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Recent highlights from ISOLDE@CERN

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Abstract. The ISOLDE online mass separator located at CERN provides a large variety of radioactive ion beams for research on nuclear physics, nuclear astrophysics, fundamental interactions, atomic physics, radiochemistry, nuclear medicine, condensed matter science, life sciences and others. The recently operational REX-ISOLDE post-accelerator is capable of accelerating the isotopes produced at ISOLDE to energies of up to 3.0 MeV/u by using an ion trap and charge breeder and a compact linear accelerator structure. The post-accelerator is complemented by a highly segmented Ge array in conjunction with a compact silicon strip detector at one of the secondary target positions, while a general spectroscopy setup occupies a second station. REX-ISOLDE has opened up the possibility of nuclear spectroscopy studies by means of transfer reactions and Coulomb excitation of exotic nuclei. The facility maintains an extensive physics-driven target and ion source development program, which has helped ISOLDE keep its international status for more than 35 years. Some recent experimental highlights and technical developments are discussed.

PACS. 25.40.-h Nucleon-induced reactions – 28.60.+s Isotope separation and enrichment – 29.25.Rm Sources of radioactive nuclei

1 The ISOLDE facility

Forty years ago CERN opened a call for proposals to explore the feasibility of nuclear physics experiments at the laboratory. The response was immediate, and already by the end of 1964 a proposition had been presented by a strong international collaboration. In 1967 the ideas of these enterprising scientists had been realized into the ISOLDE facility [1]. It was originally located at the CERN SC, the Synchrocyclotron providing 600 MeV protons. ISOLDE has been producing an extraordinary output in experimental nuclear physics and related fields ever since.

Today ISOLDE is located at the CERN PS Booster, which delivers a pulsed beam of 3×10^{13} protons per pulse with an average intensity of $2\,\mu$A and energies of 1.0 or 1.4 GeV. The proton beam impinges on a thick target kept at high temperature and produces the radioactive species by fission, fragmentation and spallation reactions. The reaction products diffuse out of the target and are subsequently ionized, mass-separated on line and transported to the different experimental setups in the ISOLDE hall [2]. At present more than 850 radioactive isotopes from more than 65 elements are produced.

2 Production of radioactive ion beams

The target and ion source development has been the driving force of ISOLDE during decades. The pulsed structure of the driver beam, seen at first as a major concern due to the instantaneous power deposited in the targets, has now become one of the strengths of the facility, as it makes it possible to perform measurements of the release of the exotic isotopes from the target-ion source units. Within this context the TARGISOL project [3], hosted by the European Union, aims at the optimization of the release properties of ISOL targets [4,5]. This involves the development of beams of new elements and more exotic isotopes as well as the improvement of existing beams in terms of intensity, purity and reproducibility.

Technical developments have helped ISOLDE keep its competitiveness throughout the years. In particular, the development of the Resonant Ionization Laser Ion Source (RILIS) [6] in collaboration with the Institute of Spectroscopy in Troitsk (Russian Academy of Sciences) set a milestone for selective ionization. The RILIS is used not only to ionize new beams with extraordinary purity, but also to enhance the intensity of existing beams or to probe the properties of nuclear isomers utilizing the hyperfine splitting. Currently the ISOLDE RILIS can ionize 25 different elements and is used in almost 50% of the physics shifts delivered by the facility [7].

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The neutron converter target [8] is other development worth mentioning. Instead of hitting directly the target material the protons are focussed into a metal rod parallel to the target, container, the neutron converter, resulting in a shower of neutrons that irradiates the production target made of an actinide. In this way, the fission fragments are enhanced with respect to the spallation and fragmentation products, at the cost of a small decrease of the total production yield. The neutron converter has proven itself invaluable to perform spectroscopy experiments of very neutron rich nuclei [9]. The fact that the proton beam does not directly strike the production target slows down its ageing, but the deterioration of the neutron converter still poses troubles.

