18th SPARC Topical Workshop

Book of Abstracts

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Contribution ID: **1** Type: **Poster**

Laser spectroscopy of the 2s-2p transitions in relativistic Li-like carbon ions

Monday, September 6, 2021 4:10 PM (3 minutes)

The 2s-2p transitions in stored and cooled Li-like carbon ions were measured by means of laser spectroscopy at the Experimental Storage Ring of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany, for a relativistic velocity of ß=0.47 (y=1.13). Using a new cw UV laser system (257 nm) and a novel XUV photon detection system, the 2s-2p transition wavelengths were determined with a relative precision of 8.4E-6 and compared with earlier experimental data and with theoretical calculations.

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Session Classification: Poster Session 1

Contribution ID: **2** Type: **Poster**

Simulation of a spherical Johann spectrometer for few ppm-accuracy determination of x-ray transitions

Monday, September 6, 2021 4:13 PM (3 minutes)

Highly accurate differential measurements of innershell transitions of the L-shell of H- and He-like uranium provide a sensitive test of quantum-electrodynamics in the strong Coulomb-field regime with suppression of electron-correlation effects. Such measurements have been done recently using two spherical Johann spectrometers installed at the storage ring CRYRING at GSI. In this context, the LIBPhys group is implementing an independent data analysis to assist on further accuracy optimization and verification of systematics. Here we present preliminary simulations of the spherical spectrometer that will assist on this data analysis. These simulations are based on an adaptation of a Monte-Carlo code used to simulate a double-crystal spectrometer to retrieve energies and widths with ppm accuracy [1-4].

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Session Classification: Poster Session 1

Contribution ID: **3** Type: **Poster**

Proof-of-Principle Experiment at the ESR for the NECTAR project

Monday, September 6, 2021 4:16 PM (3 minutes)

Investigating the interactions of neutrons with unstable nuclei is imperative to our understanding of nuclear astrophysics as it provides insight into the stellar nucleosynthesis of heavy elements. Obtaining accurate cross section data for neutron-induced reactions on these nuclei does, however, present major experimental challenges since both beam and target are radioactive. The NECTAR (NuclEar reaCTions At storage Rings) project aims to solve this problem by using the surrogate-reaction method, where one may indirectly infer the neutron-induced cross sections of short-lived nuclei, in inverse kinematics. A heavy, radioactive nucleus in the beam is to interact with a light, stable nucleus in the target to produce the compound nucleus formed in the neutron-induced reaction of interest by using an alternative or surrogate reaction such as transfer or inelastic scattering. This compound nucleus may decay by fission, neutron or gamma-ray emission, and the probabilities for these modes of decay are to be measured as a function of the excitation energy of the compound nucleus. This information is used to constrain model parameters and to inform significantly more accurate predictions of neutron-induced reaction cross sections [1].
The heavy-ion storage rings at GSI/FAIR in Germany present an ideal arena for the development of the surrogate reaction method, which still suffers from various target-related issues. The sustained high beam quality, along with the use of an ultra-thin gas-jet target, makes it possible to measure excitation energies and decay probabilities with an unrivalled accuracy. A first Proof of Principle (POP) experiment is scheduled to be performed with the ESR storage ring facility at GSI in 2022. The 208Pb(p,p') reaction will be employed in inverse kinematics at an incident energy for the 208Pb beam of 30 AMeV, and target residues as well as heavy beam-like residues are to be measured.
This presentation will focus on the planning and preparations for the Proof-of-Principle experiment at the ESR, including all the considerations in terms of detectors, electronics, data acquisition, mechanical and vacuum-related matters.

*This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-Advanced grant NECTAR, grant agreement No 884715).

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Session Classification: Poster Session 1

Contribution ID: **4** Type: **Poster**

Concept and development of a fluorescence detector for laser cooling at the SIS100

Monday, September 6, 2021 4:49 PM (3 minutes)

At the highly relativistic energies of the ions in the SIS100 at FAIR, conventional beam cooling techniques like electron cooling become increasingly difficult. An alternative method to efficiently cool ion beams is laser cooling. Despite one specific limitation, i.e. the need for a fast electronic transition in the ions, at the SIS100 many different ions (element & charge state) can be laser-cooled, owing to the large magnetic rigidity of the SIS100 (max. 100 Tm). But also the use of new pulsed (rep. rate ~MHz) and tuneable CW laser systems (UV and VIS wavelengths), and possibly even future XUV and soft X-ray lasers, will enlarge the potential of this technique. However, the much higher beam energies at the SIS100 require also new approaches for the in vacuo detection of fluorescence light emitted by the ions, as it is required for laser spectroscopy and laser cooling. A suitable detection system, consisting of an MCP sensitive in the soft X-Ray regime combined with a position sensitive delay line readout and a laminar grating for spectroscopy, is currently being developed in Münster. The poster will present results of first test measurements and will give an overview of the detector and its current development status.
This work is funded by BMBF under contract number 05P19PMFA1.

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Session Classification: Poster Session 1

Contribution ID: **5** Type: **Talk**

Dielectronic Recombination and Observation of He-like oxygen emission near collision-excitation threshold in an electron beam ion trap

Wednesday, September 8, 2021 3:15 PM (15 minutes)

X-ray spectra from hot astrophysical plasmas contain a strong presence of spectral lines of He-like ions due to their closed shell ground state configuration. Abundant light elements, like oxygen, appear in a wide range of plasma conditions, thus providing lines that can serve as important diagnostic probes. The relative intensity ratio of their forbidden to allowed lines are key diagnostic tools of temperature and density, since the metastable state population mechanisms are highly sensitive on these physical quantities.
X-ray measurements of He-like oxygen were produced at an Electron Beam Ion Trap (EBIT). The decay of the metastable $1s2s\ ^3\mathrm{S}_1$ state population was directly observed (mean lifetime of around $956\ \mu$s in the literature) using a 70 eV ms^{-1} electron beam energy sweep rate.
A good electron beam energy dispersion of 7 eV resolves the He-like dielectronic recombination (DR) KLn structure, as well as resonant excitations (RE) superimposed to collisional excitations (CE) of H-like and He-like ions. A good agreement was found between the experimental results and a preliminary spectrum calculated with Flexible Atomic Code (FAC).
We are implementing a CRM model based on a previous work to study the physical parameters, in particular to extract experimental cross sections of the inner-shell CE of the metastable state, which are highly important in astrophysical plasma modeling. These values will later be compared with respective ones obtained from multiconfiguration Dirac-Fock.

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Session Classification: Session 3

Contribution ID: **6** Type: **Talk**

Absolute Rate Coefficients for Dielectronic Recombination of Na-like Kr25+ at the Heavy-ion Storage Ring CSRe

Thursday, September 9, 2021 2:50 PM (15 minutes)

The absolute rate coefficients for dielectronic recombination (DR) of Na-like Kr25+ ions were measured by employing the electron-ion merged-beams technique at the heavy-ion storage ring CSRm and CSRe respectively at the Institute of Modern Physics in Lanzhou, China. The detailed results of the DR experiment for Na-like 86Kr25+ at the CSRm can be found in Ref [1]. Here we report the latest DR spectroscopy measurement at the CSRe. The measured DR spectrum covers the electron-ion collision energy range of 0-150 eV, encompassing all the Δn=0 (3s⟶3p, 3d) DR resonances. The experimental result is compared with an FAC calculation as shown in Figure 1. The DR resonances associated with 4l4l' intermediate states are found strongly contributed to the measured spectrum. A very good agreement has been achieved between the experimental results and the FAC calculation by considering the strong mixing among the low-energy resonances associated with 3⟶3 and 3⟶4 core excitations. The present result demonstrates the reliability and stability for the future DR spectroscopy studies at the CSRe.

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Session Classification: Session 4

Contribution ID: **7** Type: **Poster**

Measurement of n-resolved State-Selective Charge Exchange in Ne(8,9)+ Collision with He and H2

Monday, September 6, 2021 4:19 PM (3 minutes)

With a cold target recoil ion momentum spectroscopy (COLTRIMS) apparatus, we perform a series of measurements of Ne(8;9)+ ions charge exchange with He and H2 for the collision energy ranging from 1 to 24.75 keV/u. By applying l distributions commonly-used in astrophysical literatures to experimentally derived n-resolved cross sections, we develope an new method to calculate the soft X-ray emissions following the charge exchange by considering the radiative cascade from the excited Ne7+ ion. Here by taking charge exchange between 4 keV/u Ne8+ and He, we found that reasonable agreement is found in comparison to the measurement for even and separable models.

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Presenter: ZHANG, Ruitian (Insitute of Modern Physics�Chinese Academy of Sciences)

Session Classification: Poster Session 1

Contribution ID: **8** Type: **Poster**

Commissioning of a new energy-scan-system for electron-ion crossed-beams experiments with a high-power electron gun

Wednesday, September 8, 2021 4:15 PM (3 minutes)

We report on the commissioning of a new measurement and control system of our high-power electrongun with an available collision-energy range of up to 3500 eV. The new control system allows us to set the voltages remotely with significantly better accuracy. In addition, an energy-scan-mode with fine energy steps in the meV range is established which allows us to resolve small resonance and step features in the measured cross-sections for electron-impact ionization of ions.

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Session Classification: Poster Session 2

Contribution ID: **9** Type: **Poster**

Development of a Fast Precision High-Voltage Divider for Electron-Ion Collision Spectroscopy at CRYRING

Monday, September 6, 2021 4:52 PM (3 minutes)

For a precise monitoring of fast changes of the electron cooler voltage during collision spectroscopy experiments at CRYRING a new frequency compensated divider for voltages up to 20 kV has been developed at the University of Münster. The aim of the design is to monitor voltage steps with lengths down to 10 ms with an accuracy in the 10 ppm region. The divider consists of a primary resistor chain of 28 precision resistors complemented by a low voltage section realizing measurement points with three different scale factors. The system is equipped with tuning capacitors that are used to eliminate frequency dependent distortions of the output voltage. To keep the cost down, the new system is realized as an add-on module for the existing precision divider G35 at CRYRING (see O. Rest et al. DOI: 10.1007/978-3-030-31680-8_142). The latter is used for a calibration of the DC scale factors of the new divider before and after measurement campaigns.
The poster will give an overview of the technical realization of the new divider and will present first results from commissioning measurements performed in spring 2021. This work is supported by BMBF under contract number 05P21PMFA1.

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Session Classification: Poster Session 1

Contribution ID: **10** Type: **Poster**

Simulation of bunched Schottky spectrum for laser-cooled O5+ ions at CSRe

Monday, September 6, 2021 4:40 PM (3 minutes)

Laser cooling of lithium-like O5+ ion beams with an energy of 275.7 MeV/u was successfully achieved at the storage ring CSRe in Lanzhou, China [1]. In order to explain the experimental results, by employing the multi-particle tracking method we made simulations of the bunched Schottky spectrum of O5+ ions with and without laser cooling. In the simulation, both of the transverse oscillation and the photon-ion resonant interaction process are considered while intra beam scattering is ignored. Without laser cooling, the phase space distribution of the bunched ion beams and the corresponding experimental and simulated Schottky spectra are shown in Figure 1(a)-(c). The power of the central peak is about several orders of magnitude larger than that of the sideband peaks, which was called the 'coherent effect'. The simulation systematically studied the relationship of the Schottky power and the ions number at different observation harmonics and make clear about this 'coherent effect' for the first time. For laser-cooled bunched ion beams, the phase space distribution is shown in Figure 1(d), and Figure 1(e) and (f) show the experimentally observed and simulated Schottky spectra. With more ions laser-cooled to the center of the bucket, the distribution of the Schottky spectrum becomes narrower than that of the un-cooled ion beams in Figure 1(b). However, the simulated bunched Schottky spectrum for laser-cooled ion beams in Figure 1(f) shows strong sidebands at the position where laser resonant interacts with ions. The reason is that the beta-oscilation in the laser cooling straight section is simplified by using a mean betatron-function value. The further simulation is in progress. With this simulation, the dynamics for the laser cooling of bunched ion beams are fully understood for the first time. We will present the detailed simulation results at this SPARC conference.

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Presenter: WANG, Hanbing (Institute of Modern Physics, Chinese Academy of Sciences)

Session Classification: Poster Session 1

Contribution ID: **11** Type: **Poster**

2021 ESR test beamtime for laser cooling studies

Wednesday, September 8, 2021 4:18 PM (3 minutes)

In May 2021, GSI offered our collaboration the opportunity to evaluate the improved XUV fluorescence detection system (Münster) and the new high repetition rate pulsed UV laser system (Darmstadt) at the ESR in a test beamtime. For the first time, we could demonstrate bunched (~10 MHz) ion beam laser cooling with a powerful (~200 mW) pulsed (~10 MHz) laser system at 47% of the speed of light. We could also test different laser pulse durations (110 - 740 ps) and study the effects of "ion bunch - laser pulse timing" for laser cooling and fluorescence detection. In this contribution, we will present and discuss some preliminary results of these measurements.

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Session Classification: Poster Session 2

Contribution ID: **12** Type: **Poster**

Ionization of heavy H-like ions by a short intense X-ray pulses

Monday, September 6, 2021 4:22 PM (3 minutes)

We develop a numerical approach to the solution of the time-dependent Dirac equation for an electron in a combined field of heavy nuclei and laser pulse. The nuclear potential is taken into account in the monopole approximation, and the basis wave functions are calculated using the finite basis set method. We study photoionization of a heavy hydrogen-like ions by short laser pulses and
calculate the total ionization probability as a function of laser frequency and field strength. To validate numerical approach, the obtained photoionization probability is compared with the predictions of the perturbation theory in the case of small field strength.

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Session Classification: Poster Session 1

Contribution ID: **14** Type: **Poster**

Two-Quantum Annihilation of Positrons with K-Shell Electrons of Uranium Ion

Monday, September 6, 2021 4:25 PM (3 minutes)

Two-quantum annihilation of positrons - the simplest antimatter particles - with electrons inside the matter is of fundamental interest. Annihilation with inner-shell electrons of heavy systems, in turn, provides a unique opportunity to perform antimatter researches in the presence of a strong nucleus field. This process requires a rigorous QED description with a nonperturbative account of the positron- and electron-nucleus interactions. We have worked out an approach aimed at performing such a description. We have applied the developed formalism, utilizing the exact Dirac-Coulomb Green function, for the description of the two-quantum annihilation of positrons with K-shell electrons of uranium ion. The infrared divergences which occur in this process are extracted and subtracted from the final expressions.

