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Highlights of the ISOLDE facility and the HIE-ISOLDE project

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ABSTRACT

The ISOLDE facility is an ISOL-based radioactive beam facility at CERN. It is dedicated to the production and research of nuclei far from stability. Exotic nuclei of variety of chemical elements are available for the study of nuclear structure, nuclear astrophysics, fundamental symmetries and atomic physics, as well as for applications in condensed-matter and life sciences. Since longer than a decade it has offered the largest variety of post-accelerated radioactive beams in the world. In order to broaden the scientific opportunities beyond the present ISOLDE facility, the on-going HIE-ISOLDE (High Intensity and Energy) project will provide major improvements in energy range, beam intensity and beam quality. The first phase will boost the beam energy of the current REX LINAC to 5.5 MeV/u resulting in larger cross sections for Coulomb excitation compared to the previous maximum energy of 3 MeV/u. Higher energies will also open up many transfer reaction channels. Physics with post-accelerated beams starts in autumn 2015. The second phase of the project is already approved and is expected to be completed in 2018 allowing beam energies up to 10 MeV/u for $A/q = 4.5$. In this contribution the present status of the ISOLDE facility including some highlights will be discussed. The HIE-ISOLDE project will be described together with a panorama of the physics cases to be addressed.

1. The ISOLDE facility

The ISOLDE radioactive beam facility is the CERN experiment for the production and acceleration of radioactive nuclei. Isotopes from a variety of elements are produced in a target directly connected to the ion-source of an isotope separator to minimise the time delay between production of a nucleus and its arrival at the experimental setup.

The facility is located at the Proton-Synchrotron Booster (PSB) of the European Organization for Nuclear Research, CERN. The pulsed beam delivered by the PSB injector contains up to 3.1×10^{13} protons/pulse with a minimum spacing of 1.2 s, giving an average proton current on target of 2 μA [1]. The high energy protons, such as the 1.4 GeV protons from PSB are optimum for the production of radioactive nuclei via spallation, fission and fragmentation reactions on thick targets. The reaction products are stopped in the bulk of the target material, thereafter transported to an ion source by diffusion and effusion followed by an acceleration to few tens of keV. As part of the ISOLDE upgrade we plan to make use of the higher energy of 2 GeV expected for the PSB in 2020 after the next CERN long shut down. The higher energy of the injector will increase the cross section for the fragmentation and spallation process in factors of two to ten. Fluka simulations indicate that the reduction in the fission cross section expected at higher energy will be compensated by the secondary reactions in the target. In addition, an increase of intensity of the injector by a factor of 2–3 is expected for 2020 due to the exchange of the primary ion source of the proton linac (LINAC 4). The combination of higher intensity and energy will produce an increase of power on target of a factor of four.

The success of ISOLDE is due to the continuous development of new radioactive ion beams and improvements in experimental conditions. More than 20 different target materials and ionisers are in use. The target material is kept at a temperature between 1000 °C and 2000 °C so that the radioactive atoms produced in a target diffuse out rapidly into different dedicated ion sources. Ionisation can take place in hot plasma, on a hot surface or by laser excitation. Chemical selectivity is obtained by the right combination of target-ion sources giving rise to a selective production of more than 1300 isotopes of 73 different elements of which Boron is the last one in the long list. As the reaction mechanisms are barely selective, the target-ion source system at the origin of the low-energy ion beam combined with the mass analysing magnet and other ion manipulation devices are used to reduce the unwanted contaminants and/or to identify the isotopes of interest. The target and the ion source are kept at high temperature to speed

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up the diffusion and effusion of the radioactive atoms from the target container [2]. This led to a successful design that today is still competitive and that allows using different atomic and chemical processes to purify the beam. A simple but effective approach is cooling the transfer line between target and ion source, allowing only the gaseous elements (noble gases) or most volatile molecules to reach the ion source. The suppression of elements that make a chemical bonding with the surface of a quartz line installed between target and ion source represents another approach. Recently new developments including the use of nano-structured target materials are explored to reduce the delay time and the sintering process. For a more detailed update on the development of target materials, see A. Gottberg contribution to this proceedings.

