CGS17

Monday, 17 July 2023 - Friday, 21 July 2023

MAISON MINATEC

Book of Abstracts

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Studies of Shape Coexistence in the Sr-Ru isotopes

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The evolution of ground-state shapes usually proceeds smoothly, however for Sr and Zr nuclei at N = 60 there is an abrupt shape transition, and very low-lying 0+2 states are observed [1,2]. The dramatic onset of deformation in 100Zr was recently well reproduced in state-of-the-art Monte Carlo Shell Model calculations [3,4], which also predict that the same deformed configuration may coexist at higher excitation energies in the lighter Zr isotopes. In the Mo isotopes, shape coexistence has been firmly established in 96,98,100Mo through detailed Coulomb excitation studies [5–7], and low-lying 0+2 states exist here as well, but the evolution of the ground state shape is smoother than for Zr and Sr. Proceeding to higher Z, the structure of states in the Ru isotopes evolves more smoothly than those of Mo. This change in evolution of the structures in this region, with drastically different shapes in the Sr and Zr isotopes that appear to generally mix weakly, vs. the Mo and Ru isotopes where they are more similar and appear to mix strongly, presents an ideal topic of study to understand the development of collectivity.
In an effort to elucidate the nature of excited states in the Sr–Ru isotopes near N = 60, we have performed an extensive series of measurements which include β decay, neutron capture, Coulomb excitation, and transfer reactions. As some examples of our results, from our β-decay studies populating the N = 60 nuclei 98Sr and 100Zr, we have identified the 0+3 bands and provided a measure of the collectivity in the 0+2 band of 100Zr. Combining β-decay and the (p,t) transfer reaction, the structures of excited states of 98Ru were reinterpreted into rotational bands [8]. Our study of the 99Ru(nth,γ) reaction leads to a dramatic revision of the collectivity of the 0+3 band, while the Coulomb excitation of 102Ru has established the collectivity of the 0+2 band for the first time [9]. These highlights will be outlined and placed into the context of the emerging systematics of collectivity in the region.

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Session 1 / 136

Towards a microscopic understanding the shape isomerism in medium mass nuclei

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The phenomenon of nuclear shape isomerism is an example of extreme shape coexistence in atomic nuclei. It arises from the existence of a secondary minimum in the nuclear potential energy surface (PES), at substantial deformation, separated from the primary energy minimum (the ground state) by a high potential energy barrier that hinders the transition between the minima. Shape isomers have clearly been observed, so far, in actinide nuclei at spin zero [1], and in superdeformed nuclei at the decay-out spin [2]. Only recently, being inspired by various mean-field theoretical approaches

[3-5] and by the state-of-the-art Monte Carlo Shell Model (MCSM) calculations [6], shape-isomer-like structures, of prolate deformed nature, have been observed at spin zero in the lighter nuclei of 64,66Ni, by using gamma-ray spectroscopy and employing different types of reaction mechanisms (i.e., proton and neutron transfer, neutron capture and Coulomb excitation) [7,8].
From the theory point of view, the phenomenon of shape isomerism in the Ni isotopes reflects the action of the monopole tensor force which stabilizes isolated, deformed local minima in the PES. An analogous situation is expected to occur in the 112-116Sn isotopes and in 83,84Se nuclei.
In this talk, we will discuss the extended research program carried out at ILL (Grenoble) with the FIPPS array, IFIN-HH (Magurele) with ROSPHERE, and at Argonne (USA) and Legnaro National Laboratory (Italy), with the tracking array GRETINA and AGATA, respectively. The aim is to provide complementary information on the properties of shape-isomer-like states in different mass regions, which will help shedding light on the microscopic origin of extreme shape coexistence in atomic nuclei.

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Search for low-lying octupole-isovector excitations

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Two-component quantum systems develop fundamental modes in terms of in-phase and out-of phase motion of the subsystems. For the nuclear many-body system the framework of the proton-neutron Interacting Boson Approximation (IBA-2) predicted the latter type of excitations as so-called mixed symmetry states. The experimental fingerprint is a strong M1 transition to the proton-neutron symmetric coupled state, which is usually the lowest-lying state for a given spin and parity combination, and a weakly collective decay to the ground state. In this contribution results from ^{95}Mo(n,γ) and ^{143}Nd(n,γ) experiments employing the EXILL setup are reported. These measurements aimed to confirm candidates for low-lying octupole isovector (mixed-symmetry) states by measuring the relative intensity and multipole-mixing ratio in the crucial decay to the first 3^- level. Furthermore, for ^{144}Nd the lifetime of the candidate was remeasured using GAMS. In the talk the resulting experimental picture will be presented and for ^{96}Mo an alternative interpretation for the observed M1 strength given.

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Shape evolution, mixing and coexistence around Z=30-48 studied with beyond-mean-field methods

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Nuclei in the region of the nuclear chart between Z = 28 and 50 magic numbers show a collective behavior that can be attributed to the appearance of quadrupole shape mixing and/or coexistence.

Advanced energy density functional (EDF) methods, including symmetry restorations and axial and triaxial shape mixing, are the perfect tools to study these phenomena from a microscopic point of view. In this contribution I will present recent systematic calculations performed with the Gogny EDF, comparing with the available experimental data and shell model calculations.
Furthermore, I will focus on specific examples of static and dynamic shape coexistence.

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Angular Correlations of Capture Gamma-rays from p-wave Resonances for the Study of the Boundary Condition at the Entrance Channel

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Extremely large breaking of the symmetry under the spatial inversion (P-violation) is observed in p-wave resonances of medium heavy nuclei[1]. The enhanced P-violating effect is understood as the result of the combination of the interference between neutron scattering amplitudes of P-unfavored neighboring resonances, which is referred to the kinematical enhancement, and the variance of the P-violating nuclear interaction in compound nuclear states, which is referred as the dynamical enhancement. The kinematical enhancement has been studied by determination of partial neutron widths of p-wave amplitudes in energy-dependent angular correlations of individual gamma-ray transitions emitted in the relaxation process of compound nuclear states using pulsed neutron beam at the ANNRI beamline of the J-PARC spallation neutron source[2-6]. In this paper, we overview the experimental results and discuss their consistency with theoretical models and possible extension to their application to search for the breaking of the time reversal invariance in nuclear interaction with the possible sensitivity to new physics beyond the standard model of elementary particles.

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Study of the beyond-neutron-threshold structure in the N=50 region from beta-delayed neutron and gamma spectroscopy at ALTO

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There has been recently growing evidence, from β-delayed gamma and neutron spectroscopy measurements on neutron-rich nuclei, seemingly pointing towards the existence of specific regions of the daughter nucleus excitation spectrum that clearly concentrate larger fractions of the β-strength. These regions significantly overlap with regions where highly collective excitation modes (typically E1) of the nucleus are expected to lie, raising again the question of the nature of unbound states populated by high-Qβ radioactivity. This interplay may result in unusually strong γ emission from levels located well above the neutron threshold. Should this strong γ/n competition turn out to be more general than expected e.g. throughout the r-process mass region (and particularly close to magic numbers) part of commonly admitted nucleosynthesis scenarios would be affected.
In this context, we have launched an experimental program at ALTO to investigate the structure of the neutron-threshold region of exotic nuclei. This endeavor was initiated by the unexpected observation of "ultra"-high-energy γ-rays (8-9 MeV) in the β-delayed emission products of 83Ga (Z=31 ; N=52 ; T1/2=312 ms ; Qβ=11.7 MeV) sources collected at the BEDO decay-station [1]. Further detailed investigation of the β-delayed γ spectroscopy following the decays of 80,82,83Ga sources collected at BEDO has recently been performed. The data set was considerably enriched with respect to the study of [1] thanks to the use of an improved hybrid γ-ray spectrometer composed of PARIS clusters and HPGe detectors [2]. Part of these new results will be presented and discussed, as well as further perspectives along these research lines at ALTO.

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Nuclear astrophysics with stored and cooled highly-charged ions

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Storage of freshly produced secondary particles in a storage ring is a straightforward way to achieve the most efficient use of the rare species as it allows for using the same secondary ion multiple times. Employing storage rings for precision physics experiments with highly-charged ions (HCI) at the intersection of atomic, nuclear, plasma and astrophysics is a rapidly developing field of research. The number of physics cases is enormous. The focus in this presentation will be on the most recent results obtained at the Experimental Storage Ring ESR of GSI in Darmstadt and the Experimental Cooler-Storage Ring CSRe of IMP in Lanzhou.
Both the ESR and CSRe rings are coupled to in-flight fragment separators and are employed for precision mass spectrometry of short-lived rare nuclei. At CSRe, the enabled measurement of the velocity of every stored particle—in addition to its revolution frequency—has boosted the sensitivity and precision of mass measurements, which lead to accurate determination of the remaining masses constraining matter flow though 64Ge waiting point in the rp-process nucleosynthesis.
The ESR is presently the only instrument dedicatedly utilized for precision studies of decays of HCIs. Radioactive decays of HCIs can be very different as known in neutral atoms. Some decay channels can be blocked while new ones can become open. Such decays reflect atom-nucleus interactions and are relevant for atomic physics and nuclear structure as well as for nucleosynthesis in stellar objects. Especially the two-body weak decays of HCIs will be discussed.
The experiments performed at the ESR and CSRe will be put in the context of the present research programs in a worldwide context, where, thanks to fascinating results obtained at the presently operating storage rings, a number of projects is planned.

