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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Storage ring facility at HIE-ISOLDE

A. Andreyev[1], J. Äystö[2], K. Blaum[3], Y. Blumenfeld[4], S. Bishop[5], F. Bosch[6], C. Brandau[6], P. Butler[7], T. Davison[8], P. Egelhof[6], H. Geissel[6], M. Grieser[3], R. von Hahn[3], M. Heil[6], M. Huyse[9], D. Jenkins[10], A. Jokinen[2], Y. Kadi[4], H.-J. Kluge[6], M. Kowalska[4], C. Kozhuharov[6], S. Kreim[3], R. Krücken[5], Yu.A. Litvinov[3,6], G. Neyens[9] W. Nörtershäuser[5,11] R. Page[7], M. Pasini[4], R. Raabe[9], R. Reifarth[6,12], R. Repnow[3], M.S. Sanjari[6,12], C. Scheidenberger[6], D. Shubina[3], E. Siesling[4], M. Steck[6], T. Stora[4], T. Stöhlker[6], F. Suzaki[13], P. VanDuppen[9], C. Volpe[14], P.M. Walker[15], F. Wenander[4], E. Wildner[4], N. Winckler[3], A. Wolf[3], P. Woods[8], T. Yamaguchi[13]

[1] *University of the West of Scotland, Paisley PA1 2BE, UK*
[2] *Department of Physics, University of Jyväskylä, 40014 Jyväskylä, Finland*
[3] *Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*
[4] *CERN, 1211 Geneva 23, Switzerland*
[5] *Physik Department E12, Technische Universität Mnchen, 85748 Garching, Germany*
[6] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[7] *Department of Physics, University of Liverpool, Liverpool L69 7ZE, UK*
[8] *School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, UK*
[9] *K.U.Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium*
[10] *Department of Physics, University of York, York YO10 5DD, UK*
[11] *Institut für Kernchemie, Universität Mainz, 55128 Mainz, Germany*
[12] *Goethe-Universität Frankfurt, 60438 Frankfurt, Germany*
[13] *Department of Physics, Saitama University, Saitama 338-8570, Japan*
[14] *Institut de Physique Nucléaire (IPN), 91406 Orsay, France*
[15] *Department of Physics, University of Surrey, Guildford, GU2 7XH, UK*

Spokesperson: Klaus Blaum [klaus.blaum@mpi-hd.mpg.de]
Co-Spokesperson: Yorick Blumenfeld [yorick.blumenfeld@cern.ch]
Co-Spokesperson: Philip J. Woods [pjw@ph.ed.ac.uk]
Co-Spokesperson: Yuri A. Litvinov [y.litvinov@gsi.de]
Co-Spokesperson: Riccardo Raabe [riccardo.raabe@fys.kuleuven.be]

Abstract: It is proposed to set-up a storage ring facility at the HIE-ISOLDE to perform experiments with stored exotic nuclides. The TSR ring from MPIK, Heidelberg can be used for this purpose. A possible physics program is rich and spans 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 may be employed for cleaning of the ion beams from isobaric contaminants and for systematic studies within the neutrino beam program.