The availability of powerful pulsed laser systems led to the implementation of resonance ionisation laser ion source (RILIS) for the production of RIB in the mid-80's [3]. This element selective ionisation process is based on the use of different laser beams to provoke multi-step atomic excitations into the continuum. The identification of resonante states or Rydberg states enhance the efficiency of the ionisation process and it is part of the daily quest of the RILIS team. Since the first on-line production of photo-ionised radioactive Yb beams, the laser ion source is now routinely used for over 50% of ISOLDE's beam time. A recent improvement of the selectivity of the laser ionisation is the Laser Ion Source Trap (LIST) [4] approach that integrates a standard target ion source system, the laser ionisation and the ion manipulation. It is based on the photoionisation of the plume of atoms escaping from the high-temperature ISOLDE target-ion source system, subsequent capturing of the ions in a radio-frequency trap and transporting them to the extraction region. While losses in overall efficiencies are encountered, LIST improves the selectivity by about four orders of magnitude [5]. For more details, see the contribution of B. Marsh to this proceedings.

The ions are extracted from the ion-source by 30–60 kV acceleration voltages and directed towards one of the two dipole magnets where they are separated according to their mass, one the so-called General Purpose Separator (GPS) with a mass resolving power, M/Δ M, of more than 1000, and the other, a High Resolution Separator (HRS), whose mass resolution is larger than 5000. Both separators are connected to a common central beam-line system. This allows for the optimisation of the space and the flexibility of operation as the ions can be produced from two different target-ion source units. The GPS can deliver simultaneously other nuclei with mass differences up to ±15% in two dedicated low mass (GLM) and high mass (GHM) beam lines, mainly dedicated to collections and applications in material or life sciences. Fig. 1 shows a recent photo of the ISOLDE facility including the new buildings serving the new superconducting Linac.

In order to broaden its physics scope ISOLDE developed new ways to accelerate the singly-charged radioactive ion beams (RIB) in a universal, fast, efficient and cost-effective way. The post-accelerator, REX-ISOLDE (Radioactive beam EXperiment at ISOLDE), in operation since 2001 is based on ion beam cooling and bunching in the buffer gas of a Penning trap, charge-state breeding in an Electron Beam Ion Source (EBIS) and post-acceleration in a room-temperature linear accelerator. Ion beam cooling and bunching modulates the RIB from ISOLDE into bunches suited for injection in EBIS. The efficient injection of singly-charged ions and extraction of highly-charged ions from EBIS was based on a concept from the Manne Siegbahn Laboratory (Stockholm, Sweden). Finally, the ions are injected into a compact linear accelerator via a mass separator. The normal conducting linear accelerator has a total length of about 11 m. It consists of a Radio Frequency Quadrupole (RFQ) accelerator which accelerates ions from 5 to 300 keV/u, a rebuncher section, an Interdigital H-type (IH) structure that boosts the energy to 1.2 MeV/u, three seven-gap spiral-resonators that bring the energy to 2.2 MeV/u and a 9-gap IH resonator for the final energy. Depending of the active elements a variation of the final energy between 1.2 and 3 MeV/u is possible. Fig. 2 shows the production scheme of post accelerated RIBs at ISOLDE. The accelerator cavities were based on designs from the Max-Planck-Institute for Nuclear Physics (Heidelberg, Germany), the GSI HLI-IH-structure (Darmstadt, Germany) and the lead LINAC at CERN. A thorough technical description of the REX accelerator can be found in [6].

Fig. 1. Picture of the ISOLDE facility with the new buildings that host the compressor, and the cold box of the new superconducting HIE-ISOLDE linac.

