR processes (KL-LLL) was observed and caused a broadening of Be- to N-like DR lines [2]. These results encouraged more detailed present studies of TR, specifically of KK TR. There, the resonant capture of a free electron to an ionbound state transfers two K-shell electrons to a higher atomic shell. This way, a doubly-excited K-shell state is produced and, in most cases, it decays via emission of two photons. The first transition with two vacancies in the K shell is responsible for the emission of photon ($K_a^h$) with a slightly higher energy than following satellite transition ($K_a^s$). This TR process has been not reported yet to the best of our knowledge. This work presents significant arguments for a successful observation of the KK-LMM TR process in Ar ions. The data set was collected for the trap ionization time between 100 ms and 250 ms for different electron-beam energies in the region (5200-7500) eV. This electron energy region was expected to manifest a significant enhancement of the hypersatellite Ar-K x-ray emission due to the TR processes mentioned above. Indeed, we observed a maximum-like behavior of the intensity ratio between this radiation and the satellite Ar-$K_a$ radiation. \newline References: [1] T.M.Baumann. Z.Harman, J.Stark, et al. Phys. Rev. A 90, 052704 (2014)\\ [2] C.Beilmann, P.H.Mokler, Z. Harman, et al. Phys. Scr. T144, 014014 (2011)\\ [3] G.Zschornack, M.Schmidt and A.Thorn, CERN Yellow Report 007, 165-201 (2013)

**Poster Session / 93**

## Impact of experimental DR rates on modeling astrophysical photoionized plasmas

Dr. FOGLE, Michael[1]

[1] *Auburn University*

**Corresponding Author(s):** fogle@physics.auburn.edu

Previously measured DR rates at storage rings have been used to model astrophysical photoionized environments with the CLOUDY modeling software package. The CLOUDY package uses calculated DR rates while previous comparison to experiment has shown that correlation effects can be considerable at low DR energies, leading to errant rates. Several storage ring-derived DR rates have been used to show the impact to modeling these environments.

**International Landscape: Atomic Physics Activities Related to SPARC / 94**

## QED with heavy ions: on the way from strong to supercritical fields

Prof. SHABAEV, Vladimir[1]

[1] *St.Petersburg State University*

**Corresponding Author(s):** v.shabaev@spbu.ru

The current status of tests of quantum electrodynamics with heavy ions is reviewed. The theoretical predictions for the Lamb shift and the hyperfine splitting in heavy ions are compared with available experimental data. Recent achievements and future prospects in studies of the g factor with highly charged ions are also discussed. Theoretical calculations of the pair-creation probabilities in low-energy heavy-ion collisions are also considered. Special attention is paid to tests of QED in supercritical field regime, which can be accessed in slow collisions of two heavy ions with the total nuclear charge number larger than the critical value, Z_c ≈173. In the supercritical field, the initially neutral vacuum can spontaneously decay into the charged vacuum and two positrons. It is demonstrated that this fundamental phenomenon can be observed via impact-sensitive measurements of pair-production probabilities.

**Poster Session / 95**

## Performance of a Scintillator-Based Ion Detector for CRYRING@ESR

**Author(s):** Ms. MENZ, Esther Babette[1] ; Mr. PFÄFFLEIN, Philip[1] ; Mr. HAHN, Christoph[1]
**Co-author(s):** WEBER, Günter [2] ; STÖHLKER, Thomas [2]

[1] *Helmholtz Institute Jena*

[2] *GSI, Darmstadt*

**Corresponding Author(s):** e.menz@gsi.de

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 first stored beam at CRYRING in 2017. Since then several test beamtimes have taken place and the first user experiments are scheduled for 2019. To fully exploit the multifaceted field of research thus made accessible, the availability of robust and reliable ion detectors is of significant importance [1]. These sensors will need to provide single-hit detection efficiency at MHz count rates of ions with energies ranging from sub-MeV/u to 15 MeV/u, while withstanding the radiation damage imparted by the energetic ions. Given these restrictions, a detector system based on the YAP:Ce crystal scintillator provides an attractive approach, utilizing a material that is endowed with a significant degree of radiation hardness while remaining comparatively affordable [2]. A detector system was designed and constructed as part of the CRYRING@ESR instrumentation and has been installed at the ring. The contribution details the detector design and outlines the results of characterization measurements before and after installation. A proof-of-concept measurement was conducted with various ion species at the 3 MV tandem accelerator JULIA operated by the University of Jena's Institute of Solid State Physics. This experiment confirmed the feasibility of the setup and found a destruction threshold fluence (50% signal amplitude loss) of approximately $10^{13}$ $cm^{-2}$ across the range of ion species and energies investigated. At CRYRING the detector is located downstream from the electron cooler and will be used for the observation of electron-ion recombination products. The system has already demonstrated its viability in commissioning measurements with $H_2^+$ and $D^+$ beams from the local ion source. These light ions could be detected even at the injection energy of 300 keV/u and from the measured count rate the lifetime of the $H_2^+$ beam was determined to be ˜180 ms. A further beamtime with $Mg^+$ revealed impact of the ring dipole magnetic field on the conventional photomultiplier used to detect the light produced in the scintillator. A silicon photomultiplier is being investigated as an alternative readout system. The setup will be used for e.g. dielectronic recombination and 1s Lamb shift measurements on slow, heavy, highly-charged ions of all species that the GSI accelerator complex is able to produce and transport through ESR.
References [1] Lestinsky M et al **2016** *Eur. Phys. J. Special Topics* **225**, 797 [2] Lindroth et al **2001** *Phys. Rev. Lett.* **86**, 5027

**Poster Session / 96**

# Quasimolecular radiation emission in low-energy ion-atom collisions

**Author(s):** Mr. POPOV, Roman[1]
**Co-author(s):** KOZHEDUB, Yury [2] ; Prof. TUPITSYN, Ilya [3] ; SHABAEV, Vladimir [2]

