Stored Particle Atomic Physics Research Collaboration: Atomic Physics with Stored Highly-Charged Heavy Ions at the Future FAIR Facility

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Abstract

The envisioned program of the research collaboration SPARC (*Stored Particle Atomic Research Collaboration* at the future GSI accelerator facility *FAIR* will be discussed. This future international accelerator Facility for Antiproton and Ion Research has key features that offer a range of new and challenging opportunities for atomic physics and related fields. In SPARC we plan experiments in two major research areas: collision dynamics in strong electromagnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use the relativistic heavy ions for a wide range of collision studies. In the extremely short, relativistically enhanced field pulses, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitudes and a breakdown of perturbative approximations for pair production is expected. For medium and low energies, the cooler rings NESR - a "second-generation" ESR - and the low-energy ring LSR, with optimized features and novel installations such as an ultra-cold electron target and dense internal jet-targets will be exploited for collision studies. Fundamental atomic processes can be investigated in a kinematically complete fashion for the interaction of cooled heavy-ions up to bare uranium with photons, electrons and atoms. The other class of experiments will focus on structure studies of selected highly-charged ion species, a field which is still largely unexplored. The properties of stable and unstable nuclei will become accessible by atomic physics techniques along with precision tests of quantum electrodynamics (QED) in extremely strong electromagnetic fields. Another important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP. This will enable not only high-accuracy experiments in the realm of atomic and nuclear physics but as well highly-sensitive tests of the Standard Model.

Introduction and Overview

At the proposed new accelerator Facility for Antiproton and Ion Research the investigation of extreme atomic conditions becomes accessible with highly-charged

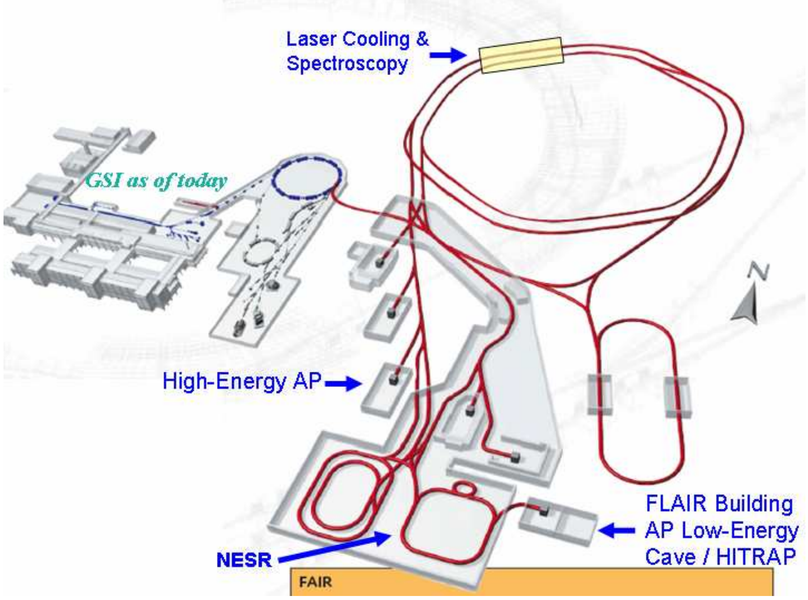

Figure 1: Overview of the existing and planned accelerator facilities; locations of the future areas for atomic physics experiments are indicated.

very-heavy ions over an energy range from rest to the relativistic regime [1]. These studies are needed for our understanding of the processes ongoing in extreme states of matter, as the majority of matter in the universe exists as stellar plasmas. There high temperatures, high atomic charge states and highest field strengths prevail. Conditions that become available at FAIR [4] will provide the highest intensities of relativistic beams of both stable and unstable heavy nuclei, in combination with the strongest electromagnetic fields, thus allowing extending atomic spectroscopy virtually up to the limits of atomic matter. In the different accelerator structures, the ions, after having stripped off most of their electrons can be decelerated basically to rest. The wide ranges of ion energies and electromagnetic field strengths that will become available are demonstrated in Fig. 2.