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The ISOLDE Decay Station: recent activities and perspectives

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The ISOLDE Decay Station (IDS) was designed as a flexible tool for decay spectroscopy studies, operating since 2014 at ISOLDE. At the core of IDS there are 4-6 HPGe clovers to detect γ rays with high energy resolution together with a moving tape system and a complex array of ancillary detectors such as LaBr3:Ce crystals to measure excited-state lifetimes down to a few picoseconds, silicon detectors (annular, PAD, DSSSD, Solar Cell) for charged particle (p, α, e−, e+) or β-delayed fission fragments spectroscopy and an efficient plastic scintillator array acting as a neutron Time-of-Flight detector for β-delayed neutron emission studies. In recent years, IDS has also been used as a decay-spectroscopy tool for in-source laser spectroscopy studies together with RILIS.
Following the end of the CERN Long Shutdown 2 development campaign, ISOLDE has resumed the experimental campaign in June 2021 and there have been several new decay spectroscopy experiments performed at IDS, including the 2023 experimental campaign that will be highlighted in the current presentation alongside a detailed description of the upgraded setup and future development plans.

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High-Pressure, High-Temperature Gamma Ray Spectroscopy Measurements in the Oil Field: Data Quality Improvements Due to Cerium-Doped Lanthanum Bromide Scintillator Crystal Material

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In the oilfield industry, exploration of the subsurface is essential to answer questions regarding location, type, quantity and producibility of hydrocarbons. The subsurface environment in which logging tools are used can be severe. Downhole tools must perform at temperatures exceeding 175˚C while being exposed to repeated shocks of 100 g and more and at pressures that can exceed 200MPa. Under these harsh conditions, the tools must deliver accurate and reliable measurements while operating for hundreds of hours of operation.
Since drilling rig operation time is very expensive, the measurements must be acquired as fast as possible. Therefore, any improvement which reduces the statistical uncertainty of the measurements without increasing the time spent on the rig is welcome.

Nuclear modeling is widely used to design nuclear tools in the oilfield. It allows improving the measurements by optimizing the tool design without a lot of time-consuming experimentation, provides a very convenient method for checking the impact of environmental effects such as borehole fluid composition, pore fluid and rock composition on the tool response, and allows predicting measurement performance before building the first tool or evaluating performance for new scintillator materials.
Modeling of neutron induced gamma ray spectroscopy is more complex than that of any other nuclear measurements as it combines the spectral response in energy and time and requires modeling of the coupled neutron gamma ray transport and subsequent detector response combined with sensitivity to small amounts of specific materials with large neutron interaction cross sections.

NaI(Tl) is still the most commonly used scintillator material today. In the oilfield industry, NaI(Tl) was used initially for natural gamma ray detection, gamma ray scattering based density measurements, and the detection of neutron-induced capture and inelastic gamma rays. In the early 90s,

BGO and GSO were introduced to the oilfield in downhole tools for the detection of natural gamma ray spectra, formation density measurements, and capture gamma ray spectroscopy. The new detector materials were well suited for gamma ray spectroscopy given their high density and average atomic number. However, their spectroscopy performance was not optimal and worsened rapidly with temperature. More recently, LaBr3:Ce was introduced in two new instruments, enabling step changes to the neutron-induced gamma-ray spectroscopy measurement performance.
In addition, the new material makes it possible to unlock information regarding elements such as oxygen, carbon, manganese, aluminum and increasing the information on the subsurface composition.

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Decay Spectroscopy of Deformed, Neutron-rich Nuclei: Nuclear Structure and Role of K Forbiddenness*

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Properties of deformed, neutron-rich nuclei in the A~110 and 160 mass regions are important for achieving better understanding of the nuclear structure where little is known owing to difficulties in the production of these nuclei at the present RIB facilities. They are essential ingredient in the interpretation of the r-process nucleosynthesis and are needed in fission-like applications since theoretical models depend sensitively on the nuclear structure input. Predicated on these ideas, a dedicated decay spectroscopy experimental program has been initiated at Argonne National Laboratory, by combining the CARIBU radioactive beam facility with the newly developed Gammasphere decay station. The initial focus was on several deformed odd-odd nuclei, where β decays of both the ground state and an excited isomer were investigated. Because of the spin difference, a variety of structures in the daughter nuclei were selectively populated and characterized, which in turn provided information about the structure of the isomers. Mass measurements using the Canadian Penning Trap aimed at discovering of long-lived isomers in these regions and at determining of their excitation energies were also carried out.
Overview of the decay spectroscopy program at ANL will be presented together with results from recent experiments and comparison with multi-quasiparticle blocking calculations. The effect of K-forbiddenness on the β-decay strength will also be discussed.

* Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and the National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation R & D (NA-22).

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Nuclear structure, nuclear models and symmetries

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I will start the talk with some thoughts on our current theoretical understanding of the structure of the nucleus, avoiding as much as possible technical details and concentrating on recent advances and broad aims. Despite the recent trend to view the nucleus from a computationally intensive angle, I will argue that this can only provide a partial picture and that parametrised models will remain

an unavoidable element of nuclear structure. Specifically, models based on symmetries can play a vital role in establishing an understanding of complex nuclei from a simple perspective. After a brief historical review of the benchmark symmetry models of the nucleus, I will provide examples on how the symmetry approach can be relevant for the interpretation of recent nuclear data.

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Absolute electromagnetic transition rates in semi-magic N = 50 and 126 isotones as a test for $(\pi_{9/2})^n$ single particle calculations.

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Assuming the presence of one- and two-body interactions, single-j calculations for $(j)^n$ configurations with n = 1,..,2j+1 can be performed using a semi-empirical approach, provided that the energies and absolute electromagnetic transition rates are known for the two-particle (hole) nucleus. Using those and the coefficients of fractional parentage, all needed matrix elements for the $(j)^n$ configurations can be predicted.

At the Cologne Tandem Accelerator of the Institute for Nuclear Physics we have tested these relations by measuring lifetimes of excited states in the $(\pi_{9/2})^n$ isotones with N = 50 and N = 126 over the last years. We started the studies in the two-proton nucleus ^{210}Po where the abnormal B(E2:$2_1^+ \to 0_1^+$) value was remeasured, providing important input for the other configurations [1]. Then lifetimes of excited states in ^{211}At were measured using the electronic γ-γ fast timing technique, the Recoil Distance Doppler Shift (RDDS) method, and the Doppler Shift Attenuation (DSA) method~[2,3]. Very good agreement with the analytical single-j calculation is obtained. We will also shortly report on our study of ^{213}Fr.

For N=50 isotones, we recently started by remeasuring the previously unknown B(E2:$4_1^+ \to 2_1^+$) value needed for the prediction of other N=50 isotones with Z= 41-50 [4]. We will also report on experiments on ^{93}Tc, ^{94}Ru and ^{96}Pd, as well on ^{94}Ru and ^{95}Rh at FAIR Phase-0 [5].\\

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Triaxiality and shape coexistence as basic modes of collective bands of heavy nuclei

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Many of deformed heavy nuclei, such as 166Er and their neighbors in the nuclear chart, are shown to have triaxial ground and gamma bands with gamma equal to about 10 degrees, with gamma stretching in the gamma bands.
Some other nuclei, like 154Sm, show prolate ground bands, but their side bands are produced by the shape coexistence of triaxial shapes with gamma equal to about 15 degrees.
Monopole interactions containing tensor force contributions are essential for these structures. If time permits, M1 excitations from these ground states may be discussed, with a possible mode specific to triaxial ground states.
The calculated results are obtained by the advanced version of the Monte Carlo Shell Model (MCSM), called the Quasiparticle Vacuua shell model.

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The Nuclear Structure of ^{74}Ge from Inelastic Neutron Scattering

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Inelastic neutron scattering (INS) provides non-selective or statistical population of low-lying, low-spin $(J^\pi \leq 6)$ states. As such, the reaction populates non-yrast states allowing a determination of the comprehensive level scheme. In addition, the Doppler-shift attenuation method following INS can be utilized to measure level lifetimes in the femtosecond regime. Overall, the method allows the extraction of γ-ray energies, level energies, level lifetimes, a_2 and a_4 angular distribution coefficients, branching ratios, and multipole mixing ratios. These data can then be used to calculate reduced transition probabilities, which are a sensitive test of the nuclear structure and can be compared to theoretical calculations to further our understanding.

The germanium nuclei have been of recent interest for multiple reasons. First, ^{76}Ge is one of the leading candidates for the observation of neutrinoless double-beta decay. The structure of both the parent and daughter are important for calculating the nuclear matrix element for the process, which cannot be experimentally determined. Moreover, the deformation of the parent and daughter have an impact on the magnitude of the matrix element; similar deformations would lead to a larger matrix element, and thus a shorter lifetime for the decay. Thus, understanding the nuclear structure of these nuclei becomes important. The Ge nuclei are also interesting from a structural perspective. Open questions of triaxiality among these isotopes remain a topic of investigation. In order to better understand the structures of the Ge nuclei, we have undertaken studies of ^{76,74,72,70}Ge using inelastic neutron scattering. A number of new structural features have been identified and characterized in each nucleus, but ^{74}Ge will be the focus of this presentation. Large-scale shell-model calculations have been performed and show remarkable agreement with experimental data.

This material is based upon work supported by the U. S. National Science Foundation under Grant No. PHY-2209178.

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Muonic X-ray spectroscopy at the Paul Sherrer Institute

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Muonic atoms are exotic bound systems consisting of a negative muon and a nucleus. Due to the small Bohr radius of the muon and thus significant overlap of its wave function with the atomic nucleus, this hydrogen-like system forms an excellent laboratory to study nuclear finite size effects.