[1] *Saint Petersburg State University*

[2] *GSI, Darmstadt*

[3] *St.Petersburg State University*

**Corresponding Author(s):** st016948@student.spbu.ru

Quasimolecular radiation emission spectra have been calculated in long wavelength approximation for low-energy Ar-$Cl^{16+}$ collisions. The calculation technique is based on numerical solution of the time-dependent Dirac equation in two-center basis set constructed from atomic Dirac-Fock-Sturm orbitals. Coherent superposition of the transition amplitudes on the inbound and outbound halves of the collision trajectory leads to interference structures in the radiation emission spectra. Comparison of the calculated spectra with experimental data can give information about electron dynamics and the energy levels of the quasimolecule formed during the collision. It cam be used to search for effects induced by supercritical electric fields appearing when total charge number of

the colliding ions exceeds $Z_{\text{cr}} \approx 173$. Another possible application is for detection of superheavy elements.

**Interaction of Ions with Intense Laser Fields / 97**

## Anomalous multiphoton ionization of hydrogenlike ions exposed to few-cycle laser pulses

**Author(s):** Ms. IVANOVA, Irina[1]
**Co-author(s):** Prof. SAENZ, Alejandro [2] ; Prof. SHABAEV, Vladimir [1]

[1] *St.Petersburg State University*

[2] *Humboldt University Berlin*

**Corresponding Author(s):** ira.ivanova.v@gmail.com

Recent technological advances in ultrafast optics give us an opportunity to produce short, only few-cycle laser pulses. The development of laser technologies has stimulated investigations of ionization by few-cycle pulses.
Earlier it was shown that few-cycle effects should be found for any atom, ion, or molecule. It was tested in the nonrelativistic case by solving the time-dependent Schrödinger equation [Chengpu Lui and Takashi Nakajima, Phys. Rev. A **76**, 023416 (2007)]. Few-cycle effects can be described as increasing of the ionization efficiency by fewer-cycle pulses in comparison with the ionization by larger-cycle pulses in the low intensity region, where multiphoton ionization is the dominant ionization mechanism.
In the current research, we have focused on further investigation of anomalous ionization yields. Based on the previous results, we have investigated the same effect of anomalous ionization for the relativistic systems. We have considered the one-electron uranium exposed to few-cycle laser pulse. Ionization probabilities have been calculated by solving the time-dependent Dirac equation. We can conclude that the effect of anomalous ionization still exists and has the similar behaviour in the relativistic case as it is in the nonrelativistic one. Also, we have tried to explain why the change in ionization to the anomalous one always occur in a very sharp manner, almost instantaneously, and why the behaviour of anomalous ionization does not follow the expected perturbative results.

**Poster Session / 98**

## QED theory of the specific mass shift in few-electron ions

**Author(s):** Ms. MIRONOVA, Darya[1]
**Co-author(s):** Dr. MALYSHEV, Aleksei [2] ; Ms. ANISIMOVA, Irina [2] ; Prof. SHABAEV, Vladimir [2] ; Prof. PLUNIEN, Günter [3]

[1] *St. Petersburg State University*

[2] *Department of Physics, St. Petersburg State University*

[3] *Institut für Theoretische Physik, Technische Universität Dresden*

**Corresponding Author(s):** darvlmir@gmail.com

Within the Breit approximation, the nuclear recoil effect on binding energies in atoms and ions can be treated by employing the mass shift (MS) Hamiltonian [1-2]. The MS operator is widely employed nowadays in relativistic calculations of the atomic electronic structure and, especially, isotope shifts (see, e.g., Refs. [3-5] and references therein). This Hamiltonian allows one to take into account the nuclear recoil corrections within the $(m/M)(\alpha Z)^4 mc^2$ approximation. The fully relativistic theory of the nuclear recoil effect to all orders in $\alpha Z$ can be formulated only in the framework of quantum electrodynamics (QED) [1,6-8].
All the previous calculations of the nuclear recoil contributions to all orders in $\alpha Z$ were limited by the independent-electron approximation, i.e., the interelectronic-interaction effects were treated only to zeroth order in $1/Z$. The present study aims at further development of the QED theory of the nuclear recoil effect in atoms. The formalism of quantum electrodynamics for treating the interelectronic-interaction correction of first order in $1/Z$ to the two-electron part of the nuclear

recoil effect on binding energies in atoms and ions is developed [9]. The nonperturbative (in $\alpha Z$) calculations of the corresponding contribution to the energies of the $1s^2$ state in He-like and the $1s^2 2s$ and $1s^2 2p_{1/2}$ states in Li-like ions are performed in the range $Z = 5 - 100$. The behavior of the two-electron part of the nuclear recoil effect beyond the lowest-order relativistic approximation as a function of $Z$ is studied.

[1] V. M. Shabaev, Theor. Math. Phys. **63**, 588 (1985); Sov. J. Nucl. Phys. **47**, 69 (1988).
[2] C. W. P. Palmer, J. Phys. B **20**, 5987 (1987).
[3] I. I. Tupitsyn *et al.*, Phys. Rev. A **68**, 022511 (2003).
[4] N. A. Zubova *et al.*, Phys. Rev. A **93**, 052502 (2016).
[5] J. Ekman *et al.*, Comput. Phys. Commun. **235**, 433 (2019).
[6] V. M. Shabaev, Phys. Rev. A **57**, 59 (1998).
[7] K. Pachucki and H. Grotch, Phys. Rev. A **51**, 1854 (1995).
[8] G. S. Adkins, S. Morrison, and J. Sapirstein, Phys. Rev. A **76**, 042508 (2007).
[9] A. V. Malyshev, I. S. Anisimova, D. V. Mironova, V. M. Shabaev, and G. Plunien, Phys. Rev. A **100**, 012510 (2019).