Recently, radioactive singly-charged ions from ISOLDE have been successfully charge bred with an ECR (Electron Cyclotron Resonance) ion source. In spite of the large stable background contamination, the technique has already been used to purify Ar beams that suffered from multiply-charged heavier noble gas ions coming from the ISOLDE target. This was achieved by tuning the ECR to select a particular mass over charge for the Ar ions, at which the contaminants were strongly reduced.

The target and beam research and development program, driven by the physics requests, will continue with further tests on solid state lasers for resonant ionization, the investigation of new carbides for target materials or the implementation of negative ion sources, just to mention a few. A new development of a RFQ (RadioFrequency Quadrupole) cooler and buncher [10] will reduce the transverse and longitudinal emittance and will allow the bunching of the beam delivered to the experiments. This will improve the measurements of nuclear moments and half-life, and open new possibilities for REX-ISOLDE.

3 The ISOLDE Physics programme

The ISOLDE facility provides a large variety of radioactive isotopes for many experiments in nuclear physics and related areas like nuclear astrophysics, atomic physics, radiochemistry, physics of the fundamental interactions, nuclear medicine, material science, life sciences and others. The main experimental equipment includes high-resolution laser spectroscopy devices, high-precision mass spectrometers, an on-line nuclear polarization setup, spectrometers for emission channelling and angular correlation measurements, a total absorption gamma spectrometer, a HV platform for up to 200 kV post acceleration, ultra-high-vacuum experimental chambers for surface and interface studies, several general purpose nuclear spectroscopy setups and the REX-ISOLDE post-accelerator (sect. 4).

Figure 1 summarizes the variety of experiments performed during the 2001 to 2003 campaigns and the relative distribution of the radioactive beam used. ISOLDE delivers 300 to 350 eight-hour shifts of radioactive beam to some 35 different experiments per year. The experimental programme carried out at ISOLDE is well represented in these proceedings. It is worth mentioning the systematic work carried out in the $N \sim 20$ island of inversion where investigations by fast timing in β-decay [11], Coulomb excitation at REX-ISOLDE [12] and moment measurements [13,14] have been performed. An extensive mass measurement programme is carried out at the facility [15,16], together with particle and gamma spectroscopy in β-decay, nuclear astrophysics studies [9], search for physics beyond the standard model by $\beta\nu$ correlations (WITCH) and many others.

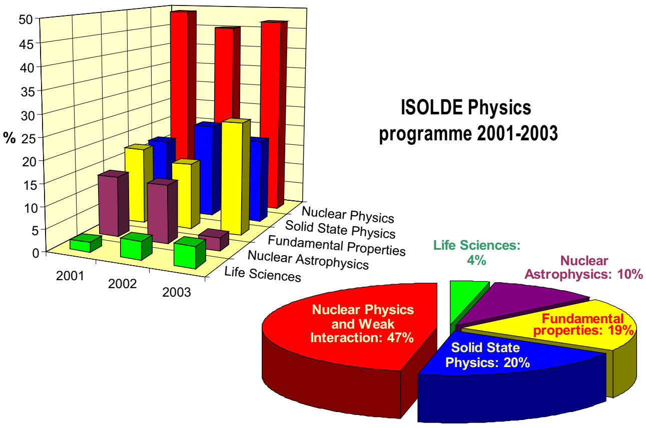

Fig. 1. Shift distribution and evolution of the experimental beam time at ISOLDE during years 2001 to 2003.

