Advances in Radioactive Isotope Science

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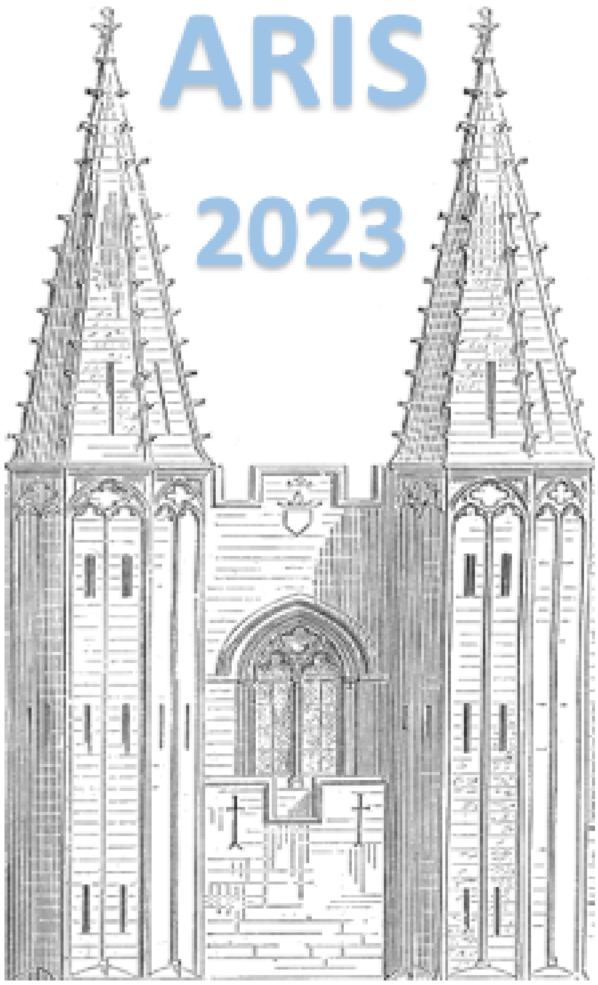

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Welcome to ARIS in Avignon

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High-resolution gamma-ray spectroscopy at a neutron beam: news from ILL

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Thermal neutron capture gamma-ray spectroscopy and prompt gamma-ray spectroscopy of fission fragments are powerful tools to obtain detailed nuclear structure information for nuclides close to stability and medium mass neutron-rich isotopes. The power of coupling a high-efficiency Ge detector array with an intense pencil-like neutron beam provided by the ILL reactor, has been recently demonstrated by the success of the EXILL (EXogam at ILL) campaign. This success led to the installation of permanent setup at ILL, the new instrument FIPPS (FIssion Product Prompt Spectrometer). In its first phase, it consists of a halo-free pencil neutron beam incident on a target surrounded by an array of 8 HPGe clovers. This setup has recently been exploited for a variety of (n,γ) experiments on stable (rare) and radioactive targets. Additional HPGe clovers from IFIN-HH were added during the last year allowing for a higher efficiency and granularity. Recently, targets consisting of ^{235,233}U diluted in a liquid scintillator has been used to study the spectroscopy of neutron-rich nuclei with a fission tag. In a second phase, the instrument will be complemented with a fission-fragment identification setup, based on diamond detectors. This will increase the sensitivity and selectivity for nuclear spectroscopy of fission products and enable fission studies of the correlation between excitation energy, angular momentum and kinetic energy.

After a general introduction to the nuclear physics activity at ILL, the details of the FIPPS instrument, its performance and first physics results will be shown. An overview on the physics cases investigated in last years, together with the techniques used, will be given. The future developments foreseen, in particular for fission studies, will be also reported.

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Nuclear Structure investigations of most exotic nuclei via mass measurements at TITAN

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High precision mass measurement using ion trapping continue to play an important role in shaping our understanding of the nucleus. State-of-the-art spectrometers nowadays are able to reach far from the valley of beta stability, where new phenomena, as e.g. shell quenching, weakening or disappearance of classical and appearance of new magic numbers can be observed and studied via their characteristic signatures in the mass surface.
TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [1] located at the Isotope Separator and Accelerator (ISAC) facility, TRIUMF, Vancouver, Canada is a multiple ion trap system specialized in performing fast high-precision mass measurements and in-trap decay spectroscopy of short-lived radioactive species. Since its installation in 2017, the new Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) has been in routine operation [2] and has expanded TITANs reach to even more exotic nuclei.
Mass selection is achieved using dynamic re-trapping of the ions of interest after a time-of-flight analysis in an electrostatic isochronous reflector system [3]. Re-using the injection trap of the device for the selective re-trapping, the TITAN MR-TOF-MS can operate as its own high resolution isobar separator prior to a mass measurements within the same device. This unique combination of operation modes boosts the dynamic range and background handling capabilities of the device, enabling high precision mass measurements with ion of interests to contaminant ratios of 1:10^7.
Among other, we will discuss recent results of mass measurements of neutron-deficient Yb and Tm isotopes investigating the persistence of the N=82 neutron shell closure far from stability, made possible by online mass-selective re-trapping supressing strong isobaric background. On the opposite side of the nuclear chart, we will investigate the evolution of the N=40 island of inversion in the neutron-rich Mn to Fe isotopic chains and give an outlook towards future mass measurements for nuclear structure investigations.

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Complex-energy based description of alpha-tunneling in intense laser fields

Auteur: Réka Szilvási[1]

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Abstract

Several attempts have been made to investigate the case when an alpha-decaying nucleus is coupled to an external time-dependent potential field, in particular coherent electromagnetic fields (lasers). The main question is how the time-dependent laser field alters the half-life of the decay, or correspondingly, the lifetime of the alpha cluster in the nuclei.
There are two crucial aspects of the problem: how to treat the time-dependence of the external field and how to describe the alpha-particle states.

In this research alpha decay is studied in the frame of quasi-stationary states which are associated with complex energy ($E_{\mathrm{qs}} = E_0 - i\frac{\Gamma}{2}$), the imaginary part of which is proportional to the lifetime of the state ($\Gamma \propto \frac{1}{\tau}$). Using the quasi-stationary description of alpha-decay, in order to determine a quantitative effect of a time-dependent coherent electromagnetic field on the complex energy of a quasi-stationary state the procedure of the (t,t')-perturbation calculation is followed which provides a way to perform formally time-independent perturbation calculation on the time-dependent system, in an extended Hilbert space. The (t,t')-formalism requires the wavefunction-centered description

of decaying states, although due to the complex nature of the alpha energy the corresponding eigenfunctions diverge in coordinate representation. To treat this problem, alpha decay is studied within the framework of non-Hermitian quantum theory, which, I argue, might be regarded as the natural coordinate system of decaying states. The special complex scaling transformation renders the divergence of the quasi-stationary eigenfunctions and allows one to apply the (t,t')-method.

From the nulcear theory perspective, as an additional gain, the formalism guaranties that the complex spectrum of a non-Hermitian (complex-scaled) operator representing an alpha-decaying system can be determined by non-Hermitian spectral calculations numerically, using the complex variational calculus, hence the lifetime of the alpha decay can be elicited directly from the spectrum of a non-Hermitian operator.

During this research, to demonstrate the appliance of the non-Hermtitian formalism, the lifetime of the alpha particle of a specific isotope was extracted from the complex-scaled, mean-field Hamiltonian operator of the nuclear system and was determined upon finite numerical error, considering only spherically symmetric nucleus. I computed the laser-field-induced correction to the lifetime of the alpha-particle $\varepsilon^{(1,\mathrm{p})}$ by first-order (t,t')-perturbation calculation in regards of different polarization states (p) and control parameters of the external laser field, and also examined the limit of the non-relativistic approximation of the problem.

Related publications:

Réka Szilvási and Dániel P Kis, *J. Phys. A: Math. Theor.* **55, 275301** (2022)

Réka Szilvási and Dániel P Kis, Computation of the complex-energy shift of decaying states in intense laser fields (Researchgate, preprint)

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Measurement of the bound-state beta decay of highly charged ions 205Tl81+

Auteurs: G. Leckenby[1]; R. Mancino[2]; R. S. Sidhu[2]; Rui-Jiu Chen[3]; Yu. A. Litvinov[2]

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Neutrinos are produced as a result of the nuclear fusion reactions happening inside the Sun. Precise measurement of the solar neutrino flux is crucial for a better understanding of the various nuclear reactions taking place in the Sun but also gives us important information about the Sun's core [1]. The geochemical experiment LOREX (LORandite EXperiment) [2], proposed by Freedman and collaborators aims to determine the long-time average (over ~4.3 million years) of the solar pp-neutrino flux Φν through the neutrino-capture reaction. The interaction cross-section of νe and 205Tl nucleus is important for the determination of the neutrino flux in the LOREX project. To determine the interaction cross-section, the half-life of bound state β- decay of bare 205Tl81+ nuclei is required as the two processes share the identical nuclear matrix element.
In this talk, we report on the first direct measurement of the bound-state beta decay of 205Tl81+ ions [3]. The experiment was performed at GSI, Darmstadt in 2020, wherein the entire accelerator chain was employed. Highly charged ions 205Tl81+ ions were produced with the projectile fragmentation of 206Pb primary beam on 9Be target, separated in the fragment separator (FRS), accumulated, cooled, and stored for different storage times (up to 10 hours) in the experimental storage ring (ESR). The experimentally measured half-life value agrees with the theoretically predicted values by E. Braun [3] and deviates from the theoretically predicted values [4,5]. The interaction cross-section between neutrino and 205Tl nucleus is determined. The impact of our result on LOREX project will be discussed in this talk.

This research has been conducted in the framework of the SPARC, ILIMA, LOREX, NucAR collaborations, experiment E121 of FAIR Phase-0 supported by GSI. The authors received support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 682841 "ASTRUm").

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Electromagnetic Dipole Response of Nuclei: Exploring Nuclear Structures and Constraining Nucleosynthesis Processes

Auteur: Mathis Wiedeking[1]

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The gamma-ray decay of nuclear states in the quasi-continuum provides important insights into nuclear structure effects and constraints to nucleosynthesis processes. In particular, measurements of Nuclear Level Densities (NLDs) and Photon Strength Functions (PSFs) have and will continue to play a central role as we are entering an era of incredible potential for novel measurements. This is due to many institutes across the world having established programs to provide enhanced, state-of-the-art research infrastructure. These range from significant increases in efficiencies for particle and gamma-ray detectors, to new or upgraded radioactive ion beam facilities. In parallel, several new experimental and analytical techniques were developed which allow for more reliable PSF and NLD studies, even on nuclei away from stability. All this progress will undoubtedly lead to unprecedented insight into the structure of nuclei and provide reaction rates of relevance to nucleosynthesis processes.

In this talk, I will provide an overview of the most significant advances made and how these have laid the foundation for novel and ambitious measurements of PSFs and NLDs at radioactive and stable ion beam facilities. I will further discuss recent progress in exploring the underlying nuclear structure of resonances from PSF measurements, focusing on the scissor's mode and the low-energy enhancement, whose mechanisms are still not fully understood. Our understanding of observed isotopic abundances can be improved greatly through the measurement of PSFs and NLDs as will be demonstrated.

This work is supported by the National Research Foundation of South Africa under grant number 118840.

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Studies of Weakly-Bound, Neutron-Rich Nuclei using HELIOS and SOLARIS

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The solenoidal-spectrometer technique developed at Argonne some 15 years ago in the form of HELIOS continues to evolve, adding new capabilities. A similar device has been recently installed at the Facility for Rare Isotope Beams (FRIB), called SOLARIS, for use with reaccelerated (ReA) beams. SOLARIS operates as a dual-mode spectrometer, both in a vacuum with position-sensitive silicon arrays and in Active-Target Time Projection Chamber (AT-TPC) mode. This allows for reaction studies across a broad dynamic range in terms of beam intensities (hundreds of particles per second to nano-Ampere beams), masses, and incident beam energies. SOLARIS has been used in both modes of operation during the operation of ReA with long-lived radioisotopes. The capabilities of these two devices will be demonstrated via a series of recent highlights: for HELIOS, the role of quenching in weakly-bound systems using the (*d*,*p*) reaction [1], and for SOLARIS studies using the (*t*,*p*) reaction [2] where the inverse kinematics technique allows for almost background-free measurements and a determination of branching ratios of unbound states.

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β-decay of ^{36}Mg and ^{36}Al: Identification of a long-lived isomer in ^{36}Al

Auteur: Rebeka Sultana Lubna[1]

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A long-lived isomeric state in ^{36}Al has been identified for the first time via β-decay of ^{36}Mg and ^{36}Al. Neutron-rich ^{36}Mg and ^{36}Al were produced at the Facility for Rare Isotope Beams(FRIB) via projectile fragmentation of a ^{48}Ca beam of energy 172.3 MeV/u. The beam was impinged on a 8.89 mm thick ^{9}Be target. The fragmented beam was delivered to the β-decay station after being resolved by the Advanced Rare Isotope Separator(ARIS). A fast timing scintillator of 2mm thickness followed by two Si PIN detectors, each 500 μm thick, were placed in the upstream side for the particle identification (PID). The energies lost by the ions in PIN2 were plotted against the time-of-flight between the ARIS scintillator and the sintillator at the decay station in order to generate the PID. At the heart of the decay station, a 5mm thick YSO scitillator implantation detector was placed. The β-delayed γ-rays were identified with 11 clover detectors and 15 $LaBr_3$ detectors. The half-lives of the two parent nuclei were determined and were compared to the previous measurements. The β-delayed γ-ray transitions were observed in ^{36}Al and ^{36}Si for the first time and their level schemes were built from the correlated β-decays of ^{36}Mg and ^{36}Al. Excited energy states of ^{36}Al populated by the β-decay of ^{36}Mg are proposed, whereas only the ground state information was available prior to this work. A long-lived isomer in ^{36}Al was identified which undergoes β-decay to an excited state of ^{36}Si. The experimental results were interpreted by using the nuclear configuration interaction studies with the FSU shell-model Hamiltonian. The results will shed light in our understanding of the structure of more exotic neutron-rich nuclei to be produced with the new generation facilities like FRIB.

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New Technique of Injecting Radioactive Ions into Charge Breeding ECR Ion Source

Auteur: Gabriel Tabacaru[1]

Co-auteurs: Juha Arje [1]; Veli Kolhinen [2]; Don May [1]; Brian Roeder [1]; George Kim [1]; Henry Clark [1]; Hyo-In Park [1]; Fred Abegglen [1]

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Cyclotron Institute at Texas A&M University started a project to develop the reacceleration of radioactive ions using the two operational cyclotrons and a Charge Breeding ECR ion source. The radioactive ions are produced primarily via (p,n) reactions using the well-known IGISOL technique. The reaction products are transported into a Charge Breeder ECR ion source where their charge state is boosted from 1+ to higher, depending on the product of interest and the operational state of the Charge Breeder ECR ion source. The transport of the products and the injection into the ion source are essential for the efficiency of charge breeding. Two techniques have been used: acceleration–deceleration method (classic) and low - energy RF-only sextupole ion guide transport and injection method (innovative technique). The last method appears to be very efficient and excellent charge breeding efficiency was observed. The presentation of the entire project, the new injection technique, experimental results, and future plans will be discussed.

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Breakdown of the Isobaric Multiplet Mass Equation at $A = 54$, $T = 3$

Auteur: Xing XU[1]

Co-auteurs: Chaoyi Fu [1]; Hongfu Li [1]; Meng Wang ; Wenjia Huang [2]; Yuhu Zhang [1]

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The determination of basic properties of the so-called isobaric analog states(IASs) which are states with the same isospin T and spin-parity $J\pi$ in a fixed A isobar has long been an important research subject in nuclear physics. A famous and simple formula, isobaric multiplet mass equation (IMME), which is derived 60 years ago on the basis of the perturbation theory in Quantum Mechanics and the isosopin symmetry, can successfully describe the masses of IASs.

Using the recently-measured mass of ^{52}Ni and the two-proton decay energy of ^{54}Zn, the ground-state mass excess of ^{54}Zn is deduced to be $-6504(83)$ keV. A cubic fit to the existing mass data of the $A = 54$, $T = 3$ isospin multiplet yields a surprisingly large d-coefficient of IMME, i.e., $d = 18.6(27)$ being 6.9σ deviated from zero, with the $|b/c|$-ratio significantly deviated from the systematics. This phenomenon is analyzed and we conclude that the breakdown of the quadratic form of IMME could be most probably due to mis-assignment of the $T = 3$ isobaric analog state (IAS) in the $T_z = 1$ nucleus ^{54}Fe or extremely strong isospin mixing. To confirm and further investigate the breakdown, accuate determination for masses of corresponding $A = 54$, $T = 3$ IASs states and dedicated theoretical calculations are highly recommended.

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Performance Test of Beam Drift Chamber for LAMPS

Auteur: CheongSoo LEE[1]

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Large Acceptance Multi-Purpose Spectrometer (LAMPS) which is designed for studying equation of state(EoS) and symmetry energy of nuclear matter above the saturation density ρ0, is under construction at Institute for Basic Science, Korea. LAMPS detection system consists of Start Counter(SC), Beam Drift Chamber(BDC), Time Projection Chamber(TPC), Time-of-Flight/Trigger Detector, Neutron Detector Array, and Superconducting Solenoid Magnet. Each part of the detection system has been tested individually to assure its performance, and most of the results so far meet the requirements from the experimental design well. In this presentation, detection system of LAMPS will be briefly introduced and beam line detectors, in particular BDCs are focused to be explained in detail.

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Development of LAMPS Time Projection Chamber at RAON

Auteurs: HyoSang Lee[1]; Young Jin Kim[1]; Cheong Soo Lee[1]

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Rare isotope Accelerator complex for ON-line experiments (RAON) is the rare isotope (RI) beam accelerator facility in Korea. Large Acceptance Multi-Purpose Spectrometer (LAMPS) is the nuclear science facility to study a nuclear equation of state (EoS) via heavy-ion collisions at RAON. At the end of the In-Flight separator, LAMPS will be located for completing an event reconstruction by detecting all particles produced in heavy-ion collisions within a large acceptance angle to measure particle spectrum, yield, ratio and collective flow of pions, protons, neutrons, and intermediate fragments at the same time. LAMPS consists of a solenoid spectrometer and a forward neutron wall. A Time Projection Chamber (TPC) and a time-of-flight (ToF) detector will be placed inside cylindrical solenoid magnet of 0.5 T for charged particle tracking and particle identification. The forward neutron wall will be made of 8 layers of plastic scintillators for neutron tracking.
TPC is the main tracking detector of the LAMPS solenoid spectrometer to identify particle species and reconstruct the momentum of each track with high precision over a large acceptance. Development and test result of LAMPS TPC will be presented.

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Searching for CP-violation in nuclear beta decay: First results of the MORA experiment

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The "Matter's Origin from RadioActivity" (MORA) project focuses on ion manipulation in traps and laser orientation methods for the searches for New Physics (NP) in nuclear beta decays, looking for possible hints to explain the matter-antimatter asymmetry observed in the Universe.

Located in Finland within the JYFL Accelerator Laboratory, the IGISOL facility delivers the right ion beam, the ^{23}Mg^{+}, for the initial phase of the MORA experiment. It is an ideal candidate to extract the so-called D correlation parameter which is sensitive to Time reversal violation and, according to the CPT theorem, to CP violation.

A measurement of the D parameter to the 10^{-5} level is sensitive to the existence of leptoquarks and/or to a right-handed W boson. By using an innovative in-trap laser polarization technique, we will be able to reach a sensitivity below 10^{-4} on D, according to simulations. This sensitivity should allow us to probe not only NP but also the Final State Interaction process.
After an offline commissioning has been carried out by using a ^{23}Na^{+} spark source, the first tests with ^{23}Mg^{+} have been conducted in the IGISOL facility. An efficient trapping process has been achieved up to 11s. Despite a large contamination of the radioactive beam with the stable ^{23}Na, around 30h of data have been registered in November 2022, using a trapping cycle of 3s and alternating 1h run with cloud laser polarization (sigma +, sigma -) and without. The analysis is currently ongoing.
In this talk, a short introduction of the commissioning performed followed by a detailed presentation of the first results will be presented.

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Electromagnetic moments of the antimony ($Z = 51$) isotopic chain $^{112-133}$Sb in comparison to shell-model ab initio calculations

Auteur: Simon Lechner[1]

Co-auteurs: Agota Koszorus [2]; Anastasios Kanellakopoulos [2]; Bradley Cheal [3]; Charles S. Devlin [3]; Deyan Yordanov [4]; George Sanamyan [5]; Gerda Neyens [2]; Hanne Heylen [1]; Jacinda S. M. Ginges [5]; Jason Holt [6]; Klaus Blaum [7]; Liss Vazquez Rodriguez [8]; Mark L. Bissell [9]; Peter Plattner [10]; Phillip Imgram [11]; Rainer Neugart [12]; Ronald Fernando

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Antimony (Sb) contains 51 protons, one proton above the magic $Z = 50$ proton shell closure. Therefore, its nuclear magnetic moments serve as an ideal candidate to probe the proton single particle behavior along the Sb isotopic chain, while its quadrupole moments shed light on collective effects as a function of neutron number towards the shell closure at $N = 82$.

Phenomenological shell-model calculations work well in the mass region around magic tin. Moreover, *ab initio* methods such as the valence-space in-medium similarity renormalization group (VS-IMSRG) have recently expanded their scope and are now capable of computing nuclear properties around $Z = 50$. Following collinear laser spectroscopy measurements of the antimony isotopic chain from $^{112-133}$Sb, the experimental magnetic and quadrupole moments are compared to their calculation in the phenomenological shell-model and VS-IMSRG. Since both nuclear models employ the same valence-space diagonalization, their full comparison as well as the artificial use of the shell model's effective g-factors and charges in VS-IMSRG allows to investigate the operator-evolution within VS-IMSRG separated from the obtained wave functions.

This contribution will present the new experimental results from collinear laser spectroscopy and discuss the underlying physics with the help of state-of-the-art shell-model and *ab initio* calculations.

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A systematic analysis of nucleon emission in deuteron-induced reactions

Auteurs: Brett Carlson[1]; Fatemeh Torabi[1]

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Considering its weakly-bound nature, a complete description of deuteron-induced reactions remains a challenging problem for theoretical studies. To examine this problem, we perform a systematic analysis of inclusive nucleon emission cross sections for deuterons incident on a wide range of nuclei at different energies up to 100 MeV. The local-energy approximation to the post form DWBA is used

to calculate the elastic and nonelastic breakup cross sections [1,2]. The breakup cross sections are integrated into the EMPIRE nuclear reaction code [3] in order to take into account the pre-equilibrium and equilibrium decay of the three compound nuclei formed in the reaction. Theoretical double differential and integrated nucleon emission cross sections are compared with the experimental ones. Our investigations demonstrate a general good agreement between the theoretical and experimental integrated cross sections. The comparisons of the experimental data with the calculated double differential cross sections show that the general behavior of the experimental spectra is reproduced at small angles and for the lighter systems, but that systematic discrepancies between the calculations and the data occur for heavier targets. Possible reasons for the disagreements are discussed.

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Evolution of single-particle structure along the Mg isotopic chain: the d(30Mg,p)31Mg reaction measured with the ISOLDE Solenoidal Spectrometer

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

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

The ISOLDE Solenoidal Spectrometer (ISS) collaboration published results on the nuclear structure of ^{29}Mg recently [1], measuring its neutron occupancies from the $d(^{28}\text{Mg},p)^{29}$Mg reaction (9.47 MeV/u) performed before CERN's long shutdown. An analagous $d(^{30}Mg,p)^{31}Mg$ reaction (8.52 MeV/u) has been performed at the ISS to examine the neutron occupancies of ^{31}Mg, which can be compared to the measurement of ^{29}Mg to understand this transition into the island. This measurement was performed with a new on-axis silicon developed specifically for ISS. Preliminary results from this new measurement will be presented, with reference to the previous measurement on ^{29}Mg.

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CERN-MEDICIS: a unique facility for the production of non-conventional radionuclides for medical research

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The MEDICIS facility is a unique facility located at CERN dedicated to the production of non-conventional radionuclides for research and development in medical imaging, diagnostics and radiation therapy. Located in a laboratory equipped to safely handle unsealed radioactive samples, it comprises a dedicated isotope separator beam line, a target irradiation station at the 1.4 GeV Proton Synchroton Booster (PSB), or alternatively receives activated targets from external institutes e.g. during CERN Long Shut-Downs. The target is heated up at high temperatures to allow for the diffusion and effusion of the produced atoms out of the target that are subsequently ionized. The ions are accelerated and sent through an off-line mass separator. The radionuclide of interest is mass-separated and implanted into a thin metallic collection foil. After collection, followed by a radiochemistry process when necessary, the batch is prepared to be dispatched to a research center for further processing and usage. Since its commissioning in December 2017, the facility has provided novel radionuclides including, but not limited to, Ba-128/Cs-128, Tb-149, Sm-153, Tb-155, Tm-165/Er-165, Er-169, Yb-175 and Ac-225 with high specific activity values, some for the first time, to research institutes part of the collaboration. CERN-MEDICIS' research and development around the topics of production, extraction and mass-separation is in constant evolution. The facility also contributes in the education and training of young researchers. Moreover, MEDICIS is one of the pillars of PRISMAP, a network of world-leading European facilities including nuclear reactors, medium- and high-energy accelerators, radiochemical laboratories and biomedical facilities. PRISMAP acts as a European platform for medical radionuclides and supports the ongoing research on nuclear therapy and molecular imaging by providing immediate access to novel radionuclides.

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Observation of the radiative decay of the low energy thorium-229 isomer: En route towards a nuclear clock

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The radioisotope thorium-229 features a nuclear isomer with an exceptionally low excitation energy of ≈ 8 eV and a favourable coupling to the environment, making it a candidate for a next generation of optical clocks allowing to study fundamental physics such as the variation of the fine structure constant [1,2]. While first indirect experimental evidence for the existence of such a nuclear state dates from almost 50 years ago, the proof of existence has been delivered only recently by observing the isomer's internal electron conversion decay [3]. This discovery triggered a series of successful measurements using the α-decay of uranium-233 of several properties, including its energy, an important input parameter for the development of laser excitation of the nucleus. In spite of recent progress, the difficulties to observe the isomer's radiative decay remains a dark spot of this research field. The development towards a "nuclear clock" is further hindered by a too large uncertainty on the isomer energy.

In order to overcome limitations of previous experiments and to increase the population of the isomer while easing at the same time background contributions, a novel approach is used to populate the isomeric state in radioactive decay [4]. It is based on the β-decay of actinium-229 and
uses radioactive ion beams provided by the ISOLDE facility at CERN implanted into large-bandgap crystals.

In this contribution, a dedicated setup for the implantation of a francium/radium/actinium-229 beam into large-bandgap crystals and the vacuum-ultraviolet spectroscopic study of the emitted photons will be presented. From the results obtained during a first measuring campaign using MgF2 and CaF2 crystals as host material it can be concluded that the radiative decay of the thorium-229 isomer has been observed for the first time, the excitation energy of the isomer has been determined with a factor of 5 improved uncertainty.

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High-resolution in-beam γ-ray spectroscopy at RIBF

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In-beam gamma-ray spectroscopy experiments have been actively performed at Radioactive Isotope Beam Factory (RIBF) of the RIKEN Nishina Center owing to the high secondary beam intensities from the BigRIPS fragment separator [1]. These experiments mostly employed the DALI2 NaI array with the very high γ-ray detection efficiency [2], and the Zero Degree Spectrometer [1] and the SAMURAI spectrometer [3] for reaction product identifications. Among the abundant scientific achievements from in-beam γ-ray spectroscopy experiments, the first spectroscopy of ^{54}Ca [4], ^{78}Ni [5], and ^{70}Kr [6] are examples of the capability of the RIBF facility.
Despite the notable accomplishments, experiments have been mostly limited to even-even nuclei in the vicinity of shell closures due to the moderate energy resolution of the DALI2 array. For the new capability in spectroscopy, a germanium-based high-resolution γ-ray detector array was constructed in 2019 under the High-resolution Cluster Array at RIBF (HiCARI) project [7]. The HiCARI array was comprised of several different types of high-purity germanium detectors, six segmented triple clusters from the Miniball collaboration, four segmented Clover detectors from the IMP, a quad-type tracking detector from the RCNP, and a triple-cluster tracking detector P3 from the LBNL. Through the improved position and energy resolution, the spectroscopy capabilities could be extended to further regions of interest such as odd-mass and deformed nuclei. Moreover, the HiCARI array was capable to measure level lifetimes based on the line-shape method [8].
In 2020 and 2021, 8 experiments were successfully carried out during 31.5 day of beam times with ^{238}U and ^{70}Zn primary beams. The campaign included a wide range of exotic neutron-rich nuclei covering various physics motivations, such as shell and shape evolutions. An overview of the HiCARI project and first preliminary results from the rich physics program will be presented.

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Microscopic study of nuclear monopole excitations

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A systematic study of the isoscalar giant monopole resonance (ISGMR) in spherical and deformed nuclei from various isotopic chains is performed within the microscopic self-consistent Skyrme HF+BCS method and coherent density fluctuation model. The calculations for the incompressibility in finite nuclei are based on the Brueckner and Skyrme energy density functionals for nuclear matter. The good agreement achieved between the calculated centroid energies of the ISGMR and their

recent experimental values for various nuclei demonstrates the relevance of the proposed theoretical approach. The latter can be applied to analyses of neutron stars properties, such as incompressibility, symmetry energy, slope parameter, and other astrophysical quantities.

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Spectroscopic Factor Investigation in the N=40 Island of Inversion

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The focus of this work is on the Fe and Mn neutron-rich isotopes with $N \sim 40$, which lie within one of the so-called Islands of Inversion. Here, a quenching of the $N = 40$ shell gap allows deformation to develop in the ground-state configurations. Limited spectroscopic information is available in the region of $N \sim 40$ below the Ni isotopes. For the even-even nuclei, this consists of systematics of 2_1^+ and 4_1^+ state energies and, for the Fe and Cr isotopes, of $B(E2; 2_1^+ \rightarrow 0_1^+)$ values up to ^{68}Fe and ^{64}Cr. Large-scale shell-model calculations well reproduce the energy systematics of the observed low-lying states of the even-even Fe and Cr isotopes around $N = 40$. A good agreement is found also within the rotational Nilsson model. Such two descriptions, however, provide different predictions for proton spectroscopic factors. A measurement of such quantity would thus allow us to probe the validity of the considered models.
In this context, proton knockout reactions on the neutron-rich $N = 38$ and $N = 40$ isotopes ^{64,66}Fe and ^{63,65}Mn have been performed to investigate the proton spectroscopic factors of the parent nuclei. The experiment took place at the NSCL laboratory in the US and exploited the γ-ray tracking array GRETINA coupled to the S800 spectrograph to perform an in-beam γ-ray spectroscopic study. Preliminary results of the data analysis will be presented.

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Extremely neutron-rich nuclei beyond the drip line

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The limit of the nuclear stability, called neutron drip line, reflects structure of atomic nuclei with extremely proton-neutron asymmetry. It is known that the neutron drip line of oxygen isotope is 24O (Z=8, N=16), while that of fluorine is 31F (Z=9, N=22). This sudden change of the neutron drip line is called oxygen anomaly. Theoretical study [1] suggests that three-nucleon forces play an important role in the binding of the oxygen isotopes especially for N>16. This region is also interesting in terms of the island of inversion. It is well known that the N=20 shell closure disappears for magnesium and neon isotopes in the vicinity of N=20 while the shell structure for fluorine and oxygen is not clear. Recent experimental studies [2,3] suggest that the island of inversion extends to 29F (Z = 9, N = 20). It is a question whether the 28O nucleus, having the canonical magic numbers Z=8 and N=20, shows doubly magic characters or not. In these contexts, experimental study on the neutron-rich oxygen isotopes located beyond the neutron drip line is strongly desired.
Series of experiment for the unbound oxygen isotopes 25-28O has been performed with the SAMURAI setup [4] at RI Beam Factory (RIBF). Results of the experiments and related studies will be presented in the talk.

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Production of Tb-155 with highly enriched targets : first results

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The PRISM (PRoduction d'Isotopes et Séparation pour le Médical) project's objective is to optimize the production and the vectorization of radio-isotopes of medical interest, especially for internal vectorized radiotherapy. The aim is to develop a complementary method to those already used, based on the use of an electromagnetic isotope separator before production of the radio-isotope of interest. A study of the functionalization of the radio-isotope by a biological vector at room temperature completes this project. *

The production of radio-isotopes of medical interest is accompanied by the production of other radio-isotopes. These contaminants can induce additional and unnecessary radiations to the patient. The use of more enriched targets that is currently available will make it possible to reduce the number of reaction channels and then limit production of these contaminants while maintaining production of the radio-isotope of interest.

The PRISM project, which will be briefly described, applies this method to the production of Tb-155 from Gd. A production target with an isotopic enrichment superior to 99% has been produced with the electromagnetic isotope separator SIDONIE at IJCLab, Orsay, then irradiated at Nantes with the cyclotron ARRONAX. First results will be presented, as well as some perspectives.

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Production and characterization of 111Ag radioisotope in a TRIGA Mark II nuclear reactor for medical use in the framework of the Italian ISOLPHARM project

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Nowadays radiopharmaceuticals represent a fundamental aid in nuclear medicine. They contain a radionuclide bound to a ligand, which selectively accumulates into a target tissue allowing either a precise imaging or a focalized treatment, without significantly damaging neighboring healthy tissues. ISOLPHARM is an Italian project that aims to develop innovative radiopharmaceuticals prototypes. It exploits the capability to produce high specific activity carrier-free radioisotopes at the SPES (Selective Production of Exotic Species) facility of the INFN–LNL (Istituto Nazionale di Fisica Nucleare–Laboratori Nazionali di Legnaro, Pd, Italy), through the ISOL (Isotope Separation On Line) technique. In the framework of the ISOLPHARM method, ^{111}Ag was proposed as a very promising radionuclide for internal radiotherapy. It is a β- emitter with medium half-life, convenient β- energy and medium tissue penetration, and low percentage of associated γ-emission. A study on the production and characterization of the ^{111}Ag radioisotope in a TRIGA Mark II nuclear research reactor, for its utilization in the ISOLPHARM research activities, will be presented. Experimental results of the radioactivity coming from ^{nat}Pd and ^{110}Pd-enriched samples irradiated in the reactor main irradiation facility are collected and spectroscopically characterized with a cost-effective, robust and easy-to-use detection system, based on a Lanthanum Bromo-Chloride (LBC) inorganic scintillator. The radioisotope production is simulated starting from an MCNP6-based reactor model producing the neutron spectrum and flux in the selected irradiation facility. A comparison between experimental results of the activity of irradiated targets and theoretical predictions obtained with MCNPX and PHITS Monte Carlo codes, coupled with inventory calculation programs, allows models to be normalized to experimental data. In this way a reliable planning of the ^{111}Ag production for the aims of the ISOLPHARM project is achieved.

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Design of the High Rigidity Spectrometer at the Facility for Rare Isotope Beams

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A High Rigidity Spectrometer (HRS) [1] has been designed in support of the scientific program at the newly constructed Facility for Rare-Isotope Beams (FRIB) at Michigan State University. The HRS will allow experiments to be performed with the most exotic neutron-rich isotopes at high beam energies (⊠100MeV/⊠). The HRS consists of an analysis beamline called the High-Transmission Beamline (HTBL) and the spectrometer proper called the Spectrometer Section. The maximum magnetic rigidity of the HRS is 8 Tm, which corresponds to the rigidities at which rare-isotope beams are optimally produced at FRIB. The resolving power, angular acceptance, and momentum acceptance are set to match the anticipated scientific program. An ion-optical design developed for the HRS will be presented along with those of the specifications of the associated magnet and detector systems.

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Laser Spectroscopy of the Hyperfine Splitting in ^{208}Bi^{82+}

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We present results of a laser spectroscopy experiment on the hyperfine splitting of hydrogen-like ^{208}Bi^{82+} at the Experimental Storage Ring (ESR) at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt. This is the first time that an artificially produced isotope is successfully targeted by laser spectroscopy in a storage ring.
During the campaign in May 2022, the ions of the radioactive isotope were produced in-flight before injection into the ESR. After isotope separation, a few 10^5 ^{208}Bi^{82+}-ions were stored with $\beta = 0.72$ ($E_{\mathrm{ion}} = 408$ MeV/u). To excite the hyperfine transition ($\lambda_0 = 221$ nm) the ion beam was superimposed with a counterpropagating beam of a pulsed dye laser at $\lambda_{\mathrm{lab}} = 548$ nm. Fluorescence detection was realized spatially separated from the laser interaction with a new detection region to obtain the required low background.
The result is compared to the theoretical and semi-empirical predictions in [1]. It will later be combined with a measurement on lithium-like ^{208}Bi^{80+}, which is in preparation, to provide the so-called specific difference between the two hyperfine splittings [2,3]. This will constitute the most stringent test of QED in strong magnetic fields.
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Materials Science with radioactive isotopes – results from emission Mössbauer Spectroscopy

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The intentional incorporation of foreign atoms in semiconductors, with the aim to realize new and/or novel functionalities with potential applications in optoelectronic and spintronic devices, gives rise to structural changes that profoundly affect their electronic, magnetic, and optical properties. Consequently, information on material properties and on dynamic processes such as dopants diffusion and relaxation processes are necessary and can be determined using a wide variety of techniques. Of particular importance are techniques employing radioactive isotopes implanted in materials as probes as they combine a two-fold function: (a) material modification and (b) material characterization at the atomic level. The latter is achieved through utilizing the isotopes mainly as "spies" via the radiation/particles they emit in their decay. This provides knowledge on lattice sites of desired daughter dopants, lattice location changes with thermal annealing, and the defects/complexes formed with host atoms.

Mössbauer Spectroscopy (MS) is a very sensitive technique capable of detecting minor shifts in energy levels that emanate from hyperfine interactions between the nuclear moments of the probe/dopant and any local electric and magnetic fields in their immediate environment. A novel extension is emission Mössbauer Spectroscopy (eMS) employing short-lived radioactive isotopes developed at ISOLDE, CERN. eMS studies have been undertaken mainly using ^{57}Mn* ($t_{1/2}$ = 1.5 min) which is produced via proton-induced fission in a UC_2 target followed by multistage laser ionization[1], mass separation and acceleration to 40-60 keV. In addition, other precursor isotopes such as ^{57}Co* ($t_{1/2}$ = 272 days) and ^{119}In* ($t_{1/2}$ = 2.4 min) have also been applied for offline ^{57}Fe studies and for online ^{119}Sn measurements, respectively.

Over the years, eMS has been applied in several different material systems at ISOLDE, with investigations initially on the role of Fe in silicon to recent studies on the nature and origin of magnetic effects observed in transition metal doped semiconductors[2-5] envisaged for spintronic applications. Special features of the technique will be presented and discussed, together with representative results in binary[4] and ternary III-nitrides. The results will mainly focus on investigations of the lattice sites of the probes, their charge and spin states, and the magnetic interactions of dopants in ternary-nitrides (virgin and Mn pre-doped)[6] and metal halides[7].

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Beta-delayed fission of neutron-rich actinides

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Beta-delayed fission (βDF) is a two-step process where a parent nucleus β-decays into excited states of the daughter nucleus that are high enough with respect to the fission barrier and can therefore potentially lead to the daughter's fission [1]. Besides its relevance in understanding the nuclear structure, this process, as any other type of fission, may have a strong impact on the termination of the r-process. βDF has been only partially studied experimentally, especially in the neutron-rich side of the nuclide chart important to nucleosynthesis.
In order to expand the knowledge on βDF in the neutron-rich region, a recent campaign was carried out at ISOLDE (CERN) with the purpose of measuring βDF in ^{230,232,234}Ac [2] (LOI216, May 2022). From this 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 at least two orders of magnitude lower than the one reported in literature [3].
This contribution will discuss in more details the systematics of βDF, the preliminary results obtained during the LOI216 experimental campaign, as well as a comparison with theory, and present some of the future plans of the βDF campaign.

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Cross-shell interactions at the N=28 shell closure via 47K(d,p) and 47K(d,t) with MUGAST+AGATA+VAMOS.

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Shell evolution in the region around the magic numbers $N = 28$ and $Z = 20$ is of great interest in nuclear structure physics. Moving away from the doubly-magic isotope ^{48}Ca, in the neutron-rich direction there is evidence of an emergent shell gap at $N = 34$ [1], and in the proton-deficient direction, the onset of shape deformation suggests a weakening of the $N = 28$ magic number [2]. The ^{47}K(d,p)^{48}K reaction is uniquely suited to investigating this region, as the ground state configuration of ^{47}K has an exotic proton structure, with an odd proton in the $\pi(1s_{1/2})$ orbital, below a fully occupied $\pi(0d_{3/2})$ orbital [3]. As such, the selective neutron transfer reaction (d,p) will preferentially populate states in ^{48}K arising from $\pi(1s_{1/2}) \otimes \nu(fp)$ cross-shell interactions. The implications of this extend both down the proton-deficient $N = 28$ isotonic chain, where these interactions are expected to dominate the structure of the exotic, short-lived ^{44}P nucleus [4], and across the neutron-rich region, where the relative energies of the $\nu(fp)$ orbitals is the driving force behind shell evolution.

The first experimental study of states arising from the interaction between $\pi(1s_{1/2})$ and the orbitals $\nu(1p_{3/2})$, $\nu(1p_{1/2})$ and $\nu(0f_{5/2})$ has been conducted, by way of the ^{47}K(d,p) reaction in inverse kinematics. A beam of radioactive ^{47}K ions was delivered by the GANIL-SPIRAL1+ facility, with a beam energy of 7.7 MeV/nucleon. This beam was estimated to be > 99.99% pure, with a typical intensity of 5×10^5 pps, and was impinged upon a 0.3 mg/cm^2 CD_2 target. The MUGAST+AGATA+VAMOS detection setup [5] allowed for triple coincidence gating, providing a great amount of selectivity. An analysis based both on excitation and gamma-ray energy measurements has revealed a number of previously unobserved states in ^{48}K, and preliminary differential cross sections for the most strongly populated of these states will be presented. Spectroscopic factors for these states will be discussed in the context of shell model calculations, with regard to the N=28, 32 and 34 shell gaps. Additionally, results for positive and negative parity states in ^{46}K, measured simultaneously via the ^{47}K(d,t) reaction, will also be presented.

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Study of 11Be excited states via the 10Be(d,p) reaction in SOLARIS with the AT-TPC

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The commissioning of transfer reaction measurements in inverse kinematics in SOLARIS with the Active Target Time Projection Chamber (AT-TPC) was successfully completed in the summer of 2021 at the NSCL. The goal of this experiment was to demonstrate the possibility of performing transfer reaction measurements at low beam intensities (between 100 Hz - 1 kHz) using the high luminosity provided by the AT-TPC. A beam of 10Be was accelerated to about 9 MeV/u in the ReA6 linac and delivered to the AT-TPC placed in a 3 Tesla magnetic field provided by the SOLARIS solenoid. The AT-TPC was filled with pure deuterium gas at 600 Torr. Although multiple reaction channels were simultaneously detected, in this presentation we focus on the 10Be(d,p) channel that populates bound and unbound states in 11Be, with a particular interest towards a 3.41 MeV resonance for which the parity is still an open question. We present the preliminary analysis of the 10Be(d,p) channel, including angular momentum transfer identification and determination of spectroscopic factors from comparison with DWBA calculations. The AT-TPC's ability to perform transfer reaction measurements at low intensities opens the door to further study neutron-rich nuclei using the rare isotope reaccelerated beams available at FRIB in the near future.

