Recent Highlights of the ISOLDE Facility

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Abstract. The on-line isotope mass separator ISOLDE is the radioactive beam facility of CERN. Its objective is the production 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. A description of the facility, some recent results and future plans are presented here.

1. Introduction

The ISOLDE facility is one of the World-leading laboratories for the production and investigation of radioactive nuclei and has the World largest ISOL-production of radioactive nuclei. It is able to produce and deliver one thousand three hundred different nuclei of which seven hundred has been used for physics. This large variety of radioactive ion beams is used for many different experiments in the fields of nuclear and atomic physics, materials science and life sciences. The facility was approved fifty years ago, the 19th of December 1964 by the Council of the European Organization for Nuclear Research, CERN. It started operation three years later. Presently the facility is located at the Proton-Synchrotron Booster, PSB, of the CERN accelerator complex. The radioactive nuclei are produced in reactions of 1.4 GeV protons from PSB into thick targets. The beam delivered by the PSB injector is pulsed and contains up to 3.10^{13} protons/pulse with a minimum spacing of 1.2 s, giving a typical average proton current on target of 2 μA [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. Higher energy of the protons, 2.0 GeV, is expected in 2020 gaining up to a factor of 5 in the deep spallation process, therfore favouring the production of neutron deficient heavy nuclei.

The success of ISOLDE is due to the continuous development of new radioactive ion beams and to the improvement of the experimental conditions. More than 20 different target materials and ionizers are in use. The target material is kept at a temperature between 1000 and 2000 degree Celsius so that the radioactive atoms produced diffuse out of the target into different dedicated ion sources. Ionization 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 isotopes of, at the moment, 72 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 are 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. ISOLDE has

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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 resolution of the High Resolution Separator (HRS) exceeds 5000. Figure 1 shows the main elements of the ISOLDE facility.

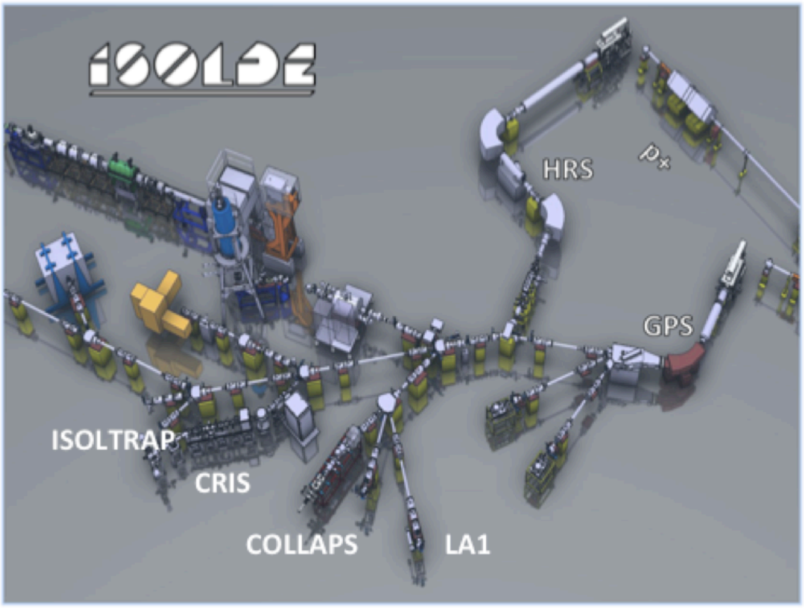

Figure 1. The main elements of the ISOLDE facility are shown. The high intensity (3.10^{13}/pulse) and high energy (1.4 GeV) proton beam from the PS Booster of CERN is directed to one of the two target-ion source stations for the production of radioactive species. The out coming 1^+ ions are mass separated in A/Q either in the HRS or in the GPS magnets and injected into the main beam line. The 60 keV beam is directed to the different low energy experiments such as LA1 for movable experiments, COLLAPS and CRIS for hyperfine structure studies, ISOLTRAP for mass measurements or post-accelerated at HIE-ISOLDE.

