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SPARC at FAIR: New Opportunities for Atomic Physics with Highly Charged Ions

For probing fundamental laws of physics in the largely unexplored regime of extreme electromagnetic fields, the Stored Particle Atomic Physics Research Collaboration (SPARC) was formed to perform precision experiments with beams of cooled, highly charged, heavy ions and exotic nuclei provided by the portfolio of the Facility for Antiproton and Ion Research (FAIR) storage rings and traps. SPARC is one of the four collaborations in the APPA research pillar of FAIR, consisting of Atomic and Plasma Physics, and Applied Sciences collaborations with more than 700 scientists from 30 countries [1]. The SPARC physics program is concentrated at the storage rings and traps of the FAIR instrument portfolio, shown in Figure 1 for the Modularized Start Version (MSV). The broad SPARC science program aims at exploiting the full parameter range of FAIR beams at different experimental areas. Beams from the existing Helmholtz Center for Heavy Ion Research (GSI) SIS18 are injected into the Experimental Storage Ring (ESR) and in future into SIS100 and from there to different experimental stations of the FAIR facility. The SPARC experimental sites are indicated in Figure 1 by orange dots. Presently, SPARC has the ESR, the low-energy storage ring (CRYRING@ESR) and the Highly Charged Ion TRAP (HITRAP) for experiments within the current research program of GSI, FAIR phase-0, available. Both CRYRING and HITRAP are coupled to the ESR, which stores and cools ions at typically 400 MeV/u and allows to decelerate them to the injection energies of 10 MeV/u for CRYRING@ESR and 4 MeV/u for HITRAP, whereby maintaining their high charge-state. Later, heavy ion beams of up to 10 GeV/u will be used by SPARC in SIS100, in the APPA cave, as well as in the High Energy Storage Ring (HESR).

FAIR is unique, as its accelerators will deliver highly intense, brilliant beams of highly charged heavy stable ions up to bare U, as well as exotic ions. Together with the storage rings and traps, these ions can be cooled to low momentum spread and stored for long observation times and high luminosities. The international SPARC (about 430 members) will exploit this *world-wide unique* combination of storage and trapping facilities with top-of-the-line particle accelerators. As depicted in Figure 2, the FAIR storage and trapping facilities cover a beam-energy range of more than 17 orders of magnitude.

SPARC focuses on the study of atomic matter subject to extreme electromagnetic fields. One prominent example concerns the binding energies of electrons in high-Z one-electron ions where the K-shell electrons are exposed to electric fields (e.g., 10^{16} V/cm in U^{91+}) close to the Schwinger limit. In a concerted effort at HITRAP and CRYRING and in close collaboration with the leading expert groups in theory, SPARC has initiated a comprehensive research program to accomplish a significant validity check of nonperturbative bound-state quantum electrodynamics (QED).

We will apply different experimental approaches (1s Lamb shift, 1s hyperfine-structure, bound-state g-factor, mass measurements, di-electronic recombination spectroscopy), thus probing QED at different mean-distances of the electron to the nucleus and in different sectors of interactions (electric and magnetic fields). At the

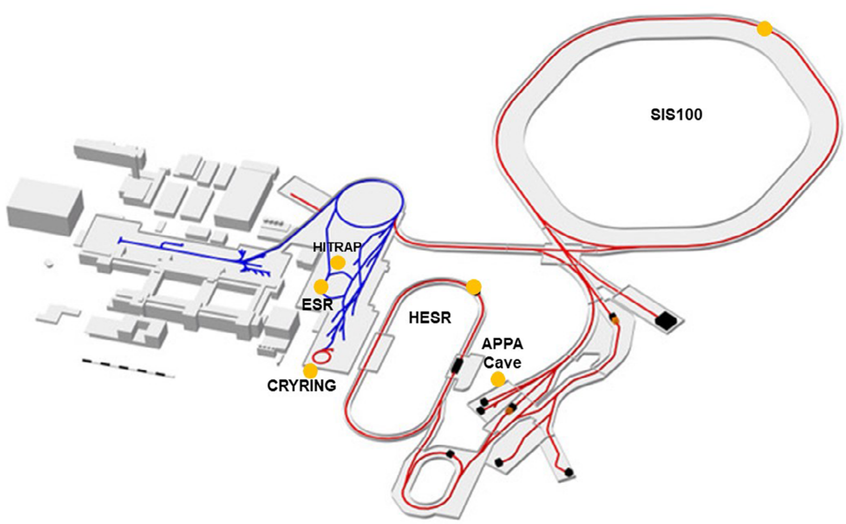

Figure 1. *The experimental facilities of the MSV of FAIR with the SPARC experimental stations indicated by orange dots.*

