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PRECISION EXPERIMENTS WITH HEAVY-ION STORAGE RINGS*

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This contribution is based on our input to the NuPECC LRP on perspectives of precision experiments at heavy-ion storage rings in the realm of nuclear structure, atomic- and astrophysics. A focus here is on experiments with secondary beams of heavy ions, which can either be stable or long-lived nuclei in specific, high atomic charge states, or unstable nuclides.

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1. Introduction

Through several decades of successful operation, heavy-ion storage rings have proven to be versatile instruments for a broad variety of precision studies addressing, often cross-discipline, questions in nuclear structure, atomic physics, astrophysics, and fundamental symmetries, see, for instance, [1–4].

Secondary ions are inevitably produced in limited amounts and their storage is a straightforward way to achieve their most effective usage. In this context, storage rings are machines which offer a range of unparalleled beam manipulation and handling capabilities, like:

- As a rule, storage rings are high-acceptance machines which allow for the simultaneous storage of a variety of ionic species [5]. By employing non-destructive diagnostics, continuous monitoring of the beam is available. Such monitoring has a huge dynamic range and can be employed for mA beams as well as for single stored ions [6];

- Of utmost importance is the ability to achieve high phase-space densities of the stored beams through cooling [7], where the stochastic (S) [8] and electron (E) [9] cooling methods are routinely in use and tremendous progress has been achieved in laser (L) cooling [10, 11]. Cooling allows for reducing the momentum spread induced by the production reaction process yielding beams with small geometrical size and well-defined momentum. Depending on the stored-beam intensity, even crystalline beams can be achieved [12];

- A storage ring can be operated as a synchrotron to modify the beam energy either by accelerating or, what begins to be intensively used, by decelerating a stored beam [4]. In this way, a cooled beam of secondary ions can be provided at an energy far different from the one needed to produce the corresponding particles [13];

- High revolution frequencies of several hundred kHz to MHz allow for reaching relatively high luminosities even for the low-intensity secondary beams and thin targets [14–17];

- Ultra-pure, windowless internal atomic gas targets [18–20] with small spatial size combined with excellent parameters of cooled beams enable experiments with unprecedented angular and energy resolutions. The targets are thin which reduces multiple scattering and reaction events during their passage;

- On the one hand, the ultra-high vacuum (UHV) environment of a storage ring preserves the high atomic charge state of the stored beam [21, 22]. On the other hand, it creates a challenge to construct equipment to be brought into the ring aperture [23];

- Coupling of laser beams allows for high-precision laser spectroscopy (laser cooling) of stored ions [24]. Photon beams with wavelengths down into the X-ray regime were successfully brought into UHV and overlapped with stored ion beams [25];

- Longitudinal [26] and transverse [27] electron targets enable studies of electron–ion collisions;

- Excellent mass resolving power can be attained either through cooling or by employing a special isochronous ion-optical mode [1, 28].

A storage ring as a machine is an integral part of the experiment [1, 4]. Therefore, the physics reach and the properties of the underlying facilities are strongly interconnected.

2. Existing facilities

There are presently three radioactive-ion beam facilities running heavy-ion storage rings for precision experiments at the intersection of atomic physics, nuclear structure, and astrophysics [30]. These rings are summarized in Table 1 along with their main parameters.

2.1. GSI Helmholtz Center for Heavy-Ion Research

The Experimental Storage Ring (ESR) [31] is in operation since 1990. The primary beams from the heavy-ion synchrotron SIS18 are either used to produce radionuclides of interest in the FRagment Separator (FRS) [32] or are stripped of bound electrons to produce highly-charged ions of interest in the direct transfer channel (TE) [33]. The ESR is equipped with electron [34] and stochastic [35] cooling systems, internal gas target [36], laser setups [24], spectrometers to detect recoil ions [37], electrons [38], photon detectors [39], and non-destructive Schottky diagnostic [6, 40]. The ESR is capable of decelerating a stored beam to an energy of 3 A MeV [41], see Fig. 1.

Table 1. Major parameters of existing and planned heavy-ion storage rings.

