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ISOLDE highlights and the HIE-ISOLDE project

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Abstract. The ISOLDE facility has as objective the production, study and research of nuclei far from stability. Exotic nuclei of most chemical elements are available for the study of nuclear structure, nuclear astrophysics, fundamental symmetries and atomic physics, and for applications in condensed-matter and life sciences. The most recent highlights are presented. The on-going upgrade, the HIE-ISOLDE project, is discussed. HIE-ISOLDE aims to improve the ISOLDE capabilities in a wide front, from an energy increase of the post-accelerated beam to improvements in beam quality and beam purity. The first phase of HIE-ISOLDE will start for physics in the autumn of 2015 with an upgrade of energy for all post-accelerated ISOLDE beams up to 5.5 MeV/u. The proposed day-one experiments are summarized.

1 The ISOLDE Facility

The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams for many different experiments in the fields of nuclear and atomic physics, materials science and life sciences. The facility is located at the Proton-Synchrotron Booster (PSB) of the European Organization for Nuclear Research, CERN. The radioactive nuclei are produced in reactions of 1.4 GeV protons in thick targets. The beam delivered by the PSB injector is pulsed and contains up to 3.10^{13} protons/pulse with a spacing of 1.2 s or more, giving a typical average proton current on target of 2μA [1]. The use of high-energy protons such as the ones delivered by the CERN PSB injector has been recognized to be optimum for the production of radioactive nuclei. More than 20 different target materials and ionizers are in use. The target material is kept at a temperature between 1000 and 2000 degrees so that the radioactive atoms produced diffuse out of the target into different dedicated ion sources. Ionization can take place in a 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 isotopes of more than 70 of the chemical elements. The knowledge accumulated over decades on how to construct targets and ion sources tailored to release pure beams of specific elements is one of ISOLDE's strong points. The ions are extracted from the ion-source by 30-60 kV acceleration voltages and directed towards an electro-magnet where they are separated according to their mass. Currently ISOLDE is able to deliver more than 700 isotopically pure beams with intensities ranging from 1 to more than 10^{10} ions/s. ISOLDE has two isotope separators on-line with independent target-ion source systems. The general purpose separator (GPS) has a mass resolving power, M/ΔM, of more than 1000 while the one of the high resolution separator

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(HRS) exceeds 5000. The GPS and the HRS separators are connected to a common beam-line system as displayed in figure 1.

The post-accelerator, REX-ISOLDE, in operation since 2001, has opened new fields of research in particular in reaction studies of light-medium mass nuclei with energies up to 3 MeV/u. A thorough technical description of the REX accelerator can be found in [2]. Put briefly 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 3 and 4.5. The higher charge of the beam allows it to be efficiently accelerated in a compact linear accelerator. REX is being upgraded (HIE-ISOLDE) to provide a maximum energy of 5.5 MeV/u in 2015, see section 3. Post-accelerated radioactive beams of 5.5 MeV/u will allow reaching the Coulomb barrier threshold for a wide range of nuclei. In a second phase of HIE-ISOLDE energies up to 10 MeV/u for the radioactive beams will be obtained.