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Session Classification: Poster Session 1

Contribution ID: **15** Type: **Poster**

Cusp electron studies in MeV collisions of pre-excited 1s2s 3S ions with gas targets: A progress report.

Monday, September 6, 2021 4:55 PM (3 minutes)

The APAPES (Atomic Physics with Accelerators: Projectile Electron Spectroscopy) installation at the tandem accelerator laboratory of the NCSR "Demokritos" is currently fully operational providing a solid research foundation for the field of fast ion-atom collisions based on the ZAPS (Zero-degree Auger Projectile Spectroscopy) technique [1-3]. Recently, the upgrade of the installation has been initiated through a collaboration with German institutes under the support of the IKYDA2020 program [4]. This upgrade includes, among others, the installation of a magnetic charge state selector downstream of the ZAPS setup, to permit the recording of the projectile charge change events in coincidence with the electron spectra. This upgrade, along with special methods already developed to exploit mixed-state (1s2, 1s2s 3S) He-like ion beams [5], will extend our studies to cusp electrons, and the related processes of electron loss to the continuum and electron capture to the continuum, produced from 1s2s 3S pre-excited ion beams. These studies are of common interest with the corresponding cusp electron investigations at GSI [6,7] and have already attracted the interest of theorists. The up-to-date progress of the upgrade and the offered prospects will be presented.

We acknowledge support of this work by the project IKYDA2020 [4].

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Session Classification: Poster Session 1

Contribution ID: **17** Type: **Poster**

Significance of high charge state of projectile ions inside the target and its role on electron capture leading to target ionization phenomenon

Monday, September 6, 2021 4:58 PM (3 minutes)

The K x-ray spectra of different targets (Cu, Zn, and Ge) induced by 3 to 5 MeV/u Si projectile ions have been measured to determine the K-shell ionization cross-section. We observed that the measured ionization cross-sections differ at least a factor of two from the theoretical direct ionization cross-sections. This underestimation is attributed to the charge-exchange from target K-shell to projectile K- and L-shells. Electron capture from the target K-shell to the K- and L-shell of the projectile ions was required to resolve this difference. Such observation can only be possible if the projectile ions attain up to H- and He-like charge states. In this regard, projectile charge state inside the target is extremely essential. Corresponding projectile charge state fractions have been evaluated from the Lorentzian charge state distribution, where mean charge state is taken from the Fermi gas model [Phys. Rev. Lett. 30, 358 (1973)] and width from the Novikov and Teplova approach [Phys. Lett. A378, 1286–1289 (2014)]. The bare and H-like projectile ions inside the targets have been utilised to calculate the K-K capture contribution from Lapicki [Phys. Rev. A 15, 896]. While all the charge state fractions are used for K-L capture calculations. The sum of the direct ionization cross-section and K-K + K-L capture cross-sections gives a good agreement with the measured cross-sections. Furthermore, we have validated this methodology with available data for Si-ion on Ti target. Such results may be useful in many solid target based applications.

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Session Classification: Poster Session 1

Contribution ID: **18** Type: **Poster**

Spin-polarization effects in the processes of one-photon electron-positron pair production and synchrotron radiation in a supercritical magnetic field

Monday, September 6, 2021 4:28 PM (3 minutes)

The relevance of this study is primarily due to the processes of quantum electrodynamics in a magnetosphere of magnetars, where the magnetic field strength exceeds the supercritical value and the theory of the main processes of such a magnetosphere is far from complete. In particular, it is believed that magnetars are the main candidate for the source of powerful ultrashort radio bursts, a full understanding of the nature of which does not yet exist. The presence of supercritical magnetic fields also leads to a number of significantly nonlinear effects that have not yet been observed in weak fields. In addition to pulsars, in modern experiments on collisions of heavy relativistic ions, a strong magnetic fields that are close to the critical field can occur in the region between them. The FAIR mega-project (Facility for Antiproton and Ion Research) plans a broad research program, in particular, the SPARC (Stored Particles Atomic Physics Research Collaboration) will conduct a study to test quantum electrodynamics in heavy electromagnetic fields of heavy ions.

This work is devoted to the theoretical study of elementary processes of quantum electrodynamics (QED), namely synchrotron radiation and one-photon production of an electron-positron pair in a supercritical magnetic field with polarized particles. The spin-polarization effects in these processes in a strong magnetic field have been studied.

The probabilities of the studied processes for the case of the lowest possible Landau levels are found. For synchrotron radiation, the transition of an electron from the first excited Landau level to the main one is considered, and for the process of one-photon pair production, the case of pair production to the basic Landau level is considered. It is shown that in a strong magnetic field in the process of synchrotron electron radiation the polarization of radiation coincides with the polarization obtained in classical electrodynamics if the electron does not change the spin direction and it is either in the ground or inverse spin state. The spin-flip process in the ground spin state changes the linear polarization of radiation from normal to abnormal. Taking into account the spin-flip process reduces the degree of polarization of the radiation. It is shown that in the process of one-photon pair production at the basic Landau levels and for an abnormally polarized photon, the pair are completely oriented to the ground spin states.

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Session Classification: Poster Session 1

Contribution ID: **19** Type: **Talk**

Non-perturbative dynamics in heavy-ion-atom collisions

Tuesday, September 7, 2021 3:30 PM (15 minutes)

One of the research topics of SPARC focuses on the dynamics of those heavy-ion-atom collisions, whose theoretical description exceeds the applicability of relativistic first-order perturbation theories. Two characteristic cases of such collision systems have been investigated recently at GSI:
(1) For collisions of U^{89+} projectiles with N_2 and Xe targets at 76 MeV/u, we studied the electron-loss-to-continuum cusp both experimentally and theoretically. We compared the continuum electron spectra of the two collision systems, which originate from the ionization of the projectile, and were able to identify a clear signature for the non-perturbative character of the collision systems [Phys. Rev. A 104, 012809 (2021)].
(2) In a recent beam time in 2020, we performed an x-ray spectroscopy experiment for slow collisions of Xe^{54+} and Xe^{53+} with a Xe target at 30 and 15 MeV/u. Experimental data for such slow symmetric collision systems are important for testing relativistic two-center calculations, and provide an intermediate step towards understanding heavy-ion collisions in super-critical fields. In a preliminary analysis, we used the target $K\alpha$ satellite and hypersatellite lines to derive cross section ratios for double-to-single target K-shell vacancy production, and compared the results to the theoretical prediction.

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Session Classification: Session 2

Contribution ID: **20** Type: **Talk**

APEX collaboration at HIAF and the cooperation with SPARC

Tuesday, September 7, 2021 5:00 PM (15 minutes)

A brief introduction to the APEX collaboration (an international collaboration for scientific research on Atomic Processes at EXtreme conditions based on the large scale modern accelerator complex HIRFL and HIAF), atomic physics program, and the future perspectives, especially the new design of detection system of e+e- pair creation in super critical fields created by ion-ion collisions.

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Session Classification: Collaboration Meeting

Contribution ID: **21** Type: **Poster**

Measurement of the bound-state beta decay of bare $^{205}\mathrm{Tl}^{81+}$ ions

Monday, September 6, 2021 4:43 PM (3 minutes)

Ever since the construction of the Experimental Storage Ring (ESR), measurement of the bound-state beta decay of $^{205}\mathrm{Tl}^{81+}$ ions was one of the main physics cases to be performed. Bound-state beta decay (β_b), accompanied by the emission of a monochromatic anti-neutrino, was first predicted by Daudel *et al.* [1] in 1947, and the first direct observation of the β_b decay was done in 1992 by Jung *et al.* [2] at the ESR in GSI, Darmstadt.
The measurement of the bound-state beta decay of fully-ionized $^{205}\mathrm{Tl}$ ions contains two very strong physics motivation cases. One is linked with the LOREX [3] project (acronym of LORandite EXperiment) wherein the measurement is needed to determine the matrix element for the pp neutrino capture by the ground state of $^{205}\mathrm{Tl}$ to the 2.3 keV excited state in $^{205}\mathrm{Pb}$. This capture reaction has by far the lowest threshold (E_{ν_e} > 53 keV) and is thus of utmost significance for extending the neutrino flux to lower energies. The second physics case is associated with the $^{205}\mathrm{Pb}/^{205}\mathrm{Tl}$ pair as an s-process cosmochronometer. In a stellar medium, $^{205}\mathrm{Tl}$ can exist in ionized form and β_b decay to the first excited state of $^{205}\mathrm{Pb}$ can counter-balance the reduction of $^{205}\mathrm{Pb}$ ions due to the electron capture process. The measurement is crucial for the clarification of the fate of $^{205}\mathrm{Pb}$ in the early solar system.
In this talk, results from the first direct measurement of the most awaited and novel experiment will be reported [4]. The experiment was finally performed in March-April last year, after a long wait of almost three decades, amidst of corona crisis by employing the unique accelerator facility at GSI.
This research has been conducted in the framework of the SPARC, ILIMA, LOREX, NucAR collaborations, experiment E121 of FAIR Phase-0 supported by GSI. The authors received support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 682841 "ASTRUm").

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Session Classification: Poster Session 1

Contribution ID: **22** Type: **Poster**

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

Monday, September 6, 2021 4:31 PM (3 minutes)

In order to facilitate new electron-ion collision experiments with free electrons, a specially tailored free-electron target for the heavy-ion storage ring CRYRING@ESR has been developed and built at the University of Giessen. The new device allows for the production of a ribbon-shaped, high-intensity electron beam with energies up to 12.5 keV (in the laboratory coordinate system) and electron densities in the interaction region reaching as high as 10^9 cm^{-3} (at 1 keV). We report on the completion of the assembly and start of the offline commissioning in our laboratory in Giessen, during which the operation and performance of the target will be evaluated before its transfer to FAIR later this year and on-site commissioning with heavy ion beams at CRYRING in 2022.

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Presenter: BOROVIK, Alexander (Justus-Liebig Universität Gießen)

Session Classification: Poster Session 1

Contribution ID: **23** Type: **Poster**

E151: Measurement of the astrophysically relevant alpha-capture reaction rate Ti-44 to V-47

Monday, September 6, 2021 4:34 PM (3 minutes)

The radionuclide ^{44}Ti ($t_{1/2}$=60 a) is one of the few cosmogenic nuclei that were directly observed by satellite based gamma-ray observatories. It is produced in core collapse supernovae by the reaction ^{40}Ca(α,γ)^{44}Ti. The dominant consumption reaction is ^{44}Ti(α,p)^{47}V. The precise knowledge of both reaction rates is therefore crucial for the determination of the final amount of ^{44}Ti produced in the supernova. The goal of the experiment E151 is to measure the reaction ^{44}Ti(α,p)^{47}V at CRYRING at the Gamow window for core collapse supernovae using the CARME detector system and the internal gas-jet target. The proposal was ranked "A" at the 2020 G-PAC. However, due to delays caused by the Covid-19 pandemic situation the experiment cannot be performed before 2023. Here we will present the current status and prospect of E151.

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Session Classification: Poster Session 1

Contribution ID: **24** Type: **Talk**

Polarization of recombination X-rays studied with a state-of-the-art polarimeter installed at the Tokyo-EBIT

Thursday, September 9, 2021 3:20 PM (15 minutes)

We report polarization measurements for recombination X-rays of highly charged heavy ions. Recently, we have developed a Compton polarimeter for hard X-rays and installed it at the Tokyo electron beam ion trap. The polarimeter consists of Si detector layers that work as a scatterer and Cd/Te detector layers that surround the Si detector and work as an absorber. Both Si and Cd/Te detectors are so segmented that the scattered and the absorbed positions can be three-dimensionally determined. From the azimuthal angular distribution of the Compton scattered incident X-rays, the degree of linear polarization can be determined. Excellent performance of the polarimeter was confirmed by observing radiative recombination (RR) X-rays of bare and hydrogen-like krypton (Tsuzuki et al., Rev. Sci. Instrum.92, 063101). We present the results of applying the polarimeter to the RR and dielectronic recombination (DR) X-rays of helium- to fluorine-like bismuth.

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Session Classification: Session 4

Contribution ID: **25** Type: **Poster**

Complex-scaled ab initio QED treatment of autoionizing states

Monday, September 6, 2021 4:46 PM (3 minutes)

Autoionizing states of atomic or ionic systems are the excited states which can decay by virtue of the electron-electron interactions via emission of one (or more) electrons. The high-precision values of the autoionizing-state energies are urgently needed for plasma diagnostics, e.g., in fusion facilities or astrophysical searches. The possibility of using these states as the reference ones in the synchrotron radiation facilities is currently investigated. To obtain the energies of the autoionizing states with the required precision, accurate calculations of the electron-electron correlations and quantum electrodynamics (QED) corrections are required. However, such states are embedded into the positive-energy continuum, that makes standard high-precision many-electron methods inapplicable in the case of the autoionizing states. Most naturally, this problem can be solved within the complex-scaling approach which is based on the analytical properties of the Hamiltonian dilated into the complex plane. The autoionizing states described by dilated Hamiltonian are separated from the positive energy continuum and admit the application of the standard high-precision methods with minor modifications.

Here we combine the complex-scaling technique with the ab initio QED approach to evaluate the energies of the autoionizing states of heliumlike uranium. We account for the leading QED contributions, the corrections due to the two-electron self-energy and two-electron vacuum polarization as well as the contributions of the two-photon-exchange diagrams beyond the Breit approximation. We also dilate the mass shift operator and the model Lamb-shift operator into the complex plane to obtain the accurate values for the nuclear recoil effect and partially account for the higher-order QED corrections, respectively.

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Session Classification: Poster Session 1

Contribution ID: **26** Type: **Poster**

Possibilities of laser spectroscopy for optical clocks in CRYRING@ESR

Wednesday, September 8, 2021 5:00 PM (3 minutes)

Highly charged ions have proven to have many favorable properties for testing fundamental theories, but they might also have more practical applications, such as novel frequency standards [1]. These investigations require novel, precision measurement schemes of the HCI electron structure, which have so far been very scarce due to low availability of suitable candidates. One notable example is the recent coherent laser spectroscopy of Ar^{13+} using quantum logic [2]. However, accurate laser spectroscopy on HCI generally lags many orders of magnitude behind state-of-the-art optical clocks, mostly because of yet unknown transition energies and lack of both suitable production and cooling possibilities.

