ISOLDE Workshop and Users meeting 2022

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Book of Abstracts

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Ab initio advances for open-shell and heavy nuclei

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In the physics of nuclei there have been rapid advances combining innovative ab initio many-body methods with nuclear forces based on chiral effective field theory. This talk will focus on ab initio calculations based on the in-medium similarity renormalization group (IMSRG), which has enabled systematic calculations of nuclei up to 100 nucleons, first global ab initio calculations of nuclei up to iron, and many exciting explorations with ISOLDE experiments. Moreover, I will discuss new ab initio advances for the description of open-shell and heavy neutron-rich nuclei.

Heavy Nuclei / 37

First observation of the radiative decay of Thorium-229 low-lying isomer

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Owing to its very low excitation energy the isomer of thorium-229 has been proposed as a candidate for a possible future frequency standard, a nuclear clock and is expected to outperform the current atomic clocks [1,2]. Currently, the best values of the excitation energy are 8.28(17) eV and 8.10(17) eV [3,4]. These were measured using two different techniques where the population of the isomer was achieved via the α-decay of uranium-229. However, a precise knowledge of the isomer excitation energy is a necessary for the development of an optical clock.

Recently, spectroscopy measurement has been possible using an alternative approach of populating the isomer via the beta decay of actinium-229 [5]. The laser ionized actinium-229 ions produced online at CERN's ISOLDE facility were implanted onto a large bandgap crystal at specific lattice

positions. A favourable feeding fraction of the isomer from the beta decay of actinium-229 compared to that via the α−decay of uranium-229 and a low beta energy compared to alpha decay leads to a significantly reduced radioluminescence. This allowed us to study the VUV-photons stemming from the radiative decay of the isomer for the first time resulting in a much precise determination of the energy and lifetime of the isomer.

In this contribution, a dedicated setup developed at KU Leuven for the implantation of francium/radium/actinium-229 beam into large-bandgap crystals and the vacuum-ultraviolet spectroscopic study of the emitted photons will be presented.

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Heavy Nuclei / 17

N=126 Kink in Mean-square Charged Radii of Tl Isotopes Studied by In-source Laser Spectroscopy at IDS/RILIS-ISOLDE

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Zixuan Yue - University of York, on behalf of LOI219, RILIS and IDS collaborations

It is well-known that there is a kink in nuclear charge radii when crossing the magic number N=126. This phenomenon has been observed in the Hg(Z=80), Pb (Z=82) and Bi (Z=83) isotopes [1]. At present, the charge radii of Tl (Z=81) isotopes are only known up to 208Tl (N=127). In order to observe such a kink for the Tl chain, the isotope shift (IS) and hyperfine structure (hfs) of heavier isotopes needs to be measured. However, production of pure heavy Tl isotopes is hampered by strong Fr isobaric contamination.

During the April 2022 LOI219 experiment, a collaborative effort was made by the RILIS and IDS teams to measure the IS/hfs of Tl isotopes from 205Tl to 209Tl (N=124-128). The RILIS in LIST mode was applied to suppress Fr contamination. Counting of photo-ions was made by Faraday cup and IDS. For the first time, IS/hfs has been measured for 209Tl establishing the kink at N=126 for the Tl isotopic chain. In addition, the first measurement of the magnetic moment and charge radius for the 11/2- isomeric state of 207Tl has been achieved. In this contribution, results on the HFS/IS of the 207-209Tl isotopes, as well as some preliminary data on charge radii and magnetic moments, will be presented.

[1]: Day Goodacre, T. et al. "Laser Spectroscopy of Neutron-Rich 207,208Hg Isotopes: Illuminating the Kink and Odd-Even Staggering in Charge Radii across the N=126 Shell Closure."Physical review letters 126 3 (2021): 032502.

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Single-particle state evolution along the N = 127 isotone chain using the $d(^{212}$Rn,$p)^{213}$Rn reaction

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The study of single-particle states can provide insight into properties of nuclear structure. In light neutron-rich systems, features of single-particle states along isotonic chains have highlighted changes in shell closures, such as the weakening of N = 20 and formation of N = 16 [1, 2]. In heavier closed-shell stable nuclei, trends have been seen in the behaviour of high-*j* states from the filling of other high-*j* orbitals, the effects of which have been attributed to the tensor interaction [3]. From the availability of radioactive beams at ISOLDE, these studies can be extended in the region around N = 126. Currently, states up to Z = 84 are known with spectroscopic factors and assignments [4, 5]. Above this, there is very little information on the single-particle properties of nuclei. Only the energies of states are available with tentatively assigned orbital configurations and no spectroscopic information. In order to probe single-particle nature beyond this, the reaction $d(^{212}\mathrm{Rn},p)^{213}\mathrm{Rn}$ has been performed at the ISOLDE Solenoidal Spectrometer (ISS) with a 7.63 MeV/u radioactive beam at an intensity of ˜10^6 pps. States have been identified up to ˜4 MeV and single-particle centroids have been extracted for the neutron outside of N = 126, providing information on the magnitude of monopole shifts caused by the interaction between the neutron and protons filling the $\pi 0h_{9/2}$ orbital. These data will also be used to inform modern shell-model calculations in this region of the nuclear chart. Preliminary data from measurements will be presented.

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News from ISOLDE's Decay Spectrometers / **4**

Total absorption gamma-ray spectroscopy measurements for isospin mirror asymmetry and nuclear structure

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In this contribution we will present recent experimental studies with the Lucrecia total absorption spectrometer at ISOLDE aimed at investigating the beta decays of nuclei of interest for nuclear structure. The Pandemonium effect [1] is known to hamper the determination of beta intensities with conventional HPGe approaches, while a high efficiency detector as Lucrecia [2] has proved the capabilities of the total absorption gamma-ray spectroscopy (TAGS) technique to determine the complete beta intensity distributions.

Isospin mirror asymmetry in mirror systems along the sd shell has been suggested to be an evidence of proton halo structure. An example is the 27Na-27S pair, where the recently reported asymmetry could be due to the incompleteness of the decay data of 27Na [3,4]. As will be shown in this contribution, the recent TAGS study of this decay at ISOLDE points to previously undetected beta intensity at high excitation energies.

Finally, we will also comment on other fresh measurements of interest for nuclear structure, in the framework of a very active program that has recently started with Lucrecia after some upgrades of the setup. Some examples include shape evolution studies of yttrium isotopes in the region close to A=100 [5] and nuclear structure studies in the Z=20 shell closure by means of the beta decay of neutron-rich potassium isotopes.

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News from ISOLDE's Decay Spectrometers / **47**

Spectroscopic investigation of very neutron-deficient Tl isotopes and their daughters

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Very neutron-deficient nuclei in the vicinity of the $Z = 82$ proton shell gap and the $N = 104$ neutron mid-shell are well known for the interplay between single-particle and collective nuclear structure effects, such as shape coexistence and the systematic presence of low-spin isomeric states. This makes Tl and Hg isotopes highly interesting study cases within the shell model approach. With the use of the ISOLDE Decay Station (IDS) detector set-up equipped with 6 HPGe clover detectors, 3 $LaBr_3$(Ce) detectors and fast plastic scintillators, measurements were performed for the extracted $^{181,183,184,185,187}Tl$ isotopes(in their ground and isomeric states), as well as their associated decay chains. The report will focus on some preliminary results of the spectroscopic investigation which includes lifetime measurements through the electronic fast-timing method.

News from ISOLDE's Decay Spectrometers / **52**

Status of the Miniball detector array

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The Miniball array comprises eight clusters of three high-purity germanium detectors arranged around a reaction target located downstream of the HIE-ISOLDE beamline. The array measures gamma rays emitted following nuclear reactions of radioactive isotope beams of a few MeV per nucleon. Complimenting the Miniball array are beam-particle detectors and a newly-implemented conversion electron detector.

In 2022, seven Miniball clusters returned to ISOLDE following their use in experiments at other facilities and their refurbishment. In addition to the detector refurbishment, a new digital data acquisition system was developed to better accommodate the experimental conditions of Miniball experiments.

This presentation shall detail the re-installation and commissioning of the Miniball array and associated devices with special attention given to developments made since the last Miniball campaign at ISOLDE. In addition, an overview of the Miniball experiments performed during November, 2022 will be given.

News from ISOLDE's Decay Spectrometers / 65

New results from the ISOLDE Decay Station

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The ISOLDE Decay Station (IDS) [https://isolde-ids.web.cern.ch/] was designed as a flexible tool for decay spectroscopy studies, operating since 2014 at ISOLDE. At the core of IDS there are 4-6 HPGe clovers to detect γ rays with high energy resolution together with a moving tape system and a complex array of ancillary detectors such as LaBr3:Ce crystals to measure excited-state lifetimes down to a few picoseconds, silicon detectors (annular, PAD, DSSSD, Solar Cell) for charged particle (p, α, e−, e+) or β-delayed fission fragments spectroscopy and an efficient plastic scintillator array acting as a neutron Time-of-Flight detector for β-delayed neutron emission studies. In recent years, IDS has also been used as a decay-spectroscopy tool for in-source laser spectroscopy studies together with RILIS.

Following the end of the CERN Long Shutdown (2019-2020) development campaign, ISOLDE has resumed experiments in June 2021 and there have been several new decay spectroscopy experiments performed at IDS: laser spectroscopy of neutron-rich Tl, Po and At isotopes; fast timing studies around neutron-rich Cu and Cd, beta-delayed neutron spectroscopy of 8He. These measurements will be highlighted in the current presentation alongside a detailed description of the setup and future development plans for IDS.

Atomic Techniques for Nuclear Structure 1 / 63

Ten years of CRIS

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Ten years have passed since the first successful measurement was performed at the CRIS experiment. The setup has since established itself as a versatile tool for the study of nuclear and atomic properties and was recently used for the first study of radioactive molecules as well. Along the way, CRIS has demonstrated the ability to perform high-precision measurements throughout the chart of nuclides, consistently achieving the high efficiency required to study the most exotic isotopes. This has required continuous refinement of the technique, bringing in the state-of-the-art in laser technology and fully exploring the richness of atomic and molecular structure.

In this contribution, the highlights of the first decade of CRIS will be shown. Far from having reached its full potential, the plans to further push the limits of the technique will be outlined.

Atomic Techniques for Nuclear Structure 1 / 3

Mass Measurements of Isomeric States for Nuclear Structure Studies

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The nuclear binding energy arises from various effects that govern a nuclei's properties. Different nucleon configurations within nuclear isomers lead to modified binding energies, often resulting in mass differences of tens to hundreds of kilo-electronvolts. These isomeric excitation energies can be directly accessed by measuring the difference in atomic masses of ground and isomeric states. Here, we present such measurements performed with the ISOLTRAP mass spectrometer. By evaluating the excitation energies of neutron-deficient indium isotopes down to the shell closure at N=50 against state-of-the-art shell model, DFT, and ab initio calculations, we contrast the performance of these theories applied to several nuclear properties. We further present evidence for shape-coexistences close to N=50 through the precise excitation energy measurement of the (1/2)+ state in zinc-79, supported by accurate large-scale shell model calculations.