While the original goals of the REX-ISOLDE project [7] were limited to energies up to 2 MeV/u and masses below $A = 50$, the concept proved to be very successful and meanwhile beams with A/q ratio <4.5 and with masses up to 220 have been accelerated up to 3 MeV/u, with efficiencies reaching 10%. Most of the beams have been used for Coulomb excitation measurements using a gamma-ray detector array, MINIBALL [9], for low-intensity low-multiplicity RIB experiments or few-nucleon transfer reactions surrounding the target with a dedicated charged-particle detector, T-REX [10]. The main physics outcome of the experiments done at REX is summarised in [8].

2. Recent ISOLDE highlights

The CERN Council approved the ISOLDE facility 50 years ago in December 1964. With more than 47 years of activity, 23 of them at the PS-Booster, ISOLDE is still growing and attracts presently more than 450 researchers working on 90 experiments, with a rate of 50 experiments taking data per year. This radioactive beam facility has pioneered many achievements both at the level of designing new devices and of producing frontier Physics. Over the years the experiments of the ISOLDE facility have produced many valuable results, but year 2013 was really exceptional. Three papers published within a month in Nature journals have crowned the remarkable results obtained along the years. The RILIS team in their quest to find new ionisation schemes was able to measure for first time the ionisation potential of astatine, the least abundant element in nature, by laser ionisation spectroscopy. The discovered series of high-lying Rydberg states enabled a high precision determination of binding energy of the valence electron of the astatine atom. The ionisation potential (IP) was determined to be 9.31751 (8) eV [11].

The total binding energy of a nucleus contains great physics information and precision mass measurements often provide important tests of nuclear models. In the ISOLTRAP setup, the beam from ISOLDE is collected and bunched before being sent to the preparation trap where purification takes place. A detailed analysis of the ion motion in the precision trap shows that the cyclotron resonance of the ion can be determined through the measurement of the time of flight of the ion when ejected from the trap. Recent calculations predicts ^{52}Ca as a new double magic nucleus far from the valley of stability. The magic number character could be

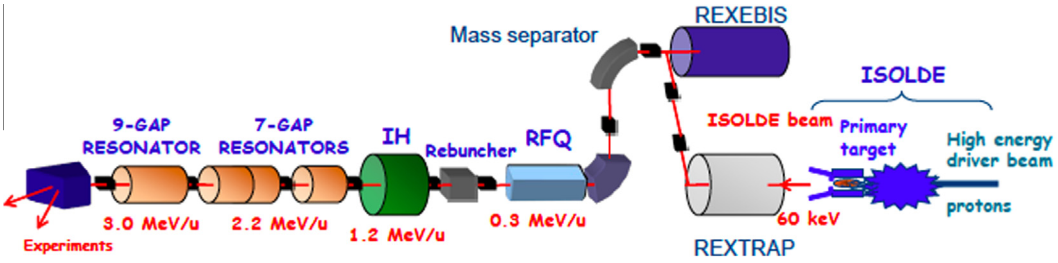

Fig. 2. REX-layout: the singly charged ions from ISOLDE are captured and bunched in a large acceptance Penning trap (REXTRAP) and charge bred in the REXEBIS ion source to an *A*/*q* ratio between 2 and 4.5. The ions are injected into a compact linear accelerator via a mass separator. The normal conducting linear accelerator consists of a Radio Frequency Quadrupole (RFQ), a rebuncher section, an Interdigital H-type (IH) structure, three seven-gap spiral-resonators and a 9-gap IH. The accelerator energy steps are shown in the drawing and detailed in the text.

