ISOLDE NEWSLETTER 2024

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ISOLDE Newsletter 2024

Introduction

Sean J Freeman

Welcome to the 2024 ISOLDE Newsletter!

As the many articles in this newsletter will show, the 2023 running period was one of the most successful and probably one of the busiest. There were around sixty experiments and isotope collections, despite a shorter than usual proton running period, including ten using post-accelerated beams from HIE-ISOLDE. There were 470 shifts for physics and machine development and three weeks for winter physics with pre-irradiated targets after the end of the proton run. The latter included measurements of transfer reactions with a ^{7}Be beam for ISS, studies of radioactive molecules at CRIS and collections of ^{226}Ra and ^{110m}Ag. We hosted more researchers than ever, with more than 740 researcher-visits in 2023, 25% of whom were women. Operating a facility like ISOLDE is never without a few problems along the way, but thanks to the commitment of our talented operations, target and RILIS teams alongside the wider CERN technical specialists, these were generally solved very quickly.

It has been a sad time so far in 2024 with the tragic loss of two dear colleagues who have made very significant contributions to ISOLDE, made even sadder as their deaths were so untimely.

Bruce Marsh was a very talented physicist and a highly respected colleague. Over the years, he made many significant contributions to ISOLDE and the science done at the facility, particularly in the area of laser ion sources. As Section Leader in Accelerator Systems for Lasers and Photocathodes, he had significant impact more widely at CERN. But he will be remembered as much as for his warmth, friendliness, and strong sense of right and wrong, as his many scientific and technical qualities and achievements.

Mats Lindroos spent much of his career at CERN, as research fellow and staff member working at ISOLDE and at the PS Booster. He made many significant contributions to the ISOLDE Facility as Technical Coordinator, especially to the development and initiation of the HIE-ISOLDE Project. He left CERN to help establish the European Spallation Source in Sweden and led the ESS Accelerator Division. He had a deep knowledge and insight with regards accelerator systems and how best to use them for science, contributing to the future of many different facilities. At the same time he was a kind and supportive colleague.

You can read more about Bruce and Matts in the following CERN Courier articles: *Bruce Marsh* and *Matts Lindroos*.

Progress has continued with the improvements programme for ISOLDE planned for Long Shutdown 3 (LS3). This is a series of measures to improve the capability, capacity and reliability of ISOLDE, seeded by the discussions from the EPIC Workshops in 2019 and 2020. The major elements of the mid-term improvement programme are the replacement of the proton beam dumps and upgrade of the BTY line to deliver 2-GeV protons and to take the full intensity currently available from the PSB, alongside other improvements and consolidation items. Several urgent items totalling 3.8 MCHF were already included in CERN's Medium Term Plan MTP2024 (developed and approved during 2023), mainly for improvements in fire safety and ventilation in the primary areas. During 2023, the LS3 plans were presented to the INTC and Research Board who were very supportive. Later in the year, the project definition, risks and resources were considered by a "Cost, Schedule and Scope" review. All this work is paying off; I've recently heard that 13 MCHF were included in this year's MTP for the beam dump replacement. This is great news, particularly considering the financial pressures that CERN is under at the moment. We were also pleased that consolidation funding was secured to update the REX HLRF/LLRF (2.180 MCHF) and for power

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converters on the BTY line consistent with 2 GeV delivery (around 2.0 MCHF).

This is not quite the end of the story - there is a lot of work underway to develop a request to next year's MTP covering: magnets for the BTY line along with vacuum and civil engineering for 2 GeV delivery; an upgrade study for EBIS; beam switching through the central beam line; and a number of other smaller items. There is also a task force of experts from our operations team and CERN cryo and rf groups looking at the cryo maintenace of HIE-ISOLDE, with promising ideas to recover and to maintain the performance of the accelerating cavities. This task force will make proposals to the Injectors and Experimental Facilities Committee in the coming weeks and the required resources will be added to the MTP request.

I hope this will secure the resources needed for all of the proposed improvements so that work can begin in a timely fashion in LS3 - the dates of the shutdown will be confirmed later this year. However, the ISOLDE Collaboration Committee has begun to consider how the facility might be improved at the next available opportunity, LS4 - if you have any thoughts, please pass them to your national representative. Indeed, one might already want to discuss larger investments and projects that require a longer time frame for LS5 - such as the expansion and remodelling of the facility that arose as an aspiration from the EPIC Workshops. The timescales for project development and approval place them into the period where the post-LHC future for CERN becomes important. We will have to remain agile and try to develop and align our longer term goals for ISOLDE with CERN's emerging strategy.

During the early part of 2024, there has been a significant activity to improve the facility's safety environment after a number of worrying incidents. This has largely fallen on the shoulders of those people who take the lead on the day-to-day maintenance and operations of the beam-line instruments at ISOLDE. They have been reviewing in detail all the written safety documents with the support of the EP Safety Office. This has been a substantial effort and I am very grateful to everyone involved. However, it should not be forgotten that everyone working at ISOLDE contributes to our safety culture and so I would ask that all users pay particular attention to maintain the safest working environment that we can. Of course, it is the very nature of the work we undertake that creates hazards, so we need to be vigilant in identifying and owning these risks and making efforts to mitigate them. I would therefore like to take the opportunity to remind you to use the necessary personal protective equipment and safety protocols to enter the ISOLDE Hall and please follow to the letter any approved procedures concerning your activities. EP Safety is available to help you; if you have any concerns or if a procedure needs adapting for your activities, please talk to them first. They are very knowledgable about CERN as an organisation and can offer a lot of useful advice and support.

Being a nuclear physics facility within a large particle physics laboratory can be challenging; I can't recall the number of times since I started at CERN when I have had to carefully explain that our research culture is not the same as a large LHC experiment. This is often met with puzzlement and then curiosity, followed by enlightenment when they realise that, compared to the rest of science, the way particle physics works is an outlier! And the differences are never show stoppers, whatever the subject of the conversation - open access publications, sharing data, maintenance and operations costs, memoranda of understanding - a way forward is always found. Moreover, when you explain the science we do, it is clear that we have considerable impact in broadening and diversifying CERN's scientific programmes. In early 2024, I was given the seemingly impossible task of speaking about the 10-20 year future scientific programmes of non-LHC "nuclear physics" at CERN at the Charmonix meeting that brings together the CERN management and all the accelerator, engineering and technical groups. This would have been a daunting invitation even if it was to only talk about ISOLDE science, but I was also asked to cover neutron-induced measurements at n_TOF, anti-proton work at AD and fixed-target heavy-ion collisions in the North

Area. The audience were engaged and very supportive of the work done at all these facilities - and that is thanks to the imagination and innovation of the scientific communities that generates such productive programmes. So a "thank you" to everyone in the ISOLDE community - you make my job easier with the amazing science that you do!

News for users 2024

ISOLDE schedule 2024

The physics period in 2024 started on April 8th and will run with protons until November 25th, followed by 2 weeks of Winter Physics. Afterwards, we plan to organise a "Separator Course", giving new users the opportunity to familiarise themselves with the fundamentals of operating the ISOLDE machine, covering aspects such as the control system, beam instrumentation, vacuum systems, and logbooks.

The published schedule for 2024 can be found online here, and the weekly schedules here. EURO-LABS TNA support will be available and spokespeople of scheduled experiments will be contacted in advance of their experiments running by Jenny.

Preliminarily, in 2025, ISOLDE will run with protons between 25th March and 17th November 2025.

Upcoming INTC meetings

We inform you that in view of the approaching Long Shutdown at CERN (LS3) and considering the large backlog of approved experiments, the upcoming sessions of the INTC will have a reduced scope of accepted documents.

- The next INTC meeting, on 12-13 November 2024, will be open for nTOF physics and ISOLDE low-energy experiments only. No HIE-ISOLDE proposals and LoIs will be discussed. Please note that, with high probability, this will be the last meeting where new low-energy documents will be considered before LS3.
- The 78th INTC meeting, on 5-6 February 2025, will be open only to HIE-ISOLDE proposals and all letters of clarification. No nTOF and low-energy ISOLDE proposals and LoIs will be discussed. Addenda will be accepted in exceptional cases, please contact the physics coordinator before submitting. Please note that, with high probability, this will be the last meeting where new HIE-ISOLDE documents will be considered before LS3.
- The plans for the subsequent INTC meetings (May 2025, November 2025, and later) will be announced at the end of 2024.

User registration and access to the ISOLDE facility

A full description of the procedure for registering at CERN is given on the ISOLDE website. Note that the teamleader and deputy teamleader who sends the information *must* have a valid CERN registration. This also applies to paper forms which have been signed at the visiting institute. Please register under **"ISOLDE"** as your experiment and **"USER"** as status.

All information for getting access to the ISOLDE facility is outlined on this page on the ISOLDE website. There are a variety of training courses, managed via the CERN training hub, required before access to the ISOLDE hall can be granted. These are divided into classroom courses, which take place at the CERN training centre in Prevessin, and online courses which can be taken via the CERN online training. Enrollment for the classroom courses should take place before coming to CERN (at least 2 weeks before the course takes place, otherwise, they might be cancelled). If a user is not yet registered, an email can be sent to safety training: safety-training@cern.ch. However, once registered it will be still necessary to register for the hands-on courses in the CERN training hub in order to validate the training.

Safety in the ISOLDE hall

Access to ISOLDE is only permitted if you are wearing a dosimeter, helmet, and safety shoes. Before leaving, always use the hand-foot monitor to check for any contamination. Always consult the local person responsible for your experimental setup, to get introduced to

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the safety procedures for activities you want to perform. If your experiment or activity introduces additional hazard, check that the required processes with the EP Safety Office have been followed. Clearly label all equipment in the hall with contact information, setup details, and the date. If items need to stay at CERN after the run, contact the physics coordinator to find a suitable location. All items must be checked by RP checks leaving ISOLDE and when opening the beamline or chamber. Remember, radioactive items need to be added to TREC and should be stored in the dedicated cupboard.

In case of doubt, please don't hesitate to contact your local contact, the physics coordinator or the EP safety office (Letizia Di Giulio and Theo Vafeiadis). The list of contacts for safety both for local experiments and visiting setups can be found via https://isolde.cern/safety.

ISOLDE Publications, open access and CERN EP preprints

ISOLDE should be mentioned in the abstract of articles related to experiments performed at the facility and, if possible, the ISOLDE team should be mentioned in the acknowledgements. Experiments which have benefited from previous **ENSAR2** funding at ISOLDE should also mention this in the acknowledgements of any articles which emerge and which should echo the following: *This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654002.*

For **Eurolabs** support, publications should acknowledge in the following way: *"The research leading to these results has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101057511."*

Please note that under CERN's general conditions, all publications originating from a CERN experiment or featuring a CERN author must be published as open access. Detailed information on open access publishing can be found on this dedicated website, supported by the CERN Scientific Information Service. New agreements have been signed with numerous publishers which facilitate OA publishing with a CERN author. In many cases publication costs will be covered centrally at CERN if there is at least one CERN-affiliated author in the author list. For IOP and the APS publications, costs can be covered even without a CERN author as long as the ISOLDE collaboration and IS number are mentioned e.g. "CERN, ISOLDE Collaboration, ISXXX" in the collaboration field of the submission form, and this should be added to the paper itself.

In case of any further questions, authors can ask the experts in the CERN library questions via email: open-access-questions@cern.ch.

ISOLDE papers can also be uploaded to the CERN EP preprint server, which will allow them to receive a CERN-EP number as is done for many other experiments at CERN. Details on the submission process can be found here. If there are any questions about this process, please contact the physics coordinator.

Publications on CDS

There is a specific area of the CERN Document Server from which all ISOLDE spokespeople and contacts will be able to upload DOI links (and extra information if required). Once you have signed in with your CERN credentials, you should be able to upload any new articles or theses. The link to use is here. If there are any problems with uploading, please contact the physics coordinator.

Open data

Please note that having an open data management programme is now a requirement for the receipt of EUROLABS support. All experiments are now requested to provide information about their Open data policy at the time of beam requests. ISOLDE has also recently published an open data policy, following approval by the ISCC, and this can be found here.

RIB Applications

Formation mechanism of PbV centers from implanted Pb in diamond, including first results from the ISOLDE PL setup

Results of experiment IS668

Ulrich Wahl for the EC-SLI collaboration

Among the group-IV vacancy centers in diamond, PbV^- has recently attracted particular interest for possible applications in large-scale quantum networks [1], motivating us to study its formation mechanism through ion implantation by means of the emission channeling (EC) technique. In our first Pb beam time (10/2023) we investigated the lattice sites of ^{209}Pb ($t_{1/2}$=3.25 h) in CVD diamond following low-fluence (1.5×10^{12} cm^{-2}) 50 keV implantation as a function of implantation (T_i) and annealing (T_a) temperature. A first analysis of the EC data using 2-site fits that allow for ^{209}Pb on substitutional (S) and bond-center (BC) sites, the latter being a characteristic of PbV in split-vacancy configuration, shows comparable fractions around 40% of Pb on S and BC sites directly following room temperature (RT) implantation, a situation which remains for T_i or T_a=900 ℃ (Fig. 1 left). This behavior is similar to Sn [2] but in stark contrast to the case of Ge [3], where annealing or implanting at elevated temperatures lead to loss of GeV complexes, considered to be less thermally stable than simple substitutional Ge. An ongoing analysis is investigating whether, besides S and BC, a third type of lattice site, e.g., resulting from Pb in higher-order vacancy complexes such as PbV_2, could be compatible with the experimental results.

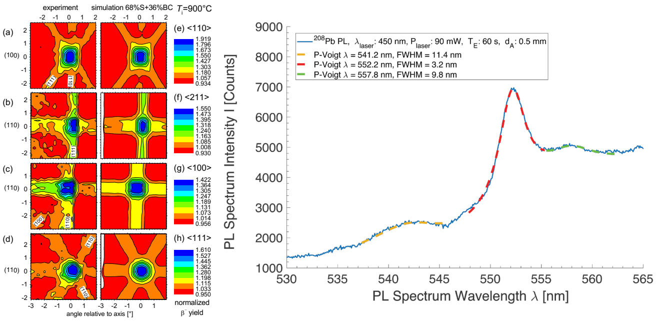

Figure 1: Left: EC patterns and best 2-site fits from ^{209}Pb at T_i=900 ℃. Right: RT PL spectrum from ^{208}PbV^-, following excitation with a 450 nm blue laser.

We have recently commissioned a photoluminescence (PL) setup at ISOLDE, with the aim of using it for radiotracer experiments, where the intensity of PL lines is followed as a function of time in order to correlate it with the half life of implanted radioactive impurities. Before using the setup with radioactive impurities, proper sample processing conditions have to be established using stable isotopes. We therefore implanted stable ^{208}Pb at ISOLDE (available off-line, 5×10^{12} cm^{-2} at RT) into a CVD diamond single crystal (Element 6, “Electronic Grade”, [N]<5 ppb), followed by furnace annealing at 1100 ℃ (30 min), revealing the characteristic zero-phonon lines of PbV^- (Fig. 1 right). We are currently acquiring an electron beam heated furnace that will allow for fast annealing up to 1600 ℃ and extend our capabilities for thermal processing of diamond samples.

The major conclusions of our study so far are that PbV is created in significant amounts (40%) directly during RT implantation and shows high thermal stability. No annealing nor the related vacancy diffusion is required to form it. That PbV^- has not been reported by PL without high-temperature annealing ≥950℃ must be due to the fact that it is in a “dark state”, e.g., not in the required negative charge state, or its luminescence is quenched by implantation defects.

