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Recent Results from ISOLDE and HIE-ISOLDE

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Abstract. ISOLDE is the CERN facility dedicated to the production of rare ion beams for many different experiments in the fields of nuclear and atomic physics, materials science and life sciences. The HIE-ISOLDE, Higher Intensity and Energy upgrade has finished its stage 1 dedicated to upgrade the energy up to 5.5 MeV/u, producing the first radioactive beams with this energy in September 9th 2016. Recent results from the low energy and post-accelerated beams are given in this contribution.

1. The ISOLDE Facility

The Isotope Separator On Line, ISOLDE is the CERN facility dedicated to the production of radioactive ion beams. ISOLDE's production of radioactive nuclei began in October 1967, and half a century later, ISOLDE has developed into a versatile facility dedicated to the production of high purity rare beams for many different experiments in the fields of nuclear and atomic physics, materials science and life sciences. By a clever combination of target and ion source units pure beams of over 1000 different nuclei of 74 elements have been produced and delivered to experiments. The core of ISOLDE is its target and ion source systems, which provide a selective production of the nucleus of interest. ISOLDE produces radioactive nuclei by spallation-, fragmentation- and fission-reactions between the nuclei contained in thick targets and high energy, 1.4GeV, and high intensity, $2\mu\text{A}$ proton beam accelerated in the first circular accelerator of CERN, the Proton Synchrotron Booster (PSB). The targets are heated between 1000°C and 2000°C depending on the material to facilitate the fast release of radioactive nuclei. Target materials partly determine the radioactive nuclei production rate and their release time, thus a careful selection of "seed-material" is of paramount importance. Thus up to twenty different materials are available. Chemical selectivity is obtained by the right combination of target-ion sources giving rise to a selective production of more than 1000 isotopes of 74 different elements from He to Ra, of which germanium produced as GeS is the last addition. ISOLDE uses three types of ion sources: surface, plasma and laser, being the latter combined with the other two the one that achieves a higher degree of chemical selectivity. The Resonance Ionisation Laser Ion Source (RILIS) takes advantage of resonant excitation of atomic transitions using tunable laser radiation and allows for a high degree of isobar-free selectivity. The ISOLDE beam is then mass separated and delivered to the different experimental stations or post-accelerated. For many experiments the beam quality is of major importance. To achieve reduced emittance and energy spread an ion cooler and buncher, ISCOOL [1], was designed and installed after the high resolution separator (HRS) of ISOLDE. Using its bunching capabilities, ISCOOL permits an increase in the sensitivity for experiments using pulsed lasers such as those devoted to collinear



laser spectroscopy. 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 home-made post-accelerator based on previous expertise existing in the Facility, REX-ISOLDE (Radioactive beam EXperiment at ISOLDE), is in operation since 2001. The mass separated radioactive ions are collected in an ion-trap. After cooling and bunching in the trap the ions are brought into a charge-state breeder (REXEBIS) using the technique of electron-beam ionization. The charge-bred ions pass a Nier Spectrometer, and are brought into a room temperature linear accelerator able to reach 3 MeV per nucleon (MeV/u) and A/q values up to 4.5. Although designed for low middle mass the method has proven to be universal and has provided post-accelerated beams covering the entire mass range from ${}^6\text{He}$ up to ${}^{224}\text{Ra}$ for reaction studies.

