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Status and perspectives of atomic physics research at GSI: The new GSI accelerator project

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Abstract

A short overview on the results of atomic physics research at the storage ring ESR is given followed by a presentation of the envisioned atomic physics program at the planned new GSI facility. The proposed new GSI facility will provide highest intensities of relativistic beams of both stable and unstable heavy nuclei – up to a Lorentz factor of 24. At those relativistic velocities, the energies of optical transitions, such as for lasers, are boosted into the X-ray region and the high-charge state ions generate electric and magnetic fields of exceptional strength. Together with high beam intensities a range of important experiments can be anticipated, for example electronic transitions in relativistic heavy-ion collisions such as dynamically induced e^+e^- pairs, test of quantum electrodynamics (QED) in strong fields, and ions and electrons in ultra-high intensity femtosecond laser fields.

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1. Introduction

Accelerator-based atomic physics has always opened new, widely unexplored fields of research. The heavy-ion storage cooler ring ESR at GSI has provided a first access to basic processes associated with strong electromagnetic fields in collisions of heavy, highly charged ions. This has been done by various experimental methods, e.g. X-ray spectroscopy addressing the 1s Lamb shift in heavy ions [1], collinear laser spectroscopy of the hyperfine splitting in hydrogen-like heavy atoms [2], or by the investigation of dielectronic recombination in heavy, few-electron atoms [3]. The dynamical aspect of atomic collisions has been probed by means of radiative electron capture [4], resonant electron transfer [5] and first kinematically complete measurements of many-electron transitions [6]. The conditions of atoms mentioned above

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might be understood as 'extreme' with regard to our daily experience. However, the majority of matter in the universe exists as stellar plasmas, where high temperatures, high atomic charge states and high field strengths prevail. The investigation of these extreme atomic conditions is, therefore, indispensable for our understanding of the processes ongoing in the 'real' matter.

Accelerators are very efficient tools to provide such extreme conditions in the laboratory. In particular the proposed new GSI facility [7] will open up exciting and far-reaching perspectives: it will provide the highest intensities of relativistic beams of both stable and unstable heavy nuclei, in combination with the strongest possible electromagnetic fields, allowing to extend atomic spectroscopy up to the virtual limits of atomic matter. Based on the results already achieved at the ESR, a substantial progress in atomic physics research has to be expected in this domain, due to a tremendous improvement concerning intensity, energy, and production yield of unstable nuclei.

2. The planned new facility

The central part of the planned new accelerator facility [7] is a synchrotron complex consisting of two separate synchrotron accelerator rings with 100 and 200 Tm maximum magnetic rigidity (Fig. 1). Both synchrotron rings have the same circumference of about 1100 m. For the highest intensities, it is planned to operate the 100 Tm synchrotron at high repetition rate (2–4 Hz). The goal of the first synchrotron ring ($B = 100$ Tm) is to achieve intense beams of 10^{12}/pulse U^{28+} at 1 AGeV and 2.5×10^{13} protons/pulse at 29 GeV. With the double ring facility, continuous beams with high average intensities of up to 10^{12} ions per second can be provided for 1 AGeV heavy ions, either directly from the SIS100 or by transfer to, and slow extraction from the 200 Tm ring. The 200 Tm ring can provide high-energy ion beams with maximum energies around 30 AGeV for Ne^{10+} beams and close to 25 AGeV for fully stripped U^{92+} beams, respectively. The maximum intensities that are possible in this mode are 5×10^{10} ions per second.