Laser spectroscopy can determine the energy levels of a muonic atoms with unprecedented precision, and has been applied to hydrogen and helium atoms with great success. The nuclear charge radii of most stable nuclei have been determined using X-ray spectroscopy with high-purity germanium detectors, a method which is currently being extended to long-lived radioactive isotopes. For light nuclei from lithium until oxygen, a new experimental method using metallic magnetic calorimeters is being developed.

I will give an overview of ongoing and planned muonic atoms spectroscopy measurements at the Paul Scherrer Institute.

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Recent Results from GRETINA and the Status of GRETA

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The Gamma-Ray Energy In-beam Nuclear Array (GRETINA) has been operating for scientific campaigns for more than 10 years, with multiple campaigns at both the NSCL and ATLAS facilities in the U.S., and now most recently at FRIB. With more than 80 scientific publications and numerous theses based on GRETINA data, the detector system has had a most productive decade. I will present on recent results from GRETINA at both ATLAS and FRIB, and give a progress report on the Gamma-Ray Energy Tracking Array (GRETA), which will be the realization of a 4pi HPGE gamma-ray detector array for the U.S. community, expected to begin operations in 2025.

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Recent highlights and prospects on (n,γ) measurements at the CERN n_TOF facility

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Neutron capture cross-section measurements are fundamental in the study of astrophysical phenomena, such as the slow neutron capture (s-) process of nucleosynthesis operating in red-giant and massive stars. One of the best suited methods to measure neutron capture (n,γ) cross sections over the full stellar range of interest is the time-of-flight (TOF) technique.

TOF neutron capture measurements on key s-process branching isotopes are very challenging due to the limited mass (~mg) available and the high experimental background
arising from the sample activity.. Overcoming the current experimental limitations requires
the combination of facilities with high instantaneous flux, such as n_TOF, with detection systems with an enhanced detection sensitivity and high counting rate capabilities.

This contribution will present an overview about the recent highlights in the field of (n,γ) measurements at n_TOF. The recent upgrades on the facility, such as the opening of the
high-flux n_TOF-NEAR activation station, and the future prospects for new measurements involving unstable targets will be discussed.

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Quadrupole-octupole coupling and the onset of octupole collectivity

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Octupole deformations and related collective phenomena are studied using the framework of nuclear density functional theory. Axially-symmetric quadrupole-octupole constrained self-consistent mean-field calculations with a choice of universal energy density functional are performed for actinides, Xe, Ba, Ce, and Nd isotopes from proton-rich to neutron-rich sides, and neutron-rich Ge, Se, and Kr, in which enhanced octupole correlations are expected to occur. Low-energy positive- and negative-parity spectra and transition strengths are computed in terms of the interacting boson model, with the parameters determined by the constrained mean-field calculations. Octupole-deformed equilibrium states are found in the potential energy surfaces of those nuclei in the regions corresponding to the neutron or/and proton numbers equal to 34, 56, 88, and 134. The evolution of the calculated spectroscopic properties indicate the onset of octupole deformation and exhibit signatures of octupole shape-phase transitions around these nucleon numbers.

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Neutron transfer (d,p) reactions to inform neutron capture

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Essentially all of the elements heavier than iron are synthesized via neutron capture through slow (s) and rapid (r) nucleosynthesis processes. Since both the neutron and many of the isotopes involved in these nucleosynthetic processes are unstable, direct measurements of neutron capture reactions are in most cases not feasible, especially when half-lives are much less than 100 days. Fortunately, with the advent of radioactive ion beam (RIB) accelerator facilities, neutron transfer reactions, such as (d,p), can be measured in inverse kinematics to inform both direct neutron capture and as a surrogate for (n,gamma) processes that proceed via a compound nucleus. The (d,p gamma) reaction in normal kinematics has been validated as a surrogate for (n,gamma) reactions that proceed through a compound nucleus (CN) [1].

To enable (d,p) reactions with RIBs, the Oak Ridge Rutgers University Barrel Array (ORRUBA) [2] of position-sensitive silicon strip detectors has been developed and mounted successfully in measurements with beams ranging in energy from 4 to 45 MeV/u interacting with CD2 targets. Beam-like recoils have been analyzed with ion chambers and magnetic spectrographs. The first measurements were performed near the N=50 and N=82 closed shells where direct neutron capture processes are expected to dominate. More recently, ORRUBA has been coupled to large arrays of gamma-ray detectors, Gammasphere and GRETINA, to realize GODDESS – Gamma-array ORRUBA: Dual Detectors for Experimental Structure Studies [2].

The present talk would present results from the first measurement of the (d,p) reaction with a fast (45 MeV/u) RIB of 84Se [3] that when combined with previous measurements at 4. 5 MeV/u [4] constrains the spectroscopic factors for states above the N=50 gap needed to inform direct neutron capture cross sections. In addition, we can separate the 85Se recoils from 84Se beam-like residues, data that could inform the statistical (n,gamma) rates using the surrogate reaction method. The talk would also present an overview of the capabilities to measure the (d,p gamma) reaction with GODDESS, including upcoming measurements of the (d,p gamma) reaction with 45 MeV/u 80Ge and 75Ga beams.

This work is supported in part by the National Science Foundation and U.S. Department of Energy National Nuclear Security Administration. The invaluable contributions of the ORRUBA and GODDESS collaborations are recognized, in particular by my colleagues Drs. Steven Pain, Andrew Ratkiewicz, and Harrison Sims.

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Session 6 / 54

Status of nuclear spectroscopy program at center for exotic nuclear studies

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Center for exotic nuclear study in institute of basic science was recently founded to study fundamental questions in astrophysics and nuclear physics through investigations of radioactive atomic nuclei. The center is composed of four groups experimental nuclear structure, experimental nuclear reaction, experimental nuclear astrophysics and nuclear theory.
In the experimental groups, many detectors are currently under development/planned which can be applied for the nuclear spectroscopic study at the new accelerator facility RAON, such as Clover HPGe detector array (ASGARD), Co-axial Ge detector array, Si detector array (STARK and STARK-Jr), LaBr3 detector array (KHALA), conversion electron detector array (SCEPTER) and neutron detector array (PANDORA II). Several projects utilizing detectors such as decay station and in-beam gamma-ray spectroscopy have recently started for low-energy branches at RAON. Also, many international collaboration projects are also ongoing such as the IDATEN project utilizing the LaBr3 detector array from Korea and UK forming the largest LaBr3 array at RIBF RIKEN. The current status of the detector system development for nuclear spectroscopy and possible setups will be presented.

Session 7B / 114

Efficient production routes of 129m,131m,133Xe for a novel medical imaging technique, gamma-MRI

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The future gamma-MRI imaging modality will allow the simultaneous exploitation the advantages of SPECT – sensitivity of gamma-ray detection, and MRI – spatial resolution and flexibility. The combination of these technique requires use gamma-emitting nuclei (like in SPECT) with higlhly polarized spins, leading to anisotropic emission of gamma-ray, and thus make possible to manipulate these states by adding rf pulses (like in MRI). The signal in gamma-MRI is the change in the ratio of gamma rays emitted longitudinally and transversally to the spin (and magnetic field) direction. The first nuclei used in the project are 11/2- spin isomers ^{129m}Xe(T1/2=8.9days), ^{131m}Xe(T1/2=11.8days) and ^{133m}Xe(T1/2=2.2days).

An efficient production of the ^{129m,131m,133m}Xe is one of the most important of the first stage of gamma-MRI project. This contribution will present two main routes of selected xenon isomers production tested so far. The first method is based on neutron irradiation of stable ^{128}Xe and ^{129}Xe samples in the high-flux nuclear reactors: RHF reactor at Intitute Laue-Langevin (ILL, Grenoble, France) and MARIA reactor in the National Centre for Nuclear Research (NCBJ, Swierk, Poland). The second method of production is an extraction of ^{129m,131m,133m}Xe from uranium carbide (UCx) target hitting by proton beam at ISOLDE, CERN. Both methods provide high values of xenon isomers activities that can be extracted efficiently and used in polarization experiments.

The presentation will give a brief introduction to the gamma-MRI technique and will mention the results of xenon isomers production by using both methods. It will then briefly describe the method of metastable xenon samples characterization.