partially determined by measuring the mass and deducing the two neutron separation energy in the calcium isotopes around $N = 32$. A multi-reflection time-of-flight mass separator (MR-TOF), shown in Fig. 3, was recently designed and installed at ISOLTRAP for outstanding isobaric purification. It gave a suppression of contaminants an order of magnitude better than conventional devices without relevant intensity and time losses. It demonstrated that it can be used for precision mass measurements on nuclides with ms half-lives and minute production rates and as an efficient and sensitive diagnostic station for laser spectroscopy. These developments have lead to the successful determination of the mass of neutron rich calcium isotopes at the verge of existence $^{51-54}$Ca [12]. The determination of the $^{51-52}$Ca masses was done using the ISOLTRAP Penning trap mass spectrometer. The previously mentioned MR-TOF spectrometer was used for the first time for mass determination of the extremely rare short-lived species $^{53-54}$Ca. The binding energies contain information about the ordering of shell occupation, and are essential to explore shell closure in exotic nuclei. These results helped to test of three-body forces in the region, i.e. the subtle components of nuclear forces. Very recently the mass of very neutron-rich, short-lived $^{129-131}$Cd isotopes were measured at ISOLTRAP. The masses of these isotopes are important for calculations of the synthesis of heavy nuclei in explosive stellar environments. Little was known on the exotic isotopes of interest, $^{129-131}$Cd. Only the laser-spectroscopy setup COLLAPS at ISOLDE had determined spins and electromagnetic moments of the $^{107-129}$Cd isotopes observing long-lives isomers in ^{127}Cd and ^{129}Cd [13]. The mass of ^{130}Cd was determined at ISOLDE through beta-decay studies several years ago, but with insufficient accuracy. The ISOLTRAP Penning-trap mass spectrometer succeeded in the determination of the masses of $^{129-131}$Cd isotopes with unprecedented precision. The new measured masses deviate considerably from previous values obtained by beta decay. Due to the waiting-point character of the ^{130}Cd nucleus the new determined mass values have a direct impact on the calculation of the abundances in the $A = 128–132$ region, and show the direction of the r-process towards the birthplace of the heavy elements [14].

The heaviest accelerated REX-ISOLDE beams of Radon and Radium nuclei were employed to investigate shape asymmetric configurations. Strong octupole correlations leading to pear shapes can arise when nucleons near the Fermi surface occupying states of opposite parity with orbital and total angular momentum differing by three units. Pear shape nuclei have enhanced E1 and E3 transitions connecting rotational states of opposite parity. The E1 moments are small and dominated by single-particle and cancellation effects, while the E3 transition moments are collective in behaviour and insensitive to single-particle behaviour. Octupole correlations were studied by the determination of the electric octupole transition strengths in ^{220}Rn and ^{224}Ra. The E3 moment is an observable that provides direct evidence for enhanced octupole correlations for deformed nuclei. The measured E1, E2 or E3 transitions for ^{220}Rn and ^{224}Ra allowed the determination of the reduced matrix elements and the intrinsic moments. The measurement done at REX-ISOLDE using the MINIBALL setup showed that ^{220}Ra nucleus has Q_3 values typical of an octupole vibrator, while the Q_3 values obtained for ^{224}Ra gives convincing evidence that this nucleus is of quadrupole–octupole shape in its ground state [15].

3. The HIE-ISOLDE project

Radioactive nuclear beams are given a high priority in the present planning of future nuclear physics facilities on all continents. The HIE-ISOLDE upgrade (HIE stands for High Intensity and Energy), intends to improve the experimental capabilities at ISOLDE over a wide front [16]. The main features are to boost the energy of the beams, going in steps from currently 3 MeV via