4 REX-ISOLDE

One of the fundamental achievements at ISOLDE has been the realization of the REX-ISOLDE post-accelerator [17], which provides radioactive ion beams accelerated to energies of several MeV. It consists of a highly innovative low-energy section made up of a Penning trap (REX-TRAP) [18] for cooling and bunching the radioactive singly charged species from ISOLDE, and an electron beam ion source (REX-EBIS) [19] where the ions are charge bred. A particular charge state can be selected with a mass separator and then injected into the REX-LINAC. As sketched in fig. 2 the REX-LINAC is a compact low-energy linear accelerator [20] that consists on a RFQ followed by an interdigital H-type (IH) structure and multi-gap resonators. The REX-LINAC has recently undergone an upgrade in order to increase the final energy from 2.3 MeV/u to 3.0 MeV/u. For this purpose a new accelerating IH-structure of 0.5 m running at 202.56 MHz, twice the REX frequency, has been installed, commissioned and successfully used for the first experiments during 2004. The post-accelerator is complemented by a highly segmented Ge array, MINIBALL [21], in conjunction with a compact silicon strip detector, located at a dedicated secondary target position. A second beam line allows performing experiments with tailored detection setups.

A very significant fraction of the isotopes produced at ISOLDE are already available for experiments at REX-ISOLDE. Virtually all the isotopes produced can be accelerated through REX provided the charge breeding of heavy masses to higher charge states in REX-EBIS can

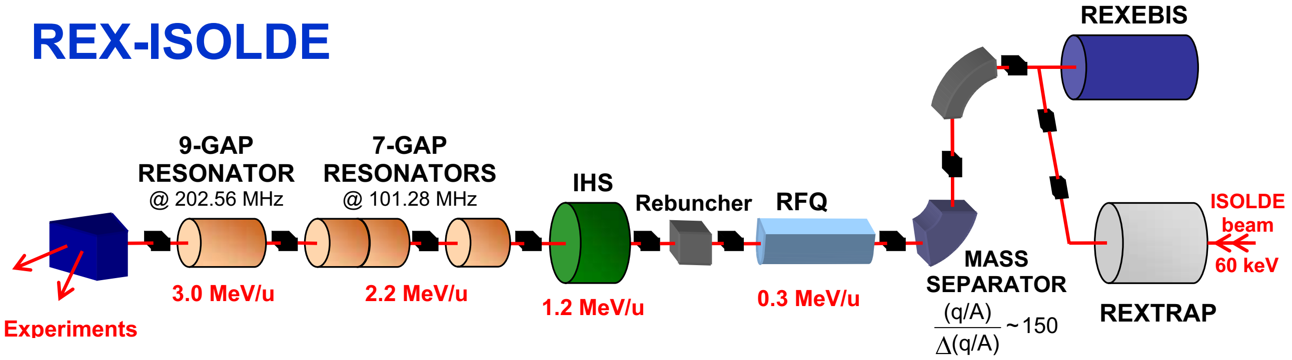

Fig. 2. Schematic layout of the REX-ISOLDE facility.

Table 1. A summary of the radioactive beams delivered by the REX-ISOLDE facility during the 2004 campaign, *i.e.* after the energy upgrade to 3.0 MeV/u.

Isotope	A/q	Energy (MeV/u)	Experiment	Comment
^{9}Li$^{(a)}$	4.5	2.6	n pick-up (d, p) (Be, 2α)	Gas cooling with Ne and Ar. Foil stripping
^{11}Li	3.7	2.9	Scattering (Pb)	Test beam
^{17}F	3.4	2.5	(p, α) reaction	Beam development: molecular sideband & foil stripping
^{28}Mg	3.1	2.1–2.2	Fusion (Si)	Test beam
^{30}Mg [12]	4.3	2.7	Coulomb Excitation (Ni)	Previously at 2.3 MeV/u
^{32}Mg [12]	3.6	2.8	Coulomb Excitation (Ag)	Previously at 2.3 MeV/u
^{70}Se	4.1	2.8	Coulomb Excitation (Pd)	Beam development: molecular sideband [22]
^{74}Zn [7]	3.7	2.9	Coulomb Excitation (Pd)	Previously at 2.3 MeV/u
^{76}Zn [7]	3.8	2.9	Coulomb Excitation (Pd)	Previously at 2.3 MeV/u
^{78}Zn [7]	3.7	2.9	Coulomb Excitation (Pd)	New beam
^{110}Sn	4.1	2.8	Coulomb Excitation (Ni)	New beam
^{122}Cd	4.1	2.8	Coulomb Excitation (Ni)	New beam
^{124}Cd	4.1	2.8	Coulomb Excitation (Ni)	New beam
^{126}Cd	4.1	2.8	Coulomb Excitation (Ni)	New beam
^{148}Pm	4.9	0.3	Implantation (SiC) for DLTS	Test beam at 300 keV/u (RFQ)