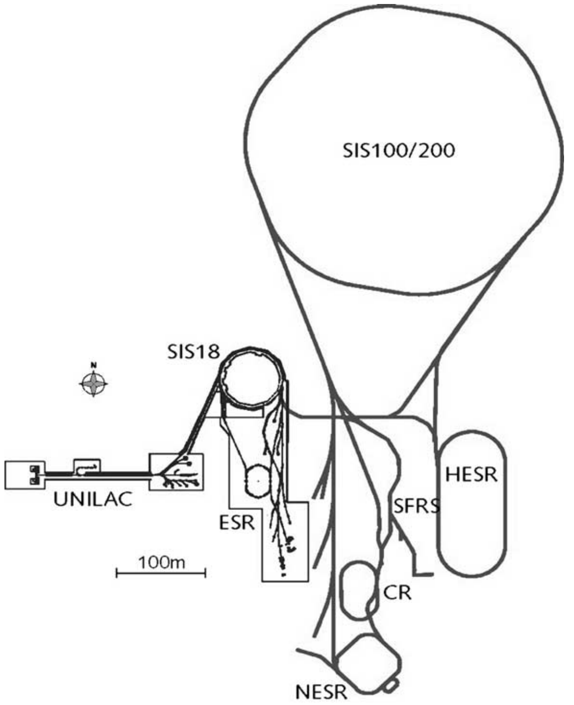

Fig. 1. The existing and planned GSI facility. The linear accelerator UNILAC, the heavy-ion synchrotron SIS18, and the experiment storage ring ESR are shown to the left. On the right, the lay-out of the new project is given [7] consisting of the double-ring synchrotron SIS100/200, the high-energy storage ring HESR, the collector ring, CR, the new experiment storage ring, NESR, the super fragment separator, SFRS and several experimental stations. The UNILAC/SIS18 complex serves as injector for the double ring synchrotron.

The accelerator facility will be complemented by three additional cooler-storage rings: a collector ring (CR) for stochastic cooling of radioactive ion or antiproton beams from the production targets. A new experimental storage ring (NESR) – a "second-generation" ESR with optimized features and novel experimental installations (Fig. 2) will be the workhorse for atomic physics experiments and will serve as an accumulator and storage ring both for ions and antiprotons. Compared to all the other heavy-ion storage rings currently in operation or under construction, the NESR will be the most flexible one, providing intense beams up to bare uranium. New possibilities will be opened up by instrumentations such as a second electron target and an electron-ion collider. The intense

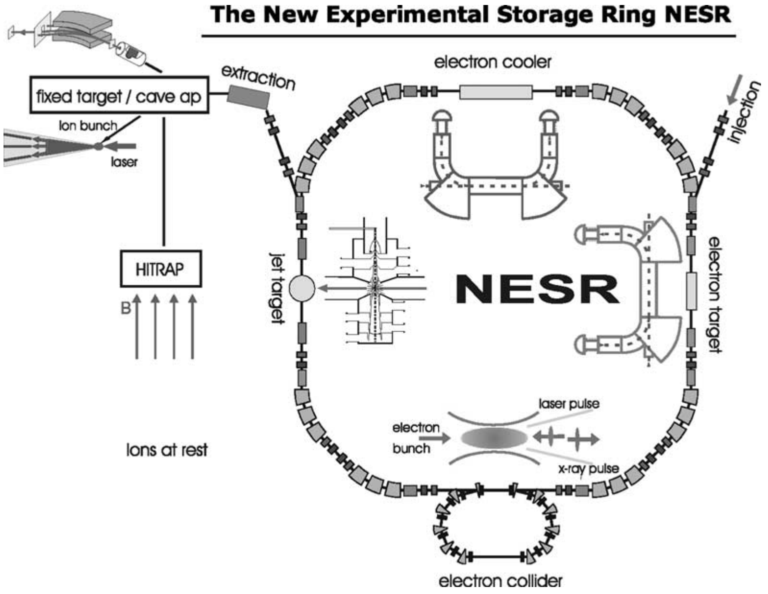

Fig. 2. The new experimental storage ring, NESR, with its instrumentation for atomic physics experiments [7].