References

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[2] U. Wahl, *et al.*, *Phys. Rev. Lett.* **125**, 045301 (2020).

[3] U. Wahl, *et al.*, *accepted for publication by Materials for Quantum Technology* (2024).

Data acquisition and Python processing using CAEN Digitizer DT5730S for Perturbed Angular Correlation Spectroscopy: the PACIFIC^2 route.

P. Rodrigues for the IS730 and IS738 collaboration

The γ-γ Perturbed Angular Correlation (PAC) spectroscopy technique has been a staple of ISOLDE Solid state Physics for more than four decades [1, 2, 3]. Historically, ISOLDE's PAC spectroscopy setups have been tethered to analog equipment, some exceeding 30 years in operation, or to digital processing systems that are both costly and bulky. To modernize and streamline our PAC data processing capabilities, we embarked on a series of performance evaluations using the DT5730S digitizer from CAEN S.p.A. Characterized by its 8 input channels, a 500 MS/s sampling rate, and a 14-bit ADC, this compact digitizer seamlessly integrates into both 4 and 6-detector PAC configurations. Notably, it supports space-efficient data storage in ROOT format through its List acquisition mode, where each detected γ-photon is cataloged with time and energy stamps via the digitizer's online pulse processing algorithms.

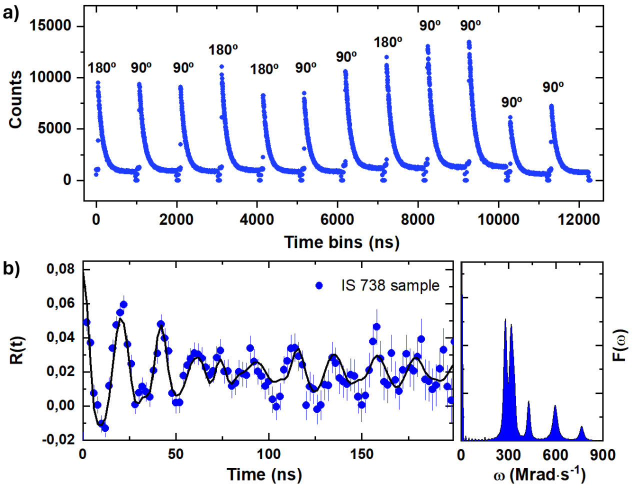

Figure 1: a) Coincidence spectra at 90° and 180° obtained with PACIFIC^2 processing software from data collected with the DT5730 digitizer during the ^{111m}Cd beam time. b) Respective Perturbation function (R(t)), alongside its mathematical fit, and the Fourier transform of the fit (F(ω)).

Given the challenge of managing and analyzing vast data sets, which can reach up to 100 GB per measurement, our team has developed the PACIFIC^2 suite—a collection of Python-based tools designed specifically for PAC spectroscopy data analysis. This innovative suite enables efficient filtering and analysis of large-scale data sets to search γ_1-γ_2 coincidence pairs, thereby facilitating the construction of 90°/180° coincidence spectra, which are fundamental to PAC spectroscopy. The time resolution of the digitizer was first analyzed by using a ^{22}Na calibration source and a set of two LaBr$_3$ scintillator-based detectors. The detection of pairs of simultaneously emitted γ-photons, with an energy of 511 keV, following positron-electron annihilation processes, was registered. Under optimal conditions, a time resolution of $\approx$ 362 ps was achieved. This performance matches that of the digital systems currently in use [4]. Data acquisition tests were also run during the previous ^{111m}Cd beam time with the digitizer connected to a set of 4 BaF$_2$ scintillator-based detectors. The developed PACIFIC^2 software was used to filter and search the γ_1-γ_2 coincidence pairs of 150-245 keV post-acquisition. Fig. 1 a) shows the obtained respective 90°/180° coincidences spectra obtained for a 44 min acquisition with a sample exhibiting an initial radioactive activity of $\approx$ 700 counts/s. The data processing, executed on a contemporary laptop powered by an 11th Gen Intel®Core™i7-1165G7@2.80GHz, was achieved in less than a quarter of the acquisition time, showing the feasibility of running the Python processing software both in post-acquisition or in real-time conditions while using four-detectors PAC arrays.

The experiment shown in Fig. 1 focused on a Ca-based Rudlesden-Popper polycrystalline sample studied within the IS738 proposal. As observed in the Fourier transform, the fitted perturbation function accounts for two distinct local environments, agreeing with the results obtained in parallel with currently in-use spectrometers, showcasing the CAEN DT5730 and PACIFIC^2 software's robustness.

The strategic application of Python, a programming language commonly taught in Physics and Engineering courses, for data processing, combined with the use of more affordable digitizers, fosters a deeper understanding of instrumentation within research teams and facilitates the sharing and adaptation of software across different digital acquisition systems. This approach democratizes access to advanced data analysis tools and encourages collaborative innovation. Future efforts will focus on performance evaluations of Python-based processing in conjunction with the digitizer on setups involving 6-detector cubes and explore its applicability to isotopes with significantly shorter half-lives. These initiatives are expected to test the limits of our current setup, particularly concerning the digitizer's 500 MS/s sampling rate, and push the boundaries of what can be achieved with our integrated software and hardware solutions.

References

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[3] H. Haas, *et al.*, *Physical Review Letters* **126**, 103001 (2021).

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Towards understanding the mechanism of multivalent ion intercalation in vanadia and vanadates

Results of experiment IS732

Anastasia Burimova, Arnaldo Alves, Juliana Schell and
Artur Carbonari for the SSP collaboration

A revitalized interest in vanadates and vanadium bronzes ($M_xV_2O_5$) is mostly due to their ability to guide and store $M^{(n\geq2)+}$ ions and thus their potential as electrode materials in multivalent ion batteries [1, 2, 3]. Meta- (MV_2O_6) and pyro- ($M_2V_2O_7$) vanadates are of interest as primary and, consequently, “thrift” ion hosts, i.e. the products of recycling-targeted processing of spent bronzes saturated with charge carriers [4].

Though essential for performance improvement, full understanding of ion (de)intercalation in vanadia-based compounds is lacking. In this regard, we promote perturbed angular correlation (PAC) spectroscopy as a local-scale investigation technique capable of shedding light on the behavior of guest ions in vanadates. To take full advantage of PAC sensitivity to the variations in charge distribution, the first (and non-trivial!) step is tracking the location of PAC probes. Although probe ions will likely reside within the dominant phase, they perturb the local environment, and can even serve as nucleation centers for contaminant structures. Meanwhile, a distinctive feature of nMO–V_2O_5 (n = 1, 2) systems is the cross-contamination of stoichiometric phases, which may be exacerbated by defects and external conditions.

In a series of γ–γ ^{111}In(^{111}Cd)PAC experiments carried out at IPEN (Brazil), wet impregnation was employed to deposit the probe isotopes to nominal MnV_2O_6. The procedure required a prolonged annealing at elevated temperatures and resulted in the propagation of pyrovanadate, as the control X-ray diffraction (XRD) measurements have shown (see figure Fig. 1a). Furthermore, the values of hyperfine parameters acquired for Mn meta- and pyrovanadates with ^{111}In generators, as well as their variations with temperature, were remarkably alike, hindering the attribution of the results to a particular system. ^{111m}Cd(^{111}Cd)-PAC data collected at ISOLDE, in contrast, revealed distinguishable interactions in nominal MnV_2O_6 and $Mn_2V_2O_7$ (see figure Fig. 1b). The dominance of monoclinic MnV_2O_6 in post-PAC metavanadate samples was established with XRD, as demonstrated in figure Fig. 1a.

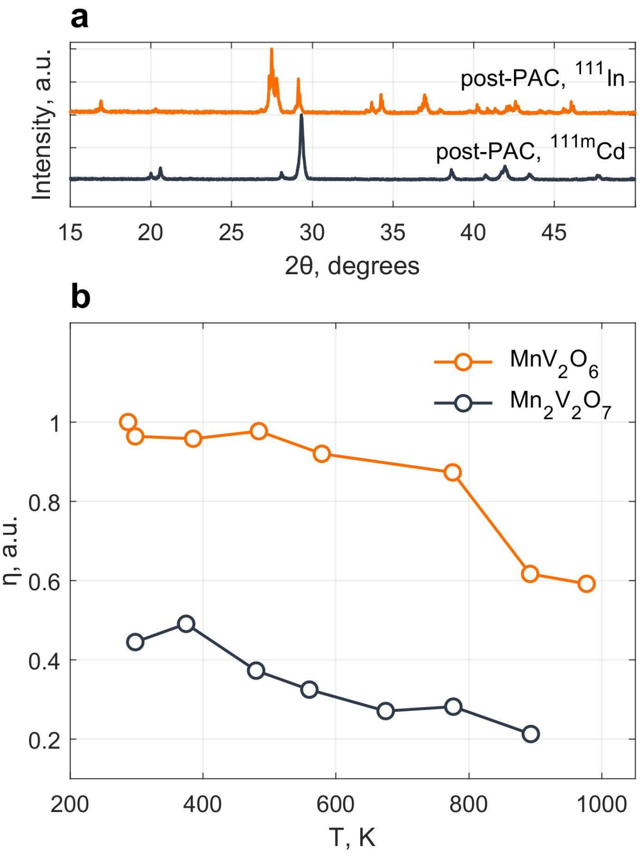

Figure 1: (a) XRD patterns recorded after PAC experiments in nominal MnV_2O_6 at 973K. (b) Asymmetry of electric field gradient, $\eta(T)$, probed with ^{111m}Cd(^{111}Cd)-PAC at ISOLDE.

Despite being promising, we caution against considering this result as conclusive, since parent isotopes may be responsible for the discrepancy in the relaxation of probe surroundings. The conventional method is to investigate this effect with *ab initio* simulations. Alternatively, the sites may be identified with the help of characteristic phase transitions, and, conveniently, $Mn_2V_2O_7$ undergoes one at experimentally attainable conditions. This temperature range will be explored in the upcoming studies.

References

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Multifunctional Perturbed Angular Correlations Spectrometer (MULTIPAC)

Results of experiment LOI249

Thien Thanh Dang, Ian Chang Jie Yap, Nicole Pereira de Lima, Juliana Schell for the SSP collaboration

MULTIPAC is an advanced spectrometer that is capable of simultaneously performing vibrating sample magnetometer (VSM) experiments and $\gamma - \gamma$ time-differential perturbed angular correlation (TDPAC) measurements under controlled conditions: an applied external magnetic field of up to 8.5 T and temperatures ranging from 3 to 375 K [1]. The VSM vibrates the sample in a uniform magnetic field, which induces an electromagnetic force (emf). Macroscopic magnetic properties of the sample can be inferred, such as ferromagnetism, and magnetic phase transitions. In addition, TDPAC provides information about hyperfine interactions occurring in materials. Local properties can be investigated microscopically, such as magnetic and electrical charge distribution in the vicinity of the TDPAC probe nuclei.

The VSM components comprise three distinct parts: the cryogen-free magnet (CFM) system, the variable temperature cryostat (VTC) system, and the VSM probe. The CFM and VTC System is a highly effective investigative device that utilizes the latest cryogen-free technology, magnet, and active shield design. It is capable of achieving high magnetic fields within a small, confined space while also preserving helium gas as a scarce natural resource. Furthermore, it is a safer alternative to using liquid helium as a coolant. The utilization of the VSM allows for the direct measurement of the magnetic properties of the sample, eliminating the need to remove it from the sample holder before or after TDPAC measurements.

The TDPAC has two main components: cylindrical $LaBr_3$:Ce crystals + MPPCs and high-speed digitizers. Cylindrical $LaBr_3$:Ce crystals measuring 4.54 cm in diameter and 4.82 cm in height were chosen due to their high energy resolution (6.8% with 511 keV photons) and time resolution (ranging from sub-nanoseconds to single digits of nanoseconds) (refer to Fig. 1, left). The crystals demonstrated a remarkable energy resolution of 2.81% @1173.2 keV and 3.19% @1332.5 keV, along with a time resolution of 1.01 ns. High-speed digitizers are utilized to capture waveforms that represent single photon pulses. The 10-bit digitizers that can sample at 10 GS/s are employed to ensure precise timestamps of the photon pulses (refer to Fig. 1, right).

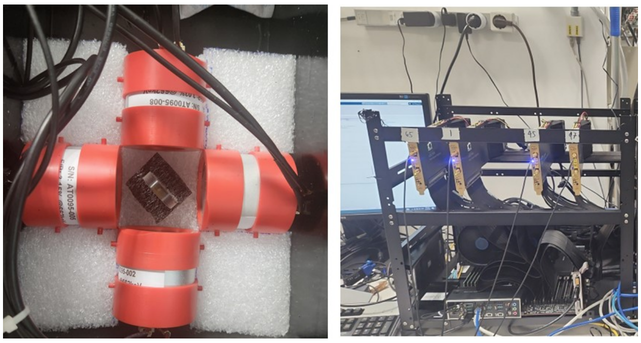

Figure 1: (Left) Cylindrical $LaBr_3$:Ce crystals + MPPCs, (Right) Digitizers (U5310A by Acqiris).

MULTIPAC is a system that offers a wide range of possibilities, allowing for the investigation of samples of interest at both microscopic and macroscopic levels. It facilitates innovative research projects and collaborations with ISOLDE-CERN. The MULTIPAC team has initiated material science projects described in LOI249 [1], that are expected to yield important results from April 2024.

This project has received funding from the Federal Ministry of Education and Research (BMBF) under grants 05K16PGA, 05K22PGA and 05K22PGB.

References

[1] J. H.-Schell, D. C. Lupascu, et al., *CERN-INTC-2023-012 / INTC-I-249. Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee (2023). https://cds.cern.ch/record/2845935/files/INTC-I-249.pdf* .

Ground-state properties

News from CRIS

Abigail Charlotte McGlone for the CRIS collaboration

In 2023, CRIS experienced another successful year, conducting four experiments exploring atoms and molecules across the nuclear landscape. The year began with an upgrade of the CRIS beamline, improving the beam transport efficiency and facilitating the installation of new detection chambers and a Decay Spectroscopy Station (DSS) to enhance the experiment's capabilities. This upgrade continued with the addition of a new tape station shown in Figure 1 which enables long-lived contaminants to be removed, allowing for the study of short-lived radioactive species with decay-assisted laser spectroscopy and laser-assisted decay spectroscopy. This follows on from the technical upgrades of previous years, including the installation of voltage scanning [1]. The continual upgrades of the CRIS beamline provide improvements in the sensitivity of our measurements and enable the study of further radioactive isotopes.

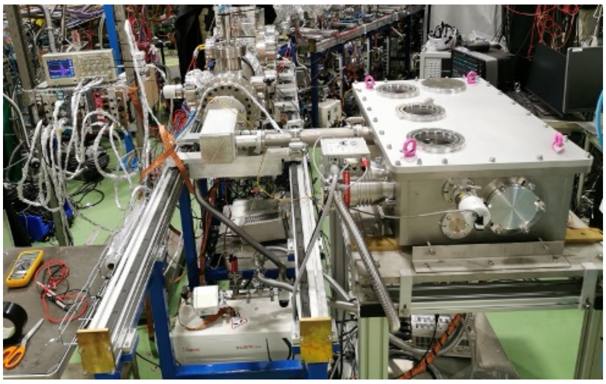

Figure 1: Image of the new end of the beamline and tape station installed at CRIS in August 2023

Four experiments were conducted at CRIS between June and December. In June 2023, the isotope shifts of ^{33,34}Al were measured at CRIS, to extend measurements past the $N = 20$ shell closure for investigation into the island of inversion surrounding this region. The $N = 20$ island of inversion describes a region of enhanced collectivity and deformation and the weakening of the $N = 20$ shell closure, this is shown well in Ne, Na and Mg. The new measurements of ^{33,34}Al complement existing data from 2022 and allow for the study of the evolution of ground-state structure entering the $N = 20$ island of inversion at the border between spherical and well-deformed nuclei.