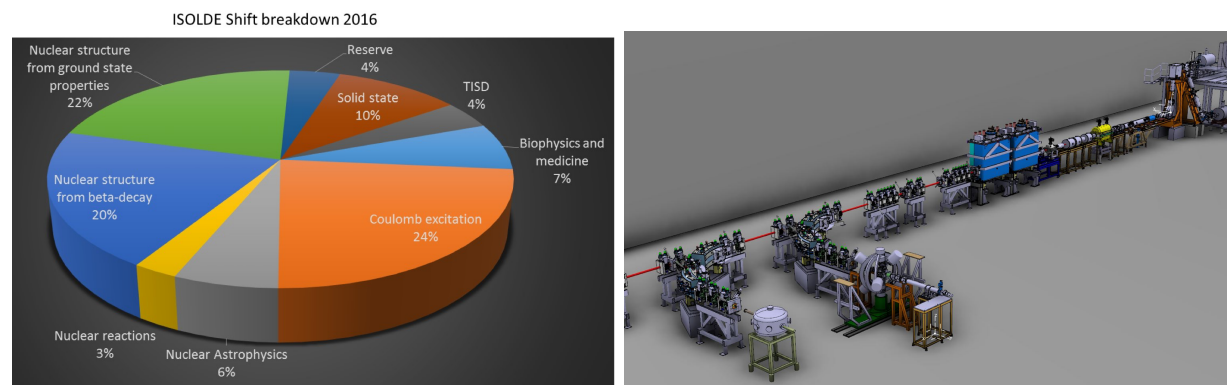


Figure 1. On the left hand side, the pie-plot shows the ISOLDE beamtime distribution in 2016 among the different physics domains. Notice that 27 % of the beam was dedicated to post-accelerated beams with energies up to 6.8 MeV/u. On the right hand side, 3D-layout of the HIE-ISOLDE post-accelerator as it looked in 2016 when stage 1 of the energy upgrade was finished. The REX-ISOLDE post-accelerator is at the right and two high-beta cryomodules are installed downstream of REX. Two beam transfer lines take the post-accelerated beam to the experiments: beamline XT01 is connected to the MINIBALL array and XT02 to the SEC scattering chamber.

2. Physics with low energy beams, Recent results

This year ISOLDE celebrates the fifty anniversary of production of radioactive beams. Since 1992 ISOLDE is connected to the PSB, that provides higher energy, increasing the cross section for spallation and fragmentation reactions than with the continuous 600 MeV proton beam of the synchrocyclotron where ISOLDE was previously located. ISOLDE is still growing and attracts presently more than 500 researchers working on 100 experiments, with a rate of about 50 experiments taking data per year. This ISOL facility has pioneered many achievements both at the level of designing new devices and of producing frontier physics. Figure 1 shows the beam distribution in 2016 with 73 % dedicated to low energy physics. In the following I present some recent highlights non covered by the contributions of G Benzoni, LM Fraile, and H. Heylen to this issue.

2.1. Beta-delayed alpha decay of ${}^{16}\text{N}$ relevant for Nuclear astrophysics

It has been known that during the helium burning process carbon is converted to oxygen through the reaction ${}^{12}\text{C}(\alpha,\gamma){}^{16}\text{O}$. The astrophysical relevant center-of-mass energy for the reaction is around 0.3 MeV. At this energy the cross section is too low to be measured directly at the laboratory, and it has to be extrapolated. The present cross section estimate at this energy has an error of 20% while the desired precision is of 10 % [2]. The β -delayed alpha emission of ${}^{16}\text{N}$ has proven to be a good indirect method as it allows for the determination of the E1