At high, relativistic energies, the FAIR facility will be unique by providing the heaviest ions over a wide energy range from 1 to 30 GeV/u. In the special case of pair production there are very few and only inclusive measurements of pair production available in the intermediate relativistic regime of a few GeV/u. Here, even the target charge dependence is not well understood, whereas at extreme energies, in the region beyond hundred GeV/u, there is good agreement between theory and experiment. The new facility will be worldwide the only one capable of filling this important gap. Utilizing the high luminosity of the future GSI facility, beyond inclusive cross section studies also differential aspects of atomic processes at high energies become accessible, for which the electromagnetic interaction differs significantly from the low-energy regime. A measurement of the impact parameter dependence for both inner-shell ionization and excitation processes will enable the separation of the longitudinal and the transversal field contributions to the interaction. For such investigations, precise spectroscopy of photons as well as of electrons and positrons

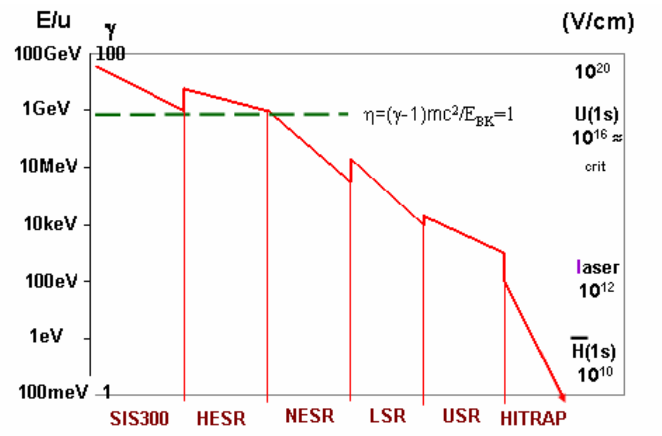

Figure 2: Ion energies and Lorentz factors γ that can be obtained with the different FAIR facilities. The adiabadicity value $\eta = 1$ (specific kinetic ion energy corresponding to the mean velocity for an electron bound with E_{BK} in the uranium K shell) is indicated. On the right hand scale the electric field strengths that are reached in collisions, in bound states and with lasers are shown. Note LSR, USR, and HITRAP are storage ring and trap installation located in the FLAIR building.

is required (energy diagram and basic atomic processes which occur in relativistic ion-atom collisions, compare Fig. 3a). The photon and electron emission gives the details of the specific excitation mechanism in those fields. One may also mention the possibility to search for recombination followed by e^+-e^- pair production instead of photon emission. This higher-order process, requiring high collision energies, is similar to dielectronic recombination, but with one electron being excited from the negative continuum into a bound state.

The new facility will provide intense beams of stable and unstable isotopes up to uranium at the highest charge states. At the NESR storage ring these ions can be stored and cooled at energies of 760 MeV/u down to 4 MeV/u and at the LSR (LSR: *Low-Energy Storage Ring* even down to 0.5 MeV/u). For the low-energetic ions (below 100 MeV/u) the possibility to extract them into the dedicated low-energy Cave exists. The storage rings NESR and LSR in their combination with the facilities installed have a decisive advantage over other experimental techniques as they allow to address fundamental process which become feasible at this time only in inverse kinematics: fully differential photoionization cross sections - including polarization - for the heaviest ions in arbitrary charge states, recombination, complete differential cross sections for the short wavelength limit of electron-nucleus bremsstrahlung and fully differential (e,2e) cross sections for ions by mapping the complete momentum balance of all emitted particles. Also, the combination of these very heavy, highly-charged ions with the low collision energies, where the Sommerfeld parameter q/v becomes very large, is an additional unique feature not available at any other machine. Furthermore, spectroscopy in the NESR will be a key instrument for frontier experiments on highly-charged ions and radioactive isotopes.

