# TSR@ISOLDE Workshop

Monday 29 October 2012 - Tuesday 30 October 2012

CERN

# Book of Abstracts

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## The TSR@ISOLDE Project

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The TSR will be the first low-energy storage ring at an ISOL-type radioactive beam facility. Specifically, we intend to setup the heavy-ion, low-energy ring TSR at the ISOLDE facility in CERN, Geneva. Such a facility will provide a capability for experiments with stored secondary beams that is unique in the world. The envisaged physics programme is rich and varied, spanning from investigations of nuclear ground-state properties and reaction studies of astrophysical relevance, to investigations with highly-charged ions and pure isomeric beams. The TSR might also be employed for removal of isobaric contaminants from stored ion beams and for systematic studies within the neutrino beam programme. In addition to experiments performed using beams recirculating within the ring, cooled beams can also be extracted and exploited by external spectrometers for high-precision measurements. The existing TSR, which is presently in operation at the Max-Planck Institute for Nuclear Physics in Heidelberg, is well suited and can be employed for this purpose. An overview on the status of the project, on the physics cases as well as on technical details of the existing ring facility and of the beam and infrastructure requirements at ISOLDE are summarized.

**1**

## A HELIOS spectrometer for HIE-ISOLDE

**Author:** David Jenkins[1]

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The HELIOS concept is a new approach to the study of transfer reactions in inverse kinematics using a large solenoidal magnet. Light ions are transported in helical trajectories in this field and detected in silicon detectors along the axis. Particles can be discriminated on the basis of their cyclotron period and the kinematics reconstructed. This leads, in principle, to improved resolving power compared to standard silicon box spectrometers like T-REX . A successful implementation of such a spectrometer exists at Argonne National Laboratory where it will be used with radioactive beams from the CARIBU facility.

A project has already started to implement a HELIOS spectrometer for HIE-ISOLDE phase 1. A collaboration is forming and a suitable magnet, being the largest capital item needed for the project, has been secured following the donation by the University of Nottingham of a large bore 3-T redundant MRI magnet. The present status of this project will be discussed. In addition, the perspectives for an eventual move of this spectrometer to a position following the TSR will be considered. In principle, the isobaric purity of TSR beams and their excellent emittance would lead to considerably improved performance. The reimposition of a suitable time structure into the extracted TSR beam would be crucial, however, to allow the compatible operation of the TSR and a HELIOS spectrometer. Due to the unshielded nature of the magnet obtained, consideration should also be given to the suitable housing of the magnet which would benefit from being placed in its own building as an annex to the construction needed for the TSR, to remove the need for elaborate magnetic shielding.

**2**

## Status and Future Perspectives of the HIE-ISOLDE Project

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A major upgrade called High Intensity and Energy ISOLDE (HIE-ISOLDE) was approved by the CERN Research Board in 2009 and is currently under construction. A new superconducting LINAC will increase the energy of the post-accelerated beams to 5.5A MeV (2014) and subsequently 10A MeV (2017) while an improved target area will be designed to make use of the higher intensities delivered by LINAC4 and the 2 GeV protons from the upgraded PS booster. An overview of the project and the timeline will be presented.

**3**

# Overview of the Heidelberg Heavy ion storage ring TSR

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In the late eighties and beginning of the nineties a number of laboratories started construction of synchrotrons or small storage rings for light and heavy ions for research in various fields of atomic, molecular and nuclear physics. The small rings became possible due to the successful demonstration of phase space cooling as well the progress in vacuum technology allowing vacua in the 10-12 mbar regimes to be achieved in accelerators at moderate cost. The heavy ion
cooler storage ring located at MPI for nuclear physics belongs to this family of heavy ion cooler storage rings. It is proposed to install the TSR storage ring at ISOLDE to cool and store
post-accelerated beams available from HIE-ISOLDE at CERN. An overview about the TSR at
HIE-ISOLDE will be given

