Symposium Precision Physics with highly Charged Ions (SYHC)

jointly organised by
the Mass Spectrometry Division (MS),
the Atomic Physics Division (A), and
the Molecular Physics Division (MO)

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Precision studies with highly charged ions are in the focus of several research fields as they provide conditions inaccessible in neutral atoms. For example, enormous electromagnetic field strengths, which a bound electron experiences in a heavy ion, allow for precision tests of quantum electrodynamics. In the absence of bound electrons, nuclear decay modes can significantly differ from the ones known in neutral atoms. In astrophysical plasmas, atoms are as a rule highly ionized. This symposium aims at discussing the most recent advances in experimental and theoretical investigations with highly charged ions in the realm of the atomic physics, nuclear structure, astrophysics and applications.

Overview of Invited Talks and Sessions

(Lecture hall E415)

Invited Talks

SYHC 1.1	Mon	11:00–11:30	E415	**First experiments at CRYRING@ESR** — •Esther Babette Menz, Michael Lestinsky, Håkan Danared, Claude Krantz, Zoran Andelkovic, Carsten Brandau, Angela Bräuning-Demian, Svetlana Fedotova, Wolfgang Geithner, Frank Herfurth, Anton Kalinin, Ingrid Kraus, Uwe Spillmann, Gleb Vorobyev, Thomas Stöhlker
SYHC 1.2	Mon	11:30–12:00	E415	**Testing quantum electrodynamics in the simplest and heaviest multi-electronic atoms** — •Martino Trassinelli
SYHC 1.3	Mon	12:00–12:30	E415	**Indirect measurements of neutron-induced reaction cross-sections at heavy-ion storage rings** — •Beatriz Jurado
SYHC 1.4	Mon	12:30–13:00	E415	**Laboratory X-ray Astropohysics with Trapped Highly Charged Ions at Synchrotron Light Sources** — •Sonja Bernitt
SYHC 2.1	Mon	17:00–17:30	E415	**Observation of metastable electronic states in highly charged ions by Penning-trap mass spectrometry** — •Kathrin Kromer, Menno Door, Pavel Filianin, Zoltán Harman, Jost Herkenhoff, Paul Indelicato, Christoph H. Keitel, Daniel Lange, Chunhai Lyu, Yuri N. Novikov, Christoph Schweiger, Sergey Eliseev, Klaus Blaum
SYHC 2.2	Mon	17:30–18:00	E415	**Towards extreme-ultraviolet optical clocks** — •José R. Crespo López-Urrutia
SYHC 2.3	Mon	18:00–18:30	E415	**Coupling atomic and nuclear degrees of freedom in highly charged ions** — •Adriana Pálffy
SYHC 2.4	Mon	18:30–19:00	E415	**Laser Spectroscopy at the Storage Rings of GSI/FAIR** — •Wilfried Nörtershäuser

Sessions

SYHC 1.1–1.4	Mon	11:00–13:00	E415	**Highly Charged Ions for Atomic, Nuclear and Astrophysics**
SYHC 2.1–2.4	Mon	17:00–19:00	E415	**Intersection of the Electron-Shell and Nuclear Degrees of Freedom**

SYHC 1: Highly Charged Ions for Atomic, Nuclear and Astrophysics

Time: Monday 11:00–13:00 Location: E415

Invited Talk SYHC 1.1 Mon 11:00 E415
First experiments at CRYRING@ESR — •Esther Babette Menz[1,2,3], Michael Lestinsky[1], Håkan Danared[4], Claude Krantz[1], Zoran Andelkovic[1], Carsten Brandau[1,5], Angela Bräuning-Demian[1], Svetlana Fedotova[1], Wolfgang Geithner[1], Frank Herfurth[1], Anton Kalinin[1], Ingrid Kraus[1], Uwe Spillmann[1], Gleb Vorobyev[1], and Thomas Stöhlker[1,2,3] for the SPARC-Collaboration — [1]GSI, Darmstadt — [2]Helmholtz-Institut Jena — [3]IOQ, Friedrich-Schiller-Universität Jena — [4]European Spallation Source, Lund — [5]I. Phys. Institut, Justus-Liebig-Universität Giessen

After its move from Stockholm and successull commissioning at its new site at GSI, CRYRING@ESR is now in operation and able to accept previously inaccessible ion species available from the accelerator complex as well as a smaller selection from a local injector. As a user facility is serves experiments on nuclear and atomic physics proposed through the SPARC collaboration as well as material science experiments at the newly installed extraction beamline. In the last few years a number of new experimental setups have been installed, tested and used for first experiments. These include a dielectronic recombination setup as well as a microcalorimeter-based X-ray spectroscopy setup that make use of the ultra-cold electron cooler to perform merged-beam experiments and a gas jet target for atomic collisions in the experimental section. We will give an overview of the setup and the progress in recent years, present data from the first experiments and take a look at the plans for upcoming beamtime periods.