**Poster Session / 99**

## QED calculations of the transition energies in high-Z heliumlike ions

**Author(s):** Dr. MALYSHEV, Aleksei[1]
**Co-author(s):** Dr. KOZHEDUB, Yury [1] ; Dr. GLAZOV, Dmitry [1] ; Prof. TUPITSYN, Ilya [1] ; Prof. SHABAEV, Vladimir [1]

[1] *Department of Physics, St. Petersburg State University*

**Corresponding Author(s):** alvlamal@gmail.com

Heliumlike ions play a special role in studying highly charged ions. Possessing only two bound electrons, they represent the simplest system where the many-electron QED effects can be studied. The calculations of the $n = 1$ and $n = 2$ energy levels in He-like ions performed in Ref. [1] more than ten years ago are considered as a benchmark theoretical treatment of these effects in two-electron systems. Drawing on the x-ray transition measurements in He-like titanium and statistical treatment of the previous experimental data, Chantler *et al.* [2] claimed that a divergence between experimental results and the theory from Ref. [1] growing as $Z^3$ takes place. New measurements [3-7] and statistical studies [5,7,8], which include the extended sets of experimental data, have shown that there is no evidence for the aforementioned $Z$-dependent deviation. Moreover, in our recent study [9] we have performed completely independent *ab initio* calculations of the x-ray transitions in middle-$Z$ heliumlike ions. We found no possible explanation from the theoretical side for the significant discrepancy between the theory and measurements with heliumlike titanium performed in Ref. [2]. On the other hand, our results were found to be generally in agreement with the the most recent high-precision experimental values. In the present study, our calculations are extended to high-$Z$ ions. The most advanced methods are applied in order to evaluate the transition energies in heliumlike xenon and uranium.

[1] A. N. Artemyev *et al.*, Phys. Rev. A **71**, 062104 (2005).
[2] C. T. Chantler *et al.*, Phys. Rev. Lett. **109**, 153001 (2012).
[3] J. K. Rudolph *et al.*, Phys. Rev. Lett. **111**, 103002 (2013).
[4] K. Kubicek *et al.*, Phys. Rev. A **90**, 032508 (2014).
[5] P. Beiersdorfer and G. V. Brown, Phys. Rev. A **91**, 032514 (2015).
[6] S. W. Epp *et al.*, Phys. Rev. A **92**, 020502(R) (2015).
[7] J. Machado *et al.*, Phys. Rev. A **97**, 032517 (2018).
[8] S. W. Epp, Phys. Rev. Lett. **110**, 159301 (2013).
[9] A. V. Malyshev, Y. S. Kozhedub, D. A. Glazov, I. I. Tupitsyn, and V. M. Shabaev, Phys. Rev. A **99**, 010501(R) (2019).

**Poster Session / 101**

## Scaling Relations for a Hydrogen-Like Ion in an Intense Laser Field in the Quasi-Static Regime

**Author(s):** Mr. KHUJAKULOV, Anvar[1]
**Co-author(s):** Prof. SAENZ, Alejandro [2]

[1] *Humboldt University*

[2] *Humboldt University Berlin*

**Corresponding Author(s):** anvar@physik.hu-berlin.de

Identifying relativistic effects is one of the interesting, but challenging subjects in the interaction of highly charged ions with intense ultra-short laser pulses. Within the dipole approximation the time-dependent Schr\"{o}dinger equation (TDSE) of hydrogen-like ions can be mapped onto the one of the hydrogen atom by scaling relations [L. B. Madsen and P. Lambropoulos, Phys.\,Rev.\,A \textbf{59}, 4574 (1999)]. In contrast to the non-relativistic regime, strict analytic scaling relations are, however, not known for the Dirac equation. Thus the nonrelativistic scaling relations can be a practical tool for a systematic analysis of relativistic effects. If the variation of the electric component of the laser pulse is slow on the time scale of the ion, the electron of the ion can follow the field adiabatically. This is known as the quasi-static approximation. In this case, ionization at any instant of time is given by the ionization rate induced by the instantaneous electric-field component of the laser pulse. Therefore, within the dipole approximation the time-independent Schr\"{o}dinger and Dirac equations in a static electric field are solved. This is achieved by the complex-scaling method. The deviation of the relativistic results from the non-relativistic ones is discussed, and it is explained based on a semi-classical theory of tunneling ionization. Novel, though approximate relativistic scaling relations are introduced and their validity is discussed. These scaling relations are the useful tool to predict \textit{relativistic} ionization rates using the \textit{non-relativistic} Schr\"{o}dinger equation solution. Moreover, it is discussed how these scaling relations can be used for calibrating novel high-intensity light sources.

**Poster Session / 102**

## ECR ion source for the local injector of CRYRING at GSI/FAIR

**Author(s):** Mr. WILLAMOWSKI, Paul[1]
**Co-author(s):** Mr. FUCHS, Sebastian [1] ; Dr. BOROVIK, Alexander [2] ; Dr. FEDOTOVA, Svetlana [3] ; Dr. LESTINSKY, Michael [3] ; Dr. VOROBJEV, Gleb [3] ; Prof. SCHIPPERS, Stefan [1]

[1] *Justus-Liebig-Universität Gießen*

[2] *Justus-Liebig Universität Gießen*

[3] *GSI, Darmstadt*

**Corresponding Author(s):** sebastian.fuchs@physik.uni-giessen.de

We report on the adaption of an all-permanent-magnet 10-GHz electron-cyclotron-resonance (ECR) ion source for the local injector of the heavy-ion storage ring CRYRING at the international Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. Optimizations are being carried out for a first in-ring experiment with $C^+$ ions.