To address these challenges, we intend to prepare laser spectroscopy experiments with several highly charged ion species stored in CRYRING@ESR, on the road towards final, high-precision measurements in Penning traps. By employing ion storage and electron cooling at low energies, separation of excitation and detection regions, sensitive detectors and both pulsed and continuous-wave lasers, we expect to be able to identify the yet unknown transitions with a relative accuracy of 10^{-4} to 10^{-5}, which can enable further measurements in ion traps.

Among many proposed candidates suitable for optical clocks, only a fraction meets the experimental limitations: accessibility for optical lasers, sufficient transition rates and the possibility to produce and store the ions of interest. We will present the motivation and feasibility of such measurements at CRYRING@ESR with an example of fine structure transitions in W^{13+} and Ir^{16+}, both of which have been identified as possible clock transitions. Both species exhibit forbidden ground-state transitions with very narrow natural linewidths, but remain still accessible for laser spectroscopy. While the former has already been observed experimentally [3], albeit with limited accuracy, the latter transition still awaits experimental confirmation of the theoretical prediction.

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Session Classi ication: Poster Session 2

Contribution ID: **27** Type: **Poster**

Radiative electron capture to the continuum in U89+ + N2 collisions: accurate account of the projectile electronic structure

Wednesday, September 8, 2021 4:21 PM (3 minutes)

In course of the collision of heavy highly charged ions with the targets consisting of light atoms, several processes can occur. The process in which a quasifree electron ionizes from the target and captures into the projectile continuum under the emission of the photon is called radiative electron capture to the continuum (RECC). State-of-the-art experiments of this process are presently performed at GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany [1-3].

In all calculations of the RECC process, the projectile potential was described by a pure Coulomb potential corresponding to an electron-nucleus interaction, i.e. the electronic structure of the projectile was completely neglected. This approximation is well justified for highly-energetic incident electrons. At relatively low energies (several tens of keV) being studied in experiments, the contribution of the electronic structure has to be taken into account. Despite great interest from the experimental side, an accurate calculation of the RECC process treating the interaction of the quasifree electron with the nucleus and electronic structure on the same footing still was not performed.

In the present investigation, we fill in this gap and study the influence of the projectile electronic structure on the cross section of the RECC in $\mathrm{U}^{89+} + \mathrm{N}_2$ collisions, which was measured in the latest experiment [3].

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Session Classification: Poster Session 2

Contribution ID: **28** Type: **Poster**

Ab initio evaluation of energy levels in berylliumlike ions: strong interference between electron-electron correlation and QED effects

Wednesday, September 8, 2021 4:24 PM (3 minutes)

The strong mixing of close levels with two valence electrons in Be-like ions greatly complicates *ab initio* QED calculations beyond the first-order approximation. Due to a strong interplay between the electron-electron correlation and QED effects, the standard single-level perturbative QED approach may fail, even if it takes into account the second-order screened QED diagrams. We overcome the corresponding obstacles by working out the QED perturbation theory for quasidegenerate states. Within our approach [1], the contributions of all the Feynman diagrams up to the second order are taken into account. The many-electron QED effects are rigorously evaluated in the framework of the extended Furry picture to all orders in the nuclear-strength parameter αZ. The higher-order electron-correlation effects are considered within the Breit approximation. The nuclear recoil effect is accounted for as well. The developed technique is applied to high-precision QED calculations of the ground and singly excited energy levels in Be-like molybdenum, xenon, and uranium. The most accurate to-date theoretical predictions for the binding and excitation energies are obtained.

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Session Classification: Poster Session 2

Contribution ID: **29** Type: **Poster**

Proton-capture measurements on stored radioactive ions for the p-process nucleosynthesis

Wednesday, September 8, 2021 4:27 PM (3 minutes)

Highly-charged stable or radioactive ions can be stored and cooled in a heavy-ion storage ring offering unrivaled capabilities for precision studies of the atomic and nuclear structure, and for astrophysics [1]. We have employed the unique feature of the Experimental Storage Ring (ESR) facility at GSI to address astrophysically relevant reactions for explosive nucleosynthesis, in particular for the poorly understood production of the rare p-nuclei.
After the successful campaign for proton-capture measurements on stored stable beams at GSI [2-3], in 2020 and 2021 the (p,γ) and (p,n) reactions at 10MeV/u and the (p,γ) reaction for further two beam energies, 7 MeV/u and 6 MeV/u, have been successfully measured using a radioactive ion beam for the first time, namely 118Te beam with 6 days half-life. Using a Double Sided Silicon Strip Detector (DSSSD), introduced directly into the Ultra High Vacuum environment of the storage ring, the proton-capture reaction products have been detected. With the application of the recently developed "elimination of the Rutherford elastic scattering" (ERASE) technique the sensitivity for
the proton-capture products is maximized.
In this contribution, the experimental method for precision studies of the proton-capture will be introduced with the focus on the working principle of the ERASE background suppression technique. Furthermore, preliminary experimental results from the 118Te(p,γ)119I reaction measurement will be
discussed in detail.

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Session Classification: Poster Session 2

Contribution ID: **30** Type: **Poster**

X-ray Emission Study Performed for H-like Lead at CRYRING@ESR

Wednesday, September 8, 2021 5:09 PM (3 minutes)

The study of x-ray emission associated with Radiative Recombination at "cold" temperature conditions, as it prevails at electron cooler devices at ion storage rings, allows for a stringent test of atomic structure and the subsequent x-ray emission characteristics. In particular, for heavy, highly charged ions at high Z it enables to investigate in detail the prevailing cascade decay dynamics and provides detailed insight into the final state population of the recombination process itself.
We report on an experiment where bare lead ions (Pb^{82+}) were decelerated down to 10 MeV/u in the ESR storage ring at GSI-Darmstadt and injected into CRYRING@ESR [1] and, subsequently, the x-ray emission of H-Like Pb associated with radiative recombination were studied at the electron cooler. For this purpose, at the electron cooler dedicated vacuum chambers were used, equipped with beryllium view ports allowing for x-ray detection under 0° and 180° with respect to the ion beam axis. The x-ray detection was accomplished by using two standard high-purity germanium x-ray detectors. In order to suppress the dominant background, stemming from x-ray emission by the electron beam (bremsstrahlung) and the natural background, an ion detector (channel electron multiplier) was operated downstream to the cooler, enabling to record x-rays in coincidence with down-charged Pb^{81+}ions from electron-cooler section.
Even though in this very first beam time with bare, decelerated high-Z ions in CRYRING@ESR only a low intensity of 2×10^5 ions per injection was possible, a few days of continuous operation were sufficient to accumulate meaningful spectral information when combining the signals in both x-ray detectors with the particle detector. The x-ray spectrum associated with radiative recombination is governed by intense Ly-α radiation as well as by Balmer and even Paschen transition providing a unique opportunity for finale-state selective recombination studies.
This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. It is further supported by the European Research Council (ERC) under the European Union's Horizon 2020 research as well as by the innovation program (Grant No 682841 "ASTRUm") and the grant agreement n° 6544002, ENSAR2. B. Zhu acknowledges CSC Doctoral Fellowship 2018.9-2022.2; we acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA) too.

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Session Classification: Poster Session 2

Contribution ID: **31** Type: **Poster**

Correlation effects in the theory of the g factor of lithiumlike ions

Wednesday, September 8, 2021 4:30 PM (3 minutes)

Over the past two decades, significant progress has been made in the study of the g-factor in highly charged ions. The measurement accuracy for H-like, Li-like and B-like ions reached the level of $10^{-9} - 10^{-11}$ [1-7]. The most accurate value of the electron mass was obtained through joint theoretical and experimental investigations of light H-like ions [8]. There are reasons to believe that future studies of the g-factor of B-like, Li-like, and H-like ions will make it possible to test bound-state QED in the strong-field regime and to determine the fine structure constant α independently [9]. Calculations performed to date for Li-like ions have achieved an accuracy of $10^{-6} - 10^{-9}$. The theoretical results of Refs. [6,10,11] agree with high-precision measurements of the g-factor of Li-like silicon [4,6] and calcium [5], demonstrating the most rigorous test of many-electron QED effects in the presence of a magnetic field. However, in [12, 13], a significant discrepancy between the values obtained by the authors for Li-like silicon and calcium and the experimental ones was declared. From the theoretical point of view, the problem is most likely associated with the contribution of the interelectronic-interaction and screened QED corrections.

At present, the interelectronic-interaction contributions of the first and second order in Li-like ions are calculated within the framework of the bound-state QED. Higher-order contributions are accounted for within the Breit approximation by nonperturbative methods, for example, the CI-DFS method [10]. As shown in [6], calculations of the third and higher orders by perturbation theory provide significantly better accuracy than the CI-DFS method.

In this study, the calculations were carried out based on the Dirac-Coulomb-Breit Hamiltonian using a relatively new method that allows one to calculate arbitrary orders of perturbation theory without considering individual diagrams. It is based on a recursive formulation of perturbation theory with a finite basis of many-electron wave functions constructed in the form of Slater determinants [14]. In [6], the application of this method to the g-factor of Li-like silicon was demonstrated. Here, these calculations were extended to a wide range of Li-like ions, as was done previously for the hyperfine splitting [15]. An agreement with the experimental values is demonstrated for silicon and calcium.

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Session Classification: Poster Session 2

Contribution ID: **32** Type: **Poster**

The Jena S-EBIT facility

Wednesday, September 8, 2021 4:33 PM (3 minutes)

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.

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Session Classi ication: Poster Session 2

Contribution ID: **33** Type: **Poster**

Calculations of Electron Loss to Continuum in Collisions of U^{88+} and U^{89+} with N_2

Wednesday, September 8, 2021 5:03 PM (3 minutes)

Calculations of doubly differential cross sections for projectile ionization in fast collisions of Li- and Be-like uranium ions with a N_2 target are performed. These cross sections can be efficiently studied experimentally by measurements of the electron-loss-to-continuum cusp, observed as coincidence events between the ejected electron and the ionized projectile. The cusp electrons detected in the laboratory frame at small degrees with respect to the projectile beam and with velocities comparable to the projectile velocity originate from the electrons ejected into the projectile continuum. The measured energy distribution provides insight into the ionization mechanisms beyond the investigation of absolute ionization cross sections without the need for selecting arguable cuts of the continuum electron phase space for comparison of experiment and theory. Our results obtained within the first order of the relativistic perturbation theory [1] are compared with the recent measurements of the electron-loss-to-continuum cusp [2, 3] and good agreement is found. The role of relativistic and nonperturbative effects is also explored within a complementary approach [4, 5].

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Session Classification: Poster Session 2

Contribution ID: **34** Type: **Poster**

High-Resolution Electron-Ion Collision Spectroscopy with Slow Cooled Pb78+ Ions in the CRYRING@ESR Storage Ring

Wednesday, September 8, 2021 5:12 PM (3 minutes)

The experimental technique of dielectronic recombination (DR) collision spectroscopy is a very successful approach for studying the properties of highly charged ions [1–3]. Due to its versatility and the high experimental precision DR spectroscopy plays an important role in the physics program of the SPARC collaboration as is outlined, e.g., in the CRYRING@ESR Physics Book [4]. CRYRING@ESR is particularly attractive for DR studies, since it is equipped with an electron cooler that provides an ultra-cold electron beam promising highest experimental resolving power and precision. Here, we report on very recent results from the first DR experiment with highly charged ions in the heavy-ion storage ring CRYRING@ESR of the international FAIR facility in Darmstadt, Germany. The experiment was carried out in March 2021.

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Session Classi ication: Poster Session 2

Contribution ID: **35** Type: **Poster**

Redefined vacuum approach and gauge-invariant subsets in two-photon-exchange diagrams

Wednesday, September 8, 2021 4:36 PM (3 minutes)

Synopsis

The two-photon-exchange diagrams for atoms with single valence electron are investigated. Calculation formulas are derived for an arbitrary state within the rigorous bound-state QED framework utilizing the redefined vacuum formalism. The redefined vacuum approach enables the identifica-tion of eight gauge-invariant subsets and, thus, efficiently check the consistency of the obtained results. The gauge invariance of found subsets is demonstrated both analytically (for an arbitrary state) as well as numerically for $2s$, $2p_{1/2}$, and $2p_{3/2}$ valence electron in Li-like ions.}

Abstract

The treatment of the interelectronic interaction is still a cornerstone for accurate theoretical predictions of the energy levels in many-electron atoms or ions. Within the bound-state QED, the interelectronic interaction is usually treated perturbatively as an expansion over the number of exchanged photons. Recent review by Indelicato \cite{indelicato:2019:232001} suggests the necessity to extend the two-photon-exchange computations to systems with more complicated electronic structures. So far, zeroth-order many-electron wave-function constructed as a Slater determinant (or sum of Slater determinants) with all electrons involved \cite{blundell:1993:2615, shabaev:1994:4489, sapirstein:2015:062508} were used in the performed derivations. Such a derivation becomes increas-ingly difficult for many-electron systems. The vacuum redefinition in QED, which is extensively used in MBPT to describe the states with many electrons involved, is proposed as a path towards an extension of two-photon-exchange calculations to other ions and atoms. Its
benefit is the translation of the one-electron two-loop gauge-invariant subsets into many-electron system.

The employment of the redefined vacuum approach allowed us to identify the gauge-invariant subsets at two- and three-electron diagrams and separate between the direct and exchange contributions at two-electron graphs. The possibility of checking the gauge invariance allows us to control the correctness of the derived expressions and verify the numerical calculations by comparing the results for each identified subset in different gauges. The presented redefined vacuum approach can be further employed for atoms with a more complicated electronic structure, as F-like ions \cite{Soguel:Symmetry:2021}. Moreover, the identification of gauge-invariant contributions within this approach paves the way for calculating the higher-order corrections, which can be split into gauge-invariant subsets and tackled one after the other.