Lukas Nies for the ISOLTRAP Collaboration

Atomic Techniques for Nuclear Structure 1 / 61

Nuclear structure of tellurium isotopes probed by high-resolution laser spectroscopy at COLLAPS

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On behalf of the COLLAPS collaboration

In May 2022 high-resolution laser spectroscopy was performed on atomic tellurium species, ^{112}Te - ^{136}Te, using the COLLAPS experiment at ISOLDE-CERN. From the atomic hyperfine structure and isotope shifts nuclear properties like the charge radii, spins and electromagnetic moments were extracted for the ground states and long lived isomeric states. Our measurements complete the physics case Cd (Sn-2p) –Sn (Z=50) –Te (Sn+2p) and are therefore key to understand the nuclear structure in this region. In particular, the direct comparison of the quadrupole moments of the $11/2^-$ isomeric states allow us to quantify the effects of the protons outside of the tin core. This contribution will discuss our preliminary results in the context of the nuclear shell model.

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CAEN - Design of DAQ using SciCompiler and Open FPGA. FERS-5200: a distributed Front-End Readout System for multidetector arrays.

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The increasing usage of programmable logic devices in modern trigger and data acquisition systems emphasizes the advantages in having a general-purpose reusable mixed-signal platform, typically

called open FPGA board, with custom processing algorithm implemented in firmware. The benefits of using programmable logic devices with respect to standard logic modules (like NIM logic modules) is remarkable: a single programmable logic device includes the potentiality of hundreds of thousands of standard logic modules merging in a single device analog and digital signal processing. Even if several ready-to-use FPGA board are available, learning a new language like VHDL or Verilog to develop a custom logic/readout system can be a difficult step for most people.
In this presentation, we show an innovative method to simplify the firmware development. The method is based on a graphical programming interface consisting of large ip-cores catalog developed ad-hoc for nuclear physics applications. As an example, any trigger logic could be implemented by connecting specific blocks in the graphical interface, as easily as physically connecting NIM modules in a rack. The SciCompiler software allows to develop with few clicks fully customized, readout system for nuclear spectroscopy, particle imaging, neutron physics, medical imaging, exploiting, ready to use, virtual instruments like scalers, counters, TDC, energy filters, charge integration, Pulse Shape Discriminators.
SciCompiler easy implements processing algorithms and also create all necessary readout interfaces and libraries to build up the full readout chain from the detector to the data storage. The SciCompiler focuses the development on the final application and does not require a any deep knowledge of FPGA programming, making the design of the firmware as simple as connect cables between real instruments. Several open FPGA boards are available, with or without ADCs, ranging from 1 to 128 channels up to hundreds MSPS.
Modern physics experiments usually rely on experimental setup where it is possible to find a wide variety of detectors: silicon microstrip trackers, plastic scintillator calorimeters, LAr cryostats readout by a Time Projection Chamber, spectrometers composed of several drift tubes and resistive plate chambers, etc. Nowadays, waveform digitizers and/or ASIC-based front-end cards are well-established readout electronics to build a reliable system hosting many readout channels.
The FERS-5200 is the new CAEN Front-End Readout System, answering the challenging requirement to provide flexibility and cost-effectiveness in the readout of large detector arrays. FERS-5200 is a distributed and easy-scalable platform integrating the whole readout chain of the experiment, from detector front-end to DAQ. It is based on compact ASIC-based front-end cards integrating A/D conversion and data processing, which can be ideally spread over a large detector volume without drawbacks on the readout performance. Synchronization, event building and DAQ is managed by a single Concentrator board, capable of sustaining thousands of readout channels.

Solid State Physics / **38**

Cadmium doping in vanadium oxides and Cadmium vanadates investigated by hyperfine interactions at ^{111m}Cd probe nuclei

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Vanadium oxides and vanadates are nowadays the best candidates for the next generation of battery cathode for energy storage,[1,2] particularly for the aqueous zinc-ion bateries (AZIB) due the low cost and good diffusion of Zn [3]. Hydrated vanadium pentoxide ($V_2O_5{\cdot}nH_2O$) has

a bilayer structure and structural water molecules work as pillars to expand the layer spacing, and the shielding effect from water hinders the electrostatic interaction between cations accelerating the Zn ion diffusion. The doping with impurity cations (such as Mn, Al, and Zn) into the interlayers can improve the (de)intercalation of Zn ions by enlarging the spacing and obtaining a faster ion diffusion. Cd ion is 24% larger than Zn and, therefore, can help form a more efficient cathode.

In the work here reported, electric quadrupole interaction on ^{111m}Cd nuclei implanted in divanadium pentoxide doped with different concentrations of Cd were measured with time-differential perturbed angular correlations (TDPAC). Pure V_2O_5 as well as doped with 1%, 5%, and 10% of Cd were measured at different temperatures. Samples of the vanadates CdV_2O_6 and $Cd_2V_2O_7$ were also investigated. The intention is to provide a comprehensive description of the doping effects on the local crystal structure and the electronic structure around the impurity and the consequences on the properties of the host oxides. Results show that the probability of formation of cadmium vanadates is low but the temperature and atmosphere of measurements have an important effect at the local scale. Moreover, the temperature behavior of the hyperfine parameters of pure and Cd-doped V_2O_5 are similar to but distinguishable from the cadmium vanadates.

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Solid State Physics / 13

MULTIPAC: a versatile tool to investigate multiferroic and magnetic materials

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We present the cryogenic magnetic system MULTIPAC, which will be used to perform Perturbed Angular Correlation (PAC) Experiments in Multiferroic (and Magnetic) Materials. It simultaneously allows to measure magnetic as well as ferroelectric properties concurrent with local probe experiments using PAC-isotopes. On the long run, the very same set-up can serve for the investigation of purely magnetic materials of all types. A multitude of questions regarding defects and local order parameter coupling are open and become accessible through this singular equipment in the world.

Solid State Physics / 28

Magnesium-vacancy quantum defects in diamond

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The use of color centers in diamond that are suitable as single photon emitters is currently at the forefront of efforts to establish crucial building blocks for a number of quantum technologies. Besides the well-known and widely investigated nitrogen-vacancy (NV) center, other single-photon emitting color centers with appealing properties have emerged in the last decade, including group-IV impurities and other impurity-related defects. In particular, the magnesium-vacancy (MgV) defect has been recently predicted to host a large, tunable, spin-dependent ground state splitting, making it particularly attractive for quantum information processing purposes [1].
In this contribution, we report on a comprehensive experimental investigation [2] of the MgV color center in diamond: detailed characterization of the structural properties and defect-formation efficiency, using ^{27}Mg($t_{1/2}$ = 9.45 min) emission channeling at the EC-SLI setup at ISOLDE (IS668); in-depth study of the optical emission properties using photoluminescence (PL), at the ensemble and single-photon emitter levels. The emission channeling study reveals a very efficient formation of the MgV defect, i.e. a high fraction of implanted Mg (30-42%) in the split-vacancy configuration, attributed to the relevant optically-active center [1], comparable to what we have recently reported for the SnV defect also based on emission channeling at ISOLDE [3]. The PL results reveal a remarkably high emission rate, larger than that of the brightest group-IV impurity related defects (SnV, PbV). These experimental results, combined with the predicted spin-dependent properties [1], show the tremendous potential of the MgV center in the context of quantum sensing and quantum information processing applications.

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CERN Ombud's insights from 2021 for today

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Laure Esteveny is the CERN Ombud since 15 April 2021. She has worked 36 years for the Laboratory in different functions and jobs. She works as a computing engineer and project lead until 2003, then moved on to Internal Audit, She was Head of Internal Audit during the mandate of Rolf Heuer. In the International Relations sector she led the project which set up the CERN Alumni network and was Head of CERN Alumni relations until December 2020.

She looks forward to this opportunity with the ISOLDE workshop to exchange with the ISOLDE community. She will present the role of Ombud and its creation in 2011, and will share some consolidated data for the period 2021-2022 on the cases exposed in the Ombud's Office. Laure will further give some key observations and insights derived from "ombudsing"at CERN. She will be pleased to respond to all your questions.

Poster Session / 16

Commissioning Results of MIRACLS'new Paul Trap

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The Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) is a novel technique to increase the sensitivity of high-precision collinear laser spectroscopy (CLS). To access exotic short-lived radionuclides with low production yields, MIRACLS performs CLS in a Multi-Reflection Time-of-Flight (MR-ToF) device where ion bunches bounce back and forth between two electrostatic mirrors. Consequently, the ions pass the measurement region multiple times which increases the laser-ion interaction and observation time, hence increasing the sensitivity.

Building on experience from a successful proof-of-principle phase [1-3], the high-resolution MIRACLS device is now being built for online operation at the LA2 beamline of ISOLDE. The MR-ToF instrument will be the first to operate at a beam energy of 30 keV, and its use for CLS imposes stringent requirement on the ion beam quality, especially in longitudinal ion-bunch emittance. For this purpose, MIRACLS also hosts its own buffer-gas filled Paul trap for optimal ion-beam preparation [4]. This Paul trap is currently being commissioned with an offline ion source, in preparation for the acceptance of ISOLDE beams.

This poster contribution will report on the commissioning results of MIRACLS'Paul trap.

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Poster Session / 18

Towards a highly selective and high flux multi-reflection time-of-flight mass separator

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Many experiments at radioactive ion beam (RIB) facilities suffer from isobaric contaminations, i.e. unwanted ions of similar mass. Over the years, Multi-Reflection Time-of-Flight (MR-ToF) devices have gained remarkable attention for mass separation of short-lived radionuclides at RIB facilities throughout the world [1]. They exceed mass resolving powers m/Δm of 10^5 within (some tens of) milliseconds. Space charge effects, however, pose a challenge for the mass separation in cases where too many ions are confined in the MR-ToF device. This limits the wider application of MR-ToF mass separators at RIB facilities.
By performing ion-optical simulations including space charge effects, we have shown that the ion flux in MR-ToF devices can be significantly increased when changing the kinetic energy of the stored ions from 1.5 keV to 30 keV. We benchmarked the validity of the simulation approach by comparing it with time-of-flight and collision-induced fluorescence measurements with MIRACLS'low-energy MR-ToF device [2]. When an ion is colliding with a residual gas particle, an inelastic collision can occur leading to the emission of fluorescence light. The detection of the fluorescence photons allows to track the evolution of the ion bunch temporal width over revolution number and thereby understand the ion dynamics within the MR-ToF device for varying numbers of stored ions. Hence, collisional-induced fluorescence measurements provide an excellent way to benchmark the simulation code, which was applied to optimize ISOLDE'S 30-keV MR-ToF mass separator, which is currently under construction.
In this contribution we will present the measurements in MIRACLS'low-energy MR-ToF device used to benchmark the simulation code. Furthermore, we will show the simulated performance of the novel 30-keV MR-ToF device for mass separation of isobars with an increased ion flux compared to state-of-the-art low-energy MR-ToF devices.