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From Tensor Currents to Solar Neutrinos: Precision Beta-Decay Studies of ^{8}Li and ^{8}B

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The β-decays of ^{8}Li and ^{8}B provide an important playground to search for physics beyond the Standard Model, and, additionally, a detailed study of ^{8}B β-delayed α-particles provides key insights

needed to constrain the spectrum of high energy neutrinos emitted by the Sun. To accomplish both these aims, the β-decays of ^{8}Li and ^{8}B were studied with the Beta-decay Paul Trap (BPT) at the ATLAS facility of Argonne National Laboratory. The BPT traps a cloud of ions at rest in a volume of ~1 mm^3 for extended periods of time, allowing for a backing-free measurement of the emitted particles. The trapping volume is surrounded by segmented, 1 mm thick DSSDs, from which the decay kinematics can be fully constrained by a β-α-α triple coincidence measurement. This enables both a nearly background-free measurement of the β-ν angular correlation coefficient $a_{\beta\nu}$, while a α-α double coincidence measurement enables a determination of the ^{8}B neutrino energy spectrum.

We will present (1) recent results in ^{8}Li, showing the most precise measurement of $a_{\beta\nu}$ in a GT decay and highlighting both the possibility of a ~9 MeV 2^+ "intruder state" in ^{8}Be and the importance of accurate values for the recoil-order terms, (2) the first measurement of $a_{\beta\nu}$ in ^{8}B and a method to constrain C_T and C'_T in the decay of mirror systems, and (3) the preliminary analysis of a high statistics ^{8}B dataset to determine $a_{\beta\nu}$, and a new determination of the neutrino spectrum following ^{8}B β-decay, which is important for the next generation of solar neutrino experiments.

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Solar Neutrinos and Physics Beyond the Standard Model Probed through Boron-8 Beta Decay

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^{8}B beta decay is the dominant source of the high-energy neutrinos generated in the Sun and observed in solar neutrino astrophysics measurements on Earth. Consequently, these experiments require the ^{8}B neutrino energy spectrum to be known to high precision. In addition, the large Q value of the ^{8}B beta decay and the fact that the unbound daughter ^{8}Be breaks up into two alpha particles make a particularly sensitive probe to physics beyond the standard model. Preliminary results from a high-statistics experiment performed at Argonne National Laboratory using the Beta-decay Paul Trap (BPT) will be presented. The energies and relative angles of the alpha and beta particle were precisely measured with four 32x32 double-sided silicon strip detectors surrounding the BPT. The kinematics of the decay products were leveraged to reconstruct the undistorted ^{8}B neutrino energy spectrum, an important input for solar neutrino astrophysics. At the same time, high-fidelity simulations of the decay were performed to set limits on the exotic tensor current contribution to the weak interaction.

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Mass Measurement of the 123Pd with the Rare-RI Ring in RIKEN

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The rapid neutron capture process (r-process) is considered to be responsible for the synthesis of about one-half of the elements heavier than iron up to bismuth and all of thorium and uranium. To model the r-process, nuclear properties of neutron-rich nuclides are needed. Nuclear mass is one of the most important input properties for the r-process calculation. However, some of the neutron-rich nuclides involved in the r-process lie far away from the stability line and are hard to produce in the laboratory. Therefore, r-process calculations have to rely on theoretical mass predictions. Thus, the mass measurements for the neutron-rich nuclei not only provide reliable data for the r-process calculations but also can help validate and improve the theoretical mass models.

The Rare-RI Ring (R3) is a recently commissioned isochronous mass spectrometer dedicated at Radioactive Isotope Beam Factory (RIBF) in RIKEN. Based on the Isotope-Selectable Self-triggered Injection technique, the pre-identified ions can be selected and injected into R3 event by event. The mass precision of 10^{-6} is expected to be achieved within less than 1~ms. In this contribution, the first application of mass measurements with the Rare-RI Ring will be reported. In the experiment, 5 isotones, ^{127}Sn, ^{126}In, ^{125}Cd, ^{124}Ag, and ^{123}Pd , were injected into R3 and extracted from it successfully. The mass uncertainty of ^{123}Pd is improved and the final relative uncertainty is 2.3×10^{-6}. The impact of the new ^{123}Pd mass result on the solar r-process abundances in a neutron star merger event is investigated by performing PRISM reaction network model. The A=122 and A=123 element abundance ratios in twenty r-process trajectories are calculated with varying electron fraction Y_e. We found that if our new mass value is used instead of the FRDM value, the r-process abundances at A=122 and A=123 are modified toward being more consistent with solar values.

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Charge polarization on the fission fragments from U-236 calculated with a time-dependent mean-field model

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The charge distribution of fission fragments is a significant quantity to estimate and evaluate the yields of the emitted neutron from fission fragments.
The distribution has been evaluated as the deviation from the unchanged charge distribution assumption in which the fragments keep the neutron-proton ratio of the fissile parent nucleus.
It is called charge polarization (CP).
For the major fission reactions in the reactor, their CP have been compiled in a library called Wahl's systematics.
The library is designed for the nuclear engineering field, which is unsuitable for predicting the fission fragments from unmeasured fissile nuclei.

We suggest a theoretical method based on the microscopic nuclear theory to provide the CP of fragments generated from unknown fissile nuclei without empirical ways.
We employ the mean-field theories, which are the constrained Skyrme Hartree-Fock+BCS theory and the canonical-basis time-dependent Hartree-Fock-Bogoliubov theory, represented in three-dimensional space.
For the evaluation of the theoretical results, we compare several statistical quantities of the experimental data and the results deduced through the Hauser-Feshbach calculation.

In the presentation, we report on the CP of the fission products on the ^{236}U, which is assumed as the reaction of ^{235}U absorbing a thermal neutron.
We will discuss the effectiveness of our method and will mention the dynamical effects on the CP through the comparison between results calculated by static and dynamic mean-field models.

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Production of highly charged and molecular thorium ions for fundamental physics

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Thorium isotopes became of high interest in the search for fundamental physics and for testing of the standard model of particle physics because of their unique nuclear and atomic properties [1,2]. In the project *Trapping And Cooling of Thorium Ions via Calcium* ([illegible]), ion trapping and spectroscopic techniques are developed for a precise determination of nuclear moments, hyperfine intervals, and isotope shifts with different Th isotopes [3]. Two methods are used to produce atomic thorium ions, i. e., laser ablation of macroscopic thorium samples [3] and thin layers of alpha-decaying uranium isotopes which produce thorium daughter nuclei that recoil from the sample with the momentum imparted by the alpha decay [4]. While the former process yields predominantly singly charged ions, the latter also leads to substantially more highly charged ions [4]. Within this project, laser ablated thorium-232 ions were trapped in a linear Paul trap [3], a recoil ion source providing electrostatically decelerated Th ions [4] has been built and commissioned, and an apparatus for systematic studies of the laser-ablation production of atomic and molecular Th ions has been developed.

Laser ablation and in-flight reactions are used for the production of molecular thorium ions. Molecules including ThF [5] are of interest in the search for scalar dark matter [6] and could be used as quantum sensors to search for CP violations [7]. For this, further experiments are aimed at investigating the laser ablation behavior of different thorium isotopes in salt-based form and the formation and delivery of different thorium molecules from chemically different Th samples.

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The new Atomic Mass Evaluation (AME2020)

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Systematic study of the masses of exotic nuclei far from the valley of stability reveals interesting phenomena such as new decay models, disappearance of traditional shell gaps and emergence of new magic numbers, and breakdown of isospin symmetry. With the advent of the new radioactive ion beam facilities built worldwide, numerous projects of mass measurements of short-lived nuclei have been carried out and reshape our understanding of how nuclei are formed. The latest Atomic Mass Evaluation (AME2020) [1,2] was recently published, which provides the most up-to-date knowledge for nuclear masses. In this conference, the evaluation procedure will be briefly reviewed and the main influence of new mass data on the AME will be discussed. Some mass data deviating from the smooth trends of the mass surface will also be mentioned and pertinent experiments are called for.

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First characterization of Short-Range Correlations in an exotic nucleus at R3B

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Most of the knowledge we have to date about Short-Range Correlations (SRC) in nuclei comes from electron induced quasi-free scattering (QFS) experiments in large momentum transfer kinematics. Experiments performed at Jefferson Lab with a ^{12}C nucleus showed that the high-momentum tail of the nuclear momentum distribution is dominated by SRC and that the neutron/proton pairs are about 20 times more abundant than isospin-like pairs due to the tensor part of the nucleon-nucleon (NN) interaction [1]. Moreover, indications of a possible dependence of the high momentum fraction of protons and neutrons with the N/Z ratio was proposed from measurements on stable nuclei [2]. In this talk, I will present a novel experiment performed at the GSI accelerator facility with the R^{3}B setup [3]. For the first time we made use of a short-lived nucleus scattering off a proton probe in inverse kinematics, allowing a more direct and systematic access to SRC properties as function of the N/Z ratio. The study of ^{16}C will add a new measurement at N/Z = 1.67, above the largest available N/Z (^{208}Pb) and at a much smaller mass, close to the one of the reference system ^{12}C measured in the same experiment. Furthermore, we aim to extract the ratio of np/pp pairs as function of missing momentum and thus gain information about the NN interaction in comparison to different NN interaction theories. The concept of this experiment and some preliminary results will be discussed.

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Is there a dark decay in ^{6}He ?

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The neutron lifetime discrepancy between beam and bottle experiments of 4σ could be interpreted as a possible sign of the neutron into dark particles [1]. If such a decay exists, it could also occur in unstable nuclei with sufficiently low neutron binding energy, a quasi-free neutron decay into a dark matter particle χ; as is the case of ^{6}He with $S_{2n} = 975.45keV < m_n - m_\chi$ [2]. This quasi-free neutron dark decay would be as followed $^6He \rightarrow^4 He + n + \chi$ which is the only way to have the emission of a free neutron in the decay of ^{6}He. The SPIRAL1 facility at GANIL was used in June 2021 in order to produce a pure $^6He^{1+}$ radioactive beam at 25keV to observe an excess of neutrons in the decay of ^{6}He which would be a unique signature for dark matter creation. In this presentation, we report the (preliminary) results of this experiment to set an upper limit for this dark decay mode in ^{6}He.

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Study of alpha particle production in the 6He+9Be collision

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A study of reaction mechanisms involved in the production of alpha particles in reactions induced by a 6He radioactive beam on a 9Be target nuclei is presented. Experimental data [1] was obtained using the RIBRAS (Radioactive Ion Beams in Brasil) facility of the Institute of Physics of the University of São Paulo, Brazil [2-4]. It is the first RIB facility in the southern hemisphere and is presently the only experimental equipment in South America capable of producing secondary beams of rare isotopes. The RIBRAS system consists of two superconducting solenoids used to select and focus light secondary beams of nuclei out of the stability valley. 6He+9Be angular distributions were measured at Elab=16.2MeV and Elab=21.3 MeV bombarding energies. A large yield of alpha particles was observed, that is absent with gold target measurements, indicating that they come from reactions with the 9Be target. The 6He secondary beam had many kind of particles (cocktail beam) like 7Li and light particles such as α, p and t. In particular, these 7Li and α-particles can also contribute to the production of the observed alpha particles, in addition to the breakup of the 9Be target, since the 9Be nucleus has (α+α+n) cluster configuration with binding energy of 1.564 MeV. Energy and angular distributions of those events were obtained taking into account these alpha particle production possibilities. The results were compared with theoretical calculations performed using the Continuum Discretized Coupled Channel (CDCC), the Ichimura-Austern-Vincent (IAV) formalisms [5,6], in addition to the fusion-evaporation calculations.

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Charge-changing reactions of atomic nuclei and implications on the neutron skin thickness

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Measurement of charge-changing reaction cross sections (CCCS), usually performed on carbon in the intermediate and high energy region, is a powerful technique to determine proton radii for most exotic nuclei. Along with reaction cross sections it can provide the first hint of exotic structures and phenomena of unstable nuclei. In this talk, I will first review the CCCS measurements of p-sd shell nuclei on carbon and hydrogen targets at about 900 and 300 MeV/nucleon. The experiments were performed at GSI/Germany and HIRFL/China. Benefiting from the data set, we demonstrate there is a systematic defect in the state-of-art reaction model. This could result in a different *rms* proton radius from CCCS. Then I will report a new probe of *L*, the density dependence of the symmetry energy, at saturation density. We find a good linear correlation between *L* and the charge changing cross section difference (Δσcc) of mirror nuclei 30Si-30S. The linearity is found to be in the same precision as those found between *L* and neutron skin thickness or proton radius difference.

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Deformed two-body models for exotic nuclei applied to transfer reactions

Auteurs: Pedro Punta[1]; José Antonio Lay[1]; Antonio Moro[1]

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Light exotic nuclei are usually described within few-body models made of an inert spherical core and one or two weakly bound nucleons. However, for some exotic nuclei like ^{11}Be or ^{17}C, deformation is especially relevant and should be included in the structure models.

Hence, the structure of ^{11}Be and ^{17}C is described using two-body models where a neutron moves under the action of a deformed potential generated by the core. Two different models have been used according to the coupling limit of the fragemts: the semi-microscopic particle-plus-AMD (PAMD) model from [Phys. Rev. C 89 (2014) 014333] for weak-coupling and a model based on Nilsson for strong-coupling.

Energies and associated wave functions are obtained by diagonalizing the Hamiltonian in a transformed Harmonic Oscillator basis (THO) [Phys. Rev. C 80 (2009) 054605]. This basis has been successfully applied to the discretization of the continuum of two-body and three-body weakly bound nuclei for the analysis of break up and transfer reactions [Phys. Rev. Lett. 109 (2012) 232502, Phys. Rev. C 94 (2016) 054622].

The structure models are tested by studying transfer reactions ^{11}Be(p,d)^{10}Be and ^{16}C(d,p)^{17}C. Good agreement is found for these transfer reactions to bound states by comparing with the experimental data from [Chinese Phys. Lett. 35 (2018) 082501],[Phys. Lett. B 811 (2020) 135939] respectively. The transfer to the continuum is also studied for ^{16}C(d,p)^{17}C using our two models.

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Microscopic models of nuclear structure at scale

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The diversity of atomic nuclei is enormous: the number of possible species is estimated to be 7000 while we know that adding a single nucleon to one nucleus can dramatically change its properties. This diversity renders nuclear structure interesting in itself, but it is also crucial to the progress in several other fields of research: from searches for beyond-the-standard-model physics to the chemistry of (possibly long-lived) superheavy nuclei. The need for nuclear data is particularly large in astrophysics: answering fundamental questions about the Universe (What is the origin of the elements? What is the composition of the core of neutron stars?) requires data on many properties of thousands of nuclei at the extremes of isospin, temperature and angular momentum.

Since exotic nuclei are hard to produce and handle, the only realistic way to provide all required nuclear data is nuclear theory. To maximize predictive power, models should incorporate as much of the relevant physics ingredients as current computers can handle while describing the maximum number of properties simultaneously with a limited number of parameters. Models based on energy density functionals (EDFs) offer an attractive compromise: starting from an effective interaction they rely on the mean-field approximation to render the many-body problem tractable and can provide a microscopic description of all relevant quantities in terms of individual neutrons and protons and a modest amount of parameters across the scale of the nuclear chart. The success of EDF-based models is largely due to spontaneous symmetry breaking: by considering deformed configurations, these models can account for large parts of the effects of nuclear collectivity at the mean-field level.

In this contribution, I will introduce the recent EDF-based models constructed in Brussels: the BSkG-series. Fitted to over two thousands binding energies, they all achieve a root-mean-square error on the known masses of less than 800 keV which is competitive with simpler models. What sets the BSkG-series apart from other large-scale models based on EDFs is the sophistication of their representation of the nucleus: a three-dimensional coordinate representation results not only in a well-controlled numerical accuracy but also allows us to exploit the power of spontaneous symmetry breaking fully. All BSkG-models allow the nucleus to explore triaxial deformation, while the most recent ones also allow in addition for (i) non-zero angular momentum in the ground-states of odd-mass and odd-odd nuclei through time-reversal breaking and (ii) reflection asymmetry, i.e. octupole deformation.

I will discuss the performance of the BSkG-models for a diversity of (pseudo-)observables relevant to nuclear structure and astrophysical applications: from bulk properties such as masses, charge radii and deformations to the large-scale description of nuclear fission; from fine-grained aspects of ground states such as moments of inertia and magnetic moments to statistical properties such as nuclear level densities. Throughout the presentation, I will explain the impact of spontaneous symmetry breaking and underline its importance to achieve a state-of-the-art simultaneous description of all these quantities. Finally, I will discuss ongoing refinements of these models and the challenges we intend to tackle in the long run.

parallel session / **350**

Shape coexistence studies of Pb-186 employing the SAGE spectrometer

Auteurs: Joonas Ojala[1]; Janne Pakarinen[2]

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Shape coexistence is a phenomenon in which the same nuclei can possess different macroscopic shapes. The alpha-decay study for Pb-186 have shown a unique triplet of 0+ states which has been associated with spherical, prolate and oblate shapes [1]. Collective bands built upon these deformed 0+ states have been observed in in-beam gamma-ray spectroscopy experiments [2; 3]. However, gamma-ray spectroscopy can not probe E0 transitions which proceed primarily through internal conversion. These transitions are typically present in nuclei featuring shape coexistence.

Simultaneous conversion electron and gamma-ray studies for Pb-186 have been conducted exploiting the SAGE spectrometer [4] and the recoil-decay tagging technique, employing a 106Pd(83Kr,3n)186Pb fusion-evaporation reaction. The experiment was performed in 2013 at the Accelerator Laboratory of the University of Jyväskylä.

As a result of this experiment, direct feeding of the first excited 0+ state, which allowed us to reassign the shapes of the excited 0+ states in the Pb-186. Also, the 0+ -> 0+ transitions from the excited 0+ states to ground state, the E0 transitions of the 2+ -> 2+ and the 4+ -> 4+ transitions were observed. These results have been published in Communication Physics [5]. This work introduces a way to have systematic studies of E0 transitions in this region.

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Characterization of the participent zone in Xe+Sn collisions

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Collisions of heavy ions are the best tools at our disposal to probe nuclear matter. It allows us to reach extreme densities, giving us the possibility to constraint transport models. In particular at incident energies around 100 MeV/nucleon a participant zone is formed by a part of projectile and target nuclei.

The aim of this work is to characterize the participant zone. We will focus on the characteristics of cluster production (chemical composition, energy, angular distributions, multiplicities, and their correlations). These analysis reveal the neutron richness of the emitted particles, and their yield gives an insight on the mixing of target and projectile contributions. Furthermore, a systematic analysis of the transverse energy of the emitted clusters shows a link between incident energy, compression energy, and density during the reaction.

For this study, INDRA datasets for 124,129Xe+112,124Sn collisions at 100 AMeV has been used to study the effect of neutron richness on the production of light particles. The kinematic study has been done using the datasets for 129Xe+124Sn at 65, 80, 100 and 150 AMeV collisions, and using the 136Xe+124Sn collision dataset for 32 and 45 AMeV.

The results of this analysis were compared to the semi-classical event generator ELIE. This work has been done with the goal of expanding it to a lighter system, 58,64Ni+58,64Ni, measured at 32 and 52 AMeV during the E789 INDRA-FAZIA campaign.

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Total Absorption Spectroscopy of Ground and Isomeric States in 70Cu

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Theoretical models studying the origin of elements in the universe and stellar nucleosynthesis processes such the rapid neutron capture process (r-process), require physics information such as beta-decay properties and neutron-capture reaction rates [1]. Nuclei with larger β-decay Q-values have decay schemes with many weak de-excitation pathways to the ground state and β-decay branches, which are difficult to measure without high efficiency detectors. Further, information about the production mechanisms and conditions of the r-process can be investigated by considering the importance of "astromers," which are nuclear isomers with astrophysical significance [2]. Astromer calculations rely on experimental β-decay information such as half-lives, log(ft) values, and beta-feeding (I) intensities [3]. Here, we use the method of total absorption spectroscopy to investigate the β-decay of ^{70}Cu which has three β-decaying spin-parity states (6^- ground state, and two isomeric states: 3^-, and 1^+) [4]. In an experiment performed at the National Superconducting Cyclotron Laboratory ^{70}Cu was produced and delivered to the Summing NaI (SuN) Total Absorption Spectrometer [5]. Spectra from the β-decay of each spin-parity state were isolated using different beam on/off periods. I values from total absorption spectroscopy following the β-decay of each of the three β-decaying spin-parity states will be presented.

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parallel session / **353**

Microscopic study of alpha, two-alpha and cluster decays

Auteur: Elias Khan[1]

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Using covariant energy density functional approach, it was recently possible to describe alpha decay, on both medium mass and heavy nuclei [1]. Using the same formalism, a new mode of radioactivity was predicted [2]. In such a mode, 2 alpha particles are emitted back-to-back, contrary to a 8Be-like cluster mode. Cluster decay will also be analyzed with this approach [3].
Information brought by such a formalism on the preformation and the localization of the alpha particle in the nuclei will be discussed [4]. Indications on possible favorable candidates to experimentally search for 2 alpha decays with radioactive beams will also be given.

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plenary 01 / **355**

Nuclear astrophysics at storage rings (presentation sponsored by EPJ)

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Most of the time, stars gain their energy from fusion of the very light left-overs of the Big Bang into heavier elements over long periods of time. The observation of radioactive isotopes in different regions of the Universe is an indicator of this ongoing nucleosynthesis. In addition, short-lived nuclei are often intermediate steps during the nucleosynthesis in stars. A quantitative analysis of these relations requires a precise knowledge of reaction cross sections involving unstable nuclei.

The corresponding measurements are very demanding and the applied techniques therefore manifold.

Ion storage rings offer unprecedented possibilities to investigate radioactive isotopes of astrophysical importance in inverse kinematics. During the last years, a series of pioneering experiments proofed the feasibility of this concept at the Experimental Storage Ring (ESR) at GSI. I will present recent experiments and ideas for future setups for the investigation of capture reactions with astrophysical motivation.

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Towards N=126 shell closure using multi-nucleon transfer reaction between 136Xe and 198Pt

Auteurs: Alahari Navin[1]; Andrey Andreev[2]; Antoine Lemasson[1]; Chole Fourgeres[1]; Diego Ramos[1]; Dieter Ackerman[1]; Francesco Recchia[3]; Gille de France[1]; Hiroari Miyatake[4]; Jason Park[5]; Jean-charle Thomas[1]; Jeremy Dudouet[6]; Kyungyuk Chae[7]; M. Rosenbusch[4]; Mauricy Rejmund[1]; Peter Schury[4]; Sarmi Bhattacharya[8]; Seonho Choi[9]; Sunchan Jeong[4]; Sunghan Bae[5]; Wolfram Korten[10]; Yonghyun Son[9]; Yoshikazu Hirayama[4]; Youngju Cho[9]; Yung Hee KIM[11]; Yutaka Watanabe[4]

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The neutron-rich unstable nuclei in the vicinity of neutron magic numbers are relatively well studied, far from the stability lineup to the neutron magic number N = 82. However, for the neutron-rich nuclei to the south of 208Pb, there is limited knowledge of the excited states of these nuclei. This arises from the difficulty in producing these nuclei using conventional methods. Even for nuclei that have already been produced only limited information is known. The recent multi-nucleon transfer reaction showed promising results with several orders of magnitude larger cross-sections than those for fragmentation reactions.
A new experiment was carried out at GANIL to explore these isotopes of interest using multi-nucleon transfer reactions of 7MeV/u 136Xe beam and 198Pt target. Large acceptance VAMOS++ magnetic spectrometer and AGATA Ge tracking array were used to measure excited states of nuclides of interest. And several new experimental techniques were implemented in this experiment. First, a second arm detector was newly installed, which is composed of a vacuum chamber and multi-wire proportional counter to measure the velocity vector of the target-like fragments. Second, four EXOGAM HPGe clover array was installed at the end of the second arm to measure the delayed gamma rays from the excited states of the produced nuclei. Finally, a new method to determine particle identification is under development using a machine learning algorithm, where energy and charge states are determined using supervised machine learning and atomic numbers are determined by the unsupervised learning method. The preliminary result of the experiment such as particle identification with the help of machine learning and gamma-ray spectroscopy neutron-rich nuclei will be presented.

parallel session / 360

Nuclear and molecular physics studies with laser spectroscopy of radioactive molecules

Auteur: Michail Athanasakis-Kaklamanakis[1]

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The research potential of radioactive molecules for both fundamental and applied science has recently been recognized [1,2] and significant progress has been marked at ISOLDE on both the production [3] and the spectroscopy [4-7] of radioactive molecules.

In addition to the first laser spectroscopy of RaF at the collinear resonance ionization spectroscopy (CRIS) experiment [4,5] and its subsequent high-resolution study [6], the CRIS collaboration recently performed the first laser spectroscopy of AcF [8]. AcF has been proposed as a promising system for the first measurement of a nuclear Schiff moment across the nuclear chart, which is a symmetry-violating property that is predicted to be easier to measure in AcF than in RaF, YbF, ThO, and other diatomic molecules that are currently under investigation in the search for an electron electric dipole moment.

Simultaneously, experimental and theoretical progress in the excited electronic states of RaF [7] and the manifestation of nuclear observables in molecular spectra [9] carried out by members of the CRIS collaboration has highlighted the potential of laser spectroscopy of radioactive molecules at radioactive ion beam facilities to probe nuclear and molecular observables that are not easily accessible by other methods and systems.

In this talk, recent results by the CRIS collaboration on the laser spectroscopy of RaF and AcF will be presented, along with the spectroscopy of lighter radioactive molecules that can provide access to nuclear and molecular observables that cannot be studied via other methods. The future directions of laser-spectroscopic studies of radioactive molecules at CRIS will also be discussed.

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β-delayed proton decay of 23Si and isospin symmetry breaking

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The elegant concept of isospin symmetry was first applied to nuclei by Wigner[1] as a charge independence operator based on the nucleon-nucleon (NN) interaction. Nevertheless, the approximate isospin symmetry is broken, which is mainly attributed to the Coulomb force and charge dependent parts of nuclear force. Far from the stability line, various exotic decay modes of the proton-rich nuclei, especially the β-delayed particle emission, are demonstrated as an intriguing phenomena which have played a significant role of testing for the isospin symmetry[2-4]. Our research team has found that the largest value of mirror asymmetry δ = 209(96)% occurs in low-lying states of the β decay of mirror nuclei ^{22}Si/^{22}O, supporting the existence of a halo structure in ^{22}Al[5]. Systematical research on the origin of breaking is of great importance to understand the nuclear force and nuclear structure.
The proton-rich nucleus ^{23}Si, with an isospin projection of Tz = -5/2, was produced, identified and selected by the Radioactive Ion Beam Line in Lanzhou (RIBLL1) at the Heavy Ion Research Facility in Lanzhou (HIRFL). The ions of ^{23}Si were finally implanted into double-sided silicon strip detectors (DSSDs) surrounded by clover-type high-purity germanium (HPGe) detectors. The energy levels and the decay branching ratios populated to the low-lying excited states of ^{23}Al were extracted to construct the partial decay scheme by coincidence measurement of β-delayed protons and gamma rays. Comparing to the mirror β decay of ^{23}F, a large value of mirror asymmetry δ = 201(108)% and mirror energy diffenernce MED = -569(8) keV are found in the transition to the second 5/2+ state.
The ab initio valence-space in-medium similarity renormalization group (VS-IMSRG)[6-8] calculations based on chiral two-body and three-body force, in which charge-symmetry and charge-independence breakings are included, are performed to explain the large mirror asymmetries in the low-lying state of ^{22}Al and ^{23}Al. Our calculations give that the large mirror asymmetries are mainly caused by the large occupations of $s1/2$ wave, which is weakly-bound or unbound in proton-rich nuclei and deeply-bound in neutron-rich nuclei. Moreover, isospin asymmetries in the sd-shell nuclei are also extensively investigated based on ab initio VS-IMSRG calculations.

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β-decay studies of A = 107 nuclei using the Modular Total Absorption Spectrometer (MTAS)

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Determination of the true feeding intensities (I_β) in β-decay of fission products is very important in addressing the reactor antineutrino anomaly and modeling the reactor decay heat. β-decay measurements with high-resolution but low-efficiency detectors may affect by the Pandemonium effect. This effect may lead to underestimation of the feeding to high excited levels, thus systematically biases the calculation of reactor antineutrino spectrum and decay heat calculation.

Modular Total Absorption Spectrometer (MTAS), which has almost 99% gamma detection efficiency, is an ideal spectrometer to determine not only the true β feeding intensities free from Pandemonium effect, but also the intensity of ground state to ground state feeding.
MTAS has been utilized to measure the beta decay pattern of several fission products that are high-priority contributors to reactor decay heat and antineutrino spectrum.

In this talk, we will present some preliminary results of $A = 107$ decays measured at CARIBU (ANL) in March, 2020.
The β-branchings of ^{107}Tc and ^{107}Mo, which have incomplete data in current nuclear dataset, is determined experimentally using MTAS.
We found the Pandemonium Effect in the β-decay measurements of ^{107}Tc and ^{107}Mo. Plenty of new levels with high excitation energy are required to reproduced the experimental spectra.
This suggests a large shift of the antineutrino spectrum of ^{107}Tc and ^{107}Mo towards lower energy.

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Studies of astrophysically important reactions using rare isotope beams at TRIUMF

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Determining the stellar origin of the elements observed in our Galaxy today poses one of the key challenges in the field of nuclear astrophysics. Thus, we seek to understand the nuclear processes involved in stellar evolution, as their details give us insight into the fusion pathways and routes to the synthesis of heavy elements. The investigation of radiative capture reactions involving the fusion of hydrogen or helium is crucial for the understanding of said nucleosynthesis pathways as these reactions govern nucleosynthesis and energy generation in a large variety of astrophysical burning and explosive scenarios. However, direct measurements of the associated reaction cross sections at astrophysically relevant low energies are extremely challenging due to the vanishingly small cross sections in this energy regime. Continuous advances in the production of accelerated rare isotope beams provide an opportunity to simulate and study the reactions occurring inside stars. However, many astrophysically important reactions involve radioactive isotopes, which still pose challenges for beam production and background reduction.

To overcome these challenges, dedicated facilities, such as the DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) recoil separator, SONIK (Scattering Of Nuclei in Inverse Kinematics), TUDA, the TRIUMF UK Detector Array for charged particle detection as well as the EMMA (ElectroMagnetic Mass Analyser) recoil mass spectrometer at the TRIUMF-ISAC Radioactive Ion Beam Facility have been designed to experimentally determine nuclear reaction rates of interest for nuclear astrophysics in inverse kinematics.

In this contribution, I will introduce the experimental facilities - with focus on the DRAGON recoil separator - before presenting recent experimental highlights involving the use of radioactive and high-intensity stable ion beams. Finally, I will report on recent and future facility upgrades to extend the experimental capacities and versatility.

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High-precision collinear laser spectroscopy - An all-optical nuclear charge radius of ^{12}C

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The size of an atomic nucleus is a fundamental observable and can be used to benchmark nuclear structure theory and therefore test our fundamental knowledge of matter. In contrast to matter and neutron radii, the nuclear charge radius can be probed through the well-known electromagnetic interaction. Typically, charge radii of stable nuclei are extracted from elastic electron scattering or muonic atom spectroscopy, and collinear laser spectroscopy resonance ionization spectroscopy are used to measure differential charge radii of radioactive isotopes relative to a stable reference nucleus. In a few cases, the uncertainty of the charge radius of the stable isotope limits the uncertainties of the radioactive species. To overcome this limit in light mass nuclei like ^{10,11}B, an all-optical approach for the charge radius determination purely from laser spectroscopy measurements and non-relativistic QED calculations [1] was tested with the well-known nucleus of ^{12}C. Thereby, helium-like $^{12}C^{4+}$ was laser excited from the metastable $1s2s\,^3S_1$ state with a lifetime of 21 ms to the $1s2p\,^3P_J$ states and the respective transition frequencies were determined with less than 2 MHz uncertainty. The high-precision collinear laser spectroscopy was performed at the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA), situated at the Institute for Nuclear Physics at the TU Darmstadt.
This contribution will present the first high-precision laser spectroscopy in the isotopic chain of carbon and the first all-optical nuclear charge radius determination of ^{12}C. This project is supported by the German Research Foundation (Project-ID 279384907 – SFB1245).
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Effect of Halo and Bubble Nuclei in Limited Abundance Calculations Relevant for the r-process

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Nuclei away from the valley of stability, and typically near the drip lines, have challenged our understanding of nuclear structure. For example, ^{11}Be, ^{19}C, or ^{37}Mg have a long tail in their matter density distribution – popularly known as a halo. Another exciting development in this arena is the existence of bubble nuclei such as ^{20}N, ^{22}O, and ^{24}Si, which have a marked depression in their central densities and are shaped as a biconcave spheroid.
The question, therefore, we pose is what effect they have on stellar reaction rates and nucleosynthesis, which in turn can affect the astrophysical abundance pattern relevant for the r-process by a considerable margin [1]. Thus, in this work, we have considered a limited network of neutron-rich C, N, and O isotopes, taking proper structures of ^{19}C, ^{20}N, and ^{21}N into consideration. The neutron capture rates of $^{18}\mathrm{C}(n,\gamma)^{19}\mathrm{C}$ and $^{19}\mathrm{N}(n,\gamma)^{20}\mathrm{N}$ are taken from finite range distorted wave Born approximation (FRDWBA) calculations [2,3] and $^{20}\mathrm{N}(n,\gamma)^{21}\mathrm{N}$ from [4]. The required beta decay rates are calculated in the interacting nuclear shell model framework [5] using the shell model code KSHELL [6]. The shell model Hamiltonian ***psdmk*** was used to calculate the necessary wave functions of the isotopes of interest for the C, N, and O series for beta-decay rate calculations. Other rates have been taken from the JINA REACLIB database and statistical model calculations. An abundance calculation has been carried out at an equilibrium temperature and a constant density in core collapse supernova [1].
We will highlight how the improved nuclear structure and reaction rate calculations, including exotic properties like nuclear halo and bubble structure, can affect radiative capture rates associated with light and medium mass nuclei. Without the inclusion of proper structural inputs, one is often limited with the statistical estimates which are possibly uncertain. We can see how even with a limited network, the elemental abundances can change drastically with the inclusion of proper structure. We will show that the time evolution of the abundances of nuclei close to the above mentioned exotic nuclei (^{19}C, ^{20}N, and ^{21}N), show a large difference as compared to those calculated with statistical model rates.

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Fission, gamma rays and the r-process

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Nuclear fission plays a key role in the astrophysical r-process which is responsible for creating heavy nuclei in astrophysical scenarios, such as neutron star mergers. Data on fission of nuclei populated by the r-process are with current experimental techniques not accessible. However, it is possible to extend our knowledge on fission of isotopes which are as neutron rich as state-of-the-art radioactive beam facilities can reach, to improve fission models and thereby r-process model calculations.

The ISOLDE facility at CERN offers unique conditions to perform fission experiments in inverse kinematics. By using the ISOLDE Solenoidal Spectrometer (ISS), fission can be investigated in inverse kinematics. Here, plans and simulation results for the measurement of gamma rays in coincidence with fission fragments will be presented.

Such data are of importance for the observation of gamma rays emitted by neutron star mergers and r-process model calculations. However, the experimental conditions, namely the high kinetic energy of the two fission fragments in an inverse kinematics experiment and the detection inside a 2.5 T magnetic field pose challenges. Doppler correction is complicated by the fact that gamma rays can be emitted from either of two different moving sources at an angle with respect to the incoming beam axis. The impact of those conditions and the total gamma efficiency for different geometrical arrangements of 40 CeBr3 detectors will be presented.

This work is supported by the Knut and Alice Wallenberg Foundation Dnr. KAW 2020.0076.

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Storage ring facilities for radioactive ions -New detectors and upgrade plans

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I will overview storage-ring nuclear physics at GSI/FAIR and RIKEN with a focus on recent technical developments with future perspectives. The experimental storage ring ESR at GSI has pioneered mass measurements of exotic nuclei and decay studies of highly charged ions (HCI)[1]. Radioactive ions produced at the fragment separator FRS are in-flight separated and are stored into the ESR where two methods of mass spectrometry have been established. One is the time-resolved Schottky mass spectrometry where stored ions, cooled with the stochastic and/or electron cooling techniques, are frequency analyzed by non-destructive Schottky detectors, and the other is the isochronous mass spectrometry where revolutions of short-lived ions are directly measured by an in-ring dedicated time-of-flight detector under a specific optical condition. The FRS-ESR facility features relativistic energy and cooled heavy ions, highlighted by the discovery of new isotopes, new long-lived isomers, and the observation of bound-state beta decays, hyperfine effects of HCI. The facility will be upgraded to the FAIR ring branch based on the Isomeric beams, Lifetimes and Masses (ILIMA) collaboration.

The RI Beam Factory (RIBF) at RIKEN features the largest cyclotron facility complex. Taking advantage of the highest intensities of radioactive ions, a new mass spectrometer, Rare-RI Ring (R3) [2], for exotic nuclei has recently been launched. The spectrometer consists of a cyclotron-like storage ring coupled with the fragment separator BigRIPS. The isochronous mass spectrometry is employed, where only dipole magnets form a weak focusing lattice to realize the precise isochronous optical condition with a large momentum acceptance. Because of the beam characteristic, exotic nuclei of interest are individually, in-flight selected to be stored in the storage ring. Thus, single-ion mass spectrometry with the individual injection scheme has been accomplished. The first application for neutron rich Pd isotopes has recently been published [3].

Both facilities are unique and complementary. Collaborative technical studies are proceeding toward common goals; a position-sensitive transverse Schottky detector has been designed at GSI and will be tested at RIKEN. A high-resolution GAGG(Ce) crystal telescope (~50 ps time and ~1% energy resolution) was tested with heavy ions at the Heavy Ion Medial Accelerator in Chiba (HIMAC) facility in Japan and has been installed as a decay study pocket detector at the ESR. Additionally, new specific detectors: a time-of-flight detector based on delta-ray readout technique (~80 ps time resolution) and low-cost position-sensitive plastic scintillation detectors with fiber readout techniques (~1 mm spatial resolution) have been developed in Japan, which can be extended as a general purpose as well. With these instruments, the facilities will be upgraded for decay and reaction studies, beyond conventional mass measurements, of exotic nuclei available at both facilities.

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Investigation of the atomic and nuclear structures of $^{244-248}$Cm

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The transuranium element curium $(\mathrm{Z}=96)$ was discovered 1944 by Glenn T. Seaborg and coworkers [1]. Curium is one of the minor actinides beyond plutonium, contained in spent nuclear fuel (SNF) at about 20 g/t. It is produced during power reactor operation in a series of nuclear reactions starting from ^{238}U. The isotopes $^{242-248}$Cm and ^{250}Cm have the longest half-lives of the 18 known curium isotopes, ranging from 1 to 10^7 years [2]. Especially after the Chernobyl reactor accident in 1986, curium isotopes have become more relevant in the context of radioanalytics and radiation protection. The isotope ^{242}Cm $(T_{1/2} = 162.88\,\mathrm{d})$ is the largest contributor to gross alpha activity and is thus one of the strongest alpha particle emitters in fresh SNF [3].
Resonance Ionization Mass Spectrometry (RIMS) was used at the RISIKO mass separator at Johannes Gutenberg University Mainz for off-line studies of the complex and dense atomic structure of curium. The RIMS method is ideally suited for the identification of minute amounts of rare isotopes due to its high ionization efficiency and excellent element selectivity. In preparation for the identification of curium isotopes in fresh SNF, highly efficient and element-selective ionization schemes have been developed using two different excited levels with the electron configurations $5^7677\,^9{}_3$ and $5^867\,^9{}_3$. First demonstrations of the identification of curium in environmental hot particles have already been performed [5].
Apart of that, curium is of special interest for studies of atomic and nuclear structures of actinides by laser spectroscopy. For this a mixed curium sample with the isotope ratios of ^{244}Cm : ^{245}Cm : ^{246}Cm : ^{247}Cm : ^{248}Cm = 0.40 : 0.06 : 0.13 : 0.004 : 0.39 was used at the RISIKO mass separator. A

narrow band Ti:sapphire laser system was used for high-precision measurements of the $^{244-248}$Cm isotope shift. The hyperfine structure was resolved for the two odd-A isotopes of ^{245,247}Cm with 15 hyperfine transitions each. Finally, the modified King plot was used to determine the missing mean square charge radius of ^{247}Cm.

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Testing ab-initio calculations in light nuclei via high-precision spectroscopy

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The development and improvement in terms of performances of accelerator facilities and detectors has paved the way for extending the study of nuclear structure towards more exotic nuclei and experimental quantities that have been, until now, less accessible.
In parallel, theoretical methods have advances in precision and prediction capabilities.
In recent years, *ab-initio* calculations in particular have proven to be powerful tools to address open questions in nuclear structure; one example is the role of three-body forces in the evolution of nuclear structure far from stability.
The importance of their contribution is evident in the case of the oxygen isotopic chain.
In fact, only by including these forces in the calculations it is possible to correctly reproduce the neutron dripline in correspondence of ^{24}O, instead of ^{28}O as predicted by standard calculations.
However, in order to quantify the contribution of these forces, spectroscopic information is crucial.

In this context, the ^{20}O nucleus is a perfect playground for these measurements; in fact, the properties of the 2_2^+ and 3_1^+ states of this nucleus are expected to be influenced by three-body forces.
By measuring the spectroscopic properties of these nuclei, such as the excitation energy, the branching ratio and the lifetime, and comparing them to theoretical calculations, it is possible to understand the depth of their influence.

For these reasons, an experiment aimed at studying the ^{20}O was performed in GANIL. The radioactive beam of ^{19}O, provided by the SPIRAL1 complex, impinged on a deuterated target, populating the nucleus of interest by means of a (d, p) reaction.
The target was deposited on a layer of gold in order to measure the lifetime of the states by using the Doppler-Shift Attenuation Method.
The recoils of the binary reaction were detected using the MUGAST array and the VAMOS++ magnetic spectrometer, while the γ rays emitted were detected using AGATA.

The nucleus was first investigated via particle-γ spectroscopy to reconstruct the level scheme and measure the branching ratios.
Then the lifetimes of the 2_2^+ and 3_1^+ states were measured. To do so, the experimental lineshapes were compared to realistic Monte Carlo simulations and the lifetimes were extracted by using the least-χ^2 method.
Finally the reduced transition probabilities, B(E2) and B(M1) deduced from the lifetime measurements, were compared to *ab-initio* calculations.

In this contribution, the results of the particle-γ spectroscopy and the lifetime measurements of the 2^+_2 and 3^+_1 states are reported.
An interpretation of the nature of the excited states of ^{20}O is presented as well as the future perspectives for further investigation in this region.

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Detecting fission fragments at ISS

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Recent advances in the production of radioactive beams and spectrometer design allow for the measurement of fission barrier heights in inverse kinematics, also for neutron-rich nuclei. Fission reactions in inverse kinematics result in a forward focusing of
the two fission fragments which can be exploited.

The complex network of nuclear reactions known as the r-process is responsible for the nucleosynthesis of the heaviest elements in the universe. It is believed to occur in astrophysical scenarios like neutron-star mergers. In this process, nuclear fission plays a key role since it limits the maximum element number that can be produced. However, our knowledge on the fission of neutron-rich nuclei, relevant for the r-process, is very limited and lacks experimental information.