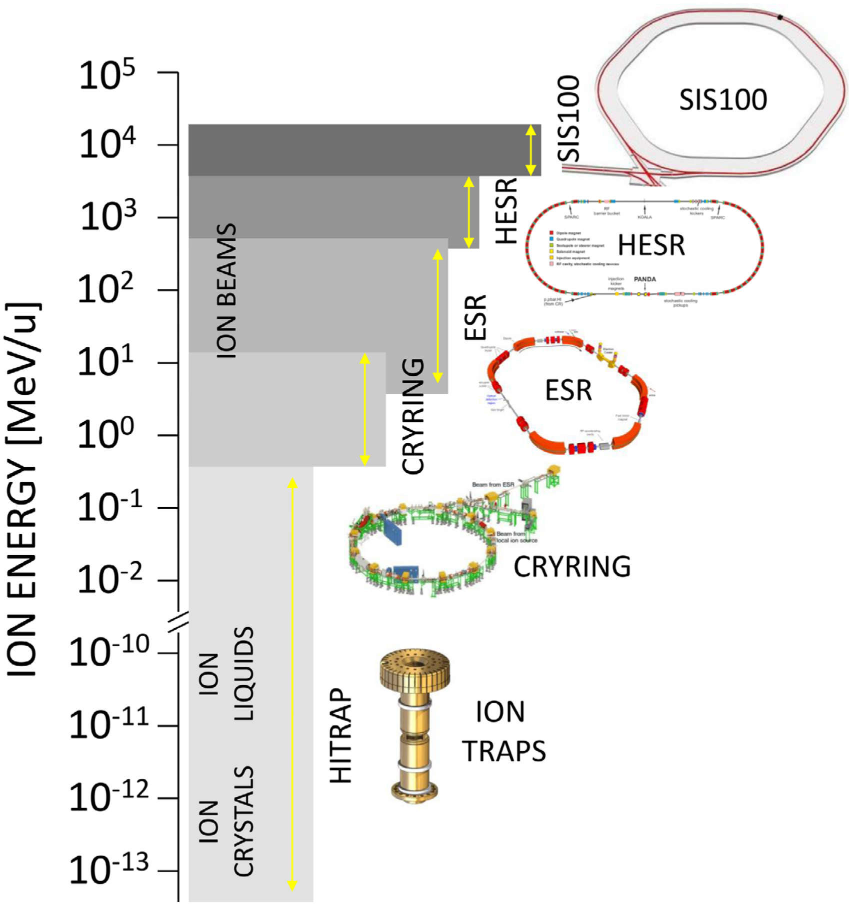

Figure 2. *Energy range covered by the portfolio of storage and trapping facilities at FAIR. All these facilities are part of the MSV.*

same time, SPARC will apply these accurate atomic-physics techniques as powerful tools for the determination of nuclear parameters such as nuclear radii and moments. At ESR and CRYRING, searches for the development of, for example, nuclear clocks are undergoing and more generally on the intersection of atomic and nuclear physics, such as the influence of the atomic shell on nuclear decay properties [2]. A very active program on nuclear reactions in the Gamow window has been initiated at CRYRING (Figure 3) recently.

Exploiting the HITRAP decelerator or the cooler trap, the potential energy of, for example, a bare U nucleus (about 1 MeV) exceeds by far its kinetic energy by which new areas of ion interactions with solid surfaces and material nano-layers will be studied. For investigations of quantum dynamics in the regime of adiabatic transitions we initiated the installation of a reaction microscope at CRYRING, that could be also used at HITRAP and later also at the HESR (see below). HITRAP is currently recommissioned and is expected to be available for first experiments in 2024 or 2025. Even high-precision determination of fundamental constants will then be possible at HITRAP.

The installation of CRYRING (Figure 3) at the ESR was completed in 2019, and first experiments with heavy highly charged ions delivered from the ESR have already been conducted for stored Pb^{78+}, Pb^{82+}, and U^{91+} beams at an energy of 10 MeV/u. In the case of the U^{91+}ions, precision X-ray spectroscopy for He-like uranium has been conducted at the electron cooler of CRYRING (Figure 4) by using two novel magnetic microcalorimeters (MMC) as developed by SPARC. An example of the "Balmer lines" of U^{90+} measured by a MMC is shown in the bottom of Figure 4 (blue lines) in comparison with a Ge(i) detector spectrum taken at the ESR [3].