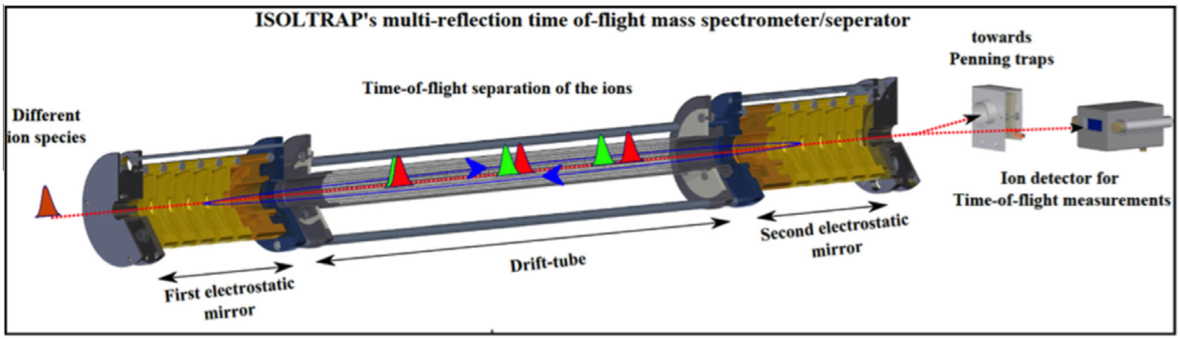

Fig. 3. View of the multi-reflection time-of-flight (MR-TOF) mass spectrometer used to clean isobaric contaminations by multiples reflection between two electrostatic mirrors. The very reduced losses in the multiple reflection process allows for a good separation of different isobars without losses in yield. This device can be used to determine masses connected to the ISOLTRAP as it has been the case for $^{51-52}$Ca or once calibrated for direct mass measurements as it has been the case of $^{53-54}$Ca [12]. Courtesy of F. Wienholtz.

5.5 MeV to finally 10 MeV per nucleon, and to increase roughly six-fold the production due to an increase in intensity and energy of the proton injector as previously discussed. In addition improvements in several aspects of the secondary beam properties such as purity, ionisation efficiency and optical quality are addressed in the project, see Fig. 4. Major project components include a new superconducting (SC) linear accelerator (LINAC) based on Quarter Wave resonators (QWRs) for the post-acceleration and the necessary 4.5 K cryogenic station for helium. The decision to keep the existing experimental hall has imposed severe constraints on the LINAC, so it has been necessary to design and build accelerating cavities with a very high voltage gradient of 6 MV/m and low heat dissipation below 10 W. The superconducting accelerator part dedicated to the increase of energy is based on a quart wave resonator (QWR) geometry with twenty high-β cavities cooled by helium and installed in four cryo-modules. The transverse focusing is achieved using four superconducting solenoids housed inside the cryo-modules maximising the transverse acceptance. Each cryo-module contains five cavities based on 101.28 MHz niobium-sputtered copper (Nb/Cu) Quarter Wave Resonator and one solenoid, see Fig. 5. shows a photo with the internal elements of the cryo-module already mounted including the five cavities, the He-vessel, the solenoide. . .etc. The first two cryo-modules with five high-β cavities each will permit to increase the energy to 5.5 MeV/u for $A/q = 4.5$ and constitute the first phase of the project. The first cryo-module was installed at ISOLDE in May. Hardware commissioning of the first cryo-module of the HIE-ISOLDE superconducting linac has been now ongoing for the last 3 months. The results of the tests validate the cryogenics, vacuum, alignment aspects, and the performance of the superconducting elements. We have plans to exchange the normal conducting linac by low-β cavities in the near future. Two beam lines are already operative for physics and a third beam line will be built next year.

3.1. First experiments at HIE-ISOLDE

The first call for proposals was made in October 2012. So far thirty experiments have been approved with more than six hundred 8 h shifts allocated for day-one physics. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE, where the increase in energy of the radioactive beams will enhance the cross section in most of the cases and the accessibility to detail nuclear structure information at higher excitation energy.

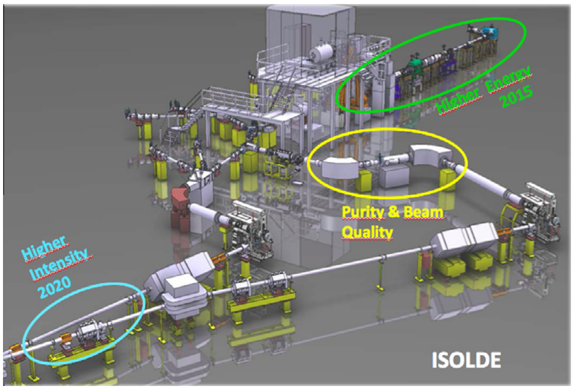

Fig. 4. 3D drawing of the core of the ISOLDE facility showing the target-ion source unit connected to each mass separator as well as the post accelerator line. The expected upgrades of the facility are indicated: Increase in intensity and energy of the injector in 2020; increase of the post-accelerator beam from 4.3 MeV/u this year to 10 MeV/u in 2017. Improvements of the beam purity and quality are a continuos effort of the technical team.