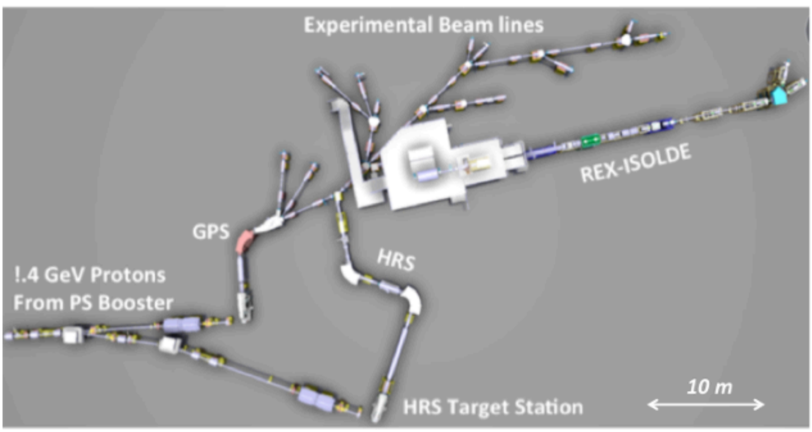

Figure 1. The main elements of the ISOLDE facility are shown. The high intensity (3.10^{13}/pulse) and high energy (1.4 GeV) proton beam from the PS Booster of CERN is directed to one of the two target-ion source units for the production of radioactive species. The out coming 1^+ ions are mass separated in A/Q either in the HRS or in GPS magnets and injected into the main beam line. The 60 KV beam is directed to the different low energy experiments or post-accelerated in REX-ISOLDE.

2 ISOLDE Highlights

After 45 years of activities, 20 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.

2.1 Use of nuclear probes for other science domains

Many science questions within nuclear physics and areas that use nuclear probes are addressed with low-energy radioactive beams. Due to the limited space I will concentrate this report on a few recent highlights in nuclear physics.

The RILIS team in their quest to find new ionization schemes has been able to measure, for the first time the ionization potential of astatine by laser ionization spectroscopy. The observed series of Rydberg states enabled a high precision determination of the ionization potential of the astatine atom to be 9.31751(8) eV [3].

An important workhorse of the facility and an example of the wider use of traps is the WITCH experiment dedicated to search for physics beyond the standard model by measuring deviations in the electron-neutrino distribution of the ^{35}Ar decay [4]. The aim is to be sensitive to deviations in the asymmetry parameter in the order of 0.5 %.

One has to emphasize that the ISOLDE facility is a perfect place for carrying out experiments with Perturbed Angular Correlation of γ-rays (PAC) spectroscopy and it has a long standing experience due to its use for material science. With this technique, problems such as: heavy metal ions - protein interaction, dynamics of protein folding or protein – protein interaction can be addressed. Furthermore, just recently β-NMR spectroscopy was successfully applied on liquid samples in the world's first experiment, an achievement, which opens new avenues of research in the fields of biophysics [5].

In the domain of solid-state physics, understanding of the magnetic behaviour of spintronic materials has recently been achieved at ISOLDE. In these materials the spin of the electron is manipulated instead of its charge to build potentially faster and smaller devices [6].

2.2 Basic properties of the Cd isotopes: spins, electromagnetic moments and isomers

One of the main advantages of an ISOL-type facility is that one can do a systematic study of the ground state properties of a certain element and study how these properties change by adding an extra neutron. Magnetic dipole and electric quadrupole moments are fundamental properties of nuclei that can provide stringent tests of nuclear models.

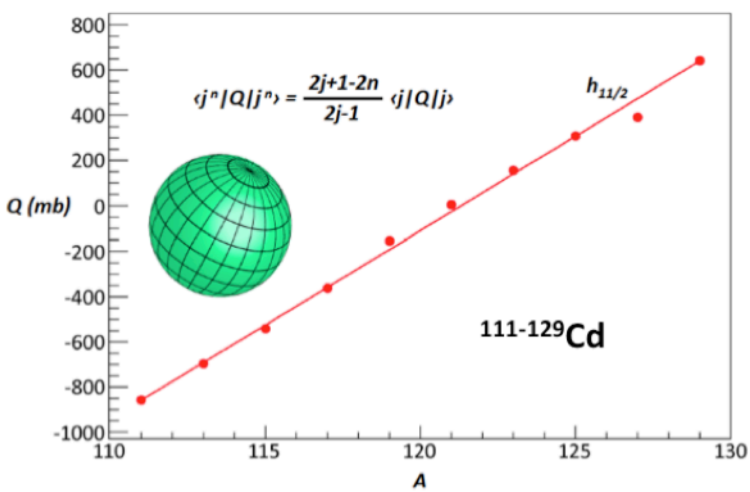

Figure 2. The quadrupole moments for the $^{111\text{-}129}Cd$ isotopes are shown. The linear dependence is most striking. The formula given for seniority ν = 1 follows the de-Shalit and Talmi formalism [12] for an even term or seniority-conserving operator (here, the quadrupole moment).