(^{a}) See text for a brief discussion.

be achieved in a reasonable time. This is attainable by an improvement on the current density of the EBIS electron beam. Longer breeding times up to 200 ms, longer accumulation times and storage of a larger amount of ions in the trap have to be investigated as well. The high vacuum of the breeding system assures that the resulting beam of highly charged ions is of high purity. The main beam contaminants result then from the buffer gas used in REXTRAP and from residual gases coming from the REX mass separator sector, and also from the isobaric contaminants originated at the ISOLDE target that end up with the same A/q ratio as the beam of interest. A summary of the accelerated beams during 2004 can be found in table 1.

An extensive physics program is carried out at REX-ISOLDE. The beam purity and general applicability are crucial to allow for investigation of bound and unbound light nuclei at the drip line, heavy fission fragments and nuclei at the $N = Z$ line. The main reactions employed are Coulomb excitation, transfer and fusion-evaporation. The disappearance of the neutron shell closures for neutron-rich nuclei ($N = 20$, $N = 28$) is investigated by means of Coulomb excitation around the barrier by determining the energy of the 2^{+}_{1} state and the reduced transition probability for excitation to that state. Recent Coulomb excitation experiments with the MINIBALL setup have succeeded to extract the deformation of neutron rich Mg, Zn and Cd isotopes [7,12] for nuclei as heavy as ^{126}Cd. The results show the versatility of REX-ISOLDE for this type of studies aiming at the investigation of the structure of exotic nuclei. First tests with fusion evaporation reactions have also started. They will enable the investigation of neutron rich compound nuclei and the study of the enhancement of sub-barrier fusion by neutron transfer. Reactions of astrophysical interest, like the study of the inelastic branch of the $^{14}\mathrm{O}(\alpha, \mathrm{p})^{17}\mathrm{F}$ [23] reaction, have been proposed too. Other experiments concerning the structure of nuclei along the $N = Z$ line, proton radioactivity, etc. are foreseen in the near future.

REX-ISOLDE is an excellent tool for the investigation of unbound light nuclei by means of transfer reactions and elastic resonance scattering. As an example, the first excited state of the nucleus ^{10}Li, unbound subsystem of the halo nucleus ^{11}Li, can be characterized by using neutron pick-up $^{9}\mathrm{Li}(\mathrm{d}, \mathrm{p})^{10}\mathrm{Li}$ and $^{9}\mathrm{Li}(^{9}\mathrm{Li}, 2\alpha)^{10}\mathrm{Li}$ reactions, which favour s-wave or p-wave pick-up, respectively. In a recent experiment by Jeppesen *et al.* [24] the incident ^{9}Li beam

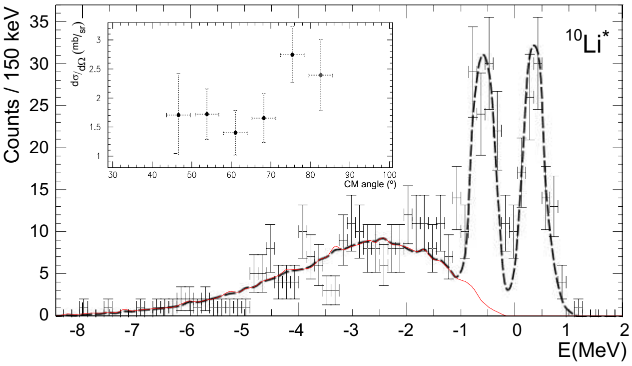

Fig. 3. Excitation energy of the unbound ^{10}Li system originating from ^{9}Li(d, p). The dashed line shows a calculation assuming a resonance on the ^{10}Li system at 350 keV and background contributions (see text for details). Adopted from [25].