**International Landscape: Atomic Physics Activities Related to SPARC / 104**

## Relativistic calculations of the binding energies in few-electron diatomic quasimolecules

Mr. GLAZOV, Dmitry[1] ; Mr. KOTOV, Artem[2] ; Dr. MALYSHEV, Aleksei[3] ; VLADIMIROVA, Anastasia[2] ; SHABAEV, Vladimir[4] ; Dr. PLUNIEN, Guenter[5]

[1] *Saint Petersburg State University*

[2] *St. Petersburg State University*

[3] *Department of Physics, St. Petersburg State University*

[4] *GSI, Darmstadt*

[5] *Technische Universitaet Dresden*

**Corresponding Author(s):** glazov.d.a@gmail.com

Investigations of the low-energy heavy-ion collisions aim at observation of the spontaneous electron-positron pair production in the supercritical field of two heavy nuclei [1,2,3]. While the dynamics of these collisions is extensively studied within the most advanced theoretical methods (see, e.g., [4] and references therein), accurate predictions for the quasimolecular spectra within the rigorous QED framework are in high demand. As an important step towards this goal, we have adapted the dual-kinetically-balanced finite-basis-set method [5,6] for two-center Dirac equation. The quasi-complete spectrum for the electron bound by two nuclei can be used to evaluate any contributions within the bound-state QED perturbation theory. We demonstrate the abilities of this method by accurate evaluation of the electron binding energies in heavy one- and two-electron molecular ions. One-electron energies are found in agreement with the previously published values [7,8,9]. For two-electron ions, the one-photon-exchange contribution is calculated to all orders in the parameter $\alpha Z$ for the two-center potential. The two-photon-exchange, self-energy and vacuum-polarization contributions are calculated to all orders in the parameter $\alpha Z$ within the monopole approximation.

---

[1] Conceptual Design Report: An International Accelerator Facility for Beams of Ions and Antiprotons, edited by W. Henning (GSI, Darmstadt, 2001).
[2] Ya. B. Zeldovich and V. S. Popov, Sov. Phys. Usp. **14**, 673 (1972).
[3] W. Greiner, B. Müller and J. Rafelski, Quantum Electrodynamics of Strong Fields (Springer-Verlang, Berlin, 1985).
[4] I. A. Maltsev, V. M. Shabaev, R. V. Popov, Y. S. Kozhedub, G. Plunien, X. Ma, and Th. Stöhlker, Phys. Rev. A **98**, 062709 (2018).
[5] V. M. Shabaev, I. I. Tupitsyn, V. A. Yerokhin, G. Plunien, and G. Soff, Phys. Rev. Lett. **93**, 130405 (2004).
[6] E. B. Rozenbaum, D. A. Glazov, V. M. Shabaev, K. E. Sosnova, and D. A. Telnov, Phys. Rev. A **89**, 012514 (2014).
[7] I. I. Tupitsyn and D. V. Mironova, Opt. Spectrosc. **117**, 351 (2014).
[8] D. V. Mironova, I. I. Tupitsyn, V. M. Shabaev, and G. Plunien, Chem. Phys. **449**, 10 (2015).
[9] A. N. Artemyev and A. Surzhykov, Phys. Rev. Lett. **114**, 243004 (2015).

**Interaction of Ions with Intense Laser Fields / 105**

## Relativistic Calculations of the Photoelectron Angular Distributions for a H-like Ion Exposed to a Strong Laser Field

**Author(s):** Mr. TUMAKOV, Dmitry[1]
**Co-author(s):** Prof. TELNOV, Dmitry [1] ; Prof. SHABAEV, Vladimir [1]

[1] *St Petersburg State University*

**Corresponding Author(s):** dm.tumakov@gmail.com

The photoelectron angular distributions for a hydrogen-like ion exposed to a strong linearly polarized laser field is presented. Time-dependent Dirac equation is solved within the dipole approximation numerically using the generalized pseudospectral method in the velocity and length gauges. The photoelectron spectrum and angular distribution are obtained with the space partition method, along with the analytical propagation of the ionized parts of the wave packet in the momentum space.

**Poster Session / 106**

## Nanostructuring of gold nanolayers by an impact of low-energy highly charged xenon ions

**Author(s):** Dr. BANAŚ, Dariusz[1]
**Co-author(s):** Ms. STABRAWA, Ilona [1] ; Dr. BORYSIEWICZ, Michał [2] ; Dr. KUBALA-KUKUŚ, Aldona [1] ; Mr. JABŁOŃSKI, Łukasz [1] ; Dr. JAGODZIŃSKI, Paweł [1] ; Mr. SOBOTA, Daniel [1] ; Mr. SZARY, Karol [3] ; Prof. PAJEK, Marek [1] ; Dr. MENDYK, Ewaryst [4] ; Mr. SKRZYPIEC, Krzysztof [4]

[1] *Institute of Physics, Jan Kochanowski University*

[2] *Department of Micro- and Nanotechnology of Wide Bandgap Semiconductors, Institute of Electron Technology*