A singular opportunity is given by the combination of the SIS 12/100/300, the

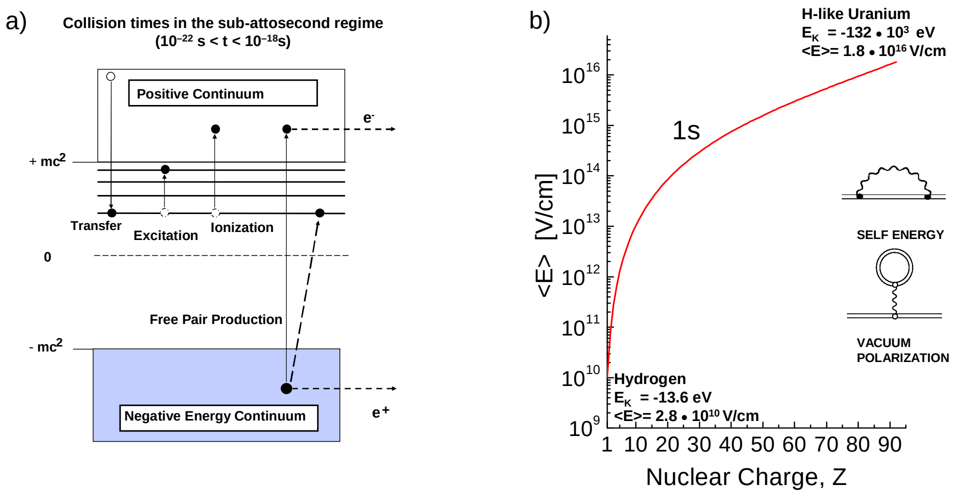

Figure 3: a): Energy diagram of the single-particle Dirac equation and basic atomic processes which occur in relativistic ion-atom collisions. b:) Expectation value of the electric field strength <E> for a K-shell electron in H-like ions as a function of the nuclear charge number Z.

NESR storage ring and the PHELIX laser facility. In contrast to the typical experimental situation in gas targets, the storage ring provides precise control of the initial ion species and diagnostics of the final states of the ions and of ejected electrons on the single-event level. This will enable research at truly undisturbed single-ion condition, where the only interacting partners will be the laser field, the highly charged ion, and the detached electron. The proposed FAIR facility with its intense heavy ion beams, in combination with novel experimental techniques such as excitation by X-ray or laser photons, mono-energetic electron beams, high-resolution spectrometers, or channelling in crystals gives world-wide unique opportunities for atomic spectroscopy. This will enable the exploration of the fundamental QED corrections to binding energies, magnetic moments, and the magnetic interactions in the strong field regime (compare Fig. 3b)).

The new accelerator complex at GSI will enable another important step by a large increase of the photon frequency range and by allowing spectroscopy for a wide variety of radioactive beams that is not available otherwise. The present limitations for the application of wavelength-restricted lasers will most certainly be widely removed. For instance, in the SIS300 ring the accessible transition energy range will be increased considerably due to a large Doppler shift. Furthermore, a completely new regime of laser cooling of heavy relativistic highly-charged ions can be opened.

The HITRAP Facility [3] where highly-charged ions can be brought practically to rest will be the only facility world-wide where bare U nuclei can be trapped in a strong magnetic field. The highly-charged ions will be cooled down to cryogenic temperatures. There the g-factor of a single electron bound in the potential of an arbitrary stable or unstable nucleus like ^{238}U nucleus and others can be determined.

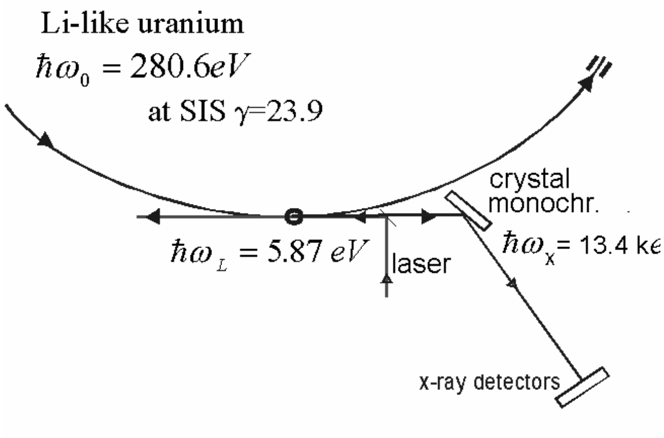

Figure 4: Setup for combined laser-excitation X-ray spectroscopy experiments showing the laser excitation at known photon energy and the measurement of the energy of the backscattered photon

Measurements of the hyperfine splitting (HFS) in hydrogen-like ions will give information about the distribution of the nuclear magnetization within the nucleus. By optical pumping within the HFS-levels of the ground state, the nuclear spins of radioactive nuclides can be polarized with high efficiency, opening unique possibilities to study questions of the Standard Model of fundamental interactions.