Simulations of such experiments using the ISOLDE Solenoidal Spectrometer (ISS) at CERN will be presented. By detecting the fission fragments in coincidence with a proton from a (d,pf) reaction, fission probabilities can be extracted as a function of the excitation energy. Ways of optimizing the acceptance of fission fragment detectors located inside or near a 2.5 T magnetic field have been investigated. Different detector configurations will be discussed and compared.

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In-beam gamma-ray spectroscopy of the exotic 79Cu with HiCARI

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An experiment aiming at performing an in-beam γ-ray spectroscopy of 79Cu after a one-proton knock-out from 80Zn was carried out at the Radioactive Isotope Beam Factory of the Riken laboratory during the 2021 HiCARI campaign [1]. An incident primary beam of 238U at 345 MeV/nucleon

produced a wide range of exotic nuclei including 80Zn, after in-flight fission. These nuclei were sent through the BigRIPS separator onto a beryllium target, in which the knock-out reactions took place. The outcoming fragments including 79Cu were subsequently identified in the ZeroDegree spectrometer. The emitted γ-rays were detected by the HiCARI germanium detector array placed around the target. The particle identification of the nuclei of interest for 80Zn(9Be,X)79Cu reaction channel has been achieved in the ongoing analysis after optical corrections and background removal. We present here the preliminary γ-spectra of 79Cu de-excitation, which we compare with the results of our previous campaign where a scintillator array was used [2].

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Li-8 and He-8 beams for hadrontherapy

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Radiotherapy with light ion beams is beneficial for treatment of tumors that are resistant to chemotherapy and radiotherapy. In addition, hadrontherapy is the preferred choice of treatment for tumors that are inoperable, e.g. due to their proximity to vital organs.
One of the advantages of hadrontherapy over conventional X-ray radiotherapy is the possibility to target the tumor site with a higher precision, both radially and longitudinally. Due to the high-energy transfer at the Bragg peak, one can increase the dose in the tumor while preserving the surrounding healthy tissue.
The high precision of the dose deposition requires also a high accuracy of deposition that is presently hindered due to the dependence on modelling and due to the current limitations of dose monitoring. A possible improvement of the latter can be achieved by using short-lived ion beams, which allows evaluation of the dose distribution by measuring the decay radiation.
An additional advantage of using specific short-lived isotopes, such as Li-8 and He-8, is the presence of beta-delayed particle emissions that are expected to increase further the dose delivery in the tumor. Moreover, in the case of He-8, a single 980 keV gamma is emitted in 84% of the beta decays, which allows delayed, background-free detection for online dose monitoring. The possible advantages of Li-8 and He-8 for hadrontherapy supported by simulation results and the upcoming experimental verification at GANIL will be discussed.
There are various schemes for production of short-lived radioactive ion beams, which are based on "isotope separation on-line" (ISOL) and/or on "In-flight production and separation" (IF). The main advantages and disadvantages of the production in various scenarios will be presented. A kinematic advantage in the case of IF production and separation of neutron-rich beams will be discussed as a possible way to reduce costs of future hadrontherapy centers.

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A DESIRable radiofrequency cooler and buncher: the GPIB

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A gas-filled radiofrequency quadrupole (RFQ) named the General Purpose Ion Buncher (GPIB) has been designed to be the beam cooler and buncher located at the entrance of the soon-to-be-built DESIR* experimental hall at GANIL. The GPIB will both cool the beams coming from the SPIRAL1 and SPIRAL2 facilities from the few-10 π.mm.mrad emittance typical of the accelerators down to a few π.mm.mrad at energies ranging from 60 to 3 keV and also bunch them if needed by the experiment further downstream in the hall while maintaining a high transmission.
The mechanical design is an upgrade of the existing ISCOOL RFQ located on the HRS beamline at ISOLDE, CERN but the new radiofrequency system based on a balun transformer enables a much stronger radial confinement of the ions inside the cooler so as to handle the high production rates expected at DESIR: around 10^8 ions per second for most nuclides but up to 10^{10} ions per second in some specific cases.
The GPIB has been assembled at LP2i-Bordeaux and is currently being commissioned in parallel with the PIPERADE double Penning trap that has been installed on the same beamline and makes use of the cooled beam of the GPIB. We will demonstrate that a transmission of 80% or higher can be maintained in continuous mode (cooling only) up to a few nA of incoming ions while the transverse emittance is lowered down to 3 π.mm.mrad at 30 keV. Preliminary results concerning energy and time dispersions will also be shown.

* Standing for Decay, Excitation and Storage of Radioactive Ions

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Constraining the electron-capture rates of neutron-rich nuclei with the $(d, {}^2\mathrm{He})$ reaction in inverse kinematics.

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Nuclear charge-exchange reactions can be used to estimate the electron-capture rates which are key quantities in various astrophysical scenarios, such as the final evolution of intermediate-mass stars, core-collapse supernovae (CCSN), cooling of the neutron star crust, and nucleosynthesis in thermonuclear supernovae. Over the past decades, great progress has been made to constrain electron-capture rates on stable nuclei by using reactions in forward kinematics. However, the unstable neutron-rich nuclei that play an important role during, for example, the core-collapse supernovae (N≈50, Z28), remained inaccessible. The use of the $(d, ^2\text{He})$ charge-exchange reaction in inverse kinematics with the Active-Target Time-Projection Chamber and the S800 Spectrograph was developed at NSCL/FRIB, for extracting Gamow-Teller strengths in the β+ direction on unstable nuclei. This makes it possible, for the first time, to constrain electron-capture rates on neutron-rich nuclei. In this talk I will discuss recent results of the pilot $^{14}\text{O}(d, ^2\text{He})$ experiment.

This work is supported by the National Science Foundation under Grants PHY-2209429, "Windows on the Universe: Nuclear Astrophysics at FRIB"

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Study of the tensor force contribution in the N isotopic chain using QFS reactions

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In the shell model framework, the two-body nuclear force can be divided into a central, spin-orbit (SO) and tensor parts. The vast majority of studies performed so far in the chart of nuclides shows that the amplitude of the SO splitting scales with the function presented by G.Mairle [1], from systematics of nuclei studied so far in the valley of stability. Two exceptions to this trend have been found so far for the ^{133}Sn [2,3] and ^{35}Si [4] nuclei. As for the first, deviation to the trend has been attributed to the effect of the continuum, while the second to the effect of the central proton depletion that induces a strong reduction of the SO splitting of orbits probing the interior of the nucleus [5,6]. There is not so far striking evidence of the effect of the tensor force that should induce a change in the SO splittings that depends on its strength.

An experiment has been recently performed using the R³B setup at GSI, within the FAIR Phase-0 program. One of the scientific goals is to study the role of the tensor force when approaching the neutron drip-line. During this experiment a "cocktail" of nuclei, among which ^{22}O was sent on a 5 cm LH2 target surrounded by tracking detectors and the CALIFA calorimeter [7]. This calorimeter allows to detect γ-rays and light particles from the QFS reactions in inverse kinematics. To study the spectroscopy of unbound states with an unprecedented energy resolution, this new setup includes the high resolution and granularity neutron detector NeuLAND [8].

In this work, the ^{22}O($p, 2p$) and ^{21}N(p, pn) QFS knockout reactions provide us information on the tensor force contribution to the $0p_{1/2}$-$0p_{3/2}$ SO splitting in the N isotope chain, from N=8 to N=14 shell closure, when the neutron $0d_{5/2}$ orbital is filled. The first reaction gives access to the $1/2^-$ and $3/2^-$ states in ^{21}N, and the second allows to check that 6 neutrons are indeed populating the $0d_{5/2}$ orbital in ^{21}N.

Preliminary results from this study will be presented.

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Searching for Alpha-Cluster States in ^{126}Te

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Clustering in nuclei provides an alternative description to their nuclear structure in addition to the Nuclear Shell Model. Although alpha-cluster configurations are widely accepted to be essential to the understanding of the structure of light nuclei, such as the Hoyle state in ^{12}C, it was experimentally reported in heavy nuclei only recently in ^{212}Po. The study showed that ^{212}Po had mixed shell and cluster configurations, where the structure of ^{212}Po could be explained by an alpha cluster coupled to the doubly-magic ^{208}Pb core. However, very recently another study of ^{212}Po showed that the enhanced E1 transitions depopulating the claimed cluster states are in fact M1 transitions and thus questioned the existence of the predicted cluster states, which remain to be discovered.

Another recent experiment performed at INFN Legnaro observed an excess cross section for the ^{122}Sn(^{13}C,^{9}Be)^{126}Te reaction. Because the fusion-evaporation cross section for this channel was negligible in PACE4 calculations, the ^{126}Te was likely populated through an alpha-transfer/incomplete-fusion reaction, which suggests alpha-clustering in its structure. In this experiment gamma rays were detected with the GALILEO array which is composed of 25 Compton-suppressed HPGe detectors, while charged particles with particle identification were detected in the EUCLIDES $E - \Delta E$ 4π Si-ball array. Gamma-ray spectroscopy with coincidence techniques, such as particle-particle, particle-gamma, and gamma-gamma, is underway to extract previously unobserved transitions and levels in ^{126}Te from this data set. Preliminary results from the Legnaro data, together with plans for a future experiment, will be presented and discussed.

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Determination of the Neutron Dripline at F and Ne and Discovery of the Heaviest Na Isotope: ^{39}Na

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The location of the neutron dripline is crucial to understand the stability of nucleonic many-body systems with extreme neutron-to-proton ratios.
It provides a benchmark for nuclear theories and mass models, and an important key to understand underlying nuclear structure and interactions.
The neutron dripline has been experimentally determined up to oxygen (atomic number Z = 8) as ^{24}O [1-4] more than 20 year ago, while no experimental confirmation has been reported for $Z \geq$ 9.

We have searched for the neutron driplines, the heaviest new isotopes, of fluorine (Z = 9), neon (10), and sodium (11) by the BigRIPS separator at the RIKEN RI Beam Factory.
The neutron-rich isotopes were produced by projectile fragmentation of a 345-MeV/u 450~500-pnA ^{48}Ca^{20+} beam impinging on a 20-mm-thick Be target.
No events were observed for ^{32,33}F, ^{35,36}Ne, and ^{38}Na [5].
Comparison with predicted yields excludes the existence of bound states of these unobserved isotopes with high confidence levels, which indicates that ^{31}F and ^{34}Ne are the heaviest bound isotopes of fluorine and neon, respectively.
We have confirmed the fluorine and neon neutron driplines for the first time.
We have observed the new isotope of ^{39}Na, which is the most neutron-rich isotope with N = 28 neutron magic number [6].

The locations of the neutron dripline from oxygen to neon isotopes and the bound nature of ^{39}Na could be explained by evolution of nuclear deformation.
By the recent large-scale shell-model calculation with $ab\ initio$ effective NN interaction [7], the oxygen dripline is determined by a new magic number of N = 16, emerging by tensor force and repulsive 3 nucleon forces.
From Z = 9 to 12, quadrupole deformation leads to a larger binding energy for neutrons and affects the location of the driplines.
The discovery of ^{39}Na suggests that its ground state is deformed and the magicity of N = 28 is lost.

In this talk, the experimental results will be presented to discuss the location of the neutron driplines as well as the underlying nuclear structure.

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Alpha-clustering in atomic nuclei from first principles

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Owing to recent computational and methodological advances, ab-initio approaches in low-energy nuclear theory have been developed rapidly in recent years. As one of such approaches, the no-core Monte Carlo shell model (MCSM) is briefly introduced in this presentation. After verifying the capability of the no-core MCSM on actual computations, the alpha-cluster structure of light nuclei is discussed from an ab-initio point of view, especially focusing on the appearance of molecular-orbital structure of valence neutrons in Be isotopes and the intrinsic shapes of the C-12 nucleus.

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Towards implantation of pure Fe-55 for radioactivity standardization by low temperature devices

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Radionuclide activity metrology techniques currently used for activity standardization show a huge variety of measurement uncertainty - from permille accuracy, e.g. for the α-decaying Am-241 ($T_{1/2}$ = 432 a) up to several percent for Fe-55 ($T_{1/2}$ = 2.73 a) which decays by electron capture. To reduce such uncertainties, a new standardization technique using direct implantation of a radionuclide on low-temperature calorimeters is being developed within the EU project PrimA-LTD. The results will have impact on theoretical models on the decay spectra and in this way contribute to the nuclear power industry, nuclear medicine and radiopharmacy.

The implantation of 5 Bq of Fe-55 into the absorbers of microcalorimetric detectors will be performed at the RISIKO mass separator at Mainz University via resonance ionization mass spectrometry. This technique is used due its outstanding elemental selectivity and overall implantation efficiency. A new 2-step ionization scheme is being developed, where the first excitation step to 39.625 cm^{-1} demands third-harmonic generation and the second step at around 24.112 cm^{-1} implies second-harmonic-generation of the pulsed Ti:Sa laser radiation used at RISIKO. The optical excitation scheme was characterized by spectroscopy studies in the atomic spectrum below and above the ionization potential. Strong auto-ionizing states were localized, which will be used for implantation, while the measurement of Rydberg states is carried out to verify the ionization potential and extend the data on even parity Rydberg states in Fe adding to results of Page and Gudeman [1]. The identification of the ionization scheme and the spectroscopy is performed on the stable Fe-56.

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Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes

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Astrophysical simulations predict that ^{22}Na is produced in novae explosions. With its half-life of 2.6 years and its characteristic γ-ray of 1.275 MeV, it could be easily identified and measured with γ-ray space telescopes, which has not been the case yet. The amount of ^{22}Na produced in novae depends on the rate of nuclear reactions, and in particular on the ^{22}Na$(p,\gamma)^{23}$Mg reaction rate. It has been shown that the amount of ^{22}Na ejected from novae is directly proportional to the lifetime of the excited state at Ex=7.785 MeV in ^{23}Mg.

We have measured this lifetime in an experiment at GANIL-France, associating the VAMOS++ magnetic spectrometer, the AGATA γ-ray tracking spectrometer and a silicon detector. The analysis of angle-integrated velocity-difference profiles allowed us to obtain a femtosecond sensitivity.

The obtained result places strong limits on the amount of ^{22}Na produced in novae, explains its non-observation to date in γ rays (flux $<$~2.5$\times$10^{-4}~ph.cm^{-2}s^{-1}), and constrains its detectability with future space-borne observatories.

Ref: https://arxiv.org/abs/2212.06302

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Visualization of nuclear many-body correlations in microscopic wave functions

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In general, the quantum many-body wave function obtained by theoretical calculation contains an enormous amount of information about many-body correlations. However, theoretical analyses in nuclear physics are mainly performed for quantities such as one- and two-body densities, which are obtained after integrating out most of the information in a many-body wave function.
On the other hand, in the field of quantum chemistry, methods have been developed to visualize the information on the correlations among all the electrons and applied to the structure studies of molecular systems [1]. We are attempting to apply such a method to nuclear systems. As the first step, we start with finding the most probable arrangement of nucleon coordinates, i.e, the set of position and spin coordinates that maximizes the square of the many-body wave function.
In this presentation, we apply this method to Hartree-Fock and Hartree-Fock+BCS wave functions of p-shell and sd-shell nuclei [2]. We find some alpha-cluster-like correlations out of the wave functions obtained without any assumption of cluster structure. Effects of pairing correlation on the cluster structure are discussed by comparing the results between HF and HF+BCS. We also investigate the relationship between deformation and the cluster structure with constrained HF+BCS wave functions. We believe that this study gives a new viewpoint to the microscopic nuclear wave function.

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Discovery of isotopes and first time broadband measurements of neutron-deficient light lanthanides via high precision mass spectrometry

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Approaching the limits of nuclear binding, the structure and properties of drip-line nuclei is of great interest and draws a lot of attention from both, experiment and theory. The nuclear properties in the light lanthanide region are shaped by the interplay between large beta-decay Q-values, low or negative proton separation energies, and the confining effects of the Coulomb barrier. From precise mass values, differential quantities, such as the proton and neutron separation energies, can be determined, and different phenomena, including a variety of beta-delayed particle emission channels, proton radioactivity, and two-proton radioactivity as well as exotic pairing phenomena, can be addressed.

Nuclei in the region of between ^{100}Sn and ^{150}Lu were produced at relativistic energies and separated in-flight with the fragment separator FRS at GSI as part of the FAIR Phase-0 experiments. They were identified by their proton number and mass-to-charge ratio in the FRS, before being slowed down, thermalized in the Cryogenic Stopping Cell (CSC) of the FRS Ion Catcher and transported to a Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) for high-resolution mass measurements. In order to calibrate and verify the particle identification at the FRS, a novel method, tagging by high resolution mass spectrometry using the MR-TOF-MS of the FRS Ion Catcher, was successfully applied.

In the experiment, new isotopes towards the proton drip-line, in the region between Nd and Tb, could be identified by the FRS particle identification. For the mass measurements a new technical approach was applied, the so called mean range bunching. The combination of achromatic ion optics of the FRS with a new variable wedge-shaped degrader system at the final focal plane allows to "correct" the range-position dependence, which enables efficient stopping of many nuclides in the CSC simultaneously. This novel technical approach was proven by the simultaneous measurement of more than 35 nuclides in a single setting. It opens up the possibility to cover large regions on the chart of the nuclides in a single measurement with stopped or thermalized nuclides, aside from mass measurements also for decay and laser spectroscopy. The masses of more than 10 nuclides were measured for the first time, and the mass uncertainties of more than 10 nuclides were significantly reduced. These results give an insight into the nuclear structure and for the first time allow tracking of the proton drip line between ^{100}Sn and ^{150}Lu. In this contribution, these recent results and the new technical approaches will be reported.

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Measurements with the FRS Ion Catcher in the region below ^{100}Sn and on the ^{252}Cf spontaneous fission fragments

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Masses of exotic nuclei provide key information for the understanding of nuclear structure and astrophysics. At GSI, exotic nuclei have been produced at relativistic velocities by projectile fragmentation or fission at the entrance of the fragment separator FRS, separated in-flight, identified,

and transported to the FRS Ion Catcher [1,2], where they were slowed down and thermalized in a Cryogenic Stopping Cell (CSC). Subsequently, their masses were measured by using a Multiple-Reflection Time-Of-Flight Mass-Spectrometer (MR-TOF-MS). Masses of nuclides with production cross sections down to a few nb and rates down to two counts per hour have been measured with the FRS Ion Catcher. The MR-TOF-MS features mass resolving powers of up to one million and relative mass measurement accuracies of down to 2×10^{-8} with measurement times of merely a few tens of milliseconds [3]. Moreover, the broadband and non-scanning properties make it an effective tool for mapping large-scale mass surfaces and searching for long-lived isomeric states.
Direct mass measurements of neutron-deficient nuclides around the N = 50 shell closure below ^{100}Sn, including the first direct mass measurements of ^{98}Cd and ^{97}Rh [5] and the discovery of new isomeric states in ^{97}Ag [4], shed light on the nuclear structure in this region and on the "^{100}Sn mass riddle" [6]. The Gamow-Teller strength $B(\mathrm{GT})$ values obtained with the new Q_{EC} values can be well understood by the large-scale shell model (LSSM) calculations. Contradictory results on ^{100}Sn investigated by the shifted empirical two-neutron shell gap and by the $B(\mathrm{GT})$ call for further experiments. Additionally, mass measurements of neutron-rich nuclei from a ^{252}Cf spontaneous fission source reveal evidence for shape transitions in the $N \sim 90$, Z = 56-63 region, and provide direct determination of independent isotopic fission yields [7]. These recent results and technical advances, as well as further measurements performed in the vicinity of the $N = Z$ line, which are currently under analysis, will be reported in this contribution.

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Nuclear structure of Pd isotopes via optical spectroscopy

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High-resolution laser spectroscopy has been proven to be a powerful tool to extract nuclear structure data in an nuclear-model-independent manner. The isotope shift which can be extracted from the hyperfine spectra gives direct access to changes in mean-square charge radii, while the extracted hyperfine parameters give access to the nuclear spin, nuclear magnetic dipole moment and electric quadrupole moment. All this provides information on e.g. deformation and shape coexistence, proton-neutron pairing correlations, evolution of nuclear shells and the presence of shell closures. In recent years, measurements of nuclear ground state properties have also been proven exceptionally potent in testing state-of-the-art nuclear Density Functional Theory (DFT) and ab-initio approaches.

The Pd isotopes are located in a transitional area in between chains which display smooth parabolic trends in the changes in mean-square charge radii (Sn, In, Cd and Ag), and a region where the changes in mean-square charge radii and corresponding electric quadrupole moments show evidence of a dramatic shape change at N=60, maximized and centred around the yttrium system. In the transitional area between both regions however, i.e. the Tc, Ru, Rh and Pd isotopes, no optical spectroscopic information has been available for radioactive nuclei so far. This is in part due to the refractory character of these nuclei, which makes their production challenging for many facilities, but also due to their complex atomic structure.

At the IGISOL facility, these difficulties were overcome thanks to the chemically insensitive production method, and the installation of a charge-exchange cell and addition of a cw Ti:sapphire laser. Collinear laser spectroscopy was performed on unstable Pd isotopes, which are known to be deformed from decay spectroscopy studies, although there is disagreement on the origin and character of the (possible) change in deformation. The measured nuclear charge radii [1], spins and nuclear moments [2] will be presented in this contribution, and the implication on the deformation/shape of the isotopes will be discussed. In addition, the results will be compared to state-of-the-art DFT calculations using Fayans Energy Density Functionals (EDFs), and using Gogny EDF including beyond mean-field calculations within the Symmetry Conserving Configuration Mixing (SCCM) framework. As all recent benchmarks of nuclear DFT were performed on spherical systems, close to (doubly-)magic systems, this presents the first test of the performance of the Fayans functionals for well-deformed isotopes.

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Determination of fission barrier height of 210Fr via neutron measurement

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Fission of 210Fr, produced by (d,p)-transfer reaction of the 209Fr beam was investigated at HIE-ISOLDE. Four Timepix3 pixel detectors were installed on the body of Actar TPC demonstrator chamber. Polyethylene converters were used for the detection of fast neutrons. Since no significant background was observed, it was possible to measure the spatial distribution of emitted neutrons. Subsequent simulations employing the results of Talys code and available data on fission fragment distributions allowed to estimate directly the value of fission barrier height for neutron-deficient nucleus 210Fr, which confirmed the reduction of the fission barrier compared to theoretical models by 15 - 30 % for such extremely neutron-deficient unstable nuclei.

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Search for near-threshold multi-neutron resonances in (p,2p) reactions with neutron-rich nuclei at R3B

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In order to constrain the largely unknown multi-neutron interactions, it is necessary to measure the relevant observables sensitive to them. One such property is the possible existence of narrow resonances related to multi-neutron cluster structures and correlations[1][2]. This can be investigated by studying multi-neutron resonances close to the corresponding neutron removal thresholds in neutron-rich light nuclei. Progress over the recent years have presented several evidences of such narrow resonances[3][4][5], which provides an indication for the generalization of the Ikeda conjecture.

With the aim of systematically studying and characterizing such resonances, an experiment has been recently concluded at the R^3B setup in GSI, within the FAIR Phase-0 program. Quasi-free scattering $(p, 2p)$ reactions are studied in inverse kinematics where a radioactive ion "cocktail" beam is impinged on a 5cm LH_2 target. The resulting reaction products are measured in the state-of-the-art setup using a large combination of detector systems providing information of the full reaction kinematics. This includes in addition to detection of fragments, the detection of the γ-rays and protons in the CALIFA[6] calorimeter. Relevant to the current work, is the neutron detector NeuLAND[7], which thanks to its high resolution and granularity provides access to the detailed study of multi-neutron resonances.

Among the nuclei populated in this cocktail beam, of specific interest is the case of ^{17}B populated via $^{18}C(p, 2p)^{17}B$ QFS reaction. This is thanks to its lower 1 neutron ($S_{1n} = 1.41$ MeV), 2 neutron ($S_{2n} = 1.33$ MeV) and 4 neutron ($S_{4n} = 5.1$ MeV) separation energies and an indication of a possible near threshold state[8]. In this communication some of the preliminary results of the analysis will be discussed.

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Spectroscopy of ^{12}Be using TexAT TPC

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The detailed spectroscopic data that can be extracted from single nucleon transfer reactions provide a useful experimental probe of nuclear structure. This work aims to complement existing data for the ^{12}Be system by measuring the proton removal spectroscopic factors to low-lying states in ^{12}Be with the ^{13}B(d,^{3}He)^{12}Be reaction in inverse kinematics. This experiment was done at the Texas A&M University Cyclotron Institute (TAMU-CI) where a ^{13}B beam was delivered to the TEXas Active Target (TexAT) Time Projection Chamber (TPC) filled with CD_4 gas. By reconstructing reaction vertices and tracks in TexAT, differential cross sections and thus spectroscopic data can be extracted. Experimental details and preliminary results will be discussed.

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Highlights of GANIL-SPIRAL2 facilities

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The SPIRAL2 Phase 1 LINAC moved from project status to full operation on December 31st 2021, after the important milestone of acceleration of 45 ⌧A deuton beam at 40 MeV. Beams of protons and alpha particles were also accelerated. These beams were sent to the Neutron For Science (NFS) experimental cave. Two NFS campaigns have been performed with neutron beams in Fall 2021 and 2022. The S3 spectrometer installation is progressing well and the commissioning should start at the end of 2024. The first heavy ion beams were already accelerated by the LINAC with the dedicated ion source, to prepare for the S3 physics program. The presentation will give an overview on these different achievements together with an update of the DESIR project status. The new project NEWGAIN will also be presented. It will increase the capabilities of SPIRAL2 LINAC with the construction of a second injector able to produce and accelerate ion beams with mass to charge-state ratios ranging from A/q=3 up to A/q=7. This second injector will be designed to be fully compatible with the existing facility and to further enhance its 'multi-user' capabilities.

In parallel to SPIRAL2 developments, a refurbishing program of the GANIL cyclotrons is being planned. New beams are under development with SPIRAL1 target-ion sources. Selected results will be presented, together with the vision for the medium and long term plans.

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Axial Shape Asymmetry and Configuration Coexistence in Neutron-Rich 74Zn

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Results from recent experiments studying nuclei in the ^{78}Ni region suggest that the $N = 50$ shell closure persists, in agreement with state-of-the-art shell model calculations. However, how collectivity manifests and evolves in this region of the Segrè chart is still an open question, particularly concerning phenomena such as vibrational modes, triaxiality and shape coexistence. This is especially true in the Zn isotopic chain in the neutron-rich region, in which even definitive spin assignments are unavailable except for the very low-lying states.

In this talk, I will present the results of a recent experiment performed at the TRIUMF laboratory (Vancouver, Canada) using the GRIFFIN γ-ray spectrometer. The excited states of ^{74}Zn were investigated via γ-ray spectroscopy following ^{74}Cu β-decay. By exploiting γ-γ angular correlation analysis, the 2_2^+, 3_1^+, 0_2^+ and 2_3^+ states in ^{74}Zn were firmly identified. The γ-ray branching and $E2/M1$ mixing ratios for transitions de-exciting the 2_2^+, 3_1^+ and 2_3^+ states were measured, allowing for the extraction of relative $B(E2)$ values. In particular, the $2_3^+ \rightarrow 0_2^+$ and $2_3^+ \rightarrow 4_1^+$ transitions were observed for the first time. The levels observed were organized into rotational-like bands and the results were compared with large-scale shell-model calculations from which the shapes of individual states were determined. Enhanced axial shape asymmetry (triaxiality) is suggested to characterize ^{74}Zn in its ground state. Furthermore, an excited $K = 0$ band with a different shape is identified. A shore of the $N = 40$ island of inversion appears to manifest above $Z = 28$, previously thought as its northern limit in the nuclide chart.

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Study of 70,72Se nuclear shapes with SPICE and TIGRESS

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The phenomenon of shape coexistence is prevalent in the Z~34 region, with isotopes of neutron-deficient even Ge , Se and Kr each exhibiting the characteristic low-lying coexisting 0^+ bands which display quadrupole deformation different to that of the ground states. In the selenium isotopes, $^{72-78}$Se seem to show a prolate ground structure with shape coexisting oblate excitation, while in ^{68}Se the oblate structure appears to have become the ground state. The exact nature of the low-lying structure ^{70}Se and any shape coexistence remains uncertain.

Combining the Spectrometer for Internal Conversion Electrons (SPICE) with the TIGRESS HPGe Array, a full electron and gamma-ray experimental study of ^{70,72}Se was undertaken at the TRIUMF ISAC-II facility to unveil the low-lying structure of these nuclei. Details of the device and experiment will be presented, alongside the experimental results and possible structural interpretations for both isotopes.

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β-decay spectroscopy of 28S

Auteurs: Xinxing Xu[1]; Yufeng GAO[2]

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As a member of the $T_z = -2$ family, ^{28}S is a nucleus rather light near the proton drip line, and has high β-delayed proton (βp) branching ratio. Precise β-decay spectroscopy of proton-rich nucleus ^{28}S serves as a powerful tool to study the isospin symmetry breaking [1], and to test the unitarity of CKM matrix through the superallowed Fermi transition between isobaric analog states [2, 3]. Nevertheless, only one experimental study was previously published by Pougheon et al. without detecting

γ rays in 1989 [4]. The present work was conducted at the Heavy Ion Research Facility in Lanzhou (HIRFL) in Lanzhou. The interested nucleus ^{28}S was produced through projectile fragmentation (PF) method where $^{32}S^{16+}$ beam (about 80 MeV/u) bombarded ^{9}Be target, and subsequently implanted into a detector system [5] composed of double-sided silicon strip detectors (DSSD), quadrant silicon detectors (QSD), and clover-type high-purity germanium detectors. Based on this detector system, our team has achieved excellent results for ^{22}Si [6], ^{26}P [7, 8], and ^{27}S [9] in recent years.
By measuring p and γ following β decay, the half-life and energy with higher accuracy were obtained. Different decay channels were clearly identified through the coincidence method to construct complete decay scheme, and the results were consistent with shell model calculations. The mirror nuclei ^{28}S-^{28}Mg [10] was also studied, which gave no evidence for existence of isospin symmetry breaking. Moreover, the correction terms proposed in [3] are to be given to deduce V$_{ud}$ (the element describing the trend of flavor change between up and down quark of CKM matrix) with theoretical calculations.

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The ISOLDE RILIS at 30

Auteur: Katerina Chrysalidis[1]

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The Resonance Ionization Laser Ion Source (RILIS) has been the principal ion source at ISOLDE for the majority of the past three decades. Unmatched selectivity, coupled to high efficiency, has been the main reason for RILIS being requested in more than half of the proposals submitted for review to the ISOLDE scientific committee (INTC). What started as a home-made system of 3 tunable dye lasers pumped by a single Copper vapor laser system with a Master oscillator/ Power amplifier configuration has now become a suite of state-of-the-art collection of >13 lasers: Ti:Sapphire and commercial dye lasers pumped by industrial solid state lasers. Over 35 chemical elements have been ionised within a variety of specially-designed laser ion source configurations and simultaneous operation at both ISOLDE front-ends is possible.
I will talk about the changes made over the past years to get to the modern RILIS system we use today and deliver a performance review. In addition I will give a summary of ongoing developments and how they might improve RILIS efficiency, applicability and selectivity further. I will conclude by presenting the work towards making RILIS a viable option for high-resolution laser spectroscopy, future-proofing the highly sensitive in-source laser spectroscopy method at ISOLDE.

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Measurement of reaction cross section for ^{17}F with a solid hydrogen target

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Measurement of reaction cross section ($\sigma_{\rm R}$) is an effective method for investigations of nuclear size properties such as radii and density distributions. In particular, $\sigma_{\rm R}$ on a proton target has the possibility to extract the proton and neutron density distributions separately because of the asymmetry of the nucleon–nucleon total cross sections. However, only a few experimental $\sigma_{\rm R}$ for unstable nuclei on a proton target are reported at this time. It is important to understand collisions between unstable nuclei and a proton from both experimental and theoretical sides. In this study, we measured $\sigma_{\rm R}$ for ^{17}F, which is the proton drip-line nucleus of fluorine isotopes, with a solid hydrogen target (SHT) in a wide energy range. So far, the existence of the proton skin in the ground state of ^{17}F has been discussed because of the small one-proton separation energy ($S_{\rm p}$=0.6 MeV), but the skin thickness of ^{17}F is not reported yet experimentally. Experiment has been performed in the Heavy Ion Medical Accelerator in Chiba (HIMAC). Our SHT was developed for $\sigma_{\rm R}$ measurements, and its effective area and maximum thickness are ϕ50 mm and 100 mm, respectively. From the present experiment, we found that $\sigma_{\rm R}$'s for ^{17}F on a proton target are almost the same as those of ^{17}Ne, which is known to be a two-proton halo nucleus. These experimental results are very interesting because, in the case of proton-rich nuclei, the decrease of $\sigma_{\rm R}$ on a proton target was reported theoretically despite the increase of the root-mean-square matter radius towards the proton dripline. In this presentation, we will explain the details of the experiment, and discuss the energy dependence of $\sigma_{\rm R}$ for ^{17}F on a proton target with the Glauber model calculation.

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Extracting β-decay strengths from 73Co using the Summing NaI (SuN) Total Absorption Spectrometer

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Knowledge of the β-decay properties of neutron-rich isotopes far from stability is critical for improving stellar nucleosynthesis and β-decay models, as well as structural information. Calculations of the abundance of elements produced via the rapid neutron capture process (r- process) require information such as β-decay rates and β-delayed neutron emission probabilities. β-feeding intensities are used to calculate β-decay strengths, which can be compared to theoretical Gamow-Teller strength (B(GT)) values to rigorously test and validate models of β- decay far beyond stability. One method used to obtain β-feeding intensities is Total Absorption Spectroscopy (TAS), which requires the use of a dedicated detector such as the Summing NaI (SuN) detector [1] based at FRIB/MSU. In this presentation, the TAS analysis of 73Co will be presented. Ions of 73Co were implanted into a DSSD whereby the subsequent β-decay electrons were detected in conjunction with the β-delayed ⊠-rays detected in SuN. β-feeding intensities are determined from a chi2 analysis between the experimental data from SuN and simulated data using a combination of the RAINIER and Geant4 software packages. This information will be compared with theory as well as the results of neighboring isotopes that have been previously studied using the same experimental setup for systematic comparison of β-decay properties across the Z = 28 shell closure [2-3].

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Study of the Pygmy Dipole Resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS

Auteur: Marine Vandebrouck[1]

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The pygmy dipole resonance (PDR) is a vibrational mode described as the oscillation of a neutron skin against a core symmetric in number of protons and neutrons. The PDR has been the subject of many studies, both experimental and theoretical [1,2]. Indeed, the study of the PDR has been and still is of great interest since it allows to constrain the symmetry energy, an important ingredient of the equation of state of nuclear matter that describes the matter within neutron stars [3]. Moreover, the PDR is predicted to play a key role in the r-process via the increase of the neutron capture rate [4]. However, despite numerous experiments dedicated to the study of the PDR, a consistent description could not be extracted. In this context, we propose to study the PDR using a new probe: the neutron inelastic scattering reaction (n,n'g).

An experiment to study the pygmy resonance in 140Ce using the (n,n'g) reaction has just been carried out. This experiment has been made possible thanks to the high-intensity proton beam of the new accelerator SPIRAL2 at GANIL and the NFS (Neutron For Science) facility. The experimental setup consisting of the new generation multi-detectors PARIS [5], for the detection of gammas coming from the de-excitation of the PDR, and MONSTER [6], for the detection of scattered neutrons, was used.

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What are the fingerprints of nucleosynthesis?

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Disentangling the different components and astrophysical sites of various nucleosynthesis processes is challenging for many reasons. Observations of metal-poor stars currently provide some of the cleanest signatures of the rapid neutron-capture process (r-process) but are sparse. Isotopic analyses of presolar grains originating from Asymptotic Giant Branch (AGB) stars give strong insight into the slow neutron-capture process (s-process) but rely on assumptions that the grains are unaltered between formation and laboratory analysis. To correctly interpret such observations, the nuclear physics in nucleosynthesis models need to be accurate and of high enough precision. Currently the characteristic fingerprints of different processes only loosely constrain the astrophysical conditions under which the elements form. In the recent past, significant advancements in constraining the nuclear physics uncertainties, together with increased availability of 'ground-truth' data have improved our understanding of how the elements are made in the cosmos.

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Harvesting Hf-172 from heavy-ion beam irradiated tungsten beam-blocker for generating Lu-172

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During the routine operation of radioactive heavy-ion beam facilities, tremendous quantities of radioisotopes get deposited or produced at multiple sites throughout the accelerator parts and beamline components. This presents an opportunity to harvest the long-lived radioisotopes that have wide ranging applications once these components and parts are decommissioned and often, considerable activities will have built up by then. One such decommissioned component from the National Superconducting Cyclotron Laboratory (NSCL) was the tungsten beam-blocker that acted as the beam-dump for the primary heavy-ion beams while NSCL was in operation. This work elucidates the radioanalytical separation techniques and methodologies used in the extraction and purification of Hf-172 from the tungsten beam-blocker and the other co-embedded radionuclides such as Lu-173, Lu-172, Na-22, Co-56, Co-57, Co-58, Co-60 amongst others. The harvested Hf-172 was used for generating Lu-172 employing the use of an extraction chromatographic resin and radiolabeling studies were carried out with the generated Lu-172.

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Strongly isospin-mixed doublet in 26Si observed by β decay of 26P

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In 1932, W. Heisenberg proposed the concept of isospin to interpret the symmetry in atomic nuclei based on nearly identical properties between protons and neutrons with respect to strong interaction [1]. However, due to proton-neutron mass difference, Coulomb interaction, and charge-dependent parts of nuclear force, isospin is not strictly symmetric. Such asymmetry leads to Fermi strength fragmented between the isobaric analog state (IAS) and its neighboring states via strong isospin mixing, instead of being contributed into only one state. Probing isospin mixing has gained considerable traction in β-decay studies.
We have performed the β-decay experiment of 26P [2] at the Heavy Ion Research Facility in Lanzhou (HIRFL), using double-sided silicon strip detectors operating in conjunction with high-purity germanium detectors [2,3,4,5]. The IAS at 13055 keV and two new high-lying states at 13380 and 11912 keV in 26Si were determined via β-delayed two-proton emission of 26P. The abnormal log ft values of IAS and 13380-keV state indicate a strong isospin mixing between these two states. The isospin mixing matrix element is determined to be 130(21) keV, representing the strongest mixing ever observed in β-decay experiments [6].

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The NEXT setup to study Neutron-rich EXotic nuclei produced in multinucleon Transfer reactions

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Neutron-rich, heavy, EXotic nuclei around the neutron shell closure at N=126 and in the transfermium region are accessible via multinucleon Transfer reactions which feature relatively high cross sections. However, the wide angular distributions of the multinucleon transfer products lead to experimental challenges in their separation and identification.
In order to overcome these obstacles, we are building the NEXT experiment [1] at the PARTREC facility in Groningen. The AGOR cyclotron at PARTREC delivers high intense heavy ion beams at energies suited for transfer reactions. The production target for the transfer reactions is placed inside a 3-T solenoid magnet with The bore of 157-cm length and 86-cm width. Within this volume the transfer products are separated according to their magnetic rigidities. The ions of interest are focused by the magnet towards a gas catcher where they are slowed down. From the gas catcher

the ions are transferred and bunched by a newly developed stacked-ring ion guide [2] into a Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [3]. The MR-ToF MS allows for precision mass measurements and provides isobaric separation. Thus, background free spectroscopy will be feasible.
In the contribution, we will present an overview of the NEXT setup, its current status and the planned experimental program.

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Hyperfine structure and isotope shift in the atomic spectrum of neptunium

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Neptunium, with atomic number 93, is a radioactive actinide and the first transuranic element. In particular, the isotope ^{237}Np is generated quantitatively within the nuclear fuel cycle with typical amounts of ∼10 kg in each conventional pressurized water reactor per year [1]. Due to its long half-live of $2.1 \cdot 10^6$ years and high radiotoxicity in the up to 12 subsequent decays along the neptunium series, it represents a major hazard in the final disposal of nuclear waste. Under environmental conditions, Np can be present in four different oxidation states +III to +VI, and can form soluble species. In this context ultra-trace analysis of Np in environmental samples is of high relevance [2]. The development of efficient and selective non-radiometric determination methods using laser mass spectrometry relies on the identification of ionization schemes and detailed atomic spectroscopy [3]. For example, for quantitative isotope ratio determination by resonance ionization mass spectroscopy (RIMS), it is important to take into account the isotope-related effects stemming from hyperfine structures (HFS) and isotope shift (IS). For this purpose, new two-step excitation schemes were investigated for their suitability for neptunium analytics.
Narrow bandwidth spectroscopy on ^{237}Np and ^{239}Np was carried out at the high transmission mass separator RISIKO using the PI-LIST laser ion source geometry [4]. Optical transitions were studied using a cw Ti:sapphire laser system [5] for seeding and injection locking of a pulsed Ti:sapphire amplifier [6]. The injection-seeded Ti:sapphire laser has a spectral bandwidth of 20 MHz, providing pulsed operation at a repetition rate of 10 kHz and high-power density as required with 150 mW average power after frequency doubling.
The HFS of the atomic ground-state transitions to the levels at 25 075.15 cm^{-1} (J = 13/2) and at 25 277.63 cm^{-1} (J = 9/2) have been measured and hyperfine coupling constants for both isotopes, as well as the isotope, shifts between ^{237}Np and ^{239}Np have been determined. Additionally, the HFS of the atomic transition between the atomic ground state, as well as the thermally excited state at 2 033.94 cm^{-1} and the level at 25 342.55 cm^{-1} (J=11/2), has been measured for ^{237}Np. Experiment and data are discussed in the framework of the analysis of the atomic structure of the lighter actinide elements.

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Development of a Thick Solid Deuterium Target

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Deducing the neutron skin thicknesses of atomic nuclei is important for studies of the equation of state of neutron matter.
A recent theoretical work suggested that the measurements of the reaction cross sections (σ_R's) with proton and deuteron targets can be used for determining the skin thickness accurately [1]. In this study, we developed a thick solid deuterium target (SDT) based on a thick solid hydrogen target (SHT) for σ_R measurements [2]. The utilization of a thicker target in RI beam experiments provides a statistical advantage, and the employment of solidified deuterium further enhances the statistics due to its higher density.
The SDT fabrication system is almost same as the SHT one [2]. In order to make thick SDT, it was necessary to optimize two key fabrication conditions. Initially, we systematically varied the temperature of the target cell to determine the optimum. Once the optimal temperature was established, the gas supply pressure was altered to further fine optimization. Through these optimizations, we succeeded in fabricating SDT with a diameter of 50 mm and a thickness of 50 mm with few voids without cracks. Subsequently, we performed an irradiation test of SDT using a ^{18}O beam with an energy of 250 MeV/nucleon at the Heavy Ion Medical Accelerator in Chiba to investigate the uniformity of solidification. From this test, it was found that there were no significant density defects inside SDT.
In this presentation, I will describe in detail on the SDT fabrication system and the irradiation test.

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Developments in muonic x-ray spectroscopy

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Muonic x-ray spectroscopy is a technique that utilizes the properties of the muon to obtain information about the structure of the atom and the nucleus. When a muon interacts with an atom, it can be captured in a high principal atomic quantum number state, after which it will fall towards the ground state emitting high energy characteristic x rays. Due to the heavy mass of muons compared to that of electrons ($m_\mu \approx 207 m_e$, the muon's orbitals are closer to the nucleus with that same factor. Hence, the muonic energy levels are more sensitive to nuclear effects. In particular, the finite size correction is increased by a factor close to 10^7. Consequently, muonic x rays can provide valuable input for laser spectroscopy in the form of high-precision absolute charge radii (10^{-3} relative precision).