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Poster Session / 21

Collinear resonance ionization spectroscopy of stable 64, 66, 67,68, 70Zn isotopes

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Collinear resonance ionization spectroscopy of stable ^{64,66,67,68,70} Zn isotopes

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To study the exotic nuclear structure phenomenon in more neutron-rich isotopes beyond the neutron magic number N = 50 in the nickel mass region [1,2], experiment to measure the ground state properties of ^{81,82}Zn isotopes has been proposed at ISOLDE-CERN by using the collinear resonance ionization spectroscopy (CRIS) setup [3]. Prior to the online experiment, offline measurements have been performed on the stable^{64,66,67,68,70}Zn isotopes at CRIS setup at ISOLDE. Several atomic transitions (4s4p $^3P_{0,1,2}$ −4s5d $^3D_1$ /4s4p $^3P_{1,2}$ −4s5d ^{3} D_2 /4s4p $^3P_2$ −4s5d $^3D_3$ / 4s4p $^3P_{1,2}$ −4s7s $^3S_1$) have been probed in this work, allowing to systematically extract their hyperfine structure parameters and isotope shifts. The experimental results show an unexpected abnormal isotope shift at the odd-A ^{67}Zn isotope, which is particularly significant in atomic transitions involving the 4s5d $^3D_{1,2,3}$ states, and could possibly be attributed to the mixing of hyperfine levels. To have a full understanding of this experimentally observed abnormal phenomenon, further atomic theoretical calculations based on the second order perturbation using relativistic multiconfiguration Dirac–Hartree–Fock wavefunctions are ongoing [4].

In this presentation, the details of this offline experimental measurement, and the achieved atomic results (hyperfine structure parameters and isotope shifts) for all probed atomic transitions of stable $^{64-70}$ Zn, will be reported. Current progress on the atomic calculation will also be introduced.

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Poster Session / 22

Enhancing ISOLDE beam purity by ion bunch width compression via fast modulated heating of the RILIS laser ion source

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The resonance ionization laser ion source (RILIS) is the principal ion source at ISOLDE, providing efficient and element-selective ion creation by laser radiation tuned to unique electronic transitions of the atoms of interest. The laser system's 10 kHz pulsed operation imprints a respective bunch structure on the extracted ion beam. This characteristic can be used for partial suppression of contamination by applying a synchronized beam gating, only letting the bunches of laser-ionized species pass while blocking the contaminant, non-laser related DC-component in between. Clearly, the efficacity of this method is enhanced if the ion bunch width is reduced.

The bunch width is predominantly determined by the applied voltage gradient along the ion source. For standard operation, an electric current of ˜300 A is needed to resistively heat the source to approximately 2000 ℃, leading to a fixed gradient of ˜2V. Voltage gradient manipulation transparent to temperature requirements can be achieved by introducing a modulated heating scheme. While the average dissipated power is kept constant to reach the defined temperature, the voltage is applied with a duty cycle: During on-time, the required electrical power (and ergo voltage) is accordingly higher. Ions of choice would then be created by the laser in the time frame of active heating and high voltage gradient, and therefore formed to a narrower ion bunch compared to standard continuous heating.

Following previous exploration work [1, 2], simulation, development, and testing of respective equipment for µs-switching of high currents for the existing ISOLDE target/ion source system is conducted in cooperation with the SY/ABT group, providing expertise in high current fast switching systems at CERN.

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Poster Session / 23

Control System of MIRACLS at ISOLDE

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The Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) is a new experiment in the ISOLDE facility at CERN which aims to conduct collinear laser spectroscopy (CLS) on exotic nuclei with low production yields by exploiting a 30-keV multi-reflection time-of-flight (MR-ToF) device [2, 3, 5]. Ions bunches prepared by MIRACLS' Paul trap are sent into the MR-ToF instrument, where they are reflected back and forth between two electrostatic mirrors. Hence, the ion bunch interacts with a laser beam thousands of times before leaving the device, which yields a significant boost in sensitivity over conventional, single-passage CLS.

The experimental setup of MIRACLS is controlled by the Experimental Physics and Industrial Control System (EPICS). EPICS is a robust set of open-source software tools for creating control systems, for both small and large scale experiments [6]. It is used internationally at dozens of facilities [7], such as IGISOL [8] at Jyvaskyla, Finland and ISAC [9] at TRIUMF, Canada. In EPICS, process variables (PVs) can be defined on a server, and then accessed from anywhere within a particular network. This allows the user to easily create, get, set, and monitor these PVs in order to control a wide range of instruments, such as pressure gauges, vacuum valves, switches, and power supplies.

Powerful EPICS-based graphical user interfaces and displays have been developed at MIRACLS using Python which can control virtually every aspect of the experiment remotely.

This poster contribution will describe the different user interfaces that have been created with EPICS and showcase its power as a control system for nuclear physics experiments.

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Poster Session / 24

Operation and new development at the MELISSA laser lab in MEDICIS.

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The CERN-MEDICIS facility aim at producing exotic nuclear isotopes with high purity and specific activity, for medical application. The collection of the radioisotope of interest is performed either with a target irradiated by a 1.4 GeV proton beam from CERN's Proton Booster, or with an externally irradiated target provided by an external institution.
The Resonance Ionization Laser Ion Source (RILIS) technique is widely used in all radioactive ion beam facilities world-wide, as it provides high efficiency and selectivity for a wide range of isotopes of interests. This technique has been implemented at the MEDICIS facility trough the development of the MELISSA laser laboratory. Relying on 3 solid state Ti:Sa lasers coupled with intra-cavity Second Harmonic Generation, the MELISSA laser laboratory has delivered its first laser ion beam in April 2019 and has been operated since then for 80% of the collected radioisotopes in MEDICIS.
New laser developments are currently under investigation, with the double objectives of increasing the versatility and the stability of the MELISSA laser laboratory. To achieve these two objectives, new nonlinear processes (Sum Frequency Generation, Difference Frequency Generation) and new laser architectures are being studied, to determine the most reliable solution for the long-term optimization and routine collection of all the radioisotopes of interest at MEDICIS.

Poster Session / **26**

Ultra-low ion energy implantation: depth control of radioactive probes in nanostructures, using the new ASCII chamber

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The solid-state physics (SSP) collaboration at ISOLDE has a long history of investigating crystal structure, phase changes and magnetic behavior of nanostructures by implanting specific radioactive isotopes and recording their decay to obtain physical information on the atomic scale, using hyperfine techniques such as perturbed angular correlations (PAC) spectroscopy or emission Mößbauer spectroscopy. However, these experiments typically use implantation energies of 30 keV or more. At these energies, most ions come to rest only several nm below the surface. Directly incorporating these probes into surface structures of only a few nm or thinner has been impossible, despite ever-rising interest in such systems, including 2D materials or thin films of multiferroics.

Here, we present a solution to this problem: the brand new ultra-high vacuum chamber, called the ASPIC's ion implantation chamber (ASCII). This chamber allows deceleration of the 30 –60 keV radioactive isotope beams available at GLM, down to 10 eV. The context, design, simulations and potential future research of the chamber are discussed.

Poster Session / **27**

Laser assisted decay spectroscopy of 178Au at the ISOLDE Decay Station

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Laser-assisted decay spectroscopy of 178Au at the ISOLDE Decay Station

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In the region around the Z=82 shell closure and the N = 104 midshell, competition between spherical and deformed configurations leads to the phenomenon of shape coexistence [1]. Previous work (e.g. [2]) has sought to understand the structure of isotopes of gold (Z=79) to establish the extent to which such competition dictates their characteristics. A recent laser spectroscopy study [3] has shown that 178Au has two isomers, one of high and one of low spin and different deformations [4].

In August 2021, a decay spectroscopy experiment was performed [5] using the ISOLDE Decay Station (IDS) with isomerically pure beams of 178Au provided by RILIS. The isomeric selectivity combined with high γ energy resolution and efficiency of IDS were necessary for making such measurements due to the extremely low α branching ratios of some decay paths. Through β decay, it is also possible to study different sets of states of 178Pt populated by the two 178Au isomers. This contribution will comprise a summary of the experimental techniques used to collect these data and an overview of the determined structures of 178Au and 178Pt.

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Poster Session / 30

Effect of temperature distribution on the spectra of RaF

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With the advancement of spectroscopic techniques at radioactive beam facilities, the spectroscopy of radioactive molecules has been achieved in the past few years at ISOLDE using the Collinear Resonance Ionization Spectroscopy (CRIS) experiment [1].

Thanks to its strong electric field gradient and the rich electronic, vibrational, and rotational structure inherent in molecules, radium monofluoride (RaF) has become the center of attention for theoretical and experimental investigations in search of the electron electric dipole moment and nuclear Schiff moments [2-4]. Such future searches depend on preparatory spectroscopic studies of the electronic structure of the molecule.

The RaF molecules arrive at CRIS after going through ISCOOL, a radio frequency quadrupolar cooler-buncher. This device aims to cool the molecules to room temperature using a helium buffer gas and release the continuous beam in bunches [5]. The final beam temperature can be probed by measuring the population distribution of the molecules in different rotational states, extracted from the relative intensities of the rotational transitions. As such, the presence of different temperature groups in a bunch leads to a more complex spectrum, and the temperature groups can be extracted from the spectral analysis.

RaF spectra measured in the 2021 CRIS campaign from transitions to high-lying electronic states up to 30,000 cm-1 have been analyzed using the molecular analysis code PGOPHER. The results show that most of the spectrum requires fitting with at least three different temperature distributions within each bunch from ISCOOL, with temperatures as high as 1000 ℃.

This poster will present the results of the analysis of the excited states in RaF, with a particular focus on extracting the beam temperature distribution. Thus, a comparison of the extracted beam temperatures with different distribution models will be shown, along with future outlooks.

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Poster Session / 33

Target material research and hot materials characterization infrastructure at SCK CEN

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An ISOL facility with a primary beam of up to 500 µA - 100 MeV protons, is currently being designed in SCK CEN (Belgium) to start operation in 2028. Target and ion source research have been, since long, research subjects at SCK CEN in order to develop the radioactive ion beams to be available at ISOL@MYRRHA.
SCK CEN has a unique and varied panoply of laboratories equipped with advanced characterization techniques to study activated/contaminated materials. It is also equipped with hot cells which allow the preparation of samples of highly radioactive materials for characterization and also post irradiation examination. With an emerging ISOL facility with dedicated target material laboratories, SCK CEN is creating a unique environment to potentiate target material research including also post-irradiation characterization studies.
Using some of the mentioned target material research infrastructure, SCK CEN has recently studied TRIUMF's uranium carbide materials by comparing samples before and after irradiation by characterizing in detail their microstructure complemented with elemental analysis.

At SCK CEN the research on Thorium based materials for radioactive ion beam production has recently been started within a PhD framework, in collaboration also with ISOLDE at CERN.
Non-actinide material experience also exists at SCK CEN: recently, a novel tantalum carbide material was developed in collaboration with KU Leuven from a Ta4AlC3 MAX phase with bimodal porosity and micrometric grain size. This material, even when brought to 2200 ℃ shows no sign of sintering, demonstrating a very good microstructural stability at extremely high temperatures. Samples have been sent to TRIUMF for radioactive isotope release studies, which are still ongoing.
In this poster, we will give an overview of ISOL target material research involving SCK CEN, but also of the infrastructure and capabilities available at SCK CEN for the characterization of radioactive materials.

Poster Session / 35

Charge radii measurements of $^{26-34}$Al transitioning into the N = 20 island of inversion

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The neutron-rich Al isotopes provide an excellent opportunity to investigate the evolution of nuclear structure crossing the $N = 20$ shell closure and the transition into the island of inversion. Indeed, the Al isotopic chain, with $Z = 13$, is located between spherical silicon [1] ($Z = 14, N = 19$) and deformed magnesium ($Z = 12, N = 21$) [2], ^{32}Mg being the center of the $N = 20$ island of inversion. At present, charge radii measurements of radioactive isotopes in this region are limited up to N = 20 shell closure for Mg [2] and Na [3], and N = 19 for Al[4]. The CRIS collaboration recently measured $^{26-34}$Al using laser spectroscopy, crossing the $N = 20$ shell closure, building on previous results measured at ISOLDE, CERN [4].