Invited Talk SYHC 1.2 Mon 11:30 E415
Testing quantum electrodynamics in the simplest and heaviest multi-electronic atoms — •Martino Trassinelli for the SPARC-Collaboration — CNRS, Institut des NanoSciences de Paris, Paris, France

Transition energy measurements in heavy, few-electron atoms allow to test bound-state QED in extremely high Coulomb fields, which enhance the impact of the quantum vacuum fluctuations on the atomic energies. Up to now, experiments have been unable to achieve sensitivity to higher-order QED effects in extremely strong fields. Here we present a novel multi-reference method based on Doppler-tuned x-ray emission from stored Uranium ions with different charge states. By performing high-accuracy x-ray spectroscopy of two, three, and four electron uranium ions in the same measurement campaign, we could obtain the absolute energy of the $1s_{1/2}2p_{3/2} \rightarrow 1s_{1/2}2s_{1/2}$ transition with an accuracy of 0.17 eV, a factor of six improvement over previous measurement. This allows to be sensitive to two-loop quantum electrodynamics effects in heavy highly charged ions. Furthermore, by comparing the transition energy in helium-like uranium transition to similar transitions in lithium-like and beryllium-like uranium, the contribution of electron-electron interaction, i.e. two-electron QED, in heavy bound systems could be disentangled from the one-electron QED contributions and from the uncertainty related to the nuclear radius. This result excludes a number of the most-accurate state-of-the-art theoretical predictions and represents a new paradigm for precision tests of bound-state QED.

Invited Talk SYHC 1.3 Mon 12:00 E415
Indirect measurements of neutron-induced reaction cross-sections at heavy-ion storage rings — •Beatriz Jurado — LP2i, Bordeaux, France

Obtaining reliable cross sections for neutron-induced reactions on unstable nuclei nuclei is crucial to our understanding of the stellar nucleosynthesis of heavy elements and for applications in nuclear technology. However, the measurement of these cross sections is very complicated, or even impossible, due to the radioactivity of the targets involved. The NECTAR (Nuclear rEaCTions At storage Rings) project aims to circumvent this problem by using the surrogate-reaction method in inverse kinematics at heavy-ion storage rings, which offer unique and largely unexplored possibilities for the study of nuclear reactions. In this talk, I will present the setup and the new methodology, which we are developing within NECTAR to perform high-precision surrogate-reaction experiments at the heavy-ion storage rings of the GSI/FAIR facility. In particular, I will present the first results of the proof of principle experiment, which we successfully conducted in June 2022 at the ESR storage ring of GSI/FAIR.

Acknowledgement: This work is supported by the European Research Council (ERC) under the European Union Horizon 2020 research and innovation program (ERC-Advanced grant NECTAR, grant agreement No 884715).

Invited Talk SYHC 1.4 Mon 12:30 E415
Laboratory X-ray Astropohysics with Trapped Highly Charged Ions at Synchrotron Light Sources — •Sonja Bernitt — Helmholtz-Institut Jena, Germany — GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

The newest generation of high-resolution UV and X-ray spectroscopic instruments onboard current and future satellite observatories has the potential to uncover previously inaccessible details of processes in astrophysical plasmas, such as the ones found in galaxy clusters and in the proximity of active galactic nuclei. This is essential for advancing our understanding of extreme environments and the evolution of the universe.

However, what can be reconstructed from spectra is currently limited by the availability and quality of atomic data, which are the basis for plasma models. That is especially the case for highly charged ions (HCI), ubiquitous in hot astrophysical environments. Laboratory measurements are necessary to provide atomic data, like transition energies, as well as rates of excitation and ionization processes.

Here, work with electron beam ion traps (EBITs) is presented, in which radiation from ultrabrilliant UV and X-ray synchrotron light sources is used to resonantly excite electronic transitions in trapped HCI. Subsequent fluorescence and changes in ion charge state are detected, allowing to gather spectroscopic data, reaching unprecedented resolving powers and signal-to-noise ratios. This has led to a variety of new insights into questions related to astrophysics.