from REX-ISOLDE with 10^5 particles/s intensity was sent to a C_3D_6 deuterium target surrounded by a compact array of position sensitive Si detectors. Most of the reaction channels, with exception of those leading to three-body or five-body final states, were identified, which shows the great applicability of the method. In particular, the (d, p) transfer leading to ^{10}Li was studied, and the excitation energy of the unbound ^{10}Li system was reconstructed, as shown in fig. 3. The only peak at positive energy can be described by a R-matrix calculation assuming a p-wave resonance at 350 keV above the $^{9}\mathrm{Li} + \mathrm{n}$ threshold with a FWHM amplitude of $\sim$ 300 keV [24,25]. The one neutron transfer differential cross-section for ^{10}Li can be then determined by selecting the events on the 350 keV peak (inset of fig. 3). There are negative-energy structures that cannot derive from the $^{9}\mathrm{Li} + \mathrm{d}$ reaction. They can be explained as originating from the elastically scattered protons from the H contamination of the C_3D_6 target and from the contribution of the compound reaction of the ^{9}Li beam on the ^{12}C of the C_3D_6 target.

5 Outlook

The breadth of the science achievable with radioactive ion beams has brought a large interest and fresh ideas to the field in recent times. Several projects are underway in Europe, being the Facility for Antiproton and Ion Research (FAIR) in Germany the most advanced at this stage. ISOLDE plays a central role in the European Union design study for the third-generation radioactive ion beam ISOL facility, EURISOL [26]. The plans for this new installation include a post-accelerator for up to 100 MeV/u radioactive ions, storage rings, recoil mass separators and large multi-segmented detectors. Such a high-intensity facility is the natural successor of ISOLDE and CERN would be an ideal site for it, with the required proton driver of several MW assuring exceptional synergies with other areas of research.

Within this context, the future of ISOLDE and REX-ISOLDE is strongly influenced by the proposed upgrades of the injector accelerators at CERN to deliver a driver proton beam of much higher intensity. An ongoing study is analyzing the feasibility of a superconducting proton LINAC (SPL) [27] on the CERN site and its impact on a later upgrade of the LHC and on new physics. In a possible staged approach to the SPL, the present 50 MeV proton LINAC of the CERN PS complex would be replaced by a high-performance H^- low-energy LINAC structure at room temperature which will later inject into a superconducting section. This will be already advantageous for ISOLDE, as it will allow increasing the PS Booster intensity up to a factor 2, on the wayt to the maximum 10 μA driver beam intensity that this facility can handle prior to the construction of a new target area.

Tests are under consideration to reduce the cycling of the PS Booster from 1.2 s to 900 ms, providing an increase of the driver intensity of more than 30%. In addition, plans are underway for a further energy upgrade of REX-ISOLDE to $\sim$ 5.0 MeV/u, which will allow overcoming the Coulomb barrier limit of the projectiles that can be used to induce nuclear reactions. Furthermore, CERN is undertaking a major consolidation of the ISOLDE facility itself including a new radioactive laboratory for target manipulation that will be ready for the 2005 campaign. The extension of the ISOLDE experimental hall is also in progress and will be completed for 2005. It will house the next REX upgrade and joint experimental equipment, and a new solid state physics laboratory.

6 Conclusions

The ISOLDE facility enjoys a lively programme of a high scientific quality. This is possible not only due to the collaboration of many European physics institutes but also to the infrastructure and manpower provided by CERN, that makes it possible to run a large facility delivering beam to many users. ISOLDE is integrated in the European research structure through the EURONS (EUROpean Nuclear Structure) infrastructure initiative, and plays a key role in the design study of the future European third-generation ISOL radioactive ion beam facility, EURISOL.

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