**4**

# The linking of TSR to ISOLDE

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With the integration of the Heidelberg Test Storage Ring at ISOLDE it would become the first storage ring at an isotope separator on-line (ISOL) facility. A substantial fraction of the vast number of radioactive beams produced at the ISOLDE facility could be injected into the ring for storage, beam deceleration or acceleration. The different operational possibilities and constraints that arise when the ring is connected to an ISOL facility with a successive charge breeder will be addressed. More specifically the required high ion charge-state and short pulse length will be motivated, the foreseen setup procedure discussed, as well as the ion throughput limitations among other things. A tentative layout of the integration with the HIE-ISOLDE linac beam lines will be presented. Finally an introduction to the study of an upgraded charge breeding system will be given.

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## Dielectronic Recombination of Low-Energy Isomers: Towards Storage Ring Studies of the 'Nuclear Clock' Isotope Thorium-229

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Long-lived atomic or nuclear states play an important role in astrophysics, for precision spectroscopy, for the study of fundamental symmetries, for energy storage or —based on their small natural widths —for applications as clocks. Within the scope of low-energy isomers 229(m)Th is truly outstanding in many aspects. It is presumed that 229 Th posses an isomeric state with excitation energy as low as 7.6 eV ([1], other values in the literature range from 0 – 15 eV [2]). It is thus the only isomer in the optical or near-optical range, i.e., suitable for laser experiments. Based on these features, a long list of ground-braking applications and physics cases is proposed (cf. [1, 2, 3] and Refs. therein). It is noted, that despite all efforts no direct evidence of the isomeric state has been published, yet [2].
Our approach for studying metastable states exploits the resonant electron-ion collision process of dielectronic recombination (DR) as a precision spectroscopic tool [4]. Experiments are performed with phase-space cooled few-electron ions at heavy-ion storage rings. For nuclear isomeric states, DR spectra show distinct resonance features that allow for a clear assignment without ambiguity. These 'fingerprints' arise due mainly to different hyperfine effects and nuclear volume shifts of ground and isomeric state.
As is outlined in the Technical Design Report of the "Storage Ring at HIE-ISOLDE" proposal [5], the application of the DR technique to investigations of long-lived nuclear states is considered a valuable asset to the physics program at the new nstallations. In my talk I will introduce and exemplify the technique with cases from atomic metastable states. In the main part, I will discuss a series of recent pioneering experiments carried out at the ESR ring in Darmstadt that leveraged the DR approach for the study of nuclear isomers. Successful experiments were performed with Li-like 234mPa88+ and 235mU89+. Here, 235mU is a particularly interesting candidate with a nuclear excitation energy of 76.8 eV [6] only, that is, the lowest evidenced isomeric transition, yet. It is worth emphasizing that in contrast to Schottky techniques the DR approach is also possible for such very low excitation energies. These initial results are very promising with respect to future extensions of this method and show ways how to implement the technique at the TSR at HIE-ISOLDE.

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## Atomic Physics Experiments at TSR@ISOLDE

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TSR@ISOLDE will provide new possibilities for atomic physics
experiments with highly charged atomic ions addressing atomic

structure (atomic lifetimes, spectroscopy with lasers and ultra-cold electron beams) and atomic collision processes (electron-ion recombination, electron-ion impact ionization). This research is motivated by fundamental physics questions and by applications in astrophysics and plasma physics.

We will present selected illustrative examples from the ongoing atomic physics research program at TSR and point out future directions at TSR@ISOLDE in view of the availability of very high ion charge states and of ions with exotic nuclei. In particular we will discuss measurements of hyperfine-induced and two-photon transitions in highly charged ions and atomic-collision processes that are relevant for the understanding of super-nova explosions and fusion plasmas.