Fig. 5. Photo of the elements inside the cryo-module vessel and thermal shield, the five cavities clearly visible.

In the light nuclear region, reaction studies of astrophysical interest such as the search for high-excited states in ^{8}Be to address the cosmological ^{7}Li problem. Nuclear structure studies are planned to characterise cluster structure in ^{10}Be by transfer reaction. Characterisation of resonant states in the proton-rich nucleus ^{21}Al will be determined by resonance elastic and inelastic scattering using the active target MAYA in order to check isospin conservation beyond the drip line. For middle mass nuclei, the validity of a shell model description around ^{78}Ni will be studied as well as shape coexistence in the region $A = 70–80$ will be determined with high precision. Statistical properties of warm nuclei will be investigated by the low-energy enhancement of the gamma strength function of neutron-rich nuclei. For heavier mass nuclei, quadrupole and octupole collectivity will be addressed in the neutron-rich Te, Xe and Ba isotopes by Coulomb excitation, lifetime measurements and magnetic moment determination. Collective effects around the double magic ^{132}Sn will also be studied. For heavy nuclei, shape coexistence in the light Pb isotopes will be explored. Measurements of octupole collectivity in the Rn and Ra nuclei using Coulomb excitation will continue. In the quest of super-heavies, it is proposed to investigate the influence of the predicted shell closures at $Z = 120$ and $N = 184$ by probing the height of the fission barrier in the compound nucleus. This will be achieved by exploring the contributions of quasi-fission and fusion-fission reactions; in particular by the use of the reaction of the deformed ^{95}Rb beam on a ^{209}Bi target is expected to permit the study of these features.

The proposed studies will be realised with the existing workhorses MINIBALL [9] and T-REX [10] plus new instrumentation for transfer reaction studies such as the active targets MAYA [17] and the future ACTAR, a new general purpose scattering chamber, the two arms CORSET setup from GSI. . .etc. The MINIBALL array will be complemented with an electron spectrometer, SPEDE, to realise Coulomb excitation studies of odd-heavy nuclei.

Three experiments are planned for year 2015. The nuclear studies approved for physics at HIE-ISOLDE are shown in red in the chart of the nuclides displayed in Fig. 6. We will start with the study of the evolution of the nuclear structure along the zinc isotopic chain close to the doubly magic nucleus ^{78}Ni. It is proposed to probe recent shell-model calculations in this area of the nuclear chart. Excitation energies and connecting B(E2) values will be measured with MINIBALL through multiple Coulomb excitation