In this talk, a brief overview of CRIS will be introduced before presenting measurements of the change in charge radii along the isotopic chain of Al. In particular, the first charge radii measurements of ^{33,34}Al will be highlighted. These results will then be discussed in relation to the $N = 20$ shell closure and the implications when entering the island of inversion.

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Poster Session / 39

Approaching N=82 through silver with the recently implemented voltage scanning at CRIS

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Understanding the nucleus and its structure relies on exploring the ground-state properties of nuclei far from stability. Many of these properties, such as the spin, nuclear electromagnetic moments and charge radii, can be measured with laser spectroscopy in a model-independent way. On-line laser spectroscopy provides access to these properties of long-lived states (>10ms). One region of interest is between the strongly deformed zirconium (Z=40) and the nearly-spherical tin (Z=50). This region features many competing configurations with rich isomerism and thus has been of central interest in recent experiments: tin [1], indium [2], cadmium [3], palladium [4] and neutron-deficient silver [5-6] have been successfully studied. Recently, neutron-rich silver has been investigated at IGISOL [7-8] in Jyväskylä and at ISOLDE/CERN [9] with the newly implemented voltage scanning at CRIS.

I will present the results of the recent CRIS experiment on silver in parallel with the IGISOL results. The spins and nuclear electromagnetic moments of the ground-state and multiple long-lived isomers have been deduced. This data provides a benchmark and challenge to state-of-the-art nuclear models in this region. Moreover, I will present a comparison of laser scanning and voltage scanning performed at CRIS, showcasing the strength of voltage scanning in collinear laser spectroscopy.

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Poster Session / 40

Challenging production of long-lived Xenon isotopes at ISOLDE: experiment vs theory

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Gamma-MRI is an EU-funded project which aims at the development of a new medical imaging modality, able to combine the high resolution of already established MRI techniques with the high sensitivity provided by SPECT gamma detection method. The nuclear species selected for this new technique are Xenon isomers (129mXe, 131mXe, 133mXe), since they are biologically inert, can be polarised, and their decay offers the maximum gamma-decay asymmetry.
One important element of the project is the efficient production of Xe isotopes, for which ISOLDE represents one of the best suited facilities. The Xe isotopes under study are collected by implanting extracted Xe beam in gold foils, whose activity is evaluated from gamma spectroscopy measurements. Unfortunately, several attempts at efficient production at ISOLDE have been challenging: very high-level of stable contaminants, lower production than expected from test collections, very low efficiency for offline collections.
These unexpected problems have led us to investigate in detail the production on 121-140Xe, and especially 129,131,133Xe during a 2.5-day beamtime. Regular mass scans and test collections, together with one main collection were performed, followed by gamma-spectroscopy of the irradiated foils.
We combined these results with Fluka calculations of in-target yields, and we were able to develop a production model in which a production curve can be obtained for each Xe isotope , considering the contribution of both direct in-target production, side feeding from neighbouring parent nuclei, and total efficiencies. A special case is represented by 133Xe, from which it is possible to estimate experimentally the Isomeric Ratio, as both its isomeric and ground state are unstable.
Consequently, the main outcome of the present work is the possibility to define the optimal conditions that can be exploited to maximize the production efficiency and predict the amount of a given Xe isotope that can be collected.

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Polarons in MoO_x implanted with cadmium (^{111m}Cd-^{111}Cd) probe

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The recent advances in the development of semiconductor devices based on nano-crystal technology have led to numerous applications in high-tech electronic and optoelectronic devices including, transistors, light emitting diodes, solar cells, photodetectors, thermoelectrics, and phase change memory cells. Among the potential material for such applications are the transition metal oxides, such as MoO_3, WO_3, V_2O_5, and TiO_2, which have shown promising characteristics in inducing efficient charge transport at semiconductors. These materials have recently been applied in organic photovoltaic (OPV) and light-emitting diode (OLED) devices. The formation of polarons is a pervasive phenomenon in these types of materials, and it was found that the polaron charge carrier is another important characteristic involved in multiple (opto)electronic processes during device operation, such as charge transport and exciton recombination/dissociation. Therefore, the investigation of polaron formation in transition metal oxides is an important concept to consider for the recent developments in semiconductor electronics.

In this work, we studied the polaron formation and transport in one of the transition metal oxides with the name of α-MoO_3 by employing the Perturbed Angular Correlation (PAC) technique to probe the local environments of the system; together with first principle calculations within the framework of Density Functional Theory (DFT). The formation of oxygen vacancies can potentially be the main factor to improve the electrochemical performance of α-MoO_3 and also the conductivity. In order to increase the values of conductivity or drift mobilities of the charge carriers in α-MoO_3, doping with ^{111m}Cd-^{111}Cd probe isotope has been proposed. Also, the effect of oxygen vacancies and their interaction with metal impurities has been investigated to analyze the main factors that affect the rate of electron and hole mobilities. We can find that the induced defect-complexes of Cd impurity and oxygen vacancies, the α-MoO_3 system shows not only electron polaron-type orbitals but also a mixture of hole polaron states which form around the Cd impurity site.

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Towards a photo-cathode driven electron-impact ion source for new molecular beams at ISOLDE –Numerical simulations of the ion extraction

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The thick-target ISOL (Isotope mass Separation OnLine) method provides beams of more than 1000 radionuclides of 74 elements. The method is optimized for operation at high temperatures of up to ca. 2000 C. Recently, an interest in radioactive molecules, e.g., for the study of Beyond Standard Model physics was emerging [1]. However, promising candidates (like RaOH) are expected to decompose at these ultrahigh temperatures. While cold target concepts have already been proposed [2], the normal mode of operation of the typically used VADIS (Versatile Arc Discharge Ion Source) with a hot cathode [3] to provide electrons by thermal emission is not well suited. As complementary approach to molecule formation in traps and ion guides [4], we have conducted first exploratory experiments with a photo-cathode driven ion source that exploits electron-impact ionization at ambient temperature [5,6]. Following the promising results, we have started to systematically model the ion source by numerical simulations and compare with the experimentally obtained characteristics. In this contribution, we present first simulation results that allow gaining further insight into the performance of the ion source and support the development of a dedicated prototype.

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Molecular Ions as Powerful Low-Energy Probes for Fundamental Physics

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In the search for $\mathcal{P},\mathcal{T}$-odd effects, polar molecules can exhibit orders of magnitude larger enhancements than atoms [1,2] due to large internal fields. Choosing molecules, however, imposes additional challenges, such as the need of molecular instead of atomic theory or an analysis of congested rovibronic spectra. The initial difficulty is the search for suitable systems with large enhancements of $\mathcal{P},\mathcal{T}$-odd properties, that are easy to produce, simple to handle and, preferably, contain optical cycling centers for laser-cooling. Highly-charged actinide molecules like PaF^{3+} [3] are predicted to fullfill these criteria.
Ions have the experimental advantage that they can be guided by electric fields and sympathetically cooled [4] with long trapping times which might open up a pathway for subsequent direct laser-cooling of well chosen systems. With increasing charge, relativistic effects become more dominant, which increases the $\mathcal{P},\mathcal{T}$-violating enhancement factors and the electronic spectra become typically compressed, which is favourable for the search for variation of fundamental constans.

In this contribution we will discuss trends in the enhancement of various properties relevant for tests of fundamental physics of simple diatomic, molecular ions with the focus on molecules with a doublet ground state. The properties are computed using the quasi-relativistic toolbox approach outlined in [5].

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Vacuum-ultraviolet spectroscopy of thorium-229m: En route towards a solid-state nuclear clock

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A unique feature of thorium-229 is its isomeric first excited state with an exceptionally low excitation energy, proposed as a candidate for future nuclear optical clocks serving as a versatile quantum sensor for fundamental physics [1]. A novel approach to populate the isomeric state in radioactive decay using the beta decay of actinium-229 is studied at ISOLDE as an alternative to the 'traditional' alpha decay of uranium-233 [2].

In this contribution, results from recent vacuum-ultraviolet spectroscopic measurements of the isomer's radiative decay using a A=229 beam implanted into large-bandgap MgF2 and CaF2 crystals are presented [3]. The observation of the radiative decay in such media marks an important milestone in the development towards a solid-state nuclear clock.

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Poster Session / 49

Studies of triaxial deformations in ^{140}Sm at ISOLDE

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Nuclei in the rare-earth region, especially the samarium (Sm) isotopes, exhibits a variety of shapes. The aim of the present work it to test the theoretical calculations predicting the ^{140}Sm isotope to be a transitional nuclei in between a spherical and a deformed shape [1].

Relativistic Hartree-Fock-Bogoliubov (HFB) calculations find a smooth transition from spherical ^{144}Sm to well-deformed prolate ^{134}Sm with a γ-soft potential energy surface for the transitional nucleus ^{140}Sm [2]. The observation and tentative assignment of a 2_2^+ state at 990 keV and a 3_1^+ state at 1599 keV in ^{140}Sm following the β-decay of ^{140}Eu was interpreted as evidence for a low-lying γ-band [3].

To investigate this transitional nucleus a CoulEx experiment was performed at REX-ISOLDE in 2012 by M. Klintefjord et al. [4]. The results showed no indication of low-lying shape coexistence, rather it seems ^{140}Sm shows weak quadrupole deformation with maximum triaxility of $\gamma = 30^o$ and significant γ-softness.

To investigate the degree of γ-softness a new CoulEx experiment was performed using the newly upgraded HIE-ISOLDE in 2016. With the higher beam energies provided by the new HIE-ISOLDE post-accelerator and the resulting higher cross-section many higher-lying states were populated. The goal of the analysis is to measure transition probabilities connected to the states in the γ-vibrational band and to the excited 0^+ states. This will be a large GOSIA analysis, and the results from this experiment will improve existing B(E2)-values, create new B(E2)-values and quadrupole moments.

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Poster Session / 51

Nuclear electromagnetic moments of scandium isotopes studied by laser spectroscopy

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Studies of exotic nuclei have revealed numerous unexpected structure phenomena, extending our knowledge of nuclear forces and nuclear quantum many-body systems [1,2,3]. The scandium isotopes, with one valence proton added in the f7/2 orbit above the Z = 20 shell closure in the shell-model picture, are expected to be sensitive to the single-particle behavior, and nucleon-nucleon correlations. Nuclear electromagnetic properties of 44-49Sc were measured at ISOLDE-CERN using high-resolution collinear laser spectroscopy (COLLAPS). Together with earlier studies in the literature, this work completes the systematic trends of the electromagnetic moments of Z = 21 isotopes and N = 28 isotones when valence neutrons and protons filling the distinctive f7/2 orbit, respectively [4]. In addition, the nuclear charge radii of scandium isotopes up to N = 28 shell closure have been extracted.

In this talk, the details of the COLLAPS experiment, as well as the extracted experimental results (nuclear electromagnetic moments and charge radii) of scandium isotopes will be presented. These results will then be discussed by a comparison with region systematics and with theoretical calculations by large-scale shell-model and ab-initio VS-IMSRG.