The installation of the post-accelerator REX-ISOLDE opened up thirteen years ago new fields of research with radioactive ion beams of higher energies. REX-ISOLDE has made used of the large variety of radionuclides that were extracted from the on-line mass separators GPS and HRS covering the whole mass range from He to U for reaction studies and Coulomb excitation with energies up to 3 MeV/u. REX-ISOLDE used the method of charge-state breeding to enhance the charge state of the ions before injection into a compact linear accelerator. The radioactive singly-charged ions from the separators were first accumulated, bunched and cooled in a Penning trap, REXTRAP. The trap stored the ions during the breeding in the subsequent charge breeder. Bunches of ions were then transferred to an electron beam ion source, REXEBIS, where the ions are charge bred to a mass-to-charge ratio between 2 and 4.5. Finally, the ions were injected into a compact linear accelerator. More details can be found in [2]. The efficiency of the system varied from 5 to 20 %. REX operational since 2001 has accelerated over 100 isotopes of more than 30 different elements.

To increase the energy a superconducting linear accelerator, which is due to start operation in 2015, is under construction downstream the normal conducting accelerator, HIE-ISOLDE project. The first phase of the HIE-ISOLDE project will provide beams accelerated to an energy of 4.3 MeV/u in 2015 and 5.5 MeV/u at the start of 2016. Post-accelerated radioactive beams of 5.5 MeV/u will allow reaching the Coulomb barrier threshold for a wide range of nuclei facilitating multi-step Coulomb excitation in the full mass range. In a second phase of the HIE-ISOLDE project energies up to 10 MeV/u for the radioactive beams will be obtained. This energy will allow to do scattering studies mainly transfer reaction studies in a wide mass range.

2. Recent Highlights from ISOLDE

In the following some of the recent highlights of ISOLDE will be presented covering examples from light to heavy nuclei and concentrating in ground state properties and exotic decay modes.

2.1. Observation of beta-delayed protons in the neutron rich halo nucleus ^{11}Be

Close to the beta-stability line all beta-decays will populate particle bound states, i.e. states that are long lived (stable, beta or gamma decaying) and therefore have narrow widths, less than 1 keV. Moving towards the driplines a larger and larger fraction of beta-decays will feed states that are unbound for the proton emission in the neutron deficient side and neutron emission in the neutron rich side or alpha emission that is possible in both sides of the valley of stability. Further close to the dripline beta-delayed particle emission become often the dominating decay mode. A general overview of the different decay modes and their impact on the knowledge on nuclear structure near the drip line and beyond can be found in recent reviews [3, 4]. At the same time β^- decay and proton emission take a nucleus in almost opposite directions on the nuclear chart, so β^--delayed proton emission, β^-p, is forbidden in all but a few nuclei where is highly suppressed as the available energy is $Q_{\beta\text{-}p}$ = 782 keV – S_n, being S_n the neutron separation energy. This new decay mode only possible for nuclei with very low S_n energy, has been recently observed at ISOLDE in the decay of ^{11}Be. The low decay energy implies that the branching ratio for this decay mode is very low and it is estimated for the most favourable case, ^{11}Be, to be around 10^{-8} [6].

The β^-p decay mode is expected in 1n-halo nuclei due to both energetics and to the more pronounced single-particle behavior of haloes. Two neutron halo nuclei were similarly candidates for β^-d emission and indeed this decay mode has been observed in ^{6}He and ^{11}Li with branching ratios of 10^{-6} and 10^{-4} respectively [4].

To investigate the new decay mode, β^-p, in the more favorable case ^{11}Be one has to face the difficulty of detecting protons of maximum energy of 280.7(3) keV with a very reduced branching ratio. Therefore the idea is to produce a very intense and pure sample and search for the β^-p daughter with a level of sensitivity better than 10^{-8}. Considering that the half-lives of ^{11}Be and the β^-p daughter, ^{10}Be, are very different respectively 13.8 s and 1.5x10^6 y one can consider to make a sample and sending it to a state of art accelerator mass spectrometry (AMS) device that have the required sensitivity.

