Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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Nuclear physics research at heavy ion accelerators: Precision studies with stored and cooled exotic nuclei

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Abstract. This contribution is based on the plenary presentation at the 14$^{\mathrm{th}}$ International Conference on Heavy Ion Accelerator Technology (HIAT-2018) in Lanzhou, China.

Heavy-ion storage rings offer unparalleled opportunities for precision experiments in the realm of nuclear structure, atomic physics and astrophysics. A brief somewhat biased review of the presently ongoing research programs is given as well as the future projects are outlined. The limited space does not allow for detailed description of individual experiments, which shall – to some extent – be compensated by extended bibliography.

1. Introduction

Atomic nuclei are many-body systems which are composed of two types of quantum mechanical particles protons and neutrons. The strong, weak and electromagnetic fundamental interactions are in play in the nuclei, which makes them extremely complex systems to describe. However, the nuclei are "natural laboratories" themselves, by studying which one learns about underlaying fundamental interactions. The latter determines our world to be as it is and is thus the very reason for us to study them as good as we can.

Nuclear physics is more than 100 years old and is still one of the rapidly developing fields of research. This development is made possible by the progress in accelerator concepts and detector technologies, as were discussed *e.g.* at this conference. Today, scientists have created in laboratory about 3000 nuclides [1]. However, about 7000 nuclides are expected to exist with majority of yet unknown nuclei belonging to neutron-rich systems [2]. The path of the rapid-neutron capture process of element synthesis in cosmos is expected to be in this region [3–5]. There, the nuclear structure at large proton to neutron asymmetries is expected to change dramatically [6]. For instance, the nuclear shells in light neutron-rich nuclei are at different neutron numbers than the magic numbers established at stability [7–9].

New-generation accelerator facilities aim at reaching further into the unknown nuclear territory. However, the yet unknown nuclei have extremely small production cross sections and short lifetimes [10]. Sophisticated experimental techniques are needed to be able to produce and handle them, especially if their precision studies are aimed for. Here, heavy-ion storage rings coupled to radioactive ion beam facilities offer unique capabilities [11].

2. Existing heavy-ion storage rings

If focusing on the radioactive-ion beam facilities, there are presently three operational heavy-ion storage rings [12]. These are the Experimental Storage Ring (ESR) at GSI [13], the experimental Cooler-Storage Ring (CSRe) at IMP [14], and the Rare RI Ring (R3) Facility at RIKEN [15].

Historically the first, the ESR at GSI is in operation with radioactive beams since 1992 [16,17]. There, the exotic nuclei are produced at the Fragment Separator FRS [18] through fragmentation or in-flight fission of primary beams accelerated by the heavy-ion synchrotron SIS18. The exotic nuclei are produced at high energies such that they emerge the production target as highly charged ions (HCI) [19–22]. The FRS can either be used as a pure magnetic rigidity ($B\rho$) analyser efficiently transmitting all produced nuclides within its $B\rho$ acceptance or, if a specially shaped degrader is employed, a pure mono-isotopic beam can be prepared by means of $B\rho-\Delta E-B\rho$ separation method, where ΔE stands for the energy loss in the degrader material. Also a direct, bypassing the FRS, injection into the ESR of primary and intense secondary beams is possible [23].

The ESR is a versatile machine offering numerous and flexible beam manipulation options. The ESR can store ions in a broad range of energies from about 3 A MeV to about 420 A MeV, corresponding to the maximum $B\rho(\text{ESR}) = 10$ Tm. The average rest gas pressure of the ring is about $10^{-10} - 10^{-11}$ mbar. Such ultra-high vacuum environment sets strict constraints on experimental equipment that can be brought inside the vacuum.

Indispensable for experiments is the ability of cooling the secondary beams. The latter is especially important for radioactive beams which inevitably have a large momentum spread due to nuclear reaction process. Electron [24] and stochastic [25] cooling systems are routinely available. Whereas the former cooling method is operational in the entire energy range of the ESR, the latter is fixed to a specific ion velocities of 400 A MeV. First laser cooling experiments were successfully performed [26, 27]. Although the combination of stochastic pre-cooling and electron cooling has proven that hot ion beam can be cooled within about a second, this time is much too long for short-living rare ions [28, 29]. In the latter case, the isochronous ion-optical mode allows for (in first order) compensation of different particle momenta by orbit lengths in the ring [30, 31]. This mode operates at the transition energy of the ring, γ_t.