While muonic x rays have been extensively studied at the end of the twentieth century, it was limited to target quantities above 10 mg. However, in 2017, our collaboration investigated the use of a high-pressure hydrogen cell with a small deuterium admixture in order to enhance the transfer of the muon to the target atom of interest [1]. With this advancement, measurements on targets of ~5 µg became possible, opening the door to long-lived radioactive isotopes (>20 years) [2]. At low-to-medium atomic numbers, a high isotopic purity is required in order to reliably extract the nuclear charge radius. This purity can only be obtained by using magnetic mass separation for certain isotopes. Therefore, we investigated the feasibility of using implanted targets during a beamtime in September 2022. Besides measurements on implanted targets, the attenuation of the muonic x-ray signal through graphite was quantified. These advancements will allow for absolute charge radii measurements of medium-Z elements that are not available in sufficiently large quantities and/or isotopic purity.

In this contribution, we will report on the recent advancements of the muX collaboration as well as their implications for future research.

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Cluster structure of neutron-rich beryllium isotopes probed by cluster knockout reactions in inverse kinematics

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The emergence of cluster structures within the nucleus is a fascinating phenomenon that requires a complete understanding of the nuclear structure and the fundamental nuclear interactions. So far α-clustering has dominated cluster state studies among all other possible partitioning due to the large binding energy of the α-particle and its inert character. The famous Ikeda diagram conveyed the idea that cluster states appear near α threshold in stable N=Z nuclei [1]. However, clustering in the ground-state of exotic nuclei with large imbalance of proton and neutron number is still a question. Neutron-rich beryllium isotopes 10Be,12Be,14Be are the very appealing candidates of clustering studies as being built on the well-developed alpha-alpha rotor of 8Be (N=4, Z=4). It is predicted by calculations in antisymmetrized molecular dynamics model that alpha clustering in the ground-state develops from 10Be going to the dripline [2].

The SAMURAI-12 experiment performed at the Radioactive Isotope Beam Factory (RIBF) in RIKEN aims to investigate the cluster structure of neutron-rich beryllium isotopes using the cluster quasifree scattering reaction (p,pα) in inverse kinematics. The reaction of interest was induced by radioactive 10,12,14Be beams at 150MeV/u impinging on a 2-mm-thick pure solid hydrogen target. Recoil protons were detected using the Recoil Proton Spectrometer (drift chamber, plastic scintillator, and NaI(Tl) rods) in a two-arm configuration, covering an angular range of 50°-70°. Two telescopes composed of silicon strip detectors and CsI(Tl) modules were placed at forward angles for detecting alpha clusters. The detection of helium residues was performed by using the SAMURAI spectrometer and its standard detectors. Experimental results concerning missing mass spectra and triple differential cross-sections will be presented. The latter will be compared to calculations using a microscopic description of the reactions of interest implemented in the distorted wave impulse approximation, allowing to probe the alpha cluster structures directly and quantitatively.

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Spectroscopy of heavy neutron-rich N > 126 nuclei at RIKEN

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The experimental information available to test shell-model calculations south of 208Pb is almost non-existent at present due to the challenges in accessing the exotic neutron-rich region around and beyond N=126. Such information are essential not only for understanding how the shell structure evolves below and beyond N=126, and if deformation or new shell gaps develop in the region, but to calculate more complex configurations in the more exotic, inaccessible nuclei on the r-process pathway towards the trans-bismuth fissile elements [Hol19].

In the present contribution, we will show for the first time new isomeric transitions observed in the "south-east" quadrant of 208Pb in an experiment carried out during the 2021 spring campaign of the BRIKEN collaboration at the RIBF factory in RIKEN (Japan) [Wu17,Tol19]. The level schemes will be discussed in terms of the latest shell-model calculations in the region [Yuan22]. Future perspectives to continue with the investigation of isomerism around and beyond 208Pb exploiting the BigRIPS spectrometer at RIKEN will be discussed as well.

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Towards in-gas-jet studies of isomeric 229Th+

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Short half-lives, low production rates and the need to produce them by fusion-evaporation reactions all complicate laser spectroscopy studies of (trans)actinides. The In-Gas Laser Ionization and Spectroscopy (IGLIS) technique has been succesfully employed in studies on short-lived actinides (see for instance [1,2]). The addition of a convergent-divergent (de Laval) nozzle to create a cold hypersonic gas jet combines efficiency with sub-GHz spectral resolution. The new generation of nozzles with a Mach number of 8 enables laser spectroscopy studies of actinides with spectral resolutions around 200 MHz [3].

The light actinide ^{229}Th and its nuclear clock isomer have attracted significant attention in the last years. A remarkable feature is the suggested short half-life (< 10 ms) of the isomer in its, not-yet observed, singly charged state [4]. We report on the design of a fast-extraction gas cell (evacuation time of ~ 1 ms) and tailor-made recoil ion sources of ^{233}U prepared by TU Vienna and JGU Mainz which are installed inside the gas cell to provide the isomeric thorium ions. A new set of de Laval nozzles was designed and characterized to operate under the required low-stagnation-pressure conditions of the recoil sources as well as for spectroscopy studies of (trans)actinides in the JetRIS experiment at GSI [5]. A level search above the second ionization potential of thorium revealed several auto-ionizing states which are used to improve laser ionization efficiency for future in-gas-jet laser spectroscopy studies of $^{229m}\mathrm{Th}^+$.

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Indirect measurements of neutron-induced reaction cross-sections at heavy-ion storage rings

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Obtaining reliable cross sections for neutron-induced reactions on unstable nuclei nuclei is crucial to our understanding of the stellar nucleosynthesis of heavy elements and for applications in nuclear technology. However, the measurement of these cross sections is very complicated due to the radioactivity of the targets involved. The NECTAR (NuclEar reaCTions At storage Rings) project aims to circumvent this problem by using the surrogate-reaction method in inverse kinematics. A heavy, radioactive nucleus in the beam is to interact with a light, stable nucleus in the target to produce the compound nucleus formed in the neutron-induced reaction of interest via an alternative or surrogate reaction such as transfer or inelastic scattering. This compound nucleus may decay by fission, neutron or gamma-ray emission, and the probabilities for these modes of decay are to be measured as a function of the excitation energy of the compound nucleus. This information is used to constrain model parameters and to obtain much more accurate predictions of neutron-induced reaction cross sections [1].
Yet, the full development of the surrogate method is hampered by numerous long-standing target issues. The objective of the NECTAR project is to solve these issues by combining surrogate reactions with the unique and largely unexplored possibilities at heavy-ion storage rings. In these storage rings, heavy radioactive ions revolve at high frequency passing repeatedly through an electron cooler, which greatly improves the beam quality and restores it after each passage of the beam through the internal gas-jet serving as ultra-thin, windowless target. This way, excitation energy and decay probabilities can be measured with unrivaled accuracy.
In this contribution, we will present the technical developments and the methodology, which we are developing within NECTAR to measure for the first time simultaneously the fission, neutron and gamma-ray emission probabilities at the heavy-ion storage rings of the GSI/FAIR facility. In particular, we will present the first results of the proof of principle experiment, which we successfully conducted in June 2022 at the ESR storage ring of GSI/FAIR.

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Recent results with the Active Target Time Projection Chamber

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The Active Target Time Projection Chamber (AT-TPC) has been used in experiments aimed at the exploration of structural effects in radioactive nuclei using one step reactions such as transfer or resonant scattering. The high luminosity of this type of detector allows to perform this type of measurement in inverse kinematics with much reduced beam intensities, while preserving a good resolution, hence extending their reach towards the most rare isotopes. This presentation will feature recent results obtained as a proof of principle on several reaction channels observed between a 10 MeV/u ^{10}Be beam and a pure deuterium target. The methodology used to analyze the complex data recorded by the AT-TPC will be presented, as well as its performance in extracting the physical quantities of interest for structure studies of nuclei far from stability.

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Light-exotic nuclei studied with the (t,p) reaction in inverse kinematics using HELIOS

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We report on studies of '^{14}B and ^{10}Li using the (t,p) reaction in inverse kinematics with HELIOS at Argonne National Laboratory. Two-neutron transfer provides information complementary to that obtained with one-neutron transfer. The selective nature of (t,p) is ideal for studying neutron pairing, configuration mixing and shape-coexistence, effects necessary to understand regions where the shell-model orbitals are changing rapidly with N/Z. Here, we have studied the ^{12}B(t,p)^{14}B and ^{8}Li(t,p)^{10}Li reactions. In ^{14}B, data for ^{14}Be beta-decay [1] and the ^{14}Be(p,n)^{14}B reaction [2] suggest a 1^+ excitation at E$_X$(^{14}B)=1.27 MeV interpreted as a low-lying intruder state with strong $\nu(1s_{1/2})^2$ character. The properties of this and other ν(sd)^2 states in ^{14}B that can be populated in (t,p) provide information about the changing nature of the p-sd splitting in this mass region that is important, for example, in understanding the disappearance of the N=8 shell gap suggested in ^{12}Be. In ^{10}Li, the nature of the low-lying structure remains controversial with conflicting interpretations of data from the ^{9}Li(d,p)^{10}Li reaction[3,4] suggesting the dominance of either s-wave or p-wave excitations. The selectivity of (t,p) can shed more light on this behavior, but also identify two-neutron (sd)^2 excitations that, due to their small overlap with ^{9}Li$_{g.s.}$+n, may be narrow despite ^{10}Li being unbound. The properties of such states in ^{10}Li can provide information that is important for a detailed understanding of the two-neutron halo structure of ^{11}Li.

Secondary ^{12}B and ^{8}Li beams produced using the RAISOR separator at the ATLAS facility at Argonne National Laboratory bombarded a ^{3}H target consisting of ^{3}H adsorbed into a 450 μg/cm^2 Ti foil.

Protons transported by the HELIOS uniform magnetic field were detected using an array of position-sensitive silicon detectors, and recoiling beam-like reaction products were detected at forward angles using a set of ΔE-E silicon-detector telescopes. We will present the results of first measurements of the $^{12}B(t,p)^{14}B$ and $^{8}Li(t,p)^{10}Li$ reactions, and compare the observations with predictions of shell-model calculations for two-neutron transfer leading to states in ^{14}B and ^{10}Li.

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Study of muon capture reaction on Si via in-beam muon activation

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The muon capture reaction is a capture of a negative muon by a proton in the nucleus via the weak interaction. This reaction produces an excited Z-1 nucleus having the same mass as the original nucleus. Although the existence of the muon nuclear capture event has been well known since the 1950s, the measurement data of the excitation energy of the nuclei or the branching ratio of particle emissions from this excited state are sparse, and there is no established model of muon capture. The production branching ratio of each daughter nucleus produced by the muon capture of Si isotopes, which gives information on the energy distribution of the excitation states populated by the muon nuclear capture, was measured with some methods [1-4]. But these methods contain several assumptions, and they show some discrepancies in the production branching ratio. Therefore, to obtain accurate data and evaluate the excitation state of the nuclei after the muon capture, we measured the absolute production branching ratio of the muon capture of Si isotopes with a new method, the in-beam activation method.
The experiment was performed at the Materials and Life Science Experimental Facility (MLF), J-PARC [5]. In the facility, the pulsed muon beam is produced by decay of pions, which are generated by irradiating the graphite target with the 3-GeV proton beam. The pulsed beam has a quiet time period between any neighboring pulses, suited for the β-decay measurement without beam background. In the in-beam activation method, β- delayed γ-rays are simultaneously measured during the beam irradiation thanks to the time structure of the pulsed muon beam. The negative muon beam at 38 MeV/c irradiated targets at 25 Hz. The targets were enriched 28,29,30Si powders and a natural Si plate. Two Ge detectors were used for gamma-ray detection, and a thin plastic scintillator was used for the muon counter. The response function of the plastic scintillator was also measured with the proposed in-beam activation method of the Al target by changing the intensity of the muon beam.
From this experiment, some β- delayed γ-ray peaks from Na, Mg, and Al isotopes were observed.

The absolute production branching ratio of muon capture of Si isotopes is obtained from the counts of these gamma-ray peaks and the number of irradiated muons. This result is also compared with the PHITS simulation. The result of the experiment will be reported in this presentation.

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Determination of electromagnetic moments within nuclear DFT

Auteurs: Jacek Dobaczewski[1]; Jérémy Bonnard[2]; Gauthier Danneaux[3]; Ronald Fernando Garcia Ruiz[4]; Markus Kortelainen[3]; Paolo Sassarini[1]; Herlik Wibowo[1]

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Nuclear electromagnetic moments provide essential information in our understanding of nuclear structure. Observables such as electric quadrupole moments are highly sensitive to collective nuclear phenomena, whereas magnetic dipole moments offer sensitive probes to test our description of microscopic properties such as those of valence nucleons. Although great progress was achieved in the description of electromagnetic properties of light nuclei and experimental trends in certain isotopic chains, a unified and consistent description across the Segré chart of nuclear electromagnetic properties remains an open challenge for nuclear theory.

In our nuclear-DFT methodology, we align angular momenta along the intrinsic axial-symmetry axis with broken spherical and time-reversal symmetries. This allows us to explore fully the self-consistent charge, spin, and current polarizations. Spectroscopic moments are then determined for symmetry-restored wave functions and compared with available experimental data.

We determined the nuclear electric quadrupole and magnetic dipole moments in all one-particle and one-hole neighbours of eight doubly magic nuclei [1]. Such a dataset allowed us to adjust the time-odd mean-field channel of nuclear functionals to experimental data. Without further adjustments, we then determined the electromagnetic moments in paired nuclear states corresponding to the proton (neutron) quasiparticles blocked in the $\pi 11/2^-$ ($\nu 13/2^+$) intruder configurations [2]. We performed calculations for all deformed open-shell odd nuclei with $63 \leq Z \leq 82$ and $82 \leq N \leq 126$.

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We obtained good agreement with data without using effective π-factors or effective charges in the dipole or quadrupole operators, respectively. We also showed that the intrinsic magnetic dipole moments, or those obtained for conserved intrinsic time-reversal symmetry, do not represent viable approximations of the spectroscopic ones, see the results plotted in the figure.

In this talk, I will review recent nuclear-DFT results obtained in the unpaired odd near doubly magic nuclei [1], heavy paired odd open-shell nuclei [2], and indium [3], silver [4], and tin [5] isotopes.

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Collinear laser spectroscopy in medium-mass elements at BECOLA

Auteur: Kristian König[1]

Co-auteurs: Andrew Klose [2]; Felix Sommer [1]; Gaute Hagen [3]; Jason Holt [4]; Jeremy Lantis [5]; Kei Minamisono [6]; Paul-Gerhard Reinhard [7]; Robert Powel [5]; Skyy Pineda [5]; Stephan Fritzsche [8]; Takayuki Miyagi [4]; Thomas Papenbrock [9]; Wilfried Nörtershäuser [1]; Witold Nazarewicz [10]

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Collinear laser spectroscopy in medium-mass elements was performed at the NSCL/FRIB facility at Michigan State University at the BECOLA setup to investigate the nuclear structure in the proximity of the neutron shell closures at N = 20 and 28. The extracted nuclear charge radii were compared to state-of-the-art density functional and ab initio theories yielding a surprisingly similar behavior between the strong/soft shell closures in 48Ca and 56Ni, respectively, [1] and a restoration of the N = 20 kink in Sc that absent in K, Ar and Ca.
In this talk, we will present and discuss the experimental findings and give an outlook of the capabilities of BECOLA in the FRIB era to further explore this fascinating region of the nuclear chart.

This work was supported in part by US NSF Grant No. PHY-21-11185 and DOE Office of Science Award No. DE-SC0000661 and by the DFG – Project-Id 279384907*SFB 1245.

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Statistical and shell effect in beta-delayed neutron emission

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With access to very neutron-rich isotopes, the neutron emission from excited states populated after beta decay becomes a dominant decay mode. The neutron energy measurement informs about beta-decay strength distribution, which is driven by shell effects. The neutron emission is considered to be statistical. Discrete neutron and gamma-ray spectroscopy measurements performed in nuclei ranging from 24O to 134In were performed with hybrid neutron arrays at RIBF, ISOLDE, NSCL, and FRIB. In addition to providing the first measurement of the strength distribution for many nuclei with a large beta-n energy window, we found evidence for non-statistical neutron emission process. It forced us to revisit a conventional picture of neutron emission thought to proceed via a compound nucleus phase. A model which connects nuclear structure and neutron emission was developed to explain the observed phenomena [1].

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Doubly magic 78Ni as a beta-delayed neutron precursor

Auteur: Krzysztof Rykaczewski[1]

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78Ni is a unique doubly magic nucleus far from beta stability line, the only one decaying with β-delayed neutron emission channel. Its decay properties influence the early r-process nucleosynthesis and the beta decays of exotic nuclei north-east of Z=28 and N=50. Nuclei in the 78Ni region were created with the 345 MeV/u 238U beam reaching nearly 70 part*nanoAmp. Fragmentation products were separated by means of BigRIPS spectrometer at RIKEN (Wako, Japan). The spectroscopy of radiation emitted by beta-delayed neutron precursors was performed using BRIKEN 3He array [1] modified to achieve larger gamma efficiency [2]. ORNL contributions included 87% of 3He neutron detection volume and two Ge clovers. The fragment implantation and decay array were consisting of four smaller double-sided Si-strip counters of WASABI complemented by a position sensitive YSO scintillator developed at the UTK. The BigRIPS setting was maximized for the transmission of 82Cu. Isotopes between 61V-69V up to 95Br-97Br were produced and identified. The total rate of identified 78Ni ions was around 65,000, with about 40,000 ions implanted for decay study. Beta-gamma and beta-neutron-gamma decay channels were identified for 78Ni precursor. The P1n branching ratio of about 27(4)% was determined from the analysis [3] of β-1n decay pattern. New levels in 78Cu as well as new level associated with proton p3/2 state in Z=29 77Cu were observed. The accepted proposal to study 78Ni decay with the recently commissioned ORNL's Modular Total Absorption Spectrometer at the Facility for Rare Isotopes Beams will be briefly presented.

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Gas Cell Development using a 248Cm Fission Source at the ZD MRTOF Mass Spectrograph at RIBF

Auteur: Jinn Ming Yap[1]

Co-auteurs: Aiko Takamine [2]; D. Hou ; Hironobu Ishiyama [2]; Jenny Lee [3]; Marco Rosenbusch [4]; Michiharu Wada [5]; Peter Schury [6]; Phong Vi [7]; Shuji Nishimura [8]; Shun Iimura [9]; Sidong Chen [3]; Sota Kimura [6]; T. Sonoda [10]; T.M. Kojima [10]; Ting Gao [1]; Toshitaka Niwase [6]; Wenduo Xian [11]; Yutaka Watanabe [6]

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To perform high-precision experiments on exotic nuclei, efficient capture and transport of radioactive isotope (RI) beams in accelerator facilities are required, leading to many efforts over the years [1, 2, 3, 4]. Downstream from the ZeroDegree spectrometer at RIKEN, RIBF, we employ a cryogenic He filled gas catcher [5] for ion capture and transport to the multi-reflection time-of-flight mass spectrograph (ZD MRTOF-MS) [6] for high precision mass measurements. To study ion transport from the gas catcher to the ZD MRTOF-MS, we have installed a fission source to perform offline mass measurement of fission products. The capture of the fission products in the gas catcher was optimized by rotating a thin Ti degrader attached to the fission source. Recently, mass measurements of fission products, such as $^{104-106}$Nb, Mo, Tc, and Ru, from ^{248}Cm were performed. The transport efficiency was evaluated based on the stopping efficiency obtained from Monte Carlo simulations of the gas cell and well-known fission yields of ^{248}Cm provided by JAEA [7]. In this presentation, we report the transport efficiency investigations of the gas cell, mass measurements of the fission products, and our gas catcher development.

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Evolution of the neutron $1d$ spin-orbit splitting in ^{35}S and ^{39}Ca

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Nuclei along N=20 provide an excellent region to investigate the change in nuclear structure and interactions. From their evolution from the doubly magic nucleus ^{40}Ca through to the Z=16 and Z=14 nuclei ^{36}S and ^{34}Si, respectively, to ^{32}Mg with a deformed $2p-2h$ intruder ground state [1]. The mechanism responsible for the change in shell structure is not well understood and is suspected to be a subtle combination of the different components of the nuclear force namely the central, spin-orbit (SO), and tensor parts. A significant reduction of the neutron $d_{5/2}$ and $d_{3/2}$ spin-orbit splitting between ^{40}Ca and ^{36}S, as protons are removed from the $d_{3/2}$ orbital, would be indicative of the proton-neutron tensor force. By comparing the neutron $d_{5/2}$ hole strength between these nuclei, the strength of the tensor force is probed in an unprecedented manner.

The centroids of the hole states in ^{35}S have been inferred from a ^{36}S(p,d)^{35}S experiment performed at iThemba LABS. A ^{36}S(p,d)^{35}S reaction is a useful tool to probe the neutron spin-orbit splitting in ^{36}S, provided a reliable ^{36}S target is available. This was achieved by specifically developing a new target system at iThemba LABS which allows for a cost-effective ^{36}S target without heavy contaminants to be used. This novel target encapsulates sulfur between two Mylar foils and has been shown to be an effective way to produce targets with a significant amount of material (0.5-1 mg/cm^2).
Using this moving ^{36}S target with 66 MeV incident protons, states in ^{35}S were measured with the K600 magnetic spectrometer at iThemba LABS. States up to 20 MeV were observed, identifying the neutron single-particle strength below and above the Fermi surface using the detection of the deuterons at the focal plane of the K600 spectrometer with an energy resolution of approximately 30 keV [2]. The results from the ^{36}S(p,d)^{35}S experiment were compared to the ^{40}Ca(p,d)^{39}Ca study by Matoba *et al.* [3]. The results show an increase of the neutron $1d_{5/2}$ - $1d_{3/2}$ SO
splitting between ^{35}S and ^{39}Ca by 0.411 MeV. This is contrary to the universal trend of SO splitting with increasing mass number which would predict a decrease of $\sim$ 0.450 MeV. This deviation is highly indicative of the effect of tensor forces. At present, the tensor force is not implemented in the vast majority of the available mean field and relativistic mean field calculations, whereby the amplitude of the SO
splitting is solely attributed to the spin-orbit force. This study provides an unambiguous result indicating the role of the tensor force. It is shown that the strength of the tensor force is, however, lower than predicted by the shell model and ab-initio theory.

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Mass measurement of neutron-deficient Tz=3/2 nuclides at CSRe

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Masses of neutron-deficient T_z=3/2 nuclides, from ^{69}As through ^{103}Sn, have been measured by using the experimental storage ring CSRe at the Institute of Modern Physics (IMP), Lanzhou, China. The nuclides of interest were produced by projectile fragmentation of a ~400 MeV/u ^{112}Sn beam on a ^{9}Be target. The neutron-deficient projectile fragments were injected into CSRe and their revolution times were precisely mearsured and accumulated to form spectra. In our data analysis, the well-separated revolution time peak shapes corresponding to certain ion species were systematically described by exponentially modified Gaussian functions. Then the overlapped peaks from different ion species with similar m/q values were properly deconvoluted and the mass values were accurately determined. The masses of ^{69}As, ^{73}Br, ^{75}Kr, ^{79}Sr, and ^{81}Y were redetermined with mass uncertainties of a few keV, which is comparable to the results obtained from MR-TOF or Penning-trap mass spectrometry. The mass excesses of ^{103}Sn as well as the low-lying $1/2^-$ isomers in ^{87}Mo, ^{91}Ru, and ^{95}Pd were directly measured for the first time. With the help of the new obtained isomer masses, systematics of the excitation energies of the low-lying $1/2^-$ isomers in the N = 45, 47, 49 isotones are presented. By employing the state-of-the-art shell model calculations including tensor forces, such systematic trends are well reproduced. For more details, see Phys. Rev. C 107, 014304 (2023).

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Resonance Ionization Mass Spectroscopy on Americium

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Americium (Am, Z=95) is a transuranic member of the actinide series and was discovered in 1944 by the group led by Glenn T. Seaborg. All its isotopes are radioactive. The two most long-lived ones are ^{241}Am with a half-life of $t_{1/2}$ = 432.2 a and ^{243}Am with a half-life of $t_{1/2}$ = 7370 a. As any primordial americium has decayed by now, these isotopes are produced artificially by neutron irradiation, also in nuclear power reactors. One ton of spent nuclear fuel contains about 100 g of Am. Applications for americium have been proposed, e.g., as fuel for spaceships with nuclear propulsion, and ^{241}Am is routinely used today in ionization-type smoke detectors and - when mixed with Be - as a neutron source. Regarding fundamental atomic and nuclear data obtained in optical spectroscopic studies, only few have been reported to date and the accumulated knowledge on atomic and nuclear properties in literature is rather scarce.
Resonance ionization spectroscopy (RIS) was used as a very sensitive technique to precisely study atomic excitation schemes and level positions in the spectrum of americium, both for fundamental studies as well as in preparation of laser mass spectrometric ultra-trace analysis.
Here we report on two-step high resolution RIS in Am at the RISIKO off-line radioactive ion beam facility. About $3 \cdot 10^{13}$ atoms of both isotopes ^{241}Am and ^{243}Am were prepared on zirconium foil and loaded into a resistively heated tantalum oven. A wide-range tuneable, frequency doubled, continuous wave Ti:sapphire laser was used for spectroscopy by injection locking of a high power pulsed Ti:sapphire ring laser setup. Hyperfine structures of the two isotopes ^{241,243}Am were investigated in two different ground state transitions at 23437.0 cm^{-1} and 25409.5 cm^{-1}, which served as first excitation steps for resonant ionization via suitable autoionizing states. In addition, the isotope shift was measured. Results regarding the atomic structure of Am as well as hyperfine parameters extracted will be discussed.

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Investigation on Isomeric ratio of ^{211}Po produced via MNT approach using ^{136}Xe + ^{209}Bi/ ^{nat}Pb at the IGISOL facility

Auteur: Deepak Kumar[1]

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Investigations on Multi-Nuclear Transfer (MNT) reaction processes are currently a hot topic for theorists as well as experimentalists [1-3]. The MNT reaction processes facilitate access to very neutron-rich rare-earth nuclei, nuclei around the shell closure N = 126, and neutron-rich actinides, which are highly relevant for understanding the nucleosynthesis process of heavier elements [4,5]. The MNT approach provides the advantage of extensive production of isotopic distributions over a wide mass range around target-like and projectile-like fragments, along with the possibility of significant production of isomers [4].
In this endeavor, experiments were performed at the Ion-Guide Isotope Separator On-Line (IGISOL) facility in the JYFL Accelerator Laboratory of the University of Jyväskylä, Finland [5]. The neutron-rich actinides were produced through the MNT reaction process using the 945 MeV ^{136}Xe beam from the K-130 cyclotron on ^{209}Bi and ^{nat}Pb targets. The energetic MNT fragments were thermalized within a new dedicated MNT Ion Guide (IG) by penetrating through a nickel/havar window of the gas cell. The thermalized ions were extracted from the gas cell using a sextupole ion guide, accelerated to 30 keV, and mass-separated using a dipole magnet [4]. Finally, the alpha spectroscopy of the produced isotopes was carried out. Different isotopes of Bi, Po, and At were identified using a Si-detector placed at the Switch Yard (SW) of the IGISOL facility.
The alpha spectra exhibiting ^{211}Bi as a dominant peak in the ^{136}Xe+^{209}Bi reaction were consistent in the three independent runs performed in different experimental conditions. The isomer of ^{211}Po (i.e., 7225 keV of ^{211m}Po) was observed as a dominant peak in the case of the ^{136}Xe+^{nat}Pb reaction. The isomer-to-ground state ratio (IR) of ^{211}Po obtained in ^{136}Xe+^{209}Bi/^{nat}Pb was determined. The results were deduced from the experiments performed in 2019 and 2021. Interestingly, the IR of ^{211}Po produced in the ^{136}Xe+^{nat}Pb reaction was two times higher than that observed in ^{136}Xe+^{209}Bi, indicating the dominant role of entrance channel parameters in the MNT process. Moreover, the measured data were compared with the theoretical calculations that qualitatively explain the deduced results. This talk will focus on the discussion of the production of MNT ions and the entrance channel effect on the MNT process via IR measurements.

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Recent highlights from high-precision atomic mass measurements using MRTOF-MS at RIKEN/RIBF

Auteur: Marco Rosenbusch on behalf of the RIBF-MRTOF collaboration and the KISS collaboration[1]

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Multi-reflection time-of-flight (MRTOF) mass spectrometry [1] has become a new powerful tool for fast and precise measurements of atomic masses. It is a breakthrough-technology considering the required duration of a measurement and the small number of rare events needed to reach a relative mass precision of $\delta m/m \leq 10^{-7}$. This mass spectrometry technology has been developed at RIKEN's RIBF facility for about two decades. Presently, three independent systems are running at different access points to radioisotopes, where gas cells built the essential hub for low-energy access. Recent achievements like high mass resolving power [2] and installations like α/β-TOF detectors [3] and in-MRTOF ion selection have tremendously increased the selectivity of the systems and improved the reduction of background. This makes us capable to distinguish between a rare radioactive ions and unwanted molecules or dark counts.
In this contribution, I will give an overview about recent MRTOF atomic mass measurement highlights achieved at RIBF. Among other measurements presented, these results include new mass values for neutron-rich titanium and vanadium isotopes revealing a vanishing of the empirical two-neutron shell gap at $N = 34$, which is known to be pronounced in Ca isotopes [4]. Furthermore, I will present the discovery of the isotope ^{241}U using the KISS facility [5], and the present status of MRTOF mass measurements of superheavy nuclides using the MRTOF setup at the GARIS-II separator [6].

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Recent progress of mass measurements for short-lived nuclides at CSRe-Lanzhou

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Accurate nuclear masses not only provide indispensable information on nuclear structure, but also deliver important input data for applications in nuclear astrophysics. The challenge today is to obtain accurate masses of nuclei located far away from the valley of stability. In the past few years, we have devoted to the mass measurements of exotic nuclei below A=100 using the isochronous mass spectrometry (IMS) at the heavy ion storage ring CSRe in Lanzhou. New mass values have been obtained including ^{27}P, ^{29}S [1], ^{407}Ti, ^{44}Cr, ^{46}Mn, ^{48}Fe, ^{50}Co, ^{52}Ni [2], ^{44g,m}V, ^{46}Cr, ^{48}Mn, ^{50}Fe, ^{52g,m}Co, ^{54}Ni, ^{56}Cu [3,4], ^{79}Y, ^{81,82}Zr, ^{83,84}Nb [5], ^{101g,m}In [6], ^{87m}Mo, ^{91m}Ru, ^{95m}Pd, ^{103}Sn [7]. Some physics issues have been addressed using our new and improved mass data. In this talk, the experiment details and some selected topics in nuclear structure and in nuclear astrophysics are presented and discussed. We also outline the plans and the technique improvements in our future experiments.

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Two-centre self-consistent approach to fission with arbitrary distance, deformations and orientations of fragments

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Fission is one of the most challenging processes to describe in nuclear physics. Contrary to most of the nuclear properties, which can be explained in terms of a smaller set of valence nucleons out of an inert core, in fission all the particles are involved. Because of this, many-body approximations and theoretical assumptions that simplify the problem are mandatory when trying to describe mathematically the whole process. For connecting the properties of the nascent fragments to the structure of the initial compound nucleus, it seems adequate to consider a two-centre basis to build

the single particle states of the nuclear wave functions [1-3]. Even though there are some existing results computed with that approach, in all of them axial symmetry was preserved [4], which appears as a limitation for describing more complex phenomena. In the present work, for the first time, symmetry-unrestricted two-centre harmonic oscillator states are used within the density functional solver HFODD [5] to solve the Hartree-Fock-Bogoliubov equations.

The effects of the separation and orientations between centres are analysed in super-deformed states (as doorway states to scission configurations) and the results are compared to the usual one-centre calculations as a benchmark.

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This novel work opens the door to developing more sophisticated theoretical technologies in the near future. Time-dependent methods will allow computing properties relevant to both spontaneous and neutron-induced fission (collective inertia, mass distributions or angular momenta of the fragments) without the classical assumptions about adiabaticity or thermalisation[2].

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The nuclear charge radius of ^{13}C

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Nuclear charge radii extracted from collinear laser spectroscopy are often used to benchmark nuclear structure models. Light nuclei, such as ^{11}Be and ^{8}B, which have a well known neutron-halo or are expected to have a proton-halo, respectively, are of particular interest. Unfortunately, for boron there is insufficient knowledge of the charge radius of the stable isotopes from elastic electron scattering or muonic atom spectroscopy, to extract reliable nuclear charge radii of radioactive isotopes using collinear laser spectroscopy. However, recent developments in atomic structure calculations enabled us to directly extract absolute nuclear charge radii from laser spectroscopy measurements in helium-like systems [1]. As a starting point for this effort, the isotopic chain of carbon was chosen due to the relatively well-known nuclear charge radius of ^{12}C.

We have now measured the $1s2s\,^3\mathrm{S}_1 \rightarrow 1s2p\,^3\mathrm{P}_{0,1,2}$ transitions in helium-like $^{12,13}\mathrm{C}^{4+}$ at the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA), located at the Institute for Nuclear Physics at TU Darmstadt. In combination with state-of-the-art mass-shift calculations, we are able to determine the differential nuclear charge radius $\delta\langle r^2\rangle^{12,13}$ with unprecedented precision. This is the first step towards an extraction of absolute all-optical nuclear charge radii, which require more sophisticated atomic structure calculations. Particularly challenging are systems such as $^{13}\mathrm{C}^{4+}$ or the helium-like ions of the halo-candidates $^{8}\mathrm{B}^{3+}$ and $^{11}\mathrm{Be}^{2+}$ whose electronic excited states are affected significantly by hyperfine-induced mixing.

In this contribution we report on our measurements in $^{13}\mathrm{C}^{4+}$ and the extraction of the isotope shift from the mixed hyperfine structure which is used to determine $\delta\langle r^2\rangle^{12,13}$. This project is supported by the German Research Foundation (Project-ID 279384907 – SFB1245).

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First study of proton capture reaction on stored radioactive ^{118}Te beam

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For the first time, the proton capture reaction for a stored radioactive isotope has been directly measured. This measurement became possible by combining two unique facilities at GSI (Helmholtz Centre for Heavy Ion Research),
the fragment separator (FRS) and the experimental storage ring (ESR). The combination of sharp ion energy, ultra-thin internal gas target, and the ability to adjust the energy of the beam in the ring enables precise, energy-differentiated measurements of the (p,γ)-cross-sections. This provides a sensitive method for measuring (p,γ) and (p,n) reactions relevant for nucleosynthesis processes in supernovae, which are among the most violent explosions in the universe and are not yet well understood.

The cross section of the ^{118}Te(p,γ) reaction was measured at energies of astrophysical interest. The heavy ions were stored with energies of 6~MeV/u and 7~MeV/u and interacted with a hydrogen gas-jet target providing the protons. A Double-sided silicon strip detector was used in order to detect the produced ^{119}I ions. The radiative electron capture process occurring in collisions of the fully stripped ^{118}Te ions with electrons from the hydrogen target were used as a luminosity monitor.
These measurements follow a proof-of-principle experiment which was performed in 2016 to validate the method on the stable isotope ^{124}Xe [1].
An overview of the experimental method and preliminary results from the ongoing analysis will be presented.

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Mass measurement in the neutron-rich Mo region using the new ZD MRTOF system

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The ZD MRTOF system at RIKEN BigRIPS is a new high-precision multi-reflection time-of-flight (MRTOF) mass spectrograph for low-energy radionuclides, which is located downstream of the ZeroDegree spectrometer. A novel helium-filled gas-catcher cell based on radiofrequency (RF) ion guides has been developed to thermalize and transport radioisotopes (RIs) produced via in-flight fission and fragmentation at relativistic energies [1]. The stopped RI ions were extracted from the gas cell as atomic or molecular ions and transported to the MRTOF mass spectrograph [2,3] for direct mass measurements with high resolving power. The first online commissioning experiment was performed in winter 2020. During the commissioning, many atomic masses were measured in a series of parasitic experiments, which provides valuable input for nuclear astrophysics and nuclear structure studies [3]. In this contribution, we would like to report the mass measurement results of ^{111,113} Ag, $^{111-113}$ Pd, ^{111,113} Rh, $^{111-113}$ Ru, and ^{111,112} Mo. We have obtained a good agreement with the previously known data (AME2020), and have achieved the first mass measurement of the isotope ^{112} Mo. Based on the systematics of two-neutron separation energies(S_{2n}) around N = 70, we discuss our results in the context of the sudden onset of nuclear deformation in this region visible by S_{2n} values, which maximizes for Sr, Y, and Zr isotopes [4]. Furthermore, we compare our data with global mass models and present new results from a Bayesian machine-learning approach.

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Production of medical grade Ac-225 with resonant laser ionization and mass separation at CERN MEDICIS

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The medical radioisotope Ac-225 is produced at a handful of accelerator facilities by high energy proton irradiation of thorium-based targets. The current standard separation protocol of this isotope and its generator parent Ra-225 from irradiated targets is based on radiochemistry. This method can recover Ac-225 and Ra-225 with high radiochemical yields of >90%. Nonetheless, a major issue is that the recovered Ac solutions contain the long-lived Ac-227 with an activity potentially unsafe for medical use. In order to address this, the method of resonant laser ionization and mass separation can instead be performed on Ac-225-containing samples including irradiated ThO2 matrices, or as solutions dried on refractory foils. This contribution will provide a comprehensive overview of the multiple collections of Ac-225 that have been performed with this method at CERN MEDICIS from

different starting samples. For each collection, the total separation efficiency as measured by complementary alpha- and gamma-spectroscopy techniques will be reported and discussed. Furthermore, the separation factor of Ac-225 compared to Ac-227 through this method and hence its suitability for producing medically relevant Ac-225 samples will be reported where applicable. During the discussion, emphasis will be placed on the systematics of the laser ionization efficiency, as well as Ac-225 release as a function of its chemical environment and temperature. The contribution will conclude by recommending an optimum method for separating medical grade Ac-225 from thorium-based targets irradiated with protons.

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Onset of deformation in the neutron-rich krypton isotopes via transfer reactions with the ISOLDE Solenoidal Spectrometer

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In the A = 100 region, the dramatic shape change observed for Zr [1-3] and Sr [4-7] (Z = 40 and 38, respectively) is not present in Kr (Z = 36) isotopes [8-10]. 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. The $\nu g_{7/2}$ orbital is filled in the ground states of the 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.

Previous studies in this region have shown a smooth onset of deformation in Kr isotopes at N = 60 [9,10] and evidence of a new oblate structure coexisting with the prolate ground state [11]. Accurately predicting ground-state spins and parities of odd-mass isotopes in this region is challenging due to the large valence space, and lack of ESPE data and accurate shell-model interactions. The single-particle energy differences and spectroscopic factors extracted from neutron adding reactions will provide a more complete experimental picture of the underlying single-particle configurations, which will allow for comparison to modern shell-model calculations [12] that try to describe the onset of deformation around A = 100.

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 7.5 MeV/u using the ISOLDE Solenoidal Spectrometer at ISOLDE, CERN. The main goals are to determine the energy difference between the $2\nu s_{1/2}$ and $0\nu g_{7/2}$ orbitals below N = 60 using the ^{92,94}Kr *(d,p)* reactions to identify the likely $\Delta\ell$ = 4 transfer to the $7/2^+$ state. Preliminary results obtained from the October 2022 experiment will be presented.

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Systematic nuclear-DFT calculations of electromagnetic moments of $\pi 7/2^+$ and $\nu 11/2^-$ configurations in heavy deformed open-shell odd nuclei with $50 \le Z \le 64$

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The study of nuclear electromagnetic moments can provide detailed information on nuclear structure [1]. While the quadrupole moments serve as an excellent tool to probe nuclear deformation and collective behavior, the magnetic moments are significantly affected by the single-particle orbits of unpaired nucleons. The shell model [2] has been successfully applied to describe the experimental electromagnetic moments, albeit with the necessity to introduce the g-factors and effective charges in the dipole and quadrupole operators, respectively. In our recent work [3,4], systematic calculations of the electric quadrupole and magnetic dipole moments were performed using the nuclear-density-functional-theory (nuclear-DFT). The spectroscopic moments of angular-momentum-projected (AMP) wave functions were determined and compared with the available experimental data. It was shown that a good agreement with data can be achieved without the use of effective g-factors and charges.

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In the present contribution we consider triaxial deformations. As the triaxial deformations strongly modify the single-particle orbits, it is instructive to investigate its effects on nuclear magnetic moments. The nuclear magnetic dipole properties of ground and Z-vibrational bands in Dy and Er isotopic chains have been studied using the triaxial projected shell model [5]. The study has found that the N-factor ratio of the γ state in ground bands to that of g-bands varies as a function of triaxiality. This result motivates us to investigate the effects of triaxial deformations on the properties of nuclear magnetic moments both for even-even and odd nuclei. Specifically, we perform systematic calculations of magnetic dipole and electric quadrupole moments for paired nuclear states associated with the proton (neutron) quasiparticles blocked in the 2^+ (γ) configurations of deformed open-shell odd nuclei shown in Fig 1. The self-consistent shape and spin core polarizations are established in the self-consistent calculations based on the spherical and time-reversal symmetry breaking. Calculations are performed using code HFODD. To consider the triaxiality, we first perform the potential energy surface (PES) calculations $7/2^+$ in the gamma-unstable region around $11/2^-$Ba nucleus. For the obtained triaxial shapes, we then determine the spectroscopic moments of the AMP wave functions.

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Charge-current and neutral-current quasielastic (anti)neutrino scattering on ^{12}C and ^{40}Ar targets with realistic spectral and scaling functions

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Charge-current (CC) and neutral-current (NC) quasielastic (anti)neutrino scattering cross sections on ^{12}C and ^{40}Ar targets are analyzed using a realistic spectral function $S(p, calE)$ that gives a scaling function in accordance with the (e, e') scattering data. The spectral function accounts for the nucleon-nucleon correlations and has a realistic energy dependence. The standard value of the axial mass $M_A = 1.03$ GeV is used in the calculations. The role of the final-state interaction on the spectral and scaling functions, as well as on the cross sections is accounted for. Our results in the CC case are compared with those from other theoretical approaches, such as the Superscaling Approach and the relativistic Fermi gas, as well as with those of the relativistic mean field and the relativistic Green's function in the NC case. Based on the impulse approximation our calculations for the CC scattering underpredict the MiniBooNE and Minerνa data but agree with the data from the NOMAD experiment. The NC results are compared with the empirical data of the MiniBooNE and BNL experiments. The possible missing ingredients in the considered theoretical methods are discussed.

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First in-gas-jet laser spectroscopy with S^3-LEB

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The Superconducting Linear Accelerator (SPIRAL2-LINAC) facility of GANIL will extend the capabilities of studying exotic nuclei by producing beams of rare radioactive isotopes with highest intensities achieved so far [1,2]. The SPIRAL2-LINAC coupled with the Super Separator Spectrometer (S^3) recoil separator will allow the production of neutron-deficient nuclei close to the proton dripline and super heavy nuclei via fusion-evaporation reactions and separate them from the intense background contamination [3]. The S^3-Low Energy Branch (S^3-LEB), currently under commissioning at LPC Caen, will sit at the focal plane of S^3 and stop, thermalize, and then neutralize the radioactive isotopes using a buffer gas cell set-up. The S^3-LEB is dedicated to the study of ground state and isomeric state properties using laser ionization with high efficiency and high selectivity.