Experimental Concepts

Laser Experiments at SIS100/300

Laser cooling and spectroscopy installation at SIS100/300 will mostly use Li-like very heavy ions. Laser interaction with highly-charged ions stored in SIS100/300 benefits tremendously from the relativistic Doppler boost experienced in the ion rest frame when counter-propagating beams are used (compare Fig. 4. This advantage is twofold: on the one hand, the Doppler boost will increase the peak intensity in laser-ion interaction experiments at ultra-high intensities and shorten the pulse length in the ion rest frame for ultra-fast spectroscopy. On the other hand, this boost will allow for the use of standard laser systems in the visible range for the optical excitation of ground-state transitions of highly-charged ions in the X-ray range. Precision spectroscopy of heavy few-electron systems will become possible, complementary to the X-ray laser experiments proposed to be performed at NESR, as well as laser cooling, a unique cooling technique for relativistic ion beams. Laser cooling of highly charged ions in the SIS100/300 holds the promise of producing ultimate beam quality in terms of temperature, divergence and density. Even beam crystallization might become possible due to the favorable lattice symmetry of the synchrotron. Especially for experiments at the luminosity limit, like the investigation of nuclear effects due to the interaction with well focused, ultra-intense laser pulses, this combination will considerably facilitate the planned experiments.

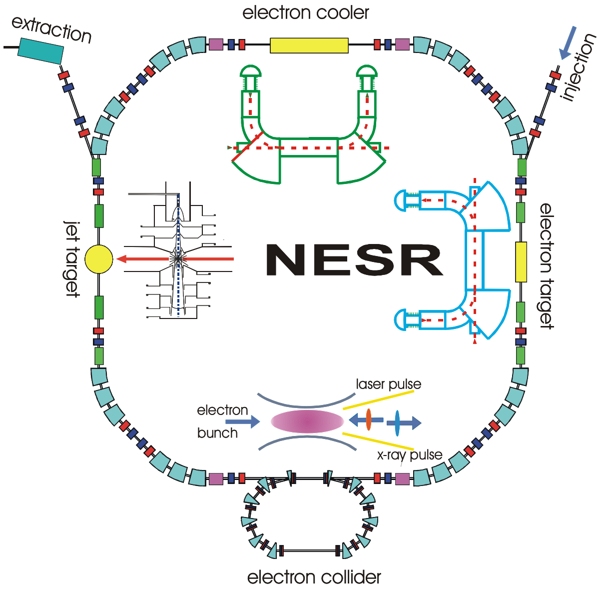

Figure 5: The New Experimental Storage Ring NESR with its instrumentation for atomic physics experiments.

Collision Experiments using Relativistic Beams from SIS100

For atomic physics experiments and applications in radiobiology, space and materials research a dedicated experimental Cave for extracted beams from SIS100 will be available. The investigation will concentrate on atomic structure (resonant coherent excitation) and collision studies at moderate and high-relativistic energies (ionization, capture, and pair production) as well as on irradiation of individual samples for biological or solid material research.

For atomic physics experiments with highly-charged, few-electron ions the cave will be equipped with a charge state spectrometer allowing for charge state separation behind a reaction target for beam energies up to about 1 GeV/u ($\approx$ 20 Tm). For this purpose, beside a beam line from SIS100 also a direct beam line from SIS12 to the cave has to be installed. The current experimental program in Cave A has shown, that life-time measurements and experiments on precise photon and electron spectroscopy and on channelling strongly profit from coincidence measurements with the final projectile charge state. Here, beam intensities of up to 109 ions/spill with spill lengths of the order of 1 sec are required. For atomic physics experiments at even higher beam energies of up to $\approx$ 10 GeV/u, e.g. resonant coherent excitation using channelling techniques and investigation of different channels for pair production, no charge state separation is foreseen and the desired beam intensity amounts to 10^8 ions/spill.