Requested shifts: 0

1 Introduction

Nuclear physics experiments with stored exotic nuclei have been proven high potential over the last decades [1, 2]. Presently there are two storage ring facilities worldwide performing such experiments, namely ESR in Darmstadt and CSRe in Lanzhou [3]. These facilities, however, are specialized for experiments at relativistic energies. Efforts are presently undertaken to employ the existing storage rings also for nuclear physics experiments at lower energies, which inevitably requires the still inefficient and time consuming slowing down of stored ion beams.
A dedicated workshop (TSR@ISOLDE) has been organized at the Max-Planck-Institute for Nuclear Physics (MPIK) in Heidelberg on 28th and 29th October 2010. The workshop has collected about 50 participants from all over the world. New physics ideas which can be enabled employing a low-energy storage ring at ISOLDE have been discussed. It was suggested to employ the existing ring TSR (located at MPIK) for this purpose. This LOI is based on the ideas proposed during the workshop.
The heavy ion storage ring TSR was constructed at MPIK and is in operation since 1988 [4]. The circumference of the TSR is 55.4 m and the maximal magnetic rigidity is 1.5 Tm. Each of the four symmetric focusing periods consists of two 45° dipole magnets, five quadrupole magnets and three sextupole magnets. The TSR has four 5.2 m long straight sections between the 90° bends. It is equipped with injection as well as with extraction elements. The electron cooler allows achieving stored beams with extremely small horizontal and vertical emittances. Also the laser cooling can be applied to a selected number of heavy ion species. The TSR has an RF resonator which can be used to accelerate or decelerate stored beams. An overview of stored beam intensities and beam lifetimes achieved in the TSR can be found in [4].
The four straight sections offer ideal conditions for setting up different experiments. In comparison, the ESR has only two $\sim$10 m straight sections where one is fully occupied by the electron cooler. A dedicated ultra-cold electron target has been developed in the TSR for high-resolution experiments with electrons. A peculiar property of the TSR is a high momentum acceptance of about $\pm 3\%$ [5] which may be used for storing exotic ions in several charge states or different radioactive nuclides with similar mass-over-charge ratios.
The high resolution of storage rings can be employed for cleaning the ion beam from isobaric contaminants. This can be achieved in two ways. The first one is to use the resonant character of the di-electronic recombination process (see section 2.6), which however requires a relatively long time. In particular, ground and isomeric states can, in principle, be separated with this method. The second one is to mechanically scrape the contaminants in the dispersive place of the TSR. A proof of principle has been demonstrated in the ESR where the ^{140}Pr ions were removed keeping the ^{140}Ce isobars stored [6]. Such procedure should be feasible in many cases using cooled ion beams. The cleaned beams can then be used for in-ring experiments or can be extracted to an external experiment.
In the following we sketch the physics ideas for possible in-ring experiments at HIE-ISOLDE.

2 Physics case

2.1 Half-life measurements of ^{7}Be in different atomic charge states

The knowledge of ^{7}Be half-lives in different atomic charge states is indispensable for Solar physics, since it is predicted that 20-30% of ^{7}Be in the core of the Sun is present as hydrogen-like ions [7]. However, this textbook experiment [8, 9] could not be performed up to now.
The half-life of neutral ^{7}Be is 53.22(6) d [10] and the expected half-life of hydrogen-like $^7Be^{3+}$ions is about 106 d [9]. The lifetimes of these ions can be probed via the counting of their reactions in the storage ring. For this method, a number of a few 10^5 ions is required, while the ISOLDE yield for ^{7}Be is $2.8 \cdot 10^{10}$ particles/s. Achieving the required charge state can be done with the existing electron beam ion source (EBIS). The time needed for breeding (well below 100 ms) is negligible in comparison with the half-life of $^7Be^{3+}$ ions. Taking into account the transmission efficiency, space charge limitations of REX-TRAP, an estimated intensity in front of the TSR is about $10^8 - 10^9$ of $^7Be^{3+}$ ions per second. Such intensity is by far sufficient to perform this experiment. Half-life measurements of $^7Be^{2+}$ ions can be performed in addition.

2.2 Capture reactions for the astrophysical p-process

Experimental information on capture reactions (p, γ) and (α, γ) is very scarce and is restricted to stable isotopes so far. The stored beam is intersected by an internal gas-jet target and the recoils from the capture reaction are measured with high efficiency after one of the ring's bending magnets. The TSR, owing to the "pseudo"-continuous accumulation scheme is a versatile tool for such measurements. A proof of principle experiment has been performed at the ESR ring of GSI, where a cross-section of the proton capture on stable ^{96}Ru nuclei (^{96}Ru$(p, \gamma)^{97}$Rh) has been measured [11]. A new proposal to investigate (α, γ) and also (p, n) reactions has been accepted at GSI [12]. At GSI, in order to perform measurements in the Gamow window of the p-process, the stored ions have to be slowed down to energies below 10 MeV/u. Such procedure is time consuming and inefficient. The TSR at HIE-ISOLDE would be an ideal combination, where the post-accelerated stable or radioactive beams are injected and stored at the right energy.
The number of cases for possible studies is huge. It is suggested to start the experimental program with stable beams (e.g. ^{96}Ru, ^{112}Sn), which can also be done during proton-accelerator shutdowns. The data are hardly available and even the first experiments will make high scientific impact. The cross-sections for (p, γ) and (α, γ) reactions in the Gamow-window of the p-process are relatively high. For the first experiments one can select the cases with cross-sections in the range 0.1-10 mb and, thus, moderate intensities would be required (a few 10^5 stored ions only).
Atomic electron stripping reactions have huge cross-sections at our low energies and are the main beam loss process. Therefore, the above experiments require high atomic charge states. Fully-ionized, or at least helium-like, atoms are required for elements in the Z-range $30 \leq Z \leq 70$. Such high-ionization grades cannot be achieved with the present