Development work has been ongoing at the S^3-LEB setup [4, 5]. It uses in-gas-jet laser ionization, to resonantly ionize the neutralized atoms, and ion guides to send them to the Piège à Ions Linéaire du GANIL pour la Résolution des Isobares et la mesure de Masse (PILGRIM), a Multi-Reflection Time Of Flight Mass Spectrometer (MR-TOF-MS), or to a decay spectroscopy study station, SEASON. A buffer gas cell with 400 ms extraction time has been coupled to the ion transport ensemble and a de-Laval nozzle of Mach number M ~ 8 (developed at KU Leuven) has been installed at the gas cell aperture, which can create a hypersonic jet of narrow velocity distribution in a reduced collision environment. The hypersonic jet environment reduces the Doppler and pressure broadening by at least an order of magnitude compared to the gas cell [6,7]. Laser spectroscopy with suitable atomic transition schemes at S^3-LEB offers improved spectral resolution (≤ 300 MHz) while maintaining high efficiency, enabling access to isotope shifts and hyperfine constants measurements and thus to nuclear structure such as nuclear spin, moments and difference in nuclear charge radii for the exotic nuclei.

Here, we present the results from the offline commissioning of S^3-LEB with first in-gas-jet ionization and high-resolution laser spectroscopy in-gas-jet results for erbium, performed to validate the potential of the setup. Measurements of the isotope shifts and hyperfine constants in the hypersonic gas jet will be compared to literature and measurements in an Atomic Beam Unit (ABU). Characterization of the pressure broadening effects in gas cell will be reported. Additionally, first optimization of the overall transport efficiency for the setup with laser-produced ions will be presented.

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Ab initio calculation of the ^{3}He$(\alpha,\gamma)^7$Be astrophysical S factor

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The ^{3}He$(\alpha,\gamma)^7$Be reaction is an important part of ongoing processes occurring in stars like our very own sun. In the fusion reaction network of the sun, the ^{3}He$(\alpha,\gamma)^7$Be reaction is key to determining the ^{7}Be and ^{8}B neutrino fluxes resulting from the pp-II chain . In standard solar model (SSM) predictions of these neutrino fluxes, the low-energy ^{3}He$(\alpha,\gamma)^7$Be S factor, $S_{34}(E)$, is the largest source of uncertainty from nuclear input. The SSM uses $S_{34}(E)$ near the Gamow peak energy, roughly 18 keV, which cannot be experimentally measured since the Coulomb force between ^{3}He and ^{4}He suppresses the fusion reaction at such low energies. Theoretical calculations are needed to guide the extrapolation to the solar energies of interest. To this end, I will present *ab initio* calculations of the ^{3}He$(\alpha,\gamma)^7$Be reaction using the no-core shell model with continuum starting from two- and three-nucleon chiral interactions. To demonstrate that the NCSMC provides an accurate S factor, I will also compare NCSMC ^{3}He + ^{4}He elastic-scattering cross sections with those recently measured by the SONIK collaboration.

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Bρ-defined isochronous mass spectrometry using two TOF detectors at CSRe-Lanzhou

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A novel isochronous mass spectrometry, termed as Bρ-defined IMS, has been established at the experimental cooler-storage ring CSRe in Lanzhou. Its potential has been studied through high precision mass measurements of ^{58}Ni projectile fragments. Two time-of-flight detectors were installed in one of the straight sections of CSRe, thus enabling simultaneous measurements of the velocity and the revolution time of each stored short-lived ion. This allows for calculating the magnetic rigidity Bρ and the orbit length C of each ion. The accurate Bρ(C) function has been constructed, which is a universal calibration curve used to deduce the masses of the stored nuclides. The sensitivity to single stored ions, fast measurement time, and background-free characteristics of the method are ideally suited to address nuclides with very short lifetimes and smallest production yields. In the limiting case of just a single particle, the achieved mass resolving power allows one to determine its mass-over-charge ratio m/q with a remarkable precision of merely ~ 5 keV. Masses of Tz = −3/2 fp-shell nuclides are re-determined with high accuracy, and the validity of the isospin multiplet mass equation is tested up to the heaviest isospin quartet with A = 55. The new masses are also used to investigate the mirror symmetry of empirical residual proton-neutron interactions.

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Direct mass measurement of neutron-deficient Fe isotopes

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The two-proton radioactivity, so-called $2p$ decay, is a decay mode where two protons are simultaneously emitted from a ground state of nuclei with a large proton excess, such as ^{45}Fe and ^{48}Ni. Theoretical models suggest that the valence two protons in the $2p$ decay process are strongly correlated due to the pairing effect and paired protons tunnel through the Coulomb potential [1, 2].
Although some events of $2p$ decay and half-lives are reported in recent studies [3, 4], the paring energies of two protons in $2p$ emitters are not investigated experimentally and the mechanism of $2p$ decay is still not fully understood.

We, therefore, performed direct mass measurements around ^{45}Fe to reveal the development of energy structure towards the $2p$-decay nucleus.
Two-proton separation energies and proton-paring energies of neutron-deficient nuclei will be evaluated by using experimentally-obtained mass differences from this experiment.
The experiment was performed at RI beam Factory in RIKEN, Japan. In this study, the TOF-Brho technique was used to measure the masses of short-lived nuclei. The ions produced by fragmentation reactions of ^{78}Kr were separated through the BigRIPS separator and transported to the OEDO-SHARAQ beamline. We confirmed that the cocktail beam included a two-proton emitter ^{45}Fe nucleus even with a small fraction and many Fe, Cr, and Ti isotopes around ^{45}Fe. The data analysis is still underway, but we will determine these masses from the presently-obtained data.

In this talk, details of the experiment and the preliminary results of the analysis will be reported.

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Development of Ti:Sapphire laser system for resonance ionization laser ion source, PALIS RIKEN

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A parasitic low-energy RI-beam production system (PALIS) at BigRIPS, RIKEN has been developed to allow effective use of the RI species surrounding the main beam. We confirmed resonance ionization of stable Bi atoms in the gas catcher of PALIS using broad bandwidth dye and Ti:Sapphire laser systems. Toward high-resolution resonance ionization spectroscopy in gas jet at PALIS, we developed a narrow bandwidth injection-locked Ti:Sapphire pulsed laser system using a direct diode-pumped continuous wave Ti:Sapphire laser as a single-frequency seed source. Output powers of up to 2.8 W and 150 mW were achieved at a repetition rate of 10 kHz in the fundamental and second harmonic generation, respectively. High-resolution resonance ionization spectroscopy of stable Cs and Ga atoms in a graphite furnace was demonstrated by the injection-locked laser system coupled with a time-of-flight mass spectrometer.

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Precision velocity measurements of ions in the storage ring CSRe-Lanzhou

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Storage-ring-based isochronous mass spectrometry (IMS) is a powerful tool for mass measurements of short-lived nuclei. The IMS [1] depends on precision measurements of the mean revolution times of stored ions in a given acceptance of magnetic rigidity of $\sim \pm 0.2 [1] M.Hausmann et al., Nucl.Instr.Meth.A446(20$
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Measurements of β-delayed one and two neutron emission probabilities south-east of 132Sn within the BRIKEN project at RIKEN

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Recent observations of metal-poor star elemental and isotopic abundances [Roe22, Wen18] have sparked new interest in the nucleosynthesis of elements around the second *r*-process abundance peak, as it may shed light on the *r*-process conditions. To understand the *r*-process conditions and link these observations to astrophysical models, it is crucial to have information on the nuclear properties of the radioactive progenitors of the second *r*-process peak.
Following *r*-process freezeout, the final abundances of the second peak are the result of various competing reactions, such as neutron capture, photodisintegration, fission, and β-delayed neutron emission. The latter has been the main focus of our experiment, conducted within the BRIKEN project [Tol19] at the RIBF facility of RIKEN (Japan).
In the present contribution, we will present new experimental results on β-delayed one and two neutron emission probabilities of very neutron-rich nuclei located south-east of ¹³²Sn [Pho20] and compare them with recent macroscopic-microscopic and self-consistent global models with the inclusion of the statistical treatment of neutron and γ emission [Kaw08, Min21]. The impact of our results on the odd-even staggering of the final *r*-process abundance around the second *r*-process peak, as well as the observed odd-mass isotopic fractions of Ba in metal-poor stars [Wen18] will be presented. Continuing our experimental program on *r*-process nuclei, we will present a new experimental setup that will allow β-decay and β-delayed neutron spectroscopy studies to be conducted in parallel with MR-TOF mass measurements program at RIKEN RIBF.

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The Super Separator Spectrometer (S^3) at GANIL/SPIRAL2

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The Super Separator Spectrometer S^3 [1] is, with the NFS (Neutrons For Science) facility, a major experimental system developed for SPIRAL2. It is designed for very low cross section experiments at low (<15MeV/u) energy. It will receive the very high intensity (more than 1pμA) stable ion beams accelerated by the superconducting LINAC accelerator of SPIRAL2. S^3 will be notably used for the study of rare nuclei produced by fusion evaporation reactions, such as superheavy elements and neutron-deficient isotopes. Such experiments require a high transmission of the products of interest but also a separation of these nuclei from unwanted species. Hence S^3 must have a large acceptance but also a high selection power including physical mass resolution. These properties are reached with the use of seven large aperture superconducting quadrupole triplets which include sextupolar and octupolar corrections in a two-stage separator (momentum achromat followed by a mass spectrometer) that can be coupled to the SIRIUS implantation-decay spectroscopy station [2] or to a gas cell with laser ionization to provide very pure beams for low energy experiments [3,4]. S^3 is now in the installation and tests phases. We will present the scientific objectives of S^3 as well as the current status of the facility.

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Recent Nuclear Structure Studies at N=50 Through Masses of Isomeric States

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The nuclear binding energy arises from various effects that govern nuclear 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 through mult-reflection time-of-flight [1] and ion-cyclotron resonance mass spectrometry [2]. 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 [3,4]. We further present evidence for shape-coexistences close to N=50 through independent excitation energy measurements of the $1/2^+$ state in ^{79}Zn with JYFLTRAP at IGISOL and ISOLTRAP at ISOLDE, supported by accurate large-scale shell model calculations [5].

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L. Nies, A. Kankainen, K. Blaum, D. Lunney, L. Schweikhard for the JYFLTRAP and ISOLTRAP collaborations

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Development of 14C cavity ring-down spectroscopic system for biomedical tracer and environmental applications

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Long-lived radioactive carbon isotopes ¹⁴C are widely used as a tracer in environmental and biomedical studies. We are developing a ¹⁴C analytical system based on highly sensitive cavity-enhanced laser absorption spectroscopy, i.e. cavity ring-down spectroscopy (CRDS). Using a distributed feedback diode laser stabilized by optical feedback from a V-shape cavity, a single detection limit of 1×10^{−9} cm^{−1} Hz^{−1/2} corresponding to a detectable abundance of 0.2 in fraction modern ¹⁴C for a 10-second averaging time was demonstrated. To achieve further abundance sensitivity, the ¹⁴C analytical system was combined with a mid-infrared optical frequency comb. In this presentation, we will show an overview of the ¹⁴C analytical system based on CRDS and recent results in ¹⁴C determinations for bio-tracer applications.

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Shape studies in neutron-rich cerium isotopes

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Octupole correlations are the result of the long-range octupole-octupole interaction between nucleons occupying pairs of orbitals which differ by 3 units in both orbital and total angular momentum. This interaction gives rise to an asymmetric pear-shaped form that can be manifested by the appearance of low-lying negative-parity states [1]. The presence of octupole deformation has only been observed in localized regions of the nuclear chart and more specifically in the mass region around $Z = 88$, $N = 134$ [2-5] with the next promising region to be around $Z = 56$, $N = 88$ [6]. Isotopes with their Fermi surfaces close to these particle numbers are predicted to possess an octupole collectivity [7] which can be characterized by enhanced $B(E3)$ values, as observed in recent experiments on ^{144,146}Ba [8-9]. The neighbouring cerium isotopes with $146 \leq A \leq 152$ are also considered to be excellent candidates to study this kind of deformation [10-11]. Studying the electromagnetic properties of excited states is essential in our understanding of the magnitude and mode of octupole deformation, whether it is static or vibrational in nature [3].

A β-decay experiment has been performed at the radioactive ion beam facility ISAC-I at the TRIUMF particle accelerator center in Vancouver, Canada, aiming to look for low-lying negative-parity states in neutron-rich cerium isotopes. Beams of Cs were initially produced from a UC_x target and implanted on an aluminized mylar moving tape collector. The population of states in ^{146,148,150,152}Ce was possible through the decay of the grand-daughter La isotopes. Spectroscopy measurements have been performed using the GRIFFIN spectrometer, which consists of an array of 16 Compton-suppressed HPGe clover detectors for the detection of gamma-rays, 5 scintillators for conversion electron spectroscopy and 8 $LaBr_3$ detectors to allow for fast-timing measurements of excited-state lifetimes.

In this talk, preliminary results of this experimental campaign will be presented including the identification of new excited levels in ^{148}Ce. Additionally, from angular distribution measurements, the assignment of spin and parity of the proposed low-lying 1^- and 3^- states in ^{146,148}Ce [12] will be discussed.

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Technical progress at the double Penning trap PIPERADE

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The double Penning trap PIPERADE (PIèges de PEnning pour les RAdionucléides à DESIR) [1] for the DESIR facility has been advancing in its commissioning phase at the LP2i-Bordeaux laboratory. The traps were designed with the objective of performing high-precision mass measurements and high-resolution mass purification of strongly contaminated ion beams. The latter will be produced by the existing SPIRAL1 facility and the S3 spectrometer. In order to push the limits of existing devices, PIPERADE is equipped with a new type of high-capacity large trap that aims to separate up to 10^4 - 10^5 ions per bunch.
The purified samples will be re-injected in the main DESIR beam line for downstream setups to perform trap-assisted spectroscopy. Alternatively, the purified samples will be utilized to perform high-precision mass measurements. In this context, standard ion-beam manipulation techniques are now being routinely demonstrated, i.e. the sideband buffer gas cooling (BGC) [2] and the time-of-flight ion-cyclotron-resonance (ToF-ICR) [3], while others are being implemented - phase-imaging ion-cyclotron-resonance (PI-ICR) [4]. Last year, as part of the implementation process of PI-ICR, an imaging system consisting of a microchannel-plate detector coupled to an anode constructed of helical wire delay lines was installed. RoentDek Handels GmbH has developed the delay-line anode with a specific three-layer geometry ("Hexanode") [5] to improve the ambiguity of multi-hit position and time encoding on the detector.
In this contribution, we will present the latest achievement from the BGC technique, the first mass measurement by using ToF-ICR and finally, the detector installation to allow the position encoding for future PI-ICR measurements.
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Nuclear collective inertia in the adiabatic time-dependent Hartree-Fock-Bogoliubov method

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A novel method to solve equations of the adiabatic time-dependent Hartree-Fock-Bogoliubov (ATDHFB) method is developed and applied to study nuclear collectivity. Collective motion, in which many nucleons act coherently, is of fundamental importance in nuclear physics and attracts both experimental and theoretical attention. Although the collective motion can be described by the phenomenological liquid drop model or Bohr Hamiltonian [1, 2], the physical determination of the inertia against this motion needs knowledge about nuclear microscopic dynamics. In the Hartree-Fock-Bogoliubov theory, each nucleon moves independently in a field created by all the others. Once excited, the nucleus evolves with time along a collective path in the multidimensional energy surface. The ATDHFB method assumes the velocity of the collective motion is much smaller than that of single-particle motion. It allows for a microscopic evaluation of the inertia for surface vibrations, rotations and fission. As such, the ATDHFB method is a bridge between the microscopic many-body theory and phenomenological models based on collective variables.

To study full vibration-rotation collective motion in the adiabatic limit without constraints, we implement the ATDHFB method for the Skyrme density functional solver HFODD [3]. The nuclear Hartree-Fock-Bogoliubov problem is solved on a 3D Cartesian deformed harmonic-oscillator basis to deal with arbitrary shapes and angular rotational frequencies. The ATDHFB equation is solved iteratively which avoids the explicit calculations of the stability matrix [4]. Since the collective motion is not time-reversal invariant, the proper treatment of the time-odd mean fields is essential. Neglecting the time-odd term would lead to incorrect collective inertias [5, 6]. In this work, the dynamical effects of the time-odd mean fields are highlighted by comparing the ATDHFB results with those obtained in the cranking approximation.

The ATDHFB method implemented in this work gives universal and reliable estimations of collective inertia for both even and odd heavy nuclei, which will be helpful to determine the collective path for spontaneous fission. In the future, we will study the influence that non-axial deformation and the pairing interaction have on the nuclear collective inertias, as well as investigate the possible impacts of the isospin-breaking terms and finite-range higher-order regularized terms in the density functional. By performing extensive calculations across the Segre chart, the information on collective nuclear observables will be included in building novel nuclear density functionals.

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MEASUREMENTS OF 161TB PRODUCTION CROSS SECTION FOR NUCLEAR DATA AND NUCLEAR MEDICINE

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161Tb has interesting physical properties for therapeutic applications in nuclear medicine. It has a half-live of 6.88 days and it is a β- emitter with a mean energy of 154 keV and a maximum energy between 42.85 and 593.1 keV. It corresponds to an electron range of 3 millimeters in water. Its coordination chemistry and energy range, comparable to that of 177Lu used in vectorized radiotherapy, allow a stable coordination with a DOTA chelator, a localized effect on targeted cells and limits the dose received by the surrounding healthy tissues. The therapeutic effect of 161Tb may be enhanced due to the co-emission of a larger number of conversion and Auger electrons as compared to 177Lu. In a theranostic approach, it could be coupled at another terbium isotope dedicated to diagnostic.

Production cross section of various β- and α emitters dedicated to therapy were measured by the PRISMA team of the Subatech laboratory at the GIP ARRONAX using a multiparticle C70XP cyclotron, the stacked-foil technique and gamma spectroscopy. From irradiated stacks, composed of natGd foils, Ni monitors and Al degraders, we are able to obtain the natGd(d,x)161Tb cumulative production cross section coming from the reactions 160Gd(d,p)161Gd and 160Gd(d,n)161Tb between 6.69 and 16.47 MeV. Previous data sets published in the literature by Tarkanyi et al. [1] and Szelecsenyi et al. [2] are not in accordance, one objective of this work is to better define the shape and the maximum of the excitation function. Additional data have also been collected for the natGd(d,x)155Tb, 156Tb, 160Tb. Results are presented along with values extracted from TENDL-2019.

The only three series of published experimental data have been complemented in the energy region, near 12 MeV, of the maximum cross section, around 50 mb. This production cross section is of interest for nuclear models as it fixes the shape and the amplitude associated to this nuclear reaction and for nuclear medicine as it allows to defined optimized irradiation parameters to produce 161Tb that can be beneficial for vectorized radiotherapy to take advantage of its β- and Auger electron emissions.

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Latest results from MARA

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A new vacuum-mode separator, MARA (Mass Analyzing Recoil Apparatus) [1, 2], has been completed and has extended the research possibilities whit the existing gas-filled recoil separator, RITU [3] at JYFL-ACCLAB. The ion-optical configuration of MARA is QQQDEDM, differing significantly from the other existing in-flight separators around the world. MARA has turned out be a very reliable separator and easy to operate. The studied nuclei of interest have been produced using fusion-evaporation reactions, mainly employing symmetric or inverse kinematics. In-beam studies,

isomeric studies as well as production of new isotopes have been performed at and beyond the proton dripline starting from a mass number 66 up to a mass number 180.
In this work some highlights of the latest results using the JYFL in-flight separator MARA will be given.

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Isospin-symmetry breaking in the $B(E2)$ transitions of $T = 1$ isotriplets

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The study of $T = 1$ triplets plays an important role in our understanding of isospin physics. A linear dependence of the proton matrix elements (M_p) with respect to isospin projection T_Z indicates the isospin purity of states, an effect that has been studied and observed for triplets of $22 \leq A \leq 50$ [1]. As measurements of reduced electromagnetic transition probabilities become available for heavier $T_Z = -1$ nuclei, some studies suggest that beyond-Coulomb isospin symmetry-breaking (ISB) effects affect this observable in mirror nuclei [2].

In this work, we investigate all even-even $T = 1$ mirrors with $42 \leq A \leq 98$ within the nuclear-density-functional-theory (nuclear-DFT) approach and analyse systematic properties of the obtained $B(E2 : 0^+ \to 2^+)$ values. For this purpose, we use the numerical software HFODD [3] to identify the deformed minima and to perform angular momentum projection. In addition, we employ the Generalised Bohr Hamiltonian [4, 5] to study effects of the quadrupole collectivity. For both methods, we utilise the Skyrme energy density functional with the UNEDF1 parameterisation [6]. We compare the obtained results with the available experimental data. Our results show significant differences between the mirror pairs without considering beyond-Coulomb ISB effects.

Furthermore, for the $A = 70$ and $A = 78$ triplets, including the odd-odd $N = Z$ nuclei, we perfom calculations utilising a variety of nuclear-DFT parameterisations. The $A = 70$ triplet is the heaviest one for which the $B(E2)$ are known for all members, whereas the $A = 78$ triplet is the subject of interest for further experimental measurements. To obtain the $B(E2)$ of the odd-odd $N = Z$ nuclei, we performed the angular-momentum projection of the Hartree-Fock-Bogoliubov states with pair-blocked configurations. Our results allow for a full investigation of the linearity of M_p in function of T_z.

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Structure of A=22 analogue states revealed through mirrored-transfer

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The isospin formalism describes protons and neutrons as two projections of the nucleon and provides a powerful tool for identifying and classifying states in the vicinity of the line of $N = Z$. Under the assumption that isospin is a good quantum number, a number of relations arise to describe isobaric analogue states their properties. This provides access wealth of information, from tests of the isospin-symmetry conserving nature of the nuclear interaction, to applications in nuclear astrophysics. In truth, however, this assumption is known to be false, broken by the Coulomb interaction and components of the nucleon-nucleon interaction.

Here, we employ mirrored transfer reactions using beams of radioactive ^{21}Na and stable ^{21}Ne delivered by the ISAC-II facility at TRIUMF. These are used to populate isobaric analogue states in ^{22}Na and ^{22}Ne, respectively, through (d,p). Making use of proton-γ coincidences, we are able to selectively probe the single-particle nature of individual states, and probe their isospin purity. I will present initial findings, focusing on the role of isospin mixing in 2^+ states through single-particle transfer, as well as future directions involving (d,n) data taken simultaneously to the (d,p).

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Study of medium-mass and heavy hypernuclei produced through spallation and fission reactions in inverse kinematics

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Innovative experiments using the inverse kinematics technique to accelerate light, medium-mass, and heavy nuclei at relativistic energies have become excellent tools to produce and study hypernuclei [1]. In this work, we investigate hypernuclei created in spallation reactions, where multifragmentation, particle evaporation, and fission processes play an important role in the formation of final hypernuclei residues. For the description of spallation reactions, we couple the Liège intranuclear cascade model, extended recently to the strange sector [2], to a new version of the ablation (ABLA) model that accounts for the evaporation of Λ-particles from hot hyperremnants produced during the intranuclear cascade stage [3,4]. These state-of-the art models are then used to study the production of hypernuclei close to the drip lines through spallation-evaporation and fission reactions. Moreover, we will also present the recent results obtained for the study of hypernuclei dynamics, in particular, for the constraint of the viscosity parameter involved in hyperfission reactions [5].

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Is 70Zn(d,x)67Cu the best way to produce 67Cu for medical applications?

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The theranostic approach combines diagnostic and therapy towards personalised treatment for patients. Among the different possibilities, associating two radionuclides of the same element is appealing, one for imaging purpose and the other for therapy. Copper offers such a pair of radionuclides with 64Cu (T1/2=12.7 h) allowing PET imaging and 67Cu (T1/2=61.8 h) for targeted beta therapy. If for 64Cu the production route is well defined (a biomedical cyclotron delivering protons on a 64Ni target), this is not the case for 67Cu. Many production routes have been explored using neutrons, charged particles or photons. For charged particles, the main challenge relies on the limitation of 64Cu co-production, even if its real impact on the patient and staff radioprotection needs to be studied and clarified. This work aims at identifying and studying an optimized production route for 67Cu while limiting the impact of 64Cu.
Within this frame, a preliminary research identified the production route 70Zn(d,x). We have measured its production cross sections for 67Cu up to 30 MeV. Measurements were done using the well-known stacked foils technique on 97.5 % enriched 70Zn homemade electroplated targets. Beam intensity has been obtained using an instrumented Faraday cup. Cross sections were also measured for the monitor reactions natTi(d,x)48V and natNi(d,x)61Cu. They complement at higher incident energies the only set of data available in nuclear databases. The maximum of the cross section is reached for an incident energy of 23 MeV. Its value, 30 mb, is twice higher than the one obtained

with a proton irradiation. With deuterons below 26 MeV, 64Cu production is limited and directly connected to the enrichment of the target. Using this data, the production yield was calculated and production optimization parameters were proposed (energy incident of the deuteron, thickness crossed by the particles, irradiation time, waiting time).
This production route is of great interest as it limits strongly the production of 64Cu that is directly linked to the level of 68Zn impurity in the target. Using a 26 MeV deuteron beam and an enriched 70Zn target, it is then possible to produce high purity 67Cu. Activity of 16.4 GBq can be obtained for 26 MeV and 80 µA beam crossing 576 µm of 70Zn thickness during 40 hours. By waiting 70 minutes after irradiation for decays, the activity of 67Cu reaches 99.99 % of the total cooper activity and, at this time, the specific activity is 1.87 GBq/nmol or 27.9 TBq/mg. This specific activity value is very close to the theoretical maximum (28 TBq/mg). This production route can be of interest for future linear accelerators under development where mA deuteron beams can be available if adequate targetry is developed.

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The N=126 Factory: A new multi-nucleon transfer reaction facility at Argonne National Laboratory

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Multi-nucleon transfer (MNT) reactions between two heavy ions offer an effective method of producing heavy, neutron-rich nuclei that cannot currently be accessed efficiently using traditional projectile-fragmentation, target-fragmentation or fission production techniques [1]. These nuclei are important for understanding many astrophysical phenomena. For example, properties of the neutron-rich nuclei near the $N = 126$ shell closure are critical to the understanding of the r-process pathway and the formation of the $A \sim 195$ abundance peak [2]. The $N = 126$ Factory currently under construction at Argonne National Laboratory's ATLAS facility will make use of these reactions to allow for the study of these nuclei [3]. Due to the wide angular distribution of MNT reaction products, a large-volume gas catcher will be used to convert these reaction products into a continuous low-energy beam. This beam will undergo preliminary separation in a magnetic dipole of resolving power $R \sim 10^3$ before passing through an RFQ cooler-buncher and MR-TOF system of resolving power $R > 10^5$, sufficient to suppress isobaric contaminants. These isotopically separated, bunched low energy beams will then be available for experimental systems at ATLAS such as the CPT mass spectrometer for precision mass measurements. Results of commissioning the component devices will be presented, as will the status of the final assembly and commissioning of the facility, which is expected to be operational this year.

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The role of tensor forces in polarised nuclear matter

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In the last decades, standard Skyrme functionals have reached their limits with respect to experimental data. To overcome this issue, people started to develop extensions for such functionals. For example, some groups reconsidered the use of the so-called tensor forces in calculations[1-4]. However, the terms introduced by these interactions are of a different nature from others. In particular, as well as spin-orbit terms, they couple momenta and spins.

These recent studies were focalised on the impact of the tensor interactions on nuclear shell structure and, more precisely, on the orbital-dependent correction it brings to nuclear spin-orbit splittings. However, unlike spin-orbit terms, the aforementioned interaction also contributes to the properties of infinite spin polarised nuclear matter, as expected to be found in compact astrophysical objects. Most importantly, the presence of the tensor interaction changes the formalism for the description of infinite matter, as single particle energies depend on the relative orientation between the momentum of each particle and the direction of spin polarisation.

In this work, we investigate these non trivial effects which are expected to modify the phenomenology of infinite polarised matter by going further than some exploratory studies of the past[5].

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Study of the ^{10}Be(t,p)^{12}Be reaction with the SOLARIS spectrometer

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The ^{10}Be(t,p)^{12}Be reaction has been studied with the SOLARIS solenoidal spectrometer. This measurement was carried out in inverse kinematics using a 9.6 MeV/u ^{10}Be beam provided by the ReA6 re-accelerator in stand-alone mode. SOLARIS provides excellent resolution (about 150 keV FWHM) and background rejection capabilities via recoil detection. A titanium tritide target was used. The advantages of this approach, contrasted to the classic study of this reaction in normal kinematics, are higher bombarding energies coupled with recoil detection, allowing for a clean Q-value spectrum and insights into the decay of unbound states in ^{12}Be. We observed the well-known bound states of ^{12}Be and known states above the one- and two-neutron separation energies along with some additional, weakly populated states. Using angular distributions and coincident recoils (^{10}Be, ^{11}Be), we favor spin-parity assignments of 3- and 4+ for the states at 4.58 and 5.72 MeV, respectively. We observe states at approximately 5.0 MeV and 5.4 MeV which have not been clearly observed before. The SOLARIS device, the analysis procedure, and the preliminary results are discussed.

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Towards the r-process path at N=126

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The 208Pb nuclide is the heaviest known doubly-magic nucleus. Information on its neutron-rich neighbourhood is rather scarce, due to the limited mechanisms by which these nuclei can be populated. However, experimental information on neutron-rich N=126 nuclei is of paramount importance not only for nuclear structure physics, but also for implications for astrophysics. Theoretical predictions for exotic nuclei in this region are essential inputs into nucleosynthesis calculations, influencing the yields in the A~195 r-process peak.
Neutron-rich nuclei around 208Pb are under intense scrutiny. However, no B(E2;2+->0+) transition strength was extracted on any of the N=126 nuclei below 208Pb. This quantity, connected to the wave functions of the involved states, often provide the first hint of the erosion of the magicity by exhibiting enhanced collectivity.
The radioactive semi-magic two proton-hole 206Hg nucleus was Coulomb excited for the first time at a safe beam energy using the HIE-ISOLDE facility at CERN [1]. Two gamma rays depopulating low-lying states in 206Hg were observed. The determined reduced transition strength B(E2;2+->0+) of the 1068 keV transition is in line, but slightly lower, than the shell-model predictions. Furthermore, a collective octupole state was identified, and the corresponding transition strength of was extracted. The obtained results were confronted with large scale shell model and time-dependent Hartree-Fock calculations, and are crucial for furthering understanding of both quadrupole and octupole collectivity in the neutron-rich vicinity of the heaviest doubly-magic nucleus 208Pb.
The most exotic N~126 nuclei studied so far were populated in fragmentation reactions at GSI (see e.g. [2,3]). Within the FAIR-0 experimental campaign a number of such studies will be performed within the DESPEC (Decay Spectroscopy) collaboration in spring 2022. An experiment aimed at the beta decay and isomeric decays of the most neutron-rich N=126 nuclei presently accessible, 202Os and 203Ir took place May 2022. The obtained statistics is an order of magnitude higher than previously [2].
The status of knowledge on neutron-rich N=126 nuclei will be presented. This will include the new results on the Coulomb excitation of 206Hg, and hopefully isomeric decays in 202Os, as well as recent works on the competition between allowed and first-forbidden beta decays [4].

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Elucidating the structure of the 16.6 - 16.9 MeV doublet of ^8Be through β-decay feeding

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Elucidating the structure of the 16.6 - 16.9 MeV doublet of ^8Be through β-decay feeding
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The β-decay of the proton halo nucleus ^8B is a precise probe to study the structure of ^8Be. This decay has been studied via several experiments due to its interest in astrophysics, as ^8B is the main source of high-energy solar neutrinos above 2 MeV, i. e. the main contributor to what was known as the "solar neutrino problem" [1]. On the nuclear structure side, the 2^+ isospin doublet formed by two narrow levels at 16.6 and 16.9 MeV, with respectively dominant configurations of ^7Li+p and ^7Be+n, has not been reached in β-decay. This doublet is the best case of predicted full isospin mixing between nuclear states [2].

The β-decay of ^8B (J^π = 2^+, Q_{EC} = 17980(1) MeV)) proceeds mainly (>88%) through the 2^+ state at 3 MeV [3] being this feeding the main source of neutrinos. The remaining decay occurs through the doublet and can be modelled assuming that Fermi strength only goes to the T=1 component and Gamow-Teller strength only to T= 0. Employing this assumption, a B_{GT} of 2.06 can be deduced. In addition, within the Q_{EC} window, the 17.640 MeV 1^+ state can be factorised [4] as a p-halo around the ^7Li-core. This EC-decay can be modelled as occurring in the core ^7Li with the halo proton as a spectator. The strength of this branch is then estimated from the β-decay of ^7Li giving a B_{GT} of 1.83 [5].

The ^8Be nucleus is unbound and breaks up into two α-particles. Theoretically, the transition is dominated by the Gamow Teller contribution up to 15 MeV, however, experimentally this has only been observed up to 8 MeV. The decay of ^8B into the 16.626(3) MeV state has been observed previously, but the (mainly EC) decay into the 16.922(3) MeV state was first hinted at, with only 5 events, in an experiment at JYFL [6].

The MAGISOL (Madrid-Aarhus-Goteborg at ISOL)-collaboration has conducted several beta-decay experiments to study the structure of ^8Be [6,7]. In the IS633 experiment at ISOLDE, a compact 4 particle-telescope setup [7] formed by a Double-Sided Silicon strip Detector (DSSD) of 40 and 60 µm thickness stacked with a 1000 µm thick Si-PAD detector was used. At the centre of the setup, a carbon foil catcher of 30 g/cm^2 was placed to stop the mass-separated 50 keV $^8BF_2$ beam.

The two orders of magnitude higher statistics than any previous 8B experiment, allowed us to resolve the feeding to the 16.6-16.9 MeV doublet for the first time in a beta-decay work. Using these high-statistics data, the feeding of the 2^+ states in ^8Be was studied using the R-Matrix formalism. This has allowed for the first time to experimentally verify whether the 16.6 and 16.9 MeV states of ^8Be are completely isospin mixed [7].

In this contribution, we will present the results of these experiments with special emphasis on the Gamow Teller and Fermi contribution of the ^8B decay. The B_{GT} distribution strength and the isospin mixing the character of the doublet will be addressed.

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Surrogate Reactions in the FRIB Era – New Challenges and Opportunities

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Neutron-induced reactions play an important role in the synthesis of heavy elements in stars. However, many of the nuclei involved in these processes are unstable, so the most important reactions often cannot be measured directly. The Surrogate Reactions Method was developed to indirectly constrain the properties of these elusive nuclei. In it, an experimentally-tractable reaction which forms the "same" compound nucleus as is created in the desired reaction is chosen. The decay of the compound nucleus is measured as a function of its excitation energy, and its properties are used to constrain calculations of the desired reaction.

The advent of FRIB will make many exotic beams and important reactions accessible for the first time. I will discuss the Surrogate Reactions Method, give some experimental highlights, and share ideas about opportunities and challenges in the FRIB era.

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Conversion coating method development for thin-film vanadium targetry

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Nuclear reactions studies provide data that are important for a variety of disciplines and applications. However, experimentally measured neutron reaction cross-section data for radionuclides are limited. Having the capability to produce radioactive targets would enhance the ability to obtain accurate nuclear data which leads to improved computational models for studies predicting yields from stellar nucleosynthesis or for nuclear validation applications. One radioisotope of vanadium, V-48, is important for nuclear validation purposes and currently lacks experimentally measured neutron-induced charged particle reaction cross-section data. Targets for such studies must be thin and durable during irradiation. A vanadium chemical conversion coating onto an aluminum foil may provide a method to produce radioactive vanadium targets that meet the specifications demanded from neutron-induced charged particle cross-section studies. The efforts to develop these thin-film vanadium targets will be discussed.

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KDK: first measurement of the rare electron-capture decay of 40K to the ground state of 40Ar

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Potassium-40 (40K) is a naturally-occurring radioactive isotope. It is a background in searches for exotic subatomic particles, plays a role in geochronology, and has a nuclear structure of interest to theorists. This radionuclide decays mainly by beta emission to calcium, and by electron-capture to an excited state of argon. The electron-capture decay of 40K directly to the ground state of argon has never been measured, and predicted intensities are highly variable (0–0.22%). This poorly understood intensity may impact the interpretation of a controversial claim of dark matter discovery [1]. The KDK (potassium decay) experiment has carried out the first measurement of this electron-capture branch, using a novel setup at Oak Ridge National Labs [2]. KDK deployed a very sensitive inner detector to trigger on the ~keV radiation emitted by both forms of electron capture, surrounded by a very efficient veto to distinguish between the decays to ground state and those to the excited state. We present result of the experiment [3] and implications for various fields.

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Super-allowed alpha decay to doubly-magic ^{100}Sn

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The proton-rich doubly-magic self-conjugate nucleus ^{100}Sn and neighboring nuclei are a site of unique nuclear phenomena and a test bed for modern nuclear models. The ^{100}Sn nucleus is one of the fastest known Gamow-Teller β emitters. Due to close proximity of the proton drip line, nuclei with Z>50 and N>50 near ^{100}Sn form an island of α and proton emitters which decay towards ^{100}Sn. Alpha decays of proton-rich Te isotopes were proposed to terminate the astrophysical rp-process. Consequently, despite small production cross sections, this region of nuclear chart has been an aim of numerous experimental studies.
In an experiment with the Fragment Mass Analyzer at ATLAS, the super-allowed α-decay chain ^{108}Xe-^{104}Te to doubly-magic ^{100}Sn was observed [1] using the recoil-decay correlation technique. This was the first time that evidence was found for production of ^{100}Sn in a fusion-evaporation reaction. This observation is an important stepping-stone towards developing a microscopic model of α decay, since it is only the second case of α decay to a doubly-magic nucleus besides the benchmark ^{212}Po α decay to ^{208}Pb, and it triggered a flurry of theoretical activity. The decay properties of ^{108}Xe and ^{104}Te indicate that in at least one of them the reduced α-decay width is a factor of 5 larger than in ^{212}Po, which confirms their super-allowed character. This could be explained by an enhanced α-particle preformation probability due to a stronger interaction between protons and neutrons, which occupy the same orbitals in N=Z nuclei. The Q_α-values deduced for the very exotic ^{108}Xe and ^{104}Te nuclei are consistent with the doubly-magic nature of ^{100}Sn. Interestingly, a weak proton-decay branch in ^{108}I was found in the same experiment. The deduced ^{104}Sb Q_p value rules out the formation of the Sn-Sb-Te cycle at ^{103}Sn.
Further experiments to observe more ^{108}Xe-^{104}Te α-decay chains and to better characterize the properties of other α emitters in the ^{100}Sn region are planned. Tests with the recently constructed Argonne Gas-Filled Analyzer, which offers much higher efficiency, will be discussed.

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Gamma-ray spectroscopy of the neutron-rich ^{55,57,59}Sc isotopes

Auteur: Radostina Zidarova[1]

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Experimental data have shown that far from the valley of stability the nuclear shell structure evolves. New magic numbers can emerge and the traditional ones can disappear. In particular, two new magic numbers at N=32 and N=34 have been suggested in the vicinity of Z=20 based on gamma-ray spectroscopy and mass measurements. In order to assess the impact of a single valence proton outside of the Z=20 shell on the shell-evolution mechanism in this region, it is necessary to study the neutron-rich Sc isotopes around, and even beyond, neutron number N=34. Investigation of exotic nuclei in this region was the goal of the third SEASTAR campaign at RIKEN-RIBF. Neutron-rich isotopes in the vicinity of ^{53}K were produced by fragmentation of a primary ^{70}Zn beam on a ^{9}Be target. Known and new γ-ray transitions of the isotope ^{55}Sc were observed and γ-rays from ^{57,59}Sc were identified for the first time. Observed γ spectra from ^{55,57,59}Sc will be presented together with preliminary level schemes. They will be discussed in the framework of the tensor-driven shell evolution.

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The ALTO facility of IJCLab

Auteur: Enrique Minaya Ramirez[1]

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The ALTO (Accélérateur Linéaire et Tandem d'Orsay) research platform of IJCLab consists of two accelerators : a 15 MV Tandem electrostatic accelerator for stable beams from proton to heavy ions, clusters and neutron production, and a 50-MeV 10-µA electron linear accelerator for the production of low energy radioactive beams by photofission. These machines are surrounded by a large variety of experimental instruments/devices located on 10 different beam lines. The diversity of the beams produced facilitates wide-ranging research in nuclear physics, nuclear astrophysics and interdisciplinary activities such as health physics. ALTO has some unique features: It delivers low-energy radioactivity beams from the photofission of 238U, it can provide rare heavy-ion beams such as 3He and 14C, and is also unique in its capacity to provide high-flux naturally directional neutron beams

with the LICORNE neutron converter. An overview of the ALTO facility as well as some of the highlights and prospects of the experimental schedule will be given.

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Beta-neutrino angular correlation measurements of mirror transitions with St. Benedict

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Co-auteurs: Maxime Brodeur [1]; Daniel Burdette [2]; Jason Clark [2]; Aaron Gallant [3]; Alicen Houff [1]; Biying Liu [1]; Patrick O'Malley [1]; Fabio Rivero [1]; Guy Savard [2]; Adrian Valverde [4]; Regan Zite [1]

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Precise measurements of nuclear beta decays provide a unique insight into the Standard Model due to their connection to electroweak interactions. These decays can provide constraints on the unitarity or non-unitarity of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix, where non-unitarity would signal potential physics Beyond the Standard Model. The most precise of these tests involves the matrix element V_{ud} as determined from superallowed pure Fermi beta decays, and indicates a deviation from unitarity on the order of 2.4σ. As such, cross-checks from additional methods, including superallowed mixed mirror beta decays, are necessary. V_{ud} precision from mirror decays is currently limited by the absence of precise Fermi-to-Gamow Teller mixing ratios, which are most sensitively determined via the angular correlation of the neutrino and beta particle emitted during the decay. At the Nuclear Science Laboratory (NSL) at the University of Notre Dame, the Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict) is being constructed to determine the beta-neutrino angular correlation parameter of various mirror decays. We plan on measuring this correlation parameter for the beta decays of nuclei ranging from ^{11}C to ^{41}Sc using radioactive ion beams from the NSL's TwinSol separator, which will result in significantly improved precision of the V_{ud} element of the CKM matrix from superallowed mirror transitions. The status of the development of St. Benedict, including its beam preparation and measurement stages, will be presented.

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Core-breaking effects around 100Sn: lifetime measurements in the most neutron-deficient Sn isotopes.

Auteurs: guangxin Zhang[None]; Daniele Mengoni[1]; Marta Polettini[2]; giovanna benzoni[3]

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The long Sn isotopic chain is a formidable testing ground for nuclear models aiming at describing the evolution of the shell structure. Low-lying excited states roughly exhibits the typical behavior predicted by the generalized seniority scheme. However, the corresponding B(E2; $0^+ \rightarrow 2^+$) values, approaching the N=Z=50 shell closure, have shown a presumed deviation from the expected parabolic

behavior [1]. From a theoretical point of view, various attempts have been done to explain such experimental results, in particular by including core-breaking excitations in the shell-model calculations and promoting protons and neutrons from the g9/2 orbital across the shell gap [2]. From the experimental side, limited data are available beyond 104Sn and no lifetime information are known in this extremely neutron-deficient region, leading to a difficulty in a firm evaluation of any core-breaking effects.

