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Current and future electron spectroscopy experiments in relativistic storage rings

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Abstract

Storage rings as the ESR and the future NESR in the FAIR project are unique tools to study the dynamics of electron-ion and ion-atom collisions in the realm of strong perturbations and short interaction times. A telling sign of the character of such collisions are the electrons emitted into the continuum. For high Z projectiles and low Z targets the projectile centred continuum is dominating. Precision studies of these electrons emitted in relativistic collisions thus are of paramount importance for an understanding of the ionization mechanisms active in transferring electrons into the continua. Forward electron spectroscopy thus appears to be the tool of choice. For high precision studies in collision spectroscopy of high Z projectiles we have implemented an imaging forward electron spectrometer into the ESR supersonic jet target zone. In combination with a reaction microscope to be implemented next this enables investigations of several fundamental processes ranging from kinematically complete studies of multiple ionization and (e, 2e) on ions to radiative and non-radiative electron transfer processes to the projectile continuum and for the first time kinematically complete measurements of the short-wavelength limit of the electron nucleus Bremsstrahlung. We report first results.
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1. Introduction

The emergence of the Facility for Antiproton and Ion Research FAIR opens rich opportunities for research with highly-charged ions (HCI) in a wide range of fields from investigations of nuclear matter at very high densities to atomic physics at extreme conditions, to material science and radiobiology [1]. Utilizing the highest possible electromagnetic fields in atomic systems under investigation and the option of exotic beams will extend atomic spectroscopy in the widest sense to the limit of atomic matter. A worldwide unique feature of the FAIR facility is to permit experiments with high luminosity beams of bare U^{92+} ranging from relativistic collision energies equivalent to $\gamma \approx 34$ at

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the SIS300 synchrotron continuously down to subthermal energies. A collection of magnetic and electrostatic storage rings combined with high precision traps will be equipped with a variety of position sensitive spectrometers for photons, electrons and recoiling ions [1–3] to serve the next generation experiments in strong field processes, as there are studies of relativistic effects on higher order QED corrections to binding energies, of dynamics of target- and projectile continua, of many body effects and of correlated many electron emissions.

2. The FAIR facility with the NESR storage ring

The NESR storage ring is the major workhorse for future atomic physics at FAIR. Energetic highly-charged heavy ions from SIS18 or exotic nuclei from the SFRS will be injected into the NESR (see Fig. 1). The ring with a magnetic rigidity of 13 Tm (compared to 10 Tm for the present ESR) allows to store U^{92+} ions with energy from 780 AMeV down to 3 AMeV. After electron cooling the momentum spread will be better than 1×10^{-4}. In the supersonic gas jet target area the dynamics of ion-atom reactions will be studied; also open questions in fundamental interactions are addressed, high resolution structure studies of few electron high Z ions will be performed utilizing X-ray spectroscopy, zero-degree electron spectroscopy, recoil-ion-momentum spectroscopy, and laser spectroscopy. At the electron target dielectronic recombination over a wider dynamic range than ever before will be studied; here also laser techniques and X-ray spectroscopy will support the experiments. At the electron collider forward emitted X-ray pulses will be generated via the head-on interaction of electron pulses with laser pulses. An important feature of the NESR will be that the highly-charged heavy ions can be decelerated in the NESR down to the low AMeV region. They are either extracted toward a fixed target area or toward the low energy storage ring LSR. There, atomic reactions in the very strong perturbation regime with highly-charged ions at low velocities will be investigated; X-ray spectroscopic and laser techniques will be available as well.

3. The forward electron spectrometer in the present ESR storage ring

In collisions of non-bare high Z ions the projectile centred electron continuum plays an eminent role and thus it is imperative to conduct precision studies of the forward electron cusps. For these types of experiments at the internal target of the present ESR a forward electron spectrometer has been implemented (see Fig. 2). The imaging forward electron spectrometer shall reconstruct, after momentum analysis, on the 2D position sensitive detector the primordial vector momenta of electrons emitted in the target zone using telescopic imaging. A 60° dipole magnet is followed by a quadrupole triplet, another 60° dipole, momentum defining slits and a 2D position sensitive electron detector.

4. First results: the radiative electron capture to continuum (RECC) cusp

The forward electron spectrometer was designed to permit in conjunction with a reaction microscope for low energy electrons and recoil ions kinematically complete experiments for the fundamental process of (e, 2e) on ions and for the short-wavelength limit of electron nucleus