A special attention is given to the ability to efficiently decelerate stored beams to low-energies. At present, the slowing down from the maximum to the lowest energy takes about a minute which limits the range of exotic nuclides that can be decelerated. A dedicated low-energy storage ring CRYRING has been installed behind the ESR [32]. It is being commissioned now. First experiments are planned for 2019. Worth noting is the HITRAP setup aiming at further slowing down and then trapping in a Penning trap HCIs extracted from the ESR [33, 34].

The CSRe at IMP was taken into operation in 2007 [35,36]. Secondary radioactive beams are produced by projectile fragmentation of primary beams accelerated by the synchrotron CSRm. They are analysed by the fragment separator RIBLL2 and injected into the CSRe. Highly charged stable ions are produced in the same way with the only difference that thick production targets can be replaced by thin stripper foils. The CSRe is routinely operated in isochronous mode. Electron and stochastic cooling systems have been taken in operation. Also the laser cooling of stored ions was demonstrated [37]. There are plans for establishing beam deceleration.

At RIKEN, the R3 ring is coupled to the presently most powerful radioactive ion beam facility, BigRIPS. The main accelerator at RIKEN is a superconducting cyclotron which is dramatically different from the facilities at GSI and IMP. Different to pulsed synchrotron beams, the cyclotron provides quasi-DC beam. Therefore a specific, single-particle injection scheme has been developed [38, 39]. Magnetic rigidities and energy deposition in special detectors along the

BigRIPS provide particle identification (PID) for each secondary ion. A trigger signal can be sent from the middle-focal plane of BigRIPS to the R3 injection kicker which arrives earlier than the particle itself. If the PID satisfies the set conditions, the injection kicker is activated and the corresponding particle is injected. The speciality of the ring is that it consists of dipole magnets only. Such lattice is very well-suited for isochronous ion-optical operation mode. The very first experiments at the R3 have been successfully accomplished just during the time of the writing of this work [40].

3. Experimental installations

Precision experiments require versatile experimental installations. They undergo steady development to meet the increasing requirements of experiments. Some examples are listed below. The availability of setups in specific rings is indicated in the brackets.

- Internal gas-jet target is a supersonic jet of gas molecules crossing the vacuum pipe of the ring [41–43]. It enables reaction studies of stored beams with a windowless ultra-thin target. The combination of beam cooling and thin target allows for reaching very high energy and angular resolution in experiments. There are ports at several angles with view on the interaction region offering for optical and/or X-ray detection. (CSRe, ESR). We note, that at CRYRING a novel sophisticated detector system for nuclear and atomic reaction studies with the internal gas-jet is being constructed [44].
- Various detectors can be placed either in special vacuum pockets (scintillators, gas-filled multiwire chambers, silicon, diamond, etc.) [45–47] or directly into vacuum. (CSRe, ESR, CRYRING, R3)
- Laser beams can be merged with the stored ion beams along straight sections of the ring in both – co- and counter-propagating – directions [48]. (CSRe, ESR, CRYRING)
- Time-of-flight (ToF) detector is equipped with an extremely thin, a few μg/cm^2, carbon foil [49–53]. Secondary electrons emitted from the foil due to passing ions provide accurate timing signals which are used to determine particle revolution frequencies. (CSRe, ESR, R3)
- Schottky detectors are non-destructive monitors which are able to provide information on the frequencies and intensities of all particles stored in the ring [31]. The sensitivity of these detectors has been continuously improved over the last decade [54–58]. Present Schottky detectors allow for measurement of frequencies of single stored particles within merely a few ten ms. The dynamic range of Schottky detectors is such that single particles as well as beams with mA-intensities can be measured simultaneously. (CSRe, ESR, R3)

4. Precision experiments

Some examples of ongoing research are given below [59].