In this contribution, we will report recent results on lifetime measurements in 102,103Sn. The experiment was performed in May 2021 at GSI using the AIDA Si active stopper surrounded by the EUROBALL HPGe and the FATIMA LaBr3 array. The nuclei of interest were identified in the FRS separator, following the production via fragmentation reactions of a 124Xe beam on a ^{9}Be target. The Sn isotopes have been stopped in the AIDA array and the decaying gamma rays collected by the FATIMA array, which allowed for a direct lifetime measurement with a precision up to few tens of ps. The analysis is ongoing and the preliminary results will be presented, together with their possible implications.

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Exploring low-lying states in 136Cs and 136Ba relevant for 136Xe neutrinoless double beta decay

Auteur: Bernadette Rebeiro[1]

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Benchmarking against experimental data is critical for nuclear matrix element (NME) calculations of various neutrinoless double beta decay (0nbb) candidates. As next-generation xenon-based detectors are expected to scale up in size and enhance their sensitivity to probe the inverted neutrino mass hierarchy region and beyond, it is increasingly important to accurately calculate the matrix element for 136Xe 0nbb decay. This talk will focus on recent spectroscopic studies of low-lying states in 136Cs and 136Ba, and discuss their impact on calculations of the 136Xe 0nbb NME.

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Elastic scattering of 6He+d at 26 MeV/A

Auteur: Bogumił Zalewski[1]

Co-auteurs: Krzysztof Rusek [1]; Mikhail Golovkov [2]; Sergey Belogurov [2]; Andrey Bezbakh [2]; Vratislav Chudoba [2]; Andrey Fomichev [2]; Elvira Gazeeva [2]; Alexander Gorshkov [2]; Grzegorz Kamiński [2]; Sergey Krupko [2]; Bakytbek Mauyey [2]; Ivan Muzalevskii [2]; Paweł Napiorkowski [1]; Yuri Nikolskii [2]; Wojciech Piątek [1]; Adilzhan Serikov [2]; Sergey Sidorchuk [2]; Roman Slepnev [2]; Pavel Sharov [2]; Natalia Sokołowska [3]; Gurgen Ter-Akopian [2]; Agnieszka Trzcińska [1]; Roman Wolski [2]

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Nuclei far away from the stability line are at the center of attention of modern nuclear physics. With the considerable imbalance between neutron and proton numbers, they are a great testing point for theoretical models. Neutron halo nuclei are the most prominent examples of such nuclei. They consist of a stable core and one or two loosely bound neutrons orbiting the core. The lightest halo nucleus is Helium-6 which due to the small number of nucleons is among the most straightforward systems to treat from a theoretical point of view. Experimental studies of such an unstable nucleus are complex due to the low intensities of produced beams. One of the solutions for this problem is using high cross-section processes such as elastic scattering.
For ^6He, many experiments have been performed investigating the coupling of the elastic scattering with the breakup channels. At low energies, the method of continuum-discretized coupled channels (CDCC) is one of the most effective for the interpretation of experimental results [1]. This presentation will review the most recent results for the $^6He + d$ elastic scattering measurement, in inverse kinematics, at 26MeV/n beam energy. The experiment was performed in 2018. Such a scattering, involving these two weakly bound nuclei, was performed for the first time. The results could be useful for expanding the CDCC method for a four-body framework [2].
The obtained data set was analyzed in two steps. First, an effective optical model potential was derived from the analysis of $^6He + p$ elastic scattering data measured at the same energy. This potential accounts for the effects due to the ^6He breakup [3]. In the second step, this potential was used to derive the optical model potential for $^6He + d$ by means of the single folding (SF) method [4]. The wave function of the deuteron ground state included the S- and D- state contributions [5]. The nuclear part of the $^6He + n$ optical model potential used in the SF calculations was assumed to be the same as that for $^6He + p$. A comparison of the optical model calculations involving the SF $^6He + d$ potential showed good agreement with the experimental data. This result suggests that the effects due to deuteron breakup on the $^6He + d$ elastic scattering are small. In the same experiment differential cross-section for the $^6He(d, t)^5He$ reaction was obtained. The results of the analysis with DWBA and Coupled Reactions Channels will be presented.

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parallel session / 521

Precision half-life measurements of mirror transitions at Notre Dame

Auteur: Maxime Brodeur[1]

Co-auteurs: Adrian Valverde [2]; Alicen Houff [1]; Biying Liu [1]; Catherine Nicoloff [3]; Dan Bardayan [1]; Daniel Burdette [4]; Fabio Rivero [1]; Jacob Long [1]; James Kolata [1]; Patrick O'Malley [1]; Regan Zite [1]; Sam Porter [1]

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Despite its success, the Standard Model (SM) is currently being scrutinized on multiple fronts as it fails to explain many features of nature including the matter/anti-matter asymmetry, dark matter and even gravity. One probing mechanism for new physics is the unitarity test of the Cabibbo-Kobayashi-Maskawa matrix. A series of recent transition-independent radiative corrections resulted in a reduction of the Vud matrix element creating a 2.4 sigma tension with unitarity. Consequently, the determination of this matrix element, derived from the ft-value of superallowed beta decays, is under scrutiny. While superallowed pure Fermi transitions currently allow for the most precise determination of Vud, there is currently a growing interest in obtaining that matrix element from

superallowed mixed transitions to test the accuracy of Vud and the calculation of isospin symmetry breaking corrections. In the past few years, a research program aimed at solidifying the determination of Vud from mirror transitions was initiated using radioactive ion beams from the Twin Solenoid (TwinSol) separator at the Nuclear Science Laboratory of the University Notre Dame. As part of this program, several half-lives have been measured, some for the first time in 40 years, to relative uncertainties in the 0.01% range. These range from 11C to 33Cl and include the measurement of 20F and, more recently, 28Al, which are also both of interest for searches of second-class currents. These recent measurements as well as future measurements will be presented.

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Possible Existence of Extremely Neutron-Rich Superheavy Nuclei in Neutron Star Crusts Under a Superstrong Magnetic Field

Auteur: Kazuyuki Sekizawa[1]

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We investigate outer crust compositions for a wide range of pressures (densities) and magnetic-field strengths, adopting the latest experimental masses (AME2020) supplemented with various theoretical mass models. By exploring the optimal composition of nuclei in the entire nuclear chart, we find emergence of neutron-rich heavy nuclei, which are much heavier than previously thought (that was at most $Z \approx 50$), mainly because of the increasing electron density with the magnetic field strength, which allows nuclei to exist at higher densities without leakage of neutrons. We point out a clear manifestation of neutron magic numbers, e.g. $N = 50, 82, 126$, as well as 184, and possibly those around the next spherical magic number $N \approx 258$. Furthermore, surprisingly enough, for $B \geq 4 \times 10^{18}$ G, we find that superheavy nuclei with $Z > 110$, including the unknown element 119, naturally emerge as optimal compositions that minimize the Gibbs energy. In this talk, we will explain the aforementioned findings and discuss possible consequences.

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First results from ATLANTIS - A new collinear laser spectroscopy setup at Argonne National Laboratory

Auteur: Bernhard Maaß[1]

Co-auteurs: Alex Brinson [2]; Daniel Burdette [1]; Jason Clark [1]; Adam Dockery [3]; Max Horst [4]; Phillip Imgram [5]; Kristian König [4]; Kei Minamisono [6]; Patrick Müller [7]; Peter Mueller [1]; Wilfried Nörtershäuser [4]; Skyy Pineda [8]; Simon Rausch [9]; Laura Renth [10]; Brooke Rickey [3]; Daniel Santiago-Gonzalez [1]; Guy Savard [1]; Felix Sommer [10]; Adrian Valverde [11]

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The region of refractory metals, below the magic number $Z = 50$ is of particular interest for nuclear physics studies and exhibits phenomena such as deformations, shape coexistence and hints of triaxial nuclei. Laser spectroscopy has provided valuable and complementary input, providing information about the shape, size and electromagnetic moments of radioactive isotopes and isomers in this region. The CARIBU californium-252 fission source at Argonne National Laboratory can uniquely produce sufficiently intense low-energy ion beams of neutron-rich isotopes in this part of the nuclear chart. Therefore, the new collinear laser spectroscopy setup, ATLANTIS – the Argonne Tandem hall LAser beamliNe for aTom and Ion Spectroscopy– was installed at the low-energy branch of CARIBU.

The setup includes a dedicated open-gate cooler-buncher that prepares and delivers cooled ion beams with minimal energy and time spread and a laser ablation source to produce stable isotope beams. The laser spectroscopy beamline is fitted with a low-energy charge exchange cell suited for high-temperature application to also allow spectroscopy on atomic beams and a highly efficient 4π mirror system to collect fluorescence ions.

In this talk, the results of the first measurements of short-lived isotopes of palladium and ruthenium obtained at ATLANTIS will be discussed, and an outlook of future laser spectroscopy endeavors at Argonne National Laboratory will be given.

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Precision Lifetime Measurements of Excited States in 38Si and 36Si

Auteur: Mara Grinder[1]

Co-auteurs: A. Dewald ; ALDRIC REVEL [2]; Alexandra Gade [2]; Brandon Elman [2]; Brandon Longfellow [2]; Charles Loelius [2]; Daniel Bazin [2]; Dirk Weisshaar [3]; Eric Lunderberg [2]; Hironori Iwasaki [4]; J. Belarge [2]; John Ash [5]; Kenneth Whitmore [6]; M. Mathy ; Nobu Kobayashi [2]; Peter Bender [2]; Robert Elder [7]; S. Heil ; T. Haylett ; Tea Mijatovic [2]

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Rapid shape transitions are predicted by the shell model calculations as a result of the nuclear shell structure significantly evolving in the neutron-rich region at the traditional magic numbers N=20 and 28. The energy ratios between the first 2+ and 4+ states in the even-even silicon isotopes from N=20 to 28 suggest a variety of collectivity evolving from vibrational, to possible triaxial, to rotational modes. The systematic behavior of the level schemes along the silicon isotopic chain suggests 38Si as the turning point in this transition. The lifetime measurements of 38Si and 36Si were performed at the National Superconducting Cyclotron Laboratory based on the Recoil-Distance Method using the Gamma-Ray Energy Tracking In-Beam Nuclear Array (GRETINA). The data was used to extract the B(E2) ratios for the yrast 2+ and 4+ states in 38Si and the yrast 4+ and 6+ states in 36Si. These ratios were then compared to theoretical models.

Friday / **527**

Present status and future prospect of the SCRIT electron scattering facility

Auteur: Kyo Tsukada[1]

Co-auteurs: Akitomo Enokizono [2]; Clement Legris [3]; Daiki Abe [3]; Hikari Wauke [3]; Kazushi Ishikura [3]; Kazuyoshi Kurita [2]; Masahiro Hara [4]; Masamitsu Watanabe [4]; Masanori Wakasugi [1]; Rika Danjo [3]; Ryo Obara [3]; Ryo Ogawara [1]; Satoru Yoshida [1]; Shin'ichi Ichikawa [4]; Shun Iimura [2]; Tadaaki Tamae [3]; Tadatoshi Hori [4]; Taiga Goke [3]; Tetsuya Ohnishi [4]; Toshimi Suda [3]; Tsubasa Yamano [2]; Yasushi Abe [4]; Yoshiki Maehara [1]; Yuki Honda [3]; Yuki Ito [1]; Yuma Ishikura [3]

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The SCRIT (Self-Confining RI Ion Target) electron scattering facility [1] was constructed to realize electron scattering from short-lived unstable nuclei at RIKEN in Japan. Electron scattering is one of the most powerful tools for structure studies of atomic nuclei because of the well-understood mechanism of electromagnetic interaction. It has, however, never been applied to short-lived unstable nuclei because of the difficulty in preparing thick target although it has been long-desired to investigate exotic features of unstable nuclei by electron scattering [2].
Recently, we succeeded in realizing the world's first electron scattering from online-produced unstable nuclei at the SCRIT facility after years of developments. Caesium nuclides were produced via photo-fission of uranium by irradiating 28-g uranium with 15-W electron beam and were ionized with the surface ionization type ion source at an ISOL system [3]. Thanks to a high production rate of caesium nuclides and the development of beam stacking methods in the ISOL and a Cooler-Buncher [4] systems, approximately 10^7 of ^{137}Cs ions/pulse beams were delivered into the SCRIT system, the averaged luminosity of 0.9×10^{26} cm^{-2}s^{-1} was achieved. The obtained angular distribution of elastically scattered electrons is consistent with a calculation. This experiment perfectly mimics the experiment of electron scattering from short-lived unstable nuclei produced online after the power of the ISOL driver is upgraded.
In this contribution, we will report recent results and future prospect of the SCRIT electron scattering facility.

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New structure features revealed in isomeric spectroscopy in the Z ~ 82,N ~ 104 region

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Neutron-deficient nuclei around mid-shell at N ~ 104 in the lead region provide many examples of shape coexistence and shape isomers [1]. In order to study shape coexistence in this region, prompt and delayed γ-ray spectroscopy of the ^{187}Pb and ^{183}Hg isotopes produced in the reaction ^{50}Cr+^{142}Nd→^{192}Po* has been performed at the Argonne Gas-Filled Analyzer.
In ^{187}Pb, a new 5.15(15)-μs isomeric state at 308 keV above the spherical 3/2− ground state was identified. A strongly-coupled band is observed on top of this isomer, which is nearly identical to the one built on the prolate 7/2−[514] Nilsson state in the isotone 185Hg. Based on this similarity and on the result of the potential-energy surface calculations, the new isomer in 187Pb was proposed to be prolate with J^π = 7/2− and classified as a shape isomer. The retarded character of the 308-keV (7/2−)→3/2− gs transition with a deduced $B(E2)$ = 5.6(2) × 10−4 W.u. can be well explained by the significant difference between the prolate parent and spherical daughter configurations, leading to the shape isomerism [2].
In ^{183}Hg, the decay of the nearly spherical 13/2+ isomeric state was first observed following the α decay of the 13/2+ isomer in ^{187}Pb. By the α−γ correlation measurement, the half-life of this isomer was measured to be $T_{1/2}$ = 290(30) μs. This isomer was proposed to deexcite by retarded $M2$ transition, which can be explained by the notable shape change between the initial and the final states [3].

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Initial RI Beam Commissioning of the RAON ISOL Facility

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The ultimate goal of RAON (Rare Isotope Accelerator Complex for Online Experiments) is to combine the Isotope Separator On-Line (ISOL) and In-Flight Separator (IF) systems to produce more exotic rare isotope (RI) beams and access unexplored regions of the nuclear landscape. As the first step, we completed the installation of the ISOL facility in June 2021. The RAON ISOL facility consists of a driver accelerator, a target/ion source (TIS) capable of full remote handling, a pre-mass separator, a Radio Frequency Quadrupole Cooler Buncher (RFQ-CB), an Electron Beam Ion Source Charge Breeder (EBIS-CB) and an A/q separator. The driver accelerator utilizes an H- Cyclotron with an energy of 70 MeV. The primary proton beam of up to 0.75 mA is delivered to the ISOL target/ion source (TIS) module, producing relatively pure and low-energy rare isotopes. The existing TIS module can accommodate up to 10 kW beam power, and it is expected that neutron-rich isotope ions will be produced by uranium fission reaction processes with the rates of 10^{13} fission/s from the maximum beam power. The development of a high-power target and module system that can be operated reliably up to 70 kW proton beam power without compromising the yield of rare isotopes will be a future challenge.
The RI ion beams extracted from the TIS can be transported to the pre-mass separator and cooled in the RFQ-CB. Cooled ion beams can be sent to either a mass measurement system (MMS) or collinear laser spectroscopy (CLS) for the investigation of the fundamental properties of exotic nuclei in the ISOL experimental hall. Alternatively, RI beams can be transported to an A/q separator after charge breeding with the energy of 10 keV/u through RFQ-CB and EBIS-CB and later sent to the RAON injector system for post-accelerator.
The beam commissioning of the 70 MeV proton cyclotron was completed in January 2023, and the first RI beam commissioning using the SiC target for RAON ISOL has started.

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Investigation of negative-parity band in ^{130}Cs

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Investigation of negative-parity band in ^{130}Cs
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Odd-odd Cs isotopes have been extensively studied by means of in-beam γ-ray spectroscopy, especially the positive-parity band based on $\pi h_{11/2} \otimes \nu h_{11/2}$ for the chiral symmetry and signature inversion [1,2]. Our present study focuses on a negative-parity band based on $\pi h_{11/2} \otimes \nu g_{7/2}$ valence particle configuration in ^{130}Cs [3]. We have studied the band structure by measuring lifetimes (in ps) of excited states using Doppler shift attenuation method (DSAM). Our new results on reduced transition probabilities (B(E2) and B(M1)) established the triaxial nature of the band consistent with the total Routhian surface (TRS) calculation.

We utilized the fusion-evaporation reaction ^{124}Sn(^{11}B, 5n)^{130}Cs to populate the high spin states of ^{130}Cs. Energetic ^{11}B beam at 70 MeV was delivered by the Pelletron accelerator facility at the Tata Institute of Fundamental Research, Mumbai, India. We utilized a self-supporting target (^{124}Sn) of thickness $\sim$ 2.2 mg/cm^2 sufficient to stop most of the recoiling nuclei. The emitted γ-rays were detected by the 21 Compton suppressed HPGe Clover detectors of Indian National Gamma Array (INGA) [4]. The valid two- and higher-fold coincident γ-events were recorded in list mode using PIXIE-16 based digital data acquisition system. The standard procedure of data analysis was adopted as described in our earlier work [5]. For the concerned negative-parity band, we first confirmed the decay scheme and spins up to 22 $\hbar$ by finding the Directional Correlation ratios. To extract the lifetimes, we fitted the DSAM lineshape profiles using the code LINESHAPE [6] for detectors located at angles of 23^0, 90^0, 157^0.

From our DSAM analysis, we determined the lifetimes of four states (14$^-$ to 20$^-$) within the range of 0.4 to 1.2 ps, with an average B(E2) value of 0.4 e^2b^2. There seems to be a slight decrease in B(E2) values with increasing spin. Interestingly, the band exhibits some striking features. Only the even spin states are populated above the bandhead 8$^-$, so the M1 transitions are missing. Above the backbend at around $\hbar\omega \simeq$ 0.38 MeV, both signature spins are observed with M1 transitions. However, the M1 is much weaker than the E2 transitions. The band shows the decoupling behaviour up to 16 $\hbar$, with energy spacings similar to the neighboring even-even and odd-even nuclei – the ground state band of ^{128}Xe [7] and $\pi h_{11/2}$ band of ^{129}Cs [5].

We performed the total Routhian surface (TRS) [8] calculation to study various features of the band. Firstly, we determined the deformation parameters values (β, γ) for the minimum energy configuration, from the contour plots for the band configuration $\pi h_{11/2} \otimes \nu g_{7/2}$. In addition, we identified the first band-crossing for the neutron alignment in $h_{11/2}$ orbit from the quasi-particle Routhian diagram. The theoretical crossing frequency (0.40 MeV) was in agreement with the experimental observation. The proton alignment was ruled out because of the high values of the band-crossing frequencies for both positive and negative-parity orbits. Furthermore, we confirmed the neutron alignment by comparing the experimental B(M1) values with those obtained from the geometrical model of Donau and Frauendorf [9,10]. We extracted the experimental B(M1) values from the B(M1)/B(E2) ratios determined from the γ-ray intensity measurements, and B(E2) estimated from the DSAM analysis. Again, the proton alignment was ruled out by comparing the estimated and experimental B(M1) values.

In summary, we have investigated thoroughly the structure of the negative-parity band through lifetime measurement near and above the band-crossing region. A triaxial nuclear shape was inferred with deformation parameter values β = 0.16 and $\gamma = -30^0$ (in Lund convention) using the total Routhian surface calculation. We also established the neutron alignment with configuration $\pi h_{11/2} \otimes \nu g_{7/2}(h_{11/2})^2$.

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Beta-Delayed Neutron Spectroscopy of Californium-252 Fission Fragments with BEARtrap at Argonne National Laboratory

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Beta-delayed neutron emission properties are important to both basic science and applications-driven nuclear physics research. Branching ratios for these decays of neutron-rich nuclei play a role in r-process nucleosynthesis calculations as they are needed to determine final abundance patterns. The energy spectra of beta-delayed neutron precursors are also of interest to the development of advanced fuel cycles for nuclear reactors. A new recoil-ion technique has been developed to measure these properties without direct neutron detection. This method involves trapping the parent nucleus at the center of a Paul trap, and then measures the time of flight of the recoiling ion relative to the beta particle following beta decay. This allows for identification of beta-delayed neutron events, as well as a kinematic reconstruction of the neutron energy. This technique was conducted on various fission fragments generated by the californium-252 source of the CARIBU facility at Argonne National Laboratory using the Beta-decay Paul Trap (BPT), which was designed for precision measurements of beta decay on lighter nuclei. These measurements allowed for the determination of branching ratios and energy spectra for various beta-delayed neutron precursors, however, they also provided a good learning benchmark in how the trap and detector systems could be improved to perform future measurements. As a result, a dedicated trap and detector array, referred to as the BEtA Recoil-ion trap (BEARtrap), have been developed. The experimental setup is located in CARIBU's low-energy experimental area to study the large number of unmeasured beta-delayed neutron precursors generated by both the current source, and the forthcoming nuCARIBU upgrade. An overview of the experimental method, ion trapping, and detector systems as well as the first science case of the new apparatus will be presented.

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Medical Radioisotope Production Using Inverse Kinematics

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A novel approach to produce medically important radionuclides using inverse kinematics [1-3] has been developed at the Cyclotron Institute at Texas A&M University. The methodology involves a heavy-ion beam of appropriate energy impinging on a light gas target (e.g., H_2, D_2, $^{3-4}$He, ...) and collecting the isotope of interest, focused along the beam direction, on a foil catcher after the target. In addition, secondary emitted particles such as neutrons from the primary nuclear reaction can be used to irradiate a secondary target for further radionuclide production. As the quantity of the material required to prepare the heavy-ion beam is considerably smaller than that used in the standard solid target approach, material costs are expected to be reduced via this methodology. The theranostic radionuclide ^{67}Cu ($T_{1/2} = 62h$) was produced through the reaction of a ^{70}Zn beam at 15 MeV/nucleon with a hydrogen gas target [1-2]. The ^{67}Cu radionuclide alongside other coproduced isotopes, was collected after the gas target on an aluminum catcher foil. Their radioactivity was measured by off-line γ -ray analysis. In addition, the forward-focused neutrons from the primary reaction were used to irradiate a ^{nat}Zn target in order to produce more ^{67}Cu. Pursuing this initial investigation, the well-known $^{99}Mo/^{99m}Tc$ generator system [3] was also investigated with a beam of ^{100}Mo at 12MeV/nucleon on ^{4}He gas cell target for three different gas pressures. The methodology was tested with success. The production of the ^{67}Cu and ^{99}Mo were predominant in comparison with the various radio-impurities. In order to achieve production appropriate for preclinical studies, high-intensity heavy-ion primary beams are necessary.

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First measurement of a p-process reaction using a radioactive ion beam

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Approximately 30 stable nuclides on the neutron-deficient side of stability cannot be produced via the same neutron-capture driven mechanisms responsible for synthesizing all other elements heavier than iron. These "p-nuclei" are instead thought to originate from photodisintegration reactions on s- and r-process seed nuclei, which can occur in the extreme high-temperature environments of core-collapse supernovae. However, significant discrepancies exist, in some cases extending to orders of magnitude, between observed p-nuclei abundances obtained via isotopic analysis of meteorite samples, and supernovae model predictions. Improving on the available nuclear reaction data is an essential part of solving the puzzle of the p-nuclei, but experimental efforts in this regard must overcome significant technical challenges. This talk will describe the first ever measurement of a p-process reaction cross-section obtained with a radioactive ion beam. The 83Rb(p,γ)84Sr reaction was investigated at the TRIUMF-ISAC facility using a radioactive 83Rb beam impinged on CH2 foil targets. The recoiling reaction products were selected by m/q using the newly commissioned Electromagnetic Mass Analyser (EMMA), with γ-rays detected in-coincidence using the TIGRESS HPGe array. The high sensitivity of the combined EMMA-TIGRESS set-up allowed detection of low-lying transitions in 84Sr populated by 83Rb(p,γ)84Sr. The measured partial cross-section was then combined with statistical model calculations to obtain a total reaction cross-section that is 4x smaller than predicted, in-turn affecting the abundance of the 84Sr p-nucleus predicted by massive-star models.

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Ξ hypernuclei ${}^{15}_{\Xi}$C and ${}^{12}_{\Xi}$Be, and the ΞN two-body interaction

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The study of interaction in the strangeness $S = -2$ sector is important in hypernuclear physics for unified understanding of baryon-baryon interaction. To this end, it is crucial to study structure of double-strangeness hypernuclei such as double-Λ and Ξ hypernuclei.

In this work [1], we focus on the new experimental data, which is named "IRRAWADDY" event, of ${}^{15}_{\Xi}$C nucleus observed at $B_\Xi = 6.27 \pm 0.27$ MeV. We estimate the strengths of the ΞN interaction and give a consistent interpretation for all the existing events of the Ξ hypernucleus including IRRAWADDY. In addition to our previous work [2] based on the relativistic mean-field (RMF) model, we introduce an ΞN residual interaction and infer that KINKA ($B_\Xi = 8.00 \pm 0.77$ or 4.96 ± 0.77 MeV) and IRRAWADDY events are the ground-state spin doublet with the Ξ particle in the s orbit, and that IBUKI ($B_\Xi = 1.27 \pm 0.21$ MeV) and KISO ($B_\Xi = 3.87 \pm 0.21$ or 1.03 ± 0.18 MeV) events are members of the excited-state multiplets with the Ξ particle in the p orbits.

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First results with the Advanced Rare Isotope Separator (ARIS) at FRIB

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Commissioning of the Facility for Rare Isotope Beams (FRIB) in-flight separator system Advanced Rare Isotope Separator, ARIS, began in early 2022. The system consists of up to three stages of achromatic separation based on large superconducting magnets and can deliver beams to various experimental stations for nuclear and astrophysics studies, as well as other societal needs. ARIS is

designed to be able to work with 400kW of primary beam power. The conceptual design and the comparison to commissioning studies will be presented.

In this contribution we summarize first results of rare beam isotopes production, and then to focus on high Z isotopes production in the recent commissioning experiment, that demonstrates ARIS abilities to separate and identify isotopes produced in the energy range of 100-200 MeV/u. Isotope production results and comparison with production models will be presented.

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Isospin symmetry in the A=78 triplet - gamma-ray spectroscopy of 78Y and 78Zr

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The isospin symmetry concept has its origins in the charge-symmetry and charge-independence characteristics of the strong nuclear force. This implies that the strong interaction has an equal strength between the proton-proton, neutron-neutron and proton-neutron pairs. Therefore, the isobaric analog nuclei of the same mass $A = N + Z$, but with the neutron and proton numbers differing as $N = Z - 2$, $N = Z$ and $N = Z + 2$, should contain the same set of excited states at similar excitation energies. This assumption holds in the absence of the electromagnetic effects, but in practice the isobaric analog states (IAS) manifest energy differences resulting, e.g., from the Coulomb interaction. Investigations of the Coulomb, mirror and triplet energy differences have proven to be an effective probe for the nuclear structure, but have also provided information on the conservation of the isospin symmetry. During the past two decades a wealth of evidence has been collected for an isospin-breaking two-body interaction in the $A = 50 - 70$ mass region. This additional schematic interaction, in combination with the Coulomb force, appears to be required to reproduce the experimental data on the triplet energy differences.

Since the $N = Z$ line approaches the proton-drip line in the $A > 70$ mass region, spectroscopic data for these triplets are scarce, which in turn prevents the investigations of the energy differences between IAS. This is particularly true for the mass $A = 78$ triplet (^{78}Zr, ^{78}Y and ^{78}Sr). The excited states in ^{78}Zr are not currently known at all, while only two excited states have been tentatively assigned in ^{78}Y. Recently, an experiment was performed at the Accelerator Laboratory of the University of Jyvaskyla to investigate the structures of ^{78}Zr and ^{78}Y. This study employed the ^{40}Ca(^{40}Ca, *2n/pn*)^{78}Zr/^{78}Y fusion evaporation reaction, the JUROGAM 3 Ge-array coupled to the vacuum-mode recoil separator MARA and the recoil-beta tagging technique. The preliminary analysis of this data has resulted in the discovery of several new excited states in ^{78}Y and a candidate for the 2^+ -> 0^+ transition in ^{78}Zr observed via recoil-beta-beta correlations. This presentation discusses the new experimental results obtained for the mass $A = 78$ triplet in the context of the predictions obtained from nuclear theory.

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Investigation of axial shape in ^{130}La through lifetime measurements

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The shape coexistence in a collective excitation mode of atomic nuclei is widely discussed in the last decades [1]. In mass region ≈ 130, the doubly odd nuclei are the excellent examples because of their γ-soft core as well as the presence of valence particles (protons and neutrons) in unique parity $h_{11/2}$ orbitals. The case of ^{130}La is a beautiful example of shape coexistence [2-6]. Many different shapes – triaxially deformed, axially deformed, excited collective oblate structure, and superdeformation – were seen in ^{130}La. In the present study, we focus on the axially deformed (prolate) band based on the valence particle configuration $\pi h_{11/2} \otimes \nu g_{7/2}$. The band shows signature splitting and backbending. Our motivation has been to test experimental values of reduced transition probability (B(E2)) over two-quasiparticle plus rotor model as well as cranking calculations. We extracted the B(E2) values by measuring lifetimes (in ps) of the excited states using the Doppler shift attenuation method (DSAM). We have indeed found a near axial symmetry in nuclear shape, and neutron alignment above the band crossing.

We performed an experiment at the Inter-University Accelerator Center (IUAC) (New Delhi, India) to populate the high spin states of ^{130}La. The Indian National Gamma Array [7], consisting of eighteen compton-suppressed clover HPGe detectors placed at the angles 32°, 57°, 90°, 123°, and 148°, was utilized. We decided a self-supporting target ^{116}Cd of thickness 4.6 mg/cm^2 sufficient to stop most of the recoiling nuclei. It was bombarded with ^{19}F beam at energy 94 MeV using the 15UD pelletron accelerator, forming ^{130}La via the reaction ^{116}Cd(^{19}F, 5n)^{130}La with maximum cross-section. We constructed symmetric as well as asymmetric matrices to determine lifetimes by fitting the DSAM lineshape profiles corresponding to detectors in the forward (32°), backward (148°), and 90°.

The gamma transitions belonging to the negative-parity band were observed in the gated spectra of two low-lying transitions 177 keV and 118 keV. The nicely spaced gamma transitions are the characteristics of a prolate deformed shape. The Doppler-shifted lineshapes were globally fitted for eight transitions via the gate on transition below (GTB). The gate on transition above (GTA) was also used to cross-check the lifetime values, and were found in good agreement. The value $K = 6$ was used considering the Gallagher-Mozowoski rule. The lifetime values were found within the range of 0.5 to 1.5 ps for states below the backbending. There was a smoothly decreasing trend in experimental B(E2) values. At high spins, the average B(E2) value experimentally found was 0.33 ± 0.05 (e^2b^2).

We performed total Routhain surface (TRS) calculation and obtained the deformation parameters (β, γ = 0.2, 7°) from the contour plot for the minimum energy configuration. The band configuration was confirmed to be $\pi h_{11/2} \otimes \nu g_{7/2}$, with mixing from other positive-parity neutron orbital ($\nu d_{5/2}$). Also, the first band-crossing frequency (0.46 MeV) for the neutron alignment obtained from the quasi-particle Routhian diagram, matched well with the experimental value (0.47 MeV). For the two-quasiparticle plus rotor model (PRM) calculations, we utilized the TRS results on β. γ values. The signature splitting were well reproduced. However, the theoretical B(E2) values agreed only at high spins, and remained roughly constant for the entire spin range.

In summary, we measured lifetimes using DSAM for eight states of a negative-parity band in ^{130}La. The band was known to be prolate and we confirmed it from our TRS result. Our experimental results on B(E2) were limited to only levels below backbend, and the values agreed with the PRM calculation at high spins. The particle configuration $\pi h_{11/2} \otimes \nu (h_{11/2})^2 g_{7/2}$ was established above the band-crossing.

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Cross-section measurement in proton-, deuteron- and carbon-induced reactions on 136Xe in inverse kinematics

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Spallation/fragmentation reactions are promising in the production of both the proton-rich and neutron-rich nuclei. In order to optimize the production of the radioactive ion beams, a comprehensive understanding of the reaction mechanisms is required. In particular, the energy and target dependence is essential. Therefore, a large amount of high-quality experimental data has to be obtained. Many studies have been conducted to investigate on the reaction mechanisms of the spallation/fragmentation reaction, such as ^{76}Ge, ^{107}Pd, ^{137}Cs, ^{197}Au, and so on. As a primary beam used in worldwide for the radioactive beam generation, the reactions on the stable nuclei ^{136}Xe attracted much interest. However, the study of the ^{136}Xe on deuteron and heavy-ion is limited, only the reactions at high energy is performed. In order to gain more information on the energy dependence of deuteron- and heavy-ion- induced reactions, and to investigate the target dependence, we have measured the cross sections in the reactions of ^{136}Xe induced by proton, deuteron and carbon at 168 MeV/nucleon.

The experiment was performed at the RIKEN Radioactive Isotope Beam Factory. By using the inverse kinematics method, the production cross sections over a wide range of isotopes including stable isotopes, can be obtained. The secondary beams including ^{136}Xe were produced by the in-flight fission of ^{238}U beam at 345 MeV/nucleon. The particles in the secondary beams were identified event by event in the BigRIPS separator. CH_2, CD_2 and C targets were used to induce the secondary reactions. The reaction products were analyzed and identified unambiguously by the ZeroDegree spectrometer. The cross sections for the reactions of ^{136}Xe on proton, deuteron and carbon will be presented as well as the target dependence. The energy dependence was also investigated by the comparison of these experimental results to previous studies for ^{136}Xe at higher reaction energies. These results were compared with the DEURACS calculations, the PHITS code including both the intra-nuclear cascade/dynamical and evaporation processes, and with empirical SPACS and EPAX parameterization. In the presentation, the detailed results will be discussed.

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Recent Progress with the MLLTRAP double Penning Trap Mass Spectrometer at ALTO

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The double Penning trap mass spectrometer (PTMS) MLLTRAP is currently being setup at the Accélerateur Linéaire et Tandem à Orsay (ALTO facility) in France. The ISOL facility ALTO provides neutron-rich radioactive ion beams from the interaction of a γ-flux induced by a 50 MeV 10 μA electron beam in a uranium carbide target. A magnetic dipole mass separator and a resonance ionization laser ion source allow selecting the ions of interest. A new beamline dedicated for MLLTRAP will transport the 30 keV monocharged radioactive beams to a linear segmented Paul trap (RFQCB) where the ions are cooled and bunched. When ejected from the RFQCB, the bunched beam is decelerated to 100 eV before being injected into the PTMS. The goal of the MLLTRAP project at ALTO is to perform high precision mass measurements of silver isotopes toward the N = 82 neutron shell closure prior to its move to SPIRAL2/DESIR at Caen.
In order to ensure a good beam transmission from the target-ion source vault to the PTMS, detailed simulations of the transport and preparation areas have been started. Currently, calculations focus on the beam transport up to the entrance of the RFQCB. The transport and the preparation area are being finalized to be ready for off-line and on-line commissioning. New diagnostics has been installed in the new beamline such as beam profilers, faraday cup, and MCP. Moreover an emittancemeter is expected to be placed as close as possible to the target-ion source vault and in front of the RFQCB as a way to characterize the transverse beam Twiss parameters. The off-line commissioning will include the characterization of a new high voltage ion source located few meters upstream to the RFQCB. This source will also produce the ions of reference for the mass measurements. An overview of the project and a report on the recent progress will be given.

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Laser spectroscopy of the Heaviest Elements

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The heaviest elements are of interest to nuclear and atomic physicists due to their peculiar properties. While nuclear shell structure effects are responsible for their very existence stabilizing them against spontaneous disintegration, the structure of their electronic shells is affected by strong relativistic effects leading to different atomic and chemical properties compared to their lighter homologs. The atomic structure can be probed by laser spectroscopy. This is a powerful tool to unveil fundamental atomic and, from the determination of subtle changes in atomic transitions, nuclear properties. The lack in atomic information on the heavy element of interest, the low production rates, and the rather short half-lives make experimental investigations challenging and demand very sensitive experimental techniques.
Laser spectroscopy of accelerator produced heavy nobelium (No, Z=102) isotopes in atom-at-a-time quantities became accessible in the pioneering experiment employing the RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) technique at the velocity filter SHIP at GSI, Darmstadt. More recent measurements with additional advancements of the setup and employing a novel mode of the RADRIS technique, where the desired nuclides are bred by radioactive decay on the capture filament, extended the reach of the method to ^{251,255}No and, for the first time, to on-line produced fermium (Fm, Z=100) isotopes. These on-line experiments are complemented by off-line laser spectroscopy measurements at the RISIKO mass separator at Mainz University on reactor-bred heavy actinides with suitable long lifetimes. Hot-cavity laser spectroscopy on radio-chemically purified samples enabled the investigation of isotopes of the heavy actinides curium (Cm, Z=96), californium (Cf, Z=98), einsteinium (Es, Z=99), and fermium. This experimental endeavor is accompanied by improvements of theoretical atomic calculations enabling the determination of nuclear ground state properties from the extracted atomic observables of isotope shifts and hyperfine structure parameters. This provides insight to the peculiar nuclear nature and especially the deformation of the

heaviest elements. The obtained results will be discussed in view of nuclear theory predictions together with the perspectives for laser spectroscopic investigations in even heavier elements.

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Simultaneous pH sensing and gamma-ray imaging via angular correlation measurement using cascade nuclides

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Gamma-ray imaging techniques such as positron emission tomography and single photon emission computed tomography (SPECT) have been utilized in nuclear medicine for diagnosis. The radioactive tracer imaging can provide functional or metabolic information non-invasively at the molecule or cellular level. However, nuclear medicine imaging techniques cannot extract the local molecule or cellular environment information. While single photon emission radionuclides are conventionally used for SPECT, some of them emits two or more cascade photons with a short duration of intermediate state; for example, In-111 emits 171 keV and 245 keV gamma-rays with 84.5 ns time constant. An angular correlation between cascade photons that originates from the nuclear spin state is perturbed by the external fields. We have proposed a novel simultaneous gamma-ray imaging and local environment sensing method via the angular correlation measurement, which provides radionuclide position and its local environmental information simultaneously. In this study, we demonstrated simultaneous measurements of angular correlation and gamma-ray imaging using 8 x 8 array high-resolution Gd3(Ga,Al)5O12(Ce) scintillator detectors coupled with silicon photo multipliers (Hamamatsu, S13361-3050). We succeeded to obtain the local pH information of In-111 solution and the accumulation image simultaneously. We will report the detail in our presentation.

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High-precision mass measurements of ground and isomeric states of (super)heavy nuclides with SHIPTRAP

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Quantum shell effects stabilize heavy nuclei against spontaneous fission, making the existence of superheavy elements possible. Direct mass measurements performed with Penning traps provide information on the nuclear shell structure via binding energies, as well as excitation energies of low-lying, long-lived isomers obtained from the directly measured masses.

The SHIPTRAP experiment is devoted to the study of heavy and superheavy nuclei produced via fusion-evaporation reactions at rates well below one particle per hour. Thanks to the Phase-Imaging Ion-Cyclotron-Resonance technique, the resolving power has been increased beyond 10⁷, bringing many low-lying isomeric states within reach for mass spectrometry. In this contribution the latest results, obtained as part of the FAIR Phase-0 campaign, will be discussed. These encompass ground-state masses and isomeric-state-energy measurements of several nuclides, ranging from ²⁴¹Cf to ²⁵⁸Db. The alpha-decay chain ²⁰⁶Fr-²⁰²At-¹⁹⁸Bi was also studied, with the aim to pin down the excitation energies of several isomers for the first time.

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New Super-pulse Fitting Algorithms for Decomposing Pile-up Pulses and Application to the α-decay of ^{222}U

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The region to the "north-east" of ^{208}Pb, with $Z\geq84$ and N=128-130, hosts the shortest-lived α-emitters, with half-lives in the range of nanoseconds to microseconds. The implantation and subsequent α-decay signals result in pile-up events in the charged particle spectroscopy with Double-sided Silicon Strip Detector (DSSD) detector, which were successfully resolved with digital pulse processing (DPP) technique by recording the waveform of the signals [1]. This technique introduces much flexibility as the digitized waveforms can be analyzed offline using different algorithms and has demonstrated significant advantage over conventional analog systems. Following the super-pulse scheme proposed in [2], we developed two new algorithms [3,4] to decompose pile-up events by fitting the super-pulse to the experimental traces. In [3], with proper baseline correction and plateau-region fitting, the spectroscopic information of piling-up signals with time separation down to 80 ns and amplitude of subsequent pulse down to 70 keV, can be readily extracted. In our latest algorithm development, a more general one based on the least square fitting method [4] shows better performance with higher sensitivity and energy resolution. The details of the algorithms will be presented in this contribution.

The α-decay of ^{222}U was studied at GSI recently [5], however the reduced decay width obtained was found to deviate exceptionally from the systematics in the N_pN_n scheme in the N>126 region (see Fig 3b in [6]). ^{222}U was also produced in our recent experiment [7] performed at the gas-filled recoil separator SHANS [8]. The α energy of ^{222}U was revised to be 9246(6) keV using the new algorithms, the precision much improved compared with the GSI results (9.31(5) MeV) [5], though with lower statistics. Using the present α energy, the α-decay reduced width of ^{222}U was revised and fit in the systematics in the N>126 region very well, removing the anomaly in δ^2 at ^{222}U [6].

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Study of the N = 32 and N = 34 shell gap for Ca and Ar isotopes with quasi-free scattering reactions

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Shell gaps represent the backbone of nuclear structure and are a direct fingerprint of the in-medium many-body interactions. The nuclear shell structure is found to change, sometimes drastically, with the number of protons and neutrons, revealing how delicate the arrangement of interacting nucleons is. The neutron-rich *pf*-shell nuclei have received much attention on both experimental and theoretical fronts with the possible appearance of new subshell closures at N = 32 and 34. The N = 32 subshell closure has been reported in the region from Ar to Cr isotopes based on E(2_1^+), transition probability, and mass measurements. However, the laser spectroscopy of Ca and K isotopes reveals an increase of the charge radii with a slope larger than expected from N = 28 to N = 32 and 33, which were interpreted to challenge the magic character of N = 32. For the N = 34 subshell closure, experimental evidence favors a new doubly-magic nucleus ^{54}Ca with a neutron subshell closure at N = 34, although the systematics of E(2_1^+) and B(E2; $0_1^+ \rightarrow 2_1^+$) in Ti and Cr isotopes does not show any evidence for the N = 34 magicity. It is natural to ask how the N = 34 subshell evolves below Z = 20 towards more neutron-rich systems, such as ^{52}Ar.
In this presentation, I will present the quasi-free one-nucleon removal measurements performed at the RIBF facility using the MINOS and DALI2 set up to study the N = 32 and 34 shell gaps in Ca and Ar isotopes. The ^{52}Ca(p, pn) reaction in inverse kinematics was performed at ∼230 MeV/nucleon. The measured partial cross sections and momentum distributions support the doubly-magicity of ^{52}Ca. The analysis of the momentum distributions leads to a difference of the root-mean-square radii of the neutron $1f_{7/2}$ and $2p_{3/2}$ orbitals of 0.61(23) fm, in agreement with the modified-shell-model prediction of 0.7 fm suggesting that the large root-mean-square radius of the $2p_{3/2}$ orbital in neutron-rich Ca isotopes is responsible for the unexpected linear increase of the charge radius with the neutron number. The low-lying structure of ^{52}Ar was extracted using the ^{53}K$(p, 2p)$ reaction. The 2_1^+ excitation energy is found at 1656(18) keV, the highest among the Ar isotopes with N > 20. This result is the first experimental signature of the persistence of the N = 34 subshell closure

beyond ^{54}Ca. Shell-model calculations with phenomenological and chiral-effective-field-theory interactions both reproduce the measured 2_1^+ systematics of neutron-rich Ar isotopes and support a $N = 34$ subshell closure in ^{52}Ar.