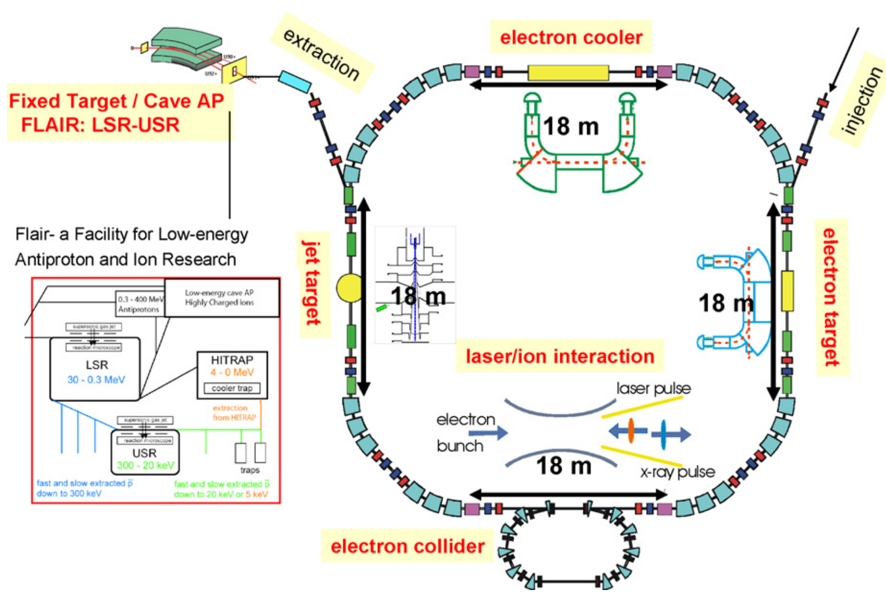

Fig. 1. Layout of the NESR storage ring. As part of the FAIR facility for antiproton and ion research The NESR is one main instrument for atomic physics with stable and exotic beams. Beams can be injected directly from the synchrotrons; exotic nuclei from the fragment separator precooled in the RESR storage ring before injection.

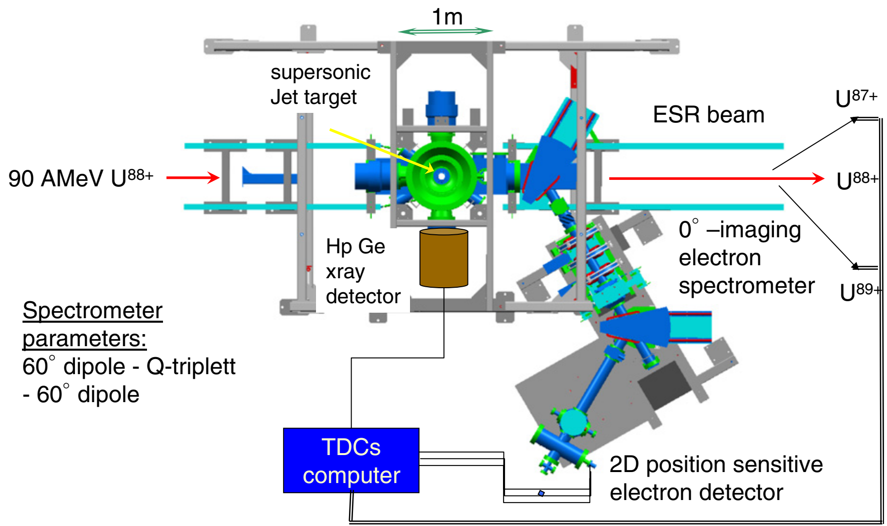

Fig. 2. The internal target zone with the supersonic jet target of the ESR storage ring. A target chamber traversed by the jet beam and with multiple ports for X-ray detectors is followed by the imaging forward electron spectrometer consisting of a 60° dipole, a quadrupole triplet and another 60° dipole. Electrons are detected with an 80 mm diameter 2D position sensitive electron detector and can be measured in coincidence with charge exchanged projectiles and X-ray photons.

Bremsstrahlung. Before implementing the reaction microscope we are already able to perform measurements of the double differential cross section for radiative and non-radiative electron cusps produced in ion atom collisions. This new spectrometer thus offers the opportunity to address a long standing question about the relationship of the RECC with the short-wavelength limit of electron nucleus Bremsstrahlung. In the standard configuration kinematically complete investigations of the electron nucleus Bremsstrahlung are restricted to the soft-wavelength part of the spectrum as the electron coincident with the short-wavelength limit of the Bremsstrahlung spectrum has zero energy in the laboratory frame, thus cannot leave the target foil and for this reason cannot be detected. In inverse kinematics electron nucleus Bremsstrahlung can be observed in relativistic collisions of highly-charged ions with low Z target in the supersonic internal target area of the ESR. Here, now the electron associated with the short-wavelength limit of the electron nucleus Bremsstrahlung will be at rest in the projectile frame – in the laboratory frame it will appear in the zero-degree cusp around $v_e \approx v_{proj}$. In a first step towards a kinematically complete experiment we have measured for 90 AMeV Be-like $U^{88+} + N_2$ coincidences between cusp electrons (emitted under $0 \pm 1.9°$ with velocities around the beam velocity) and charge exchanged projectiles and between cusp electrons and X-rays emitted under 90° with respect to the beam direction. We observe a strong electron loss to continuum cusp from the coincidences of electrons with the U^{89+} charge exchanged beam (see Fig. 3). Preliminary calculations by A. Surzhykov indicate that the dominant fraction of coincident electrons arises from 2s ionization of the projectile. In the coincidences of electrons with X-rays we observe almost exclusively X-rays from the