Another attempt for precise atomic structure studies (1s Lamb shift) for all H-like ions up to uranium and a further highlight of the SPARC program is resonant coherent excitation (RCE) of relativistic heavy ions passing through a crystal [4]. Thereby, atomic and possibly also nuclear transition can get resonantly and coherently excited by the periodic potential of the crystal lattice. The system was tested with beams from SIS18/ESR and Li-like U (Figure 5). Once beams from SIS100 to the APPA cave are available, experiments can be done for 1s excitation (1s Lamb shift) of all H-like ions up to uranium and also for the very first time to excite nuclear levels with high selectivity.

At the HESR, an extremely short, relativistically enhanced field pulse can be created in heavy ion collisions. Thereby, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitude and a breakdown of perturbative approximations for pair production is expected. The detection methods of reaction microscopes will measure the momentum of all fragments produced when atoms or molecules disintegrate in such extremely short (zepto s) but strong field pulses (>10^{16} V/cm) of the ions. This allows

Figure 3. *CRYRING@ESR is a Swedish in-kind contribution to FAIR installed at the ESR storage ring of GSI [2].*

a very detailed characterization and test of theories of multiphoton processes in regimes that are still far from being reached with high-power lasers. In addition, we investigate the correlated motion of electrons bound to atomic targets in a kinematically complete fashion, thus providing much needed benchmarks for a relativistic *a priori* many body theory.

In this experiment series, SPARC has also planned the exploration of a novel pair-production process mediated by electron–electron–positron interaction. A target electron (treated as quasi-free) is transferred into a bound state of the projectile via excitation of