Name	Facility	$B\rho$ [Tm]	Cooling systems E	S	L	Deceleration	Iso. mode	Int. target	Neutr. target
Existing rings									
ESR	GSI	0.6–9.5	x	x	x	x	x	x	—
CRYRING@ESR	GSI	$\sim$0.1–1.44	x	—	(x)	x	—	x	—
CSRe	IMP	$\sim$1.5–8.4	x	x	x	—	x	x	—
R3	RIKEN	$\sim$7	—	—	—	—	x	—	—
Storage ring facilities in construction									
CR	FAIR	$\leq$13	—	x	—	—	x	—	—
HESR	FAIR	$\leq$50	(x)	x	(x)	x	—	x	—
SRING	HIAF	$\leq$13	x	x	x	—	x	x	—
Storage rings in discussion									
—	ISOLDE	$\sim$1.5	x	—	(x)	x	—	x	—
—	LANL	$\sim$1.5	x	—	(x)	x	—	x	x
TRISR	TRIUMF	$\leq$2	x	—	(x)	x	—	x	x
CR@DERICA	JINR	$\sim$7	x	—	—	x	x	x	—

A dedicated low-energy CRYRING storage ring has been moved from Sweden and re-built behind the ESR [13]. The lowest energy in CRYRING is only determined by the interaction with residual gas and can merely be a few 100 A keV or even lower. The ring is equipped with electron cooling, laser coupling, internal gas-jet and Schottky detection, electron target, fast and slow extraction, *etc.* [42]. Various experimental stations can be installed in a dedicated straight section. It is important to emphasize that a separate local ion-source/injector is available at CRYRING, which enables a stand-alone operation with selected available ions.

An ion trap facility HITRAP [43, 44] is being commissioned behind the ESR. Here, the 4 A MeV decelerated beams are further slowed down by a chain of linear accelerators and finally cooled and trapped basically at rest.

The GSI facility offers primary beams of essentially all stable elements from hydrogen to uranium. The maximal magnetic rigidity of SIS18 of 18 Tm enables effective production of highly-charged ions up to bare uranium and radioactive nuclides through mainly projectile fragmentation or fission reactions [45, 46]. All these secondary particles can then be made available in the ESR, CRYRING@ESR, and/or HITRAP, see Fig. 1.

2.2. Institute of Modern Physics, Chinese Academy of Sciences

The experimental cooler-storage ring CSRe is part of the high-energy facility in Lanzhou, which comprises the heavy-ion synchrotron CSRm and the fragment separator RIBLL2 [47]. The CSRe can be operated in isochronous and standard ion-optical modes. Electron [48], stochastic [49], and laser

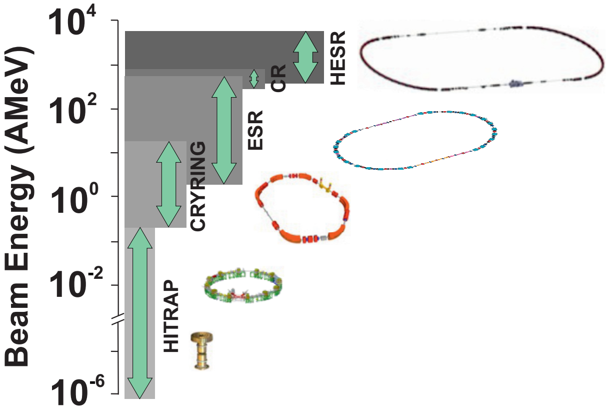

Fig. 1. Energy coverage for stored secondary beams at the heavy-ion storage and trapping facilities at GSI/FAIR MSV (Modularized Start Version) [29]. Please note the logarithmic scale.

cooling [50] have been successfully demonstrated as well as experiments conducted employing an internal target [51] and Schottky diagnostics [52]. The deceleration option, although feasible in principle, is not available.

The present accelerator chain allows for efficient acceleration of beams up to about xenon, which limits the range of secondary systems to be studied. The situation will dramatically improve with the installation of a new linac as a primary injector of the CSRm [53].