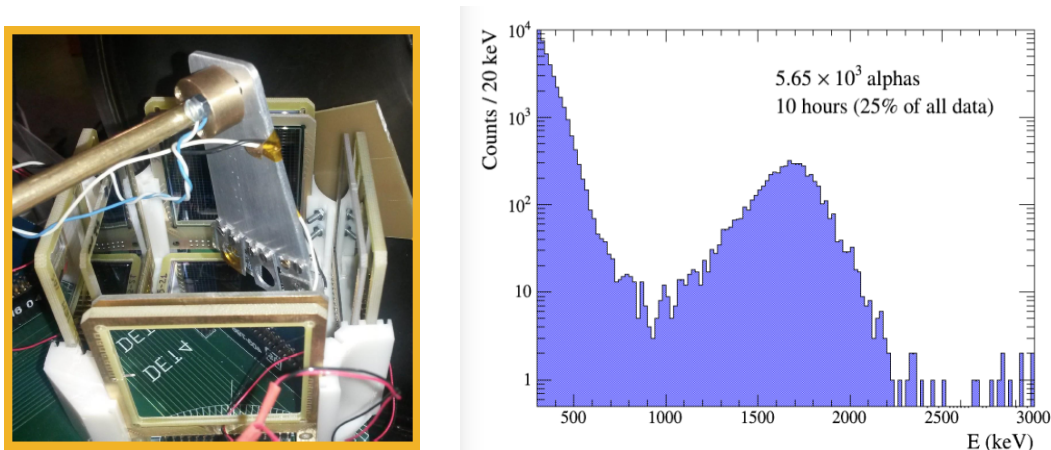


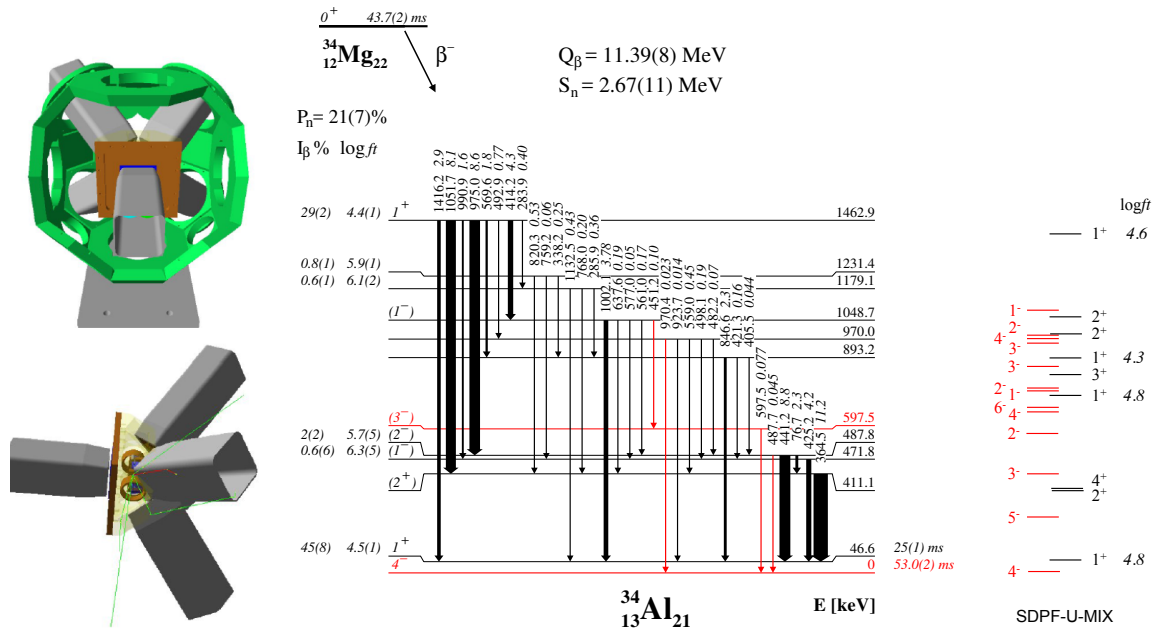
Figure 2. On the left hand side, a photo (courtesy of R. Lica) of the charged particle setup used at IDS, ISOLDE to study the $\beta\alpha$ spectrum of the ^{16}N decay. On the right hand side the $\beta\alpha$ spectrum is shown for 25% of the data. Notice the good separation between β and α in the spectrum. This separation is better for only the thinner detector of $40\ \mu\text{m}$.

component of the S-factor of this reaction. While the shape of the experimental α -spectrum is consistent among the different experiments [3, 4], this indirect method requires an improved determination of the $\beta\alpha$ branching ratio. The TUNL evaluation [5] quotes an $\beta\alpha$ branching ratio of $1.20(5)\times 10^{-5}$ while recent measurement give a value of $1.49(5)\times 10^{-5}$ [6]. An experiment was recently realized at the ISOLDE Decay Station (IDS) to obtain a more precise measurement of the alpha particle centroid energy and the $\beta\alpha$ branching ratio. An average of 2×10^4 $^{14}\text{N}^{16}\text{N}$ ions with an energy of 50 keV were stopped in a thin carbon foil surrounded by 4 telescopes with double sided Si Strip detector (DSSSD) at the front and silicon-pad detector (PAD) at the back. Another DSSSD was mounted below the carbon implantation foil. The system was surrounded by 4 HPGe clovers in the direction of the incoming beam. Figure 2 shows a photo of the very compact charged particle setup surrounded by the HPGe clovers and, on the right hand side, the charged particle spectrum for 25% of the data, where one can observe the good separation of the β and α particles obtained by the use of thin DSSSD detectors. The analysis of the data is progressing well and new results will emerge soon from this data.