The spotlight then shifted to chromium isotopes in July, exploring the region between the $N = 28$ and $N = 40$ shell closures. Thirteen isotopes of Cr were studied during this week long experiment, with the first firm spin assignments for ^{57,59,61}Cr, and complete measurements of the charge radii and nuclear moments from $^{50-62}$Cr. The new spin assignments will have consequences on the physical interpretation of beta decay data within the region.

In the summer, the installation of the new tape station was a significant milestone. It facilitated an extensive operation encompassing both decay-assisted laser spectroscopy and laser-assisted decay spectroscopy measurements of Zn isotopes, extending beyond the $N = 50$ shell closure. This endeavor confirmed spin assignments and acquired new charge radii measurements for ^{81,82}Zn.

During the Winter Physics period at ISOLDE, CRIS performed measurements on the long-lived radioactive molecule RaF, continuing the work recently published in Nature Physics in [2] and producing new measurements which are presented in [3]. For further insights into the investigation of radioactive molecules at CRIS, please refer to the additional contribution.

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https://isolde-cris.web.cern.ch

CRIS would like to thank the ISOLDE operational team for the successes in 2023 and plan for another busy year in 2024.

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Advances in molecular spectroscopy of RaF at CRIS

Results of experiment IS663

Carlos M. Fajardo-Zambrano for the CRIS collaboration

In the past few years, molecules have become a promising tool for diverse fields. Among them, the rich electronic structure and ease of polarizability have made diatomic molecules the most sensitive system for studies of charge conjugation and parity (CP) violation moments, such as the electron electric dipole moment (eEDM) and nuclear Schiff moment [1]. Both of these moments scale with the atomic number faster than Z^2, while the latter is further enhanced in octupole deformed nuclei [2]. However, since such nuclei tend to be radioactive, the current studies have been limited to stable molecules.

As a first step towards more sensitive studies of CP-violation using radioactive probes, in the past years, the CRIS collaboration has studied the electronic structure of RaF and its predicted laser-coolable transition $A^2\Pi_{1/2}$ in high resolution on different isotopologues, making RaF the first radioactive molecule studied using laser spectroscopy [3].

In the 2021 RaF campaign, the spectra of ^{226}RaF (I = 0) and ^{225}RaF (I = 1/2) were measured. Since the former is non-sensitive to the hyperfine structure (HFS), its spectrum has been used to extract with high precision the molecular parameters of RaF [4]. These parameters can be obtained for different isotopologues, scaling them with the reduced mass ratio. As such, they could be set as constant for retrieving the HFS molecular parameters of ^{225}RaF. This has made RaF the first radioactive molecule where the magnetic dipole moment has been measured and provided further experimental data to be compared with theoretical calculations.

In 2023, we were able to measure the missing predicted electronic states on RaF [5]. Furthermore, the HFS of ^{223}RaF (I = 3/2) was successfully measured, allowing the extraction of the electric quadrupole moment. Moreover, with the measurement of the HFS in three different isotopologues, the molecular isotope shift could be obtained and compared to the atomic isotope shift literature value. Figure 1 shows the HFS in one of the rotational transitions of the R-branch on ^{223,225,226}RaF.

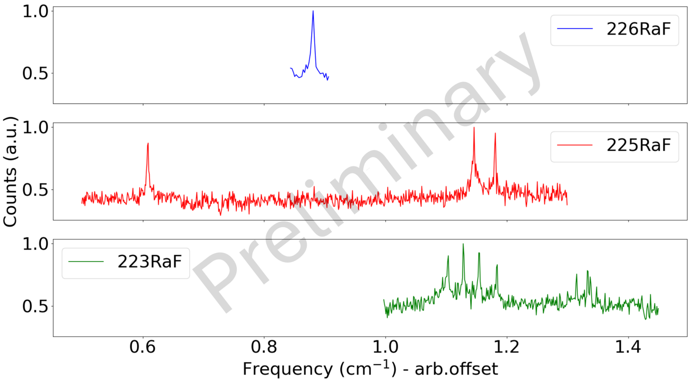

Figure 1: Measured rotational hyperfine transition of the R= 20.5 rotational band in ^{226}RaF (blue), ^{225}RaF (red), and ^{223}RaF (green) using CRIS. The results are preliminary.

Finally, the RaF 2023 campaign also aimed to measure the lifetime for the $A^2\Pi_{1/2}$ state, as this would determine the maximum photon scattering rate in a laser-cooling transition. The accuracy of such measurement was corroborated through a systematic study using the known lifetime of the ^{221}Fr ($8P_{3/2}$) atomic state with an excellent agreement.

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Towards absolute charge radius measurements of Ag isotopes

Results of experiment IS672

Marie Deseyn for the IS672 collaboration

Charge radii of silver isotopes have been extensively studied using laser spectroscopy [1], but have large systematic uncertainties originating from the mass and field shift being calculated from large scale atomic calculations in combination with interpolation of nearby elements. Discrepancies with nuclear density functional theory [2] further motivate experimental determination of the mass and field shifts. This will be investigated through muonic x-ray spectroscopy of ^{107}Ag, ^{109}Ag and ^{108m}Ag ($t_{1/2} = 483$ y). While the two stable isotopes are available with sufficient enrichment, ^{108m}Ag requires bespoke production: at least 3×10^{16} atoms and $\approx 95\%$ purity are needed for sufficient intensity and resolution for the muonic x-rays, respectively, as established from a test experiment in 2023 at PSI.

Neutron irradiation of enriched ^{107}Ag produces ^{108m}Ag via the ^{107}Ag(n, γ)^{108m}Ag channel, but with only $\sim 0.25\%$ purity at most. To investigate the subsequent separation procedure, a separation test was performed at GLM. A natural silver target underwent neutron irradiation, yielding a target with 42(6) Bq of ^{108m}Ag and 65(2) kBq of ^{110m}Ag. Since the hyperfine structure of ^{108m}Ag and ^{110m}Ag are near-identical, and the specific activity of the latter is substantially higher, the test study was performed with ^{110m}Ag.

Different laser conditions were explored to optimize ion source performance, ensuring the best combination of collection efficiency and fraction of ^{110m}Ag compared to ^{109}Ag. One of the main outcomes stems from the resonant frequency of the $5s_{1/2} \rightarrow 4p_{3/2}$ transition in ^{110m}Ag being within the tails of the corresponding ^{109}Ag resonance. Detuning the lasers from the ^{110m}Ag resonance, further from the ^{109}Ag resonance, enhanced the relative fraction of ^{110m}Ag in the beam, predominantly by reducing the number of ^{109}Ag ions. Ion load effects, where excessive space charge perturbs the confinement potential in the ion source, significantly impacted the collection as can be seen in Fig. 1. This figure shows the beam current for the lasers configured on the ^{109}Ag and ^{110m}Ag resonance divided by the rescaled beam current for the lasers off-resonance of ^{110m}Ag. The rescaling ensures alignment of all three beam currents at the start of the collection, when no ion load effects are expected. Hence, deviations of this ratio from 1 are attributed to a decrease in laser ionization efficiency induced by ion load effects, which is observed when the beam current increases too much.

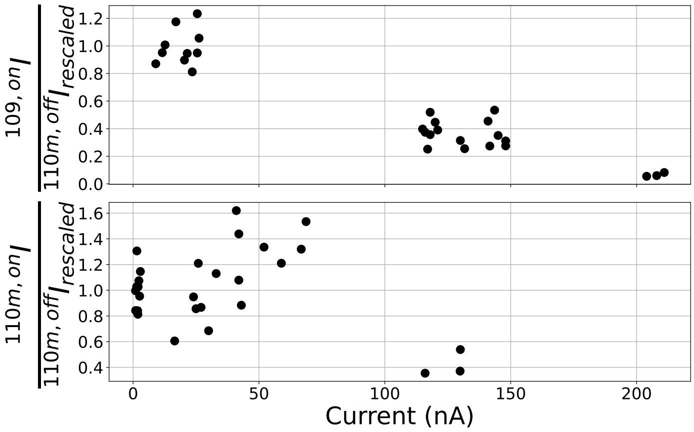

Figure 1: Beam current for lasers on the ^{109}Ag ($^{109,on}I$) and ^{110m}Ag ($^{110m,on}I$) resonance divided by the rescaled beam current for lasers off-resonance for ^{110m}Ag ($^{110m,off}I_{rescaled}$) as a function of $^{109,on}I$ and $^{110m,on}I$, respectively.

Collection on the ^{110m}Ag resonance is more constrained by ion load effects due to more ions overall present in the ion source, in particular ^{109}Ag ions. Consequently, collection on the ^{110m}Ag resonance necessitates lower currents, resulting in a longer collection time, despite its higher ionization efficiency.

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Pushing the sensitivity limits of Laser Spectroscopy

Edward N. Matthews for the COLLAPS collaboration

In 2023, the COLLAPS collaboration pushed the boundaries of experimental sensitivity through the execution of three successful experiments, each of them in a different region of the nuclear chart and with a unique contribution to our understanding of nuclear structure. The year commenced with the investigation of neutron-deficient thallium ($Z = 81$) isotopes, aiming to extend our previous knowledge of the heavy region. The goal was to quantify the effect of a single hole in the $Z = 82$ shell closure and to compare the electromagnetic moments to its magic lead neighbours. The focus then shifted to thulium ($Z = 69$), where the collaboration aimed to explore the region of the most neutron-deficient cases, edging toward the proton emitter nucleus ^{147}Tm. These measurements were conducted in collaboration with ISOLTRAP enabling the assessment of yields and contamination in the region. These tests also showed an efficiency of 1/500 ions for the instrumentation thus making the very exotic ^{147}Tm feasible for a second beamtime, already accepted by the INTC. The final efforts of the year were dedicated to the light region of semi-magic calcium, with a focus on $^{53-54}$Ca. These two very exotic isotopes, produced at only 20 and 1 ions per second respectively, were not in reach of the conventional COLLAPS setup and required a more sensitive detection method, the ROC technique.

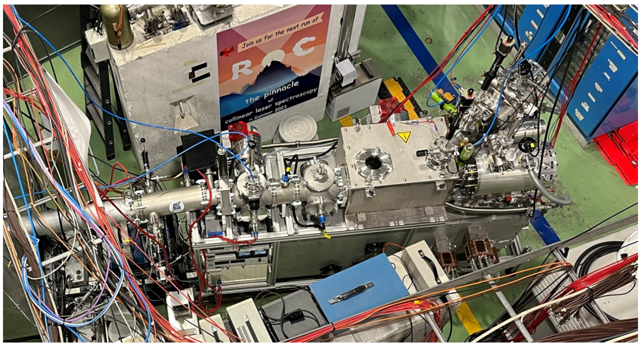

Figure 1: Photo of the new ROC setup.

The Radioactive detection of Optically pumped ions after state selective Charge exchange (ROC) operates by resonantly populating different electronic states in the calcium ion beam with a 393 nm laser. The calcium beam is then passed through a sodium charge exchange cell with each of these electronic states producing differing ratios of calcium atoms and ions. This difference is turned into a signal by splitting the beam into atomic and ionic components and detecting their decays with β detectors. This particle detection method is in contrast to normal COLLAPS fluorescent spectroscopy and enables ROC to significantly lower background and increase sensitivity.

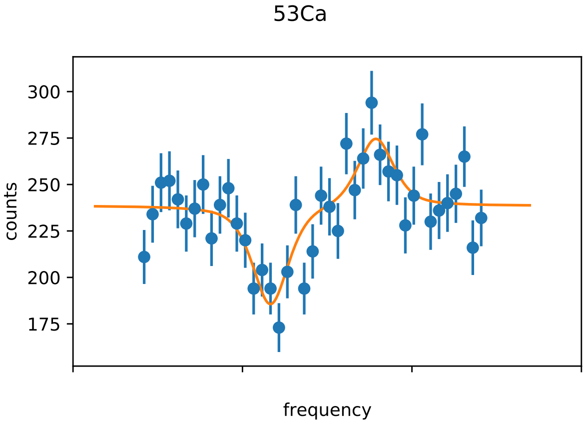

Figure 2: High resolution spectrum of ^{53}Ca with particle counts against frequency. This optical pumping technique can produce both positive and negative peaks[1].

The upgraded instrumentation (see Fig. 1) was designed, built and attached to the COLLAPS beamline in 2023. This was then used successfully to obtain the first measurement of the hyperfine structure and isotope shift of ^{53}Ca (see Fig. 2). The magnetic moment and charge radius extracted from these results will shed some light on the potential shell gap at $N = 32$. Further technical developments are being implemented to access ^{54}Ca in a second ROC beamtime in 2024.

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https://collaps.web.cern.ch/

MIRACLS’ new high-resolution setup

A. Roitman for the MIRACLS collaboration

Collinear Laser Spectroscopy (CLS) is a powerful technique to measure nuclear ground state properties of short-lived radionuclides, used extensively at ISOLDE [1].

Following the successful demonstration of its measurement principle with stable ions, the Multi-Ion Reflection Apparatus for CLS (MIRACLS) aims to improve the sensitivity of conventional fluorescence-based CLS for short-lived isotopes with low yields. This is achieved by trapping the ion bunches in a novel high-energy MR-ToF device, as shown in Fig. 1. Inside the MR-ToF trap, ions are reflected back and forth between two electrostatic mirrors for several thousands of revolutions. This allows the ions to interact with the laser beam for a much longer time than with conventional CLS, where ions are lost after travelling once through the optical detection region (ODR). In this way, ion bunches are “recycled" with the MIRACLS technique, and more statistics can be gathered, allowing for more exotic radioactive ions to be probed [2].

The first physics case planned for MIRACLS is the measurement of charge radii of exotic magnesium isotopes ^{33,34}Mg, which can be used to probe the island of inversion around ^{32}Mg. Accurate measurements of the charge radii in this region can serve as a stringent benchmark for ab-intio nuclear theory [3, 4]. Also of interest is the neutron-deficient ^{20}Mg, which can be used to study the shell-closure at $N = 8$ [3, 5].

In August 2023, MIRACLS conducted commissioning tests for the first time with ISOLDE beam. A resonance spectrum of stable ^{24}Mg was taken by performing single-passage CLS, finalizing the complete integration of the laser coupling scheme and the photon data acquisition system into the new MIRACLS setup. Demonstrating the functionality of the new MR-ToF device, ^{26}Mg ions were trapped with a beam energy of 6 keV for up to 16 revolutions. High voltage instabilities, increasingly observed during the course of this commissioning run, prevented us from more systematic measurements.

As a result of these tests, we have implemented several improvements to the MIRACLS apparatus. One of these improvements was electropolishing the MR-ToF mirror electrodes, which greatly improved the HV performance of the MR-ToF device. Moreover, commissioning measurements of the MIRACLS Paul trap with isolde beam resulted in a bunching efficiency of around 20 - 30% for a wide range of ion species, the lightest and heaviest being ^{20}Ne and ^{238}U, respectively.