A first attempt was made in 2001 but the signal was not strong enough and a β^-p branching ratio of 2.5(25)x10^{-6} was obtained [5]. Although compatible with zero this result meant that the branching ratio could be higher than theoretically expected. Due to the improvements in the production of ^{11}Be at ISOLDE and a higher sensitivity in the AMS detection of ^{10}Be, the experiment was tried again in 2012. Samples of ^{11}Be and the possible contaminant ^{11}Li were collected. The activity produced was monitored by the measurements of the gamma activity connected to the respective decays. The ^{10}Be AMS measurements were performed at the Viena Enviromental Research accelerator (VERA). The branching ratio of the β^-p decay mode in ^{11}Be was determined by detecting the number of final nucleus ^{10}Be obtained by the AMS method with respect to the deduced number of ^{11}Be ions collected in the original sample. The branching ratio was of 8.3(9)x10^{-6} [6]. This branching ratio is astonishing large but consistent and of the same order of magnitude that the previous measurement [5]. This unexpected high rate can only be understood if one assumes that the decay proceeds through a new very narrow resonance in ^{11}B. The B_{GT} could reach a value of 3, which correspond to a free neutron decay. A natural interpretation will be then in terms of a peripheral beta decay of the halo neutron in ^{11}Be into a single proton state.

2.2. Confirmation of magicity in the calcium isotopes at N=32 and N = 34

A pioneering work done at CERN thirty years ago [7] indicated that the magic numbers of neutrons and protons corresponding to closed shells could loose their special character due to the proton-neutron asymmetry. It is since then a great challenge for theory to predict the new magic numbers emerging far from stability, and closely related, to understand the different components of the strong force that acts between neutrons and protons.

The mass of a nucleus is together with its half-life and decay modes the first quantity to measure and reveals the strength of nuclear binding. The total binding energy of a nucleus contains great physics information and precision mass measurements often provide important test of nuclear models. The ISOLTRAP mass measurements have successfully pioneered other precision mass devices established nowadays worldwide [8]. 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.

The study of calcium isotopes with two double magic isotopes is always a good test ground for shell model. At the same time calcium isotopes with close proton shell mark the frontier of applicability of 3-nucleon forces from chiral effective field theory. The magic number character could be partially determined by measuring the mass and deducing the two neutron separation energy in the calcium isotopes around N = 32.

At ISOLDE the objective 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 [9] by the TITAN trap confirming the expected new magic number far from stability, N=32. At ISOLDE these masses were revisited using ISOLTRAP for $^{51\text{-}52}$Ca getting compatible values but much more accurate due to the higher yield. The Multi-Reflection time of flight device, MR-ToF, is a mass analyser where the ions are separated by multiple reflections between electrostatic mirrors. The flight time is proportional to the square root of charge over mass, so well calibrated it can be used to determine the mass of a nucleus. It fact it was used for first time at ISOLDE to go beyond the double magic nucleus and determine the mass of ^{53}Ca and ^{54}Ca demonstrating the feasibility of precision mass measurement at the production level of 10 atom/s. These measurements allow for the determination of the two-neutron separation energies, $S_{2n} = B(Z,N) - B(Z,N\text{-}2)$, i.e. the difference of binding energy of two isotopes that differ in two neutrons. The S_{2n} is a sensitive probe of the evolution of nuclear structure with neutron number. The pronounced decrease in S_{2n} deduced from the data is well followed by the microscopic calculations using three nucleon forces based on chiral effective theory, and unambiguously establish N=32 as a closed shell neutron number for neutron rich nuclei very far from stability. The results that follow surprising well the predictions of 3-body forces increase our understanding of neutron-rich matter and were published recently in Nature [10].