SYHC 2: Intersection of the Electron-Shell and Nuclear Degrees of Freedom

Time: Monday 17:00–19:00 Location: E415

Invited Talk SYHC 2.1 Mon 17:00 E415
Observation of metastable electronic states in highly charged ions by Penning-trap mass spectrometry — •Kathrin Kromer[1], Menno Door[1], Pavel Filianin[1], Zoltán Harman[1], Jost Herkenhoff[1], Paul Indelicato[2], Christoph H. Keitel[1], Daniel Lange[1], Chunhai Lyu[1], Yuri N. Novikov[1], Christoph Schweiger[1], Sergey Eliseev[1], and Klaus Blaum[1] — [1]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, — [2]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, Paris, France

The vast landscape of transitions in highly charged ions including transitions in the optical and the extreme ultraviolet (XUV) regime offer up the opportunity for next generation clock research. Thanks to the rapid advances in the development of frequency combs, the XUV spectral range has become accessible for spectroscopy. However, the search for suitable clock transitions, e.g. involving long-lived metastable electronic states, usually relies heavily on complicated atomic structure calculations. With the mass spectrometer Pentatrap, we have found a new way to measure metastable state energies without actively driving the transition and therefore being independent of theoretical predictions. We use the metastable states populated during the ion production inside an electron beam ion trap (EBIT) and measure their mass difference to the ground state in a Penning-trap mass spectrometer. With this method we have detected a metastable state in lead and measured its energy as a mass difference of just 30.X(0.6) eV on top of the mass of the lead nuclei of ≈194 GeV, making it the most precise mass determination to date with a relative uncertainty of 3×10^{-12}.

Invited Talk SYHC 2.2 Mon 17:30 E415

Towards extreme-ultraviolet optical clocks — •José R. Crespo López-Urrutia — Max-Planck-Institut für Kernphysik

Frequency metrology with optical clocks has become a key tool for novel fundamental physics studies using atomic systems. Its outstanding resolution, reproducibility and accuracy makes it in principle capable of sensing effects of all Standard Model interactions on the frequency of electronic transitions, such as, e. g., a variation of the fine-structure constant. Disentangling the different sources of the underlying modifications of the electronic wave function is thereby crucial. For this, it is necessary to change the neutron number as well as the overlap of the electronic wave function with that of the nucleus in a well-defined way, as in the generalized King-plot method [1]. Isoelectronic and isonuclear sequences of highly charged ions (HCI) offer a plethora of possibilities in this regard [2], since they possess many different types of exceptionally long-lived metastable states up to x-ray energies. The development of an optical clock based on HCI [3] show the promise from an extension of frequency metrology beyond the optical range. For this purpose, we are preparing an experiment combining an extreme-ultraviolet frequency comb based on high-harmonic-generation [4] with a superconducting radio-frequency trap [5].

[1] Berengut, J. C., et al., Rev. Res. 2, 043444 (2020)
[2] Kozlov, M. G., et al., Rev. Mod. Phys. 90, 045005 (2018)
[3] King, S.A., et al., Nature 611, 43 (2022)
[4] Nauta, J., et al., Opt. Express 29, 2624 (2021)
[5] Stark J., et al., Rev. Sci. Instrum. 92, 083203 (2021)

Invited Talk SYHC 2.3 Mon 18:00 E415

Coupling atomic and nuclear degrees of freedom in highly charged ions — •Adriana Pálffy — Institut für Theoretische Physik und Astrophysik, Universität Würzburg

Nuclear transitions of low energy can couple efficiently to the atomic shell in a variety of processes such as internal conversion, its inverse process nuclear excitation by electron capture or electronic bridge. The talk will illustrate two such examples involving highly charged ions.

First, the talk will follow theoretical developments on employing electronic bridge processes for the driving the nuclear clock transition in ^{229}Th [1]. This nucleus possesses the lowest known nuclear transition energy and promises a novel and unprecedently precise nuclear clock. The nuclear excited level is a metastable state with energy of 8.19(12) eV, allowing driving with vacuum-ultraviolet lasers. Second, we will discuss recent results for nuclear excitation by electron capture employing electron vortex beams whose wave function has been especially designed and reshaped on demand [2]. On the example of ^{93m}Mo, we show theoretically that the use of tailored electron vortex beams increases the depletion by 4 orders of magnitude compared to the spontaneous nuclear decay of the isomer.

[1] P. V. Bilous *et al.*, Phys. Rev. Lett. 124, 192502 (2020).
[2] Y. Wu *et al.*, Phys. Rev. Lett. 126, 162501 (2022).

Invited Talk SYHC 2.4 Mon 18:30 E415

Laser Spectroscopy at the Storage Rings of GSI/FAIR — •Wilfried Nörtershäuser — TU Darmstadt, Institut für Kernphysik, Schlossgartenstr. 9, 64289 Darmstadt — Helmholtz-Forschungsakademie Hessen für FAIR (HFHF), Campus Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt

The availability of highly charged ions and the large Doppler shifts of relativistic beams make laser spectroscopy at storage rings an attractive tool to test strong-field QED as well as electron-electron correlations in few-body calculations. Laser light can also be used to address and analyze internal and external degrees of motion of the stored ions. An overview on recent results and activities in these fields at the GSI/FAIR storage rings ESR and CRYRING@ESR will be presented.