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Poster Session / 53

Development of a Liquid Sample Dispensing System Facilitating Novel Applications of β-NMR at VITO

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β-NMR has proven its capabilities and advantages in the world of nuclear spectroscopy: Not only does it open the door to high precision measurements of nuclear properties, but it also facilitates investigations of unstable, short-lived isotopes, otherwise inaccessible to conventional NMR. Additionally, β-NMR allows for real-time observations of chemical processes, such as biomolecular folding mechanisms.

Recently, the VITO collaboration has been striving towards novel applications of this technique in interdisciplinary fields. One of the ongoing projects aims at investigating the dynamics of selected DNA structures and their interaction with different alkali metals. Deep eutectic solvents, such as Glycholine, are used as hosts for these biological samples.

Performing experiments with liquid samples in a high vacuum setup poses technical challenges, not faced in typical nuclear spectroscopy. So far, a simple support with a plate on top is used to position the liquid sample for beam implantation. Exchanging the droplet, however, is time consuming, as it requires venting and opening the beamline. At the same time, prolonging the measurement duration without changing the sample would increase background activity from daughter nuclides, thus introducing additional noise.

Addressing this issue, a new project has been launched at the VITO beamline, aiming to develop, test and implement a new sample holding and dispensing system. Not only does the design presented with this poster contribution reduce the need of opening the beamline, but it continuously provides fresh samples for implantation. Thereby, it contributes to a more efficient measurement process and an enhanced signal to noise ratio.

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Transfer reactions in the neutron-rich krypton isotopes

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The evolution of neutron single-particle properties and their role in the onset of deformation towards N = 60 in the neutron rich Kr isotopes has been studied via the one-neutron transfer reactions ^{92,94}Kr(d,p). These were performed in inverse kinematics at an energy of ~8.0 MeV/u using the ISOLDE Solenoidal Spectrometer (ISS).
In the A = 100 region, a dramatic shape change observed for Zr and Sr (Z = 40 and 38, respectively) is not present in Kr (Z = 36) isotopes. The 2^+_1 energies and the B(E2;$2^+_1 \rightarrow 0^+_1$) values vary smoothly across the Kr isotopes but Sr and Zr isotopes display a large jump at N = 60, indicating a significant increase in the ground state deformation of these isotopes [1-15]. 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 [16, 17].
Previous studies in this region have shown a smooth onset of deformation in Kr isotopes at N = 60, and evidence of a new oblate structure coexisting with the prolate ground state [18, 19]. Accurately predicting ground-state spins and parities of odd-mass isotopes in this region is challenging. The data obtained from the ^{92,94}Kr<em>*(d,p)* reactions, will provide a more complete experimental picture of the underlying single-particle configurations, aiding in our understanding deformation around A = 100.
Preliminary results obtained in the October 2022 experiment will be presented.

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Poster Session / 70

Limits of the 'classical' laser ion source for medical radioisotope production

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Resonant laser ionization is an efficient and highly selective method for producing radioisotopes. In the laser ion source of the ISOLDE –RILIS (Resonance Ionization Laser Ion Source), the laser interaction region is inside a metal tube, the so-called "hot cavity"which is heated to temperatures of up to 2200 degrees Celsius. In addition to providing a longitudinally confining electrostatic potential due to electron emission from the cavity material, this heating also induces surface ionization of elements with low (< 6 eV) ionization potential. If the overall ion load of laser and surface ionized species reaches a certain threshold the confining potential breaks down and the efficient extraction of these ions is compromised. In concrete terms this means that the extraction efficiency of laser ions which have a distinct and short time structure induced by the pulsed lasers reduces drastically whereas the surface ions, which have a constant mode of creation, remain unaffected (if the half-life is long enough). This effect is especially prevalent in facilities like MEDICIS which demand a high ion throughput and fast extraction for quick and efficient delivery of radioisotopes for medical applications (half-lives of ˜ 5 days). This work aims to define the limits of the "classic"laser ion source which is currently used for medical radioisotope production at MEDICIS. The measurements were performed using the ISOLDE OFFLINE 2 facility to determine the operational parameters under high ion load. An outlook on possible alternative ion source geometries will be given, which might remedy the problem for future laser ion extraction.

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The first real-world test of the single-mode Raman laser for RILIS applications

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Tunable, single-frequency laser sources are a great tool for high-selectivity spectroscopy, allowing hyperfine structure and isotope shift measurements. In this study we demonstrate monolithic diamond resonators as a narrow linewidth laser source, suitable for high-resolution spectroscopy. The Stokes field from the diamond resonator at a wavelength of 433.9 nm and linewidth of 170 MHz was used in a crossed-beams spectroscopy setup (PI-LIST). The targeted atom was 152Sm, and the ionization experiment resulted in the measurement of a 0.51 GHz FWHM spectral profile affected by saturation, which demonstrated the suitability of diamond resonators as a high-selectivity spectroscopy tool.

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The PI-LIST Laser Ion Source at ISOLDE: Implementation and Initial Results

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Laser resonance ionization spectroscopy in the ion source coupled directly to the isotope production target has been proven to be a highly sensitive tool for nuclear structure investigations on isotopes with low production and extraction yields [1]. While the efficiency of this technique is unrivalled, the spectral resolution is ultimately limited by Doppler broadening. At the ion source temperature of ˜2000 ℃ typically required for efficient operation, Doppler broadening results in a 1-10 GHz experimental resolution limit whereas precise measurements of nuclear magnetic and quadrupole moments often require resolving hyperfine structure splittings below the GHz regime.
A new laser ion source design has been implemented at ISOLDE recently to provide in-source spectroscopy capabilities down to experimental linewidths of 100 –200 MHz, an order of magnitude below usual limitations. It is based on the high beam purity Laser Ion Source and Trap (LIST) [2, 3], featuring spatial separation of the hot cavity where potential ion beam contamination can arise from non-laser related ionization mechanisms such as surface ionization, and a clean laser-atom interaction region in an RFQ unit directly downstream, where solely element-selective laser ionization takes place. In the so-called Perpendicularly Illuminated LIST (PI-LIST) [4], a crossed laser/atom beam geometry reduces the effective Doppler broadening by addressing only the transversal velocity components of the effusing atom ensemble.

Following the integration of this device as the standard tool for high-resolution spectroscopy applications at the off-line mass separator facility at Mainz University [5, 6], we present its first on-line application at ISOLDE for nuclear structure investigations. Neutron-rich actinium isotopes in the region of assumed octupole deformation were probed, pinning down predictions of recent Energy Density Functional nuclear theories that incorporate reflection symmetry breaking [7].

The applicability of this technique to ISOL facilities in general, its limits especially in terms of significant efficiency loss, and technical implementation challenges are discussed.

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News from our Sister Facilities / 69

FRIB status and plans

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The Facility for Rare Isotope Beams (FRIB) started user operations in May 2022. This presentation will give an overview of the initial experimental program and the plans for the immediate and mid-term future.

News from our Sister Facilities / 34

The ISOL facility of MYRRHA at SCK CEN: current status

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An ISOL facility is currently emerging within the MYRRHA project in Belgium. This facility will use 100 MeV protons with intensities up to 500 µA to produce a vast range of radioisotopes, namely isotopes for medical purposes, such as Ac225, but also radioactive ion beams for fundamental research. This facility is part of the MYRRHA-ADS (a Multipurpose hYbrid Research Reactor for High-tech Applications), where its first phase has been fully funded by the Belgian government. The first phase consists of the first part of the accelerator (100 MeV, later to be upgraded to 600 MeV) and also the mentioned ISOL Facility and a fusion material irradiation station.
This ISOL facility uses a modular frontend system which is largely based on the ARIEL design at TRIUMF. This type of frontend presents the main advantages of easing the maintenance and repair processes. Additionally, also following ARIEL, the ISOL facility at MYRRHA uses a Target and Ion Source (TIS) Assembly as a modular and remotely coupled vessel, which allows a high turnover of beams since the target is pre-mounted and conditioned before operation. This facility is currently completing its conceptual design and fixing its building layouts. For development tests an offline prototype of the ISOL system is also being constructed at SCK CEN. In this talk we introduce the project, its current status and the main highlights.

News from our Sister Facilities / 29

Gaussian Process Bayesian Optimization of an Isotope Separator Online system

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Isotope separator online systems (ISOL) are facilities constructed for producing radioisotopes used in multiple fields, such as nuclear & solid state physics and research related to medical applications. However, the quality (purity) and quantity (intensity) of the supplied Radioactive Ion Beam (RIB) depends on the proper tuning of the underlying process parameters and their mutual interaction. From experience with existing ISOL facilities like ISOLDE at CERN and ISAC at TRIUMF, the selection of initial design parameters to produce a RIB is performed by qualified operators. Here, the main concern is the long duration that the parameter tuning process demands due to the high number of control knobs that must be set. Therefore, incorporating online optimization techniques is crucial to reduce the initial parameter tuning time and provide an optimal performance of the ISOL system over the full running period. The optimization of this kind of system is challenging due to the high dimensionality, difficulty of modelling through physical laws, and the cost function being expensive to evaluate.
On that account, Bayesian optimization (BO) appears as an ideal technique to tackle the ISOL system based on the effectiveness of this method in optimizing highly costly objective functions using few iterations. In addition, to capture the complex dynamics of the ISOL system, Gaussian Process (GP) is proposed due to its ability to model non-linear multi-dimensional functions. Indeed, the combination of the Gaussian process and Bayesian optimization (GPBO) has been successfully applied to the online optimization of similar facilities like accelerator mass spectroscopy, linear particle accelerators, and recoil separator system.
One limitation for optimizing this type of process is the physical constraints imposed by the ISOL system itself. Therefore, strict measures must be taken to avoid the violation of those constraints. This contribution proposes a constrained GPBO to simultaneously learn the feasible design space and efficiently search for the parameters that allow an optimal operational regime. The method is tested through simulations of the transport beamline of ISOL@MYRRHA at SCK CEN.

News from our Sister Facilities / 64

Highlights and plans of the GANIL/LISE facility

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In this presentation, I will present some recent highlights obtained at the LISE beamline at GANIL using transfer reactions, decay studies, as well as nuclear and Coulomb excitation with the ACTAR-TPC, MUST2, EXOGAM2 and/or PARIS detectors. Topics will cover clustering, mirror symmetries, magicity and shell evolution, nuclear astrophysics, as well as physics at the drip line. I will also briefly discuss about the plans for the forthcoming 3-4 years.

News from the ISOLDE Technical Team / 10

ISOLDE's new high-resolution laser ion source PI-LIST: Nuclear structure investigations and isomer-pure beams

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On-line in-source laser resonance ionization has been proven to be a highly sensitive tool for nuclear structure investigations on isotopes with low production and extraction yields [1]. While the efficiency of this technique is unrivalled, the spectral resolution is ultimately limited by Doppler broadening in the hot cavity required to ensure atom volatilization. At typical operation temperatures around 2000 ℃, this leads to a 1-10 GHz experimental resolution limit, whereas precise measurements of nuclear magnetic and quadrupole moments often require resolving hyperfine structure splittings below the GHz regime.

A new laser ion source design has been implemented at ISOLDE this year to provide in-source spectroscopy capabilities down to experimental linewidths of 100 −200 MHz, an order of magnitude below usual limitations. It is based on the high beam purity Laser Ion Source and Trap (LIST) [2, 3]: laser ionization takes place in a quadrupole structure directly downstream the hot cavity, while potential contamination from non-laser related ionization machanisms in the latter is electrostatically blocked. In the new so-called Perpendicularly Illumination LIST (PI-LIST) mode [4], a crossed laser / atom beam geometry reduces the effective Doppler broadening by addressing only the transversal velocity components of the effusing atom ensemble –a method that was employed very successfully at off-line experiments at Mainz University [5, 6].