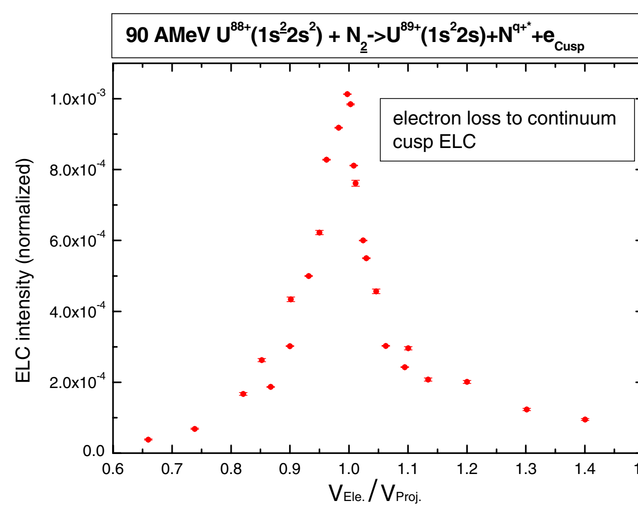

Fig. 3. Electron loss to continuum cusp measured for 90 AMeV Be-like $U^{88+} + N_2$. Electrons emitted under 0° with respect to the beam direction and momentum analyzed with the electron spectrometer are detected in coincidence with charge exchanged projectiles U^{89+}.

short-wavelength limit of the electron nucleus Bremsstrahlung and thus confirm the close association of the RECC cusp with Bremsstrahlung; in Fig. 4 coincident X-ray spectra with electrons from three velocities around the cusp are compared with the singles, i.e. non-coincident X-ray spectrum. It is apparent that emission of electrons in the forward direction in the projectile frame is favoured.

With the pending implementation of the reaction microscope in the internal target zone of the ESR the range of useful experiments for the forward electron spectrometer will be extended considerably to kinematically complete experiments on (e, 2e) ions and the 4-fold differential cross section of the short-wavelength limit of electron nucleus

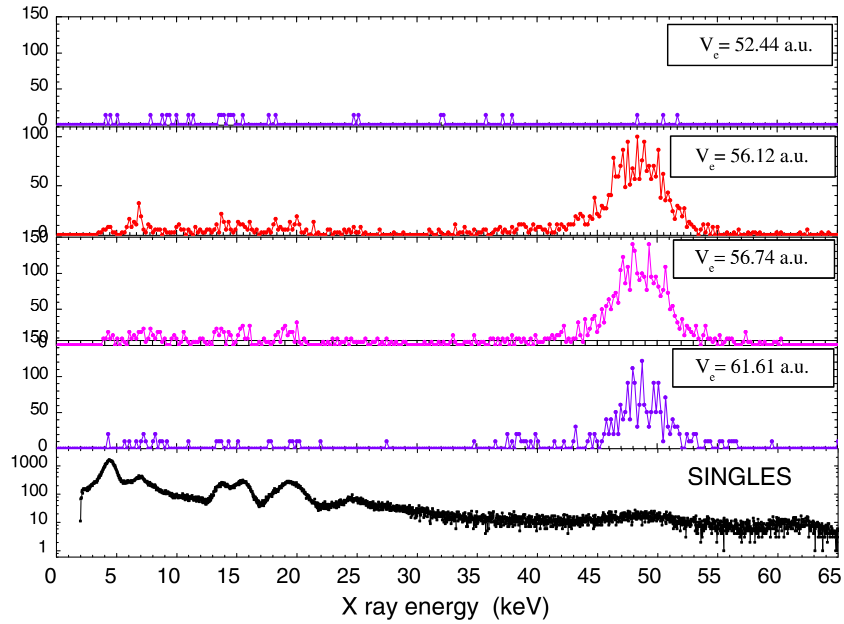

Fig. 4. X-ray spectra measured in coincidence with electrons emitted in the forward direction and momentum analyzed with the forward electron spectrometer. It is clearly seen that only coincidences with X-rays from the short-wavelength limit of the electron nucleus appear; it is very apparent that mostly electrons with projectile frame momenta parallel to the incident projectile are generating coincidence events.

Bremsstrahlung. In parallel we have begun a pilot study for a new type of reaction microscope for the NESR. In this type of reaction microscope the potential weakness of the longitudinal design with the proximity of large 2D detectors for electrons to the coasting beam is avoided by a toroidal design of the low energy electron branch, thus removing the electron detector from the direct view of the beam. We have found using simulation calculations with the OPERA code that a mapping of electrons onto the detector is possible which still permits the reconstruction of the primordial electron momenta. A prototype of this spectrometer will be built and tested in the near future.

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