REX-EBIS and an upgrade to higher electron densities and voltages to a so called Super-EBIT is indispensable.
The scientific program is rich. The higher beam intensities achieved by accumulation in the TSR will allow moving away from the valley of β-stability reaching νp- and later rp-process nuclei. Furthermore, gaining experience and improving beam handling and detection techniques may allow experiments at much lower beam energies (1 MeV/u or lower). A longer term upgrade could include a co-propagating proton beam in one of the straight sections of the TSR. In such a scenario, the energies of both beams can be kept relatively large to enable easy beam handling while the relative, interaction energy can be tuned to a small value. Though the luminosity in this approach is much lower, one obvious advantage is that the effect of electron screening present in neutral-atom experiments is disabled. Moreover, up to 100% detection efficiency can be reached for the high-energy recoil particles.

2.3 Nuclear structure through transfer reactions

One- and two-nucleon transfer reactions, thanks to their selectivity, provide rich information on nuclear structure. In combination with post-accelerated radioactive ion beams, they are an important tool to investigate the evolution of the shell structure far from stability. The regions around (expected) shell closures are of particular interest: n-rich Ni isotopes between N=40 and N=50, the regions around ^{100}Sn and ^{132}Sn, and the neutron-deficient Pb isotopes. The energy of beams at HIE-ISOLDE, 10 MeV/nucleon, is well-suited for these studies.
The time structure of the beams from the REX-EBIS, with short bunches ($\sim$100 μs) repeated a few times per second, is well-adapted for the injection into the TSR. The beams would be efficiently stored and cooled; possibilities for further purification from isobar contaminants need to be investigated. At 10 MeV/u, higher ionization states than those presently achieved in REX-EBIS are required to fit the maximum magnetic rigidity allowed in the TSR. Those charge states could be reached by an upgrade of the REX-EBIS, or possibly using a stripping foil (with varying efficiencies).
Gas-jet targets of H_2, d, and ^{3,4}He would be used. The low target thickness is compensated by the recirculation of the ion beam in the TSR and the possible accumulation of ions from several bunches from REX-EBIS. Reaction of interest typically imply the detection of the outgoing light particle and possibly gamma rays in coincidence. Solutions for placing charged-particle detector arrays in ultra-high vacuum have been proposed by the EXL collaboration [13]. Because of the very good beam energy definition and the absence of straggling in the target, a superior energy resolution is expected. An external array like Miniball is used for the detection of gamma rays.
The loss factor in thickness by using a gas-jet target with respect to a usual foil is a few 10^5. Given the revolution frequency in the TSR (10^6 turns/s), the technique ensures an advantage, in terms of reaction yields, for accumulated isotope beams with a lifetime of about 1 s and longer. For such cases, studies become possible for very weak HIE-ISOLDE beams (10^4 pps and lower, depending on the storage times). Transfer reaction on the Ni isotopic chain could extend to ^{70}Ni(d,p) and possibly further. More in general, on the neutron-rich side, (d,p) reactions can be used to investigate the shell evolution towards the

nuclei of the astrophyical r-process. Around ^{100}Sn, the proton and neutron shell closures can be studied with (d,p), (^{3}He,^{4}He) and (^{3}He,d) reactions. In the neutron-deficient Pb region, the same studies could be performed as far as to ^{186}Pb.