beams of highly charged, radioactive ions but also of antiprotons makes novel experiments possible. A further important feature of the NESR is its capability to decelerate the heavy ions and antiprotons to beam energies of as low as 3 MeV/u. For a wide range of ion velocities, the interaction of the highly charged ions with matter will be investigated in the new experimental Cave A (fixed target experiments). This experimental area will be attached to the NESR and is devoted to the physics with fast- or slow-extracted ions. At Cave A, the ions or antiprotons can be actively slowed down even to rest, a prerequisite for precision studies using the trap facility HITRAP [8]. The HITRAP facility will allow to capture any element up to bare uranium with high yields in combination with decelerated ions from the NESR. The high intensity of secondary beams produced at the super fragment separator (SFRS) and decelerated in the NESR will allow the trapping even of exotic nuclei, a unique potential. Trapped radioactive ions in high charge states may open up a new domain for precision studies in the realm of atomic and nuclear physics. This new combination of accelerator and storage rings aims for 100 times higher primary ion beam intensities than the present system and, in conjunction with the new fragment separator (SFRS), for an increase of radioactive beam intensities by a factor of up to 10,000. Finally, the high-energy storage ring (HESR) for antiprotons up to 14 GeV has to be mentioned. This ring will operate with an internal target and associated detector set-up. It will be equipped with a high-energy electron cooler (up to 5 MeV electron energy) and a stochastic cooling system.

3. Atomic physics research at the new facility

Atomic physics research on relativistic, highly charged heavy-ion beams at the new GSI facility can be associated mainly with three types of experimental studies.

The first type uses highly relativistic heavy ions for a wide range of collision studies that involve photons, electrons, and atoms, it exploits the large Doppler boost and the rapidly varying fields in those reactions (Fig. 3). An understanding of those collision phenomena, for example $e^{+}e^{-}$ pair creation, is required for all lines of research in atomic physics, including the interaction in solids (material research).

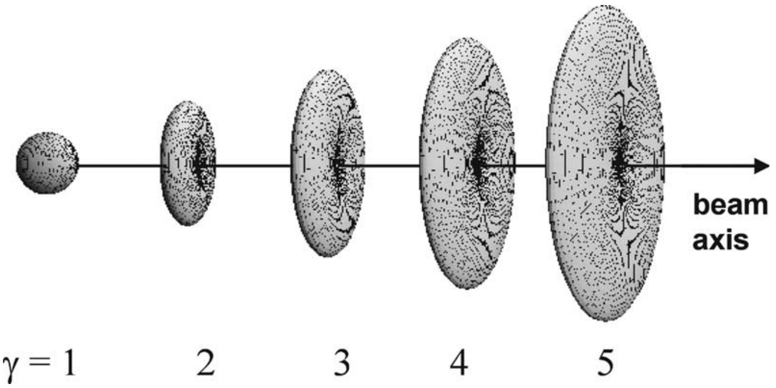

Fig. 3. Angular dependence of the electric radial field strengths of a point charge moving with a Lorentz factor γ ($\gamma = 1, 2, 3, 4$ and 5 corresponds to 0%, 87%, 94%, 97% and 98% of the speed of light) as observed in the laboratory frame. Perpendicular to the trajectory, the electric field of the moving ion steadily increase with γ while the duration of the electromagnetic pulse decreases. Note, for large γ values the electric and magnetic components become almost equal (natural relativistic units ($\hbar = m = c = 1$)). Along the direction of motion, however, the field decreases by a factor of γ^2.

The second type uses high-energy beams for achieving high stages of ionization up to bare uranium nuclei. It focuses on structure studies for these ion species, a field being still largely unexplored, but intimately connected to astrophysics, allowing precision tests of quantum electrodynamics in extremely strong electromagnetic fields. Here, a precise determination of QED contributions in the heaviest one- and few-electron atoms, in particular for the $1s_{1/2}$ and $2s_{1/2}$ states is of particular interest. For Li-like heavy ions, a direct excitation of the 2s–2p transition by Doppler-boosted, counter-propagating laser fields comes into reach at the new facility, which will tremendously