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Session Classification: Poster Session 2

Contribution ID: **36** Type: **Poster**

Resolving the disagreement between theory and experiment for lithiumlike silicon and calcium g factor values

Thursday, September 9, 2021 4:15 PM (3 minutes)

In past decades, the Zeeman effect in highly charged ions has been a subject of intense theoretical and experimental investigations. Nowadays, the bound-electron g factor can be measured with relative accuracy of few parts 10^{-11} in hydrogenlike ions [1,2,3]. Such high-precision measurements of ground-state g factor in hydrogenlike ions combined with the theoretical studies have led to the most accurate up-to-date value of electron mass [3]. Apart from that, the accurate measurement of the g factor in highly charged ions provides an opportunity to probe bound state QED beyond the Furry picture in extreme electromagnetic fields. Thus, the measurement of the g factor in lithiumlike isotopes of calcium [4] has opened the possibility to test relativistic recoil shift in the presence of a magnetic field.
The experimental value of bound electron g factor in lithiumlike silicon was recently improved by factor 15 and currently, it is the most accurate lithiumlike g factor value [5]. However, the theoretical value of the g factor at the time was found to be 1.7σ away from the experimental value. Trying to resolve this discripancy, Yerokhin et al. evaluated the screened QED correction and provided a new theoretical value for the g factor [6], which is 5σ away from the experiment. Additionally, Yerokhin et al. recalculated the two-photon-exchange contribution [7] and presented new theoretical values for lithiumlike silicon and calcium. Their theoretical values still deviate from the experimentally measured g factors for both ions, namely, by 3.1σ for silicon and 4.2σ for calcium.
We report a significantly improved evaluation of the two-photon exchange and screening QED corrections to the g factor in lithiumlike calcium and silicon within the framework of rigorous QED approach based on the extended Furry picture [8]. As a result, we provide a new theoretical value for lithiumlike silicon and calcium. Our theoretical values diviate from the experiment by 1.4σ and 0.6σ for silicon and calcium ions, respectively.

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Session Classification: Poster Session 3

Contribution ID: **37** Type: **Poster**

Properties of polycapillary optics dedicated to low-energy parallel-beam wavelength-dispersive X-ray spectrometer

Monday, September 6, 2021 4:37 PM (3 minutes)

The polycapillary X-ray optics [1] is widely used technology in the X-ray fluorescence applications, for guiding X-ray beams. The development of the polycapillary optics is an active direction for X-ray research due to its wide potential applications in many fields, such as high-quality X-ray diffraction [2], chemical mapping [3], a variety of clinical applications [4], or fluorescence techniques and X-ray focusing optics for synchrotron radiation. The X-ray polycapillaries can work in different geometries. They can be used to collect the radiation emitted from a small source into a large solid angle, to collimate the divergent photons to the quasi-parallel X-ray beam, or to focus the nearly parallel X-rays beam into small spot. The polycapillary optics can be also used to construction the compact parallel-beam wavelength-dispersive spectrometer (PBWDS) [5].
A straightforward procedure to determine the characteristics of a polycapillary optics as well as the optical properties of crystal spectrometer is a X-ray-tracing simulation approach. In presented studies, the Monte – Carlo simulations of X-ray tracing in parallel-beam wavelength-dispersive spectrometer (PBWDS), equipped with polycapillary optics is discussed. The study concentrate on the polycapillary model description, simulations of X-ray polycapillary optics properties and on the simulations of X-ray track in the PBWDS spectrometer. By using geometrical parameters of the polycapillary, its characteristics such as transmission, exit divergence, spatial distribution of X-rays behind the polycapillary, were determined and used for optimization of the PBWDS spectrometer energy resolution. The results of simulations were compared with experimental data obtained for different spectrometer crystals and energies of fluorescence X-ray.

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Session Classification: Poster Session 1

Contribution ID: **38** Type: **Poster**

Model-operator approach to relativistic calculations of the nuclear recoil effect in many-electron atoms and ions.

Thursday, September 9, 2021 4:18 PM (3 minutes)

The fully relativistic theory of the nuclear recoil effect (beyond the Breit approximation) can be formulated only within the rigorous QED approach [1]. However, it is quite complicated to carry out such ab initio QED calculations by perturbation theory in $1/Z$ (see, e.g., Refs. [2,3]), and even more so for systems where electron correlations contribute significantly. For this reason, in the present work a simple model-operator approach to the fully relativistic calculations of the nuclear recoil effect is developed. Similarly to Ref. [4], the model operator is represented by a sum of local and nonlocal potentials. These potentials are constructed using the results of ab initio calculations of the diagonal and nondiagonal matrix elements of the QED nuclear recoil operator with wave functions for hydrogenlike ions. The model operator is tested in QED calculations of the nuclear recoil effect in hydrogenlike and berylliumlike ions. A good agreement with the ab initio values is found. Finally, it should be noted that nonpertrubative (in αZ) calculations of the nondiagonal elements have not been performed previously.

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Session Classi ication: Poster Session 3

Contribution ID: **39** Type: **Poster**

Review of recent results obtained with the use of main magnetic focus ion sources

Monday, September 6, 2021 5:01 PM (3 minutes)

The main magnetic focus ion source (MaMFIS) technology is realized in a family of compact room-temperature devices for the production of highly charged ions in a rippled electron beam with a high current density significantly exceeding the characteristic limit for Brillouin focusing. The highest values of the electron current density are achieved in local ion traps, which are formed in a sequence of focuses of thick magnetic lens [1, 2].

At the Joint Institute for Nuclear Research in Dubna, a modified MaMFIS with the electron beam energy extended up to 40 keV was built [3]. The drift tube consists of three sections with a total length of 3 cm. The focusing system utilizes permanent magnets. Extraction of highly charged ions from the crossovers (focuses) of the rippled electron beam by variation in potentials applied at different sections of the drift tube (electron beam ion source technology) was shown to be possible for certain length-to-diameter ratio of the drift tube, electron trajectories, positions of focuses and the value of extraction voltage. The X-ray radiation spectra for ions of the cathode material, as well as injected xenon and bismuth atoms, were studied as dependent on the ionization time. Charge states such as Ir67+, Ce56+, Xe52+ and Bi60+ were obtained. The ionization of the M-shell electrons of iridium occurs 5 ms after the local ion trap has been formed. These results prove that the achieved electron current density is of the order of 10 kA/cm2. MaMFIS devices can be employed both as injectors for accelerators and as charge breeders for special tasks.

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Session Classification: Poster Session 1

Contribution ID: **40** Type: **Poster**

Superheavy quasimolecular formation in collision of Xeq+-ions with Au

Thursday, September 9, 2021 4:54 PM (3 minutes)

Low energy (2−5 MeV) Xeq+-ions, obtained from the 15 GHz ECR ion source at the Low En-ergy Ion Beam Facility (LEIBF) in Inter-University Accelerator Centre (IUAC), New Delhi, India, were bombarded on Au thin films. The collision-induced X-rays from both the col-lision partners were detected using two silicon drift detectors with a resolution of ~129 eV at 5.9 keV. These detectors were located at 45° and 90° with respect to the incoming beam direction. Additionally, a thin (20 μm) Al foil was placed in front of the detector at 90° to reduce the in-tensity of the low energy X-rays.
Figure 1 shows the resulting X-ray spectrum of Xe12+ incident on Au. Notably, a continuum band at the higher energy end of the spectrum was observed. The energy range of this band was found to be 7.4−9.8 keV, which corre-sponds to the 4f⟶3d transition in the united atomic systems ZUA=(Z1+Z2)=133 [1], indicating the formation of quasimolecules during the colli-sion. Similar observations were obtained for 11−42 MeV Iq+-ions interacting with Au reported by Mokler et al. in 1972 [2] and for 1.5−5.5 MeV Xeq+ bombarded on 73<Z2<92 by Lutz et al. in 1976 [3].

Figure 1. X-ray spectrum of 4 MeV Xe12+-ions incident on Au, showing the M molecular orbital (MO) X-ray band at the higher energy end.

Slight shifts in the target X-ray energies and altered target to projectile intensity ratios have been observed, indicating multiple ionization and the presence of spectator vacancies. Nota-bly, cross-section enhancements have been ob-served as well [4]. Observation of the MO X-rays with solid targets promises interesting simi-lar experiments which are planned at SPARC facility with both solid and gas targets.

Figure 2. ICS vs. target atomic number plot from Mokler et al. [5]. Our calculated ICS, shown in red color, agrees well with the cross-sections reported in [5].

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Session Classification: Poster Session 3

Contribution ID: **41** Type: **Poster**

Mechanism of nanostructure formation in interaction of slow, highly charged xenon ions with gold surface

Wednesday, September 8, 2021 4:39 PM (3 minutes)

Nanostructures created as a result of single highly charged ion bombardment have been observed so far mainly on insulator surfaces such as halides, oxides and polymers. For metals only single experiments were carried out, which due to the small systematics did not allow for a detailed examination of the mechanism of nanostructures production on such surfaces. The reason for the small interest in this type of studies was the earlier sputtering experiments which suggested that in the interaction of the HCI with high thermal conductivity materials the production of nanostructures is unlikely due to the rapid outflow of energy, deposited by an ion, from the interaction region.
In this work we present results of experiments performed at the Kielce EBIS facility (Jan Kochanowski University, Kielce, Poland). In these experiments, we investigate the mechanism of nanostructure formation in the interaction of HCI xenon ions (Xe^{q+}, q = 25-40+) of kinetic energy from 100 to 400 keV with gold nanolayers [1,2].
The results were interpreted within recently developed micro-staircase model based on the quantum two-state vector model of the ionic Rydberg states population [3]. In this model the formation of the nanostructure is governed by the processes of the ionic neutralization in front of the surface and the kinetic energy loss inside the solid. The interplay of these two energies in the surface structure creation is described by critical velocity. Using the model neutralization energy, deposited kinetic energy and critical velocities were calculated and compared with experimental results.

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Session Classification: Poster Session 2

Contribution ID: **42** Type: **Talk**

Zeeman splitting in helium-like ions: quadratic effect and nuclear magnetic shielding

Wednesday, September 8, 2021 3:00 PM (15 minutes)

Experimental and theoretical investigations of the transition energies and the g-factor of highly charged ions together make it possible to determine with high accuracy the fundamental constants and parameters of nuclei, and to test bound-state quantum electrodynamics. In many cases, the spectroscopic experiments are performed in the Penning traps. An external magnetic field in the trap leads to a level shift. The linear effect in the magnetic field is directly used for g-factor determination. In the measurements of the transition energies it can be compensated for by averaging over the projections of the total momentum. However, there remains the contribution of the quadratic effect, which must be taken into account as a correction to the transition energies. This is usually a very small effect, but it is amplified for close levels of the same parity with values of the total momentum differing by no more than 1. For example, nonlinear contributions have a large impact in boron-like ions [von Lindenfels et al., Phys. Rev. A 87, 023412 (2013); Varentsova et al., Nucl. Instum. Methods Phys. Res. B 408, 80 (2017)]. This is due to the magnetic-field mixing of close levels 2p_1/2 and 2p_3/2. In particular, the quadratic effect is important for determination of the g-factor of the 2p_3/2 state in boron-like ions [Egl et al. Phys. Rev. Lett. 123, 123001 (2019)]. In addition to spectroscopy, the quadratic Zeeman effect is a significant source of systematic error in important applications such as atomic clocks [Ludlow et al., Rev. Mod. Phys. 87, 637 (2015)] and magnetometers [Bao et al., Phys. Rev. Lett. 120,033202 (2018)].

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 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)]. Meanwhile, the nuclear g-factor can be determined with ppm precision from the ion g-factor measurement as described 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 related to the nuclear magnetic shielding constant.

In atomic systems with closed shells, e.g., helium-like ions in the ground state, the electronic part of the magnetic moment is zero. So, the total g-factor is fully determined by the nuclear g-factor and the shielding constant. Despite some experimental difficulties, this allows one to access directly the nuclear magnetic moment in high-precision Penning-trap measurements. The quadratic Zeeman effect is important for transition energies in helium-like ions, because the intervals between the excited states can be tenths of electron-volt [Malyshev Phys. Rev. A 99, 010501(R) (2019)], which makes their mixing in magnetic field quite strong.

In this work, we use the non-perturbative in external field approach based on the 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. Also, using the A-DKB method, the electron-electron interaction is taken into account. The one-photon-exchange corrections to the quadratic contribution to the Zeeman effect and to the nuclear magnetic screening constant are obtained by differentiation with respect to the corresponding parameters. In our recent work [Volchkova et al., arXiv:2009.00109], these values for the ground state of helium ions were obtained. Now we present also the results for some excited states: the quadratic Zeeman effect and the nuclear magnetic shielding taking into account the electron-electron interactions.

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Session Classification: Session 3

Contribution ID: **43** Type: **Talk**

How to access QED at supercritical Coulomb field

Tuesday, September 7, 2021 3:45 PM (15 minutes)

In low-energy collisions of heavy bare nuclei with a total charge exceeding the critical value Z_cr=173, the initially electrically neutral vacuum can spontaneously decay via creation of two electron-positron pairs. This can also be interpreted as the decay of the resonant state formed when the unoccupied ground state of a quasipolecule dives in the negative-energy continuum. Direct observation of this process is precluded by the fact that the lifetime of the resonance is two orders of magnitude longer than the duration of the collision. Therefore, the contribution of the spontaneous channel to the pair-creation probability is very small compared to the dynamic one. For the same reason, the formation of the resonant structures in the positron spectra is also impossible. In this work, we have performed calculations of the pair-creation probabilities and the positron energy spectra within a wide range of collision parameters. The results of the calculations show clear evidence of the transition to the supercritical regime. We have also found that their manifestation can be significantly enhanced if, when considering positron spectra, we limit ourselves only to the energy region to which the spontaneous pair-creation mechanism can contribute. Thus, they become visible already for the collision of bare uranium nuclei.