Next, we plan on conducting systematic measurements in the MR-ToF device utilizing stable Mg ions delivered by the MIRACLS offline ion source. This will facilitate the preparations for upcoming measurements of exotic Mg isotopes.

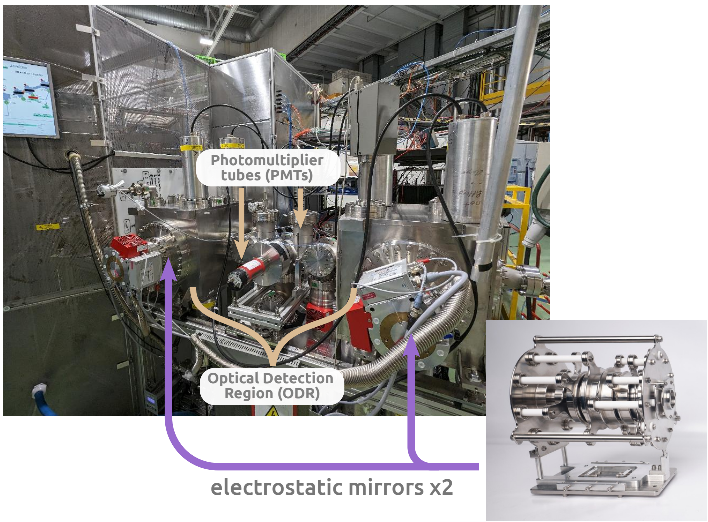

Figure 1: Photo of the high-energy MR-ToF device at MIRACLS. The inset shows a photo of one of the electrostatic mirrors.

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https://miracls.web.cern.ch

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Recent measurements and developments at ISOLTRAP during 2023

Daniel Lange for the ISOLTRAP collaboration

The ISOLTRAP [1] mass spectrometer performs high-precision mass measurements on radioactive ions. These measurements are crucial for determining the unique atomic mass of various radioactive nuclei, reflecting both, the masses of the constituents and the binding forces that unite them. Such measurements play a role in advancing our understanding of nuclear structure, nuclear astrophysics, neutrino physics, and the weak interaction.

ISOLTRAP uses a range of ion traps, including a tandem Penning-trap system and a Multi-Reflection Time-of-Flight mass spectrometer (MR-ToF MS). The MR-ToF MS is suitable for both mass separation and rapid, precise mass measurement. With mass-selective ion ejection from the MR-ToF through pulsed in-trap lift [2] and active voltage stabilization for the mirror electrodes [3], recent advancements have enabled isobaric mass separation with a resolving power of up to $5 \cdot 10^5$.

In June 2023, a prototype LaC_x target to deliver neutron-deficient cadmium beam was tested in collaboration with the Target and Ion Source Development (TISD) team. Design improvements included a new way of mounting the tantalum ion source enhancing structural integrity and a new container and modifications to the heat screens, ensuring improved temperature homogeneity across the target material. The observed yield was five times higher compared to the ISOLDE yield database. This enabled precision mass measurements of neutron-deficient cadmium with the MR-ToF MS (see Fig. 1) leading to an improved mass excess of ^{98}Cd and first direct measurement of ^{97}Cd together with its isomeric state ^{97,n}Cd. The latter peak is superimposed with ^{97}Rb, not separated in time-of-flight but distinguishable in abundance comparing laser (de-)tuned for cadmium (in Fig. 1 red and blue, respectively) normalized to the number of bunches. Moreover, the outstanding target performance enabled an upper yield determination for ^{96}Cd and demonstrates ^{96}Cd to be within reach, for which a dedicated measurement is to be performed this year following the acceptance of the proposal [4].

Furthermore, ISOLTRAP was involved in various other experiments for beam composition studies and yield checks with the MR-ToF including the joint LOI244 with IDS for the development of neutron-rich mercury beams to study properties south-east of ^{208}Pb. In contrast to the molten lead target used in the past for the

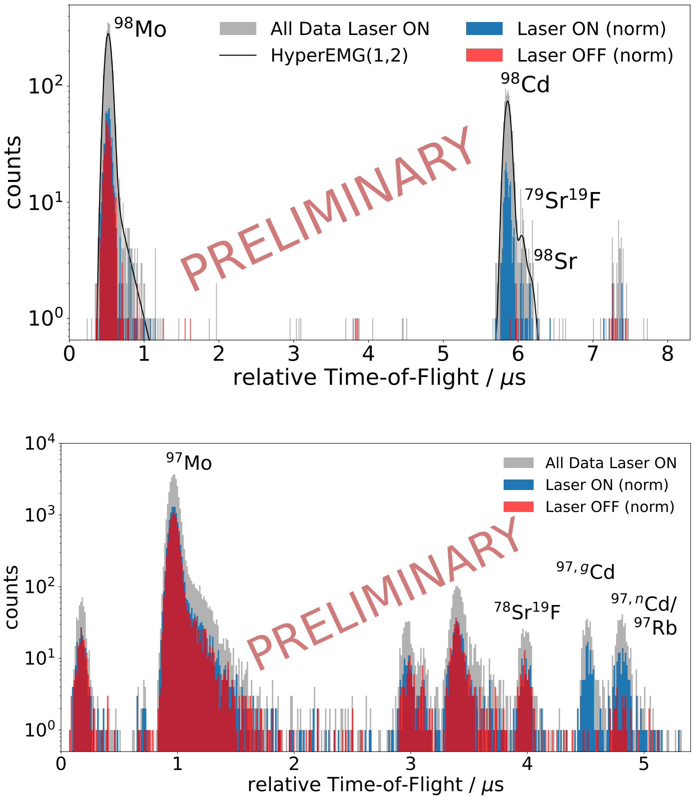

Figure 1: Time-of-flight spectra for the $A = 97, 98$ ISOLDE beam from a LaC_x target with laser ionization (de-)tuned for cadmium in (red) blue. The ground (left) and isomeric (right) states of ^{97}Cd in the lower ToF spectrum are well separated. The latter is superimposed with ^{97}Rb, which can be seen in the laser (off-)resonant comparison normalized to the number of bunches.

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https://isoltrap.web.cern.ch/

mass measurements of $^{206-208}$Hg at ISOLTRAP [5], a UC$_x$ target with low-temperature quartz transfer line and RILIS promises production of neutron-rich mercury beyond ^{208}Hg together with isobaric contamination suppression (especially Fr). The recorded ToF spectra in Fig. 2 present the first direct observations of ^{209,210}Hg, for which a yield of (2.2 ± 1.1) and (3.8 ± 1.9) ions/μC was determined, respectively. Due to time restrictions, the beam composition study had to be made with high ion-loads inducing systematic shifts on the ToF peaks due to the space-charge effects [6]. For this reason, a dedicated beamtime is required to exclude data-acquisition and space-charge effects by using lower ion-loads, which was proposed in the joint proposal with IDS [7]. Further isobaric contamination suppression is expected for lower quartz line temperatures due to the difference in adsorption enthalpies.

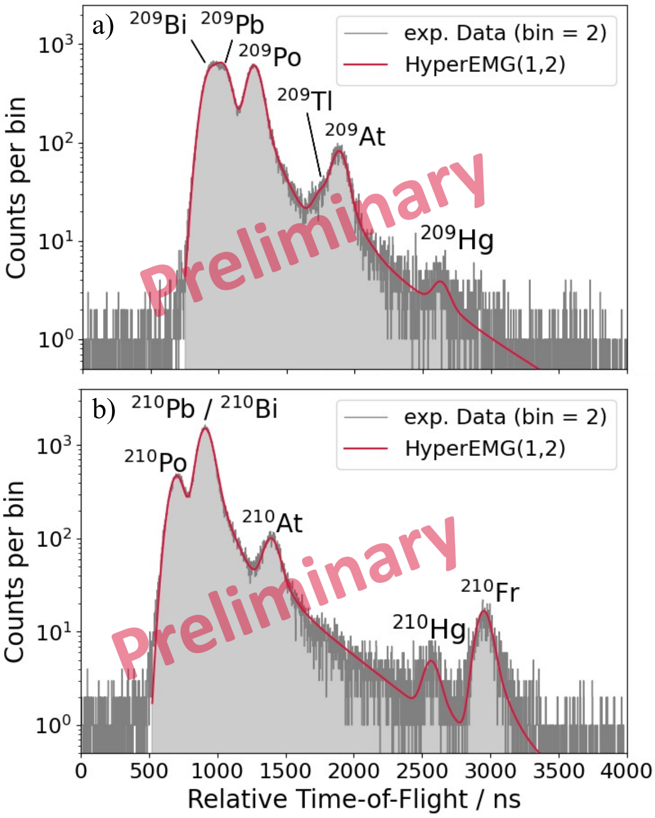

Figure 2: Time-of-flight spectrum for the $A = 209, 210$, respectively, ISOLDE beam from a UC$_x$ target with low-temperature quartz transfer line and laser ionization tuned for mercury.

To handle strong contamination more generally, a new radio-frequency quadrupole (RFQ) cooler and buncher will be commissioned for beam purification following the MR-ToF device this year. The new Mini-RFQ buncher will perform mass-selective re-trapping [8] and re-bunching of the ions of interest from the isobarically separated bunch ejected from the MR-ToF MS before being re-injected to perform mass measurements free of space-charge effects. Devices used in this beamline extension are controlled using a new EPICS-based control system which was integrated in the old LabVIEW-based control system. The EPICS integration now allows the gradual migration of the setup towards the new control system.

With newly installed environmental monitoring sensors around the setup, time-of-flight drifts were clearly assigned to temperature fluctuations. In order to improve stability, the temperature stabilization of the MR-ToFs voltage stabilization is currently ongoing.

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Beta-decay studies

Total absorption spectroscopy of ^{152}Tb for its medical interest.

Results of experiment IS722

C. Fonseca-Vargas, E. Nacher, J.A. Briz, U. Köster
for the ISOLDE-TAS collaboration

Radionuclides are widely applied in different medical techniques for diagnosis and treatment. The correct calculation of the dose administered to the patient in both cases depends on knowing very well the decay characteristics of the radionuclide used.

A recent work by Nichols [1]. He shows a list of radionuclides of potential medical applications and points out the deficiency in the nuclear decay data. He explicitly suggests the necessity to study some nuclei using total absorption spectroscopy (TAS).

In the experiment IS722 we applied the TAS technique to measure the beta decay of ^{152}Tb for its relevance in medicine, whose decay properties are not well enough established. The main goal of the experiment was to determine the beta intensity distribution, essential to calculating the total rate of electron capture and beta decay, and the relation between the energy per decay in the form of γ-ray and β-particles, which is important for calculating dose distribution.

A comparison between the experimental data and a Geant4 simulation of the same decay under the same conditions, using the evaluated ENSDF data, is shown in Fig. 1. The top panel displays the beta-gated TAS spectrum, while the lower panel exhibits the X-ray-gated spectrum. In both cases, the dark blue signifies the experimental data, and the magenta represents the total simulated spectrum.

If the ENSDF was correct and complete, one would expect the magenta spectrum to fit the blue one perfectly. However, what we obtained indicates a clear presence of the Pandemonium systematic error [2].

If we concentrate on the X-ray-gated spectrum Fig. 1 (bottom), the structures of both spectra match each other, they contain roughly the same populated levels. However, the intensity differs from 2 MeV onwards.

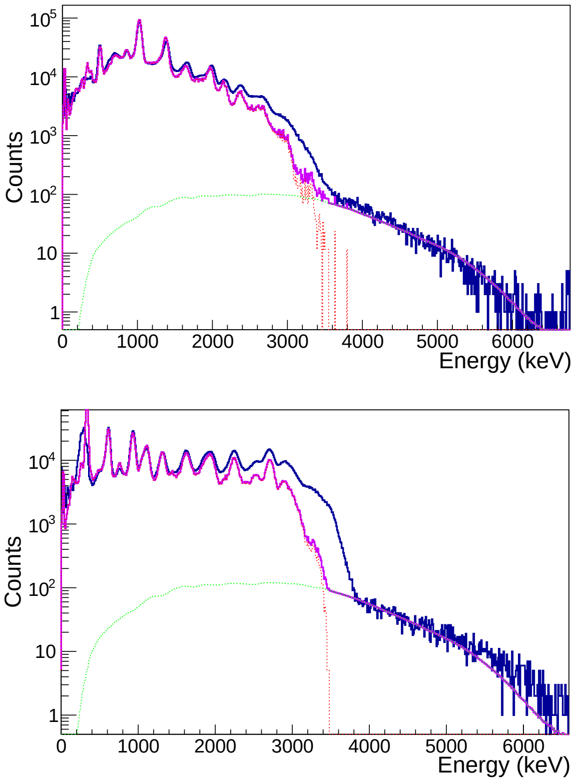

Figure 1: The top panel displays the beta-gated TAS spectrum. The bottom panel shows the X-ray-gated one. In both cases, the dark blue represents the experimental data obtained at ISOLDE. The light green represents the estimated pile-up contribution, the light red corresponds to the Geant4 simulation, and in magenta we have the sum of these two components.

The analysis procedure is still ongoing. In a next step the data would be unfolded to obtain the the quantity of interest, in this case the beta-intensity distribution.

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New station at VITO for β-decay spectroscopy with laser-polarised beams

Results of experiment IS733

Monika Piersa-Siłkowska for the DeVITO collaboration

In the summer of 2023, a new experimental station was integrated with the VITO beamline, creating new opportunities for β-decay studies at ISOLDE [1, 2]. This setup, called “DeVITO" (see Fig. 1), allows for β-decay spectroscopy with laser-polarised beams. The use of spin-oriented nuclei helps overcome some of the limitations of conventional β-decay measurements, particularly the limited ability to assign spins and parities. This is achieved by measuring the β-decay asymmetry of the excited state in coincidence with β-delayed radiation depopulating that state. The success of this technique in studies of allowed β transitions has been demonstrated by the Osaka group [3, 4]. It has been shown that the key ingredient towards unambiguous spin-parity assignments is the high polarisation of the beam. The VITO beamline [5], where spin orientation is induced via optical pumping, has proven to be a great place to implement this technique and develop its extensions.

At the heart of the DeVITO station is an implantation chamber mounted inside a compact water-cooled magnet built locally at CERN. This chamber contains two β-particle detectors placed at 0° and 180° angles with respect to the beam-axis (and polarisation) direction. Between them is a cubic crystal serving as an implantation host. The detection system also includes three Clover detectors and two VANDLE neutron time-of-flight arrays [6], enabling coincident measurements of γ rays and neutrons. Signals from the detectors and logic triggers are recorded by the XIA Pixie-16 DAQ system. The new station has been successfully commissioned with beams of neutron-rich ^{47,49,51}K [2].

The results of the first online run provided foundations for upgrades of the DeVITO setup, which were implemented last autumn. The improvements include the following: new front β-particle detector and beam collimating system, second VANDLE detector, and additional DAQ modules.