2.3. RIKEN Nishina Center for Accelerator-Based Science

The Rare-RI Ring (R3) [54] at RIKEN is based on the principle of a weak focusing synchrotron. The ring is composed only of dipole magnets and is run solely in isochronous optics at a fixed rigidity of 5.5 Tm. The ring is coupled to the superconducting cyclotron driver accelerator via the large-acceptance BigRIPS fragment separator [55]. Due to (quasi)-DC nature of the cyclotron beams, the injection of individual particles was developed at the R3 [56, 57]. The power of the facility is the highest primary-beam intensity [58] and the prior identification of the ions of interest within BigRIPS. No cooling or in-ring reaction setups are presently available at the R3. Non-destructive diagnostic has been taken into operation [59].

3. Facilities in construction

3.1. Facility for Antiproton and Ion Research (FAIR)

The FAIR facility is in construction adjacent to the GSI site in Darmstadt. The portfolio of storage rings will be extended significantly. Within the modularized start version of FAIR (MSV) [29], which the ESR, CRYRING, and HITRAP are part of, the collector ring (CR) [60] and the high-energy storage ring (HESR) [61] will be added, see Fig. 1. The CR is designed to: *(i)* efficiently collect and stochastically cool secondary ion or antiproton beams at a maximum magnetic rigidity of 13 Tm and then transport them further to the HESR, and *(ii)* to operate in isochronous ion-optical mode [62]. It will have a large acceptance of 100–200 mm×mrad matched to the future Super-FRS fragment separator aiming at 100% transmission [63, 64]. The HESR will store ion and antiproton beams up to the magnetic rigidity of 50 Tm. The half-kilometre ring allows for placement of various experiment equipment [65, 66]. Two dedicated internal target stations, coupling of various laser systems, electron and positron spectrometers, reaction microscopes, recoil detectors, *etc.* are foreseen.

3.2. High Intensity Heavy-ion Accelerator Facility (HIAF)

At HIAF in China, a complex of storage rings will be constructed in a staged approach [67]. In the first stage, a 34 Tm booster synchrotron BRing and a 15 Tm spectrometer ring SRing [68] will be built connected by the fragment separator HFRS. The SRing is aimed to be a multi-purpose machine equipped with electron, stochastic, and laser cooling capabilities, various detector and spectrometer setups, and internal targets. Special care is devoted to a high-quality isochronous ion-optical mode [69]. At a later stage, a 45 Tm superconducting MRing will be added [70, 71]. It will form a configuration with the SRing for interaction of two co-propagating beams. This will provide unprecedented conditions for investigations of vacuum decay studies in ultra-strong fields beyond the Schwinger limit [72, 73].

4. Research opportunities

4.1. Nuclear structure and nuclear astrophysics

4.1.1. Nuclear masses

Nuclear binding energies are key quantities in nuclear structure and astrophysics [74]. Today, masses of nuclides at the outskirts of the nuclear chart are needed. Such nuclei are produced in tiny quantities and have, as a rule, lifetimes of well below 1 s [75]. Here, the isochronous mass spectrometry (IMS) [76, 77] is the technique of choice. While the measurement of revolution frequencies of the stored ions is well established [78–86], there is a need to know the velocity of every ion as well [87].

At the CSRe, this is achieved by placing two foil-based timing (TOF) detectors in a straight section [88]. Mass determinations were demonstrated at a few 10^{-8} relative precision level on nuclides with production rates of merely two ions per week [89, 90]. Charge sensitivity of time-of-flight detectors is effectively employed to resolve ions with similar mass-over-charge ratios [91]. Mass measurements are among the main objectives at the SRing [67].

At the ESR, the $B\rho$-tagging approach is employed though at a cost of reduced transmission [92–94]. Another way is to use the transversely-sensitive Schottky detectors [95, 96]. Two TOF detectors and multiple longitudinal and transverse Schottky detectors are planned in the CR [97].