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Session Classi ication: Session 2

Contribution ID: **44** Type: **Poster**

One-Electron Energy Spectra of Heavy Highly Charged Quasimolecules: Finite-Basis-Set Approach

Wednesday, September 8, 2021 4:42 PM (3 minutes)

Due to the critical phenomena of the bound-state quantum electrodynamics (BS-QED), such as spontaneous electron–positron pair production, quasimolecular systems emerging in ion–ion or ion–atom collisions have attracted much interest [1-3]. While collisions of highly charged ions with neutral atoms are presently available for experimental investigations, in particular at the GSI Helmholtz Center for Heavy Ion Research [4-6], the upcoming experiments at the GSI/FAIR [7], NICA [8], and HIAF [9] facilities might even allow the observation of the heavy ion–ion (up to U(92+)–U(92+)) collisions. In a quasimolecular system, emerging during the collision, the total nuclear charge Z is comparable to the critical one, $Z_c = 173$. In other words, the lowest-lying electronic state is close to ‘'dive’' into the Dirac negative-energy continuum [3, 10]. In this case the parameter αZ is larger than 1 (α is the fine-structure constant), so the calculation must be performed to all orders in αZ, that is the so-called Furry picture of the BS-QED.

We present the fully relativistic calculation of the ground and few lowest excited sigma-states of the one-electron heavy diatomic quasimolecules valid to all orders in αZ. The generalized dual-kinetic-balance approach for axially symmetric systems is employed to solve the two-center Dirac problem [11]. The analysis of the monopole approximation with two different choices of the origin is performed. It is shown that this kind of analysis can be used to quantify the inaccuracy of the results for the various quantities, e.g., QED contributions, evaluated within the monopole approximation, but not yet within the rigorous two-center approach, which is generally much more demanding [12, 13]. The results are compared with the results of the previous calculations [14-16].

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Session Classi ication: Poster Session 2

Contribution ID: **45** Type: **Poster**

High-precision mass measurements of neutron-rich krypton isotopes

Thursday, September 9, 2021 4:21 PM (3 minutes)

While carrying about 1% of the total mass of an atom, the binding energy carries precious information regarding the forces at play within the system. Studying the evolution of binding energy differences along isotopic or isotonic chains reveals nuclear structure effects such as shell closures or regions of increased collectivity. In particular, the neutron-rich region between molybdenum and krypton isotopic chains is known to show a sudden onset of collectivity at around A = 100. Nuclear deformation is experimentally observed through the evolution of the mean-square charge radii [1], the energies of the first 2+ excited states [2], and the ratios between first 4+ and first 2+ excited states energies [3]. The A=100 region was extensively studied by many mass spectrometers. The time-of-flight ion-cyclotron-resonance measurement from ISOLTRAP mass spectrometer improved the uncertainty of 96Kr. No irregularities in two-neutron separation energies were seen at N=60[4]. It was established as a critical point boundary [5].
New mass measurements of 96Kr, 97Kr, and 98Kr were carried out during the experimental campaigns at ISOLTRAP mass spectrometer. The measurements were performed by using the multi-reflection time-of-flight mass spectrometry and the time-of-flight ion-cyclotron-resonance techniques. This contribution will present preliminary results of the aforementioned experiments.
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Session Classi ication: Poster Session 3

Contribution ID: **46** Type: **Talk**

Non-destructive detection and cooling of highly charged ions at ARTEMIS

Tuesday, September 7, 2021 3:00 PM (15 minutes)

The ARTEMIS experiment at GSI aims at high precision measurements of the magnetic moments of electrons and nuclei in heavy, highly charged ions (HCIs) using laser-microwave double-resonance spectroscopy [1]. Such measurements are the most stringent test for bound-state quantum electrodynamics in strong fields. The HCIs are stored in a half-open Penning trap in a homogeneous magnetic field of 7 T. Ion storage times of up to weeks indicate a residual gas pressure inside the trap chamber of less than 10-15 mbar, which is made possible by the cryogenic environment at ~4 K. The ions are resistively cooled to equilibrium via their image currents, and maintain well-defined trajectories throughout. This non-destructive detection and cooling is done using resonator circuits, which also passively enhance the signal before further amplification.
Such resonators can be classified according to various parameters such as design, geometry or the frequency of operation. The resonators in ARTEMIS are used to detect the axial and cyclotron motion of the ions. Detection and cooling are two aspects of the same interaction of the confined ions with the resistive circuits. For high ion number densities, we observe a transition of the ion ensemble to a fluid-like state when cooled to low temperatures [2].
The trap electrodes of ARTEMIS can be divided into two parts: the Creation Trap (CT) and the Spectroscopy Trap (ST). The novel half-open design of the ST, enables the precise determination of the spectroscopic transitions. The CT allows for the in-situ production of ions, acting as a mini-EBIT, as well as in-flight capture of the ions from the HITRAP decelerator facility. After connection to the HITRAP low-energy beamline, the method will be applied to the hyperfine structure of heavy, H-like ions such as Bi82+ and U91+ to measure their nuclear and electron magnetic moments.

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Session Classification: Session 2

Contribution ID: **47** Type: **Poster**

Measurement of Magnetic Moments in Heavy, Highly Charged Ions With Laser-Microwave Double-Resonance Spectroscoypy

Thursday, September 9, 2021 5:03 PM (3 minutes)

The ARTEMIS Penning trap will use laser-microwave doubleresonance spectroscopy to measure the intrinsic magnetic moments of
both electrons and nuclei in heavy, highly charged ions (HCIs). The
(hyper)fine and Zeeman transitions of such HCIs in ARTEMIS are in the optical or microwave regimes respectively. A closed optical cycle probes successful induction of spin flips by microwave stimulus.

The spectroscopy trap of ARTEMIS uses a half-open design with a transparent, conductive endcap. This enables ≈ 2 sr conical access to the trap center for irradiation and detection of fluorescent light. This is more than an order of magnitude greater than conventional cylindrical designs with similar harmonicity and tunability. On the opposite side, cooled ion bunches are injected from an adjacent trap, where they are created by electron impact ionization.

Currently, ARTEMIS is working on systematics measurements with boron-like Ar13+ and preparing for capture of heavy HCIs such as hydrogen-like Bi82+ from the HITRAP facility at GSI.

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Session Classification: Poster Session 3

Contribution ID: **48** Type: **Poster**

maXs: Metallic Magnetic Calorimeters for High-Precision X-ray Spectroscopy

Thursday, September 9, 2021 5:06 PM (3 minutes)

Metallic magnetic calorimeters (MMCs) are energy-dispersive X-ray detectors, which provide an excellent energy resolution over a large dynamic range combined with a very good linearity [1]. This kind of detectors converts the energy of each incident photon into a temperature rise, which is monitored by a paramagnetic temperature sensor. The resulting change of magnetisation is read out by a highly sensitive SQUID magnetometer.
For the spectroscopy of highly charged ions at FAIR we developed, fabricated and characterized several one- and two-dimensional MMC detector arrays, which together form the so-called maXs family (micro-calorimeter arrays for high-resolution X-ray spectroscopy)[2,3]. We present available detector designs, including the maXs-20 detector, which is optimized for X-ray energies below 20 keV and provides an energy resolution of 1.6 eV (FWHM) at 6 keV [4], as well as the 8x8 pixel arrays maXs-30 [5] and maXs-100. The latter combines a large detection area of 1 cm² with a stopping power of 40% for X-rays with energies up to 100 keV and an energy resolution of 40 eV at 60 keV. Two of these detectors have recently been deployed at the electron cooler at CRYRING@ESR for the investigation of electronic transitions in U^{90+}.
Furthermore, we will present the cryogenic setup that is needed to provide the necessary operating temperatures of a few millikelvin and discuss current developments for future MMC arrays.

This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19VHFA1).

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Session Classification: Poster Session 3

Contribution ID: **49** Type: **Poster**

Relativistic Stark energies of heavy H-like ions

Thursday, September 9, 2021 4:24 PM (3 minutes)

One of the new projects, proposed currently as a part of the Physics Beyond Colliders initiative, is the Gamma Factory [1]. The proposal is based on combining the relativistic beams of heavy partially stripped ions (PSI) with the laser facility. One of the promising research topic of the project is the PSI spectroscopy in strong external fields. The modern magnets can allow generation of exceptionally high electric field in the PSI frame of reference. The strong electric field makes it possible to manipulate the PSI energy levels via the Stark effect. Such manipulation requires the precise theoretical predictions. The most established approach for calculation of the Stark energies and widths is the complex-scaling method [2]. However, up to date the complex-scaling calculations of the Stark effect were mainly non-relativistic and, therefore, were done only for the light ions in relatively weak external fields. The relativistic results were obtained only for hydrogen and neon and were restricted to the point-like nuclear model [3]. In the present work, we develop the procedure for calculation of Stark energies of heavy H-like PSI. The approach is based on using the finite basis set with the external complex scaling. The Stark energies of H-like Pb ion are calculated utilizing the developed procedure.

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Session Classification: Poster Session 3

Contribution ID: **50** Type: **Poster**

Dynamics of K-vacancy sharing in near-adiabatic collisions of Xe52+ +Xe at the ESR Storage ring

Thursday, September 9, 2021 4:27 PM (3 minutes)

In near-adiabatic collisions of heavy very highly charged ions with heavy atoms the strong perturbation with Bethe parameters qproj/vproj exceeding one leads to complex multi-excitation patterns in the collision partner, markedly different from much more simple electron configurations produced in very fast collisions, Eproj≥100AMeV for heavy ions. We are studying outer-shell multi-electron transfer and −ionization processes accompanying K-vacancy processes in near adiabatic collisions (vproj/vK<0.6) of bare, H-like and He-like Xe54+…52+ ions with Xe atoms. We measure emitted target- and projectile K- and L- x rays at 359, 900 and 1450 with respect to the beam direction in coincidence with projectiles which have captured 3 to 6 electrons, and with the time of flight of recoiling Xe target ions. For Xe52+ projectiles with a filled K-shell in these collisions with Xe target atoms target and projectile K satellite x rays overwhelmingly originate from 2p□-2p□ rotational coupling and subsequent K-K-vacancy sharing in the outgoing part of the trajectory. We find discrepancies with the most advanced theoretical calculation. The coincidences of K x-rays with the multiplicity of outer-shell capture into the projectile permits to illuminate the interdependence of K vacancy creation and outer-shell populations in projectile and target.

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Session Classi ication: Poster Session 3

Contribution ID: **51** Type: **Poster**

Decisive Role of outer-shell capture multiplicity in projectile K-satellite and K-hyper-satellite emission in near-adiabatic collisions of Xe54+,53+ +Xe at the ESR Storage ring

Wednesday, September 8, 2021 5:06 PM (3 minutes)

We are studying multi-electron transfer and –ionization processes in near adiabatic collisions (vproj/vK<0.6) of bare and H-like Xe54+,53+ ions with Xe atoms. We measure emitted target- and projectile K- and L- x rays at 359, 900 and 1450 with respect to the beam direction in coincidence with projectiles which have captured 3 to 6 electrons, and with the time of flight of recoiling Xe target ions. Target K satellite and hyper-satellite x rays in these collisions overwhelmingly originate from single (for Xe53+, 54+) and double (only for Xe54+) charge transfer from the target K shell into the projectile K shell. The satellite and hypersatellite K x ray spectra emitted by the projectile, however, are created following single and multiple outer shell electron transfer from the target into the projectile. The energy resolution of the Ge(i) detectors permits to resolve for the projectile satellite from hypersatellite transitions from L-, M-, N-, O-, and P-shells into the K shell with clear evidence that even higher shells beyond the projectile P shell are significantly populated; the K x rays from high n shells indicate that outer shell transfer dominantly ends in low l states, decaying directly to the K shell. Capture dominantly going into circular states (n,l=n-1) of the projectile would feed mostly the KL2,3 transitions via Yrast cascades, which is in conflict with evidence. Projectile K x ray spectra coincident with multiple capture n⊠3 into the projectile show, however, clear absence of the Rydberg state population. We also find that single capture favors capture into the 2p3/2 over the 2p1/2 state, whereas for multiple capture n⊠3 the 2p1/2 is more strongly populated than the 2p3/2 state.
The coincidence of transfer multiplicity with projectile K x ray spectra surprisingly reveal the strong relation of projectile K-satellite spectra to single K to K resonant charge transfer, instead of expected hypersatellite –satellite cascades, whereas the projectile K hyper-satellite spectra dominantly originate from L-to L, M-to M etc quasi-resonant transitions.
For the target satellite and hypersatellite K x ray spectra, we observe that the ratio K- satellite/K-hypersatellite yields is significantly enhanced over the predictions by a relativistic theory, which exhibits a near binomial distribution for single and double K to K charge transfer for bare Xe54+ projectiles, this finding is at variance with homologue ratios at low Z collision systems. This enhancement is particularly strong for 3fold capture into the projectile simultaneous with the K-K charge transfer, but decreases with increasing capture multiplicity. Evaluation of further details of the emission characteristic is currently in progress.

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Session Classification: Poster Session 2

Contribution ID: **52** Type: **Poster**

Status of Cyogenic Current Comperators (CCCs) for beamlines in 2021

Wednesday, September 8, 2021 4:45 PM (3 minutes)

CCCs are highly sensitive current meters that, using superconducting effects, are able to measure charged particle streams in the nA range non-destructively and absolutely. Currently, two CCC systems are in use in ring systems and further CCC-sensors are in laboratory test operation.
First, after 2 years of shutdown, the CERN-Nb-CCC at CERN-AD was put back into operation in 2021, currently measured beam currents were 3.3 µA (1.3·E7 antiprotons).
Secondly, the GSI-Nb-CCC-XD was tested with its newly developed beam cryostat in the CRYRING. Low Ne3+ beam currents in the range of 150 nA with a resolution of approx. 10 nA and high U91+ beam currents in the range 20 µA with a noise level of approx. 1 µA were measured.
Thirdly, the further development of cost-effective Pb-CCC sensors with and without flow concentrator cores was driven forward in in the Cryo Detector Lab at Jena as a cooperation of the University of Jena, Leibniz-IPHT and HI-Jena.
To this end, key results from the completed BMBF project 2018-21 are presented here and the goals for the new funding period 2021-24 are outlined.

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Session Classification: Poster Session 2

Contribution ID: **53** Type: **Poster**

Micro-Calorimeters as a Universal Tools for High Resolution Energy Dispersive Photon Detection

Wednesday, September 8, 2021 4:57 PM (3 minutes)

Cryogenic micro-calorimeters - like the maXs-detectors developed by the group of C. Enss at the University of Heidelberg - have proven to be a particularly promising tool for x-ray spectroscopy experiments as they are proposed within the frame of the SPARC collaboration [1]. Due to their measurement principle requiring very low operation temperatures (50 mK), they provide an intrinsically high energy resolution ($E/\Delta E_{\mathrm{FWHM}} \approx 3000$) comparable to crystal spectrometers [2]. At the same time, their energy resolution is mostly independent of the measured photon energy, therefore making them operable in a broad spectral range of energies (≈ 0.1 - 100 keV). Thus, they combine the advantages of several conventional energy dispersive photon detection methods.