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Gamow-Teller Giant Resonance in ^{11}Li neutron drip line nucleus

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At the RIKEN Radioactive Isotope Beam Factory, the spin-isospin response of ^{11}Li was measured in charge-exchange (p, n) reaction at 182 MeV/nucleon beam energy. There is no available data for isovector spin-flip giant resonances in nuclei with large isospin asymmetry factors, where (N−Z)/A>0.25 [1]. Our work aims to investigate this unexplored region up to (N−Z)/A=0.5.
The charge-exchange (p, n) reactions in inverse kinematics combined with the missing-mass technique are powerful tools to extract the B(GT) strengths of unstable isotopes up to high excitation energies, without Q-value limitation of the β decay [1]. In our previous work on ^{132}Sn [2], we demonstrated that accurate information about giant resonances can be obtained for unstable nuclei by using this probe. The combined setup [3] of PANDORA low-energy neutron spectrometer [4] and SAMURAI large-acceptance magnetic spectrometer [5] together with a thick liquid hydrogen target allowed us to perform the experiment with high luminosity. The recoil neutrons with kinetic energy of 0.1−10 MeV were identified with PANDORA, while the SAMURAI was used for tagging the decay channels of the reaction residues.
The β decay of ^{11}Li is complex. The ^{11}Li β-decay involves the largest number of decay channels ever detected [6] and experimental results have been reported for cases, when the daughter breaks into fragments, and emission of one, two, and three neutrons, α particles and ^{6}He, tritons, and deuterons has been observed in several β-decay studies [8,9]. However, the B(GT) values were not clearly deduced as these studies were effected by the Q value.
In this talk, the final results of our analysis will be presented. Deduced double differential cross section up to about 40 MeV, including the Gamow-Teller (GT) Giant Resonance region in ^{11}Li will be reported, as well as the comparison of the obtained B(GT) values with those from β-decay studies. We will discuss the nature of several newly identified decay channels of ^{11}Be also.
Our observation, that the GT peak occurs below the Isobaric Analog State in ^{11}Li, will be discussed in connection with the variation of residual spin-isospin interaction in exotic nuclei.

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The South African Isotope Facility and Low-Energy Radioactive-Ion Beam Project

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The iThemba Laboratory for Accelerator Based Sciences is based around a K=200 Separated Sector Cyclotron (SSC) which is used for radionuclide production, for research in nuclear physics and radiobiology.

Radionuclides are currently produced with the SSC for local and export markets, with only longer-lived isotopes available for export. iThemba LABS recently supplied 20% of the worlds ^{82}Sr, 40% of the worlds ^{68}Ge/^{68}Ga generator and all of its ^{22}Na. The first phase of it's flagship project, the "South African Isotope Facility" (SAIF), is nearing completion at iThemba LABS, with the installation of an IBA C70 cyclotron. This machine will be capable of accelerating protons to 70 MeV and delivering currents of up to 700μA. It will be dedicated to isotope production, which will increase by more than a factor of two once the facility is commissioned.

With the release of the SSC from isotope production, it can be dedicated to physics research. The Low-Energy Radioactive-Ion Beam (LERIB) project of iThemba LABS will use 66 MeV protons from the SSC to produce radioactive-ion beams using the ISOL method, with non-actinide, carbide targets. The target/ion-source "Front-End" is identical to the SPES Front-end, which in turn owes its heritage to the target/ion-sources at ISOLDE. It is presently installed in an off-line test facility where the ion-source is being developed using stable beams.

The first stage of the LERIB project will see the front-end placed on an SSC beam line which will be used to produce RIBs using a low-intensity (< 10 μA) 66 MeV proton beam. The construction of LERIB Phase 0 is presently in the hands of consulting engineers who are doing the final detailed design work.

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Penning-trap mass measurements of neutron-rich Rh and Ru nuclei at IGISOL/JYFL

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Co-auteurs: Antoine de Roubin [2]; Anu Kankainen [3]; Dinko Atanasov [1]; Marek Stryjczyk [4]; Marjut Hukkanen [5]; Mathias GERBAUX [6]; Mathieu FLAYOL [7]; Michael Bender [8]; Stéphane Grévy [9]; Tommi Eronen [3]; Wouter Ryssens [10]

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The nuclear mass is a key observable to guide and constrain the theoretical descriptions of the nucleus. The evolution of binding energy differences can also reveal specific structure effects, such as shape changes or shell closure evolutions. The drastic deformation change in the A~100 region is an example, where a strong kink in the two-neutron separation energy surface has been observed and attributed to the effect of the tensor force between the neutron g7/2 and the proton g9/2 orbitals. Above this region, where the prolate deformation dominates the ground state, the nuclei are expected to exhibit triaxial shapes [1], with an expected additional contribution to the binding energy compared to axially symmetric configurations.
Experimentally, the region between Z = 38 and Z = 46 is particularly difficult to explore in terms of ground-state properties, as the elements of interest are refractory, thus are difficult to extract from ISOL-type sources. The IGISOL facility of the Accelerator Laboratory at the University of Jyväskylä is one of the very few places, where they can be produced and studied with the high-precision Penning trap technique. A mass measurement campaign has been conducted at IGISOL using the JYFLTRAP mass spectrometer [2], and allowed to measure the ground-state masses of odd-odd 110-120Rh [3] and 115,117Ru [4]. In the case of the odd-odd 110-118Rh and 115Ru, the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique [5][6] was used to separate low-lying isomeric states from the ground states. This high-resolution separation allowed, on one hand to measure clean ground-state masses and on the other hand to determine the isomer excitation energies, in most of

the cases for the first time.
The experimental techniques and the results will be presented, as well as comparisons with the predictions of the state-of-the-art global mass model BSkG1 [1].

[1] G. Scamps et al., Eur. Phys. J. A 57 333 (2021)
[2] T. Eronen et al., Eur. Phys. J. A 48 46 (2012)
[3] M. Hukkanen et al., Phys. Rev. C. 107 014306 (2023)
[4] M. Hukkanen et al., in preparation
[5] S. Eliseev et al., Phys. Rev. Lett. 110 082501 (2013)
[6] D.A. Nesterenko et al. Eur. Phys. J. A (2021) 57:302

566

Beta decay of neutron rich bromine isotopes studied by means of Modular Total Absorption Spectrometer

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\documentclass[10pt, onecolumn]{revtex4}
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\textheight220mm
\oddsidemargin10mm
\evensidemargin10mm
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\title
{\underline {Beta decay of neutron rich bromine isotopes studied}
\underline{by means of Modular Total Absorption Spectrometer}}
\altaffiliation
{This work was partially supported by the National Science Centre, Poland (NCN), under grant 2016/23/B/ST2/03559, and by the Office of Nuclear Physics, U.S. Department of Energy under Contracts No. DE-AC05-00OR22725 and FOA 18-1903 (ORNL), No. DEFG02- 96ER40983 (UTK) and by the Office of Science.}
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\maketitle

\vspace{-0.4cm}
Results of the β decay of neutron rich bromine isotopes from mass A=87 to A=91 measured with Modular Total Absorption Spectrometer (MTAS) will be presented.
Neutron rich bromine isotopes have high ^{235}U cumulative fission yields and large Q_β energies, therefore they make substantial contributions to the reactor decay heat and may create many detectable reactor anti-neutrinos. These large contributions means a complete knowledge of the decay schemes, including β-n branches, is of the utmost importance.

Decay schemes from ENSDF database of all discussed bromine isotopes have been found to be insufficient and incomplete, compared to the results of MTAS measurements. For example, even though the decay of ^{87}Br is a relatively well studied case (161 known levels, 226 known γ-transitions), our analysis shows a missing β-feedings to highly excited levels as well as incomplete γ-decay patterns for the known levels. Published ^{91}Br decay scheme lacks information on all β-feedings and γ-transitions intensities. Based on existing decay schemes, we present suggestions on how to improve them, using known levels and introducing so-called pseudo-levels where needed. Average β and γ-transitions energies are calculated as a result. Our analysis uses a multi spectra simultaneous fitting technique, which fits β-decay branches to the experimental spectra from different modules (or their sums) in parallel with the total MTAS energy spectrum.

Large Q_β energies lead to wide $Q_{\beta n}$ energy windows, what makes all isotopes in question a delayed neutron emitters. Modular Total Absorption Spectrometer, because of its volume, allows for a direct neutron measurements, thanks to neutron scatterings and captures inside NaI(Tl) crystals. Analysis results consist of estimation of P_n values, neutron energy spectra and neutron transitions to excited energy states in corresponding daughter nuclei. In the decay of ^{91}Br four β delayed neutron transitions to the excited states in ^{90}Kr have been observed for the first time.

In summary, analysis results of the MTAS data for neutron-rich, β-delayed neutron emitting bromine isotopes from mass A=87 to A=91 will be shown. Beta-neutron transitions to excited states in daughter nuclei will be discussed, as they are clearly visible in MTAS spectra. The impact of the evaluated isotopes on reactor decay heat calculations as well as on the reactor anti-neutrino anomaly will also be presented.

\end{document}

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First beta-delayed spectroscopy of neutron-rich Cl isotopes with FDSi

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The first experimental campaigns with FRIB Decay Station Initiator [1] at FRIB focused on the spectroscopy of very neutron-rich isotopes. They provided a wealth of data on beta-delayed neutron emitters. We will present the first results on the beta-delayed neutron emission spectroscopy near N=28 shell closure, such as ^{45,46,47}Cl. Using a combination of neutron and gamma-ray data, we extracted the beta decay strength distribution to neutron unbound states and compared the results with the large-scale shell model calculations by Yoshida et al. [2], providing the first test of these predictions for the dominant Gamow-Teller transitions in this region. We also extracted the neutron-emission branching ratios to excited states in Ar isotopes and compared them with those predicted by the statistical model [3]. The importance of the discrepancies between model predictions and experimental data will be discussed.

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[2] T. Kawano et al., Journal of Nuclear Science and Technology, 47(5),462, (2010), .
[3] S. Yoshida, Y. Utsuno, N. Shimizu, and T. Otsuka, Phys. Rev. C 97, 054321 (2018).

571

High-resolution spectroscopy of exotic silver with a cw OPO injection-seeded PDA.

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Short-lived radioisotopes are of special interest for nuclear structure studies, as their characteristic provide valuable reference points for theoretical predictions far from stability. By using lasers, hyperfine transitions can be accessed, allowing direct measurement of nuclear observables.For such high-resolution spectroscopy, narrow-band pulsed lasers can be created by the pulsed amplification of a cw seed laser, keeping the amplifier's high power and short time profile whilst acquiring the seeder's spectral properties. Spectroscopy on exotic silver was performed at the CRIS experiment at ISOLDE, CERN. A tunable cw single-mode OPO was employed as injection-seed for a two-stage pulsed dye amplifier. The hyperfine splitting of the ground-state $^2{}_{1/2}$ to the level $^2{}_{3/2}$ was measured and the hyperfine coupling constants were determined. For this work $^{109,111,117}Ag$ are presented, showcasing this laser system's applicability for future high-resolution spectroscopy studies.

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Indium Energy Spectrum Shape (InESS) at WISArD

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High-precision measurements of the beta spectrum shape and beta-neutrino angular correlation parameter allow to test for exotic scalar and tensor currents in the weak interaction. These measurements are the goal of the WISArD collaboration at ISOLDE/CERN. When experiments aim for the highest precision, even small Standard Model effects, usually called corrections, become important. The present work focuses on one such effect, i.e. the recoil-order correction, on the beta spectrum shape.

To overcome the effect of backscattering, an intrinsic limitation for this type of measurement, two detectors have been installed face-to-face in the high magnetic field of the WISArD set-up. This effectively forms a closed system with a 4π solid angle thus mitigating the effect of backscattering. The detector set-up was characterized using conversion-electron sources as well as a continuous-spectrum beta source.

We will present the details of the experimental approach and report the first results for the determination of the recoil-order correction, which is dominated by the weak magnetism form factor, on the beta energy spectrum of $^{114}_{49}$In. Previously, weak magnetism has only been experimentally determined for specific isotopes up to $A = 75$, which makes its determination for $^{114}_{49}$In the first within uncharted territories.

parallel session / 574

First beta-delayed neutron spectroscopy of doubly-magic ^{24}O.

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Located at the neutron drip-line, ^{24}O is the heaviest doubly-magic isotope of the oxygen isotopic chain. As the Q_β value increases and the neutron separation energy in the daughter nucleus decreases for the neutron-rich nucleus, beta-delayed neutron emission becomes a dominant decay mode, and neutron energy measurement is vital in studying the beta decay to the neutron unbound states. Also, spectroscopy of such drip-line nuclei may provide important information regarding the effects of nuclear interactions and many-body correlations in determining the limits of nuclear stability [1].

The neutron energy spectrum measurement of the beta-delayed neutron precursor ^{24}O was performed for the first time at National Superconducting Cyclotron Laboratory (NSCL) using a neutron time-of-flight array (VANDLE[2]) accompanied by gamma spectroscopy setup. New half-life and beta decay branching ratios are extracted. The beta-gamma and beta-delayed neutron measurements following the decay of ^{24}O provided the excitation energies and beta decay strength distribution to both neutron-bound and unbound states in ^{24}F. The decay of "doubly-magic" ^{24}O is an excellent case to test the quality of the state-of-the-art calculations of the beta-decay strength distribution near the neutron drip line. The experimental results are compared with the shell model calculation using the standard, empirical USDB interaction, and state-of-the-art ab initio calculations such as those using the valence-space in-medium similarity renormalization group (VS-IMSRG), coupled cluster model or shell-model embedded in the continuum.

[1] T.L. Tang et al. Phys. Rev. Lett. 124, 212502 (2020).
[2] W. A. Peters et al., Nucl. Instrum. Methods Phys. Res. A 836, 122 (2016).

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b-STILED: Search for Tensor Interactions in nucLear bEta Decay

Auteur: Mohamad Kanafani[1]

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Precision measurements in beta decay play an essential role in the search for new physics beyond the standard model (SM), by probing "exotic" phenomena such as scalar and tensor interactions. The existence of such interactions induces deviations on certain observables away from their SM predictions. The study of the full beta energy spectrum offers a sensitive property to probe these interactions.

The goal of this work is to perform the most precise measurement of the beta-energy spectrum in ^{6}He decay, in order to extract the Fierz interference term b with a precision in the order of $4 \cdot 10^{-3}$.

This term depends linearly on exotic coupling constants, allowing to search for or to constrain the presence of tensor interactions in nuclear beta decay.

The main instrumental effect observed in previous measurements of the beta energy spectrum resides in the energy loss due to electrons backscattering outside the detector volume. A new technique is used to overcome this effect. It consists of using a very low energy beam of $^6He^+$ ions (25 keV) deposited between two scintillation detectors forming a 4π calorimeter. The use of this technique ensures the deposition of the entire energy of the detected beta particles. An experiment with this setup was performed at the Grand Accélérateur National d'Ions Lourds (GANIL) in 2021.

This contribution will introduce the general context of the project, describe the experimental setup, report the status of the data analysis and present the preliminary results.

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Island of inversion at the N=Z line

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The development of collectivity along the $N = Z$ is one of the subjects that has recently attracted great experimental efforts. In particular, heavy $N = Z$ nuclei in the mass region $A = 80$ are expected to be some of the most deformed ground states which have been found [1] in mid-mass nuclei, typically $8p - 8h$, $12p - 12h$ for e.g. the cases of ^{76}Sr, ^{80}Zr. This strong enhancement of collectivity with respect to lighter $N = Z$ nuclei has its origin
in cross shell excitations across the $N = 40$ shell gap to $g9/2$, $d5/2$ and $s1/2$ which are intruder quadrupole partners generating deformations.
These structures can be interpreted in terms of algebraic Nilsson-SU3 self-consistent model to describe the intruder relative evolution in the vicinity of ^{80}Zr [2]. In this presentation, we will expose some of the latest developments in microscopic nuclear structure calculations for exotic nuclei far from stabilitity at the N=Z [3].
The new theoretical calculations for the very region of ^{80}Zr will be presented for the first time within the interacting shell model framework using an enlarged model space outside a ^{56}Ni core comprising the pseudo-SU3 $p_{\frac{3}{2}} f_{\frac{5}{2}} p_{\frac{1}{2}}$ and quasi-SU3 $g_{\frac{9}{2}} d_{\frac{5}{2}} s_{\frac{1}{2}}$ orbitals for both protons and neutrons. We will present and compare results from both exact Shell Model diagonalization [4] and our newly developed DNO Shell Model approach employing beyond mean field techniques [5]. These theoretical calculations allow a very good description of the rapid transition ($A = 60 - 100$) from spherical to deformed structures which can be intepreted in terms of "simple" many particles - many holes configurations. Emphasis will be put on the intimate relationship between shell evolution far from stability at the neutron-rich AND proton-rich edges.

[1] R. D. O. Llewellyn et al., Phys. Rev. Lett. 124, 152501 (2020).
[2] A. P. Zuker et al., Phys. Rev. C 92, 024320 (2015)
[3] D. D. Dao, F. Nowacki, A. Poves in preparation
[4] E. Caurier, G. Martínez-Pinedo, F. Nowacki, A. Poves, and A. P. Zuker, Rev. Mod. Phys. 77, 427 (2005).
[5] D. D. Dao and F. Nowacki, Phys. Rev. C 105, 054314 (2022).

579

Spectroscopy of 128In and 128Sn from the beta-decay of 128Cd

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Over the last decades, the area close to the doubly-magic nucleus ^{132}Sn has played a prominent role in spectroscopy studies of exotic nuclei. Their aim is to obtain a better understanding of shell evolution in nuclei with large N/Z ratios, providing critical information to test theoretical models. In addition, the information on the nuclear structure and decay properties of neutron-rich nuclei in this region provides input to calculations for astrophysical r-process.

In the IS685 experiment, performed at the ISOLDE facility at CERN, high purity ^{128}Cd (Z=48, N=80) beams were produced after the fission of a thick UC$_x$ target, selectively ionized by the ISOLDE Resonance Ionization Laser Ion Source (RILIS) and separated in mass using the General Purpose Separator (GPS) ISOLDE mass separator. A temperature-controlled quartz transfer line hinders the transmission of surface-ionized species, yielding extremely pure beams. The beam was taken to the ISOLDE Decay Station (IDS) where high-resolution gamma spectroscopy using six clover-type HPGe detectors were employed. The Advanced Time-Delayed $\beta\gamma\gamma$(t) method [1] was employed to access lifetimes down to the 10 ps range. We made use of a compact fast-timing setup with 2 γ-LaBr$_3$(Ce) detectors and 3 fast β-detectors.

The excited structures of the odd-odd ^{128}In (Z=49, N=79) and even-odd magic ^{128}Sn (Z=50, N=78) isotopes were populated via the ^{128}Cd$\rightarrow$ ^{128}In $\rightarrow$ ^{128}Sn β-decay chain. The level schemes for both

^{128}In and ^{128}Sn isotopes were constructed and largely expanded, profiting from the high-resolution spectroscopy measurement. Lifetimes of excited states were determined and reduced transition probabilities were obtained. The presentation will highlight the preliminary results together with a comparison with available shell model calculations.

[1] H. Mach, R.L. Gill, and M. Moszynski, Nucl. Instrum. Methods Phys. Res. A 280 (1989) 49.

581

Advances in TRIUMF's resonant ionization laser ion source

Auteur: Jens Lassen[1]

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The COVID19 pandemic required TRIUMF to operate with reduced personnel interaction while continuing to provide access to radioactive ion beams. To that end new ways of laser ion source operation had to be implemented, to reduce in-person interactions, yet maintain information flow and functionality to delivery a full spectrum of radioactive ion beams to users. In addition, development and complex beam delivery modes still are at the heart of radioactive ion beam facilities - therefore upgrades to and implementation of the ion guide - laser ion source were completed at the ISAC west target station. The results are such that the prototype IG-LIS on the ISAC east target station will also be upgraded to reflect improvements. The contribution will describe recent beams, beam delivery modes, laser system and IG-LIS improvements and capabilities.

parallel session / 584

Probing the $N = 152$ neutron shell gap by laser spectroscopy of fermium isotopes

Auteur: Jessica Warbinek[1]

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Determining the limits of existence of the heaviest nuclides is a forefront topic in nuclear-physics research [1]. Nuclides with proton numbers $Z \geq 100$ are stabilized by shell effects that retard spontaneous fission and they feature properties distinctly different from those of lighter nuclei. However, our understanding of such shell effects in the region of the heaviest elements is limited as predictions by state-of-the-art nuclear models are challenging and experimental studies are hampered by production capabilities. Recent mass measurements confirmed the location and the size of such a shell gap leading to an increased nuclear stability at neutron number $N = 152$ in a region of strong

prolate deformation [2,3].
Here, laser spectroscopy can serve as a powerful tool to extract experimental information on nuclear parameters such as the change in the mean-square charge radii and nuclear moments in a nuclear-model independent manner [4,5]. Access to the heaviest elements however is limited by production yields, their short half-lives and sparse information on atomic levels. The recent findings in the heavy actinide element nobelium ($Z = 102$) with the RADRIS method paved the way for such observations [6,7].
New studies of fermium (Fm, $Z = 100$) isotopes allowed the determination of the isotope shift in an atomic transition for a long chain of eight isotopes ranging from the accelerator-produced ^{245}Fm to the reactor-bred ^{257}Fm. On-line and off-line laser spectroscopy techniques were significantly advanced to access these isotopes via various production methods down to minute production rates. The investigated isotopic chain spans across the known deformed shell gap at $N = 152$ allowing to probe its effect on changes in the mean-square charge radii. The experimental results revealing a discontinuity in the evolution of mean-square charge radii around the neutron shell gap will be discussed. These observations will trigger new developments in theoretical models which will eventually improve their predictive power towards the heaviest elements.
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Production and laser spectroscopy studies of stable palladium

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Neutron-deficient nuclei close to the proton drip line, in particular 100Sn and its neighbors along the N=Z line, have reinforced the interest of the worldwide physics community thanks to the large variety of different nuclear phenomena occurring in this region. The study of this region of the nuclear chart has become an important goal of a large number of facilities worldwide. Optical measurements of the atomic structure readily yield fundamental and model-independent data on the structure of ground and isomeric nuclear states. The competition and balance between nuclear shell and collective effects results in a spectacular range of shapes and sizes within nuclear systems. Such shapes and structures perturb the atomic energy levels of atoms and ions at the ppm level and although this is a small absolute effect, it is readily probed and measured by modern laser spectroscopic methods, e.g., in-source laser spectroscopy at Jyväskylä and in-gas jet laser spectroscopy at S3-LEB. These techniques are particularly suitable for the study of short-lived radionuclides with lifetimes approaching a few tens of milliseconds, and production rates often at the level of a single isotope/isomer per second. To measure nuclear observables of refractory elements of interest for exotic nuclei approaching the N= Z line is a particular challenge.
In this contribution we will present two complementary feasibility studies for the study of refractory isotopes of Pd by means of laser spectroscopy. The first concerns the capabilities of the IGISOL

facility at Jyväskylä to extract a Pd beam by means of a hot-cavity ion source technique. The second is a sensitivity study to nuclear observables of the first atomic transition quoted by T. Kron et al. [1].

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Radiation-detected NMR for chemistry and life-science studies using unstable nuclei

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Radiation-detected Nuclear Magnetic Resonance (RD-NMR), especially in the form of beta-NMR in solids hosts, is an extremely sensitive NMR approach, which has been used in nuclear structure studies over the last few decades, allowing to determine magnetic and quadrupole moments of selected unstable nuclei.
RD-NMR applications in chemistry, biology, or medical diagnosis – performed on short-but also long-lived spin-polarised nuclei in liquid or gaseous samples – are much more recent but growing. Such studies are performed by our ISOLDE team as part of interdisciplinary collaborations with colleagues from other institutes. Beta-NMR on laser polarised short-lived sodium and potassium nuclei has already allowed us to study the arrangement of low-vapour ionic liquids which might be suitable for car-battery material and is being used to investigate binding of DNA G-quadruplex structures around alkali metals. A development of beta-NMR on longer-lived isotopes polarised using chemical methods known in conventional NMR in zero-to-ultra-low fields (ZULF) might lead to ultrasensitive and highly portable NMR devices. Finally gamma-detected MRI signals after spin-exchange optical pumping of long-lived Xe isomers might be used as a new medical imaging modality.
This contribution will cover the principles of RD-NMR, followed by the description of selected experimental setups and examples of ongoing studies from across the fields.

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Collinear Laser Spectroscopy on Neutron Rich Palladium Isotopes

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Collinear laser spectroscopy gives access to hyperfine parameters and isotopes shifts at high precision. From these, nuclear charge radii, moments and spins can be determined. At the new collinear laser spectroscopy setup ATLANTIS (**A**rgonne **T**andem hall **LA**ser beamli**N**e for a**T**om and **I**on **S**pectroscopy) laser fluorescence spectroscopy was performed on neutron rich refractory metals below Z=50, produced by the Californium Rare Isotope Breeder Upgrade (CARIBU). Palladium is 4 protons below the nuclear shell closure Z=50 and therefore of particular interest for nuclear physics. Neutron rich palladium isotopes and all stable palladium isotopes were investigated by ATLANTIS. First results on the measurements of $^{110,112-116}$Pd and all stable Pd isotopes are presented.
This work was supported by DFG – Project-Id 279384907-SFB 1245, BMBF 05P19RDFN1 and NSF Grant No. PHY-21-11185 and by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357, with resources of ANL's ATLAS facility, an Office of Science User Facility.

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Development of the polarizer facility at TRIUMF

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The polarizer facility at TRIUMF-ISAC provides nuclear-spin polarized radioactive isotope beams via optical pumping in collinear laser fast-beam geometry. Polarized ^{8}Li and ^{31}Mg are routinely delivered for material science, biochemistry, nuclear physics, and fundamental symmetry studies. To enhance the facility's capabilities and provide novel beams for cutting-edge research, an upgrade and development program is ongoing on laser systems, fluorescence and ion detection, auxiliary systems, and user stations. An overview of the polarizer facility, including recent developments on polarized beams and current capabilities for collinear laser spectroscopy, will be presented.

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The AGATA γ-ray tracking array at the LNL TANDEM-ALPI-PIAVE facility

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The AGATA γ-ray tracking array represents the state-of-the-art of in-beam gamma-ray detection. Its capabilities rely on the high segmentation of its High Purity Germanium detectors to provide position sensitivity and, as a result, the ability to track gamma rays.

In this contribution, we will present an overview of the experiments performed during the first phase of AGATA's installation at the TANDEM-ALPI-PIAVE accelerator complex in the "Laboratori Nazionali di Legnaro" in Italy. The gamma-ray array was initially coupled to the PRISMA magnetic spectrometer, to study the spectroscopy of isotopes produced from multinucleon transfer and fission reactions.

Moreover, part of the experimental campaign was devoted to the study of Coulomb excitation experiments that saw the array coupled to silicon detectors (SPIDER and EUCLIDES).

A brief overview of the performance and recent achievements will be presented, with a future perspective of the spectrometer at Legnaro, also in view of the future delivery of radioactive beams provided by the SPES facility.

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Magnetization distribution from hyperfine anomaly measurements

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At the VITO beamline at the CERN-ISOLDE facility we have begun a new programme of hyperfine anomaly measurements. This interesting, but tiny observable will provide a new way to look at nuclear structure due to its sensitivity to the magnetization distribution. This distribution is sensitive to the unpaired valence nucleons and thus can give information on both the proton and neutron special distribution.
By performing β-NMR in vacuum compatible liquids, it has been shown recently that we can measure the magnetic moments of short-lived radioactive isotopes with ppm precision. The first results of these measurements will be presented. The remaining ingredient of precision hyperfine anomaly measurements - the Hyperfine *A* factor will be addressed by the installation of a laser-rf double resonance setup. Progress in this new research theme will be presented along with future plans.

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Evaluation of metal-organic frameworks for room temperature noble gas harvesting at the Facility for Rare Isotope Beams

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The Facility for Rare Isotope Beams (FRIB) is a unique accelerator laboratory for nuclear science research at Michigan State University. During its operation, only a fraction of the produced isotopes will be utilized for fundamental nuclear research, leaving significant amounts of radioisotopes unused and discarded into a water beam dump. The isotope harvesting group is interested in collecting and separating numerous by-product radionuclides from the water beam dump system at FRIB. Some of the radionuclides that will be produced in the beam dump are noble gases such as Kr-77/76 and Rn-211. The decay products of the above-mentioned radioisotopes are of a high value for nuclear medicine. Therefore, the ability to collect those by-product radionuclides that otherwise would be left unused will greatly benefit the field of nuclear medicine. Consequently, an effort to develop a noble gas tuned microporous metal organic framework (MOF)-based method for noble gas harvesting at room temperature will be discussed.

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β-decay of 68Mn: Probing the N=40 island of inversion

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Although the shell model forms the backbone of our understanding of nuclear structure, the breakdown of traditional magic numbers far from stability gives insight into the nature of the underlying nuclear interactions and acts as a tool to test existing models. Islands of inversion (IoI) in the nuclear landscape are characterized by the presence of deformed multi-particle multi-hole (*npnh*) ground states instead of the *0p0h* configurations predicted by spherical mean-field calculations. In the N=40 region, the relatively large energy gap separating the *pf* shell from the neutron $g_{9/2}$ orbital points towards a strong sub-shell closure at N=40 which has been supported by the observation of a high-lying 2^+ state and low B(E2) value in ^{68}Ni (Z=28) [1]. However, systematics of $E(2^+)$ and B(E2) values have indicated a sudden increase in collectivity below Z=28 when approaching N=40, seen especially in the rapid drop of $E(2^+)$ in Fe (Z=26) and Cr (Z=24) isotopes [2,3]. This increase in collectivity around N=40 and $Z<28$ is thought to be due to the neutron occupation of intruder states from a higher shell, similar to the island of inversion around N=20 [4,5]. Recent studies also suggest the occurrence of a new IoI at N=50 and a proposed merging of the N=40 and N=50 IoIs, equivalent to the one observed between N=20 and N=28 [6,7]. Detailed spectroscopic information of the Fe, Co, and Ni isotopes will be crucial to understand the structure of nuclei near and inside the N=40 IoI and map the bridge between N=40 and N=50. To this end, an experiment was performed at TRIUMF-ISAC using the GRIFFIN spectrometer that utilized the β and βn decay of ^{68}Mn to populate excited states in ^{67,68}Fe, ^{67,68}Co and ^{67,68}Ni. Preliminary results from the analysis will be presented which include an expanded ^{68}Fe level scheme and spin-parity assignments from a gamma-gamma angular correlation analysis.

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Higher rare isotope yields at ISAC TRIUMF using proton beam rastering

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An AC rastering system has been implemented at TRIUMF's Isotope Separation and Acceleration facility (ISAC) to rotate the 500MeV proton beam from TRIUMF's H- cyclotron onto targets for rare isotope production at a frequency of up to 400Hz. Rastering enables a more uniform beam power deposition in the target allowing higher proton beam intensities (up to 50% over the stationary beam), reduces the temperature gradients across the target, and enhances the diffusion and effusion of the short-lived isotopes.
The rastering system at ISAC was successfully tested for several targets and ion sources. In depth thermal models of the targets were developed for stationary and rotating proton beams, and correlated with yield results and in-target production rates. New isotopes were extracted and yields of short-lived isotopes, such as 11Li and a wide range of lanthanides, were increased. This contribution

summarizes the technical implementation, thermal modelling of the rotating beam and experimental isotope yields in relation to static beam operation.

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A new technique for direct (n,p) reaction measurements of astrophysical interest using radioactive beams with SECAR

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The nucleosynthesis of elements above the iron peak highly depends on neutron-induced reactions. Studies have shown that key (n,p) reactions such as the ^{56}Ni(n,p)^{56}Co and ^{64}Ge(n,p)^{64}Ga can accelerate the so-called neutrino-p process (νp-process), contributing to the creation of elements between nickel (Ni) and tin (Sn) in type II Supernovae. The νp-process occurs in slightly proton-rich regions in the neutrino-driven wind of core-collapse supernovae via a sequence of proton-capture and (n,p) reactions. The small abundance of neutrons that drives the (n,p) reactions originates from anti-neutrino captures on free protons.

Such (n,p) reactions can be studied via the measurement of the reverse (p,n) reactions followed by the application of the detailed balance principle [1]. We present a new approach for such measurements, using a heavy radioactive beam impinging on a hydrogen target. Reaction recoils are separated from the unreacted beam and detected using SECAR, the SEparator for CApture Reactions [2] at FRIB. Measurements of (p,n) reaction are particularly challenging, as the recoils and the unreacted projectiles have almost identical masses. However, an appropriate separation level can still be achieved using neutron tagging along with SECAR. In a recent experiment, the first direct measurement of the p(^{58}Fe,n)^{58}Co reaction at 3.7 MeV/u was possible by the in-coincidence detection of the emitted neutrons close to the target location and the ^{58}Co ions at the end of the SECAR system. The neutron detection was achieved with a combination of liquid and plastic scintillators, while for the heavy ions the SECAR's ΔE-E detection system, which consists of an IC (Ionization Chamber) and a DSSD (Double-sided Silicon Strip) detector, was used. This direct measurement of

the ^{58}Fe(p,n)^{58}Co reaction will complement an earlier one obtained via activation. In addition, it will likely improve the cross-section data available and pave the path for many other (p,n) reaction measurements of significant astrophysical interest using radioactive beams. Preliminary results along with experimental details for the technique will be presented.

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Decay spectroscopy around neutron-rich 33Mg to probe an 'island of inversion'

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The term 'island of inversion' is used to refer to a region of the nuclear landscape in which deformed intruder configurations dominate nuclear ground states over the spherical configurations naively expected from the shell model. Theoretical models of the inversion mechanism can be tested through detailed studies of the nuclear structure of transitional nuclei, in which the normal and intruder configurations compete. One such transition occurs along the N = 20 isotones, where neutron-rich ^{32}Mg is known to have a deformed ground-state configuration, while ^{34}Si displays a normal ground state configuration. Previous studies of the intermediate N = 20 isotone ^{33}Al have yielded conflicting results regarding its structure. In the present work, ^{33}Al was studied through the β-decay of ^{33}Mg to clarify these discrepancies. A low-energy radioactive beam of ^{33}Mg was delivered at a rate of 10e3 ions/s by the Isotope Separator and Accelerator (ISAC-I) facility at TRIUMF. Data were collected with the GRIFFIN high-purity germanium γ-ray spectrometer coupled with the SCEPTAR plastic scintillator array and the ZDS (zero degree) β particle detectors. The majority of the data were collected in a cycled mode (with a period of 2 s beam on, 1.5 s beam off) to provide sensitivity to all of the ^{33}Mg, ^{33}Al, ^{32}Al (β-n daughter) and ^{33}Si half-lives. The high efficiency of the GRIFFIN detector provided new γ-γ coincidences to elucidate the excited state structure of ^{33}Al, and the capability of GRIFFIN to detect weak transitions has provided more complete β-decay branching ratios for the ^{33}Mg–^{33}Al–^{33}Si decay chain. Results following the β-decay of neutron-rich ^{33}Mg are presented. Approximately 10^8 γ-γ coincidences were used to build level schemes for ^{33}Al and ^{32}Al. The γ-gated time spectra were fit to calculate half-lives of ^{33}Mg, ^{32,33}Al and ^{33}Si, β counts were used to calculate β-feeding to the levels of the scheme of ^{33}Al, including the ground state. Clarification of ^{33}Al level scheme, and expansion of ^{32}Al are presented.

parallel session / 600

Combined Mass and Half-life Measurements with TITAN's MR-TOF-MS

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TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) operates several ion traps for high-precision mass measurements and spectroscopy. Among these traps is a Multi-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS) for mass measurement and isotope selective cleaning of beam for other traps. TITAN's MR-TOF-MS has demonstrated excellent dynamic range ($\sim 10^8$) and high-precision ($\frac{\delta m}{m} \approx 10^{-7}$) allowing for measurement of very exotic isotopes. Presented here are a set of mass measurements clarifying the nuclear structure near N=34 in potassium.

Recently we developed new techniques enabling the measurement of half-lives using the MR-TOF-MS. This has allowed for half-life measurements of isotopes ranging from ~10 ms and ~5 min. In addition to providing supplementary data for identification of species, this new measurement technique has allowed for several first time half-life measurements and improved half-life uncertainties. The TITAN MR-TOF-MS's re-trapping and ion by ion mass and decay measurement abilities have proven to be powerful tools for half-life and mass measurements of exotic low rate species in a high background environment. The implications of these and future half-life measurements for nuclear structure and nucleosynthesis will be discussed.

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Advanced Spectrometer and Separator Tuning for Commissioning or New Operational Modes

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Two complementary methods have been developed–and tested in Monte Carlo simulations–to more reliably achieve the desired ion optical properties in large acceptance spectrometer, separator, or beam transport systems by automatically tuning first order and higher order magnetic elements. The High Rigidity Spectrometer (HRS) [1] has been used as a test case for these developments. Detailed ion optical models typically allow systems to be tuned to the neighborhood of a well-performing optical tune, after which manual tuning is used to ultimately achieve the desired optical properties. The increasing complexity of these optical systems and their increasingly complex operational requirements make current approaches to bridging the gap between model-derived tunes and performant operational tunes more time consuming and less reliable. For the correction of first order optical properties (e.g. focus conditions, dispersion, etc.), once the system has had a model-derived tune applied to arrive within the neighborhood of the correct tune, we use in-system measurements to extract a quadrupole coupling matrix. The inverse of the coupling matrix then allows the direct

calculation of the corrections that must be applied to each quadrupole to achieve the desired first order tune properties. For the correction of higher order optical properties, we apply a global optimization algorithm, the Particle Swarm Optimizer (PSO), to tune the sextupole and octupole degrees of freedom and report on a study of which values of the algorithm's two controlling parameters (for acceleration and inertia) will most reliably produce improvement in a complex optimization objective. The optimization objective in our simulated online optimization includes the minimization of the final spot size on the reaction target and also beam properties at intermediate, dispersive planes that will enhance the momentum resolution of the analysis line.
[1] S. Noji et al. in these proceedings.

parallel session / 609

Probing the rapid onset of deformation below ^{68}Ni through the beta decay of ^{67}Mn

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One of the best-known divergences from the independent-particle shell model description is the existence of islands of inversion [1]. The IoI of the region N=40 draws particular attention since the neutron number 40 was postulated as a non-traditional "magic" number and N = 40 represents the boundary between the negative-parity pf shell and the positive-parity g shell. In stable nuclei, the neutron $g_{9/2}$ orbital is close enough to the pf shell to reduce this shell gap resulting in a more stable subshell closure at N = 50. Measurements of B(E2) values and E(2^+) in the neutron-rich region show increased collectivity through the N = 40 shell gap, with the clear exception of ^{68}Ni [2,3]. Deformation and shape coexistence have been identified in the area, LNPS calculations predict triple shape coexistence for ^{67}Co (N=40), with three rotational bands [4]. And, recent experiments on ^{67}Fe (N=41) propose a spin-parity of $5/2^+$ or $1/2^-$ for its ground state [5] which indicates a significant deformation. In addition, shape coexistence is also expected for ^{67}Fe. Despite the high interest in the region, very limited information is available, to this end, an experiment was performed at the TRIUMF-ISAC facility utilizing the GRIFFIN spectrometer [6], where the β and βn decay of ^{67}Mn populated the ^{67,66}Fe, ^{67,66}Co and ^{67,66}Ni isotopes.
This data set contains orders of magnitude more statistics than previous studies allowing us to build for the first time a complete level scheme of ^{67}Fe and ^{67}Ni, and to improve upon the known β- decay level schemes of ^{67}Co, by expanding the number of transitions and levels, as well as by improving the

precision of branching ratios and ground-state half-life measurement. In addition, measurements of level lifetimes down to the picosecond range will allow us to investigate the band structure in these nuclei. For the ^{67}Fe isotope, the good level of statistics will make it possible to measure the energy of the identified isomeric state and improve the lifetime measurement.
These results can provide further insight into the detailed structure of the states by comparison to simple models and large-scale shell model calculations in order to confirm or refute the shape coexistence picture predicted by LNPS calculations and the shrinking of the N=40 gap just one proton below ^{68}Ni.
Preliminary results from the analysis will be presented and discussed.
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Measurement of the Fierz interference term in 20F decay

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Precision measurements in nuclear beta decay offer a sensitive means to search for new physics beyond the standard electroweak model. The new physics signatures are parametrized in terms of exotic phenomenological scalar and tensor interactions, which induce deviations on observables relative to their standard model predictions. It has been recognized that the Fierz interference term is the most sensitive parameter to probe the presence of exotic couplings since it depends linearly on them. This term can directly be accessed through measurements of the beta-particle energy spectrum. These are notoriously difficult to perform with high precision due to distortions generally induced by back- and out-scattering of beta particles.

We report here on the measurement of the energy spectrum of beta particles emitted in 20F decay to extract the Fierz term in this decay for the first time. A 132 MeV/nucleon 20F beam was implanted in a CsI(Na) detector and beta-gamma coincidences were recorded between the implantation detector and four other CsI(Na) surrounding detectors. This configuration enabled us to implement a calorimetry technique such that the dominant distortion of the beta-energy spectrum was due to the bremsstrahlung radiation escaping the implantation detector. The measured decay is the 99.9913(8)% Gamow-Teller branch and the Fierz term is sensitive to exotic tensor couplings.

This contribution will describe the experimental conditions and will provide details on the systematic effects in the data analysis of the spectrum shape. It will also discuss the role of the weak magnetism form factor in the extraction of the Fierz interference term.

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β-decay studies of neutron-rich isotopes in the region around double-magic ^{132}Sn

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In a simple picture, nuclei in the vicinity of double magic isotopes are of great interest from both experimental and theoretical points of view. Such nuclei have a spherical shape and the excitations-energy spectrum is dominated by single-particle excitation. This simple approach may need to be revised for nuclei that are significantly off the stability path on the neutron-rich side. The study of the evolution of single-particle states, interaction energies and β-decay properties (half-lives, β-decay strength, and β-delayed neutron emission probability) are important for understanding the structure of such exotic nuclei, as well as for its relevance in understanding the astrophysical r-process.

In this particular, understanding the nuclear structure near the doubly-magic ^{132}Sn is important for validating theoretical models that predict properties of more exotic nuclei, which are not experimentally accessible. In the specificity, the single-particle energy of the neutron state $i_{13/2}$ is still not firmly established [1,2] and it was suggested that nuclear structure affects the neutron versus γ-ray competition in the decay of neutron-unbound states [3]. The n-γ competition in the de-excitation of excited states of these nuclei is relevant in the framework of the astrophysical r-process, since ^{135}In is a so-called waiting point [4]. β-decay studies of neutron-rich indium isotopes provide excellent conditions to investigate such effects since their decays are characterized by large energy windows for the population of neutron-unbound states ($Q_{\beta n} > 10$ MeV).