2.4 Long-lived isomeric states

Nuclear isomeric states are important probes to explore nuclear structure [14]. Typically, investigations of exotic nuclei far from stability, which are characterized by small production rates and short lifetimes, are done with γ-spectroscopy employing position-sensitive pixel detectors. The beam intensity on such a detector is limited by the number of pixels and the lifetime of the investigated nuclide since the implantation event has to be correlated with the decay event. It is clear that long-lived isomeric states, as e.g. predicted in neutron-rich hafnium isotopes ($T_{1/2}$ > min), can hardly be investigated with this technique.
Owing to the sensitivity to single stored ions, the storage-ring mass spectrometry is a unique tool to search for such long-lived rare nuclear species. A long-lived isomer in ^{184}Hf has been discovered by this method in the ESR of GSI [15].
Similar experiments can be performed with the TSR@ISOLDE. Here the sensitivity to single ions has to be reached still. Technical realization is different from the ESR case because of the lower-energy ions. However, a new highly-sensitive, resonant-cavity Schottky detector has been commissioned at the ESR and is being installed in the CSRe [16]. A dedicated detector with a similar design is being considered for the TSR. High-resolving power of the storage ring mass spectrometry allows determination of the isomeric- to ground-state production rates. Although, the charge breeding is not essential, higher charge states are preferable for easier detection with Schottky probes and higher beam lifetimes in the TSR. The primary task is to find long-lived states, for which breeding times of up to a few seconds are acceptable.
We note, that the interaction of isomeric nuclei with the electron target may open novel physics, including the possibility to observe the Nuclear Excitation by Electron Capture (NEEC) process (see also section 2.6).

2.5 Atomic effects on half-lives of medium-heavy nuclei

Atomic charge states can dramatically modify nuclear decay constants. For instance, the rate of orbital electron capture decay of hydrogen-like atoms is highly-sensitive to the population of hyperfine states [17]. Investigations of nuclear half-lives as a function of atomic charge states and of spin-parities for the parent and daughter nuclei can be conducted at the TSR@ISOLDE. Such experiments can be used to address the electron screening in beta decay, or employed as a thermometer for the ion-beam interacting with the electrons or gas-jet particles. An interesting option is the selective population of hyperfine states with a laser beam (a proof of principle has been done in the ESR [18]).
One well-suited nucleus for a possible experiment is ^{111}Sn. The long half-live $T_{1/2}$=35.3 min allows longer charge breeding times. The estimated ISOLDE yield is about 10^9 particles/s, which is higher than required in this case. However, the present REX-EBIS is only capable of achieving charge states lower than $Q^{Z=50}_{\mathrm{limit}}$=39+, which is insufficient (Q_{limit}

is the maximal achievable charge state for a given Z, determined by the condition that the ionization energy for a certain Q→Q+1 becomes larger than the energy of the electron beam). An upgrade of the REX-EBIS is required. Another example is ^{64}Cu ($T_{1/2}$=12.7 h). With the present value of $Q_{\mathrm{limit}}^{Z=29}$=26+ an upgrade of the REX-EBIS would be needed too in order to reach the hydrogen-like charge state, 28+.
Furthermore, long-lived isotopes decaying within a few days to 100 kilo-years by orbital electron-capture are used in cosmic ray physics to estimate the time between the nucleosynthesis in stars and the acceleration [19, 20]. High intensities of some radioactive beams at ISOLDE would allow experimental determination of half-lives of some relevant hydrogen-like systems (e.g., ^{56}Ni ($T_{1/2}$=6 d), ^{57}Co($T_{1/2}$=272 d). Since the decay rate of hydrogen-like atoms is of utmost importance here, these investigations require the upgrade of the REX-EBIS as well.

2.6 Di-electronic recombination on exotic nuclei

Di-electronic recombination (DR) is a well-established atomic physics research program at TSR and ESR. At ESR, the DR spectra of radionuclides have been measured for the first time [21]. A broad scientific program can be pursued at ISOLDE, where isotopic or/and isotonic shifts can be measured thus providing information on nuclear charge radii.
Furthermore, using resonant character of DR, purification of beams in ground or alternatively isomeric states is feasible, in principle. In that case, the electron cooler and the electron target available in the TSR are of great advantage. Experiments with such purified beams may be suitable for studies on laser interaction with the nuclei or for the search of predicted Nuclear Excitation by Electron Capture (NEEC) phenomenon [22].
One extremely important physics goal is the investigation of the lowest known isomeric states (^{229}Th (E^*=3.5 eV, $T_{1/2}$=79 h), ^{235}U (E^*=76.5 eV, $T_{1/2}$ 26 min) [10]: their existence, radii, etc. Since few-electron charge states are essential, an upgrade of the REX-EBIS is required also in this case (present $Q_{\mathrm{limit}}^{Z=90}$=60+). The experiments can be conducted if the beam intensity reaches 10^4 stored ions, which should be achievable with present EBIT technologies and/or stacking capabilities of the TSR.