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# Detector developments for storage ring experiments

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As a next generation spectroscopic tool, heavy-ion cooler storage rings will be a unique application for stored highly-charged ion (HCI) beam experiments. The storage rings provide us with an excellent particle identification capability, even for isomeric states, an efficient use of rare isotopes, and an internal target system.
In case that the magnetic rigidity of the decay daughters of stored HCI goes beyond the momentum acceptance of the ring, the daughters are momentum-analyzed by the sector magnets and may reach the dispersive focal plane, where a position sensitive detector is set up. The lifetimes thus obtained for HCI are relevant to the decays in stellar conditions. One of the unique observations for stored HCI is the bound-state beta decay, which is important for the understanding of the s-process nucleosynthesis. Thus development of the particle detectors for storage rings would be a key issue for the decay spectroscopy.
To perform such unique experiments at the heavy-ion storage ring facilities, we have developed the high-resolution position sensitive detectors; a stack of single-side silicon microstrip detectors and alternatively a fiber scintillation detector. Both detectors have an excellent position resolution, and are compact and relatively easy to install into the ring aperture. We have tested the detectors using heavy ion beams including secondary radioactive beams. In this contribution, we focus on the detector performance obtained and discuss the physics cases possible in the in-ring experiments. In addition, a new storage ring project at RIKEN, "Rare RI Ring", aiming at precision mass measurements of short-lived nuclei is briefly presented.

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# Survival of beta decaying nuclei relevant for a neutrino factory

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For many neutrino physics applications it is desirable to have an intense tunable neutrino source. In [1] the β-beam concept for constructing a neutrino-antineutrino facility was proposed. The idea is to obtain a collimated neutrino beam by accelerating radioactive ions to high energy, which subsequently β decay in the long arms of a heavy-ion storage ring. In Ref. [1], two radioactive nuclei were proposed: 6He and 18Ne. In a later development it was proposed that one could construct monocromatic neutrino beam facility using nuclei that decay by electron capture (EC) mainly to one energy level of the daughter nucleus [2].

In a recent article, we have studied the beta decay properties of several nuclei in the rare earth lantanide region in order to select the best candidates for a monocromatic neutrino beam facility [3]. In our study an effort was made to acurately determine the EC branches of the nuclei of interest to the daugther final states using the total absorption technique.

However, in oder to determine if these candidates are appropriate to build such facility several technical issues have to be clarified. The TSR at ISOLDE can provide an unique tool to study for instance the production and survival of the nuclear species of interest. In short, the possibility of producing many radioactive species at ISOLDE in combination with the storage ring offers a unique opportunity for feasibility studies for such neutrino-antineutrino facility.

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## Isospin dependence in heavy-element synthesis in fusion-evaporation reactions with neutron-rich radioactive ion-beams

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Climbing up the "Island of Stability" and approaching the long-predicted next spherical neutron shell closure at N=184 is a persistent dream hampered, among others, by the lack of (i) sufficiently neutron-rich target and projectile combinations and (ii) insufficient knowledge about the projectile isospin (T=(N-Z)/2) dependence of the fusion neutron-evaporation residue cross section. With the advent of radioactive ion-beam facilities, which are delivering ever more intense neutron-rich ion beams, the answer to the latter question is now coming within reach.

"Hot-fusion" reactions based on relatively light (A ˜ 20 - 50) neutron-rich projectiles and heavy actinide targets have been exploited to access relatively neutron-rich isotopes of the heaviest elements. See, e.g. [1] for an overview of reactions with 48Ca leading to the most neutron-rich known isotopes, which belong to elements Z=112-118. Still, in these elements, the neutron number N=184 cannot be reached using complete fusion-evaporation reactions with stable isotope beams, and when going to yet heavier elements with Z˜122-124, cross sections are predicted to be orders of magnitude smaller than those nowadays accessible in even the most advanced and sensitive experiments. Therefore, to reach N=184, more neutron-rich radioactive beams of high intensity are required [2].