[3] *Jan Kochanowski University*

[4] *Faculty of Chemistry, M. Curie-Sklodowska University*

**Corresponding Author(s):** d.banas@ujk.edu.pl

Modification of metal, semiconductor and insulator surfaces by an impact of single (i.e. each ion creates nanostructure) low-energy highly charged ions (HCI) is of great importance for developing new technologies and has the potential to introduce novel nanostructures and material properties not achievable by any other material processing methods [1].
When HCI approaches to the surface its kinetic and potential energy (the sum of binding energies of the removed electrons) is dissipated at the surface which leads to structural modification of the outermost surface layers and a nanostructure creation [2].
In this work, modifications of Au nanolayers deposited on a crystalline silicon Si (100) wafers caused by HCI xenon were analyzed. The nanolayers were irradiated with $Xe^{q+}$ (q=25-40) ions in the energy range hundreds of keV (nuclear stopping power regime) at a fluence of about $10^{10}$ ions/cm$^2$ [3, 4]. After irradiation the nanolayers were investigated using atomic force microscope. Well pronounced modifications of the nanolayers surfaces, due to impact of the HCI ions, in the form of craters, have been observed for the first time for such systems. As a result dependences of the potential energy, kinetic energy, and nanolayer thickness on the size of the nanostructures were measured systematically.
The results are consistent with previous experimental data and MD simulations for single ionized Xe and crystalline gold surface [5]. We confirmed that the crater formation is due to HCI kinetic energy deposition, but we also found that role of HCI potential energy is very important. The results showed that kinetic energy has mainly in fluence on the crater depth, while potential energy of the HCI changes the crater diameter at the surface. This can be explained by very fast deposition of the potential energy just at the surface (within a subnanometer depth). The results were qualitatively confirmed by preliminary 3D i-TS calculations [6].
**References**

1. Barth J V et al 2005 Nature 437 671
2. Aumayr F et al 2011 J. Phys.: Condens. Matter 23 393001
3. Banaś D et al Nucl. Instr. Meth. B 354 125
4. Stabrawa I et al 2017 Nucl. Instr. Meth. B 408 235
5. Bringa E M et al 2011 Phys. Rev. B 64 235426
6. Dufour C et al 2017 J. Phys.: Condens. Matter 29 095001

**Poster Session / 107**

## HILITE - A well-defined ion target for laser experiments

**Author(s):** Mr. RINGLEB, Stefan[1] ; STALLKAMP, Nils Simon[None]
**Co-author(s):** KIFFER, Markus [1] ; Mr. KUMAR, Sugam [2] ; ARNDT, Bela Peter [3] ; VOGEL, Manuel [3] ; Dr. QUINT, Wolfgang [3] ; STÖHLKER, Thomas [3] ; Prof. PAULUS, Gerhard G. [4]

[1] *Friedrich-Schiller-Universität Jena*

[2] *Inter-University Accelerator Centre*

[3] *GSI, Darmstadt*

[4] *Institute of Optics and Quantum Electronics/Helmholtz Institute Jena*

**Corresponding Author(s):** stefan.ringleb@uni-jena.de, n.stallkamp@gsi.de

The High-Intensity Laser Ion Trap Experiment (HILITE) aims to investigate the interaction of highly-charged ions with extreme laser fields. To this end, we have built the setup based on an open-endcap Penning trap that facilitates the controlled formation of an ion target comprised of selected species, to superimpose it with a high-intensity and/or high-energy laser beam, and to non-destructively detect the confined ion species. To cover a broad range of laser parameters and hence different laser-matter interaction regimes, the setup is built in a compact fashion and allows transport to various large-scale laser facilities. The Penning trap (see figure 1a) is located in the centre of a 6T superconducting magnet and cooled to cryogenic temperatures. The ions are provided by a dedicated source (EBIT), operated in a pulsed extraction mode to create a bunched beam of highly charged ions. These can be pre-selected by a velocity filter and decelerated by a pulsed drift tube. After deceleration, the ions are dynamically captured inside the trap by appropriate switching of electrode voltages. A single-pass 'charge counter' is placed on either side of the trap to determine the number, energy and structure of the incoming and outgoing ion bunches in a non-destructive way. We will present the current status of the setup that has successfully demonstrated ion extraction and selection by the source and velocity filter, as well as transport, deceleration, storage inside the trap and in-trap non-destructive detection. So far, storage times of the order of several tens of minutes have been achieved. Furthermore, we will show the planned measurements at the free-electron laser FLASH@DESY .

**Poster Session / 108**

## Characterisation of ion bunches by a single-pass non-destructive charge counter

**Author(s):** KIFFER, Markus[1] ; Mr. RINGLEB, Stefan[1]
**Co-author(s):** STALLKAMP, Nils Simon ; Mr. KUMAR, Sugam [2] ; ARNDT, Bela Peter [3] ; VOGEL, Manuel [3] ; Dr. QUINT, Wolfgang [3] ; STÖHLKER, Thomas [3] ; Prof. PAULUS, Gerhard G. [4]

[1] *Friedrich-Schiller-Universität Jena*

[2] *Inter-University Accelerator Centre*

[3] *GSI, Darmstadt*

[4] *Institute of Optics and Quantum Electronics/Helmholtz Institute Jena*

**Corresponding Author(s):** markus.kiffer@uni-jena.de, stefan.ringleb@uni-jena.de

The HILITE Penning trap will provide well-defined ion targets to investigate laser-matter interactions in both the high-intensity and high photon-energy regime with highly charged ions. The experimental setup includes an Electron Beam Ion Trap (EBIT) and a velocity filter for access to highly-charged-ion bunches of a selected charge state. For ion bunch detection and analysis we have implemented two distinct single-pass nondestructive charge counting devices. They measure the time-dependent image charge induced by an ion bunch. From such a single-pass signal we can directly extract the kinetic energy, the number of ions and the bunch length. The non-destructive nature allows measurements of products and educts in laser-ion interactions. We will show a brief overview of the HILITE experiment and present the implemented ion counting technique. This includes the theoretical background of induced image charges, the signal analysis method and calibration results for both kinetic energy and absolute ion numbers. Additionally, we will discuss the sensitivity of the setup and the minimum number of detectable ions. Also, we will outline approaches to further increase the signal-to-noise ratio to be even sensitive to less than ten ions per bunch.