The experimental determination of nuclear radii and nuclear moments [7] has been for many years a major activity at ISOLDE [8]. The nuclear properties are deduced from accurate laser spectroscopy measurements of the hyperfine atomic spectrum. The systematic measurement of nuclear moments along an isotopic, isotonic or isobaric chain is a powerful tool to extract nuclear structure changes. A recent example is the measurement of the individual hyperfine spectra of the cadmium isotopes (Z = 48) spanning over twenty masses, A = 107 to 129. The atomic spectra of the cadmium ions have common atomic features but differ in the nuclear magnetic and quadrupole moments that influence the hyperfine structure of each isotope. Yordanov et al. [9] have observed (see figure 2) that in spite of the complexity of the nuclei studied, the quadrupole moments of the nuclear state $h_{11/2}$ exhibit a linear behaviour with changing neutron number. The unpaired neutron in the $11/2^-$ state in each of the odd-mass cadmium isotopes behaves nearly the same way.

The linear behaviour of the $11/2^-$ quadrupole moments, shown in figure 2, for ten odd-mass isotopes, is the most relevant feature of the cadmium isotopes. This behaviour is most probably due to the unique parity of the $h_{11/2}$ orbit. The formula given in figure 2 follows the de-Shalit and Talmi formalism [10] for seniority $\nu = 1$ where all but one particle are coupled to spin zero. The fitting parameters are Q_{sp} = -667(31) mb and Q_{const} = -85(8) mb, where the offset term, Q_{const} represents a constant quadrupole moment contribution from correlations with the core. This behaviour was thought to occur only when protons or neutrons were in closed shells and therefore inactive. The results of the cadmium isotopes indicate that such simplicity for the neutrons has survived although cadmiun does not have a magic number of protons. This is one more proof of the validity of nuclear shell model and the pairing force. The fact that the line crosses zero around the middle of the $h_{11/2}$ shell indicates the spherical shape for the $11/2^-$ states. One should notice that the deviation from the straight line in ^{127}Cd indicates a change in shape consistent with the abnormal energy of the first 2^+ state for the even isotopes ^{126,128}Cd reported in [11]. Further long-lived $11/2^-$ states are identified in ^{127}Cd and ^{129}Cd for the first time. This is a recent example of how advanced laser spectroscopy provided access to the properties of very exotic nuclei.

2.3 Mass Measurements: From testing magic numbers to the crust of neutron starts

The mass of a nucleus is, together with its half-life and decay modes, the first quantity to measure. The total binding energy of a nucleus contains great physics information and precision mass measurements often provide important tests of nuclear models. The ISOLTRAP mass measurements have successfully pioneered other precision mass measurements established nowadays worldwide [12]. 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. Among the new highlights one should mention the determination of the masses of ^{82}Zn and $^{51-54}$Ca where a new device the multi-reflection time of flight (MR-ToF) spectrometer, has been incorporated either for cleaning the beam from more intensively produced isobars or directly for measurement of the mass.