Session 7A / 115

Lifetime measurements after neutron-induced fission using the FIPPS instrument at ILL

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The FIssion Product Prompt gamma-ray spectrometer (FIPPS) [1] is the new nuclear physics instrument at the Institut Laue-Langevin (ILL). FIPPS takes advantage of an intense "pencil-like" neutron beam (flux $10^8 \mathrm{n} \cdot \mathrm{s}^{-1} \mathrm{cm}^2$) for inducing neutron capture and neutron-induced fission reactions and study the nuclear structure via high-resolution gamma-ray spectroscopy. The array is composed by 8 Compton suppressed HPGe clover detectors. Ancillary devices are possible, as LaBr3 detectors for fast timing measurements or additional clover detectors (from the IFIN-HH collaboration) to increase efficiency and granularity.
The instrument performances will be shown with particular focus on the technique for correcting cross-talk effects affecting the energy resolution of the clover detector [2]. Using a recently developed Geant4 simulation code, angular correlation analyses using a hybrid gamma-ray array could be possible. Examples from (n,γ) and neutron-induced fission reactions will be shown.
The Geant4 simulations also allowed to analyze the scintillator-based active target data [3] in order to extract lifetimes in the sub-ps timescale in neutron-rich fission fragments, by analyzing the shape of the peaks in the energy spectrum. This method will be presented, as well as new results in Zr and Nb nuclei.
In order to extend the number of measurable lifetimes in fission fragments, a plunger device is under development. This device will be the first implementation of a system similar to the one described in [4,5] for lifetimes measurements in fission fragments produced at a neutron beam. The design of such a device, including a mass identification setup (3-5units mass resolution) will be shown and its implementation for a test with a 252Cf spontaneous fission source will be outlined. Finally, the results of the test at the LOHENGRIN spectrometer of the mass identification setup will be presented.
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Session 7A / 61

Shape evolution and Collectivity beyond 78Ni: Lifetime measurements of low-lying states in neutron-rich Zn

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Nuclear shape is a sensitive probe of understanding the many-body quantum system and nucleon-nucleon interaction. Shape coexistence was reported in doubly magic 78Ni [1]. Related features such as triaxiality [2] and onset of deformation beyond N = 50 [3,4] were also reported in this mass region. The study of these phenomena plays a crucial role in understanding the limit of nuclear stability as well as the predicted fifth island of inversion [5]. One of the observables experimentally to study nuclear shape is the lifetime of excitation state, which has a direct link with the electric quadrupole moment Q. In a recent gamma spectroscopy study of 82,84Zn [4], the magicity was confined to N = 50 in 80Zn only, while an onset of deformation for low-lying states was identified with the help of

E(2+) and E(41+)/ E(21+) ratios towards heavier Zn isotopes. However, the lifetimes of these states are still unknown. Therefore, lifetime measurement of low-lying states was performed in neutron-rich Zn isotopes to further investigate the shape evolution and development of collectivity beyond N = 50.

Neutron-rich Zn isotopes were investigated at RIKEN Nishina Center during the HiCARI 2020 campaign. 345 MeV/u 238U impinged on 9Be primary target with an average intensity 60 pnA. Production fragments were then separated and identified by BigRIPS spectrometer. A secondary 6 mm thick 9Be target was placed at F8 to induce knockout reactions. After the target, ion of interests were identified on an event-by-event base by using Bρ-ΔE-TOF technique with the ZeroDegree spectrometer. The secondary target was surrounded by HiCARI, consisting of 6 Miniball triple clusters, 4 Clovers and 2 Gretina-type tracking clusters, which was used for Doppler correction of gamma rays from in-flight ions and lifetime measurement.

Some low-lying states in neutron-rich 76-82Zn were established based on the recent experiment. The lifetime of each state was determined by gamma-ray lineshape analysis [6]. The shape evolution in neutron-rich Zn isotopes will be discussed by comparing the experimental results with shell model and mean-field calculations.

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Session 7B / **110**

Total Absorption Spectroscopy of isotopes with medical interest

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Nuclear beta decay is often the first source of experimental information on nuclear structure when we are not too close to the drip lines. However, one of the main physical quantities relevant to this process, the beta-intensity distribution, is not easy to measure in medium-mass or heavy nuclei where high density of states is at reach within the Q-beta window. In these cases, the Total Absorption Spectroscopy (TAS) technique, based on high-efficiency scintillators, has proven to be far more sensible than the high-resolution technique, based on HPGe detectors. In the former one detects entire gamma cascades rather than individual gamma rays and infers the beta intensity applying some unfolding techniques to the whole spectrum. In the latter, one infers the beta-intensity distribution from gamma-intensity balance obtained from the analysis of individual gamma peaks.

The advantage of the TAS technique over the high-resolution one, lies in the high sensitivity of the former, since it allows the measurement of weak beta decay branches to levels at high excitation energy in the daughter nucleus, where HPGe-detector arrays tend to have lower sensitivity. Despite the low sensitivity of high-resolution experiments to high-lying beta strength, they are the primary source of information on the beta-decay scheme and daughter nuclear structure.

The therapeutic and diagnostic use of radionuclides is well known and widely applied in different techniques and pathologies. The efficacy of the treatments, as well as the off-target dose minimisation in both treatment and diagnosis depend, among other things, on the decay characteristics of the radionuclide in use. In particular, the different particles and radiation emitted, the emission energies and the emission probabilities, are of paramount importance in the calculations of the dose administered to the patient in medical imaging or therapeutic treatment with radioisotopes.

In this contribution we will present a series of TAS measurements carried out at ISOLDE (CERN) since July-2022 aimed at the detection of all the beta strength missing in previous studies of some nuclei of medical interest. A proper determination of the beta-intensity distribution within the Q window is essential to calculate the distribution of energy per decay that goes as gamma rays or as kinetic energy of emitted particles, which is necessary to calculate the dose administered to a patient subject to a PET scan or theragnostic treatment. We will show results on 66Ga and comparisons of recent TAS data vs evaluated ENSDF data on 128Ba/128Cs, 76Br and others.

Session 7A / 27

New evidence for α-clustering in ^{212}Po

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^{212}Po has two protons and neutrons outside the doubly-magic nucleus ^{208}Pb and it may be assumed that the nuclear structure can be well described within the shell model. But various experimental properties, such as the short-lived ground state, are better described by an α-clustering model. The B(E2) values of the decays of low-lying yrast states are an important fingerprint to describe the structure of ^{212}Po. Especially the missing B(E2; $4_1^+ \rightarrow 2_1^+$) value is important in this discussion. We have performed an α-transfer experiment to investigate excited states of ^{212}Po and determine the lifetimes using the ROSPHERE γ-ray detector array at IFIN-HH in Magurele, Romania. This array consisted of 15 HPGe detectors and 10 LaBr$_3$(Ce) scintillator detectors and was supplemented with the SORCERER particle-detector array. The combination of γ-ray and the particle detectors was an important tool to determining the mean lifetimes of all ground-state band levels up to the 8^+ state be applying the fast-timing method. I will present our lifetime analysis and discuss the results within the shell model and α-clustering models. Supported by BMBF under Verbundprojekt 05P2021 (ErUM-FSP T07) via grant 05P21RDFN1

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The study of the ^{21}Ne(p,γ)^{22}Na reaction at LUNA

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The $^{21}\mathrm{Ne(p,}\gamma)^{22}\mathrm{Na}$ reaction is expected to be the main producer of the radioactive isotope $^{22}\mathrm{Na}$ ($t_{1/2}$ = 2.602 years) in novae. Novae explosions are the result of a thermonuclear runaway occurring on the surface of a white dwarf accreting material from a less evolved companion star in a close binary system that ejects a significant amount of nuclear-processed material into the interstellar medium. Amongst the isotopes synthesized during such explosions, radioactive nucleus $^{22}\mathrm{Na}$ is specifically produced in white dwarfs made of O and Ne, the progeny of stars with initial mass in the range of 8-10 solar mass. Once produced, $^{22}\mathrm{Na}$ beta decays to an excited state of $^{22}\mathrm{Ne}$, which de-excites by emitting a 1275 keV gamma ray [1]. If detected by satellite telescopes, this signal can provide information on the amount of $^{22}\mathrm{Na}$ produced in novae, and thus place direct constraints on the nucleosynthesis in these explosions.
Predictions of the $^{22}\mathrm{Na}$ abundance in novae strongly depend on the $^{21}\mathrm{Ne(p,}\gamma)^{22}\mathrm{Na}$ reaction rate. In the novae temperature range ($0.2 < T_9 < 0.5$), $^{21}\mathrm{Ne(p,}\gamma)^{22}\mathrm{Na}$ reaction is dominated by resonances at proton beam energies $\mathrm{E_p}$ = 126 and 272 keV [2]. In this contribution, we will report on the direct and precise measurement of the $\mathrm{E_p}$ = 272 keV resonance strength performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) [3] located at Gran Sasso National Laboratory in Italy, benefiting from the low background conditions. The experimental setup, techniques, and results will also be described in detail in the talk.

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Session 7B / 65

Direct measurement of cross sections for the ^{114}Cd(n,γ) reaction with En = 1 eV to 300 keV using DANCE

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Cadmium has many practical applications where significant thermal neutron fluences are expected, owing to the large thermal capture cross-section of ^{113}Cd. This feature has led to many applications that use cadmium to screen these thermal neutrons. Once such field where this is utilized is in non-destructive assay techniques that employ cadmium liners to interrogate spent fuel assemblies, such as Passive Neutron Albedo Reactivity. Measuring capture cross sections on the even cadmium isotopes is challenging, since the odd-mass capture products have low-lying isomers that can complicate the analysis. Capture cross section data for the cadmium isotopes exist for thermal energies, but at most other energies the experimental information on cadmium is relatively poor, save for data taken in the kT = 15 to 100 keV energy regions relevant to the calculation of Maxwellian averaged cross sections related to the astrophysical s-process. For ^{114}Cd, there are two sets of cross section data in the regions of E_n = 3 keV to 100 keV [1,2] that do not agree within uncertainty, yet these differences manifest in the choice of cross section evaluation used for these neutron energies, as the ENDF follows closely the data found in Ref. [1] while the JENDL follows closely the data found in Ref. [2]. There is no direct cross section measurement of any resonances published on ^{114}Cd(n,γ).