2.3. Sphericity preserved for the neutron-rich Cd-isotopes

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 other fundamental properties of nuclei that can provide stringent tests of nuclear models.

The experimental determination of nuclear radii and nuclear moments [11] has been for many years a major activity at ISOLDE [12]. 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 [13] have observed 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. This behaviour was thought to occur only when protons or neutrons were in close shell and therefore inactive. The results of the cadmium isotopes indicate that the simplicity for the neutrons has survived although it has not a magic number of protons. This is one more proof of the validity of nuclear shell model and the pairing force.

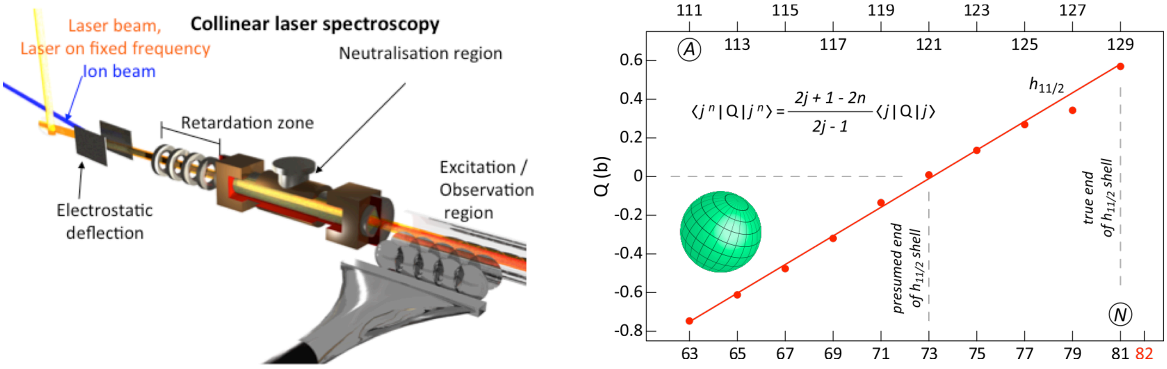

Figure 2. On the left hand side a schematic description of the elements involved in the collinear laser spectroscopy, COLLAPS, setup at ISOLDE. On the right hand side the quadrupole moments of $^{111\text{-}129}$Cd isotopes obtained with COLLAPS [15]. A straight line is fitted through the $h_{11/2}$ quadrupole moments according with the formula given in the graph showing that the spherical character unexpectedly continues until N=82 .

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 [14] 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. 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 [15]. Further long-lived $11/2^-$ states are identified in ^{127}Cd and ^{129}Cd for first time. This is a recent example of how advanced laser spectroscopy provided access to the properties of very exotic nuclei.

2.4. Collinear Resonance Ionization Spectroscopy of neutron deficient and neutron rich Fracium isotopes

The phenomenon of shape coexistence in the lead region has been studied in the francium isotopes by the determination of the magnetic moments and mean-square charge radius via the measurement of the hyperfine interaction and the determination of the isotope shifts for neutron deficient and neutron rich francium isotopes. It has been suggested the presence of intruder proton orbit in the neutron deficient francium nuclei that could polarize the nucleus creating significant deformation.

Figure 3 shows the hyperfine spectra of the ground state of the neutron deficient $^{202\text{-}207}$Fr isotopes as well as for the ^{218m,219,229,231}Fr isotopes. The measurements of the very exotic francium isotopes have been possible by the realization of a new highly sensitive, high-resolution technique of bunched collinear beam ionization spectroscopy (CRIS). The CRIS setup is designed to realize hyperfine structure studies with sensitivity up to 1 atom/s. The high sensitivity is reached through a combination of excellent overlap of laser and beam and the high efficiency of the ion detection system. The hyperfine structures associated with ground state and isomeric states were identified by the use of a decay station. The spectra were recorded by scanning the laser frequency. The ^{221}Fr was used as reference and allowed to determine the A factor and from it the magnetic moments using previously assigned spins. The charge radii were extracted from the measured isotope shifts determined as the centroid of the hyperfine structure. The extracted $\delta<r^2>$ for $^{202-213}$Fr isotopes is compared with predictions from the spherical droplet model. The resulting charged radii [16,17] show a remarkably close odd-even staggering trend to the one observed for the lead isotopes for N=118 to N=126. A departure from the trend is seen at 116, suggesting an earlier onset of deformation in the neutron-deficient francium isotopes [16] than in the lead [18] and polonium[19] chains where this happens below N=114.