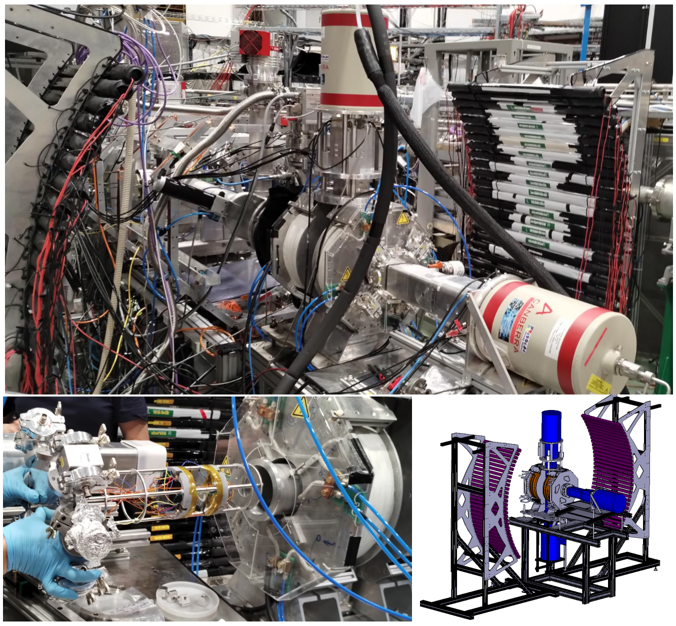

Figure 1: The new station at VITO for β-decay spectroscopy with laser-polarised beams.

As a result, the β-decay spectroscopy station at VITO is now capable of handling around 170 individual detector signals, making it ready for the main IS733 run. The second part of the commissioning experiment will be followed by studies of strong β-delayed neutron emitters in order to investigate the mechanism of β-delayed neutron emission, which is the main decay mode of the very neutron-rich nuclei involved in the astrophysical *r* process. The new setup at VITO is compact and flexible, allowing for various end-station configurations and a diverse research programme that is enabled by the ability to perform coincidence measurements of β-delayed radiation from spin-oriented nuclei.

The DeVITO station was developed by the local VITO team in collaboration with UTK, Warsaw, York,

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This project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 101032999, “BeLaPEx".

and IFIN-HH.

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Studies with post-accelerated beams

Highlights from the 2023 campaign at the ISOLDE Solenoidal Spectrometer

Patrick MacGregor for the ISS collaboration

The ISOLDE Solenoidal Spectrometer (ISS) saw another productive year in 2023. The ISS specialises in measuring single-nucleon transfer reactions in inverse kinematics with the radioactive ion beams produced by HIE-ISOLDE. In 2023, three (d,p) experiments in inverse kinematics were performed.

The first two, running in subsequent weeks during the summer, had very similar motivations. Beams of ^{49}Ca and ^{50}Ca were focused onto thin CD_2 targets within ISS, populating excited states in ^{50}Ca and ^{51}Ca. Extracting the spectroscopic factors in these reactions provides important benchmarks for phenomenological and *ab initio* calculations in this region, as well as providing information on new neutron magic numbers in calcium at $N = 32,34$.

In these reactions, the ejectile protons were detected on the ISS silicon array placed upstream of the target, and the ^{50}Ca/^{51}Ca recoiling nuclei were detected in a downstream recoil detector.

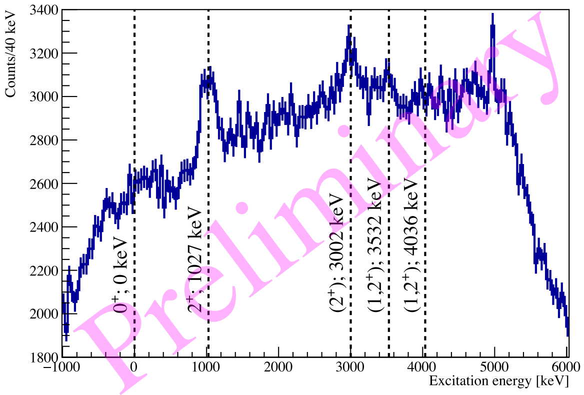

Figure 1: Excitation-energy spectrum for the d(^{49}Ca,p) reaction [1]. This is gated on the timing of the release of ions from REXEBIS, and counts collected when the beam is off have been subtracted.

While both of these experiments are in a preliminary stage of analysis, the results are looking promising. Figure 1 shows a partially cleaned excitation-energy spectrum with black vertical lines showing known states. Work is ongoing to further clean this spectrum by removing background from protons emitted in fusion evaporation, and improving time gates and event selection.

The third experiment was the ISS's first winter-physics experiment, taking a long-lived ^{7}Be beam and performing a similar (d,p) experiment in inverse kinematics, to measure excited states above 16 MeV in ^{8}Be. The recoil detector was placed immediately downstream of the target to allow for the detection of the $^8\text{Be}^* \rightarrow \alpha + \alpha$ breakup. One of the spokespersons for the experiment, Moshe Gai, was incredibly impressed with the dedication of the machine supervisors and the quality of the ^{7}Be beam and showed his appreciation for their work in Fig. 2.

Figure 2: A very pleased spokesperson with ISOLDE's excellent machine supervisors [2].

The whole ISS collaboration is grateful for the beams provided at ISOLDE and looks forward to an-

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https://isolde-solenoidal-spectrometer.web.cern.ch/

other successful year of experiments in 2024.

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The (d,p) reaction on ^{11}Be with ISS

Results of experiment IS677

*J. Chen, B. P. Kay, D. K. Sharp, L. P. Gaffney,
S. J. Freeman, P. MacGregor, C. R. Hoffman, S. Bennet,
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The available data on ^{12}Be are ambiguous and limited. It has also been difficult to access via well-understood probes such as single-nucleon transfer reactions as its nearest neighbors are all unstable. In these measurements, we see various exotic structures such as shell weakening and cross-shell excitations, but some ambiguities persist and some information is still missing experimentally. There have been three recent measurements of the (d,p) reaction, but their energies were not optimized for the (d, p) reaction or with the best angular coverage [1, 2, 3].

A new experimental measurement of the ^{11}Be(d,p) reaction was carried out at the HIE-ISOLDE Linac beam facility at CERN with the ISOLDE Solenoidal Spectrometer (ISS). A beam of ^{11}Be at 9.78 MeV/u was delivered with an intensity of 10^6 particles per second onto a deuterated-polyethylene (CD_2) target. Protons are transported backward by a 2.0-T magnetic field of ISS, returning to the beam axis and detected by the newly constructed ISS silicon detector array. A set of ΔE-E recoil detectors provides particle identification of the beam-like particles.

Figure 1 shows the excitation energy spectrum of ^{12}Be, deduced from the present ^{11}Be(d, p) reaction with timing coincidence on the recoil detectors. Unbound states decaying through one and two neutron emissions were identified with the coincidence of ^{10}Be and ^{11}Be, respectively. A resolution of $\sim$ 140 keV was obtained for the excitation energy spectrum. Four known bound states in ^{12}Be have been populated including the ground, 2.11-, 2.25- and 2.72-MeV states. One resonance at 3.18(1) MeV is observed at about 10 keV above the one-neutron separation energy S_n=3.170 MeV. The signature of this near-threshold resonance was observed in Ref. [4], but the energy resolution of the previous measurement did not allow for the determination of its precise excitation energy and width. In the present measurement, the excitation energy, and width of this near-threshold resonance were determined to be 3.18(1) MeV and ~40 keV, respectively. The near-threshold location and the very narrow width of this resonance are very intriguing features, which require future theoretical studies.

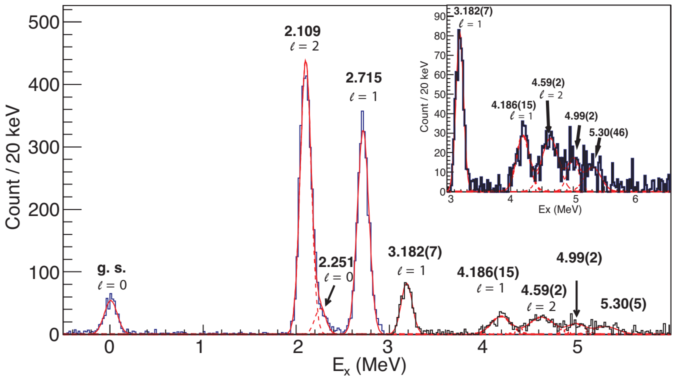

Figure 1: The excitation spectrum of ^{12}Be populated via the ^{11}Be(d, p) reaction. The peaks are labeled by their excitation energies (in MeV) together with their spin-parity assignments. The inset shows the observed unbound states.

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Evolution of single-particle states in the Mg isotopic chain: the $d(^{30}\mathrm{Mg},p)$ reaction measured with the ISOLDE Solenoidal Spectrometer

Results of experiment IS680

Patrick MacGregor for the IS680 collaboration

The $N = 20$ “island of inversion” [1] is a neutron-rich region of the nuclear chart which is of particular importance for understanding the evolution of nuclear structure. In this region, deformed intruder configurations (particle-hole excitations) dominate at ground-state and low-excitation energies which is facilitated by the weakening of the $N = 20$ shell closure. Additionally this shell gap weakens as protons are removed, leading to a new shell closure emerging at $N = 16$, which produces doubly-magic properties in ^{24}O [2].

The magnesium isotopes exhibit a swift transition into the island between ^{30}Mg and ^{31}Mg [3, 4], and thus are a useful measure of how single-particle structure evolves into the island. Data on isotopes in this region can be used to test the validity of current nuclear models and be used to further refine them.

The IS680 collaboration have measured the $d(^{30}\mathrm{Mg},p)$ reaction using a similar setup to the previous $d(^{28}\mathrm{Mg},p)$ reaction at the ISOLDE Solenoidal Spectrometer (ISS) in 2018 [5]. A 8.52 MeV/u ^{30}Mg beam was provided by ISOLDE and was incident on a CD_2 target placed in the centre of the ISS magnet, which had a uniform magnetic field of 2.0 T. Protons emitted in this reaction travel upstream, following helical trajectories, and were focused onto a bespoke silicon array surrounding the beam-axis. An annular E-ΔE detector was placed downstream to collect the recoiling ^{31}Mg in the reaction, and used for particle identification.

Figure 1 shows a recoil-gated excitation-energy spectrum, and fitting peaks at different z yields angular distributions such as that shown in Fig. 2. Work is ongoing to further refine these distributions and to use DWBA codes to extract spectroscopic factors for each state. Once the analysis is complete, these data can be compared to the data from ^{29}Mg to help understand how the single-particle structure evolves as the island of inversion is entered.

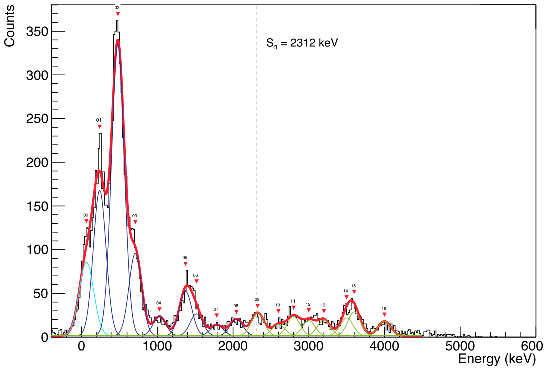

Figure 1: ^{31}Mg excitation-energy spectrum. The FWHM of bound states is 198 keV. Data from reactions on three different CD_2 targets were used to produce this spectrum. Bound states are in blue, unbound states are in green. The first peak (cyan) is a doublet.

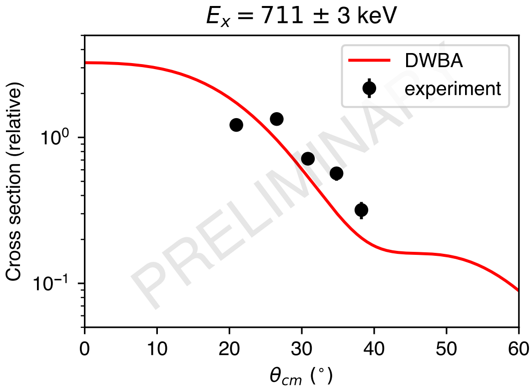

Figure 2: An example angular distribution of the 711-keV state in ^{31}Mg with $j^\pi = \frac{3}{2}^+$. The cross section in this figure has not been normalised.

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`https://isolde-solenoidal-spectrometer.web.cern.ch/`

Single neutron transfer reaction on ^{22}Ne measured with the ISS

Results of experiment IS689

Ben Jones for the ISS collaboration

The ISOLDE Solenoidal Spectrometer (ISS) allows for the study of radioactive nuclei by direct reactions in inverse kinematics. Ejectiles from reactions are transported in helical orbits back to the magnetic axis. Following an orbit, the University of Liverpool built ISS silicon array makes position and energy measurements of the ejectiles as they return back to the axis (Fig. 1). Using these measurements, the excitation energies of states in a recoiling nucleus and corresponding reaction cross sections can be extracted. Unlike conventional detector setups operating in inverse kinematics, this technique avoids the kinematic compression of the Q-value spectrum in the lab frame.

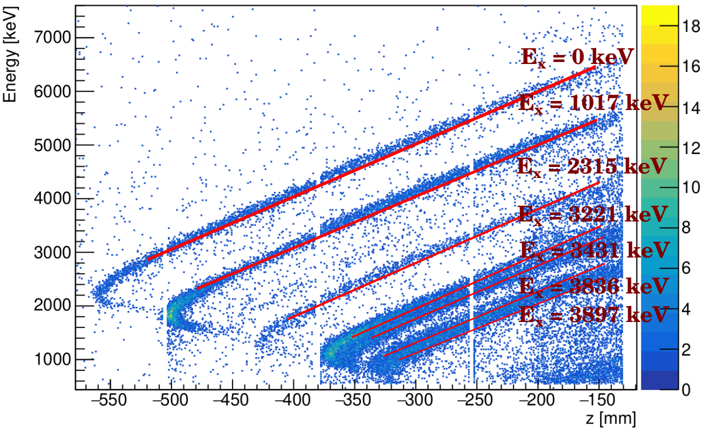

Figure 1: Recoil-gated proton energy against Z-distance for the d(^{22}Ne,p)^{23}Ne reaction. Kinematic lines of the states populated in ^{23}Ne are highlighted.

The single neutron transfer reaction d(^{22}Ne,p)^{23}Ne was used as commissioning experiment for the ISS. A stable beam of ^{22}Ne reacted with a deuterated polyethylene target at 6.05 MeV/u. This beam energy was chosen to allow for direct comparison of cross sections with previous measurements where the reaction was performed on gaseous targets in normal kinematics with 12.1 MeV deuterons [1, 2].

In this configuration, the angular coverage of the array in the centre of mass system was $10° < \theta_{cm} < 45°$, with solid angle coverage of 94% in θ and 70% in ϕ. The measured cross sections were corrected for the geometrical efficiency of the array. Simultaneously measuring the amount of elastically scattered deuterons with a detector placed downstream of the target allowed for calculation of the beam rate. This was then used to normalise the measured angular distributions to give absolute cross sections.

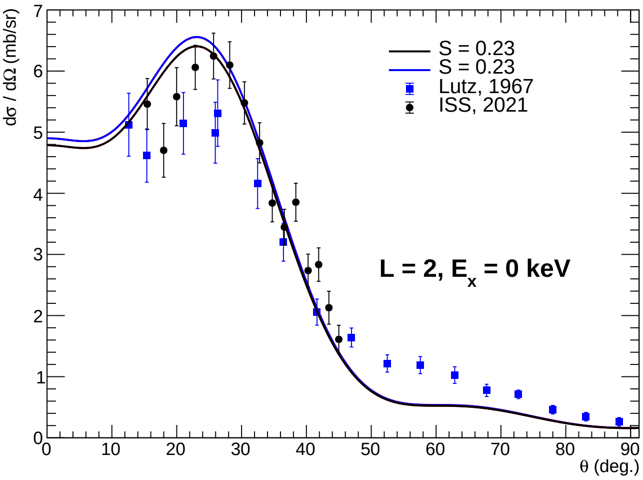

Figure 2: Angular distribution for the ground state in ^{23}Ne following a (d,p) reaction at 6.05 MeV/u measured in inverse kinematics by ISS (black) and in normal kinematics by Lutz et al., 1967 (blue) [1] with corresponding DWBA fits.