To address these issues, direct measurements of neutron capture cross sections were performed at the Los Alamos Neutron Science Center (LANSCE) using the Detector for Advanced Neutron Capture Experiments (DANCE). A highly enriched (~99%), 100 mg pressed pellet target of ^{114}Cd was used to perform the neutron capture measurements in the range of E_n = 1 eV to 300 keV using LANSCE's white neutron source. Neutron capture data were also taken on highly enriched targets of ^{112,113}Cd to enable careful background subtraction of even the small contaminants found in the ^{114}Cd target. By using large energy sum windows around the Q-value, our analysis largely circumvents any complication that may arise from population of the 180 keV isomer ($T_{1/2}$ = 44.56 d) in ^{115}Cd. Results on the cross sections for the ^{114}Cd(n,γ) reaction will be presented.
This work was supported by the U.S. Department of Energy awards SC0021424, SC0021243, SC0021175, and SSC000056.

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Session 7A / 90

Fast-timing spectroscopy with the Nu-ball2 spectrometer

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The high-precision fast-timing method has been used in a high-statistics experiment at ALTO@IJCLab to perform lifetime measurements of excited states in exotic nuclei. These observables and their corresponding transition probabilities are key fingerprints for the structure of atomic nuclei, as they are sensitive to small components of the wave function. Neutron-rich nuclei have been populated in a two-step fission-induced experiment. In the first stage, the neutron beam was produced by the LICORNE source in an inverse kinematics reaction with a pulsed 7Li beam delivered by the Tandem accelerator, incident on an H2 gas cell. The resulting neutron beam with an average energy of about 2 MeV was used in a second step to induce fissions on the 238U secondary target. The hybrid high-efficiency Nu-ball2 array comprising 24 clover detectors and 20 UK FATIMA LaBr3(Ce) scintillators was used to detect the emitted gamma rays. The physics cases encompass various topics, from lifetime measurements and building the level scheme to statistical properties studies and isomeric fission ratios investigations. This talk will focus on lifetime measurements of excited states, highlighting the improvements with respect to the previous campaign and presenting the first preliminary results.

Session 7A / 59

Electric monopole transitions in 74Se

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The subject of this presentation is a measurement of internal conversion electrons aimed to study the structure of the low-lying states in ^{74}Se.

Electric monopole (E0) transitions are determined by a change in the radial distribution of the electric charge inside the nucleus, and high E0 transition strengths are expected whenever configurations with different mean-square charge radii mix.
In this regard, an enhancement of the monopole strength in transitions between states with J=0 may be considered as a "signature" for shape coexistence.
Despite their importance, the number of E0 transition strengths that have been measured experimentally is very limited. This deficiency is primarily due to the often complex nature of the required measurements and the necessity for electron spectroscopy which can be hindered by many sources of background. There is especially a lack of data for E0 transition strengths in J ⟶ J, J >0 transitions for example for 2+ ⟶ 2+ cases.
The levels of interest of ^{74}Se were populated following the decay of the ^{74}Br isotope. Measurements of E0 strengths for transitions between the first excited 0+ states and 2+ states in ^{74}Se have been achieved. A really large value for the $\rho^2(2_2^+ \to 2_1^+)$ has been extracted. A similar unexpectedly large values for the $\rho^2(2^+ \to 2^+)$ have been extracted some years ago in the neighboring Ni isotopes.
Thanks to the internal conversion coefficients we were able also to assign some level parities.

Session 7B / 66

Cross sections for 54Fe(n,n') 54Fe and 54Fe(n,p') 54Mn deduced from the detection of de-excitation γ rays

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Iron is an important component of many structural materials; examples include energy production complexes, laboratories, devices, and shipping containers that often cross borders. The properties of iron alloys in the structural materials—strength, ductility, and stability—depend on defects that develop and grow from neutron scattering and (n, p) and (n, γ) reaction rates. 54Fe is only 5.5% abundant, but neutron scattering cross sections and reaction rates for this nucleus can affect fast reactor systems and energy transport and deposition. Neutron scattering cross sections obtained by the detection of the scattered neutrons offers the clearest path to the desired cross sections in the fast neutron region1, but such measurements are typically limited to scattering from only the lowest few excited levels because of the large energy spreads (10s to 100s of keV) inherent in neutron experiments. The detection of de-excitation γ rays (< 2.5 keV resolution) following inelastic scattering or proton production on 54Fe offers a rare opportunity to investigate (n, p) and (n, n') cross sections to higher-lying levels in a consistent way by the examination of γ-ray production rates.
Measurements have been performed on an enriched 54Fe sample (97.6%) using the neutron production and γ-ray detection facilities at the University of Kentucky Accelerator Laboratory. γ-ray excitation functions were measured for incident neutron energies from 1.5 to 4.7 MeV. Angular distributions and Doppler shifts were measured at En = 4.5 MeV. γ-ray production cross sections were deduced by considering all γ rays feeding or resulting from the decay of each level. Analogous measurements were made on natural Ti, V, Al and Fe samples for absolute normalization purposes. The results of our measurements will be presented in comparison to evaluated data (ENDF, JENDL, JEFF libraries) and with TALYS calculations.
This work was supported by the U.S. Department of Energy NNSA-SSAP award NA-0002931 and Nuclear Energy Universities Program award NU-12-KY-UK-0201-05, the U.S. National Science Foundation under grant PHY-1305801, and the U.S. National Isotope Development Program.

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Comprehensive Test of the Brink-Axel Hypothesis in the Energy Region of the Pygmy Dipole Resonance

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The validity of the Brink-Axel hypothesis [1,2], which is especially important for numerous astrophysical calculations, is addressed for ^{116,120,124}Sn below the neutron separation energy by means of three independent experimental methods. The γ-ray strength functions (GSFs) extracted from primary γ-decay spectra following charged-particle reactions with the Oslo method [3] and with the Shape method [4] demonstrate an excellent agreement with those deduced from forward-angle inelastic proton scattering at relativistic beam energies [5].
In addition, the GSFs are shown to be independent of excitation energies and spins of the initial and final states.
The results provide the critical test of the generalized Brink-Axel hypothesis in heavy nuclei, demonstrating its applicability in the energy region of the pygmy dipole resonance. The latter aspect is of particular interest for the study of the effect of the pygmy dipole resonance on the cross-section of the astrophysical neutron capture r-process.

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Session 7A / 103

Lifetime measurements in exotic nuclei at Lohengrin

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Lifetimes of nuclear excited states are key observables to study nuclear structure properties, such as the interplay between single-particle and collective degrees of freedom and more complex phenomena as the coexistence of different shapes at similar excitation energies. In this context, neutron-rich

nuclei are particularly challenging and neutron-induced fission experiments offer a unique opportunity to explore more exotic regions of the nuclide chart. Although lifetimes can be successfully measured using prompt γ rays [1], the weakest channel would benefit from the selection and the identification of fission fragments. This can be achieved with the Lohengrin spectrometer [2] at Institut Laue-Langevin, where the γ decay of long-lived isomeric states can be studied at the focal plane of the mass separator.
In this work, we present recent results obtained in different ^{235}U neutron-induced fission campaigns at Lohengrin, using a hybrid setup made of HPGe clover detectors and $LaBr_3$ scintillators. The latter were used to measure lifetimes, down to a few ps, using γ-ray fast-timing techniques [3]. In particular, results on ^{131}Sb [4] and ^{96}Rb [5] will be discussed. In the first case, the lifetime of the $11/2^+$ state was measured, yielding $T_{1/2}$ = 3(2) ps, the first such result in neutron-rich antimony nuclei and one of the shortest ever measured in beam with this experimental technique. Consequences on the origin and development of collectivity in the vicinity of the doubly magic ^{132}Sn nucleus will be presented in the framework of the shell model. In the second case, particular emphasis will be given to the observation of a retarded E2 transition deexciting the 4^- state at 554.5 keV in ^{96}Rb, for which a lifetime of $T_{1/2}$ = 599(55) ps was measured. This γ ray connects the strongly deformed band above 450 keV with near-spherical low-lying states. Its impact on the shape-coexistence phenomenon in this exotic mass region around N=60 will be addressed.

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Octupole deformation in radium isotopes using the spdf-IBM-1

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In this work we study the effects of the octupole degrees of freedom in the nuclear structure of the even-even radium isotopic chain, obtaining the energy spectra and electromagnetic transition rates between states of different parity, comparing our calculations with the experimental data currently available. The analysis of the effects produced by the octupole degrees of freedom in radium isotopes is related with the search of non-zero atomic electric dipole moments, that may be evidence of Physics beyond the Standard Model [1], and will also help to better understand the experimental results about the structure of elements in the actinide region, so this work will contribute to both of these studies.

The calculations are made in the context of the *spdf*−IBM-1, which allow us to describe the low energy collective states of medium-mass and heavy nuclei, which have been proven to give an accurate description of the energy spectra of octupole-deformed nuclei [2, 3]. The model considers the nuclear system as composed of four different bosons, each being the s $(L^\pi = 0^+)$, p $(L^\pi = 1^-)$, d $(L^\pi = 2^+)$ and f $(L^\pi = 3^-)$ boson, with the negative parity ones being related to octupole phenomena.

Different hamiltonian operators have been used for the description of these phenomena, some of them with a quite large number of parameters which need to be fit. In this context, we propose the use of a similar one to that of Ref. [4] of the form
$H = \sum_{\ell=1}^{3} \left(\varepsilon_\ell \hat{n}_\ell + \kappa_\ell \hat{Q}^{(\ell)} \cdot \hat{Q}^{(\ell)} \right),$

using just six parameters, with a given definition of the multipole operators without free parameters in them. Here, $\ell = 1, 2, 3$ corresponds with the dipole, quadrupole, and octupole term, respectively. This hamiltonian, more simple than the ones used in previous works, allows us to develop a good agreement with experimental data while using a more general expression, which needs less parameter fitting. We also eliminated the restriction in the negative-parity boson number, and as far as we know, there have not been works with the $spdf$−IBM-1 without this restriction, so this novelty may allow us to better describe the octupole phenomena in this chain, as suggested by Ref. [5] when using the $spdf$−IBM-2.