We present the first-time on-line application of the PI-LIST at ISOLDE for nuclear structure investigations. Neutron-rich actinium isotopes $^{224-231}$Ac in the region of assumed octupole deformation were probed (IS664), pinning down predictions of recent Energy Density Functional nuclear theories that incorporate reflection symmetry breaking [7]. Additionally, enhanced Fr suppression capabilites of standard LIST operation and utilizing partice identification at the ISOLDE Decay Station enabled extension of measurements on the Po isotope chain around and above N=126 (IS456).

Besides results of this experimental campaign, the general scope of using the new PI-LIST at ISOLDE also outside in-source laser spectrocopy applications, e.g. for production of isomer-pure RIBs, is explored. Its limits especially in terms of efficiency and spectral resolution are dicussed, and ongoing developments are presented.

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RILIS operation in 2022

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In this presentation I will summarize operation of the Resonance Ionization Laser Ion Source (RILIS) during the on-line period of 2022 on behalf of the local team. I will present highlights from the ongoing developments and improvements, which have contributed to the success of operating RILIS with almost no down-time this year. In addition, I will highlight the experimental campaigns performed this year with the LIST. The presentation will conclude with an outlook on future developments and planned upgrades for the next year.

News from the ISOLDE Technical Team / 31

Determination of radioactive ion beam production yields using 1.4- and 1.7-GeV protons

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CERN-ISOLDE is among the world-leading isotope separation on-line (ISOL) facilities providing radioactive-ion beams (RIBs) for research. ISOLDE's versatility is driven by the 1.4-GeV proton beam delivered by the Proton Synchrotron Booster and its target and ion source repertoire. While a wide range of RIBs can be provided for physics experiments, user interest often focuses on more and more exotic isotopes that are challenging to deliver due to low production and/or low release efficiency from the target-ion source system. As a result, target and ion source development and facility upgrades for higher quality beams are required to increase the facility's capabilities and ensure its competitiveness. Past upgrades in proton beam energy proved to be valuable and experimental data suggests that gains in isotope production yields could be achieved by further energy increases. To validate the expected gain of such an upgrade, a campaign (IS716) to measure and compare RIB yields using 1.4- and 1.7-GeV protons was launched earlier this year at ISOLDE. In this contribution we will present the status of this campaign, highlight first experimental results and compare them to theoretical predictions.

News from the ISOLDE Technical Team / 19

Radiation protection studies for the ISOLDE Beam Dump Replacement Study (IBDRS)

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In 2021, in order to evaluate the technical feasibility and the resources required to replace the ISOLDE beam dumps, a dedicated study (IBDRS) was launched. The beam dump replacement activity is divided in two main phases:
1. The dismantling worksite: it consists in safely removing and storing the present beam dumps and their shielding, including several thousands of cubic metres of soil (part of which is radioactive) presently covering the ISOLDE target area;
2. The consolidation worksite: it involves the installation of new beam dumps and related infrastructure (e.g. cooling system) and shielding able to cope with a potential beam power increase.
This contribution will provide an overview on the status of the studies performed to address the radiation protection aspects of the project; the main challenges will also be discussed. A particular focus will be dedicated to the consolidation studies for the new operational beam parameters (2 GeV beam energy and up to 6 uA beam current): the design and optimisation of the new shielding, the evaluation of the residual dose rate for interventions in the target area and the estimation of atmospheric releases from air activation.

News from the ISOLDE Technical Team / 56

Developments for actinide molecular ion beams at CERN-ISOLDE

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The ISOLDE facility at CERN provides ion beams of isotopes across the nuclear chart produced in thick targets from reactions with accelerated protons from CERN's Proton Synchrotron Booster. Molecular ion beam techniques have the potential to improve intensity and purity through volatilization and sideband extraction [1-5]. Molecules additionally provide opportunities for fundamental physics at radioactive beam facilities [6-8].

We present first results of actinide molecular ion beam development at ISOLDE. Uranium carbide targets were used to produce molecular beams via injection of reactive tetrafluoro methane (CF_4) gas. The ion beam composition was studied using: the ISOLTRAP Multi-Reflection Time-of-Flight

Mass Spectrometer (MR-ToF MS) [9] for identification by ToF mass measurements, online γ-ray spectroscopy at the ISOLDE tape station [10,11], and off-line α- and γ-ray spectrometry of ion-implanted samples. The results contribute to beam developments for actinide elements and radioactive molecule production for fundamental physics research.

This project has received funding from the European's Union Horizon 2020 Research and Innovation Programme under grant agreement number 861198 project 'LISA'(Laser Ionization and Spectroscopy of Actinides) Marie Sklodowska-Curie Innovative Training Network (ITN).

Novel Techniques for Reactions & Decay Spectroscopy / 68

Single-neutron properties of nuclei probed with the ISOLDE Solenoidal Spectrometer

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The ISOLDE Solenoidal Spectrometer was fully commissioned in 2021 with the new silicon array developed by the University of Liverpool installed. This array makes use of double-sided silicon strip detectors, with ASIC readout, to determine the position of interaction and the energy of light ejectiles when they return to the beam axis following reactions of HIE-ISOLDE accelerated beams with a light ion target.

ISS has now completed two full physics campaigns focussing on measurements of the (*d*,*p*) reaction to probe single-neutron behaviour in various systems. Highlights have included, but are not limited to; measurements of the evolution of single-neutron properties outside N=126 ,with a measurement of the ^{212}Rn(*d*,*p*) reaction, and N=16 with a study of states populated in ^{27}Na; probing single-particle structure in to the N=20 island of inversion with a measurement of the fragmentation of strength in ^{31}Mg; a study of ^{12}Be probed via a measurement of the ^{11}Be(d,p) reaction populating final states above the Sn and S2n energies.

This talk will give an overview of the commissioning of the ISS detectors and a summary of the physics campaigns from the last two years.

Novel Techniques for Reactions & Decay Spectroscopy / 1

Characterisation of the SpecMAT active target at ISOLDE and its physics perspectives

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The SpecMAT active target will be used to study shell evolution in exotic isotopes and investigate the fundamental aspects of the nuclear structure far from stability via transfer reactions in inverse kinematics. The SpecMAT is currently at the final developmental stage and undergoes characterisation measurements at KU Leuven and ISOLDE. During the most recent characterisation, SpecMAT was installed in the ISOLDE Solenoidal Spectrometer with a magnetic field of 2.5T. This characterisation was performed off-line using a standard alpha source. In this measurement spiral tracks of alpha particles were successfully observed in the time projection chamber of the detector. Gamma rays

emitted in the decay chain of 241Am were detected in coincidence with the particle tracks by the scintillation array. With this characterisation, we demonstrated that all detector components could operate in the strong magnetic field and are ready for future on-line experiments.
In this talk recent Geant4 simulations of transfer reactions that can be studied with SpecMAT also will be presented. Using the newly developed simulation toolkit, SpecMATscint, we demonstrated the feasibility of studying the shell evolution near the doubly magic 78Ni.

Novel Techniques for Reactions & Decay Spectroscopy / 55

Elastic alpha scattering on heavy exotic nuclei - report on IS698 experiment

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The uncertainties in the knowledge of the alpha-nuclear potential are still one of the main sources of uncertainty in the modeling of the production of the stable p-nuclei, with those uncertainties extending to unstable proton rich regions of the nuclear chart.

Recent developments in the production of thin silicon films containing large amounts of He allowed for the proposal of the first experiment measuring the angular distribution of elastic scattered alpha particles off radioactive tin isotopes, at energies around the Coulomb Barrier at the HIE-ISOLDE facility. Experiment IS698 was scheduled and completed last September, allowing for the study of the elastic scattering of the exotic ^{110}Sn, ^{109}Sn and ^{108}Sn.

In this contribution the performance of the thin films exposed for the first time to this heavy radioactive beams, as well as the results of preliminary analysis of the data will be presented.

Novel Techniques for Reactions & Decay Spectroscopy / 7

Neutron measurement in the IS581 experiment

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Four Timepix3 pixel detectors were installed
on the body of Actar TPC demonstrator during
the November 2021 beamtime of the IS581 experiment.
Polyethylene converters were used for detection
of fast neutrons. Since no significant background
was observed, it was possible to measure the angular
distribution of emitted neutrons. Subsequent simulations
emplying the results of Talys code and available data
on fragment distributions allowed to estimate directly the value
of fission barrier height for neutron-deficient nucleus
210Fr, which was a main goal of the IS581 beamtime.

Novel Techniques for Reactions & Decay Spectroscopy / 8

ASET: the new α- decay setup and much more

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ASET, α-setup, is a new detection system designed and built to perform particle decay spectroscopy at ISOLDE. It is based on a movable ladder system instead of a wheel, previously used in the Windmill system [1]. The working principle is the same as Windmill's: the ladder moves up and down between two silicon detectors (an annular and a full one), which are placed at each side of the ladder. The main improvement from the Windmill system is the higher efficiency for the silicon detectors as they can be placed closer to the foils, and the reliability of the system. Different ladders can be used, depending on the type of implantation foils applied. Up to now, carbon foils of $20\, g/cm_2$ thickness, and Si_3N_4 membranes of several thicknesses were used. Beside the α spectroscopy, ASET also allows the use of HPGe detectors. These can be placed outside the chamber, but close to the implantation point thanks to two recessed flanges.

The feature of having both α and γ spectroscopy opens the possibility to different kind of experiments: one example is the recent IS456 campaign about α spectroscopy of ^{219,220}Po [2].

Silicon detectors can be used also to detect fission fragments, enabling β-delayed fission (βDF) to be studied with ASET. Two campaigns were performed on βDF during the last couple of years: IS665 about βDF in ^{176,178}Au [3] (August 2021), and LOI216 about βDF in ^{230,232,234}Ac [4] (May 2022). From this last campaign upper limits for the βDF probabilities of ^{230}Ac and ^{232}Ac were preliminarily estimated, and the value for ^{230}Ac was found to be two orders of magnitude lower than the one reported in literature [5].

Moreover, during the IS665 campaign data on ^{221}Ra and ^{219}Fr were collected, to conduct investigations on the ^{221}Ra and ^{215}At half-lives. In [6], their half-lives were found to diverge substantially from literature values (16(2) s and 37(3) µs instead of 28(2) s [7] and 100(20) µs [7] respectively). A preliminary analysis of the data collected at ISOLDE agreed with the 37 µs half-life for ^{215}At but confirmed the literature value [7] for ^{221}Ra.

This contribution will discuss into more details the ASET features and strengths, describe the different experiments that were performed with it, and report some of the preliminary results obtained so far.

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Group Photo

Atomic Techniques for Nuclear Structure 2 / 58

Abrupt change in nuclear moments of indium isotopes at magic number 82 explained by nuclear theory

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In this contribution, we present measurements of the nuclear magnetic dipole moments and nuclear electric quadrupole moments of the 113-131In isotope chain, performed using the Collinear Resonance Laser Spectroscopy experiment at ISOLDE, CERN. In addition to future prospects for laser spectroscopy of In isotopes.