At the R3, the velocity is measured by tracking detectors within the BigRIPS. First results on fission fragments were reported in 2022 [98]. Furthermore, the transverse Schottky detectors are under construction. An unparalleled strength is the pre-identification of injected ions in the BigRIPS, which enables measurements of otherwise unresolvable ion species [99].

4.1.2. Radioactive decays

Owing to the ultra-high vacuum environment, storage rings are unique in addressing decays of highly-charged ions (HCI) which can be stored for extended periods of time and their atomic charge state can unambiguously be monitored [100, 101]. Especially intriguing are exotic decay modes which are either completely disabled or very weak in atoms.

The mass-spectrometry-assisted Schottky decay spectroscopy of HCIs was pursued in the last three decades in the ESR [102], where numerous highlight results on bound-state β-decay [103–105], electron capture of H- and He-like ions [106–111], electromagnetic de-excitations of nuclear isomers [112, 113], and many others were obtained. Investigations of bound-state β decay, EC, and α decays in few-electron ions will be continued.

Long-lived nuclear isomers that are produced in tiny quantities are hardly possible to study by conventional spectroscopy techniques [114]. Several such isomers were discovered in the ESR [115, 116]. In turn, this facilitates design of dedicated spectroscopy experiments elsewhere [117, 118].

Up to now, lifetimes longer than a few seconds could be measured, with an exception for two isomers addressed by destructive IMS [52, 119]. The development of the combined Schottky+Isochronous mass spectrometry [120] enabled measurements of systems with half-lives of only a few tens of ms. The basis of this technique are the high-sensitivity Schottky detectors [6, 40]. It has successfully been applied to determine the two-photon de-excitation rate of the first excited 0^+ state in ^{72}Ge [121]. Further systems [121] and exotic decay modes, like bound electron–positron conversion [122] will be addressed. Since the technique is single-particle sensitive, its major strength is the enabled simultaneous mass and lifetime determination of rarely produced nuclides. Furthermore, the measurements of beta-delayed one- and/or more-neutron emission probabilities — without neutron detection — are proposed [123].

4.1.3. Nuclear reactions

It has been a long-standing dream to use stored secondary beams for nuclear reactions [124, 125]. Meanwhile, this is a rapidly developing research field with enormous potential. The unparalleled advantage is the precisely determined momentum and size of the cooled beam and thin, localized, windowless gaseous internal target. The relatively high luminosity is achieved due to the high-revolution frequency of hundreds of kHz to MHz. First proton scattering experiments on stable ^{58}Ni and radioactive ^{56}Ni isotopes in the ESR [15, 126–128] were continued with ^{58}Ni [16, 51] and ^{78}Kr [129] beams in the CSRe. Among future plans is the measurement of isoscalar giant monopole resonance in doubly magic ^{56}Ni [130].

Interest in nuclear reactions for astrophysics [131] has led to the operation of the ESR at low energies. Here, the particles are produced at high energies and then decelerated to the energy of interest. The c.m. energy could gradually be reduced in the first proof-of-principle proton capture reactions with stable ^{96}Ru [132, 133] and ^{124}Xe [17] from about 30 A MeV to 5.5 A MeV. The advances in detection methods [134, 135], accumulation, and efficient deceleration have allowed the proton-capture measurement on radioactive ^{118}Te [136]. Furthermore, addressing (p, n) reactions is now also possible [137]. This opens the door to explore key reactions with radioactive ions for astrophysical p-process, like ^{91}Nb(p, γ) [138] and others.

However, the operation of the ESR at low energies is not easy and each step down in energy is a challenge. Therefore, the respective reaction studies for astrophysics as well as transfer reaction studies are being moved to CRYRING@ESR. The key installation here is the universal detector system CARME [139], which was commissioned in 2022. The number of reactions to be studied is enormous and covers BBN, rp-process, electron screening [140], *etc.* Installation of a dedicated source for radioactive ion species, such as ^{44}Ti or ^{7}Be, at the local injector is proposed [141, 142].