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Development and research of a single-plane Compton gamma camera

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The detection of environmental radiation is of great importance and efficient, compact, and cost-effective instruments are highly needed. One of the potentially suitable detection tools for the detection of gamma radiation is the Compton gamma camera (CGC), which, in contrast to gamma cameras with mechanical collimations, uses electronic collimation based on the kinematics of the Compton scattering. The evolution of CGCs started with semiconductor detectors, which provide excellent spatial resolution, but suffer from complexity and high costs, later shifted to scintillator detectors, initially with photo-multiplier tubes and more recently with Silicon photomultipliers (SiPMs). Scintillator-based CGCs have lower, yet still acceptable angular resolutions compared to the ones based on semiconductors, but higher efficiencies and lower cost. Most CGC realizations comprise two separate detector planes, the scatterer and the absorber or they implement complex realizations to be able to determine the depth-of-interaction of the incoming gamma radiation.

We designed a novel concept of a single-plane CGC based on segmented scintillators, read out on a single side by silicon photomultipliers (SiPM). In this concept, a detector element consists of two identical GAGG:Ce scintillator crystals of 3 mm x 3 mm x 3 mm optically coupled by a plexiglass light guide of 3 mm x 3 mm x 20 mm between them. Detector elements are placed in an 8x8 matrix with a 3.2 mm pitch, separated by an ESR reflector. In this configuration, the front scintillator layer is acting as the scatterer and the back scintillator layer is acting as the absorber, while both are read out by the same silicon photomultiplier array coupled to the back side of the matrix. This is the most prominent feature of this concept since it keeps the minimum number of read-out channels, which is crucial for a compact and portable device. The silicon photomultiplier array is read out by the TOFPET2 data acquisition system. We constructed the Compton gamma camera according to the above-mentioned design and tested it in our laboratory by irradiating it with gamma-ray sources of different energies. The average energy resolution of the front and the back detector layer was found to be 8.9 ± 1.9% and 10.8 ± 1.6%, respectively for gamma-ray of 662 keV energy. The basic imaging test obtained with a Cs-137 source (diam. ≈ 3 mm) placed 50 mm in front of the detector using a simple back-projection algorithm, shows a Gaussian peak standard deviation of
σ=5.1±0.2 mm. In this contribution, we present the results of the detailed characterization of the detector performance at gamma-ray energies of 511 keV and 662 keV as well as the estimate of its

imaging capabilities for gamma sources located at various positions within the field-of-view. Finally, we will discuss the potential of the designed detector for application as a highly-compact and portable Compton gamma camera.

Key words: Radiation detection, Compton camera, gamma imaging, GAGG, SiPM

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Fast timing characteristics and lifetime measurement using $1.5'' \times 1.5''$ $CeBr_3$ detectors coupled with PMT Hamamatsu R13089-100

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Measurement of lifetime of nuclear excited states and determination of electromagnetic transition strengths from that provides direct insight into nuclear structure. The measurement of lifetime in $\gamma - \gamma$ electronic coincidence method depends on the time resolution and energy resolution of the detector system. The ideal γ-ray spectroscopy requires a combination of excellent energy and time resolution along with the good photo-peak efficiency. With the availability of new generation scintillator detectors with reasonably good energy resolution, the precise measurement of lifetime in sub nanosecond ranges have been possible.
At Variable Energy Cyclotron Centre (VECC), Kolkata, $1.5''\times 1.5''$ $CeBr_3$ detectors coupled with a new Photo-Multiplier tube Hamamatsu R13089-100 has been characterized [1]. The typical energy and time resolution obtained with $1.5'' \times 1.5''$ $CeBr_3$ detectors are 4.1% (at 662 keV of ^{137}Cs source) and 199(2) ps (for 1173-1332 keV cascade of ^{60}Co source). The systematic variation of the time-resolution for different PMT bias voltages and external CFD delays has also been studied. It has been observed that the time resolution improves with shorter CFD delays and higher PMT bias voltages.
With the knowledge of the basic characteristics of two detector set-up, time-walk response for this set-up was determined using Mirror Symmetric Centroid Difference (MSCD) method [2]. In order to calibrate the Prompt Response Function (PRF) of the experimental set-up for the energy range of interest, Prompt Response Difference (PRD) calibration curve [3] has been determined for two $1.5'' \times 1.5''$ $CeBr_3$ detectors with ^{152}Eu source. As this detector+PMT assembly was found to be linear upto PMT Bias voltage of -1400 V, hence the PRD calibration was first carried out at this bias voltage with 5 ns CFD external delay. Then the variation of the PRD curve has been studied at different PMT bias voltages and CFD external delays.

Nuclei near ^{208}Pb region are expected to have spherical structure at lower spin and collective structure at higher spin and excitation energies. For even-even Po (Z=84) isotopes in this region, the variation of $R_{4/2}$ ratio approaches towards vibrational limit as neutron holes increase whereas, E2 transition strength increase from ^{210}Po to ^{206}Po [4]. The low-lying states of neighbouring odd-A nuclei in this region are mainly described by the coupling of one neutron hole with the nearest even-even core. The lifetime measurement of low-lying states of Po isotopes will be of great importance to understand how the collectivity arises for the lower and the higher spin states. In this regard,the lifetime of $11/2^-$ state of ^{209}Po, has been measured with two $1.5'' \times 1.5''$ $CeBr_3$ detectors in MSCD method. The ^{209}Po was populated via electron capture decay of ^{209}At, which was produced using the reaction ^{209}Bi(α,4n)^{209}At with 52 MeV α beam from K-130 cyclotron at VECC, Kolkata. The lifetime of $11/2^-$ state at 1521.85 keV of ^{209}Po has been obtained as 98(6) ps using 239-195 keV cascade [5], which is found to be in good agreement with a recently reported value [6].

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Evolution of nuclear shape around 28 shell gap in neutron deficient nuclei.

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N,Z ~ 28 is the first shell gap originated due to the inclusion of spin - orbit (l.s) coupling term in the nuclear Hamiltonian. The lowering of 1f$_{7/2}$ orbital from other fp space creates this shell gap though small excitation energy can excite nucleons from 1f$_{7/2}$ orbital to upper fp orbitals and also to 1g$_{9/2}$ orbital (depending upon the deformation of the system). The nuclei near stability line in neutron deficient side have proton Fermi energy below this 28 shell gap and neutron Fermi energy above 28 shell gap. The large shape driving effect of 1f$_{7/2}$ and 1g$_{9/2}$ orbitals can also bring collectivity in the system. Thus the nuclei in this mass region is a good testing ground to investigate the competition between the single particle excitation and collective excitation. Further the coupling between 2p$_{3/2}$ and 1g$_{9/2}$ orbitals ($\triangle$j=3, $\triangle$l=3), which are present in the configuration space can lead to octupole correlation in the system. Many interesting nuclear structure phenomenon are predicted and some of them are already observed in this mass region [1-6], including new magic numbers and prompt particle decay from the excited state.
An experiment was performed at VECC, Kolkata using 34 MeV α beam from K-130 cyclotron at VECC on ^{55}Mn target to populate nuclei around shape coexistent core (prolate and oblate shapes) of ^{56}Fe(Z=26, N=30) [1]. The aim was to see how the coupling of odd proton hole (^{55}Mn), odd neutron particle (^{57}Fe) and both proton and neutron hole (^{54}Mn) affects the structure of shape coexistent core of ^{56}Fe. The γ rays were detected using an array of 11 CS clover detectors placed at 3 different angles (2 at 40°, 6 at 90°, and 3 at 125°) and a LEPS detector at 40°. The PIXIE-16 digitizer based data acquisition system and IUCPIX package, developed by UGC-DAE CSR Kolkata [7], was used to record and process the data. The $\gamma\gamma$ symmetric and $\gamma\gamma\gamma$ matrices were constructed to establish the level scheme of the nuclei of interest. The asymmetric matrices were constructed to assign spin, parity and lifetime of the nuclear states. The analysis and interpretation have been almost completed. Different nuclear shapes including spherical and deformed (both axial and triaxial shapes) at different excitation energies have been observed for these nuclei for the first time. The octupole correlation has also been observed. Detailed results will be presented in the conference.
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Isomer data and its implications

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Isomeric studies are crucial for understanding the fundamental nuclear structure as well as for practical applications. Because nuclear isomers are known to exist throughout the nuclear landscape, it is interesting to depict their global features and, if any, systematics. This resulted in the first compilation of (more than) 2400 isomers in 2015, with a lower limit on the half-life of 10 nanoseconds, known as the 'Atlas of Nuclear Isomers,' [Nucl. Data Sheets 128, 1 (2015)] presenting isomeric spectroscopic properties such as excitation energies, half-lives, and so on, as well as the original references. We have recently updated the atlas with a literature cut-off date of October 31, 2022. Along with the addition of 200 new isomers, numerous isomers' spectroscopic observables are changed in the second version [At. Data Nucl. Data Tables 150, 101546 (2023)]. In comparison to the 2015 edition, the Atlas(2023) now comprises a substantially bigger set of evaluated data. In this presentation, the isomer data and their implications on nuclear structure will be discussed.