However, to achieve this high level of performance, besides a technically challenging operating setup, the signal readout relies on an almost complete digital signal processing with very few analog stages. Therefore, calorimeters require a complex signal analysis software based upon a detailed understanding of the detector. During the last years, several experiments were performed at the site of GSI/FAIR in Darmstadt where calorimeter detectors have been deployed as x-ray spectrometer detectors. The insights gained during these campaigns were used to develop and improve an analysis software API within the frame of this work. Results of the analysis will be presented with the particular focus on experiments performed at the ESR, namely the study of x-rays produced in collisions of Xe^{54+} projectiles with Xe gas atoms at 50 MeV/u (see fig. 1) as well as for U^{89+} on N2 collisions at 76 MeV/u.

%figure1 (see attached file Spectrum_XeOnXe.pdf)
Figure 1: X-ray spectrum recorded by a maXs-200 detector resulting from the collision of Xe^{54+} ions (50 MeV/u) with a Xe gas-target in the internal target of the ESR of GSI.

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Session Classification: Poster Session 2

Contribution ID: **54** Type: **Poster**

Laser-induced ionization of ions from liquid alloy ion sources of high brightness

Thursday, September 9, 2021 4:45 PM (3 minutes)

The ionic laser targets are particularly suitable for studying light-matter interactions of fundamental systems, such as He^+ and $H_2{}^+$, and special molecules that only appear in the ion source, e.g., HeH^+.

In this work, we have generated ion beam targets of metal and metalloid ions using a high-brightness liquid metal ion source (LMIS) originally applied in focused ion beam systems. Using an eutectic Au-Si alloy as a low melting point source feed material, ions of different ion species were detected: Si^{2+}, Si^+, Au^{2+}, Au^+, $Au_2{}^+$, $Au_3{}^+$ and $Au_3{}^{2+}$. The source current between emitter needle and extractor electrode (configuration in Fig. 1 (a)) is in the range of 10 - 60 µA and can be adjusted up to about 150 µA. The ion source is characterized by high ion current stability and a suitable emission lifetime of several days, which is limited by the amount of material and can be further increased.
To study the strong-field laser ionization, we used a E x B filter and selected Si^{2+} and Au^+ ions as ionic targets, because of their high beam intensity. We investigated ultrafast laser-induced ionization, which leads to higher charge states after multiple ionization of both ion species. Fig. 1 (b) shows a part of the ion beam setup at HI Jena with time and position sensitive microchannel plate detector and with delay line anode. Laser intensities of up to 10^{16} W/cm^2 allow observation of up to 10-fold ionization of Au^++ ions and 3-fold ionization of Si^{2+} ions.

The aim of further work is to extend the available ion beam targets to other elements of the periodic table to study ultrafast laser-induced fragmentation and ionization dynamics of atoms and molecules in strong laser fields. Another goal is the further increase of the density of ion laser targets for more reliable statistics and shorter measurement times. Further steps are technical improvements of ion source and ion optics as well as the investigation of heavy metal dimers such as $Au_2{}^+$.

Fig. 1 (a) Ion source housing with LMIS ion emitter (red) and einzel lens. (b) Schematic drawing of the ion beam setup with time and position sensitive microchannel plate detector and with delay line anode to record every reaction in coincidence and synchronized with the phasemeter-signals.

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Session Classification: Poster Session 3

Contribution ID: **55** Type: **Poster**

Numerical study of the thermal interaction of polymethylmethacrylate-metal when irradiating with high energy laser beam

Thursday, September 9, 2021 4:57 PM (3 minutes)

The numerical study in COMSOL of PMMA-Me thermal interaction (PMMA = polymethylmethacrylate, and Me = Ag, Cu, Fe, Ni, Zn) under laser beam irradiation 150 mJ, 532nm 10 Hz, 10 ns pulse, 325 µm spot radius, 45° angle of incidence is presented with this work. The aim is to estimate parameters and conditions for the experimental set up. The main purpose of the investigation is to improve the properties of the composite targets by means of PLD and a better understanding of the phenomena and processes that occur during interaction between the high fluency laser ablation and solid state material as part of our project theme to enhance ion acceleration by laser irradiation of special thin polymers layers containing nanoparticles. In order to obtain such layers using PLD technic, namely a continuous phase polymer composite (PMMA) doped with metal nanoparticles as dispersed phase, a primary target is required. The primary target can also be produced by PLD method. Based on numerical models developed in the LOASL Laboratory (Atmosphere Optics, Spectroscopy and Laser Laboratory) and their implementation in COMSOL software [1,2], the simulations were conducted with the required specificity of this study. After numerical analysis in COMSOL of the laser-induced thermal effects in the metal component of the PMMA-Me target and the phenomena of heat transfer from metal to PMMA by thermal diffusion, an optimal option for producing the primary target by PLD method was estimated. This optimal option found as suitable consists in depositing a thin layer of metal according to certain geometry on a PMMA substrate, and the most efficient metals among those numerically studied resulted as being copper and iron. These results are to be used for the experimental production of the primary target followed by the production of the thin layer of polymer containing metal nanoparticles (PMMA-Me).
Key Words: composite thin layers, COMSOL, high fluency laser ablation, thermal diffusion

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Session Classification: Poster Session 3

Contribution ID: **56** Type: **Poster**

HILITE - stored and confined ions for laser-ion experiments

Thursday, September 9, 2021 4:30 PM (3 minutes)

The development of high-intensity photon sources with photon energies up to the X-ray regime opens up new possibilities to investigate non-linear laser-matter interactions. Particularly, the K-shell electrons of certain ions become accessible. In single electron systems, the ionisation cross sections can be predicted precisely by theoretical models, which can be compared to the experimental results. In case the ionization cross section is known it is also possible to measure the laser intensity.
To this end, we have built, commissioned and operated the HILITE (High-Intensity Laser Ion-Trap Experiment) Penning trap. The design (figure 1a) allows both laser and ion access from outside. The ions are produced by an Electron-Beam Ion Trap (EBIT), charge-to-mass selected by a Wien filter, and captured dynamically in the trap centre. The whole setup is portable and build to be used at different laser facilities.
For example, C2+ and C5+ ions have been captured and stored for roughly a quarter of an hour. In addition, the ion trap content was destructively characterized using time-of-flight spectroscopy. Last year, for our first laser experiment, we have transported the HILITE setup to the FLASH2 free-electron laser at DESY in Hamburg. We have connected both systems and brought the ion trap back into operation. We have had to deal with unexpectedly bad vacuum conditions which only allowed the storage of C2+ ions for a short time. We have used the 10 Hz master clock of the FLASH FEL to synchronise the ion capture, ejection and detection procedure with the laser pulses. During laser-ion interaction, the ions have been located about 20 mm around the trap centre in axial direction where the laser waist diameter has been nearly constant. This allowed for a good overlap of the stored ions with the laser focus of a well-known shape. The interaction of the laser with the stored ions led to a loss of the initially stored C2+ ions which can be assigned to laser ionisation (figure 1b).
We will present the setup, the commissioning results and results from our first beamtime. In addition, envisaged upgrades of the setup will be presented.

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Session Classification: Poster Session 3

Contribution ID: **57** Type: **Poster**

A portable UV spectrometer with fixed VLS grating for overview luminescence measurements

Thursday, September 9, 2021 4:33 PM (3 minutes)

We present a design study for the energy resolved photon detection in the UV and VUV energy regime. A grating with Variable Line Spacing (VLS) allows for dispersion of a wide spectral range onto flat detector surfaces. With two VLS gratings in parallel, spectra from 30nm
to 120nm and 120nm to 300nm can be imaged simultaneously, but spatially separated. Managing coincidence capabilities and single photon detection, two position and time resolving MCP-based detectors will be used. Exemplary showcase-applications at FAIR (Facility of Antiproton and Ion Research) will be outlined. With this compact spectrometer with high efficiency and high resolution from 30nm to 300nm, it will be possible to collect time efficiently wide range luminescence spectra in experiments for the characterization of the highly charged ion beams beam diagnostics and other AMO experiments.

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Session Classification: Poster Session 3

Contribution ID: **58** Type: **Talk**

FAIR Phase-0: X-ray spectroscopy experiments

Monday, September 6, 2021 3:10 PM (30 minutes)

He-like ions, being the simplest multi-body atomic systems, offer the unique possibility to test QED correlation and electron-electron interaction effects. For such a simple system, theory can provide high-accuracy prediction. However, the presence of extremely high electric fields, as for high-Z ions, provides still a significant challenge and different approaches leads to different results. A first attempt to test such contributions has been made in an experiment in 2007. We present here a new relative measurement of the intra-shell $2p_{3/2} \to 2s_{1/2}$ transitions in He- and Li-like uranium with an accuracy gain with respect to the past experiment by more than one order of magnitude. The experiment was conducted at the internal gas jet target of the ESR at GSI. We employed twin spectrometers with two bent Ge(220) crystals, both under 90° observation angle to the ion beam and equipped with X-ray CCDs. By appropriately choosing the ion velocities, the energies of the two transitions (~ 4509 eV for He-like U and 4459.37 eV for Li-like U) correspond to basically the same X-ray photon energy in the laboratory frame (4319 eV) with a drastic reduction of many systematic effects. A FWHM resolution of ~ 2.7 eV has been obtained, mainly due to the Doppler broadening caused by the finite size of the gas jet. After several days of data acquisition, we collected more than 1000 photons per transition, allowing for a statistical accuracy of about 0.03 eV. To additionally control the systematics in the experiment, we also measured reference lines from a stationary Zn fluorescence target as well as the intra-shell transition from Be-like uranium ions. Preliminary results of the experiment will be presented with an accuracy of about 0.16 eV on the absolute energy of the intra-shell transition in He-like uranium, mainly dictated by the accuracy of the Li-like uranium reference line, and of ~ 0.05 eV for the relative measurement between those lines. This will allow for an unmatched test of electron correlation effects and two-loop QED contributions in few electron systems in strong electric fields, which are in the order of 0.8 eV.

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Session Classification: Session 1

Contribution ID: **59** Type: **Poster**

Precision x-ray spectroscopy of U^{90+} at CRYRING@ESR

Wednesday, September 8, 2021 4:48 PM (3 minutes)

He-like ions are the simplest atomic multi-body systems and atomic structure studies of these systems along the isoelectronic sequence provide a unique access to probe our understanding of the interplay between electron correlation, relativistic and QED effects [1]. However, virtually there are no spectroscopic data for the ground state and intra-shell transitions in He-like ions with a nuclear charge greater than Z=54 available. During the last FAIR phase-0 beam time campaign at the GSI storage rings (spring 2021 at ESR and CRYRING@ESR) we started a coordinated effort to overcome this shortcoming by measuring precise spectroscopic data for the x-ray emission in He-like uranium by addressing the Δn=0 (n=2) [2] as well as the ground state transitions. The goal of this endeavour is to benchmark atomic structure theory and to enable to test the different theoretical approaches leading to different predictions.

In this contribution we present preliminary results from a high-resolution x-ray measurement of the ground state transitions in U^{90+} conducted at the electron cooler of the CRYRING@ESR. Within the experiment, x-ray radiation emitted as a result of radiative recombination of cooler electrons and stored U^{91+} ions were recorded by two novel maXs-type (maXs = cryogenic **m**icro-calorimeter **a**rrays for high resolution **X**-ray **s**pectroscopy experiments at FAIR) detectors [3] featuring a spectral resolution of about 50 to 75 eV FWHM. This should enable to resolve the two fine structure components belonging to each of the two Kα lines as they were observed in previous experiments [1]. We note that the unresolved line blend of the fine structure components prevented up to now to extract spectroscopic information from the observed Kα lines. Here it is also noteworthy to mention a recent publication where a systematic deviation between experimental results and theoretical predictions for the ground state transitions in low- to mid-Z systems was claimed to be identified and even a scaling law for the deviation as function of the nuclear charge was formulated [4]. This publication has sparked a lively debate in the scientific community and lead to several follow-up studies [5,6]. The preliminary spectra for both detectors will be presented.

This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA and 05P19VHFA1).

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Session Classification: Poster Session 2

Contribution ID: **60** Type: **Poster**

First application of maXs detectors for precision x-ray spectroscopy of high-Z ions at CRYRING@ESR

Thursday, September 9, 2021 4:36 PM (3 minutes)

In this contribution we present the first application of maXs-type (maXs = cryogenic micro-calorimeter arrays for high resolution X-ray spectroscopy experiments at FAIR) detectors for high resolution X-ray spectroscopy [1,2,3,4] at the electron cooler of CRYRING@ESR, the low energy storage ring of GSI, Darmstadt. Within the experiment, X-ray radiation emitted as a result of radiative recombination events of the cooler electrons and the stored U^{91+} ions was studied. For this purpose, two maXs detectors with spectral resolutions between 50 and 75 eV FWHM were positioned under observation angles of 0° and 180° with respect to the ion beam axis. This report will focus on details of the experimental setup, its performance and its integration into the storage ring environment. Noteworthy aspects are a quasi-continuous energy calibration, as well as the first usage of the time resolution of the maXs detectors to achieve a coincidence measurement with a particle detector for background suppression.

This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA).

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Session Classification: Poster Session 3

Contribution ID: **61** Type: **Talk**

Laboratory X-ray Astrophysics with Stored Highly Charged Ions

Thursday, September 9, 2021 3:05 PM (15 minutes)

The next generation of x-ray satellites, like XRISM or Athena, will be equipped with state-of-the-art spectroscopic instrumentation. However, the accuray of plasma parameters, like elemental composition, velocity, density, and temperature, that can be extracted from the expected high-resolution spectra will be limited by the uncertainties and availability of atomic data [1], especially for highly charged ions (HCI). Reliable access to line positions, line strengths, and cross-sections for different atomic processes is indispensable for gaining insight into the formation and evolution of hot astrophysical objects, such as active galactic nuclei (AGN), in which accretion of mass onto supermassive black holes and mass outflows provide feedback mechanisms during the co-evolution of AGNs with their host galaxies. We pursue two complementary approaches to laboratory x-ray spectroscopy, to provide atomic data for astrophysical applications.