Spectroscopic factors were extracted by comparing the measured cross sections to DWBA calculations performed by the code Ptolemy [3]. Figure 2 compares angular distributions measured by the ISS in inverse kinematics with data taken in normal kinematics using gas targets by Lutz et al. [1]. Both distributions were fitted with the same DWBA calculation from Ptolemy, with the same optical model parameterisation for the deuteron [4] and proton [5]. As shown, the extracted spectroscopic factor for both data sets are in good agreement. These results help demonstrate the validity of the technique for studying reactions with radioactive ions beams and consolidate future results.

`https://isolde-solenoidal-spectrometer.web.cern.ch`

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Deformation in neutron-rich ^{93}Kr

Results of experiment IS711

Annie Dolan for the ISS collaboration

Deformation is observed in neutron-rich nuclei in the A = 100 region. As N approaches 60, the Zr and Sr isotopes (Z = 40 and 38, respectively) show a large jump in the 2_1^+ energies and the B(E2;$2_1^+ \to 0_1^+$) values [1, 2], indicating a dramatic shape change. However, for the neighbouring nuclei with fewer protons, these values change more smoothly, indicating a less dramatic shape change. This is the case for the Kr (Z = 36) isotopes [3]. The $\nu g_{7/2}$ orbital is filled in the ground states of krypton isotopes around N = 59 and is thought to lower the energy of the $\pi g_{9/2}$ orbital and help to drive deformation in this region.

In October 2022, a ^{92}Kr*(d,p)*^{93}Kr reaction was performed in inverse kinematics with a beam energy of 7.35 MeV/u using ISS, to study the neutron single-particle properties of the ^{93}Kr nucleus. The excitation energy spectrum shown in Fig. 1 shows the 19 states that were observed. Angular distributions were obtained for each of the observed states, and where possible, ℓ values have been assigned and spectroscopic factors extracted. These are shown in Fig. 2.

The doublet at 354-359 keV has been resolved in the angular distribution, allowing for the determination of the strength of the $\ell = 4$ transition. This is important for understanding the evolution of the $\nu g_{7/2}$ involved in driving the deformation in this region.

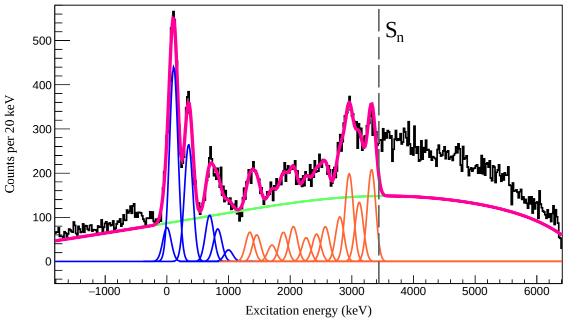

Figure 1: Excitation energy spectrum of the ^{93}Kr nucleus. States observed in previous experiments shown in blue. Possible newly observed states shown in orange.

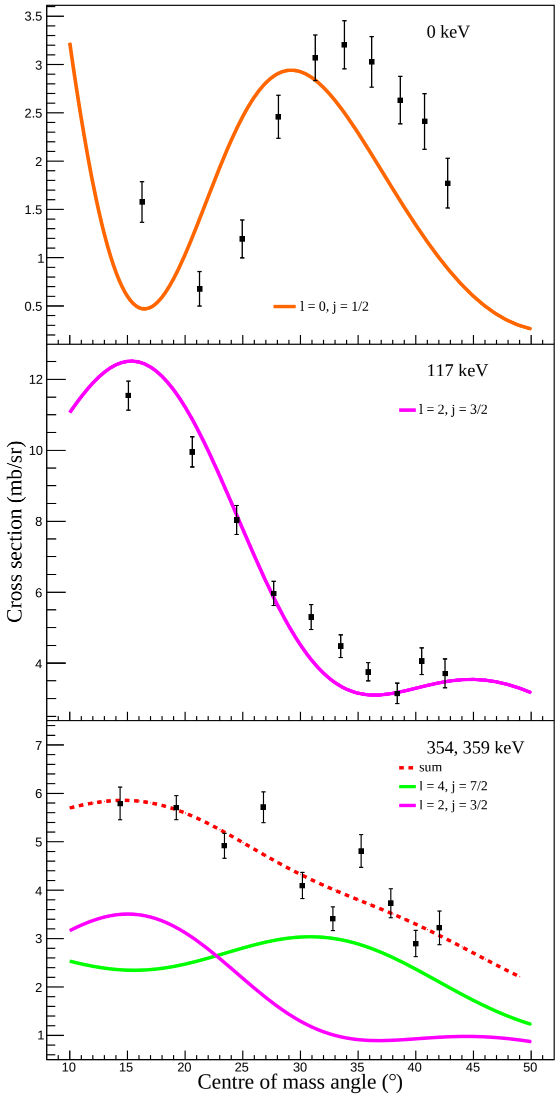

Figure 2: Angular distributions of low-lying states in ^{93}Kr.

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Miniball activities and highlights from 2023

Frank Browne for the Miniball collaboration

The Miniball γ-ray spectrometer made its return to ISOLDE in 2022 with experiments focussed around the neutron-rich tin and proton-rich mercury regions. In 2023 Miniball activities ramped up significantly to conduct eight experiments across the nuclear chart utilising Coulomb-excitation and particle-transfer reactions.

Starting on the GPS, the first stop on Miniball's tour of the nuclear chart were two experiments on proton-rich mercury isotopes. Ranging south, Coulomb excitation of ground and isomeric states of neutron-rich Zn isotopes was performed. Switching over to the HRS, the so-called "plunger technique" was utilised for the first time at ISOLDE to measure lifetimes in states of ^{144}Ba. This was followed by experiments utilising both particle transfer and Coulomb excitation around doubly magic ^{132}Sn on both the GPS and HRS. Summarising, the experiments addressed a diversity of physics questions including, but not limited to:

- Octupole correlations in ^{144}Ba
- Particle-phonon states in ^{133}Sb
- $B(E2)$ sum rules around ^{132}Sn
- Collectivity of ^{130}Sn
- Shell structure near ^{78}Ni
- Shape coexistence at $N = 50$ in ^{79}Zn
- Shape coexistence and quadrupole moments of ^{182,184,185}Hg

This wide-ranging physics campaign was made possible by the efforts of the ISOLDE machine supervisors and their provision of very pure and intense beams. The majority of the experiments performed were aided by the RILIS team without which the crucial separation of isomeric states and suppression of contaminants could not be achieved.

Of the many interesting experiments performed at Miniball in 2023, the Coulomb excitation of ^{79}Zn is timely with regard to other ISOLDE activities. The spin-parities of ground and isomeric states of ^{79}Zn are $9/2^+$ and $1/2^+$, respectively, with the latter's energy being recently reported by the ISOLTRAP and IGISOL collaborations [1]. It is suggested that the isomeric $1/2^+$ state is the bandhead of a low-lying deformed structure. Coulomb excitation of both the ground and isomeric states can be used to investigate in detail these separate and coexisting structures. Figure 1 shows the γ-ray spectrum taken by Miniball in coincidence with the Coulomb excitation of ^{79}Zn with clearly observed transitions from decays of states excited from the isomeric and ground states.

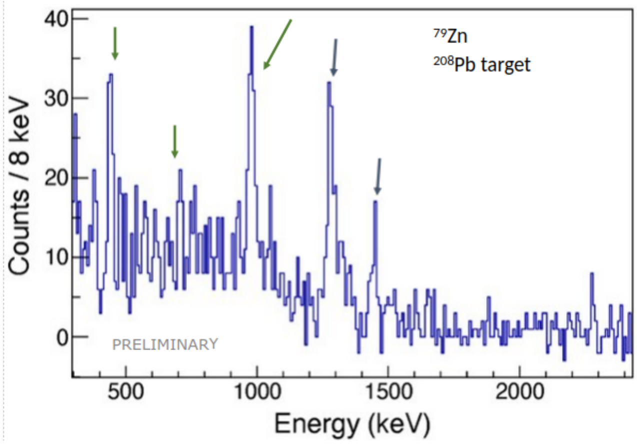

Figure 1: Gamma-ray energy spectrum in coincidence with the ^{79}Zn Coulomb-excitation reaction on a ^{208}Pb target [2]. Clearly identified are excitations of the ground and isomeric states of ^{79}Zn.

Before the next LS, Miniball looks forward to many exciting experiments, and further synergy with other experimental setups at ISOLDE.

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https://isolde.cern/miniball

News from the Superconducting Recoil Separator (ISRS)

Results of LoI INTC-I-228

I. Martel, R. Berjillos, I. Bustinduy, C. Garcia-Ramos, C.A. Gonzales-Cordero, N. Deelen, D. Dominguez, A. Iziquel, T. Junquera, G. Kirby, T. Kurtukian-Nieto, J.L. Muñoz, E. Page-Mason, J. Resta, and O. Tengblad
for the ISRS collaboration

The HIE-ISOLDE physics program can greatly benefit from the installation of the "ISOLDE Superconducting Recoil Separator" (ISRS) [1] being developed by the ISRS Collaboration (www.uhu.es/isrs/). ISRS is based on Non-Scaling Fixed-Field Alternating-Gradient optics (FFAG)[2, 3], and multi-function nested Cosine-Canted Theta Superconducting Coils (CCT) [4].

An update of the ISRS layout using 8 straight magnets (*MAGDEM*) and 3 m diameter is shown in Fig. 1 (based on [5]). Each MAGDEM unit is composed of nested dipole and quadrupole solenoids with integrated fields of 0.75 Tm and 0.25 Tm, respectively, with an homogeneity better than 100 ppm. No iron yoke/collars were included in the design. The cryostat is cryogen-free cooled by a standard cryocoolers. The MAGDEM cryostat beam pipe has a 150 mm diameter and 750 mm length. The design study was recently completed (Fig. 2). The possibility of using MAGDEM units for developing a compact hadron-therapy gantry should also be highlighted [6]. The FUSILLO system being developed at CERN complements the magnet designs for ISRS [7, 8].

ISRS operation requires downscaling the HIE-ISOLDE linac frequency by 1/10th. This will be achieved by a low energy dispersion, high transmission, multi-harmonic buncher (MHB) placed before the linac RFQ (Fig. 3). There are three main tasks: MHB and RF power-supply design/prototyping, and the test in the ESS-Bilbao injector, for which a specific beam diagnostics will be developed. After beam validation the MHB will be ready to be installed at ISOLDE.

This work was funded by Spanish MCIN, Recovery and Resilience Funds, and European Union "NextGenerationEU".

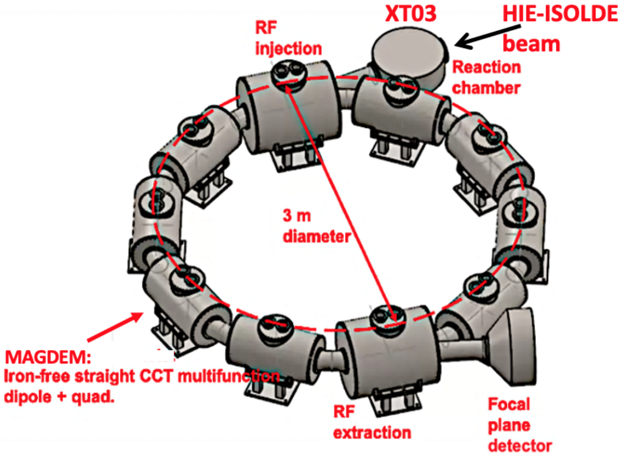

Figure 1: A conceptual design of the ISRS ring showing the main subsystems.

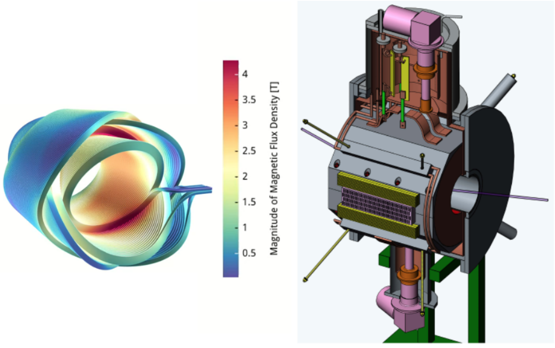

Figure 2: MAGDEM. Left: nested dipole and quadrupole CCT superconducting solenoids. Right: cryostat.

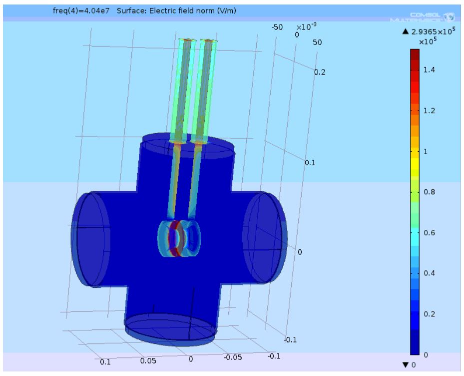

Figure 3: Electromagnetic study of the buncher system.

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Breakup reactions of ^{7}Be on ^{12}C at 5 MeV/u

Results of experiment IS554

Ritankar Mitra, Dhruba Gupta for the IS554 collaboration

The ^{7}Be nucleus is radioactive ($\tau_{1/2} \sim 53.22d$) and has an α + ^{3}He cluster structure. It has a low breakup threshold of 1.587 MeV. Though several measurements of breakup of the corresponding stable mirror nucleus ^{7}Li exist, such studies on ^{7}Be are very limited. Earlier experiments involving ^{7}Be on ^{12}C and ^{58}Ni targets did not yield any significant coincidence counts of the breakup fragments [1, 2]. In particular, the work of Amro *et al.* reports the predominance of transfer reactions over breakup of ^{7}Be [1]. Here we report on the measurement of the breakup of ^{7}Be on ^{12}C at 5 MeV/u. The experiment was carried out at HIE-ISOLDE, utilizing the scattering chamber (SEC). A ^{7}Be beam of intensity $\sim 10^5$ pps was incident on a 15μm thick CD$_2$ target. The pentagon charged particle detector array covering laboratory angles of 8^o-165^o was used, for the detection of the emitted particles [3]. The coincident events for ^{3}He and α were obtained by applying gates on the respective particle bands in the $\Delta E - E$ spectrum, with multiplicity of two. In the resultant coincidence spectrum Fig. 1(a), a correlation between E$_\alpha$ and E$_{3He}$ is visible, which delineates a signature of breakup events from ^{7}Be. Fig. 1(b) depicts the opening angle (θ_{rel}) distribution of coincident ^{3}He and α. The corresponding relative energy (E_{rel}) of the ^{3}He and α is reconstructed event by event using the following expression,

$$E_{rel} = \frac{m_1 E_2 + m_2 E_1 - 2\sqrt{m_1 m_2 E_1 E_2}\cos\theta_{rel}}{m_1 + m_2} \qquad (1)$$

$$\cos\theta_{rel} = \cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2) \qquad (2)$$

where m_i and E_i are the mass and energy of each breakup fragment and (θ_i, ϕ_i) are the measured polar and azimuthal angles. In the E_{rel} distribution of Fig. 1(c), the peak at $\sim$ 0 MeV corresponds to contributions from the direct breakup of ^{7}Be. Further work is in progress to apply coincidence efficiency corrections to the E_{rel} distribution to segregate the contribution of direct and sequential breakup of ^{7}Be. Detailed CDCC calculations will be carried out to compare with the experimental breakup cross sections.