- Heavy-ion storage rings offer the possibility to store HCIs in a specific high atomic charge state for an extended period of time. This capability enables measurements of weak decays of HCIs [60–63]. Numerous experiments have been performed at the ESR and since recently also at the CSRe for investigations of continuum β-decay [64–67]. Of special interest are the two-body beta decays. These are the orbital electron capture (EC) [68] and bound-state β^--decay (β_b^-) [69, 70]. Concerning the studies of EC decays the reader is referred to Refs. [71–86]. The bound-state β^--decay was experimentally discovered in the ESR [87]. So far β_b^--decay of fully-ionised ^{163}Dy^{66+}, ^{187}Re^{75+}, ^{205}Hg^{80+} and ^{206,207}Tl^{81+} have been measured [87–92]. The next goal is the measurement of the β_b^--decay of ^{205}Tl^{81+} [93], which is needed for Solar neutrino and s-process physics [94–98]. The corresponding experimental proposal is approved at GSI.

Journal of Physics: Conference Series **1401** (2020) 012001 doi:10.1088/1742-6596/1401/1/012001

- Storage-ring mass spectrometry [31, 99] is a very successful approach for measuring nuclear masses of short-lived nuclides. There are two approaches to perform such measurements. The Schottky mass spectrometry (SMS) is based on the electron cooling of the particles and Schottky detectors providing their revolution frequencies. Several hundred masses were obtained with this method [100–113]. The second method, the isochronous mass spectrometry (IMS), is based on the isochronous ion-optical setting of the ring. The cooling is then not required and the masses of nuclides with half-lives as short as a few ten μs can be addressed. TOF detectors are typically used for fast determination of revolution times. At CSRe the system of double TOF detectors allows in addition for an in-ring velocity measurement of each ion [114–118]. The IMS is pursued at all three storage ring facilities [12] and many highlight results have been achieved [119–139]. Both techniques are broad-band [140] and allow for addressing masses of many nuclei simultaneously. With the development of very sensitive and fast Schottky detectors, they are being considered in the IMS [67].
- The high resolving power of storage ring mass spectrometry and especially the sensitivity to single ions allow for the search of very rarely produced long-lived isomeric states. Due to long half-lives and tiny production rates such states are very difficult to address with conventional gamma spectroscopy [141, 142]. Several isomeric states were discovered in the past experiments as well as their decay properties as HCIs were studied [64, 143–152]. The region of interest of the future investigations are the neutron-rich nuclei around ^{188}Hf where isomers with exceptional properties are predicted to exist. Also proposed is the search for the exotic bound electron-positron decay [153].
- Light-ion induced direct reactions, like elastic and inelastic scattering, transfer, charge-exchange, or knock-out reactions, are powerful tools for obtaining nuclear structure information [154–157]. Owing to the thin windowless targets and the beam cooling, high resolution measurements, even for very slow target-like recoil particles, can be achieved. Scattering of ^{56}Ni beam on the H_2 has been studied in the ESR proving the feasibility of such experiments [158–162]. Also the ^{20}Ne$(p, d)^{19}$Ne* reaction was investigated at the ESR [163] which is the first step towards the measurement of the α-decay width of the 4.033 MeV state in ^{19}Ne. The latter is needed to conclude on the rate of the ^{15}O$(\alpha, \gamma)^{19}$Ne reaction in X-ray bursts. One shall emphasise the complex detection systems developed for such reaction studies [164].
- Storage rings offer the possibility to address capture reactions on unstable ion beams. The proof-of-principle experiments addressing proton capture reactions relevant for the astrophysical p-process were performed in the ESR with decelerated ^{96}Ru [165, 166] and ^{124}Xe [167] beams. For these studies double-sided silicon strip detectors (DSSSD) were brought directly into the vacuum of the ring. In the future also (α, γ) and (p, n) reactions will be addressed. Still, the major goal is to perform these reaction studies on radioactive beams [168].
- The well-known in atomic physics dielectronic recombination (DR) process can be employed to measure isotope shifts (IS) and hyperfine splittings of radioisotopes as well as lifetimes of long-lived nuclear isomeric states [169, 170]. The highlights are the measured in the ESR DR resonances on exotic ^{237}U^{89+} and ^{234}Pa^{88+} [23, 171]. The latter isotope is a striking case since it has a low-energy isomeric level at $73.92 + x$ keV with a half-life of 1.17 min. The signatures of both, the isomeric and ground, states could be seen. One of the future goals is to address ^{229}Th which has the isomeric state with lowest known excitation energy [172]. If successful, this can pave the way to the separation of the isomer for further fundamental research studies. This goal is pursued at the CSRe and the ESR.