On one side, we employ microcalorimeter x-ray detectors [2], which have characteristics similar to the instruments which will be installed on future satellite missions. This allows us to record x-ray fluorescence spectra from stored highly charged ions with the necessary resolving powers. We present an upcoming experiment at the CRYRING storage ring, in which we will study charge exchange between bare ion projectiles and molecular hydrogen targets. A microcalorimeter detector will be used to record the spectrum of the x-ray fluorescence cascade following this process, which is ubiquitous in many astrophysical environments, but is still difficult to model.

On the other side, we use PolarX-EBIT [3], a compact electron beam ion trap, based on room-temperature permanent magents, to provide stationary targets of highly charged ions for ultra-brilliant x-ray photon beams from synchrotrons and free-electron laser (FEL) light sources. We present results of resonant-photoexcitation experiments conducted at the synchrotron facilities PETRA III in Hamburg [4, 5] and BESSY II in Berlin [6], as well as planned future measurements.

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Session Classification: Session 4

Contribution ID: **62** Type: **Talk**

FAIR Phase-0: First dielectronic-recombination experiments in CRYRING@ESR

Wednesday, September 8, 2021 2:30 PM (30 minutes)

Synopsis: The first merged-beam DR measurements were performed at the CRYRING@ESR electron cooler since its move from Stockholm. This contribution will focus on the newly established particle detection and data acquisition setup and the results of DR measurements of astrophysically relevant neon ions in low charge states.

The analysis of data from astrophysical spectra relies heavily on acurate modelling of the systems involved. For most ions in a thin plasma dielectronic recombination (DR) is the dominant capture process and thus, precise absolute data are vital for determining the charge state balance in plasma modelling. Merged-beam experiments on electron-ion collisions in heavy ion storage rings have so far proven to be the best experimental approach to provide the needed data. During its Stockholm years, CRYRING and its electron cooler facilitated many DR experiments which benefitted from the excellent vacuum conditions and ultra-cold electron beam [1]. At GSI, CRYRING@ESR is now back in operation and with the upstream accelerator complex, intense beams of previously inaccessible ion species are available for experiments.
In merged-beam DR experiments the electron cooler is used both to reduce the momentum spread of the ion beam and as an electron target. An energy range in the ions centre-of-mass system is scanned by detuning the electron energy from the cooling value and the downcharged ions produced at variable relative collision energy are detected with a particle counter installed behind the next downstream dipole magnet. Both the detuning and the data acquisition were achieved by using a single dedicated setup.
Besides injection from the GSI accelerator chain, a local injector can supply a range of ion species from a local source for both testing and experiments. After the installation of a new ECR ion source, Ne^{7+} was chosen for tests of the DR measurement setup prior to scheduled experiments to improve our understanding of the electron beam temperatures of the electron cooler and to commission our experiment controls. The Ne^{7+} test measurement took place in May 2020 and demonstrated an undegraded resolution compared to the previous measurement [2]. It was followed up in May 2021 by a scheduled experiment on astrophysically relevant low-energy DR of Ne^{2+} which this talk will focus on. Ne^{2+} has low-energy DR resonances associated with $2s \rightarrow 2p$ core excitations and theory data is available from AUTOSTRUCTURE calulations. This contribution will focus on our new DR measurement setup and detail the results of the test run and the Ne^{2+} measurements which was one of the first scheduled experiments at CRYRING@ESR.

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Session Classification: Session 3

Contribution ID: **63** Type: **Poster**

Compton Polarimetry on Rayleigh Scattering of Highly Linearly Polarized Hard X-rays

Thursday, September 9, 2021 4:39 PM (3 minutes)

Rayleigh scattering refers to the 2nd order QED process where a photon is scattered by a bound electron without a change in the photon energy [1]. For photon energies up to the MeV range it is the dominant contribution to the fundamental photon-matter interaction process of elastic scattering. This process is highly polarization-sensitive, making the analysis of polarization transfer in Rayleigh scattering suitable for a stringent test of the underlying theory [2].
A first experiment where an incident highly linearly polarized hard x-ray beam was used and the degree of linear polarization of both the incident and the scattered radiation was observed was performed in the work of Blumenhagen et al. in 2015 at the synchrotron facility PETRA III at Hamburg [3]. In this experiment the polarization-dependent features of the radiation being Rayleigh scattered within the polarization plane of the incident beam were analyzed. For the measurement of the polarization characteristics of the scat-tered radiation a prototype 2D sensitive strip detector which was developed in the framework of the SPARC collaboration for precise and efficient x-ray polarimetry was used serving as a dedicated Compton polar-imeter [4]. Well in accordance with theory a dependence of the degree of linear polarization on the polar scattering angle and the degree of polarization of the initial beam could be shown.
In a recent follow-up experiment we performed at the beamline P07 of the synchrotron facility PETRA III at DESY we extended on this previous measurement. For the first time, the polarization of the scattered beam was measured outside the polarization plane of the incident, highly linearly polarized radiation. For this experiment, the hard x-ray beam delivered by the synchrotron which was set to a photon energy of 175 keV was scattered on a gold foil target of 1 μm thickness. The scattered radiation was detected by an improved prototype Compton polarimeter [5], also developed in the framework of the SPARC collaboration, which was located under several scattering angles inside and outside of the polarization plane of the initial beam.
Preliminary results show a strong dependence of the orientation of the polarization vector of the scattered beam with respect to the scattering plane on the polar and azimuthal scattering angles outside the polari-zation plane of the incident beam.

This research has been conducted in the framework of the SPARC collaboration. Financial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA) is acknowledged.

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Session Classification: Poster Session 3

Contribution ID: **64** Type: **Poster**

Dielectronic and trielectronic recombination investigated at CRYRING@ESR

Thursday, September 9, 2021 5:00 PM (3 minutes)

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 these recombination processes is DR. DR is the time reversal to the Auger process and thus it is well-known and investigat-ed in many different highly-charged systems [1, 2]. The recombination is completed through radi-ative stabilization of the excited ion.
The previous research were conducted at the UJ-EBIT (Jagiellonian University EBIT) [3]. 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 the observed x-ray ener-gy region, in addition to the K-LL DR, a trace of the intrashell TR has been seen [2]. These results encouraged the more detailed present studies of TR, specifically of
the KK TR. Here, the resonant capture of a free electron to an ion-bound state transfers simultaneously 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 emis-sion of two photons. The first transition with two vacancies in the K shell is responsible for emission of the Kαh hypersatellite photon with an en-ergy slightly higher than energy of the following Kαs satellite transition. This TR process has been not reported yet to the best of our knowledge. A maximum-like behavior of the intensity ratio be-tween Kαh and Kαs has been observed. The position of the observed maximum suggests a successful observation of the KK-LMM TR process in Ar ions.

Currently, complementary experiments are be-ing performed. With application of the collision spectroscopy of highly charged ions merged in a cold electron beam of the CRYRING@ESR cooler [4] we have measured DR spectra of He-like oxygen ions. Preliminary results are shown in figure 1. During next beamtime, it is planned to apply this technique for identification of the TR process.

Figure 1. Preliminary results of measured DR resonances in He-like oxygen at CRYRING@ESR electron cooler.

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Session Classification: Poster Session 3

Contribution ID: **65** Type: **Poster**

Test for electron screening effect on the alpha decay rate

Wednesday, September 8, 2021 4:51 PM (3 minutes)

The question of dependence of the alpha decay rate on the electron screening is of great interest for astrophysics and laboratory research of nuclear processes in plasma. There is a contradiction between the laboratory study, which considers nuclear reactions with no respect to a possible role of the electron shell or environment, and applications, which are forced to deal with various electronic environments. Consequently, indirect approaches are developed in order to better know their cross-sections and rates, such as the asymptotic normalization coefficients, or the Trojan horse method and others. Here we discuss an experimental test for the screening effect in sole atoms of the beam.

The anticipated change of the decay rate for representative alpha radioactive nuclei is shown in the table. The calculations are performed within the adiabatic approach, which takes into account perturbating effect of the alpha particle motion on the electronic shell [1,2]. In order to have a big effect, it is desirable to use the isotopes with small Q value. But small Q values correlate with long halflives which may comprise days and years. The Y values of the effect are listed for isotopes with halflives T within seconds to minutes and the alpha branching ratios 100% or close. It follows from the table that the presence of the electronic shell retards the decay.

______
Q, *MeV* T Y*%*______
222Ra 6.681 38.0 s -0.091
213Ra 6.861 2.74 m -0.084
221Fr 6.4579 4.9 m -0.10
212Rn 6.385 23.9 m -0.11
202At 6.3537 184 s -0.11
201At 6.4733 89 s -0.10
____

Although the predicted magnitude of the effect is rather small, an advantage is that ~80% of the effect is produced by the K electrons. In order to observe the effect, it is therefore sufficient to compare the halflives for bare nuclei with the halflives of the two-electron atoms. Generally, observation of small effects via difference measurements at the same facility is more feasible. Thus, comparative measurements can be performed in the same storage rings with bare nuclei and helium-like, or neon-like ions.

Note in conclusion difference with the effect as calculated in another popular model of the frozen shell. This model treats the intraatomic potential in the mother atom as the actual field acting on the alpha particle. A typical effect for the same nuclei turns out to be of about 1%, that is of the opposite sign. Testing this difference in the storage rings is all the more a feasible task.

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Session Classification: Poster Session 2

Contribution ID: **66** Type: **Talk**

A high-resolution asymmetric von Hamos spectrometer for low-energy X-ray spectroscopy at the CRYRING electron cooler

Wednesday, September 8, 2021 3:30 PM (15 minutes)

The design of a high-resolution asymmetric von Hamos spectrometer for low energy X-ray spectroscopy experiments at the electron cooler of CRYRING [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 of down to 100 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. Performed X-ray tracing simulations [2] show that the energies of the X-ray transitions can be measured with relative precision of a few ppm, which gives access to study the QED effects for mid-Z bare ions with a high precision. For these ions the nuclear size effect is much smaller than one-loop QED corrections [3]. The proposed asymmetric von Hamos spectrometer benefits from the unique features of RR X-ray emission in the electron cooler of CRYRING, namely, the extremely long-linear (~ 1 m x 1 mm) X-ray source accepted by von Hamos geometry and very cold electron beam temperature of about meV. This is achieved by application of adiabatic magnetic expansion of the electron beam [4], which increases substantially the intensities of RR X-rays and, consequently, the precision of determination of X-ray energies. In order to control the Doppler effect, two copies of the asymmetric von Hamos spectrometer will be installed next to the dipole magnets on both sides of the electron cooler to detect blue/red (0O /180O) shifted RR X-rays, what allows to eliminate completely the influence of Doppler effect on measured X-ray energies. The X-rays diffracted by the cylindrically bent crystal will be measured by a novel type of position sensitive semiconductor detector having nanoseconds time resolution, what will be crucial to eliminate non-RR X-ray background by counting photon-downcharged-ion coincidences. The spectrometers will be mounted to the dedicated intermediate vacuum chambers on the e-cooler axis.

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Session Classification: Session 3

Contribution ID: **67** Type: **Poster**

Atomic Form Factors and Forbidden Transitions

Thursday, September 9, 2021 4:42 PM (3 minutes)

We have made highest precision measurements of M1 transitions in He-like Ar and S with the "SIMPA" ECRIS source and Paris Double Crystal Spectrometer (DCS) [1]. These represent the most accurate measurements of these transitions allowing us to test bound-state QED [2, 3]. Additionally, the high sensitivity of our instrument combined with Bayesian analysis methods [4] have revealed a sensitivity to the underlying atomic form factors describing the response of our silicon crystals to the incident radiation. This may represent a new way to probe these form factors at low energy. I will discuss our results as analyzed with different atomic form factor models and discuss potential systematic effects and implications.

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Session Classi ication: Poster Session 3

Contribution ID: **68** Type: **Poster**

The effect of electron correlation on trielectronic recombination rate coefficients for BeI isoelectronic sequence with Z = 10 - 30

Thursday, September 9, 2021 5:09 PM (3 minutes)

We present distorted-wave calculations for dielectronic and trielectronic recombination (DR and TR) rate coefficients for BeI isoelectronic sequence with $Z = 10 - 30$, most of which are abundant astrophysical elements. The ab-initio level-by-level total rate coefficients initially from all the $n = 2$ levels including the ground state $1s^2 2s^2$ as well as the excited states $1s^2 2s2p$ and $1s^2 2p^2$ are presented with a general analytic formula. Both $\Delta N = 0$ (low-temperature) and $\Delta N > 0$ (high-temperature) are included for DR and TR channels. We find that the electron correlation among DR and TR resonance states with different captured electron principal quantum numbers n (multi-n) can lead to a significant increase in plasma rate coefficients from the ground state, especially for that of Ni^{24+} the increase is up to 28% at the photoionized plasma temperature range. It is also found that the radiative decays to autoionizing levels followed by radiative cascades (DAC) are significantly important for the total rate coefficients from excited states. They increase plasma rate coefficients of BeI ions with $Z < 20$ by up to more than a factor of one at photoionized and collisional plasma temperature ranges. However, previous theoretical calculations for this system did not include multi-n electron correlation and DAC effects. Considering additionally them could accounts for most of the discrepancy between existed theoretical calculations and experimental results. Understanding electron correlation and DAC effects as well as their consequences are of great importance for obtaining the accurate DR and TR rate coefficients, which are extremely benefit for prediction of ion abundance and charge state distributions and are useful for plasma modeling and diagnostics.