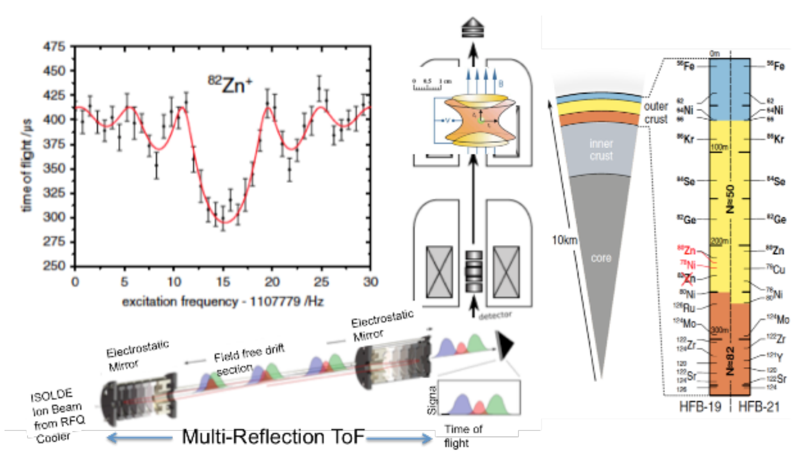

Figure 3. Partial view of the ISOLTRAP setup that includes the new Multi-Reflection-ToF device, the purification and precision traps and the MPC for the Time-of-Flight ion detection. On the top-left the ToF resonance spectrum of ^{82}Zn ions is shown. On the right the depth profile of a neutron star of 1.4 solar mass and 10 km radius, taken from [13].

The long sought-after mass of the neutron-rich atomic nucleus ^{82}Zn was finally measured at ISOLTRAP. The production and selectivity of ^{82}Zn ions combined a great part of the ISOLDE technical know-how: neutron-converter, quartz transfer line and laser ionization with the new time of flight purification spectrometer (MR-ToF) that was installed upstream from the Penning traps. The ^{82}Zn mass is important for nuclear structure, as it is two protons and two neutrons away from double magic ^{78}Ni, and as input to astrophysical models for probing the elemental composition of neutron stars, enlightening the evolutionary history of elements and the elemental abundance in the Universe. Using a robust neutron star model, the value of the newly determined ^{82}Zn mass alter and restrict the composition profile of the star crust [13]. Figure 3 shows a partial view of ISOLTRAP device with the newly incorporated MR-ToF, the ToF resonance spectrum of ^{82}Zn ions and the predictions of the composition in the outer crust of a neutron star using nuclear energy density functional theory. The new ^{82}Zn mass value changes the position in depth of ^{80}Zn and enhances the relevance of ^{78}Ni versus the newly measured ^{82}Zn [13].

The study of calcium isotopes with two double magic isotopes is always a good test ground for shell model. Calcium isotopes with a closed proton shell mark the frontier of applicability of 3-nucleon forces from chiral effective field theory [14]. The objective of this measurement was to map the masses below and above N= 32 to properly characterize this new magic number for very neutron rich nuclei. The masses of ^{51}Ca and ^{52}Ca were measured previously at TRIUMF [15] by the TITAN trap group confirming the expected new magic number far from stability, N=32. At ISOLDE these masses were revisited getting compatible mass values but much more accurate due to the higher yield. The MR-ToF device was used to go beyond the double magic nucleus and determine the mass of ^{53}Ca and ^{54}Ca. These measurements demonstrate the feasibility of precision mass measurement at the production level of 10 atom/s. The results, which match surprising well the predictions of 3-body forces, increase our understanding of neutron-rich matter and were published recently in Nature [16]. More details can be found in the contribution to this issue of S. Kreim.

2.4 Physics with accelerated beams

After a decade of physics with post-accelerated beams [17] I will mention examples of the two major type of experiment done so far.

In the energy range up to 3 MeV/u many reactions take place at or below the Coulomb barrier, so the main reaction mechanism is Coulomb excitation. The electromagnetic interaction is well understood and it is used as a probe of nuclear structure from the sub-barrier energies in Coulomb excitation experiments, “safe Coulex”. This technique has experienced a renaissance in the last decade with the availability of post-accelerated beams. The key ingredient in these experiments is the gamma detection, and at ISOLDE this is done with the Miniball gamma-detector array [18]. Gamma-ray and particle spectroscopy of excited states was pushed forward with the MINIBALL/T-REX detector system[18,19]. The shape transitions from spherical to deformed nuclei were elucidated in extreme neutron rich Krypton, Rubidium and Strontium nuclei. Contrary to previously published results [20] no sudden onset of deformation is observed. This new experimental result is supported by a new proton-neutron interacting boson model calculation [21].