**Interaction of Ions with Intense Laser Fields / 109**

## Vacuum photon emission in strong space-time-dependent electromagnetic fields

Mr. ALEKSANDROV, Ivan[1] ; Dr. PLUNIEN, Günter[2] ; Prof. SHABAEV, Vladimir[1]

[1] *Saint Petersburg State University*

[2] *TU Dresden*

**Corresponding Author(s):** i.aleksandrov@spbu.ru

We study a fundamental nonlinear phenomenon of vacuum photon emission in the presence of strong electromagnetic fields going beyond the locally-constant field approximation (LCFA), i.e. providing the exact treatment of the spatio-temporal inhomogeneities of the external field. We examine a standing electromagnetic wave and benchmark the approximate predictions against the results obtained by means of a precise approach evaluating both the tadpole (reducible) and vertex (irreducible) contributions. It is shown that the approximate methods may fail to properly describe important characteristics of the process.

**Poster Session / 110**

## Detector development for colinear laser fluorescence spectroscopy experiments in the extended visible regime

**Author(s):** Mr. BUß, Axel[1]
**Co-author(s):** Prof. NOERTERSHAEUSER, Wilfried [2] ; MOHR, Konstantin [3] ; ANDELKOVIC, Zoran [4] ; Dr. SÁNCHEZ ALARCÓN, Rodolfo Marcelo [4] ; Prof. WEINHEIMER, Christian [5] ; Dr. HANNEN, Volker [6]

[1] *Westfälische-Wilhelms-Universität*

[2] *TU Darmstadt*

[3] *Technische Universität Darmstadt*

[4] *GSI, Darmstadt*

[5] *Institut für Kernphysik, University of Münster*

[6] *Institut für Kernphysik, Uni Münster*

**Corresponding Author(s):** a_buss09@wwu.de

In order to enable laser spectroscopy experiments at CRYRING, a general purpose fluorescence detector has been developed and built at the University of Münster. The detector is capable to detect photons in the extended visible region from 250 nm up to 850 nm. This is achieved by an elliptical reflective chamber, made from MIRO-3, with good reflectivity in the UV, and two sets of three photomultipliers (one UV to visible, and one red sensitive set), which can be selected for maximum efficiency for the respective transition.
The detector has been installed at CRYRING in 2018 . Since then, the detector has proved its functionality with the detection of photons by residual gas ionization - and the initially intended detection of laser fluorescence photons of the singly charged $Mg^+$ ions. Furthermore, a prototype of this setup was tested on top of the SpecTrap experiment. The transition of research was the $1s2s\,^3S_1 \rightarrow 1s2p\,^3P_{0,1,2}$ of $B^{3+}$ ions at approximately 282 nm. Preliminary results of both beam times will be shown.

**Poster Session / 111**

## The SIS100 laser cooling activities

KLAMMES, Sebastian[1] ; Prof. BIRKL, Gerhard[2] ; Prof. SCHRAMM, Ulrich[3] ; Dr. SIEBOLD, Mathias[4] ; Dr. SPILLER, Peter[5] ; STÖHLKER, Thomas[6] ; Dr. ULLMANN, Johannes[7] ; Prof. WALTHER, Thomas[2] ; Dr. WEN, Weiqiang[8] ; Dr. WINTERS, Danyal[5] ; BOINE-FRANKENHEIM, Oliver[5] ; Dr. BUSSMANN, Michael[4] ; EIDAM, Lewin[2] ; Dr. HANNEN, Volker[7] ; Mr. KIEFER, Daniel[2] ; KÜHL, Thomas[9] ; Dr. LÖSER, Michael[3] ; Prof. MA, Xinwen[8]

[1] *GSI Helmholtz Centre for Heavy Ion Research / Technical University Darmstadt*

[2] *Technical University Darmstadt*

[3] *Helmholtz Centre Dresden - Rossendorf / Technical University Dresden*

[4] *Helmholtz Centre Dresden - Rossendorf*

[5] *GSI Helmholtz Centre for Heavy Ion Research*

[6] *GSI Helmholtz Centre for Heavy Ion Research / Helmholtz Institute Jena / Jena University*

[7] *University of Münster*

[8] *Institute of Modern Physics, Chinese Academy of Sciences*

[9] *GSI Helmholtz Centre for Heavy Ion Research / Helmholtz Institute Jena*

**Corresponding Author(s):** s.klammes@gsi.de

In the near future, the Facility for Antiproton and Ion Research (FAIR) will offer charged particle beams at highest energies and intensities for a very broad range of experiments. The heavy-ion synchrotron SIS100 is at the heart of the facility and stores, accelerates, and delivers the beams from the linear accelerators to the rest of the facility. Especially for high-precision experiments, such as laser and X-ray spectroscopy, stored relativistic cold heavy-ion beams, i.e. beams with a small relative momentum spread ($\Delta$p/p) and a small emittance ($\epsilon$), are indispensable and of great interest. Generally, cold ion beams can be obtained by electron cooling and/or stochastic cooling, but prospectively the only method for cooling of bunched heavy-ion beams at the SIS100 after acceleration at final energy is laser cooling [1,2]. For that purpose, an anti-collinear laser beam will be used to excite and thereby transfer momentum to the ions, which will then be counteracted by the rf-bucket. First estimations show that it may be possible to obtain a $\Delta p/p \approx 10^{-7}$ and cooling times of only a few seconds [3]. Laser cooling should assist in making the SIS100 ion bunches even shorter than it is currently being planned by means of bunch compression (< 50 ns), therewith offering world-wide unique possibilities. Because of the huge magnetic rigidity (100 Tm) of the SIS100, very large gamma factors (up to 13) and, correspondingly, large Doppler-shifts can be achieved, which should enable laser cooling (and laser spectroscopy) of a broad range of ion species. We will present the general concept of bunched beam laser cooling and provide an overview of the laser cooling pilot facility at the SIS100.

---

[1] D. Winters et al., Phys. Scr. **T166** 014048 (2015). [2] U. Schramm et al., Prog. Part. Nucl. Phys. **53** 583 (2004). [3] L. Eidam et al., Nucl. Instr. Meth. Phys. Res. A **887** 102 (2018).