We show that the electromagnetic properties of the neutron-rich indium isotopes significantly differ at N = 82 compared to N < 82, despite the single unpaired proton dominating the behaviour of this complex many-body system. This challenges our previous understanding of these isotopes, which were considered a textbook example for the dominance of single-particle properties in nuclei [1, 2].

To investigate the microscopic origin of our experimental results, we performed a combined effort with developments in two complementary nuclear many-body methods: ab-initio valence space in-medium similarity normalization group [3,4] and density functional theory [5].

When compared with our experimental results, contributions from previously poorly constrained time-odd channels [6,7], and many-body currents [8] are found to be important, demonstrating electromagnetic properties of 'proton-hole'isotopes around magic shell closures at extreme proton-to-neutron ratios can give us crucial insights.

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Atomic Techniques for Nuclear Structure 2 / 25

All-optical determination of the nuclear charge radii of $^{12,13}C^{4+}$

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Laser spectroscopy has since long been used to determine differential nuclear charge radii $\delta\langle r^2\rangle$ for stable and short-lived isotopes. Only for hydrogen-like systems it has been possible to extract the nuclear mean-square charge radius $\langle r^2\rangle$ directly from optical spectra, which has been successfully used for hydrogen [1], muonic hydrogen [2], deuterium [3] and helium [4]. Recently, much effort was put in improved calculations of helium-like systems to be able to extract nuclear charge radii from $1s2s\,^3\mathrm{S}_1 \rightarrow 1s2s\,^3\mathrm{P}_J$ transition frequencies [5]. This can be used also in heavier He-like ions, i.e., Be to N, in which the metastable state has sufficient lifetime to perform collinear laser spectroscopy and the transition wavelengths are in the laser accessible region.

The isotope ^{12}C has one of the best-known nuclear charge radii from elastic electron scattering and muonic atom spectroscopy. It is therefore an ideal study case to test atomic theory. So far, high-precision laser spectroscopy data is absent for all carbon isotopes. We have now studied the $1s2s\,^3\mathrm{S}_1 \rightarrow 1s2s\,^3\mathrm{P}_{0,1,2}$ transitions in helium-like $^{12,13}\mathrm{C}^{4+}$ using the **Co**llinear **A**pparatus for **L**aser Spectroscopy and **A**pplied Physics (COALA) at the Institute of Nuclear Physics, TU Darmstadt. By measuring the resonance frequencies in collinear and anti-collinear geometry simultaneously with lasers referenced to a frequency comb, we reach an accuracy of 2 MHz. As soon as theory reaches comparable accuracy, the uncertainty of the absolute mean square nuclear charge radii will be on par with the uncertainty in ^{12}C from muonic spectroscopy. Measurements performed on $^{13}\mathrm{C}^{4+}$ to investigate the hyperfine structure splitting show significant hyperfine mixing which will serves as another benchmark for testing atomic-structure theory. Finally, mass-shift calculations between $^{12,13}\mathrm{C}^{4+}$ will provide $\delta\langle r^2\rangle^{12,13}$ with very high precision in the conventional approach.

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Atomic Techniques for Nuclear Structure 2 / 14

MIRACLS - Probing exotic nuclei via laser spectroscopy in an MR-ToF device

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Collinear laser spectroscopy (CLS) is a powerful tool to access nuclear ground-state properties such as nuclear spin, electromagnetic moments and charge radii [1]. However, to explore 'exotic'nuclides with very low production yields at radioactive ion beam facilities, e.g. ^{34}Mg, more sensitive methods have been or are being developed.
To this end, the novel Multi-Ion Reflection Apparatus for CLS (MIRACLS) [2] at ISOLDE/CERN combines the high spectral resolution of conventional fluorescence-based CLS with high experimental sensitivity. This is achieved by trapping ion bunches in an unprecedented 30 keV Multi-Reflection Time-of-Flight (MR-ToF) device, in which the ions bounce back and forth between two electrostatic mirrors. Hence, the laser-ion interaction time is increased with each revolution in the MR-ToF apparatus, while retaining the high resolution of CLS.
The new experimental setup is currently being built and commissioned at ISOLDE's LA2 beam line. It consists of a buffer-gas filled Paul trap for providing cooled ion bunches, an offline ion source, two HV cages and the first MR-ToF device operated at 30 keV, with integrated optical detection region and laser access.
Besides its use for CLS, MIRACLS'30-keV MR-ToF device will enable advanced MR-ToF mass separation with increased ion capacity. At the next stage, this device will thus be able to deliver purified radioactive ion beams to PUMA and other (traveling) experiments at ISOLDE.
This oral contribution will introduce the MIRACLS concept, show the status of the experimental setup and give an outlook on the planned measurements.

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Workshop Dinner

Biophysics / 50

From magnetic moments and biochemistry to future β-NMR studies at VITO

Authors: Marcus Jankowski[1]; Nikolay Azaryan[2]; Mark Bissell[3]; Mateusz Jerzy Chojnacki[4]; Jared Croese[5]; Katarzyna Maria Dziubinska-Kuhn[None]; Beatrice Karg[4]; Ilaria Michelon[6]; Monika Piersa-Silkowska[5]; Tobias Patrick Treczoks[7]; Magdalena Kowalska[5]

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While NMR is an indispensable technique in physics, chemistry, and biology, it bears constraints of low sensitivity, which make it challenging or unsuitable to study a variety of common elements. These limitations are widely overcome by β-particle-detecting NMR. It benefits from combining a hyperpolarisation of the nuclear spin generated through optical pumping, and an efficient detection of the β particles emitted asymmetrically from the decaying hyperpolarised isotopes. Among the established use cases of β-NMR are solid-state, atomic, and nuclear physics. One novel field of interest lies in biochemistry, aiming for a better understanding of molecular structures, dynamics, and chemical reactions.
A forerunner in β-NMR is the VITO beamline at ISOLDE. This setup has recently undergone major upgrades, including the installation of a superconducting magnet, a new detector array and a new data acquisition system to push boundaries towards β-NMR with biological samples. After recommissioning the setup in 2021, the first such measurement campaign (IS666) was conducted this year, studying the interaction of 47K and 49K with DNA G-quadruplex structures.
Furthermore, two new research programmes have recently been launched at VITO. The key project' s objective is to measure the distribution of the magnetization inside the nucleus. Another project aims for recording the β decay asymmetries in coincidence with emitted γ rays and neutrons to firmly establish spins and parities of excited states populated in daughter nuclei.

Biophysics / **62**

The recent campaign of collection and chemical separation of 149Tb, along with its subsequent application for preclinical therapy studies

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Terbium is a unique element in that it includes a quadruplet of radioisotopes suitable for diagnostics and therapy in nuclear medicine [1]. With their characteristics, it can contribute to the theragnostics concept, where one can treat what one images. Much success has been gained from the PSI-ISOLDE collaboration, with the collection and purification of 149Tb (α-emitter, T1/2 = 4.1 h –for potential therapy), used for preclinical therapy studies [2, 3] and PET imaging [4], and 152Tb (β+-emitter, T1/2 = 17.5 h –for use in PET imaging), for preclinical [5] and clinical [6] PET imaging, respectively.

Two one-week campaigns to produce 149Tb took place in November 2021 and March 2022, respectively. Collections were performed overnight using Zn-coated gold foils. The foils, containing the desired product and its 149 isobars were transported to Paul Scherrer Institute for processing. The chemical separations were performed using an updated method. Usable product (yields around 100 MBq) were produced using a two-column separation system in a hot cell, allowing the labelling of 149Tb to somatostatin analogues and its use for preclinical studies.

149Tb-somatostatin analogues were labelled at >98% radiochemical purity at up to 20 MBq/nmol apparent molar activity. Mice, bearing AR42J tumours that express the somatostatin receptor, were injected twice (two consecutive days with 5 MBq each) for larger tumours, while mice with small tumours were injected once only. The mice were monitored over several weeks with regard to the tumour growth and body weight. The tumour growth was significantly delayed in all cases, while the treatment was well tolerated with no signs of obvious side effects. In addition, in vitro studies were performed to ascertain dose-dependent and receptor-specific cell killing upon exposure of the cells to 149Tb-labelled somatostatin analogues. More detailed results will be presented.

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Biophysics / 36

Intense and pure samples of 129m,131m,133mXe for a novel medical imaging technique, gamma-MRI

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Gamma-MRI is a future imaging modality that should allow the simultaneous exploitation of the sensitivity of gamma-ray detection (SPECT) and the spatial resolution and flexibility of MRI. The approach uses, like in SPECT, gamma-emitting nuclei, which are highly polarized and thus exhibit anisotropic gamma-ray emission, whereas their spins are rotated by rf pulses, like in MRI. The signal in gamma-MRI is the change in the ratio of gamma rays emitted longitudinally and transversally to the spin (and magnetic field) direction. The first nuclei used in the project are $11/2^-$ spin isomers ^{129m}Xe (T1/2=8.9 days), ^{131m}Xe (T1/2=11.8 days) and ^{133m}Xe (T1/2= 2.2days).
An efficient production and purification of the ^{129m,131m,133m}Xe is one of the first milestones in the gamma-MRI project. This contribution will present two main methods of production tested so far.

The main part will concern production by neutron irradiation of enriched stable ^{128}Xe and ^{130}Xe in the RHF reactor at Intitute Laue-Langevin (ILL; Grenoble, France) and at the MARIA reactor in the National Centre for Nuclear Research (NCBJ; Świerk, Poland). Production at ISOLDE will be also covered, with emphasis on recent upgrades to the experimental setup. Both methods provide high values of xenon isotopes activities that can be extracted efficiently and used in polarization experiments.
The presentation will give a brief introduction to the gamma-MRI technique and will mention 129m,131m,133mXe activity and purity required later for the project. It will then concentrate on production at ILL and MARIA reactors, and will compare it briefly to production at ISOLDE.

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Antimatter matters: the first decade and the next decade of the Large Hadron Collider beauty experiment

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The Large Hadron Collider beauty (LHCb) collaboration builds and operates one of the four large experiments at the LHC. We have published over 600 scientific papers in our first decade of operations. We have discovered differences in the behaviour of matter and antimatter in three new system and studied particles that can oscillate into their own antiparticles. We have found over fifty new particles, including exotic particles containing four or five quarks. By the quirks of quantum mechanics, we are searching for new fundamental physics at energies higher than those of the LHC beams. We have recently installed our new detector upgrading the technology to allow us to further our studies, taking ten times more data and operating for the next decade. Highlights of the science programme and of the new detector system will be described.

Atomic Techniques for Fundamental Physics / 5

Direct high-precision measurement of the electron capture Q-value in ^{163}Ho for the determination of the effective electron neutrino mass

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Among the most important quantities for fundamental physics is the effective mass of the electron neutrino m_ν, which has far-ranging consequences for cosmology and theories beyond the Standard Model. At present, the most precise indirect upper limit on m_ν is <120 meV/c^2 resulting from astrophysical observations while the most precise direct limit is set by the KATRIN collaboration with <0.8 meV/c^2, based on the kinematic study of the tritium β-decay. Complementary, the ECHo and HOLMES collaborations investigate the electron capture decay in ^{163}Ho using microcalorimeters. In order to reach the anticipated sub-eV limits on m_ν with calorimetric measurements, the exclusion of possible systematic uncertainties is crucial and is achieved by a comparison of the calorimetrically determined Q-value of the decay to an independently measured one with the same uncertainty level. Within this talk, an independent, direct, ultra-precise measurement of this Q-value using the Penning-trap mass spectrometer Pentatrap is presented with a sub-eV uncertainty. Using this technique, the Q-value is determined by measuring the ratio of the free cyclotron frequencies of highly charged ions of the mother and daughter nuclides, the synthetic radioisotope ^{163}Ho and ^{163}Dy, respectively. The Q-value is finally determined from the measured ratio of free cyclotron frequencies by including precise atomic physics calculations of the electronic binding energies of the missing electrons in the measured highly charged ions. This more than 40-fold improved Q-value compared to the previous best direct measurement paves the way for a sub-eV upper limit on m_ν within the ECHo and HOLMES collaborations.