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 occupy states of opposite parity with orbital and total angular momentum differing by $3\hbar$. Pear shaped nuclei have additional E1 and E3 transitions connecting rotational states having 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 moments are an observable that should provide 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. Although the E2 moment increases by a factor of 6 from ^{208}Pb to ^{334}U, the

E3 moment only changes by 50% in the same region. The large values of Q_3 measured for ^{220}Rn and ^{224}Ra point to an enhancement of octupole collectivity indicating the onset of octupole deformation in this region. While ^{220}Ra has Q_3 values typical of an octupole vibrator the Q_3 values obtained for ^{224}Ra gives convincing evidence that this nucleus is of quadrupole-octupole shape in its ground shape. Beyond the important input for models treating octupole deformation one can deduce from these data that ^{219,221}Rn candidates for atomic EDM measurements will not be adequate due to the expected similar or weaker octupole collectivity than ^{220}Rn. These results are summarized in a recent Nature paper [22].

Elastic, inelastic scattering, and transfer reactions yield important and unique information in the structure of exotic nuclei. At REX-ISOLDE the beam energies restricted the studies to the light nuclei. Experiments were performed near the drip-lines where new phenomena were uncovered in the last decade. Elastic Cross sections of halo nuclei near a strong electric field drastically changed at energies near the Coulomb barrier due to the loose character of the last nucleons. The elastic cross section of ^{11}Be and its core ^{10}Be was measured for the first time at ISOLDE [23]. The neutron transfer reaction of ^{9}Li+^{2}H was used to study ^{8}Li and to explore the unbound structure of ^{10}Li [24], and the ^{11}Be(d,p) reaction to characterize the excited states of ^{12}Be using Miniball for gamma detection [25]. Further the two-neutron transfer (p,t) reaction was used to characterize the 0^+ excited state of the island of inversion central element, ^{32}Mg. The shape coexistent excited 0^+ state in ^{32}Mg was identified by the characteristic angular distribution of the protons of the ΔL=0 transfer. The 1058 keV excitation energy of the 0^+ excited state was much lower than predicted by any theoretical model [26].

3 ISOLDE UPGRADE: HIE-ISOLDE project

Radioactive nuclear beams have a high priority in the planning of nuclear physics facilities worldwide. The HIE ISOLDE upgrade (HIE stands for “High Intensity and Energy”), intends to improve the experimental capabilities at ISOLDE over a wide front [27]. The main features are to boost the energy of the beams, going in steps from currently 3 MeV/u via 5.5 MeV/u to finally 10 MeV/u, and with a roughly fourfold increase in intensity. In addition improvements in several aspects of the secondary beam properties such as purity, ionization efficiency and optical quality are addressed.