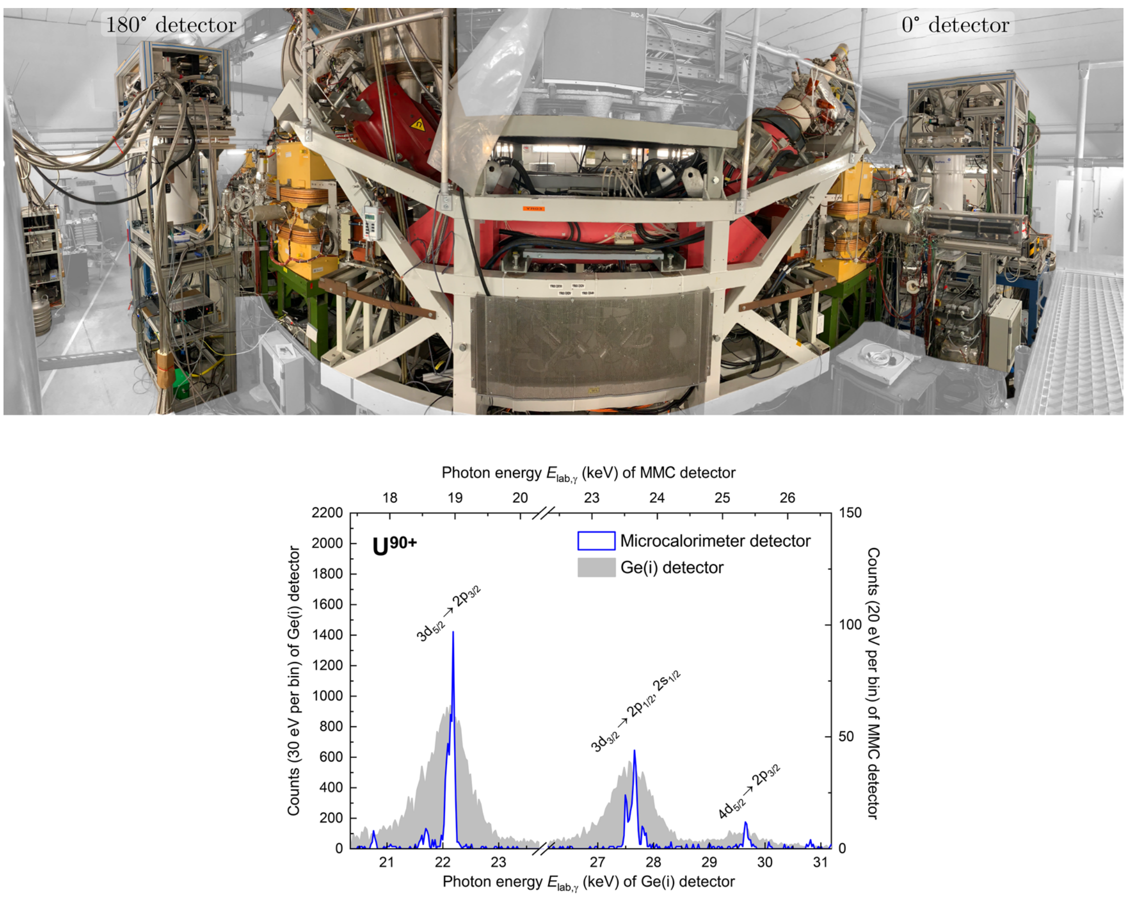

Figure 4. *(top): Experimental setup at the CRYRING@ESR electron cooler with two micro-calorimeter detectors at 0 degrees and 180 degrees observation angles. Both detectors are equipped with 8×8 pixel arrays operated at a temperature of 50 mK [3]. (bottom): "Balmer spectrum" of U^{90+} measured by a micro-calorimeter detector (blue lines) in comparison with a Ge(i) detector spectrum (gray area) taken at the ESR at higher energy [3].*

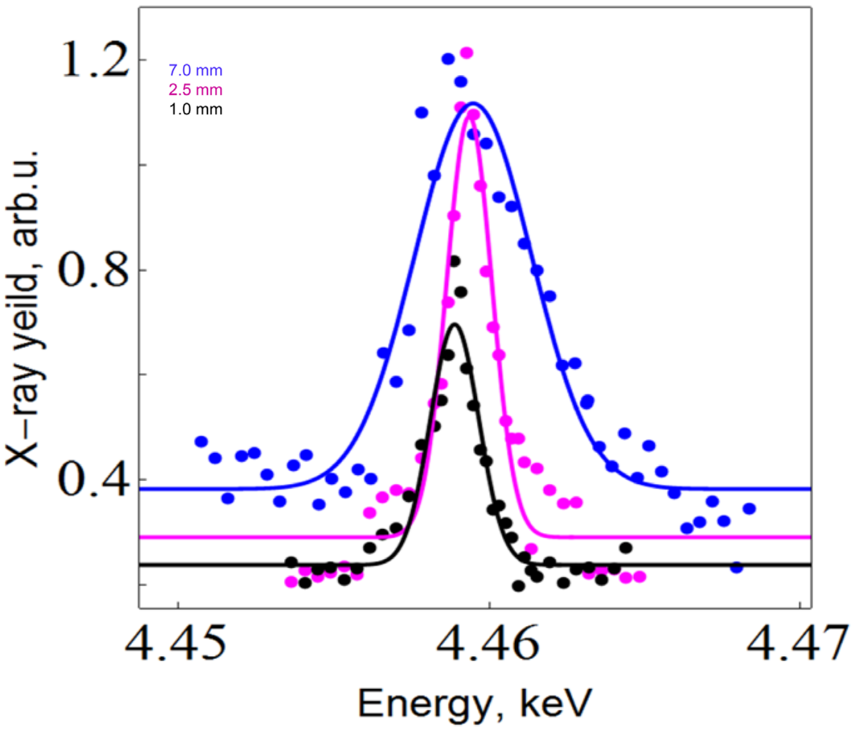

Figure 5. *RCE of U^{89+} ions passing through a Si crystal of different thickness each [4].*

an electron from the negative Dirac continuum to a bound projectile state (test of relativistic electron-correlation beyond Breit interaction) and emitting a positron.

Also at the HESR, the frequencies of novel laser and laser-driven sources in the visible- and the XUV-regime can be boosted by the large γ-values to photo-excite inner-shell electrons in heavy ions. This will allow laser spectroscopy of strongly bound states, and a test of relativistic time dilatation at much higher precision than hitherto possible.

Finally, the SPARC research program continuously evolves to address new physics questions exploiting the unique features of the storage ring environment of FAIR combined with novel SPARC instrumentation. The up-to-date instrumentation and flexibility in using the various facilities is a strength of SPARC. Prominent examples are micro-calorimeters and Compton polarimeters for hard X-rays and spectrometers for electrons, positrons, and ions. In addition, novel lasers for Doppler-tuned spectroscopy and targets (gaseous, micro droplet, and superfluid targets) should be mentioned. The progress in the development of novel equipment and instrumentation already presently enables cutting-edge experiments at ESR, CRYRING, and HITRAP as a part of GSI's FAIR Phase-0 research program, which will stay in operation in the future as FAIR facilities.

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