2.2. Identification in ^{34}Al of the crossing of the spherical and deformed configurations at $N = 20$

The evolution of the $N = 20$ magic number has attracted a lot of attention and it has been widely studied in the past thirty years using different techniques. It has been suggested that the magicity persists along the $N = 20$ isotonic chain, from ^{40}Ca ($Z = 20$) down to ^{34}Si ($Z = 14$), and suddenly disappears only two protons below, in the deformed nuclide ^{32}Mg [7]. Although the crossing should occur between ^{32}Mg and ^{34}Si , the ground state of ^{33}Al ($N = 20$) is outside the island of inversion [8, 9]. ^{34}Al ($N = 21$) is a good candidate to explore this crossing as it has two β -decaying states with spin values 4^- and 1^+ , with normal and intruder configurations, respectively. In addition, an abnormal crossover on the S_{2n} surface has been found between the Al and Mg chains at $N = 21$ [10], suggesting a structural change there.

The ^{34}Al excited structure was studied by the β -decay of ^{34}Mg produced at ISOLDE by fragmentation in an UCx target produced by the impact of a $2\ \mu\text{A}$ pulsed proton beam of 1.4 GeV energy. The average ^{34}Mg production rate obtained from $\beta\gamma$ measurements was of 700 ions/s. The β -decay half-life of ^{34}Mg was determined from the weighted average values extracted by gating on the most intense transitions in ^{34}Al at 364.5, 441.2, 975.0 and 1051.7 keV. The value obtained for the half-life was of 44.9(4) ms, twice as long as the previously measured value of 20(10) ms [11] obtained from βn data. Study of the $\beta\gamma$ -coincidences and the



anomaly prompted a Coulomb excitation experiment at REX-ISOLDE of $^{122,124,126}\text{Cd}$ at 2.85 MeV/u. The reduced transition probabilities $B(E2; 0_{g.s.}^+ \rightarrow 2_1^+)$ obtained in the safe Coulex regime and the limits for the quadrupole moments have been determined and discussed in terms of onset of collectivity in this region [13].

Going more exotic, mass measurements of the n-rich $^{129-131}\text{Cd}$ isotopes were performed at the ISOLTRAP setup [14]. This device uses four traps being the last one, a Penning trap, where the mass-to-charge ratio m/q of an ion is determined by measuring its cyclotron frequency ν_c in the magnetic field of the Penning trap, $m/q=B/(2\pi\nu_c)$. One measures the gain in motional energy of the ions as a function of an external radio-frequency-excitation around the expected cyclotron frequency. It involves performing a frequency scan and recording the ion flight time, the so called time-of-flight ion cyclotron resonance technique (ToF-ICR) is the most precise method but it is limited by production rates and half-lives. In these cases the mass measurements are realised in the Multi-Reflection-Time-of-Flight (MR-ToF) that is previously calibrated versus the Penning Trap. This device was used to determine the mass of the low produced and short-lived ($T_{1/2}=68$ ms) ^{131}Cd isotope. The new mass values showed significant deviations of more than 400 keV as compared to earlier Q-value determination. These data give evidence of a significant reduction in the N=82 shell gap for $Z < 50$ and maybe most interesting give a more reliable description of the r -process nucleosynthesis in the region. In addition, mass separation and determination between the isomeric and ground state of n-rich cadmium isotopes have been obtained by the implementation of the phase-imaging ion-cyclotron resonance technique (PI-ICR) applied at ISOLDE for first time in 2016, see [15]. The PI-ICR method no longer includes a frequency scan so it is realised in shorter time. It constitutes a gain of factor of forty in resolving power, important to separate isomeric from ground states, and factor of four in precision with respect to the TOF-ICR technique.

The beta decay of the r -process waiting point nucleus ^{132}Cd was recently measured at IDS [16]. The beta decay strength distribution of waiting point nuclei is extremely valuable to anchor nuclear models necessary to calculate half-lives farther away from stability. Due to the expected large neutron branching ratio, the neutron time-of-flight detector VANDLE [17] was installed at IDS together with the four HPGe clover shown on the left hand side of Fig. 3. This measurement confirms previous results of the absence of bound state feeding in ^{132}In . Both the ground and the isomeric states in ^{131}In were populated in the βn process. The largest neutron transition was identified to feed the first 1^+ state in ^{131}In . This single beta transition, of $\log(ft)=4.3$, dominates the decay strength and the half-life of ^{132}Cd , which is 92 ms.