Systematic studies to investigate the role of isospin on the magnitude of fusion-evaporation reacations that include exotic neutron-rich radioactive beams are still scarce (see, e.g., [3]). We suggest pursuing the "hot-fusion" path in our investigations on the projectile isospin dependence of heavy element fusion-evaporation residue cross sections at Coulomb barrier energies by exploiting the Ar + Sm ⊠ Hg system [4] and using intense beams of exotic Ar isotopes available at the TSR [5]. Neutron-evaporation residues will be detected in an ultrasensitive nuclear chemical detection system [6], which is also applied for nuclear chemical studies of single atoms of superheavy elements [7].

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[7] A. Yakushev et al., to be submitted to Inorg. Chem.

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## Overview of the TSR@ISOLDE experimental programme

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The prospective scientific programme for the Heidelberg Test Storage Ring injected with radioactive beams from HIE-ISOLDE has been published (M. Grieser et al Eur. Phys. J. Special Topics 207 (2012) 1–117). I will present some examples from this programme with emphasis on the technical challenges that lie ahead.

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## Laser Spectroscopy studies at the TSR

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The TSR presents an excellent opportunity to study difficult cases previously inaccessible for laser spectroscopy at ISOLDE. Deep UV transitions (within the vacuum ultraviolet ) which are currently difficult to study, will be Doppler shifted by up to 30 nm at 10 MeV/A. By partially stripping the ion in the REX-EBIS it is possible to preferentially populate metastable states with transitions that can be probed by existing laser technology. Additionally the TSR could be used to study elements that can only be efficiently produced at ISOLDE through chemical separation techniques, since the REX-EBIS will break up molecular beams during the charge breading process. The recirculating beam in the TSR offers a significant gain in experimental efficiency, since the same ions can be probed many times. By storing a single ion stored in the ring for 1s will allow it to circulate 105 times, resulting in a significant gain for laser spectroscopy. This work builds on the experience gained from previous laser spectroscopy experiments at the TSR, ESR and ISOLDE
The talk will present the possibilities of performing laser spectroscopy experiments on radioactive isotopes using the TSR at ISOLDE.

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# Isomer physics in the TSR at ISOLDE

**Author:** Philip Walker[1]

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Most of the beams injected into the TSR at ISOLDE will be in their nuclear ground states. However, isomers offer additional opportunities, providing their half-lives are sufficiently long (about a second or longer). These opportunities are of two kinds. (i) The opening up of the spin and excitation-energy degrees of freedom gives access to a wider range of nuclear structure, such as pair-blocked configurations. (ii) The possibility of isomer electromagnetic decay may enable the study of phenomena that are not observable from ground states. An example of the latter could be the yet-to-be-discovered NEEC (nuclear excitation by electron capture) process, for which electron-beam interactions would be exploited. The unique environment for isomers in the TSR at ISOLDE will be discussed in this context.

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# In-flight beta-decay of light exotic nuclei

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The peculiar properties of light exotic nuclei have been investigated using nuclear reaction at high and intermediate energies. The extraction of reliable information on their structure, however, depends on reaction models; beta-decay studies can be seen as complementary in this context. The beta-decay process has the advantage of being well understood. The decay probability directly relates to the overlap between mother and daughter states. In light nuclei, especially close to the drip lines, beta-decay is characterized by large Q-values and low breakup thresholds in the daughter nuclei, so that feeding to unbound resonances and delayed emission of light ions becomes possible. In the case of halo nuclei, the same phenomenon could lead to direct decays to the continuum. The detection of the emitted particles serves at once for the identification of the decay paths, and to collect additional information about the structure of the populated states. Recent results include the study of the decays 6He [1], 11Li [2], 8B [3], and to states of astrophysical relevance on 12C [4].
The light-ion emission channels are characterised by a small relative momentum of the fragments, because of the small Q-values. This represents a challenge for conventional setups where the rare, low-energy signals of the ions are drowned in an overwhelming beta-background. In the Storage Ring at HIE-ISOLDE the nuclei would circulate at high velocity and decay in-flight. The light ions emitted in the exotic channels of interest would remain in a narrow cone around the beam axis, keeping a large forward momentum. They could then be identified in a charged-particle detection setup placed after a bend, where they would separate from the beam because of the different magnetic rigidity. Cases of interest at HIE-ISOLDE are 6He, 8He, the proton-emission decay of 11Be [5], the alpha-emission decay of 16N [6].
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# Nuclear Astrophysics with the TSR@ISOLDE