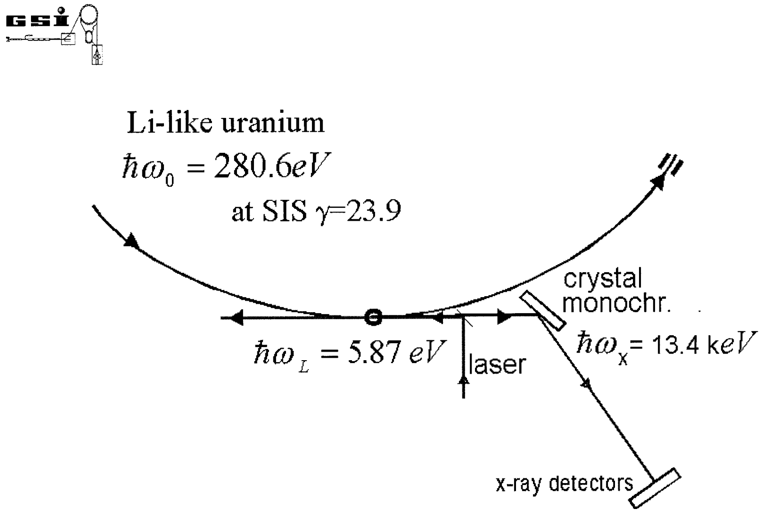

Fig. 4. Experimental setup for precision transition-energy and hyperfine-structure measurements in lithium-like systems at the SIS200 ring [9]. At the high energies available in the SIS200, even photon energies in the visible range will be sufficient for excitation of the $2s_{1/2}$–$2p_{1/2}$ transition in lithium-like uranium. For such ions, a beam energy of 21.3 AGeV corresponding to a Lorentz factor of $\gamma \approx 23.9$ can be reached at SIS200. Since after laser excitation the emitted photon again will be strongly Doppler shifted, high detection sensitivity and good suppression of scattered laser light can be reached. One can estimate that the transition energy of 280 eV in uranium can be measured with an accuracy of 0.007 eV which must be compared with the currently best value of 280.59 ± 0.09 eV [10].

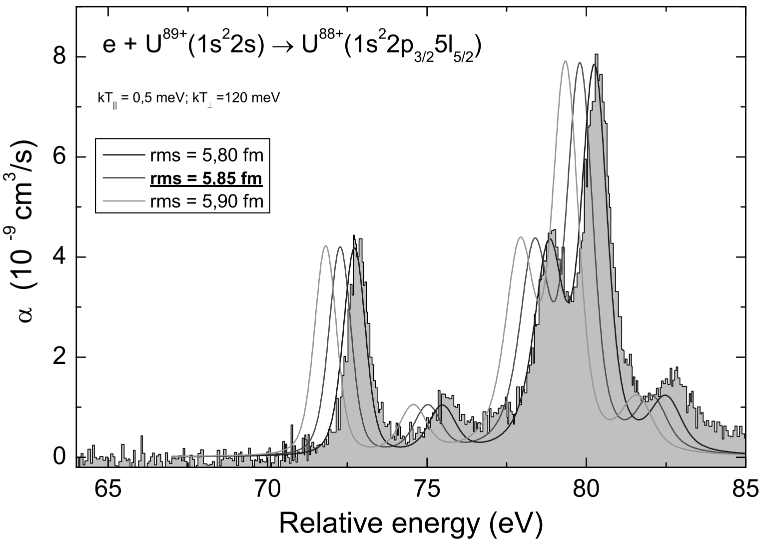

Fig. 5. The $(1s^2 2p) j = 3/2$, $(5l) j = 5/2$ dielectronic resonance group in lithium-like uranium, i.e. capture of a free electron into $j = 5/2$ state of the $n = 5$ shell accompanied by a $2s_{1/2}$–$2p_{3/2}$ excitation. The experimental data are gray-shaded [11]. They are compared with theoretical calculations for three different rms radii of ^{238}U [12]. As can be seen, small changes of the nuclear radius lead to measurable energy shifts. Therefore dielectronic recombination might be used as a novel tool to determine nuclear radii.

improve the precision [9]. Since the Doppler boost in the rest frame of the counter-propagating ion amounts to about 2γ, a direct excitation of the 2s–2p transition in Li-like uranium ($E = 280$ eV) could be achieved at SIS200 ($\gamma = 23$) (Fig. 4). The latter option can also be exploited for an efficient laser cooling of fast, Li-like heavy ions.

The third type utilizes well-defined charge states of radioactive atoms for fundamental studies and model-independent determination of nuclear quantities by applying atomic physics methods such as collinear laser spectroscopy or dielectronic recombination (Fig. 5). An important scenario for this class of experiments will be the slowing-down and trapping of carefully chosen nuclei in atom or ion traps, which will enable high-accuracy experiments in atomic and nuclear physics as well as highly sensitive tests of the Standard Model [13].

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