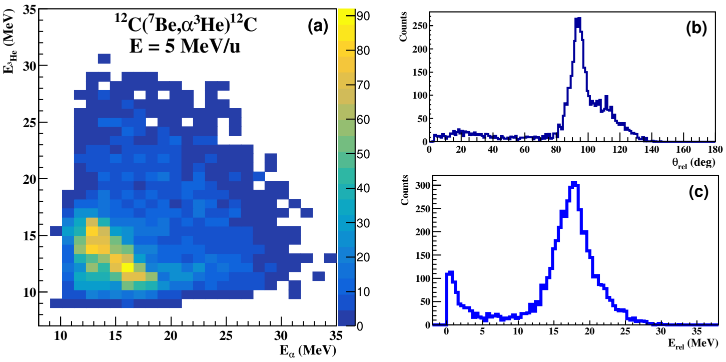

Figure 1: (a) Energy correlations of coincident ^{3}He and α from ^{7}Be + ^{12}C reaction at 5 MeV/u. (b) Opening angle and (c) relative energy distribution of the breakup fragments.

The IS554 collaboration thank the ISOLDE engineers in charge, RILIS team and Target group at CERN for their support. D. Gupta acknowledges financial support from ENSAR2 (Grant no. 654002) and ISRO, Govt. of India (Grant no. ISRO/RES/2/378/15−16). R. Mitra acknowledges the support of DST-INSPIRE fellowship (DST/INSPIRE/03/2021/000155, IF No. IF200499).

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Measurement of fission barrier height of exotic nuclei at HIE-ISOLDE

Results of experiment IS581

Martin Veselsky, Riccardo Raabe
for the IS581 collaboration

Nuclear fission is not only important for applications such as energy generation and production of radioisotopes; it has also direct consequences on the synthesis of the heaviest nuclei in the astrophysical r-process, which is terminated by fission, and on the abundance of medium-mass elements in the universe through the so-called "fission recycling". To understand such process it is necessary to know the heights of fission barriers of involved nuclei. Most of the reliably known fission barriers were measured in reactions with light stable beams and thus for nuclei close to the beta-stability line. Experiment IS581 aims at the measurement of fission barriers of short-lived nuclei. Beams of such nuclei, delivered by the HIE-ISOLDE facility, are used to study the (d,p)-transfer reaction ollowed by fission in inverse kinematics.

A beam of radioactive ^{209}Fr nuclei was accelerated using the HIE-ISOLDE linear post-accelerator and was delivered with maximum intensity of 10^6/s and energy of 7.63 MeV/u onto the entrance window of the ACTAR Time Projection Chamber (TPC) Demonstrator, which was filled with deuterium gas at a pressure of 500 mbar or 800 mbar. The results collected by the ACTAR Demonstrator active target were affected by the time structure of the delivered beam, where beam nuclei were packed in narrow bunches effectively leading to instantaneous beam rates up to 10^9/s, causing strong space-charge effects such as distortion of the electric field in the active volume. However, the Timepix3 detectors, configured to act as neutron detectors by adding a polyethylene converter, were placed outside of the TPC chamber and were not affected by the beam structure, thus allowing the goal of the experiment to be achieved.

To extract the parameters of the fission channel, detailed simulations were performed. Energy losses, kinematics of the transfer reaction and of fission were simulated. The TALYS code was used as initial guess of the (d,p) and (d,n) transfer cross sections. If the excitation energy exceeded the sum of the macroscopic fission barrier height of Sierk [1] with a ground-state shell correction, scaled down by 0% to 25%, fission was simulated and emission of neutrons from fission fragments followed. The resulting yields of neutrons at detector positions were compared to the experiment. A simulation with a scaling factor for the fission barrier of 0.85 was the only one which could reproduce the neutron yields at both pressures in all 4 Timepix3 detectors. This measurement [2] confirmed the reduction of fission barriers at low excitation energies reported earlier in complete fusion reactions, where however such reduction could not be proved unambiguously.

The second phase of the IS581 experiment will focus on neutron-rich francium isotopes and it will employ optimum combination of capabilities of both TPC and Timepix3 detectors.

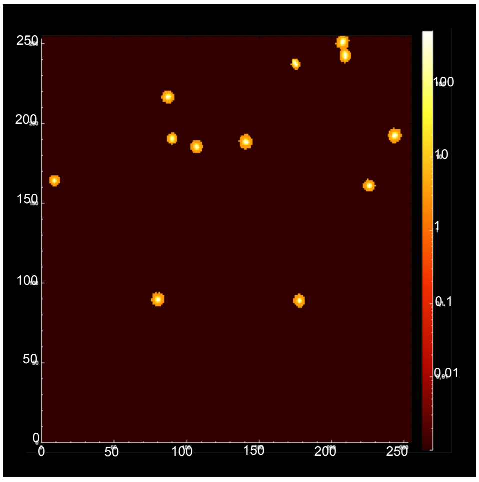

Figure 1: Tracks of protons, scattered in collisions with neutrons and detected by the Timepix3 detector with 256×256 pixels. Energy scale on the right is in units of keV.

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^{185m,g}Hg studied with Coloumb excitation at Miniball

Results of experiment IS699

Joonas Ojala, Liam Gaffney, Janne Pakarinen, Kasia Wrzosek-Lipska for the IS699 collaboration

Shape coexistence in the neutron-deficient mercury isotopes (Z=80) was observed for the first time in a radiation detection of optical pumping experiment at ISOLDE in 1972 by Bonn *et al.* [1]. They discovered an unexpectedly large difference in the mean-square charge radius between ^{185}Hg and ^{187}Hg. This finding initiated extensive studies around these nuclei. Recently, a resonance ionisation spectroscopy experiment has shown that this shape staggering is a unique and localised feature in the nuclear chart [2]. In order to shed more light on competing structures in mercury isotopes, we have combined the SPEDE [3] and the Miniball spectrometers [4] for the first Coulomb excitation experiment of odd-mass nuclei in this region, namely ^{185}Hg.

Thanks to selectivity of the resonance ionization laser ion source, pure ^{185m}Hg and ^{185g}Hg beams could be delivered for post-acceleration at HIE-ISOLDE. To increase sensitivity of performed measurements to matrix elements between excited states, the mercury beam of 4.0 MeV/u energy was impinging on two different ^{48}Ti and ^{120}Sn secondary targets.

Typical fingerprints of shape coexistence are the enhanced $E0$ components in transitions between states with the same spin and parity. The SPEDE electron spectrometer enabled the probing of these transitions and provided crucial information for the GOSIA minimisation procedure. In this light, complementary γ-ray and conversion electron spectroscopy of ^{185}Hg employing fusion-evaporation was also performed at the Accelerator Laboratory of Jyväskylä.

In the IS699 experiment, the ground state band was populated up to the $21/2^-$ state, whereas transitions up to the $29/2^+$ state on top of the isomeric $13/2^+$ state were observed. The γ-ray energy spectra obtained with ^{185m}Hg and ^{185g}Hg beams are shown in Fig. 1.

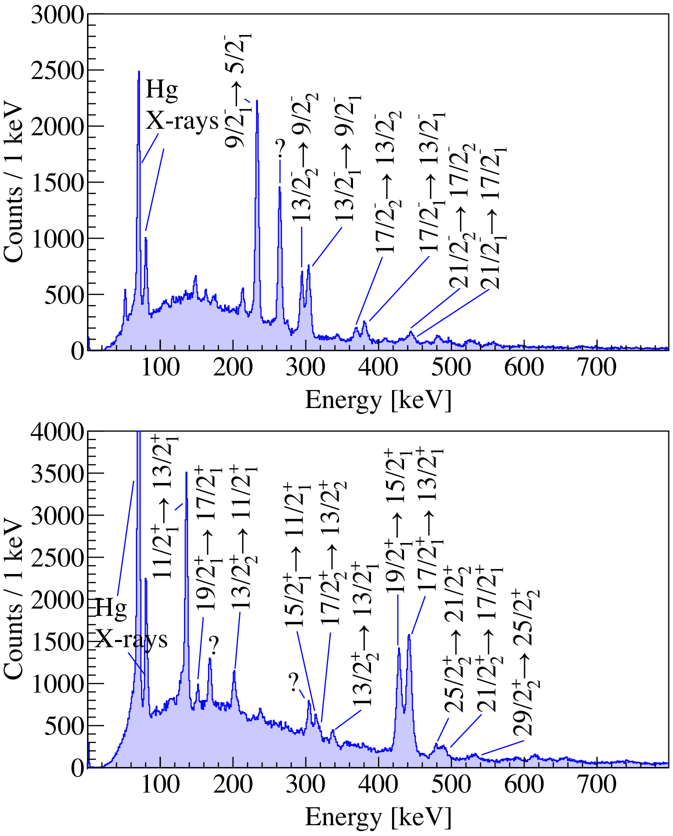

Figure 1: Particle-gated γ-ray energy spectra obtained in the Coulomb excitation of the $1/2^-$ ground state (top) and the $13/2^+$ isomeric state (bottom) in ^{185}Hg. Known transitions have been labeled with initial and final states. New transitions observed at 264 keV (top) and 166 keV and 304 keV (bottom) are labeled with question marks.

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`https://miniball.web.cern.ch`

Other News

A New Isobar Separator Beamline for ISOLDE

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With the envisaged arrival of the PUMA experiment at ISOLDE [1], a new low-energy beamline will be built to fulfill the different requirements posed by the antimatter experiment. As the trapped anti-protons in the PUMA ion traps have to be stored for several weeks, the standard vacuum in the ISOLDE low-energy beamline has to transition from 10^{-6} mbar at the entrance of RC6 (near IDS) to $< 10^{-10}$ mbar at the handover point to the PUMA beamline. This will be achieved in several differential pumping stages using turbomolecular pumps in the unbaked first section followed by a baked section with ion pumps including non-evaporable getter as cartridges or coatings next to the handover point. The conductance will be reduced as much as possible using irises and the smallest possible diameter. This will limit the propagation of gases from the helium-filled Paul Trap to PUMA.

The second requirement is a high degree of beam purity. This will be realized by employing a multi-reflection time-of-flight mass separator, which is currently being developed by the MIRACLS collaboration [2] for collinear laser spectroscopy. This device promises strong mass separation capabilities with ion flux dependent resolving powers between 10^4 and 10^5 for ion rates of 10^7 to 10^5 ions per second, respectively [3] (assuming a 30 keV operation, higher ion load meaning lower resolving power).

The layout of the beamline is shown in Fig. 1. The isobar separator and the Paul trap for accumulation and bunching are situated perpendicular to the RC6 beamline to allow for DC beam operation toward the two handover points if needed. In mass separation mode, the beam will be decelerated using an electrostatic decelerator before being bent by 90 degrees, followed by injection into the Paul trap. After accumulation and cooling, the ion bunch will be ejected and injected into the isobar separator. When entering the separator, the beam is accelerated and stored inside the separator with kinetic energies up to several tens of keV. After some hundreds to thousands of revolutions leading to effective flight paths of several kilometers, only the ion species of interest is ejected [4] and guided back into the RC6 beamline and toward the handover points.

Large parts of this setup will be recuperated and refurbished from existing hardware: the two injector quadrupole doublets in front of the mass separator part and the final switchyard near the handover point are sourced from ISOLDE spares, and the three doublets towards the handover points are spares provided from the ELENA low-energy antiproton ring. The Paul trap and the mass separator were developed by MIRACLS and are currently commissioned at LA2. The design of the beam diagnostics boxes is based on the HIE-ISOLDE diagnostics but will also include microToF single-ion counting detectors.

Apart from PUMA, this new beamline at ISOLDE can accommodate temporary experimental installations or collection chambers with increased beam and vacuum quality requirements at one of the two handover points, such as ASCII and ASPIC [5]. Furthermore, using the high mass-resolving power of the mass separator, beam identification studies using time-of-flight mea-

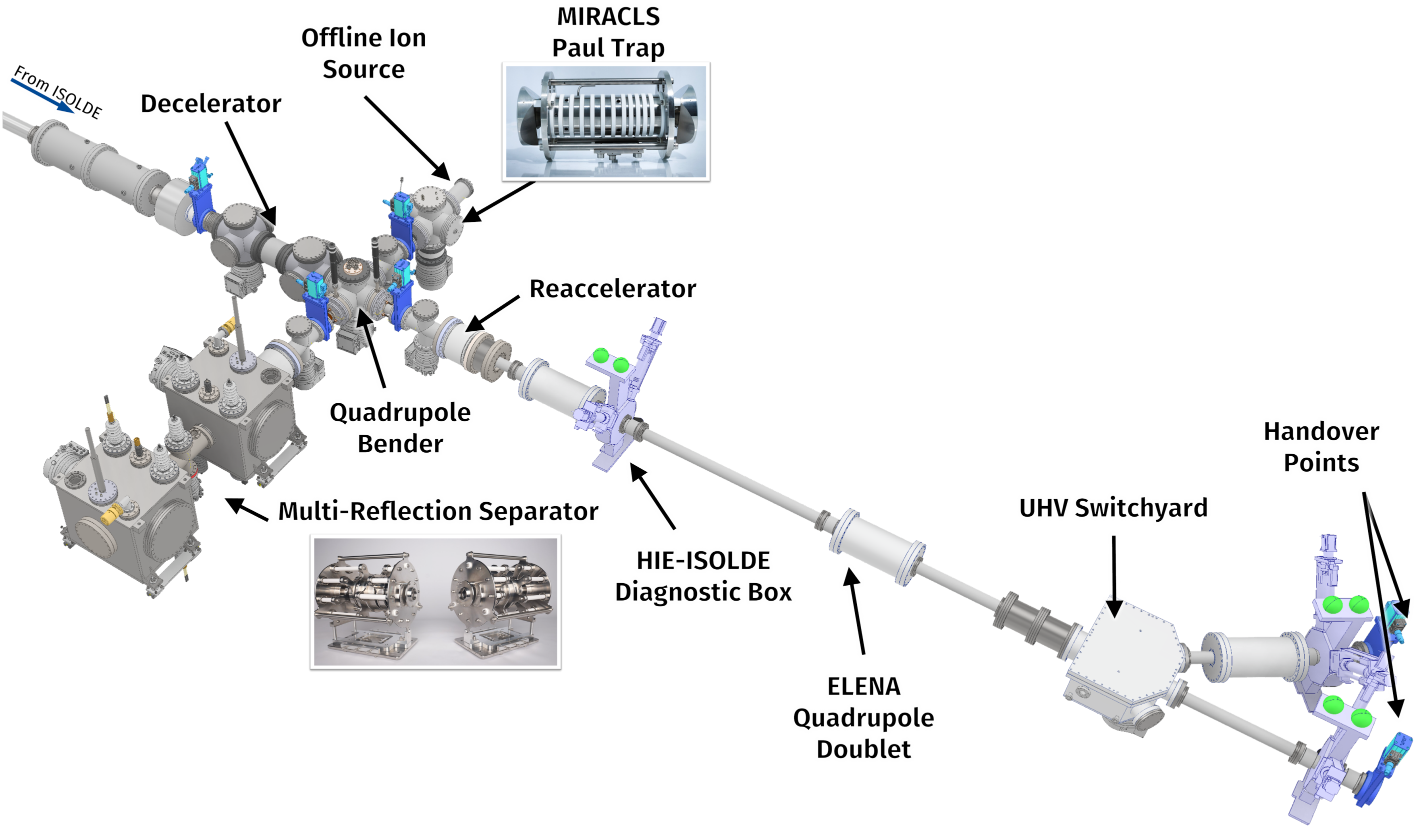

Figure 1: CAD for the RC6 isobar mass separator beamline which will serve beams to the PUMA experiment and a second experimental area.

surements can be performed for target and ion source developments [6]. Finally, owing to the perpendicular setup of the Paul trap, ion bunches could be ejected back upstream into the central low-energy beamline. This would require fast switching of many beamline elements, which is currently being investigated within the SY-STI-RBS section.