**Status of Upcoming SPARC Experiments Within FAIR Phase-0 / 112**

# Laser spectroscopy of Be-like krypton at the ESR

**Author(s):** Dr. WINTERS, Danyal[1]
**Co-author(s):** Dr. HANNEN, Volker [2] ; Prof. INDELICATO, Paul [3] ; KLAMMES, Sebastian [1] ; KÜHL, Thomas [1] ; Prof. LINDROTH, Eva [4] ; Dr. SCHNEIDER, Dieter [5] ; Dr. SÁNCHEZ ALARCÓN, Rodolfo Marcelo [1] ; Prof. SCHUCH, Reinhold [6] ; Prof. WALTHER, Thomas [7] ; STÖHLKER, Thomas [1]

[1] *GSI, Darmstadt*

[2] *Institut für Kernphysik, Uni Münster*

[3] *CNRS/Laboratoire Kastler Brossel*

[4] *Stockholm University*

[5] *Lawrence Livermore National Laboratory*

[6] *Stockholm university*

[7] *TU Darmstadt*

**Corresponding Author(s):** d.winters@gsi.de

Heavy few-electron ions are ideal atomic systems to study effects of correlation, relativity and QED. Be-like ions are interesting because their first excited state (3P0), has an almost infinite lifetime in the absence of nuclear spin, as it can only decay by a two-photon *E1M1* transition to the (1S0) ground state [1]. In addition, the energy difference between the 3P0 and 3P1 states is expected to be almost completely unaffected by QED effects and dominated by the effects of correlation and relativity [2]. We want to determine the 3P0 - 3P1 level splitting in $^{84}Kr^{32+}$ by means of laser spectroscopy at the experimental storage ring at GSI in Darmstadt, with a precision of $\sim 10^{-5}$ [3,4], and compare the result with recent calculations [1,2,5].
References
[1] K. T. Cheng *et al.*, Phys. Rev. A **77** (2008) 052504.
[2] P. Indelicato, using a MultiConfiguration Dirac Fock and General Matrix Elements program ( http://dirac.spectro.jussieu.fr/mcdf )
[3] D.F.A. Winters *et al.*, Phys. Scr. T **144** (2011) 014013.

[4] V. Hannen *et al.*, J. Instrum. **8** (2013) P09018.
[5] S. Fritzsche *et al.*, New J. Phys. **17** (2015) 103009.

**SPARC PhD-Prize / 113**

## High-Precision Measurement of the Proton's Atomic Mass

**Author(s):** Mr. HEIßE, Fabian[1]
**Co-author(s):** Dr. KÖHLER-LANGES, Florian [1] ; Mr. RAU, Sascha [1] ; Ms. HOU, Jiamin [2] ; Mr. JUNCK, Sven [3] ; Dr. KRACKE, Anke [4] ; Dr. MOOSER, Andreas [5] ; Dr. QUINT, Wolfgang [6] ; Dr. ULMER, Stefan [7] ; Prof. WERTH, Guenter [3] ; Dr. STURM, Sven [8] ; Prof. BLAUM, Klaus [4]

[1] *Max Planck Institute for Nuclear Physics*

[2] *MPIK*

[3] *Johannes Gutenberg University Mainz*

[4] *Max-Planck-Institut für Kernphysik*

[5] *RIKEN, Ulmer Initiative Research Unit, Wako, Saitama 351-0198, Japan*

[6] *GSI, Darmstadt*

[7] *RIKEN Advanced Science Institute*

[8] *Max-Planck Institut für Kernphysik*

**Corresponding Author(s):** fabian.heisse@mpi-hd.mpg.de

Please find the abstract attached.

**Poster Session / 114**

## Concept and simulations of a high-resolution asymmetric von Hamos X-ray spectrometer for CRYRING@ESR electron cooler

**Author(s):** Dr. JAGODZIŃSKI, Paweł[1]
**Co-author(s):** Dr. BANAS, Dariusz [2] ; Prof. PAJEK, Marek [3] ; Prof. WARCZAK, Andrzej [4] ; BEYER, Heinrich [5] ; GUMBERIDZE, Alexandre [5] ; WEBER, Günter [5] ; STÖHLKER, Thomas [5] ; Dr. TRASSINELLI, Martino [6]

[1] *Instytut Fizyki, Jan Kochanowski University, Kielce, Poland*

[2] *Jan Kochanowski University*

[3] *Institute of Physics, Jan Kochanowski University*

[4] *Jagiellonian University, Krakow*

[5] *GSI, Darmstadt*

[6] *Insitut des NanoSciences de Paris*

**Corresponding Author(s):** jagodzin@tu.kielce.pl

A concept of a high resolution asymmetric von Hamos X-ray spectrometer for the CRYRING@ESR electron cooler is described and its characteristics obtained by ray-tracing Monte-Carlo simulations are presented. The spectrometer will be used to study the QED effects in H-like medium-Z ions by measuring the energies of X-rays from radiative recombination of highly charged ions with cooling electrons, with a ppm precision of energy determination.
The design of a high resolution asymmetric von Hamos spectrometer (AvH) for low-energy X-ray spectroscopy experiments at the electron cooler of CRYRING@ESR [1] in the international Facility for Antiproton and Ion Research (FAIR) in Darmstadt is presented. The spectrometer will allow to measure, with a high resolution down to 70 meV, the low-energy X-rays (5-10 keV) from radiative recombination (RR) of stored bare or few-electron heavy ions interacting with cooling electrons.
(FIGURE) Figure 1. Simulated X-ray line profiles expected for asymmetric von Hamos spectrometer for different diameter of ion beam.