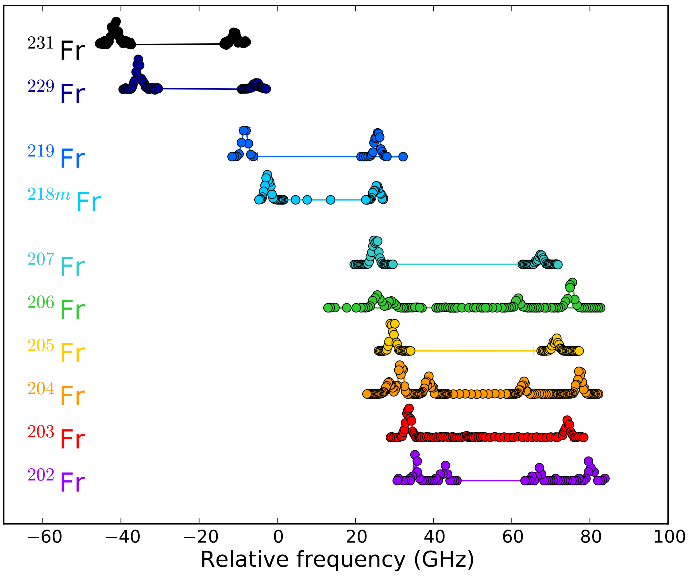

Figure 3 Hyperfine spectra of the ground state of $^{202-207,218m,219,229,231}$Fr measured at ISOLDE using the CRIS device.

3. The HIE-ISOLDE Project

The main features of the HIE ISOLDE project (HIE stands for “High Intensity and Energy) 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. A factor of six in intensity is expected from the higher energy, 2 GeV from PSB and higher intensity of the proton injector expected to occur in 2019. In addition improvements in several aspects of the secondary beam properties such as purity, ionization efficiency and optical quality are addressed.

For HIE-ISOLDE phase I where the beam energy is going to be boosted to 5.5 MeV/u twenty-seven experiments have been approved with more than six hundred shifts for day-one physics. The approved physics cases expand over the wide range of post-accelerated beams available at ISOLDE. The increase in energy of the radioactive beams will enhance the cross section and the accessibility to detailed nuclear structure information at higher excitation energy. The proposed studies will be realised with the existing workhorses MINIBALL and T-REX plus new instrumentation for transfer reaction studies such as the active targets MAYA and the future ACTAR, a new general purpose scattering chamber and the two arms CORSET setup from GSI. Plans exist of complementing the facility with a highly performing Storage Ring, TSR presently at Heidelberg in Germany. The addition of the TSR will allow the beams from HIE-ISOLDE to be stored and cooled, providing much greater luminosity and much better beam definition. A HELIOS-type solenoidal spectrometer is envisioned to be located at the exit of the TSR.

4. Summary and Outlook

In summary, the future of ISOLDE is bright. It restarts first of August 2014 for physics with the low energy program. With more than 45 year of operation ISOLDE remains as the pioneer ISOL-installation both at the level of designing new devices and production of frontier Physics.

Post-accelerated beams up to 5.5 MeV/u for the wide range of nuclei produced at ISOLDE will be available very soon**.** HIE-ISOLDE will be the only next-generation radioactive beam facility (as identified by the NuPECC LRP) available in Europe in 2015, and the most advanced ISOL facility World-wide.

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