Excited states in $^{132-135}$Sn were investigated via β decay of the respective precursors, $^{133-135}$In, at ISOLDE Decay Station [5,6]. Isomer-selective ionization using the Resonance Ionization Laser Ion Source enabled the β decays of ^{133g}In (I^{π}=9/2^{+}) and ^{133m}In (I^{π}=1/2^{-}) to be studied independently for the first time [5]. Owing to the large spin difference of those two β-decaying states, it is possible to investigate separately the lower- and higher-spin states in the daughter ^{133}Sn and therefore to probe independently different single-particle transitions relevant in the ^{132}Sn region. The single-particle $i_{13/2}$ neutron state was tentatively identified in the decay of ^{134}In and ^{135}In.
A review of the most recent results will be given and discussed in the framework of state-of-the-art shell model computations.

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The PUMA experiment at CERN

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Frank Wienholtz for the PUMA collaboration
The main goal of the PUMA [1] (antiProton Unstable Matter Annihilation) experiment is to use antiprotons as a tool to investigate properties of exotic nuclei. For this, antiprotons produced at the AD/CERN and decelerated by the ELENA storage ring will be captured, cooled and transported to the ISODLE facility where the antiprotons will be mixed with short lived isotopes. During this process, an antiproton can be captured by the nucleus and will subsequently annihilate with a neutron or a proton at the surface of the nucleus itself. The fingerprint of this annihilation will be measured using a time-projection-chamber. With this knowledge of the ratio of protons to neutrons on the outermost part of the nuclei distribution, phenomena like a neutron or a proton halo or neutron or proton skins can be investigated.
This contribution will give an overview of the PUMA experiment, present its status and highlight some of the main physics goals.

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plenary 03 / 620

The Decay Spectroscopy Setup at the GSI-FAIR fascility and the physics results from FAIR-0

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The DEcay SPECtroscopy (DESPEC) setup assembled for the future GSI-FAIR fascility in Darmstadt, Germany, aims to study the nuclear footprint mainly through gamma ray spectroscopic measurements.
As a part of the NUSTAR project, the DESPEC collaboration aims to search for the exotic nuclear structure phenomena such as shell evolution in nuclei which take part in the astrophysical r-processes. The FAIR "Phase-0" programme has already been started. In persuit of chracterising the exotic nuclei, the gamma-spectroscopy was combined with charge particle spectroscopy using an array of DSSSD's of the AIDA. AIDA could also sort out the implanted ion possition and time, with precission. The filtered out gamma-rays could be used to measure nuclear energy levels precisely by the high resolution HPGe detectors, while the nuclear level lifetimes could be measured using LaBr3 scintillator detectors of the FATIMA array. Some interesting development in the Phase-0 programme has already been observed by studying the basic nuclear structure phenomena in exotic nuclei south west to the "N=Z=50" line. In future, the neutron delayed gamma-ray spectroscopic studies would be possible using the MONSTER detectors. In summary, with a multidimensional system for particle and gamma spectroscopy, the DESPEC setup once placed at the final focal plane of FRS/SUPER-FRS of the GSI-FAIR accelarator complex, is a robust tool to explore the nuclear landscape,.

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The Future of the GANIL facility

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The first experiment performed at GANIL (Grand Accélérateur National d'Ions Lourds) was scheduled 40 years ago to study the reactions induced by a 44 MeV/u Ar beam on Ni and Au targets through the mass, charge and energy distributions of the fragments. The projectile fragmentation was found to be the dominant process at this intermediate energy and this pioneer work paved the way to the successful studies of exotic nuclei performed at GANIL in the domain of halo nuclei, magic numbers, exotic radioactivities among others…
In the years 2000, the SPIRAL1 facility gave access to ISOL type beams mainly for light and medium masses nuclei whereas the new SPIRAL2 facility will, in the coming years with S3 and DESIR, open unique opportunities for the study of medium and heavy N=Z nuclei and superheavy nuclei. In addition to nuclear physics experiments, many studies are performed in the domain of interdisciplinary researches such as atomic physics, material science, medical science, biology… Part of the beam time is also dedicated to industrial applications.
In 2020, the GANIL scientific community participated to the national prospectives that produced the "French roadmap for Nuclear, Particle and Astroparticle physics, and associated technical developments and applications". In the framework of the national landscape, particular focus was done on the future of the GANIL facility that has also been afterwards intensively discussed in the frame of a committee of international experts. Four major objectives have been expressed: i- the study of neutron rich fission fragments requiring to construct a dedicated production building; ii- a post-acceleration for the radioactive ions up to 150 MeV/u; iii- the study of electron scattering on radioactive ions and iv- the increase of beamtime for the interdisciplinary activities and industrial applications. We are now in the process of starting a preliminary project in order to define possible scenarios that will account for the four aforementioned objectives. The ARIS conference will be a unique occasion to discuss these objectives with international experts.

parallel session / 627

Structure of ^{13}Be using TexAT active target.

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^{13}Be is the first neutron-unbound isotope of beryllium on the neutron-rich side. Its structure has been the subject of many experimental and theoretical studies with often conflicting results. Even the spin-parity of the ground state is still uncertain. We performed an experiment in which the T=5/2 states in ^{13}B, the isobaric analogs of ^{13}Be, were populated in ^{12}Be+p resonance elastic scattering. The experiment was performed at TRIUMF using Texas Active Target (TexAT). New constraints on the structure of low-lying resonances in ^{13}Be will be discussed.

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Improved procedures for La-135 cyclotron production and purification

Auteur: Claire Deville[1]

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For application in radiotherapy, the production procedure of a radionuclide has to be both reliable and scalable. Lanthanum-135 (^{135}La) is an Auger emitter with very few secondary emissions making it a promising candidate for Auger therapy. However, achieving a scalable production for ^{135}La comes with some challenges. In most previously reported cases, metallic natural barium was used as target material; it has the drawback of being sensitive to moisture and oxidation, making it difficult to handle. Barium carbonate ($BaCO_3$) is more stable as target material, but it suffers from poor thermal conductivity. In order to avoid a $BaCO_3$ target to burn during irradiation, the current that can be applied has to remain low and only currents up to 10 µA have been reported.[1] We have developed a new target made of a pressed mixture of enriched [^{135}Ba]$BaCO_3$[2] and aluminum powder as filling material.[3] Aluminum is a light element with a low stopping power and high thermal conductivity. It increases the thermal conductivity of the target, which can then withstand irradiation at 16.5 MeV and 20 µA current without visible damage. After 4 h irradiation, an average of 1.62 ± 0.18 GBq was produced, corresponding to a saturation yield of 11.91 GBq ± 1.31 GBq. We developed a subsequent purification procedure involving an initial precipitation step, followed by one single column containing two different commercial resins. After purification, 97.1 ± 3.6 % of the ^{135}La activity was recovered with a radionuclidic purity over 99.9%. The effective molar activity was suitable for radiolabeling: 79.6 ± 25.3 MBq/nmol was measured for the DOTA chelator, while 104.0 ± 40.4 MBq/nmol was obtained with the chelator DTPA.

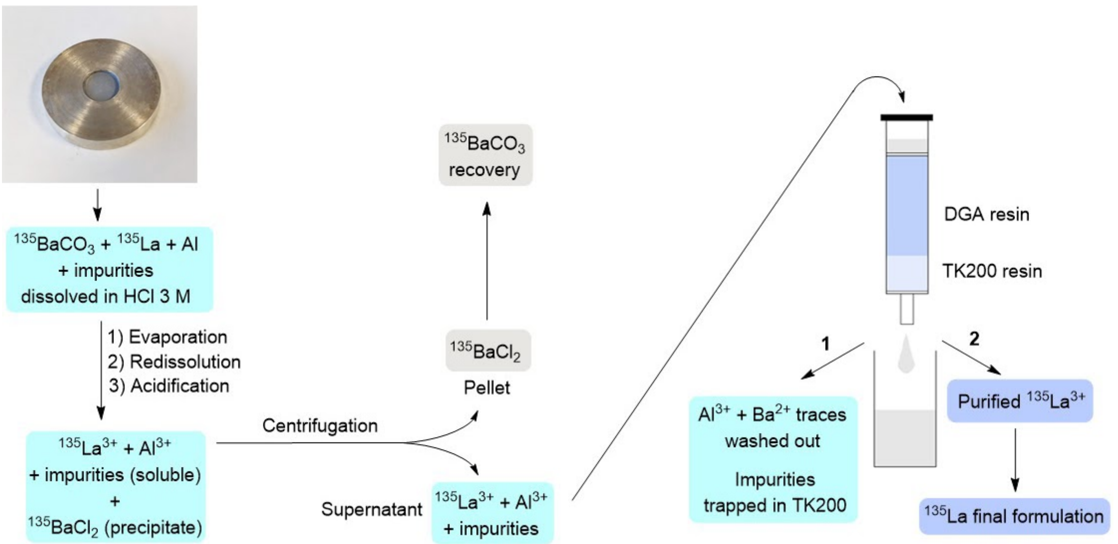

Figure 1: Summary of the La-135 purification procedure

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Charge exchange as a quantum state detector to study exotic Calcium isotopes

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Collinear laser spectroscopy (CLS) has been a reliable technique to probe nuclear structure for more than 40 years. However, both fluorescence detection and resonant ionization methods are limited in their sensitivity due to beam contamination and laser induced background. Here, an upgraded experimental setup of an existing realization of "radioactive detection of optically pumped ions after state-selective charge exchange" (ROC) is presented. With this technique, the ions are optically pumped into a metastable state. The probability for the following charge exchange within a sodium vapor cell is then greatly enhanced if this pumping was successful. After separation, the ion and atom beam respectively are implanted into a tape within a plastic scintillator detector and identified through their β-decay. This combination of optical pumping, state-selective charge exchange and β -decay identification inherently immunizes the method to stable and long-lived beam contamination as well as laser induced background, drastically improving sensitivity to a few ions/s. The technique is tested now on a new CLS setup, which was primarily optimized for rapid offline development. After moving back to the main COLLAPS beamline, the increase in sensitivity will enable optical spectroscopy of the so far unreached ^{53,54}Ca to probe the potential subshell closure at N=52 that has long been theorized and also confirmed by mass- and nuclear excitation energy measurements.

plenary 03 / 631

Evolution of single-particle properties probed with the ISOLDE Solenoidal Spectrometer

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The ISOLDE Solenoidal Spectrometer (ISS) has been built for measuring direct reactions in inverse kinematics with radioactive beams (RIBs) from HIE-ISOLDE, with a focus on obtaining excellent charged particle resolution. ISS was fully commissioned in 2021 with a new silicon array developed by the University of Liverpool. 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 from reactions of RIBs with a light-ion target, when they return to the beam axis in the solenoid field. ISS has now completed two full physics campaigns focussing on measurements of the (d,p) reaction to probe single-neutron behaviour in various systems. This talk will give an overview of ISS and a summary of the physics campaigns from the last two years with a focus on evolving single-particle structure.

The study of single-particle structure in light neutron-rich systems has led to discoveries of dramatic changes which are otherwise gradual near stability, leading to the weakening and appearance of shell closures. For example, the disappearance of $N = 20$ and emergence of $N = 16$ [1, 2] as well the emergence of $N = 32, 34$ in calcium isotopes [3]. Pronounced trends have also been observed in stable heavier nuclei, in the changes in high-j states as high-j orbitals are filling. Studies of chains of stable, closed-shell isotopes [4] and isotones [5] have pointed to robust mechanisms for these changes, such as the importance of a tensor interaction [6]. The beams available at ISOLDE allow an extension of these studies both in light neutron-rich systems but also in heavier systems such along $N = 126$. Measurements looking at the properties of the single neutron outside both $N = 16$ and $N = 126$ will be covered here.

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Study of proton and neutron excitations along Silicon Isotopes between N=20 and N=28

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The main subject of this study is the experimental investigation of the nuclear structure of exotic neutron-rich nuclei in the vicinity of shell closures in order to constrain the description of the nucleon-nucleon interaction, and in particular its tensor term. Previous studies have shown that a deformation region develops along the N=28 isotonic chain between the doubly magical and spherical ^{48}Ca nucleus (20 protons/28 neutrons) and the ^{42}Si nucleus which is extremely deformed in spite of its semi-magical character (14 protons/28 neutrons). It has been shown that this deformation results from neutron excitations above N=28 and proton excitations above Z=14, both made possible by the reduction of these shell closures under the effect of the tensor component of the nuclear interaction. The goal is now to follow the evolution of the deformation along the Si isotopic chain, between ^{34}Si (N=20) and ^{42}Si (N=28) by measuring for the first time and in a **simultaneous** way through the **E823** experiment at GANIL (Grand Accelerator National d'Ions Lourds):

- The contribution of neutrons to the excitation of the 2^+ state of $^{34-36-38}$Si nuclei by inelastic proton scattering.
- The contribution of protons and neutrons to the excitation of the 2^+ state of $^{34-36-38}$Si nuclei by Coulomb excitation on a gold target.

The experiment E823 has been set up during the 2022 campaign of LISE spectrometer (Ligne d'Ions Super Epluchés) at GANIL. This spectrometer allowed to produce and select ^{34}Si, ^{36}Si and ^{38}Si nuclei. In order to measure the proton and neutron contributions, the experimental setup was composed of two independent experiments on the same beamline with the same radioactive beam.

The first experiment was perfomed with ACTAR-TPC detector (ACtif TARget-Time Projection Chamber). The purpose of this experiment was to measure the inelastic scattering of ^{A}Si(p,p')^{A}Si* reactions, with (A=34,36,38). The analysis of this part is in progress by one of the thesis students of the ACTAR collaboration.

The second experiment was the CoulEx part (Coulomb Excitation). The goal of this experiment was to measure the effective cross section of coulomb excitations. Several types of detectors composed the CoulEx setup. The work of this thesis is mainly based on the analysis of this experiment.

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Experiments with 8Li beam at RIBRAS.

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We will present results of 3 experiments performed at RIBRAS (Radioactive Ion Beams in Brasil) with the ^{8}Li projectile impinging on ^{9}Be, ^{58}Ni and ^{120}Sn targets [1,2,3,4].
A large production of ^{7}Li particles has been observed in the three cases. The ^{7}Li can be produced either by projectile breakup or in neutron stripping reactions.
The measured ^{7}Li energy distributions indicate that the recoil system (target+n) is formed at high excitation energies around the neutron threshold as predicted by Q-optimum
transfer matching conditions. Ishimura, Austern Vincent (IAV) calculations were performed and reproduce quite well both the 7Li angular and energy distributions [2,3].
The total reaction cross sections for this process have been obtained.

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A. Lépine-Szily, R. Lichtenthäler and V. Guimarães
Eur. Phys. J. A (2014) 50: 128

[2]Evidence of the effect of strong stripping channels on the dynamics of the 8Li + 58Ni reaction.
O.C.B. Santos et al.
Phys. Rev. C103, 064601 (2021)

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O.C.B Santos et al.
Eur. Phys. J.A. 2023 ; DOI 10.1140/epja/s10050-023-00959-z

[4] Neutron transfer in the 8Li+120Sn reaction.
O.C.B. Santos et al.
to be published

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RF timer based time-of-flight spectrometer for the measurement of the absolute energy of alpha particles

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The knowledge of the absolute and accurate energies of the alpha particles emitted in the radioactive decay of a nuclide is a key factor in the construction of its decay scheme and play an important role in the evolution of the atomic-mass scale and comprise nearly 60% of the input data of atoms with A > 200. Virtually all existing data are based on a few absolute measurements made by magnetic spectrometry, to which most other measurements are traced. The combined statistic and systematic errors of these measurements in the best cases amount to be about 0.1 keV. Recently an advanced RF timing technique of single electrons has been developed at the A. I. Alikhanyan National Science Laboratory. Test studies demonstrated ~10 ps time resolution and 0.2 ps/hour stability of the technique. This 10 ps resolution is mainly due to the technical parameters of the prototype device and could be reduced essentially by suitable optimization of its parameters. In this paper we propose to develop, construct and operate time-of-flight spectrometer based on this new timing technique. By using this technique, it will be possible to measure the absolute energy of alpha particles with precision of about or better than 0.1 keV. The proposed approach is an alternative to magnetic spectrometry and will help to evaluate its possible systematic error. Meanwhile this table-top experimental setup can be used at high energy particle beams to carry out alpha spectroscopy of produced short lifetime nuclear isotopes.

plenary 09 / 639

OEDO-SHARAQ system: Its multifaceted performance and recent experimental achievements

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Co-auteurs: Daisuke Suzuki [2]; Jongwon Hwang [3]; Masanori Dozono ; Nobuaki Imai ; Rin Yokoyama [4]; Shinsuke OTA [4]; Susumu Shimoura [4]; Thomas Chillery

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The OEDO-SHARAQ system at RIBF in RIKEN was primarily started to promote high-resolution nuclear spectroscopy with radioactive isotope (RI) beams. It was recently upgraded as the world's first beamline characterized by the energy-degrading of RI beams with a followed magnetic spectrometer for fragment analysis.

The high-resolution property of the system was fully demonstrated in the direct atomic mass measurements by using the TOF-Bρ method. We recently reported the atomic masses of $^{55-57}$Ca and $^{58-62}$Ti for the first time using the OEDO-SHARAQ system in RIBF [1,2]. In this talk we would like to discuss the shell evolution in the neutron $p_{1/2}$, $f_{5/2}$ and $g_{9/2}$ orbitals in this region and the similarities or differences to a region around ^{24}O and ^{32}Mg.

The energy-degrading operation of the system began experiments in the spring of 2017. This beamline was designed to decelerate the intermediate-energy RI beam produced by the BigRIPS separator down to 10-50 MeV/u. A radio-frequency electric ion-optical element is installed in the beamline, which provides unique ion optics of time-dependent beam focusing [3]. Additionally, an angle-tunable wedge-shaped energy degrader is utilized for the compression of RI-beam energy [4]. The combination of these key equipment enables OEDO to achieve simultaneously good beam focusing and energy compression on the secondary target. Thus, the RI beams provided by the OEDO-SHARAQ system widely cover the energy range for pre-compound, pre-equilibrium, and/or direct reactions.

After OEDO's construction, we performed measurements utilizing such reaction mechanisms. Recent achievements include low-energy cross-section studies of spallation reactions on RIs, especially long-lived fission products (LLFPs) ^{93}Zr and ^{107}Pd. The results report the lowest beam energy measurements for these LLFPs and are essential when designing reduction schemes for nuclear waste management [5]. Also, experimental studies on the astrophysical neutron-capture process were done. Amplitudes of neutron-capture processes are essential for nucleosynthesis in explosive sites. OEDO-SHARAQ provides the experimental opportunity to determine survival probabilities from unbound states via a pre-compound neutron-transfer reaction. We recently measured ^{130}Sn(d,p) and ^{56}Ni(d,p) reactions to study the neutron captures in r- and νp-processes, respectively. Data analyses are ongoing. We will show here tentative achievements mainly regarding the experimental technique.

This presentation will introduce the multifaceted performances of the OEDO-SHARAQ system in intermediate-energy high-resolution spectroscopy and low-energy inverse-kinematics reaction measurements and report the recent experimental results of the system. We also discuss perspectives about future physics programs.

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Towards a cyclotron production of Ac-225 for targeted alpha therapy

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Targeted alpha therapy using the radionuclide Ac-225 has shown remarkable benefit in clinical trials to patients suffering from various cancer types. Currently most Ac-225 is produced from a few sources of Th-229 existing worldwide. However, the total amount available is only sufficient for a few thousand patient doses. Given a projected demand that is several orders of magnitude higher, alternative paths for the production of Ac-225 must be developed. We are investigating the route using the Ra-226(p,2n)Ac-225 reaction, which can be readily employed at a large number of cyclotron facilities. Its highest cross-section is near 17 MeV proton energy. The excitation function of this reaction has been previously measured by us for a few energies 1, but discrepancies with calculations remain. Hence, we are planning new irradiation experiments to improve the knowledge of the excitation function to support the industrial production of Ac-225 via this route. We have produced radium targets by electrodeposition from a mixed organic/aqueous solution in view of proton irradiation at a 30-MeV proton cyclotron. In the process, we have quantitatively determined the deposition efficiency as well as the homogeneity of deposition, which is crucial for highly precise cross-section measurements. In this talk, we will describe our electrodeposition setup and process, and report on the properties of the prepared Ra-226 targets.

1 C. Apostolidis et al., Appl. Rad. Isot. 62 (2005) 383

plenary 04 / 641

Emission channeling investigations of impurities with interesting quantum properties in single crystals

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As we enter the second quantum revolution, where non-classical properties of quantum systems are being explored for practical applications, the interest in impurity atoms embedded in crystalline materials has been extended, going far beyond previous, more conventional applications like doping to modify electrical, optical or magnetic properties of semiconductors or other materials. For instance, systems composed of a single impurity atom in a crystalline matrix, like the nitrogen vacancy (NV) center in diamond, which is already finding applications in nanoscale magnetometry, or of small ensembles of such defects, could be at the base of future quantum communication, computation and metrology devices. In that respect, one of the crucial issues is the targeted creation of specific configurations of impurity atoms in the lattice, where ion implantation plays a critical role, however, competing with other techniques.
In this talk I will discuss two examples where emission channeling experiments with radioactive ion beams at the CERN-ISOLDE facility contributed to investigating the microscopic structure of impurity configurations that may play a role in future quantum applications based on ion-implanted single

crystals. The first example will address the lattice location of the "nuclear clock" isotope 229mTh in CaF2, where for the observation of the emitted 8.3 eV photons it was crucial to have the radioactive isotope occupy substitutional Ca sites [1,2]. Another set of examples addresses the structure and formation mechanism of ion implanted colour centers in diamond based on impurities like Sn [3], Ge, or Mg [4]. For these defects with desired quantum properties it is vital to incorporate the foreign atom in the center of a double vacancy, the so-called split-vacancy configuration.

1 M. Verlinde, S. Kraemer, J. Moens, et al., "Alternative approach to populate and study the 229Th nuclear clock isomer", Phys. Rev. C 100 (2019) 024315.
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plenary 05 / **643**

Unravelling the mysteries of the atomic nucleus via high resolution laser spectroscopy at COLLAPS

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plenary 01 / **644**

FRIB and the Neutron-Rich Mg Isotopes

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The study of nuclei far from stability is one of the most active and challenging areas of nuclear structure physics. The neutron-proton imbalance in nuclei approaching the dripline(s) affects the detailed impacts of the residual interaction, modifying single-particle energies and potentially leading to altered ground and excited-state properties. In addition, at the very edge of stability, the proximity of the continuum to the bound states may modify wavefunctions further. I will discuss a range of recent experimental measurements exploring different aspects of the structure in the most neutron-rich isotopes. I will present recent work in the region of neutron number N=28, below the Ca isotopes. There is a breakdown of the N=28 harmonic oscillator magic number as protons are removed from the sd shell, and the isotones below Ar are understood to be dominated by multi-particle-multi-hole excitations and deformation in their low-lying structure. I will discuss results from the first experiment at FRIB on half-lives in this region. I will also explore the specific case of Mg-40, which sits along the N=28 isotones and very near (or possibly at) the neutron dripline, where first spectroscopy resulted in an unexpected excitation spectrum.

plenary 10 / **645**

Global ab initio calculations for the structure of exotic and heavy nuclei

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Breakthroughs in our treatment of the many-body problem and nuclear forces are rapidly transforming modern nuclear theory into a true first-principles discipline. This allows us to address some of the most exciting questions at the frontiers of nuclear structure and physics beyond the standard model.
In this talk I will highlight recent advances which now allow for global converged calculations of open-shell nuclei to the 208Pb region and beyond. In particular, I will focus on key topics in nuclear structure such as predictions of the proton and neutron driplines and evolution of magic numbers throughout the light and medium-mass regions, including new insights on the nature and existence of 28O including continuum degrees of freedom. In addition, I will discuss how correlation of the neutron skin and dipole polarizability in heavy nuclei to 208Pb provide first ab initio constraints on symmetry energy parameters for determining neutron star properties.

plenary 09 / **646**

Nuclear collectivity studied with the newly refurbished Miniball spectrometer at HIE-ISOLDE

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The Miniball spectrometer has been utilised for the study of collectivity in nuclei for two decades, exploiting post-accelerated radioactive ion beams at the ISOLDE facility. The workhorse technique has been Coulomb excitation, but few-nucleon and multi-nucleon transfer-reactions have also been exploited with the addition of ancillary devices such as the T-REX charged-particle detector.

Miniball came back to life at HIE-ISOLDE in 2022 following the second long shutdown at CERN (2018-2021), during which time it has undergone a total transformation. There has been a refurbishment of the HPGe detectors, including new cryostats, electronics and preamplifiers, as well as a newly developed data acquisition system.

In this talk, I will present some recent physics highlights from Miniball in the HIE-ISOLDE era, focusing on studies of nuclear collectivity and shapes. I will also detail the current status of the spectrometer and show preliminary results from the first experiments of the new era; including the first use of the SPEDE spectrometer for conversion electron spectroscopy in the Coulomb excitation of ^{182}Hg.

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Isospin-symmetry-breaking within DFT and IBM

Auteurs: Amir Jalili[1]; Wojciech Satula[2]

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The differences in masses and charges between the up and down constituent quarks cause a small asymmetry between neutrons and protons, which leads to isospin symmetry breaking (ISB).
The ISB within density functional theory (DFT) and the Interacting Boson Model (IBM) are two different theoretical frameworks used to describe atomic nuclei.

Within the DFT, the nucleus is treated as a collection of nucleons interacting through a mean field potential. The mean field potential is usually assumed to be isotropic and the same for protons and neutrons. Therefore, the theory assumes an isospin symmetric nuclear system. However, in reality, the proton and neutron masses are slightly different, and the Coulomb force only acts between protons. These differences break the isospin symmetry of the nuclear system. Therefore, ISB terms can be introduced into the DFT to account for these effects.
In DFT framework, we use the self-consistent isospin- and angular-momentum-projected nuclear DFT. This post-mean-field method restores rotational symmetry and considers configuration mixing within a space that includes relevant (multi) particle-(multi) hole Slater determinants.
In order to construct a basis that conserves both angular momentum and isospin, we begin by finding the self-consistent MF state $|\varphi\rangle$ and then use the projection method to build a normalized angular-momentum- and isospin-conserving basis $|\varphi;,IMK;,TT_z\rangle$ 1.
\begin{equation}\label{ITbasis}
|\varphi ;\, IMK;\, TT_z\rangle = \frac{1}{\sqrt{N_{\varphi;IMK;TT_z}}}
\hat P^T_{T_z,T_z} \hat P^I_{M,K} |\varphi \rangle ,
\end{equation}
where $\hat{P}^T_{T_z,T_z}$ and $\hat{P}^I_{M,K}$ stand for the standard isospin
and angular-momentum projection operators. Now, we can calculate the ISB based on the DFT.

On the other hand, the IBM assumes that nucleons in the nucleus form clusters of bosons (\emph{s} and \emph{d} bosons or \emph{p} bosons) [2]. These bosons interact through a Hamiltonian, which is invariant under the U(6) group of unitary symmetries. This symmetry group includes the isospin symmetry group SU(2), and the model can be extended to include the isospin degree of freedom. Within the IBM, the isospin symmetry breaking can be introduced by including isospin-symmetry-breaking terms in the Hamiltonian. However, the IBM is a phenomenological model, and its success lies in its ability to describe collective properties of atomic nuclei, rather than predicting detailed nuclear structure.
In IBM framework, we will add a term containing the vector boson in Hamiltonian, which is responsible for negative parity states and dipole resonance, as well as Coulomb terms to show the isospin impurity. To study these effects, we will use a simple two-state mixing model as the same M. Kimura, T. Fortune and others [3-5].
In order to describe the mixing impurity, we introduce two mixing bands like
\begin{align}
\Psi(1^-*1) &=\alpha \Phi(T=0) + \beta \Phi(T=1),*\\
\Psi(1^-_2) &=\beta \Phi(T=1) - \alpha \Phi(T=0),
\end{align}
Then, the ratio of the allowed and forbidden transitions gives an estimate of the mixing ratio as,
\begin{align}
\frac{B(E1){1^-*1\longrightarrow 1*^-{gs}}}{B(E1)*{1^-_2\longrightarrow 1*^-{gs}}}=\frac{\alpha^2}{\beta^2}=\frac{\alpha^2}{1-\alpha^2}.
\end{align}
where the coefficients of α and β are the mixing amplitudes. By fitting these values, we can get the information of isospin impurity α^2 in our model.

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Synthesis of cold highly charged radionuclei using antiprotons

Auteur: Fredrik Parnefjord Gustafsson[1]

Co-auteurs: A Farricker [2]; A Camper [3]; B Bergmann [4]; F Castelli [5]; F Guatieri [6]; G Kornakov [7]; G Consolati [8]; L Graczykowski [9]; Lisa Gloggler [1]; L. K. Graczykowski [7]; M Auzins [10]; M. Grosbart [1]; Michael Doser [1]; N Gusakova [11]; P Burian [4]; R Ciurylo [12]; R. S. Brusa [6]; R Caravita [6]; S Huck [1]; S Haider [1]; T Sowiński [13]; M Janik [9]; G Kasprowicz [9]; G Khatri [1]; L Klosowski [12]; Valts Krumins [10]; L Lappo [14]; J Malamant [3]; S Mariazzi [6]; D Nowicka [7]; L Penasa [6]; V Petracek [15]; M Piwinski [12]; S Pospisil [4]; L Povolo [6]; F Prelz [5]; S Rangwala [16]; Benjamin Rienacker [2]; V Rodin [2]; O.M. Rohne [3]; H Sandaker [3]; P Smolyanskiy [4]; D. Tefelski [9]; C.P. Welsch [2]; M. Zawada [17]; J Zielinski [7]; N Zurlo [18]

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At CERN's Antimatter Decelerator (AD) cold beams of antiprotons are routinely generated for a wide range of precision experiments. The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEGIS) at AD aims at performing studies of the gravitational influence on a horizontal beam of cold antihydrogen atoms 1. AEGIS has achieved remarkable performance in trapping antiprotons and successfully demonstrated the pulsed production of Rydberg excited antihydrogen [2,3]. The production process is achieved through the charge exchange reaction using laser-excited Rydberg positronium (a hydrogen like bound system of a positron and electron) interacting with cold antiprotons stored within a Penning-Malmberg trap.
This technique is currently being adapted for the synthesis of antiprotonic atoms of medium-heavy nuclei [4]. So far, antiprotonic atoms were formed in beam-on-target experiments, primarily focusing on light systems such as antiprotonic helium [5,6]. Due to the great mass of the antiproton, nearly 1836 times heavier than the electron, the antiproton naturally forms orbits inside the electron cloud and rapidly annihilates on the nuclear surface. However, using the charge exchange procedure developed at AEGIS for antihydrogen, cold trapped antiprotonic atoms can be selectively formed in highly excited Rydberg states bound outside the electron cloud. The relaxation of the bound antiproton leads to Auger electron and photon emission, eventually forming a fully or nearly fully stripped nucleus with the bound antiproton. Subsequent annihilation on the nuclear surface results in the formation of exotic, highly charged radioactive nuclei within the trap. This technique will open

avenues for exploring a variety of nuclear structure phenomena, allowing the novel formation of highly charged radionuclei and enable the search for new physics [7,8].
Recent upgrades of the AEgIS apparatus will explore the first co-trapping of iodine anions with cold antiprotons, allowing the study of antiprotonic iodine formation as a proof-of-principle of this technique.

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Accessing nuclear structure with high-energy nuclear collisions (presentation sponsored by NUPECC)

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High-energy nuclear collisions are conducted in the world's largest accelerators, the BNL RHIC and the CERN LHC, to characterize the hot phase of strong-interaction matter, the quark-gluon plasma. Following two decades of phenomenological studies and the availability of data from several different species, a picture has been established according to which high-energy nuclear scattering works as an imaging process giving access to spatial distributions of nucleons in the ground states of the colliding ions. These experiments provide, thus, complementary evidence of nuclear deformations, as well a new means to determine neutron skins.

I present recent activities that have gathered together low-energy nuclear structure physicists and high-energy heavy-ion physicists to address these issues, and I highlight the advances that they have brought for both communities. I discuss the prospects for future experimental and theoretical studies at the intersection of these two areas aimed at improving our knowledge of the strong nuclear force across energy scales.

plenary 03 / 650

r process and supernova signatures in deep-sea archives

Auteur: Anton Wallner[1]

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Half of the heavy elements are produced in r-process nucleosynthesis, which is exclusively responsible for actinide production, such as Pu-244 ($t_{1/2}$=81 Myr). The r-process requires an explosive scenario but is far from being fully understood; in particular, its sites and history.

The solar system moves through the interstellar medium (ISM) and collects interstellar dust particles that contain such signatures, including the radionuclides Fe-60 ($t_{1/2}$=2.6 Myr) and Pu-244. These

nuclides are incorporated into terrestrial archives over millions of years and once recovered can be measured with Accelerator Mass Spectrometry (AMS) with high sensitivity.

Recent technical developments have seen an exceptional gain in measurement efficiency and sensitivity, in particular for actinides, including Pu-244. On the other hand, very large accelerators with >10 million volts allow for effective isobar separation using techniques derived from nuclear physics research. Such AMS systems are unique but required for the identification of small traces of interstellar Fe-60.

New data demonstrate a global Fe-60 influx and is evidence for exposure of Earth to recent (<10 Myr) supernova explosions. In addition, the recent finding in deep-sea archives of ISM-Pu-244, exclusively produced by the r-process, allows to link supernovae and r-process signatures. The low concentrations of Pu-244 measured in deep-sea archives suggest a low abundance of interstellar Pu and supports the hypothesis that the dominant actinide r-process nucleosynthesis is rare. However, the data allow some actinide production in supernovae while implying r-process contributions from additional sources.

plenary 01 / 651

Prevailing triaxial shapes in exotic and heavy nuclei

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Shapes of heavy deformed nuclei are discussed from the viewpoint of the Monte Carlo Shell Model with realistic effective NN interactions. The prevailing triaxial shapes then emerge due to the nuclear tensor force, in contrast to the conventional picture of the prolate-shape dominance since 1950's. The triaxiality with $\gamma \sim 9^\circ$ arises commonly for rare-earth nuclei around ^{166}Er. The mechanism for the low-lying second 2^+ state is presented, and the relation to the Davydov model is mentioned. Possible new M1 mode due to the triaxiality is pointed out. Triaxial shapes of exotic Ne, Na and Mg isotopes are also discussed with the *ab initio* EEdf1 interaction for the sd-pf combined shell.

plenary 02 / 652

Observation of a correlated free four-neutron system

Auteurs: Valerii Panin[1]; Meytal Duer[2]; Thomas Aumann[3]

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An isolated system of four neutrons is studied in the SAMURAI experiment at the Radioactive-Ion Beam Factory at RIKEN 1. The key reaction 8He(p,pα)4n in inverse kinematics populates the final state of four neutrons through a prompt quasi-free-scattering process close to 180 degrees in the p-α centre-of-mass frame. The resulting energy spectrum of the free 4n system reveals a distinct peak-like structure with positive energy centered at 2.4 MeV in addition to a more broad distribution associated with the continuum. The details of the experimental method and the analysis results will be presented along with the further perspectives of studying multi-neutron systems.

plenary 11 / 653

Studies of exotic isotopes using laser ionization techniques and trapped ion techniques

Auteur: Ruben de Groote[1]

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Laser spectroscopy techniques provide nuclear-model independent access to nuclear electromagnetic moments, spins and charge radii. Advances in radioactive ion beam instrumentation and laser technologies have enabled the study of a wide range of elements and isotopes, pushing out far from the valley of stability towards the drip lines. In this contribution, I will present experimental progress along two important frontiers. I will discuss the use of methods based on laser ionization spectroscopy and how they have allowed us to reach exotic nuclei such as 94Ag 52K. Crucially, these measurements relied on the use of decay detection or ultra-selective mass separation tools to provide low-background measurement conditions.
Besides using efficient laser ionization and particle detection methods, another important area of research relies on the use of ion traps. I will show a recent example of how ions trapped in a linear Paul trap can be optically pumped into a beneficial metastable state. In particular, I will show how this approach enabled fluorescence spectroscopy of neutron-deficient singly-charged cobalt isotopes. Finally, I will conclude with a discussion on the next logical step, which entails doing optical and radiofrequency spectroscopy of radioactive ions while they are trapped in a linear Paul trap. I will discuss the status of a new setup currently under construction at the KU Leuven.

plenary 03 / 654

Proton radioactivity studies with ACTAR TPC

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(for the E690 and E791 collaborations)

For nuclear systems that are slightly unbound with respect to the nuclear strong interaction, the 1- and 2-proton radioactivity decay channel opens [1,2]. The experimental study of these radioactivities offers a unique access to the structure properties of the emitting states. Such data can represent real challenges in terms of theoretical interpretations.
This kind of exotic decay modes is part of the physics program that motivated the development of the ACTAR TPC (Active Taget and Time Projection Chamber) device [3], as well as several other TPC detectors worldwide. ACTAR TPC has been successfully used in recent experiments, related to proton(s) radioactivity in the A~50 mass region.
The first experiment allowed for the imaging of the proton emission from the ^{53m}Co and the (short-lived) ^{54m}Ni isomeric states [4,5,6]. In both cases, the observation of the high angular momenta proton branches allowed for the determination of the complete decay pattern of these states. The second experiment aimed at the direct observation of the ground state 2-proton radioactivity of ^{48}Ni [7]. The scientific context and the experimental results will be presented, and compared to state of the art theoretical interpretations.

1 B. Blank and M.J.G. Borge, Progress in Particle and Nuclear Physics 60 (2008) 403–483
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[4] J. Giovinazzo *et al.*, Nature Comm. 12, (2021) 4085
[5] D. Rudolph *et al.*, Physics Letters B 830 (2022) 137144

[6] L.G. Sarmiento *et al.*, accepted for publication in Nature Comm.
[7] A. Ortega Moral *et al.*, proceedings of Zakopane 2022 conf.

Friday / 655

Probing Nuclear and Particle Physics Phenomena with Radioactive Molecules

Auteur: Ronald Garcia Ruiz[1]

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poster session / 656

Reactor Antineutrino Spectral Excess: Cumulative Fission Yield Measurement Using Gamma-Ray Spectroscopy

Auteur: Samuel Kim[1]

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Recent measurements of the reactor antineutrino emission show that there exists a spectral excess in the 5-7 MeV region when compared to the Huber-Muller prediction based on the conversion method. Analysis within an alternate prediction technique, the summation method, suggests that the bump could be due to excess contributions from a certain few of the beta-decaying fission products. However, it has been shown that when updated fission yield values are used in the summation method, the predicted excess vanishes. In the present preliminary study, fission yields for nuclides suspected of causing the neutrino spectral bump are investigated using gamma-ray spectroscopy of 235-U and 239-Pu samples freshly irradiated using the High Flux Isotope Reactor. For several of the suspect nuclides, the derived fission yields are consistent with JEFF3.3 fission yield library. The exception is the case of 140-Cs from 239-Pu, where the discrepancy between the fitted and expected values suggests a potential error in the fission yield library. This highlights the importance of using accurate nuclear data libraries in the analysis of the reactor antineutrino spectra, and the need for ongoing efforts to improve these libraries.

public lecture / 657

Treatment of metastatic cancer by Radiomolecular Precision Oncology - an ongoing revolution

Auteur: Richard P Baum[None]

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The radiopharmaceuticals toolbox has expanded dramatically over the last few years. Isotopes with well-established chemistries continue to be used routinely, while newer isotopes have grown more available, with a wider variety of chemistries, decay modes and in vivo behaviors, making it easier to pair radiopharmaceuticals for imaging and therapy, a pairing referred to as radiomolecular theranostics. In much the same way that the development of targeted agents and immunotherapy revolutionized medical therapies for cancer, the rapid development and availability of these new isotopes and agents has fundamentally changed the landscape for radiopharmaceutical therapy.
Radiomolecular Precision Oncology is being driven by rapid advances in novel diagnostics and therapeutic interventions. As part and integral in the current era of precision oncology, theranostics aims to identify the appropriate molecular targets in neoplasms (diagnostic tool), so that the optimal ligands and radionuclides (therapeutic tool) with favorable labeling chemistry can be selected for personalized management of a specific disease, taking into consideration the specific patient, and subsequently monitor treatment response for personalized cancer care.
Peptide receptor radionuclide therapy (PRRT) and PSMA Radioligand Therapy (PRLT)
Over the past two decades, the use of 68Ga labeled peptides for somatostatin receptor (SSTR)-targeted PET imaging followed by beta emitters like 177Lu and 90Y or alpha-emitters like 225Ac and 212Pb labeled SSTR-analogues for peptide receptor radionuclide therapy (PRRT) has demonstrated remarkable success in the management of neuroendocrine neoplasms and paved the way to other theranostics indications.
Targeted Alpha radioligand therapy (ART)
While beta-emitters have demonstrated efficacy, alpha-emitters have a 100-fold higher LET. Remarkable results have been achieved by switching non-responders from 177Lu to alpha therapies. Our experiences indicate that the combination of 225Ac and 177Lu labeled PSMA and somatostatin receptor antagonists ligands for TANDEM treatments are feasible, safe, and effective, and suggest a potential synergistic effect.
FAP-targeted peptide targeted radionuclide therapy (PTRT)
FAP is overexpressed on cancer-associated fibroblasts (CAFs) in over 90% of epithelial. We recently published the worldwide first clinical experience using 177Lu-FAP-2286. We are now performing PTRT using 3BP-3940 to explore the theranostic approach applying 68Ga-3BP-3940 for PET/CT imaging and selection of the patients for PTRT with 177Lu, 90Y, 225Ac and combinations of the radioisotopes for TANDEM-PTRT.
RadioVakzination - Combination of radioligand therapy with immunotherapy
By combining molecular targeted radioligand therapy with immune check-point inhibitors (ICPI), e.g. PD-L1 mAb like pembrolizumab, a promising paradigm of cancer immunotherapy has been developed that could reprogram TME from “cold” to “hot”, to make low immunoactivity tumors sensitive to therapy.
Conclusions
PRRT lends a significant benefit in progression-free survival in metastasized NENs as compared to other treatment modalities. Quality of life is significantly improved. The combination of 177Lu and/or 90Y, 225Ac (DUO-PRRT) may be more effective than either radionuclide alone.
177Lu-PSMA RLT is safe and effective with appropriate selection/follow-up of patients by 68Ga-PSMA PET/CT. 225Ac-PSMA or TANDEM-ART is prolonging overall survival for end-stage mCRPC. The initial clinical results of PTRT provide evidence for the feasibility of radiomolecular precision theranostics in a number of advanced, therapy-refractory adenocarcinomas.
New targets, novel radionuclides (225Ac, 212Pb and Terbium radioisotopes), tumor microenvironment with optimized peptide and optimal isotopes (177Lu, 225Ac, 90Y, TANDEM) and administration schedules, RadioVax (combination of radioligand with immunotherapy), radioprotectors and radiosensitizers will be systematically explored in future.
Personalized, molecular radiotherapy of malignancies, tailored to the individual patient in a PRECISION ONCOLOGY setting (including genomics) is moving from innovation to implementation in real-world, and large patient populations are expected to be in the mainstream of future applications.

Thank you all for your participation!