3. The HIE-ISOLDE Project and first Experiments

The HIE-ISOLDE Project is a major upgrade of the existing ISOLDE facility. The first stage includes an energy increase of the REX post-accelerator up to 5.5 MeV/u, and it is already operative since the summer of 2016. A layout of the ISOLDE hall with the two experimental beamlines as it was in used in 2016 is shown on the right hand side of Fig. 1. Most of the remaining infrastructure has been installed during the winter of 2017, i.e. the third beamline, the ISOLDE Solenoidal Spectrometer for more effective transfer reaction studies and a third cryomodule that will allow to reach 7.5 MeV/u for $A/q = 4.4$. The increase in energy of the post-accelerated beams will finish in 2018 with the addition of a fourth cryomodule that will allow a further increase of energy to 10 MeV/u. An upgrade of the REX-Linac is also expected.

The beam intensity will be increased by two independent parts of the injectors. First the production will linearly increase with the enhanced proton intensity delivered by the new ion source and pre-injector called Linac-4 that will be implemented in the CERN second long shut down. Second the increase in energy of the PSB to 2 GeV will enhance the cross section for fragmentation and spallation reaction products by a factor of two to ten and with them the production. So when these devices will be operative for ISOLDE an increase between a factor of three, only from the Linac4, and thirty, from Linac4 + higher energy of the PSB is expected

[18]. The beam quality will be improved e.g. with the installation of a RFQ cooler. The beam purification upgrade foresees to include a new high resolution separator and a Multi-Reflection Time-of-Flight, MR-ToF, for mass diagnosis and separation. The higher energy allows for the exploration of interesting regions in the nuclear chart, increases the cross section in most cases and improves accessibility to detailed nuclear structure information.

In 2016 as much as 27 % of the yearly delivered beam time, see Figure 1, was dedicated to experiments with post-accelerated beams, 3% for reaction studies in XT02 and 24% using the MINIBALL array. Beams from ${}^9\text{Li}$ to ${}^{142}\text{Xe}$ were accelerated and used to produced great physics. The ${}^9\text{Li}$ beam at 6.8 MeV/u ($A/q = 3$) was used for transfer reaction studies dedicated to explore the unbound nucleus ${}^{10}\text{Li}$ using the general purpose scattering chamber SEC in XT02. The ${}^{66}\text{Ni}$ beam at 4.5 MeV/u was used to study whether the unexpected increase in the gamma strength function observed at low energy in several stable nuclei using the Oslo method is confirmed for exotic beams. They used MINIBALL together with three large LaBr₃ detectors in XT01. The ${}^{74,76,78}\text{Zn}$ beams were accelerated at 4.3 MeV/u in 2015 and 2016 to characterize with MINIBALL and via multi-step Coulomb excitation the evolution of the nuclear structure from very collective to more spherical structure when reaching $N=50$. Following the same methodology, a ${}^{110}\text{Sn}$ beam at 4.5 MeV/u was used to determine $B(E2)$ values for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in order to investigate why the results obtained for light tin isotopes in previous experiments done at different energies and facilities differ greatly. Moving from the light tin to the heavier ones, a ${}^{132}\text{Sn}$ beam was accelerated at 5.5 MeV/u to also study by multi-step Coulomb excitation the reduced transition probabilities, $B(E2)$ for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in this double magic nucleus. Equivalent method was applied for the ${}^{142}\text{Xe}$ beam at 4.5 MeV/u with the aim of studying the octupole correlations in this nucleus. Population up to the 8^+ excited state in ${}^{142}\text{Xe}$ was identified on the on-line analysis. More details of these very recent experiments can be found in the ISOLDE Newsletter 2017 [15].

4. Summary

The 16th of October 2017 ISOLDE will celebrate its 50 anniversary of production of radioactive beams. The success of this ISOL-Facility is due to two main factors. One is the continuous development of new radioactive ion beams with emphasis in the purity and the other the steady improvement of experimental conditions and devices reflected in a laboratory portrait recently published [19]. The facility is in continuous transformation to stay at the forefront of nuclear physics research. In this contribution I have presented very recent results obtained at ISOLDE centered in n-rich nuclei.

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