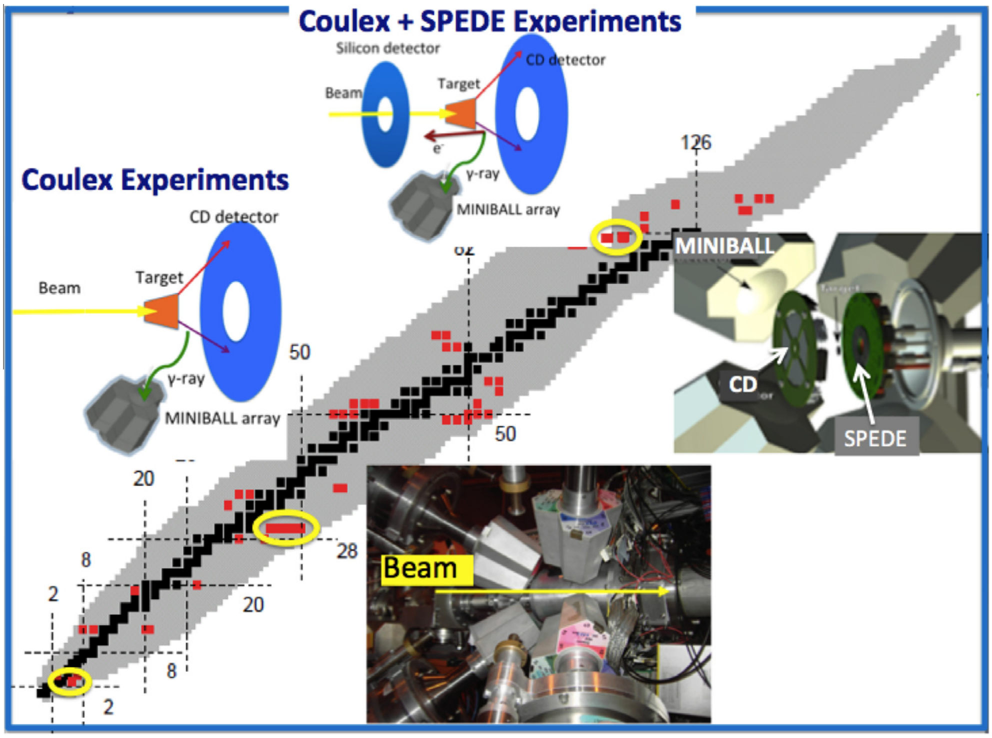

Fig. 6. The nuclear chart shows in red the cases already approved for nuclear studies at HIE-ISOLDE. Indicated with a circle the first physics cases that will be studied. In 2015 the n-rich Zn isotopes are studied with MINIBALL. Later on the neutron defficient Hg isotopes will be studied with MIiniball and complemented with the electron spectrometer, SPEDE, and in the second beam line transfer reaction with a ^{9}Li beam.

experiment with laser ionised purified beams of $^{74-80}$Zn. Combining MINIBALL with the electron spectrometer SPEDE will allow' complete studies of Coulomb excitation in the heavy nuclei. To learn about the interplay between individual nucleon behaviour and collective degrees of freedom manifested in shape coexistence in the neutron deficient lead region, we will perform Coulomb excitation on light mercury isotopes to probe their excited states and determine the transitional and diagonal E2 matrix elements. The second experimental beam line will be used to explore resonant states in ^{11}Li by transfer reaction with ^{9}Li beams. The implementation of a storage ring [18] is highly supported by the CERN Scientific Policy Committee due to its scientific potential. We intend to install the heavy-ion, low-energy ring TSR from Heidelberg served by the 10 MeV/u beam from HIE-ISOLDE. Such a device will allow the realisation of experiments with stored secondary beams, which will be unique in the world. The physics programme with the TSR is rich and extending from investigations of nuclear ground states properties and reaction studies of astrophysical relevance to unique investigations with highly-charged ions and pure isomeric beams. An implementation study was done by CERN. A large STFC grant has been obtained by our British colleagues to equip the TSR with internal detection system. They will also built a HELIOS-type spectrometer that will be placed in the third beam line of ISOLDE and later on at the extraction line of the TSR.

4. Summary and outlook

The future of ISOLDE is bright. ISOLDE restarted with the low energy physics program the first of August 2014. The knowledge accumulated over decades on how to construct targets and ion sources tailored to release pure beams of specific elements are one of ISOLDE's strong points. With more than 50 years since approval ISOLDE remains as the pioneer ISOL-installation both at the level of designing new devices and production of frontier physics. The first phase of HIE-ISOLDE will start for physics this autumn. The physics cases approved expand over the wide range of post-accelerated beams available at ISOLDE with more than six hundred shifts approved for day one physics. Our first experiment will explore the evolution of nuclear structure near ^{78}Ni by performing multi-step Coulomb excitation in n-rich Zn isotopes. We expect to complete the increase of energy of post accelerated beams up to 10 MeV/u in 2017.

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