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MEDICIS and MELISSA operation and highligths in 2023

MEDICIS and MELISSA 2023 report

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R.ROSSEL, T.STORA, R. ZABOLOCKIS
on behalf of the MEDICIS collaboration and local team

1 Highlights from operation in 2023

In 2023, MEDICIS entered its fifth year of operation with a high demand from the external collaboration as well as from the PRISMAP users across Europe. A record total activity of 3.8 GBq was collected and delivered for the biomedical programme, excluding Machine Development runs (see Fig. 1). To conclude this year, the full programme from its start was reviewed by a high level international review committee; it notably acknowledged the excellent performance and concluded with glowing recommendations towards the CERN directorate, both on its programme and implementation. In particular, this acknowledges the implementation of Key Performance Indicators used to monitor the facility and its programme, along with the required consolidation and developments.

There is an increasing interest in the production of alpha emitters such as Pb-212 and Ac-225. Pb-212 is produced at MEDICIS through the collection of Ra-224, and Ac-225 is either directly produced [1] or collected via the decay of its parent radionuclide, Ra-225. In order to support these increasing demands, laser developments on radium have been initiated (see section below) as well as the double collection possibility, successfully used to simultaneously collect the two neighboring mass nuclides Ra-224 and Ra-225 on two different samples. This has been combined with radiochemistry developments (see section below) and collaboration with Hevesy Lab in DTU, DK. The double collection system has also been used to simultaneously collect two Tm radioisotopes: Tm-165 and Tm-167. Tm-165 being a generator for the pure auger emitter Er-165. This radionuclide has been shipped to Hevesy Lab, DTU, DK in the framework of a PRISMAP user project by means of a dedicated plane that delivered this 30-hour-half-life radionuclide within 4 hours door-to-door, limiting the decay of the product upon arrival. At the same time, Tm-167 was delivered to PSI, CH and to NPL, UK. CHUV in Switzerland is assessing the possibility to use the in-vivo generator Ba-128/Cs-128 as a new calcium surrogate for the treatment of osteosarcoma. Several batches have been delivered to CHUV since the project was accepted by the collaboration in 2021. It showed that Ba-128/Cs-128 accumulates in the bone but also undesirably in the kidneys. In order to assess if this accumulation is coming from Ba-128 itself or from its decay product Cs-128, MEDICIS provided Cs-129 to resolve this question, resulting in the conclusion that the strong uptake in the kidneys is due to Cs. MEDICIS collected a record activity of 1.3 GBq of Ba-128 and Cs-129 in 2023, largely fulfilling the activity needed by CHUV to complete the first part of this study.

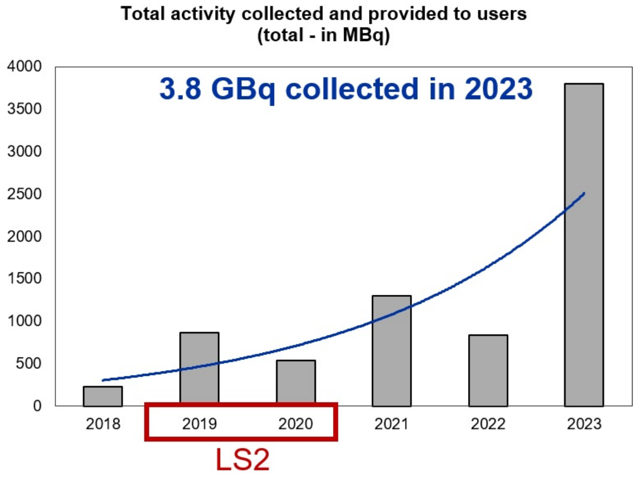

Figure 1: Evolution of the activity delivered to end-users through the years of operation

Tb-155 was produced, collected and delivered to a PRISMAP user with the required activity (10 MBq) to initiate his research project in Bordeaux, FR. This col-

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https://medicis.cern

lection was performed by first collecting the parent radionuclide Dy-155 followed by Tb-155 itself, each ionized by MELISSA lasers. Developments are still ongoing to consolidate the collection efficiency of the different radionuclides of the Tb element to better match the biomedical needs [2].

External sources were also used in 2023 at MEDICIS and especially after the end of the protons at the end of October. MEDICIS was running exclusively with external sources in November and December. Record efficiencies were achieved for Er-169 (produced at ILL, Fr) and Sm-153 (produced at SCK CEN, Be), with a 1 GBq batch of the latter delivered to the University Hospital of Heidelberg to kick-off the first clinical trial project with a MEDICIS mass-separated radionuclide. For the first time, an external Sc-43/44 source (from PSI, CH) was used at MEDICIS.

Molecular ion beam and target material developments for medical Sc radionuclide mass separation led to successful extraction and collection of Sc-44m, Sc-46 and Sc-47 with high radiochemical purities from a ^{nat}TiC (average grain size of 1-2 μm) target. The Sc radionuclides were extracted and mass separated as molecular difluoride and monofluoride ion beams with collection efficiency of more than 1%. A two-step laser resonance ionization scheme was used at MELISSA to obtain ^{45}Sc$^+$, ^{46}Sc$^+$ and ^{47}Sc$^+$ ion beams from ^{nat}V foil target for the first time at MEDICIS [3].

2 MELISSA laser laboratory update

In 2023, the MELISSA laser laboratory was used to ionize 8 different elements, for a total of 21 weeks of cumulated operation. A third pump laser for a TiSa cavity, loaned by the RILIS team, was installed at MELISSA. This third pump laser allowed more versatility and better performance of MELISSA over the year.

In parallel to regular operation, MELISSA was used for different laser development. In particular, the first test of the diamond-based Raman laser with new Z-fold design was performed at MEDICIS during summer 2023, for the ionization of Radium (see Fig. 2). Raman lasers have great potential for extending the wavelength coverage of RILIS laboratories [4], aiming at covering wavelengths for atomic transition that can not be covered easily with TiSa lasers. An example of wavelength conversion is shown in Fig. 2 (b), where the 454nm pump beam is first converted to 483nm (called 1st stoke), and 516nm (2nd stoke). The first stoke was also used to ionize Radium during a collection at MEDICIS, as a proof of principle, and showed a significant enhancement of the ion beam current, even at very low average laser power. Further developments are ongoing in order to improve the power output and the stability of the design, in order to present an operational system for future use at MEDICIS, ISOLDE and Offline.

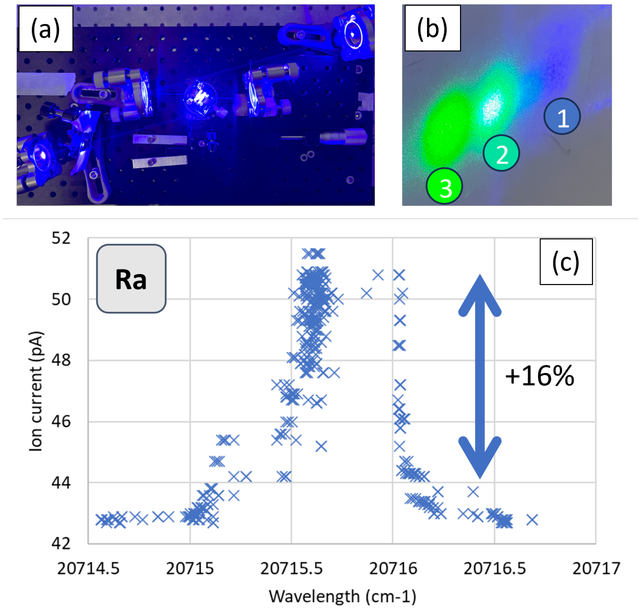

Figure 2: (a) Picture of the Raman laser z-fold design. (b) Generated beam from (1) blue pump (454nm), (2) 1st stoke (483nm), and (3) 2nd stoke (516nm). (3) First step laser ionization resonance of Radium using the Raman laser.

3 Radiochemistry developments

For the production of a new therapeutic agent Pb-212 for targeted alpha therapy, two different types of Ra-224/Pb-212 generators were developed based on several collections of Ra-224 performed at MEDICIS. Ra-224/Pb-212 generators were based on i) collection of emanated gas from a radium source (figure 3) and ii) chromatographic separation of Ra & Pb. The first type of generator was successfully tested for high purity elutions with starting activity up to 80 MBq.

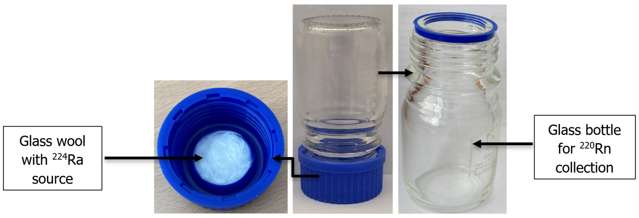

Figure 3: $^{224}Ra/^{212}Pb$ generator by gas collection

The average efficiency of the generator was found to be 37%. A similar generator was dispatched to Hevesy Lab in DTU, DK, a PRISMAP partner institute, for further studies including radiolabelling and complex stability in mouse serum.

Mass separated Sc-47 radionuclide chemical separation from MEDICIS collection foils and isobaric impurities was performed with ion exchange column chromatography. A semi-automated ion exchange column separation setup and method was developed and tested with Sc-47. A radiochemical Sc-47 recovery yield of 81.4 ± 13.2% from collection foils was obtained with DGA resin. A potential-controlled aqueous electrolysis method for removal of Zn, Al, V, Ti and Ca contaminants from the collection foil dissolution medium was developed and also tested with mass separated Sc-47 samples [5]. A non-aqueous electrolysis method has been proposed (due to a more relevant solvent electrolysis potential) and is to be tested in the near future.

4 Release studies

Release studies were initiated in 2023 at MEDICIS by using the calibration stand available for the thorium carburization in building 179. This study was made possible thanks to samples made of Ti and V parasitically irradiated by the secondary neutron field available at CHARM to produce Sc radionuclides and study their release by mean of HPGe γ-spectrometry measurements before and after heating. Scandium fractional release from activated metallic foils was determined, within the confinement of the Ta container of a typical ISOL target (see Fig. 4). A complete release of the Sc radionuclides produced in the rolls was achieved at 1600 °C for vanadium, 1200 °C for non-embossed natural titanium, and 1450 °C for embossed natural titanium samples within an hour reaching the set temperature. The study showed that the structure of the foil (embossed or not) have a high impact on the release of Sc. The scandium radionuclide relative release from embossed foil rolls is shifted towards higher temperatures in contrast to what was expected. Therefore, the findings of this study not only advance the understanding of the release of Sc but also open new doors for release studies applicable to ISOL (Isotope Separation On-Line) facilities, for radiation protection purposes (as part of the FIRIA CERN project) as well as for theoretical model developments [6].

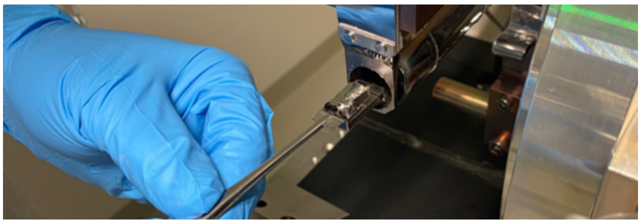

Figure 4: Ti sample being removed after release

5 Acknowledgments

We wish to thank all our colleagues from SY-STI, BE-CEM, BE-OP, HSE-RP, EP-SME, CHARM and the institutes that are part of the collaboration for their support.

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This article has been written with a heavy heart and great sadness since the passing of our cherished colleague and friend Bruce, gone too soon. Our most sincere thoughts and condolences go to his friends, family and his baby daughter.

ISOLDE support

Access and contacts

1. Use the online EDH Pre-Registration tool[1]which should be launched by your team leader or deputy team leader. You need to attach the following documents to the pre-registration:
   - Home Institution Declaration[2] **signed by your institute's administration (HR).**
   - Passport
2. When your pre-registration is accepted by the CERN users office you will receive an email telling you how to activate your CERN computer account. However, you cannot activate your CERN EDH account until you arrive at CERN and complete the registration process; this means you should register for hands on safety courses via email, see Item 7.
3. Follow the online mandatory CERN safety courses: Safety at CERN, Radioprotection Awareness, Emergency evacuation, Computer Security and Data Privacy Basics - elearning.
   - If you have activated your CERN account, you can access the mandatory on-line courses at the web page lms.cern.ch, from your computer, inside or outside CERN.
   - If you have not activated your CERN account, there are some computers available for use without the need to log in on the first floor of Building 55 (Your CERN badge will be needed in order to prove your identity).
4. Complete the following online courses available at https://lms.cern.ch:
   - Electrical Safety - Awareness Course - Fundamentals
   - Electrical Safety - Awareness Course - Facilities

   If you have not activated your CERN account see the second part of Item 3.
5. When you arrive at CERN go to the Users Office to complete your registration (Opening hours: 08:30 - 12:30 and 14:00 —- 16:00 but closed Wednesday mornings).
6. Get your CERN access card in Building 55
7. Follow the in-person ISOLDE RP safety course and the "Electrical Safety-Working in EP experiments" course for which you will have to register well in advance[3]. These take place on Tuesdays at the training centre (Building 6959) in Prevessin; the Electrical course takes place on Tuesday morning and the RP course on Tuesday afternoon. If you do not have your own transport, you can take CERN Shuttle 2 from building 500. The timetable for this is here.
8. Obtain a permanent radiation dosimeter at the Dosimetry service, located in Building 55[4] (Opening hours: Mon. to Fri. 08:30 —- 12:00). *If you do not need the dosimeter in the following month, it*

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[1] For information see the CERN users' office

[2] The Home Institute Declaration should not be signed by the person nominated as your team leader.

[3] For information about how to register see http://isolde.cern/get-access-isolde-facility

[4] http://cern.ch/service-rp-dosimetry (open only in the mornings 08:30 - 12:00).

should be returned to the Dosimetry service at the end of your visit. The "certificate attesting the suitability to work in CERN's radiation areas" [5] signed by your institute will be required.

9. Apply for access to "ISOHALL" using ADAMS: https://www.cern.ch/adams. (This can be done by any member of your collaboration, typically the contact person, having an EDH account[6]). Access to the hall is from the Jura side via your dosimeter.

   Find more details about CERN User registration see the Users Office website. For the latest updates on how to access the ISOLDE Hall see the ISOLDE website.

   New users are also requested to visit the ISOLDE User Support Office while at CERN. Opening hours: Monday to Friday 08:30 - 12:30

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[5] The certificate can be found via http://isolde.cern/get-access-isolde-facility

[6] Eventually you can contact Jenny or the Physics coordinator.