Acknowledgements: Financial support from the Croatian Science Foundation and the \'Ecole Polytechnique F\'ed\'erale de Lausanne, under the project TTP-2018-07-3554 "Exotic Nuclear Structure and Dynamics", with funds of the Croatian-Swiss Research Programme is gratefully acknowledged.

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Calculation of true coincidence summing correction factor for Broad Energy Germanium (BEGe) and Clover detector

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In nuclear astrophysics, the nuclear reactions of the stellar evolution occur within the Gamow window which lies much below the Coulomb barrier. The cross-sections of these reactions are very less around nb-pb order, thereby making these measurements very difficult [1]. In such measurements,

the low yields of measured ϒ-ray lead to insufficient statistics and hence increase uncertainty in the measurement of reaction cross-sections. A better statistics in the measurements may be achieved by increasing the yield, which is directly proportional to beam current, target thickness and efficiency of the detector. Beam current and target thickness cannot be increased beyond certain limits due to practical limitations. The detector efficiency can be increased by reducing the source to detector distance. In such close geometry measurements, the summing effect comes into the picture which needs to be accounted for. When two or more ϒ-rays emitted in the cascade from the excited nucleus are detected within the resolving time of the detector then this phenomenon is referred as true coincidence summing effect [2,3]. In close geometry measurements, it is necessary to perform summing correction for each ϒ-ray photopeak of interest. The factor for this correction is called true coincidence summing correction factor (kTCS).

The kTCS for an electrically cooled Falcon 5000 BEGe detector [4] has been calculated in close and distant geometry measurement using multi-energetic ϒ-ray sources (60Co, 133Ba, 152Eu). The correction factors were calculated using experimental method as well as analytical methods. Photopeak and total efficiency required here were obtained using Geant4 Monte Carlo simulation toolkit. A few mono-energetic radioactive sources were also fabricated using proton beams obtained from K-130 cyclotron at VECC, Kolkata. These fabricated (51Cr, 65Zn, 109Cd) and available (137Cs, 241Am) mono-energetic radioactive sources were used to validate the Geant4 simulation in close geometry measurements. Both experimental and analytical correction factors were found in good agreement with each other. From this work, it was found that significant coincidence summing is present in the BEGe detector if the detector is at 8 cm or bellow from the source. A similar study is also performed for CANBERRA clover detector as well, in which a desktop digitizer (Caen DT5725S) was used for data acquisition. The summing correction factors for this detector were also calculated in close geometry measurements. This study has been found to be crucial to make the right choice of gamma ray detection system for experimental measurement of reaction cross-section in the stellar energy region.

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Lifetime measurement in Gd isotopes around N = 90

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Quantum shape phase transitions and shape coexistence in finite many body quantum systems, such as nuclei, are of contemporary interest [1]. The phenomenon of rapid shape changes as a function of nucleon number has been observed in the rare-earth region around N = 90. The N = 90 nuclei in Sm-Gd region are well known for the observation of quantum shape phase transition from spherical to well deformed rotor as well as coexistence of different shapes with very close lying minima. Empirical signatures for shape changes in a sequence of even-even nuclei are, e.g., a rapid change in the ratio $R_{4/2}$ = $E(4_1{}^+)/E(2_1{}^+)$ or a sudden rise in the E2 transition strength $B(E2;\, 2_1{}^+ \rightarrow 0_{gs}{}^+)$ [2,3]. Another signature for a QPT is the E0-transition strength $\rho^2(E0)$. The coexistence of deformed shapes are manifested with the presence of multiple low lying 0^+ levels with one of the key signatures being the high E0 decay rates. In this context, the experimental identification of the low lying 0^+levels and the measurement of their lifetimes is very important.

Among the Gd and Sm nuclei, quantum shape phase transition has been proposed with observation of high E0 decay from the $0_2{}^+$ level in N = 88 ^{152}Gd [4]. In our recent measurement, similar signature in the $0_3{}^+$ level of N = 88 ^{150}Sm have been observed as the decay of level shows high E0 strengths [5]. Other than the Sm nuclei, the E0 strength is not known for the $0_3{}^+$ levels in any other

nuclei in this mass region. Specifically, the $0_3{}^+$ level has already been observed in N = 90 Gd and the associated structure has been conjectured as the pairing isomer. However, there is no experimental data available on the lifetime measurement in this nucleus. In the present work, the level lifetime measurement of $0_3{}^+$ in ^{154}Gd (N=90) and other spin states such as $2_1{}^+$, $4_1{}^+$ in ^{152,154}Gd has been aimed using γ-γ fast timing technique.
The low lying excited states of ^{154}Gd were populated through two different reactions - one through the $\beta-$ decay of ground state of ^{154}Tb ($T_{1/2}$ ~ 21.5 hr.) produced using ^{154}Gd(p,n)^{154}Tb reaction with 12 MeV proton beam delivered from K-130 cyclotron at VECC, Kolkata. Proton induced reaction has been performed for the cleaner population of $0_3{}^+$ in ^{154}Gd (N=90) by restricting the population of high spin isomers in ^{154}Tb. The high spin states in ^{152,154}Gd has been populated through the $\beta-$ decay of higher lying isomers in Tb isotopes produced through neutron evaporation reaction using 40 MeV α beam from K-130 cyclotron on ^{nat}Eu target. The decaying gamma rays from excited states have been detected with VENTURE array [6], which consists of eight fast scintillator $CeBr_3$ detectors, coupled to two Compton supressed Clover HPGe detectors. The pulse processing has been done with NIM electronics and VME data acquisition with high resolution Mesytec ADCs.
The data from the present experiment has been analyzed using generalized centroid difference analysis for the measurements of sub-nanosecond lifetimes. The results from this measurement will be discussed in the light of observation of exotic quantum phenomena like shape phase transition and shape coexistence in nuclei around A~150.

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Determination of α+nucleus optical potential relevant for p-process study from the ^{nat}In(α,α) elastic scattering

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Nucleosynthesis of heavier nuclei (Z $>$ 26) generally occurs through s or r-process. However, certain neutron deficient nuclei in stars are produced neither by r or s-process. They are produced by (γ,α), (γ,p), and (γ,n) reactions and are known as p-nuclei. Due to the better availability of ion beams over γ-beams, the inverse reaction cross-sections on p-nuclei are measured and gamma induced cross-sections are extracted using the principle of detailed balance in the framework of statistical model. Statistical model calculation is sensitive to the choice of the nuclear input parameters. The entrance channel optical potential is one of the sensitive input parameters. For the study of the (α,γ) reaction, the α-optical potential plays a crucial role.
There are numerous global alpha optical model potentials, but they are unable to adequately explain the (α,γ) reaction data. The ^{113}In(α,γ) reaction requires accurate knowledge of the α-optical potential at low energies. However, due to the dominance of coulomb part, the elastic scattering measurements need to be done at above barrier energies. In present work, elastic scattering angular distribution measurements of ^{nat}In(α,α) have been performed at two different energies (E = 26 and

29 MeV) above the Coulomb barrier. The data will be analyzed to obtain local α-optical potential parameters using search codes like SFRESCO.

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Circular polarization measurement of γ-rays emitted from $^{32}S(n,\gamma)^{33}S$ reactions with polarized neutrons

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The total angular momentum of resonance is one of the significant parameters in nuclear data, but the identification is difficult. The parameter has been determined by several methods: the measurement of the spin-dependent transmission ratio by polarized neutrons and a polarized target [1], the measurement of intensity ratio of cascade γ-rays emitted from neutron resonance captures [2], and the measurement of γ-cascade multiplicity [3]. In spite of these efforts, available data were limited, and estimated values of the parameter have often been recorded in the evaluated nuclear data libraries, such as JENDL-5 [4].
As an alternative, we are inventing a new method which determines the total angular momentum of resonances from the measurements of circular polarization of γ-rays emitted from capture reaction of polarized neutrons on a target [5]. This method relies on the fact that the circular polarization of γ-rays from polarized neutron capture depends on the total angular momentum. We aim to apply the experiments at the thermal region performed in the 1950s to 1970s [6-8] to the resonance region.
In order to measure the circular polarization of γ-rays, a Compton polarimeter was developed. For its operation confirmation, ^{32}S was selected as a target because its polarized thermal neutron capture is known to emit 5.4 MeV γ-rays whose circular polarization is 50%. The circular polarization of γ-rays was measured with Ge detectors at J-PARC·MLF·ANNRI, and the analyzing power at the γ-ray energy of 5.4 MeV was determined as about 2%. In this presentation, we will report on the details of the sulfur experiment and future prospects for circular polarization measurements at ANNRI.
This work is partially supported by the JSPS KAKENHI Grant No. JP20K14495 and JP21K04950.

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Study of the Spin-Memory Effect with Low-energy Gamma-rays in $^{177}\mathrm{Hf}(n,\gamma)^{178}\mathrm{Hf}$ Reaction Measurement

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The total angular momentum, J, of resonances is one of the important parameters to represent cross sections in low-energy nuclear reactions. Several methods have been proposed to estimate J of resonances from experiments [1]. One of the attractive methods was to compare the intensity ratios of appropriately chosen pairs of low-energy transitions in the gamma-ray spectrum of a resonance proposed by Wetzel and Thomas [2]. This method is based on the Spin-Memory Effect (SME) proposed by Huizenga and Vandenbosch [3]. SME means that the spin information of an initial resonance state remains, even if there are many intermediate excited levels in the cascade transitions. The strength of SME, which appears in the intensity ratio, can be quantitatively evaluated from the difference of the intensity ratios. The results of past measurements have suggested that SME is enhanced when the atomic number Z is near the magic number Z=50 [4]. In this study, neutron capture reaction measurements were performed at J-PARC/MLF/ANNRI using natural Hf (Z=72), which is the element away from Z=50. The strength of SME was determined from the intensity ratios of low-energy gamma-rays from resonances. It is found that SME observed in Hf (Z=72) was stronger than in Ta (Z=73) [5].