**Author:** Philip J WOODS[None]

The talk will explore important new opportunities that will become available for nuclear astrophysics on the TSR@ISOLDE. Measurements will be performed for reactions influencing nucleosynthesis and energy generation in explosive environments such as novae, supernovae and X-ray bursters. In particular, there will be an emphasis on the use of high resolution transfer reactions for estimates of resonance strengths in regions of high level density, relevant for example for abundances of cosmic gamma-ray emitters, and capture reaction studies relevant for the production of p-process nuclei in supernovae.

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## UHV CAPABLE DETECTOR SYSTEMS FOR NUCLEAR REACTION STUDIES WITH STORED EXOTIC BEAMS

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Within the R&D for the EXL* project at FAIR the EXL collaboration has developed in the recent years new techniques for the application of large solid angle DSSD's under UHV conditions of storage rings. Such technologies could be favourably applied at the TSR@ISOLDE project for high energy- and angular resolution detection of target like recoil ions and beam like reaction products from light ion induced nuclear reactions.
After a brief overview on the EXL project the design of UHV capable detection systems, and the results concerning spectroscopic performance, feasibility studies and application of the detection systems in first experiments at the ESR storage ring will be discussed.

- EXL: EXotic nuclei studied in Light-ion induced reactions at the NESR storage ring

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## Installation at ISOLDE (and costs)

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Several studies have started in the frame of an installation and integration of the TSR at Isolde. With spacing being a problem at Isolde all different options for a possible position of the new building to house the storage ring have been taken in consideration in an early phase of th eproject as well as allocation of parts of the infrastructure such as cooling station and electrical transformers. In it's June meeting the CERN Research Board gave outline approval to the TSR@Isolde project. This outline approval requests that CERN undertakes an integration study to identify early the requirements for the initial installation together with the necessary modifications and upgrades needed to eventually be able to run the TSR as a standard CERN facility. A TSR Integration Study Working Group has been put in place to make an inventory of the actual components of the storage ring, its equipment and necessary infrastructure.
An overview of the installation of the TSR at ISOLDE will be presented.

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## Neutrino physics with TSR

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Possible experiments for neutrino physics at TSR will be discussed.

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## The low energy Storage Ring - CRYRING@ESR - Project

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The Swedish in-kind contribution to the FAIR facility in Darmstadt, the heavy-ion storage ring CRYRING will be transported to Darmstadt this year. Instead of warehousing until installation at the Facility for Antiproton and Ion Research, FAIR, the immediate installation behind the existing Experimental Storage Ring, ESR, has been proposed and worked out in detail by a Swedish-German working group.
The proposed installation behind the ESR in combination with its own injector makes CRYRING@ESR the perfect machine for FAIR related tests of diagnostics, software and concepts on one side, and atomic physics experiments with heavy, highly charged ions stored at low energy on the other side. Challenging physics perspectives are also opened up for low-energy nuclear physics investigations. CRYRING@ESR provides beams of low charged ions independently on the GSI accelerator facility, which will have to shutdown for an extended period due to necessary upgrades towards FAIR and, hence, provides an on-line test environment for FAIR parts. CRYRING can decelerate, cool and store heavy, highly-charged ions down to a few 100 keV/nucleon. It provides a high performance electron cooler in combination with a gas jet target and thus opens up a very attractive physics program as a natural extension of the ESR, which can only operate down to about 4 MeV/nucleon. CRYRING@ESR is a first step towards atomic physics with low-energy, highly charged ions at FAIR as planned within the SPARC and APPA collaborations.

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## Welcome

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## Committee Structure

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## Concluding Remarks