Experiments with Stored and Cooled Ions at the NESR

The New Experimental Storage Ring NESR is shown in Fig. 5. The NESR can be supplied with highly-charged heavy ions from SIS 12 and with exotic nuclei

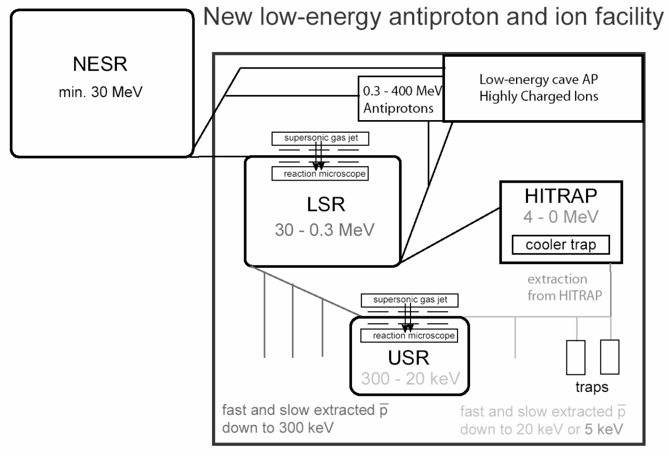

Figure 6: Simplified scheme of the various experimental facilities located inside the FLAIR building.

from SFRS. The Atomic Physics Experiments with Stored and Cooled Ions at the NESR have a variety of installations and projects with following requirements: The number of ions per cycle should reach 10^{10} at medium Z. The momentum spread after electron cooling is supposed to be less than 10^{-4}. The beam energy should range from 760 MeV/u to the low energy limit, reached by deceleration to 3 MeV/u. Fast and slow beam extraction is needed. The lifetimes of stored ions are of utmost importance. Thus, an excellent vacuum of 10^{-11} mbar is needed. The electron target should have an ultra-cold electron beam. The resulting energy spreads should be as low as a few 10 meV at collision energies below 1 eV and smaller than 5 eV at 100 keV. One should reach 300 keV in the center-of momentum frame. At the gas jet target ion-atom reaction mechanisms as well as the ionic structure will be studied; Photon Spectrometer such as crystal spectrometers for soft and hard X-rays (3-120 keV), low-temperature calorimeter and Compton polarimeter will be installed. An Electron Spectrometer for electrons from 100 keV to MeV energy and an Extended Reaction Microscope for imaging recoils and slow and fast electrons in the range of meV should operate at the Internal Target. Here, in addition, laser spectroscopy will be applied. At the electron target the atomic assisted electron-electron interaction will be studied. Here also laser techniques and X-ray spectroscopy will support the experiments.

Experiments with Cooled, Decelerated and Extracted Ions

Experiments using decelerated and cooled Highly Charged Ions with rigidities below 4.5 Tm ($<$ 130 MeV/u for ions and $<$ 700 MeV for antiprotons, respectively) extracted from the NESR will be accommodated in the so called FLAIR building *Facility for Low-Energy Antiproton and Ion Research* which is placed in the neighborhood of the NESR. This building is designed such that it includes the experimental areas requested by the experiments with low-energy heavy ions within the SPARC collaborations as well as for low-energy antiprotons promoted by the FLAIR collaboration [4]. Within the building the low-energy atomic physics cave for experiments with cooled and decelerated ions (down to 4 MeV/u) from NESR will be located as well as the HITRAP facility. In addition, it is planned to use an additional storage ring for further deceleration of the heavy ions (as low as 300 keV/u) but also for antiprotons (300 keV). For this task the CRYRING, a facility at the Manne Siegbahn Laboratory at Stockholm University seems to be ideally suited. This Low-Energy Storage Ring (LSR) will deliver electron cooled low-energy beams for experiments in the various experimental location within the FLAIR building: Low-Energy Atomic Physics Cave, experimental areas for direct, fast of slow-extracted antiproton beams from the LSR, the HITRAP facility, the USR (a Ultra-Low Energy Storage Ring) and traps for antiproton experiments. Both HITRAP as well as the USR might also be used for particle deceleration to rest, as e.g. needed for the trap experiments with antiprotons. A simplified scheme for the various experimental facilities located inside the FLAIR building is given in Fig. 6.

Summary

A condensed description of the main aspects of the planned atomic physics research activities at the future FAIR facility was given along with a short overview of the various experimental installations to be used, including storage rings and traps. These activities of the SPARC collaboration comprise the investigation of relativistic collision dynamics, the test of Quantum Electrodynamics in extremely strong electromagnetic fields, the use of atomic physics techniques for the determination of properties of stable and unstable nuclei, and ideas to test the predictions of fundamental theories besides Quantum Electrodynamics. As documented by the rich program of the SPARC collaboration, the new FAIR facility provides challenging and unique opportunities for atomic physics research in the realm of extrem electromagnetic fields.

References

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