Performed X-ray-tracing simulations [2] show that the energies of the X-ray transitions can be measured for medium-Z bare ions with relative precision of a few ppm, which gives access to study the QED effects. For medium Z = 20−30 H-like ions the nuclear size effect is much smaller than one-loop QED corrections [3] and thus such measurements are less sensitive to uncertainties of determination of nuclear charge distribution.
The proposed AvH spectrometer benefits from the unique features of RR X-ray emission in the electron cooler of CRYRING, namely, a extremely long and narrow (1 m × 1 mm) X-ray source accepted by von Hamos geometry and very cold transverse electron beam temperature of about meV achieved by application of adiabatic magnetic expansion [4] of the electron beam. This effect increases the intensities of RR X-rays and, consequently, a precision of determination of X-ray energies. In order to control the Doppler effect two copies of the AvH spectrometers will be installed on both sides of the electron cooler to detect blue/red shifted RR X-rays, what allows to eliminate completely the influence of Doppler effect.
References
[1] Lestinsky M et al, Eur. Phys. J. Special Topics 225 797 (2016)
[2] Jagodziński P et al, Nucl. Instrum. Methods A753 121 (2014)
[3] Lindgren I et al, Phys. Scr. T80A 133 (1999)
[4] Danared H et al, Phys. Rev. Lett. 72 3775 (1994)

**Poster Session / 115**

## Development of a detector to register low-energy, charge-changed ions from ionization experiments at CRYRING@ESR

**Author(s):** Dr. BOROVIK, Alexander[1]
**Co-author(s):** WEBER, Günter [2] ; ROTHHARDT, Jan [2] ; Mr. HILBERT, Vinzenz [3] ; LIN, Haifeng [2] ; PFÄFFLEIN, Philip [2] ; Mr. ZHU, Binghui [4] ; Mr. HAHN, Christoph [2] ; Dr. LESTINSKY, Michael [2] ; Prof. SCHIPPERS, Stefan [5] ; STÖHLKER, Thomas [2]

[1] *Justus-Liebig Universität Gießen*

[2] *GSI, Darmstadt*

[3] *IOQ Friedrich Schiller Universität Jena*

[4] *Helmholtz Institute Jena*

[5] *JLU Giessen*

**Corresponding Author(s):** alexander.borovik@physik.uni-giessen.de

In the frame of the upcoming proof-of-principle experiment, where $C^{+}$ ions stored in a storage ring shall be photoionized by XUV laser pulses [[1]], a specially tailored detector setup has been developed for counting product ions. Both photon beam and stored ion beam will be merged in the experimental section YR09 of the CRYRING. The product ions will be separated from the primary ions in the field of the dipole magnet. The trajectory of the product $C^{2+}$ ions, according to ion-tracking simulations, allows for their detection exclusively inside the dipole-magnet chamber. This requires the detector to be positioned and operated in a strong magnetic field, which takes well-established detectors based on secondary-electron emission, as, e.g., [[2]], out of consideration. On the other hand, moderate ion energies, required <100 ns rise and fall times to be able to detect in coincidence with the XUV laser pulses, as well as the limited space inside the dipole-magnet vacuum chamber also limit the list of possible solutions.
Product ions will hit the YAP:Ce scintillator plate producing light pulses which are to be registered by a 3×3 array of silicon photomultipliers (SiPMs), with an active area of 6.07 x 6.07 $mm^2$ each, placed on a custom-made interface board in a pocket tube outside of the vacuum. Due to the orientation of the available ports in the magnet dipole chamber, the photomultiplier cannot be mounted directly behind the scintillator. The produced photons must therefore be guided by a specially-shaped quartz crystal. The scintillator plate and the quartz light guide will be mounted onto a DN 16CF window, which is at the end of a pocket tube. To avoid unnecessary irradiation during the ion-beam preparation procedure, the entire construction can be swiftly retracted from the product-ion trajectory area and "hidden" behind a dedicated shielding. The whole

construction can be fine-positioned along the pocket axis to account for possible displacements of the product-ion trajectory. This detector should enable a variety of photoionization experiments with stored highly-charged ions.

[[1]] Lestinsky M *et al* 2016 *Eur. Phys. J. Special Topics* extbf225 797-882
[[2]] Spruck K *et al* 2015 *Rev. Sci. Instrum.* 86 023303

**Poster Session / 116**

## Angle-resolved Auger spectroscopy of K-shell ionized molecules

**Author(s):** Mr. FUCHS, Sebastian[1]
**Co-author(s):** Mr. PAUL, Daniel [1] ; Dr. BUHR, Ticia [1] ; Dr. RICZ, Sándor [2]

[1] *Justus-Liebig-Universität Gießen*

[2] *ATOMKI, Debrecen, Hungary*

**Corresponding Author(s):** sebastian.fuchs@physik.uni-giessen.de

We report on measured oxygen K-LL Auger spectra induced by 1.5-keV electron impact on $O_2$, $CO_2$, and $N_2O$ gaseous targets. An ESA-22-type electron spectrometer was employed which is capable of simultaneous energy and angular analysis covering a polar angular range of 15° to 345°. The measurements were carried out in preparation for future experiments with more complex chiral molecular targets and a spin-polarized electron source. The present experimental data are compared with results from earlier experimental studies.

**CRYRING Session: Offline Operation, Local Injector / 117**

## ECR Ion-Source as Local Injector at CRYRING

Dr. BOROVIK, Alexander[1]

[1] *Justus-Liebig Universität Gießen*

**Corresponding Author(s):** alexander.borovik@physik.uni-giessen.de

Electron-cyclotron-resonance (ERC) ion source is a well established, powerful tool for production of intense beams of ions in a wide range of ionization stages. Developed in the Giessen university, the all-permanent-magnet 10GHz ECR ion source has been successfully used to produce singly- through highly-charged ions for various collision experiments. It has recently been revealed suitable for employement as the local injector for CRYRING@ESR and is presently under installation and commitioning. In the present report, the principles of operation and methods of producing ions of different chemical elements will be explained.