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Session Classification: Poster Session 3

Contribution ID: **69** Type: **Poster**

Dissociation dynamics of doubly charged N2Ar cluster

Thursday, September 9, 2021 5:12 PM (3 minutes)

Van der Waals (vdW) clusters are weakly bound atomic/molecular systems and are ubiquitous in nature. They are an important medium for understanding micro-environmental chemical phenomena in bio-systems. In hydrogen-bond clusters, the proton transfer process plays an important role as well, it involves mass and charge migration over large distances within the cluster and results in fragmentation of the latter. Nevertheless, this transfer process is limited to hydrogen-bond clusters. Since these processes are known to be of relevance in biophysics and radiation therapy, a question arises, whether a massive ion could be transferred in biochemical processes and lead to fragmentation? In a complex bio-environment, does heavy ion transfer play a role? Van der Waals clusters may be an ideal candidate for these kinds of studies. In the present work, we use neutral vdW cluster N_2Ar as a target in collisions with 1 MeV Ne^{8+} ions to produce doubly charged cluster $(N_2Ar)^{2+}$. Surprisingly, an exotic heavy N^+ ion transfer channel $(N_2Ar)^{2+} \rightarrow N^+ + (NAr)^+$ has been observed. This bound-bound state transition involving the heavy-ion transfer process and the consequent formation of NAr^+ have never been reported so far. Our work demonstrates that this channel originates from the dissociation of parent doubly-charged cluster $N_2^{2+}Ar$ generated by the "N_2-site" two-electron loss process. Theoretical calculations show that the polarization interactions between Ar and N_2^{2+} lead firstly to an isomerization process of $N_2^{2+}Ar$ from its initial T-shape to linear-shape (N-N-Ar). Besides, the neighboring neutral Ar atom decreases the N_2^{2+} barrier height and width, resulting in significant shorter lifetimes of metastable molecular ion state $N_2^{2+}(X^1\Sigma_g^+)$. Consequently, the breakup of the covalent N^+-N^+ bond, the tunneling out of the N^+ ion from N_2^{2+} potential well, as well as the formation of N-Ar^+ bound system take place almost simultaneously. Then the Coulomb explosion starts between N^+ and $(NAr)^+$ ion pairs. This mechanism might be general for molecular dimer ions in the presence of neighboring atom, and be of potential importance in understanding micro-dynamics of biological systems \[Nature Communications 11, (2020) 2987\]. Recently, we also observed this mechanism in Ar^{2+}-N_2Ar collisions at low energy of 40 keV.

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Presenter: Prof. ZHU, Xiaolong (Institute of Modern Physics, Chinese Academy of Sciences)

Session Classification: Poster Session 3

Contribution ID: **70** Type: **Poster**

XUV Photoionization of C+ ions at CRYRING

Thursday, September 9, 2021 4:51 PM (3 minutes)

We report on the successful implementation of a photoionization experiment at CRYRING driven by a table-top XUV femtosecond laser source. This includes remote operation of the XUV source, a windowless differential pumping unit, successful beam overlap with the circulating ion beam and an online XUV beam monitor as well as the implementation and operation of a Si-based particle detector within the bending magnet. A careful data analysis is currently pursued in order to identify XUV-photoionization events via temporal coincidences with the XUV laser pulses. The experiment paves the way for ultrafast spectroscopy at heavy ion storage rings.

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Presenters: KLAS, Robert (GSI, Darmstadt); Mr KIRSCHE, Alexander (HI-Jena)

Session Classification: Poster Session 3

Contribution ID: **71** Type: **Talk**

Testing Quantum Electrodynamics in strong fields with Exotic Atoms

Wednesday, September 8, 2021 2:00 PM (30 minutes)

Testing Quantum Electrodynamics in strong fields with Exotic Atoms

Paul Indelicato
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The accuracy of quantum electrodynamics tests in strong fields with highly-charged ions (HCI) is in general limited by uncertainties on the nuclear size contribution to transition energies (see, e.g., 1 and Refs. there in). We have shown recently [2] that using circular Rydberg states in exotic atoms could provide a way to test QED in strong fields, free from nuclear uncertainties. I will present these theoretical results, which involve muonic and antiprotonic atoms. I will then report on a new experimental result on muonic Ne, obtained in the framework of the HEATES collaboration at JPARC in Japan, using "transition edge sensor" (TES) microcalorimeters [3, 4] and a low-pressure gas target (0.1, 0.4 and 0.9 atm). This is the first time a TES microcalorimeter has been used for a precision experiment on exotic atoms created in a gas target to reduce electron recapture. A previous precise experiment has been performed with a TES on pionic carbon, using a solid graphite target [5]. I will compare the results on muonic Ne to previous crystal spectrometer measurements on muonic atoms and to state-of-the art HCI results. I will then describe future plans for measurements on heavier muonic atoms at JPARC and on antiprotonic atoms on the ELENA ring at CERN.
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Session Classification: Session 3

Contribution ID: **72** Type: **Poster**

Gauge invariance of the many-electron QED contributions to the g factor of highly charged ions

Thursday, September 9, 2021 4:48 PM (3 minutes)

g factor of few-electron ions has attracted much interest in recent years. High-precision measurements of the g factor of H-like, Li-like, and B-like ions [1,2,3] combined with corresponding theoretical developments [4] provided the most accurate determination of the electron mass [5] and the most stringent test of the many-electron QED and nuclear recoil effects in the presence of magnetic field [2,6,7]. Future prospects include independent determination of the fine structure constant [8,9,10], accurate measurements of the nuclear magnetic moments [11] and many more [4].

State-of-the-art theoretical calculations of the bound-electron g factor include rigorous evaluation of the first- and second-order QED diagrams. In particular, the contribution of the two-electron self-energy diagrams is presently considered as a possible reason for the discrepancy between the theoretical g-factor values from Refs. [12,13] and the experimental ones [2,6]. Meanwhile, the values obtained in Refs. [2,14] are in agreement with the experiment. Rigorous evaluation of the two-electron self-energy diagrams is a challenging project, which includes derivation of the formulae from the basics of bound-state QED, regularization of the ultraviolet and infrared divergencies, and finally numerical computation with all of its complications. So, a stringent verification of the obtained results in all available ways is in high demand. One of these tests is provided by the gauge invariance of the total contribution of certain sets of diagrams. In general, QED ensures the gauge invariance of rather large sets of diagrams. At the same time, the smaller the sets, the more stringent the corresponding test. In Ref. [15] we have analyzed the gauge invariance of the two-photon-exchange contributions to the binding energy. In this study, we investigate the variation with respect to gauge of the two-electron self-energy contributions to the bound-electron g factor. We identify the large number of relatively small gauge invariant subsets. Verification of the corresponding numerical results is currently in progress.

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Presenter: Ms TRYAPITSYNA, Elizaveta (Saint-Petersburg State University)

Session Classification: Poster Session 3

Contribution ID: **73** Type: **Talk**

ELEMENTS: Exploring the Universe from microscopic to macroscopic scales

Thursday, September 9, 2021 3:35 PM (30 minutes)

The 2017 detection of gravitational waves, with the accompanying electromagnetic emission, from merging neutron stars have revealed that we are at a pivotal point in our understanding of matter and gravity. The Cluster Project ELEMENTS brings together scientists from distinct fields of research (the physics of particles and nuclei, the gravitational physics of merging neutron stars, the nucleosynthesis of heavy elements) to address the question of the origin of the heavy chemical elements in our Universe.

Primary author: ARCONES SEGOVIA, Almudena (TU Darmstadt)

Presenter: ARCONES SEGOVIA, Almudena (TU Darmstadt)

Session Classification: Session 4

Contribution ID: **74** Type: **Talk**

Opening / Welcome and Status

Monday, September 6, 2021 2:00 PM (10 minutes)

Presenter: SCHUCH, Reinhold (Stockholm university)

Session Classification: Opening

Contribution ID: **75** Type: **Talk**

Research at GSI and FAIR: status, developments, and perspectives

Monday, September 6, 2021 2:10 PM (30 minutes)

Presenter: GIUBELLINO, Paolo (GSI)

Session Classification: Session 1

Contribution ID: **76** Type: **Talk**

From FAIR Phase-0 to FAIR Phase-1: Roadmap for beam time planning at GSI/FAIR

Monday, September 6, 2021 2:40 PM (30 minutes)

Presenter: SEVERIN, Daniel (GSI)

Session Classification: Session 1

Contribution ID: **82** Type: **Talk**

Cusp electron studies in MeV collisions of pre-excited 1s2s 3S ions with gas targets: A progress report

Tuesday, September 7, 2021 3:15 PM (15 minutes)

Presenter: NANOS, Stefanos (University of Ioannina)

Session Classification: Session 2

Contribution ID: **85** Type: **Talk**

APPA “BMBF Verbundforschung”

Tuesday, September 7, 2021 4:30 PM (15 minutes)

Presenter: SCHIPPERS, Stefan (JLU Giessen)

Session Classification: Collaboration Meeting

Contribution ID: **86** Type: **Talk**

Strategy for SPARC experiments (2022-2025)

Tuesday, September 7, 2021 4:45 PM (15 minutes)

Presenter: STÖHLKER, Thomas (GSI)

Session Classification: Collaboration Meeting

Contribution ID: **88** Type: **Talk**

Topics: Funding Situation: International and National, Common Funds, Status Reports

Tuesday, September 7, 2021 5:15 PM (1 hour)

Presenters: BRÄUNING-DEMIAN, Angela (GSI); SCHUCH, Reinhold (Stockholm university); SCHIPPERS, Stefan (JLU Giessen); STÖHLKER, Thomas (GSI)

Session Classification: Collaboration Meeting

Contribution ID: **95** Type: **Talk**

PhD Prize Talk

Thursday, September 9, 2021 2:00 PM (20 minutes)

Session Classification: SPARC PhD-Prize

Contribution ID: **96** Type: **not specified**

FAIR Phase-0: Experiments related to laboratory astrophysics with exotic ions

Thursday, September 9, 2021 2:20 PM (30 minutes)

Presenter: GLORIUS, Jan (GSI)

Session Classification: Session 4

Contribution ID: **101** Type: **Talk**

FAIR Phase-0: Laser spectroscopy and applications

Tuesday, September 7, 2021 2:30 PM (30 minutes)

An overview of performed and planned laser spectroscopy experiments in the Phase-0 of FAIR will be provided. Special attention will be given to the results of first optical pumping experiments on Mg+ ions at CRYRING.

Primary author: NOERTERSHAEUSER, Wilfried (TU Darmstadt)

Presenter: NOERTERSHAEUSER, Wilfried (TU Darmstadt)

Session Classification: Session 2

Contribution ID: **102** Type: **Poster**

QED calculation of TEOP transition probabilities in He-like ions

Wednesday, September 8, 2021 4:54 PM (3 minutes)

We present a calculation of two-electron one-photon (TEOP) transitions, which are single photon transitions where two electrons change their quantum numbers. Such transitions occur only due to the interelectron interaction and represent a process that is very sensitive to the description of the interelectron correlation.

We investigate TEOP transitions from autoionizing LL states to the ground state of He-like ions. The main attention is paid to the TEOP transition probabilities for $(2s2p_{1/2})_1{}^3P_1$ and $(2s2p_{3/2})_1{}^1P_1$ states to the ground states $(1s)^2\ {}^1S_0$ of the He-like sequence of atomic ions $5 \leq Z \leq 92$. The calculation was performed within the QED theory. The line-profile approach (LPA) was used \cite{andreev08,andreev09}.

We compare our results with available results obtained by other authors.

Primary authors: ANDREEV, Oleg (St. Petersburg State University); LYASHCHENKO, Konstantin (Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China)

Presenter: ANDREEV, Oleg (St. Petersburg State University)

Session Classification: Poster Session 2

Contribution ID: **103** Type: **Talk**

Results from the Fermilab's Muon g-2 experiment

Wednesday, September 8, 2021 3:45 PM (30 minutes)

The Muon g-2 collaboration has recently published the most precise measurement of the muon anomalous magnetic moment with an uncertainty of 460 ppb. The new experimental world average of the muon anomalous magnetic moment (with an uncertainty of 350 ppb) differs by 4.2 standard deviations from the Standard Model prediction provided by the Muon g-2 Theory Initiative. The emerging results from ab-initio lattice QCD calculations allow to scrutinize this tantalizing hint for physics beyond the Standard Model for the first time in a three way comparison. To extract the value of the muon anomalous magnetic moment, a clock comparison experiment is performed with spin-polarized muons confined in a superbly controlled electric and magnetic field environment at the muon campus at Fermilab. The deviation of the Larmor from the cyclotron frequency, the anomalous spin precession frequency, is determined while a high-precision measurement of the magnetic field environment is performed using nuclear magnetic resonance techniques. I will discuss the most recent result from the first science data run in 2018 and will report on the experimental improvements implemented to achieve the ultimate goal of 140 ppb uncertainty on the muon anomalous magnetic moment.

Primary author: REIMANN, René (Johannes Gutenberg-Universität Mainz)

Presenter: REIMANN, René (Johannes Gutenberg-Universität Mainz)

Session Classification: Session 3

Contribution ID: **104** Type: **Talk**

Recent progress on QED theory of highly charged ions

Monday, September 6, 2021 3:40 PM (30 minutes)

The latest advances of bound-state QED in various domains are reviewed. The most accurate g-factor measurements in Li- and B-like ions are found in agreement with the theoretical predictions, which represents the most stringent test of many-electron QED in the presence of external magnetic field. Transition and ionization energies in He-like and Be-like ions are considered within the rigorous bound-state QED formalism for quasi-degenerate levels to provide deeper understanding of the many-electron QED effects. The scenario is proposed for observation of the spontaneous vacuum decay in low-energy collisions of heavy nuclei with impact-sensitive measurements of pair-production probabilities.

Primary author: GLAZOV, Dmitry (Saint Petersburg State University)

Presenter: GLAZOV, Dmitry (Saint Petersburg State University)

Session Classification: Session 1

Contribution ID: **105** Type: **Talk**

Open Questions in Atomic Structure of few-electron HCIs

Tuesday, September 7, 2021 2:00 PM (30 minutes)

In heavy ions, inner-shell electrons experience extremely high nuclear binding fields. The dynamics of electrons becomes relativistic and the electronic probability density has a considerate overlap with the nuclear matter. These properties render highly charged ions an ideal tool for basic research in relativistic atomic structure theory, quantum electrodynamics in strong fields, and in studying nuclear contributions. Because of this complex interplay, accurate theoretical calculations are necessary to explain the phenomena observed in increasingly accurate storage ring and trapped-ion experiments.

In the talk, we review latest theoretical developments in the field, in particular in the structure and dynamics of few-electron ions which have been studied in recent recombination experiments at the ESR and CRYRING, and the theory of the g factor of highly charged ions, related to HITRAP and MPIK experiments.

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Session Classification: Session 2