Apart from nuclear physics experiments, examples of which are given above, there is a broad range of experiments in realm of atomic physics, astrophysics as well as fundamental symmetries. For some examples of recent experimental results the reader is referred to Refs. [173–188].

5. Future FAIR and HIAF facilities

The great success and the variety of the running research programs at the existing facilities is the motivation that heavy-ion storage rings are a central part of the future new-generation radioactive-ion beam facilities FAIR in Germany [189, 190] and HIAF in China [191].

At FAIR, the present scope of the GSI storage rings will be extended by the collector ring CR and the high-energy storage ring HESR [192]. The CR is a dedicated machine for isochronous mass spectrometry [193–195]. Here the double-TOF system and a system of Schottky detectors shall enable direct mass and lifetime measurements of short-lived nuclides [196, 197]. The HESR will be used for accumulation and half-life measurement of long-lived radionuclides in high atomic charge states [196]. Furthermore, the HESR will offer cooled beams of HCIs accelerated to the maximal $B\rho = 50$ Tm [198], which is a new energy regime for precision experiments in atomic physics [199–205]. These experiments are being prepared by the SPARC [206] and ILIMA [196] collaborations.

At HIAF, a novel concept of two storage rings coupled together for reaction studies of two co-propagating beams has been proposed [207]. The interest in the latter are the fundamental studies of critical and supercritical electromagnetic fields. Furthermore, each of the two storage rings can be run independently. Mass and lifetime measurements of short-lived nuclei are among the main physics cases.

6. Low energies

Experiments with stored HCIs at low energies have undoubtedly huge discovery potential. For instance, capture reactions can be addressed directly in the Gamow window of the corresponding astrophysical process [32,168,208]. Also for studying nuclear direct reactions, induced fission, etc. the ideal energy range is around 10 A MeV [209,210]. Furthermore, low energies open possibilities for the search and detailed investigations of exotic decay modes [211], like for instance nuclear excitation by electron capture/transition (NEEC/T) [212–214] and many more. Coupling of a storage ring with a source of slow neutrons is probably the only realistic approach for direct measuring of neutron-indiced reactions [215–218]. Needless to say that high precision atomic physics experiments profit from low Doppler shifts. This rich physics program is the reason for installing the CRYRING at GSI. Unfortunately the slow deceleration process does not allow for experiments with nuclides living shorter than about a minute. Therefore, to enable these experiments there are several low-energy storage ring project that are initiated worldwide:

- A very detail concept for a storage ring at ISOLDE has been prepared [208]. A dedicated design of the ring fitting into the limited available space is ongoing [219].
- The new storage ring complex DERICA to be constructed at JINR in Russia has been proposed [220]. A low-energy storage ring is one of the central facilities [221].
- There is a proposal to transfer a low-energy storage ring TSR from Heidelberg to IMP in Lanzhou and to couple it to the existing CSRm facility. If realised this project could be the first in time and thus in the forefront of this research field. Furthermore, it would facilitate the optimisation of future low-energy facilities like for instance envisioned at HIAF.

7. Conclusion

In this contribution we provided a concise review of the experimental programs at the heavy-ion storage rings. The potential of the running research is still extremely large and it will enormously be extended by the future facilities. Whereas the higher energy regime will be covered at FAIR and to some extend also at HIAF, the present quest is to approach stored and cooled beams of short-lived nuclides at low-energies. Here, an exciting multidisciplinary physics program has been worked in details and awaits its realisation.

Acknowledgments
This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant No 682841 "ASTRUm").

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