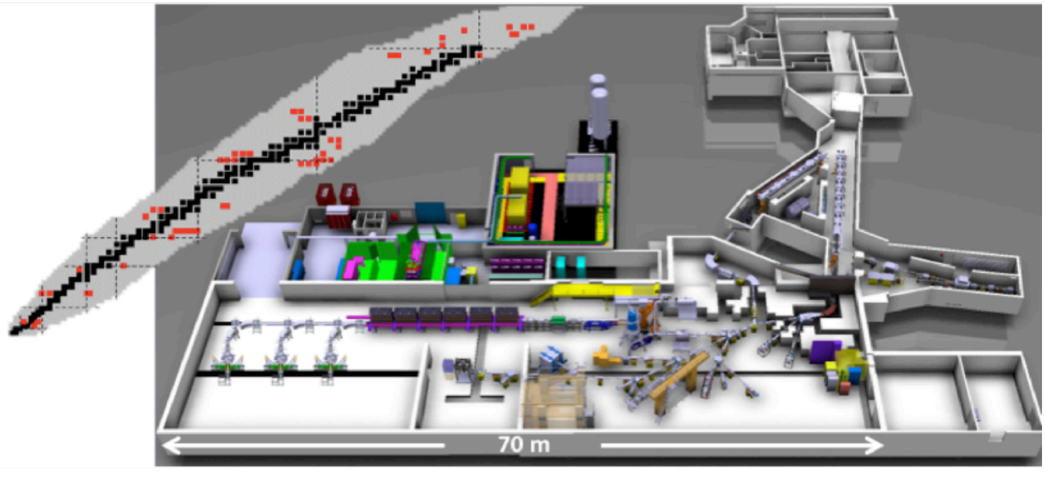

Figure 4. Layout of the ISOLDE facility seen from Jura side. It displays the existing experimental lines for low energy physics and includes the new parts: the HIE-ISOLDE Linac, the newly planned three beam lines and the two extra buildings recently finished. The new buildings house the helium compressor station, cryogenic equipment and ventilation units in one, and the helium cold box and the cryogenic control room in the other as schematically shown. On the left the chart of nuclei illustrates in red the nuclei proposed to be studied at HIE-ISOLDE in day-one experiments.

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 remain with the existing experimental hall has imposed size 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.

Prototype testing for the cavities and other major linac components have been completed. The RF SC cavities have recently surpassed the foreseen specification of 6 MV/m at 10 W and they are ready for series production. The procurement procedures for cooling and ventilation are put in place. The civil engineering work is finished.

The superconducting accelerator is based on two QWR geometries: twenty high-β and twelve low-β cavities cooled by helium and installed in six cryomodules providing a total effective acceleration voltage of 39.4 MV. The transverse focusing is achieved using eight superconducting solenoids housed inside the cryomodules maximising the transverse acceptance. The high-β cavities are grouped into four cryomodules of five cavities and one solenoid each. The first two cryomodules with ten high-β cavities will permit to increase the energy to 5.5 MeV/u and constitute the first phase of the project.

The beam diagnostic allows for the measurement of the beam current along the different elements to optimize the transmission. Two types of diagnostic boxes are considered -six in between cryomodules followed by larger ones downstream in the beam-line. The diagnostic boxes have a modular design with six ports available for different devices: faraday cage, scanner… to be placed in an octagonal shape. The beam transfer line is designed to deliver beams of a large variety of energies from 0.45 MeV/u to 10 MeV/u to three experimental stations. The three experimental beam lines are identical and are placed at 90º to the Linac. In each beam line two magnetic dipoles bend the beam 45º with a quadrupole in between to steer the beam through 90º double-bend-achromat lattices towards the experimental stations. Figure 4 shows the layout of the ISOLDE facility including the HIE-ISOLDE Linac and the two extra buildings, see explanations in the caption.

The experimental equipment will undergo extensive transformation during the present shutdown of the CERN accelerator complex to commit to the new physics challenges [28]. The first call for proposal was made in October 2012. So far thirty-five experiments have been proposed of which 22 have been approved 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 detailed nuclear structure information at higher excitation energy. In the light nuclear region, reaction studies of astrophysical interest such as the search for high-excited states in ^{8}Be is planned to study the cosmological ^{7}Li problem. Nuclear structure studies are planned to characterize cluster structure in ^{10}Be by transfer reaction or unbound states in the proton-rich nucleus ^{21}Al by resonance elastic and inelastic scattering using an active target. For middle mass nuclei, the validity of a shell model description around ^{78}Ni will be studied and 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 be studied. For the heavier 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. This will be achieved by exploring the contributions of quasi-fission and fusion-fission reactions; in particular 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 [18] and T-REX [19] plus new instrumentation for transfer reaction studies such as the active targets MAYA and the future ACTAR, a new general purpose scattering chamber, the two arms CORSET setup from GSI, and a HELIOS-type solenoidal spectrometer.

The implementation of a storage ring [29] is highly supported by the CERN management. We intend to setup the heavy-ion, low-energy ring TSR from Heidelberg. Such a device will allow the realization of experiments with stored secondary beams, which will be unique in the world. The physics program with the TSR is rich and large in scope expanding 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 has been done for CERN, hoping to get the first stored beams coinciding with the installation of the second phase of HIE-ISOLDE.

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