Given their importance for astrophysics, nuclear structure, and applications, the ways to perform neutron-induced reactions are intensively discussed. On the one hand, a surrogate reactions approach [143] has been proposed for the CRYRING@ESR, where a dedicated station NECTAR will be installed [144, 145]. A proof-of-principle experiment has been performed with ^{208}Pb beam interacting with H_2 target in the ESR in 2022. Studies with ^{238}U are approved for the ESR [146] and an extensive program is foreseen also in the CRYRING@ESR, where various radioactive beams and different targets will be employed. On the other hand, dedicated low-energy storage rings coupled to a free-neutron target would be the most advantageous way to enable collisions of two unstable species [147, 148]. Several workshops took place recently [149, 150] discussing possibilities for realizing such facilities. The project at LANL aims at merging a spallation neutron target, produced by the 800 MeV proton beam from the LANSCE facility, with a storage ring [151]. The project at TRIUMF will use stored radioactive beams from the existing ISAC facility in combination with a high-intensity neutron generator [152].

4.2. Atomic physics research

Stored and cooled beams of highly-charged ions are brought into collisions with photons, electrons, atoms, and later also ions, which enables a plethora of various investigations aiming at probing electron dynamics and correlations, quantum electrodynamics (QED) in the strongest electric and magnetic fields, fundamental symmetries, and many others [71, 73, 153]. It is impossible to cover the progress in the field within the limited space. Therefore, we focus on a few decisive recent developments and future challenges.

The key to the present atomic physics studies is precision. Therefore, beam cooling is the indispensable and most essential quality which is provided by the storage ring [3]. In general, if the laser spectroscopy experiments profit from beams at high energies, where the relativistic kinematics shifts the transition energies into the regime accessible by lasers [24], the majority of today's precision studies aim at the smallest Doppler shifts and thus are done at the lowest accessible energies [13].

Laser spectroscopy of hyperfine transitions in H- and Li-like ^{209}Bi ions indicated 7σ deviation to the prediction of the state-of-the-art theory [154], which could be resolved through an improved magnetic moment [155]. To advance further, a measurement of the corresponding hyperfine splittings in radioactive ^{208}Bi will be done at the ESR [156]. For this purpose, the overall laser spectroscopy setup at the ESR has been upgraded to achieve sufficient sensitivity for inevitably low-intensity secondary beam. Furthermore, a novel, dielectron-recombination-assisted detection is proposed. These improvements shall allow studies of predicted hyperfine mixing [157] and direct laser excitation of an 8-eV [158] isomeric state in ^{229}Th [159]. It is also noted that laser cooling experiments are successfully running at the CSRe [160].

The forward electron spectrometer at the ESR allows for precision studies of various processes in which electrons are emitted in collisions of stored beams and atomic targets, see *e.g.* [161–167]. The studies are being extended to multi-electron loss and transfer channels [168].

The CRYRING@ESR is being steadily equipped with various detector setups [169]. The local injector enables intense beams of low/medium-charged ions. For instance, photon interactions with slow Mg^+ ions are aimed at studying polarization build-up and its preservation [170]. Extensive di- and multi-electron recombination studies profit from ultra-cold temperatures achieved through transverse adiabatic expansion of the electron beam in the CRYRING cooler [171]. Here, the ion and electron beams are brought into collisions in co-propagating geometry [172]. Transverse electron targets are being developed to enable electron-impact experiments [173].

Measurements of 1S Lamb shift in the heaviest accessible ions ^{238}U are planned at GSI [174]. In a preparation beam-time, intense beams of $^{238}\mathrm{U}^{90+}$ were produced, decelerated in the ESR, and transferred and stored in the CRYRING@ESR. Furthermore, dedicated micro-calorimeter detectors could be operated at the electron cooler under the noisy storage-ring environment [175].

Last but not least, atomic data are needed to model the transport of electromagnetic radiation in kilonovae, which follow neutron-star mergers [176–178]. Here, CRYRING@ESR can provide essential input by addressing the structure of heavy low-charged ions [179].

For further examples, highlights, and details, we refer to [153, 180–182], references cited therein, and extensive documentation [183].