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The Charge Radius of 26,26mAl

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In the study of atomic nuclei, nuclear charge radii provide intriguing physics insights into the evolution of nuclear structure far away from stability and pairing effects [1, 2]. Furthermore, charge radii have been used as experimental input for the determination of V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix from superallowed nuclear β-decays [3]. In the Standard model of particle physics, the CKM matrix is predicted to be unitary but recent reviews of the matrix values [4] show a 2.2σ deviation for one of its unitarity tests, with the highest numerical contribution coming from V_{ud}.
This contribution will present the recent work of combined measurements of the charge radii of ^{26,26m}Al by means of Collinear Laser Spectroscopy (CLS) at the COLLAPS experiment at ISOLDE and at the IGISOL facility in Jyvauml;skylauml;, Finland. CLS takes advantage of the interaction between the atomic nucleus and its surrounding electrons giving rise to the hyperfine structure. Thus, properties of nuclear ground states and long-lived isomers, including nuclear charge radii, can be inferred from measured hyperfine spectra. Prior to the present work, the charge radius of the superallowed β emitter 26mAl was not known experimentally but had to be extrapolated from known nuclear charge radii to evaluate the theoretical isospin symmetry breaking (ISB) correction required for the determination of Vud.
The present measurements reveal a charge radius of 26mAl which differs by more than 4 standard deviations from the value assumed in previous ISB calculations.

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New results from the laser spectroscopy of RaF at CRIS towards searches for new physics

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More than a decade ago, radium monofluoride (RaF) was proposed as a highly promising system for the search of new physics with ultra-high-precision laser spectroscopy [1]. In addition to its predicted sensitivity to the electric dipole moment of the electron and nuclear P,T-odd effects [2], the molecular structure of RaF was also predicted to be laser-coolable [1,3], promising an improvement in ultra-high-precision spectroscopy of more than an order of magnitude.

In 2018, the collinear resonance ionization spectroscopy (CRIS) experiment at ISOLDE performed the first-ever laser spectroscopy of RaF, confirming its laser-coolability [3], measuring the excitation energies of low-lying electronic states, and measuring isotope shifts for several transitions in 223-226,228RaF [4]. In 2021, the CRIS collaboration revisited RaF, successfully performing a large number of new measurements with both broadband and narrowband collinear laser spectroscopy.

This contribution will firstly briefly present RaF as a future probe for the search for new physics, and the role of quantum chemistry in such searches. Afterwards, new measurements of the excitation energies of high-lying electronic states, isotope shifts in 210,212-214,223-228,230RaF, and high-resolution spectroscopy of the hyperfine structure of 225RaF will be presented. These measurements can be used to understand the role of electron correlations and higher-order effects (e.g. QED corrections) in the electronic-state energies, and to study signatures of the Bohr-Weisskopf effect in 225Ra in the spectra of RaF. Comparisons with state-of-the-art quantum chemistry are thus used to assess theoretical treatments of RaF across a large range of electronic energies, whose accuracy and precision is necessary for the ultimate extraction of new physics from experimental searches.

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Atomic Techniques for Fundamental Physics / 11

Highly-sensitive negative ion spectroscopy with MIRACLS

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The electron affinity (EA) of a chemical element is defined as the energy released as an electron is attached to a neutral atom. The binding of such an "extra"electron does not arise from the net charge of the atomic system but is a result of complex electron-electron correlations. Hence, precise measurements of EAs are powerful benchmarks of atomic theories reliant on many-body quantum methods, which are typically applied to several atomic spectroscopy studies aiming at answering quantum chemistry, nuclear structure, and fundamental symmetries questions. The EA is also an important parameter for understanding the chemical behaviour of an element since it is strongly related to how much such an element is prone to form chemical bonds by sharing electrons [1]. However, the EAs of several rare and radioactive elements are still unknown and detailed information, such as isotope shifts and hyperfine splittings of EAs, is available only for a handful of cases.

The standard technique for the precision determination of EAs is the laser photodetachment threshold (LPT) method, in which a photon with sufficient energy is used to detach an electron from a negative ion. This technique has been restricted to mostly stable, abundant species given the low photodetachment probabilities. At ISOLDE, we are currently exploring the use of the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) technique [2] to enhance the sensitivity of LPT to study the EA landscape among rare and radioactive species. The novel method is based on a Multiple-Reflection Time-of-Flight (MR-TOF) device to trap ions in a stable trajectory. This allows us to greatly extend the ions' exposure time to lasers, significantly increasing the sensitivity by orders of magnitude while keeping the high resolution of a collinear geometry.

The technique has been developed offline and employed in the improved measurement of the EA of ^{35}Cl. The achieved precision is superior to that obtained in previous experiments [3], yet employing orders of magnitude fewer ion samples and using high-resolution continuous wave lasers with much reduced laser power, which highlights the gains in sensitivity of this method. In this talk, I will introduce the novel technique, its development, and its first results, as well as discuss its potential implications for rare isotope sciences.

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The ^{7}Be + d reaction in the context of the cosmological lithium problem

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In nuclear astrophysics, the cosmological lithium problem is widely studied. However, the serious anomaly of around three times in the observed ^{7}Li abundance, as compared to the big-bang nucleosynthesis theory is unsolved for decades. Recent revisit to the problem searched for resonances in the destruction channel ^{7}Be + d. We carried out the measurements of relevant resonances in the ^{7}Be(d,p)^{8}Be* channel at HIE-ISOLDE [1]. The theoretical calculations normalized to the present data and extrapolated to Gamow energies, give an estimate of the contributions of excitations in the (d,p) channel. Inclusion of the 16.63 MeV state leads to a maximum S factor of 167 MeV b as compared to

the earlier value of 100 MeV b. However, even the maximum S factor would reduce the primordial Li abundance by less than 1%, and thereby fail to solve the discrepancy. In addition, the measurement of the ^{7}Be(d,^{3}He)^{6}Li reaction shows that its effect on the Li anomaly is negligible. This apparently calls for new physics to address the problem.

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Beta decay of $^{64-66}$Ga: Total Absorption Spectroscopy and Isospin Mixing

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One of the key quantum numbers that characterizes the state of a nucleus, and therefore is fundamental to understand its structure is the isospin. The limits of validity of the isospin symmetry is still an open question. In this context, the exploration of isotopes close to the $N = Z$ line can shed some light on the mechanism of isospin mixing. One isotope of very high interest in the context of isospin mixing in the ground state is the $N = Z$ ^{64}Ge. Its neighbor ^{66}Ge and their respective daughters $^{64-66}$Ga, close to the $N = Z$ line, present a certain degree of isospin mixing in their ground states as well.

Besides the isospin mixing matter, the nuclei studied within the IS570 experiment are relevant for astrophysical calculations in the rp-process. Nucleosynthesis in Type I X-ray bursts (XRB) proceeds eventually through the rp-process near the proton drip-line. Several $N = Z$ nuclei act as waiting points in the reaction network chain. Astrophysical calculations of XRB light curves depend upon the theoretical modelling of the beta decays of interest, with ^{64}Ge being a key waiting-point nucleus in this context.

Within the framework of the IS570 experiment we have measured the beta decay of $^{64-66}$Ge and their daughters $^{64-66}$Ga with the Total Absorption Spectrometer (TAS) at ISOLDE, with the main goal of determining the B(GT) distribution for these decays. Preliminary results of ^{64}Ga show a difference from the previous feeding distribution, with the noticeable emergence of feeding above the last known level, at 4713 keV. Our TAS spectrum has a peak at 6081 keV, which was nonexistent in the evaluated ENSDF data. Meanwhile, our results on ^{66}Ga show small differences in the beta feeding distribution, especially to the ground state, around 3000 keV and at 4800 keV. In both cases differences in beta feeding to the ground state is very relevant in the context of isospin mixing.

In this contribution we will present our results on the beta decay of $^{64-66}$Ga and will discuss their relevance in the context of isospin mixing of the ground state.

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The Oslo method at ISOLDE - The Nuclear Level Density and γ-ray Strength Function of 67Ni

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Nucleosynthesis of the elements beyond Fe/Ni is mainly due to neutron capture processes, with most elements created either through the rapid neutron capture process (r-process) or the slow neutron capture process (s-process) [1]. More recent astronomical observations calls for a third, intermediate neutron capture process (i-process) to explain the elemental composition of certain metal-poor stars [2].
Both the r- and i-process involves mainly unstable nuclei and relies on theoretical predictions of the neutron capture rates, calculated within the Hauser-Feshbach model. The main nuclear data input for these calculations are the nuclear level density (NLD), the γ-ray strength function (γSF) and the optical model potential. Current models of the NLD and γSF are well constrained within the valley of stabillity, but vary siginificantly for unstable neutron rich nuclei. This leads to large uncertanties in the calculated neutron capture rates, usually on the order of one or more magnitudes. To reduce these uncertanties, the NLD and γSF needs be measured in key nuclei such that model parameters can be constrained. One such key nucleus is ^{67}Ni as the $^{66}\mathrm{Ni}(n,\gamma)^{67}\mathrm{Ni}$ reaction has been identified as a significant bottleneck for the weak i-process, affecting the overall rate of the weak i-process [3].

The Oslo Method is a unique tool for investigating NLDs and γSFs of nuclei as it is the only experimental method able to measure both quantities simultaniously [4]. The method relies on excitation energy versus γ-ray energy matrices, typically obtained from particle-γ coincidences measured in light ion beam experiments. More recently, inverse kinematics have been demonstrated as an effective tool to measure such matrices [5]. The NLD and γSF of neutron rich nuclei can therefore be probed with the Oslo Method at radioactive ion beam facilities such as ISOLDE.

In experiment IS559 a $4.47(1)$ MeV/u beam of ^{66}Ni impinged on a deuterated polyethylene target and proton-γ coincidences were measured in C-REX and Miniball, suplemented with six large volume $LaBr_3$:Ce detectors. From the measured coincidences, the NLD and γSF of ^{67}Ni were extracted, and the neutron capture cross section of ^{66}Ni was constrained. Our result show a relativly high capture rate, suggesting that ^{66}Ni is not a bottleneck for the weak i-process.

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Proton emission in the neutron-rich 11Be

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Proton emission is, a priori, a contradictory decay process in neutron-rich nuclei that move the system away from the Valley of Stability instead of closer to it. However, for a handful of nuclei the last neutron is so weakly bound that the energy window for this exotic decay mode is open. These are the so-called halo nuclei, since the last nucleon(s) orbit so far away from the core that can be considered quasi-free. In this talk I will explain the experimental attempts to observe this elusive process and understand the possible mechanisms that enable it.

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Prizes and Closing Remarks

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