2.7 R&D for Beta Beams: tests with stable and radioactive ions

Beta beams are today one of the possible long baseline facilities to explore neutrino properties, primarily neutrino oscillation physics including CP violation in the leptonic sector. The TSR at ISOLDE can be used as a versatile tool to investigate different aspects useful to the beta beams. This is possible because of the large variety of the available stable and radioactive ions delivered by REX-ISOLDE at energies of 1 to 10 Mev/u, which will be used as an injector to the TSR. In the beta beam concept, the (anti-)neutrinos are produced by acceleration and final storage of beta-decaying isotopes with decay times around one second. CERN is a possible place to produce these well collimated pure neutrino or antineutrino beams since a suitable accelerator complex is available including the expertise to produce the needed radioactive isotopes. In the following we give a list of non-exhaustive topics of investigation:

Production and storage of ^{6}He/^{18}Ne or ^{8}Li/^{8}B ions: A milestone in the production of suitable intensities of ^{6}He has already been achieved at ISOLDE. The production of 10^{11} ^{6}He$^+$ ions/s is possible at HIE-ISOLDE, and, provided cw injection into REX-EBIS from ISCOOL becomes available with improved efficiencies, intensities of about $5 \cdot 10^9$ ^{6}He ions stored in the TSR can be envisaged. The investigation of different parameters such as ion injection, cooling linked with decay losses will be very valuable for the benchmarking of the numerical simulation tools used in the beta beam study. This will be extended to other candidates such as ^{18}Ne or ^{8}Li/^{8}B ions. In the latter case, ^{8}B beams are not yet available at ISOLDE and should be developped.
Production of ^{8}Li/^{8}B ions with stored ^{7}Li ions: The concept of a production ring for ^{8}Li/^{8}B based on stored ^{7}Li and ionization cooling has been proposed by C. Rubbia *et al.* While no study has yet been undertaken to see if the TSR would be suitable to test this concept, both the framework of HIE-ISOLDE and the availability of stable ions from the Linac during off-line beam time are strong motivations to explore this possibility. In that case, the production of $5 \cdot 10^8$ ^{7}Li ions/s from REX-EBIS has already been demonstrated. This can be used for a reduced scale feasibility study. Several orders of magnitude should be gained if a full scale experiment is envisaged.
Physics with low-energy neutrinos: The availability of high intensity beta-decaying ions implanted on a target offers the possibility to perform experiments with detector(s) close to the neutrino source. Such a configuration has been proposed as a variant of the low energy beta-beam proposed by C. Volpe. Experiments with this kind of source might cover searches for physics beyond the Standard Model, e.g. a measurement of the neutrino magnetic moment, or of coherent neutrino-nucleus scattering. If high intensities are reached for ions with high Q-values the neutrinos produced can be used to perform neutrino-nucleus cross section measurements of interest for nuclear and core-collapse supernova physics.

3 Requirements

The realization of the proposed project requires several improvements of the present REX-ISOLDE facility. These improvements are shortly summarized below.

- Most of the experiments suggested above require high atomic charge states reaching fully-ionized or hydrogen-like isotopes also for heavy nuclides. Therefore an upgrade of the present REX-EBIS to a Super-EBIT is requested. We emphasize, that reaching fully-ionized atoms automatically removes the issue of isobaric contaminants. We also note, that a collaboration with MSU (East Lansing, USA), TRIUMF (Vancouver, Canada) and MPI-K (Heidelber, Germany) had been established at ISOLDE to build a Super-EBIT Charge Breeder.

- The TSR ring needs about 20 m $\times$ 20 m square room for installation, which inevitably requires an extension of the ISOLDE experimental hall.

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