5. Summary and conclusions

The intention of this contribution, which is based on the input to NuPECC LRP [184], is to illustrate the breadth, power, cross-disciplinarity, and uniqueness of research conducted at heavy-ion storage rings. We could briefly address only a limited number of physics cases leaving aside many important experiments. For instance, extracted cooled beams are ideal probes for channelling and resonant coherent excitation studies [185, 186]. Also materials research profits from slow HCI [187]. Other examples include nuclear excitation by target- [13, 188] and especially by free-electron capture, which is presently controversially discussed [189, 190], investigations of fragmentation reaction mechanisms [191, 192], isomeric ratios [193], *etc.*

Storage rings are integral parts of experiments and the progress of the latter relies inevitably on the functionality of the rings. A dramatic extension of experimental capabilities has been achieved with the installation of CRYRING at the ESR. However, the deceleration of the beams of interest leads to beam losses and is simply slow. Therefore, CRYRING@ESR is not ideally suited for experiments if ions with lifetimes shorter than about a minute are required. The first experiments with low-energy ions at the ESR and CRYRING@ESR have proven the huge research potential and will be continued, also within the ERC Project ELDAR. However, a decisive breakthrough can be achieved if a dedicated low-energy storage ring is constructed at an ISOL-type post-acceleration facility. Such a scenario has been thoroughly worked out for HIE-ISOLDE [194, 195]. Numerous physics experiments were proposed and new ones can be envisioned based on the so far gained experience. The project is still under consideration at CERN [196], and shall be pursued also taking into account that enormous expansion of the physics reach, which can be achieved if such a ring is combined with the Gamma Factory proposed at CERN SPS/LHC [197, 198].

Development of instrumentation and detectors is undoubtedly indispensable. The ultra-high vacuum condition implies baking the equipment to up to 200 °C, which sets strict requirements on materials to be used. In-vacuum DSSSD detectors are successfully employed [17, 23]. Suggestions to use more radiation-hard solar-cell-based detectors are being investigated [199]. If successful, high-coverage setups will become possible. Detectors can be placed into special pockets separated from the ring vacuum by a thin window [37, 200]. However, low-energy recoils can stop in windows [69]. The recent development of non-destructive Schottky detectors was conducted within an ERC Project ASTRUm. Such devices provide the revolution frequency of a single stored ion within a few ms [6]. The next generation will be able to determine the position of the particle [201]. Special emphasis is given to the internal targets. Smaller size, more stable, and dense targets are required. Also essential are targets of rare gases like ^{3}He, which require efficient recirculation systems. Further developments include targets of polarized atomic hydrogen [202, 203] and electrons and also ionic targets [204].

Measurements of neutron-induced reactions are extremely important but as well extremely complicated, especially for short-lived nuclei. The ERC project NECTAR employing the surrogate reaction method will be continued at the ESR and CRYRING@ESR. However, a direct approach is to merge a stored secondary beam with a free-neutron target. Two projects are being discussed in North America [149–152].

Although, the focus today is on experiments at low energies — cooled beams at a few GeV energies will open a new era for atomic physics research by giving access to processes that are only discussed in theory [66, 71, 180, 181]. This is envisioned in the HESR utilizing high-intensity secondary beams from the Super-FRS. Studies of short-range nucleon correlations [205], and lifetime measurements of long-living species are immediate examples of experiments on the nuclear physics frontier.

The CR is a special isochronous ring [97]. All respective techniques developed by now will be available there. Precision masses and lifetime measurements of nuclides with production rates as small as 1 ion per day/week or even month will be possible. Thus, this might be the unique method to reach the furthermost exotic nuclei.

Last but not least, probing nuclear moments through collisions with electrons [206] was among the main motivations for the New Experimental Storage Ring (NESR) at FAIR. Since the NESR is considerably delayed, various alternatives/solutions are being discussed to be implemented at existing and/or planned rings, see, for instance, [207–209]. Another suggestion is to build a dedicated facility DERICA at JINR [210].

In a longer term, the construction of the full version of the FAIR facility will further boost the capabilities of storage-ring-based cross-disciplinary research briefly discussed here, complemented by developments and possible upgrades at the HIAF facility.

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