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Experimental cross-section measurement of ^{144}Sm(p,γ) reaction relevant to astrophysical p- process

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One of the primary aims of experimental nuclear astrophysics is to determine the rates of nuclear reactions taking place in stars under various astrophysical conditions. The reaction rates are determined from the cross sections, which need to be measured at energies as close as possible to the astrophysically relevant ones (near the Gamow window). In many cases, the final nucleus of an important astrophysical reaction is radioactive, which allows the cross-section to be determined based on the offline measurement of the number of produced isotopes. This technique is called the Activation Method. Beyond Fe, there is a class of 35 proton-rich nuclides, between ^{74}Se and ^{196}Hg, called p-nuclei. They are bypassed by the s and r neutron capture processes and are typically 10–1000 times

less abundant than the sand/or r-isotopes in the solar system. There is a typical abundance of ~1% for lighter nuclei with 34 ≤ Z ≤ 50 and 0.01-0.3% for medium and heavier nuclei with an atomic number >50. Generally, the abundance of p-nuclei decreases with an increase in atomic number, but for neutron magic p-nuclei ^{92}Mo and ^{144}Sm, it is 14.52% and 3.08%, respectively. Therefore, the study of these nuclei is important to understand why they are more abundant! For this reason, more detailed and precise information on the reaction cross-section in the astrophysical energy region is extremely important. With information on its production and destruction, the final abundance of any nuclei in nucleosynthesis can be estimated. We chose to investigate the ^{144}Sm(p,γ) reaction, which is the destructive pathway of ^{144}Sm nuclei, in this case. The molecular deposition technique has been used to prepare $^{144}Sm_2O_3$ (67% pure) targets on pure aluminium (99.45%) backing. A proton beam was used to activate these targets, yielding a ^{144}Sm(p,γ) ^{145}Eu ($T_{1/2}$ = 5.93 days) reaction cross-section between 4 and 7 MeV. A HPGe detector is used to count the gamma rays, and a Hauser-Feshbach code, TALYS 1.95, is used for theoretical calculations.

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The smooth out of shape coexistence around Z=40

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The shape of nuclei is determined by a fine balance between the stabilizing effect of closed shells and the pairing and quadrupole force that tends to make them deformed. As other well known cases, located in the A = 100 mass region, as Yb, Zr or Nb for example, Sr isotopes [1] are good candidates to study the existence of this nuclear deformation, while Ru and Mo [2] isotopes are interesting to study the disappearance of this phenomenon. In particular, in the Sr case, particle-hole excitations are favored because of the presence of the proton subshell closure Z = 40, resulting in low-lying intruder bands.

This study will clarify the presence of low-lying intruder states in the even-even isotopes considered together with the way it connects with the onset of deformations. In order to reach this aim, the study of the nuclear structure of neutron rich even-even isotopes of Sr, Ru and Mo using the description of excitation energies, B(E2) transition rates, nuclear radii and two neutron separation energies within the framework of the Interacting Boson Model with configuration mixing is developed.

For the whole chain of isotopes analyzed, good agreement between theoretical and experimental values of excitation energies, transition rates, separation energies, radii and isotope shift has been obtained. Furthermore, the wave functions, together with the obtention of mean field energy surfaces and the value of nuclear deformation have been analyzed. Finally, an analysis of the existence of quantum phase transitions for Sr, Mo and Ru isotopes is included.

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Temperature effect on nuclear statistical quantities in the isovector plus isoscalar neutron-proton pairing case.

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Due to fast progress in Radioactive Ion Beam programs, the study of neutron-proton (n-p) pairing effects has known a renewal of interest during the last decade (cf. e.g. [1-3]).
N-p pairing effects may exist in two forms: the isovector (T=1) and the isoscalar (T=0) pairing, where T is the isospin quantum number.
On the other hand, the study of the temperature effect on pairing correlations at finite temperature have been the subject of many efforts since the sixties and is still a relevant subject [3- 5].
In the present work, expressions of the various statistical quantities, i. e. , the energy, the entropy and the heat capacity are established using a path integral approach in the T=1 plus T=0 n-p pairing case [6]. A numerical study is then performed using the schematic one level model.
It's shown that the inclusion of the isoscalar pairing in addition to the isovector one leads to a lowering of the energy as well as a change of the shapes of energy, entropy and heat capacity curves as a function of the temperature.

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Session 8 / 161

The nuclear physics of r-process observables

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Over five years ago the groundbreaking gravitational wave event GW170817 provided the first direct proof that neutron star mergers produce heavy elements via rapid neutron capture (r-process) nucleosynthesis. Still, the extent of the element synthesis in this environment and the role of neutron star mergers in contributing to the galactic tally of r-process elements have yet to be clarified. Interpreting clues from r-process observables such as light curves, abundance patterns, and isotopic ratios currently suffers from large uncertainties due in part to the unknown nuclear physics of the unstable species which participate in the r-process. Here we discuss quantifications of these uncertainties and what we can learn from observables despite them. We will also consider the prospects for reducing nuclear uncertainties via advances in nuclear theory and experiments at AMS and radioactive beam facilities.

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Underground nuclear astrophysics at LUNA and the Bellotti Ion Beam Facility of the INFN-LNGS

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Deep underground nuclear astrophysics with the LUNA experiment at the Gran Sasso National Laboratory by now has a 30-year history and a long track record of measuring crucial reactions for various nucleosynthesis scenarios, from the Big Bang to p-p and CNO reactions to the production

of the heavy elements in the s process.
With the recent installation of a 3.5 MV accelerator at the LNGS and the (upcoming) inauguration of the Bellotti Ion Beam Facility the stellar scenarios and astrophysically important nuclear reactions that can be investigated is expanding greatly.
I will give an overview of the LUNA results and present the program and the experimental capabilities at the new user facility.

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Extreme Light Infrastructure – Nuclear Physics

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Extreme Light Infrastructure – Nuclear Physics (ELI–NP) [1] is the nuclear physics pillar of the pan–European Extreme Light Infrastructure project [2]. ELI–NP was implemented on the Măgurele National Physics Platform by the National Institute for R&D in Physics and Nuclear Engineering "Horia Hulubei". Two state–of–the–art sources of extreme light stay at the core of the project: a 2 x 10 PW ultra–short pulse high–power laser system and a high–intensity gamma beam system. Several experimental setups were developed to take advantage of the extreme photon beams with unprecedented characteristics provided by ELI–NP. A rich science program was established within a large international collaboration with the aim to advance the field of Nuclear Photonics. Basic science research aims at revealing the mechanisms at the basis of particle acceleration driven by high–power lasers and to enable exotic nuclear physics experiments in plasma conditions to reproduce stellar environment evolution in laboratory. Gamma beams will enable the study of electromagnetic dipole response of nuclei and nuclear reactions of astrophysical interest. The results of the basic research will enable novel applications in life sciences, industrial and medical fields. The development of the basic and applied research activities at ELI–NP have a strong interdisciplinary character as they involve laser physics, nuclear physics, material physics, biophysics, engineering, computing, ecc.
The high–power laser system is operational since 2020 and a thorough program of experimental setups commissioning was performed since then. The experimental setups at 100 TW and 1 PW laser power were successfully commissioned and are available for users. The 10 PW experimental setups are under commissioning and they will become available to users in 2024. ELI–NP started the operation as user facility in 2022 when the first call for users was launched in close collaboration with ELI ERIC.
Among the applied research topics, the ones dedicated to investigate the possibility of using laser–driven secondary sources of radiation for medical application, such as high–contrast X–ray imaging, hadron therapy with heavy ions and generation of radioisotopes of medical interest, are given a particular interest at ELI–NP.
The ELI-NP project Phase II is co–funded by the European Union through the European Regional Development Fund and by the Romanian Govern through the Competitiveness Operational Programme

Keywords: Extreme Light Infrastructure, high–power lasers, nuclear physics, medical applications.

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Giant resonances studied with quasiparticle vibration coupling

approach

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Giant monople and dipole resonances are important modes of nuclear collective vibrations, which provide direct constraints on nuclear Equation of State (EoS), such as nuclear incompressibility and symmetry energy. However, "Why is the EoS for tin so soft?" is a longstanding question, which prevents us from determining the nuclear incompressibility accurately. To solve this puzzle, a fully self-consistent quasiparticle random phase approximation (QRPA) plus quasiparticle-vibration coupling (QPVC) approach based on Skyrme-Hartree-Fock-Bogoliubov is developed. We show that the many-body correlations introduced by QPVC, which shift the ISGMR energy in Sn isotopes by about 0.4 MeV more than the energy in 208Pb, play a crucial role in providing a unified description of the ISGMR in Sn and Pb isotopes. The best description of the experimental strength functions is given by SV-K226 and KDE0, which are characterized by incompressibility values of 226 MeV and 229 MeV, respectively, at mean field level. For the dipole case, the unified description of light and heavy nuclei is also examined at QRPA and QPVC level. It is shown that it is possible to give good descriptions of centroid energies for Ca, Sn and Pb already at QRPA level, and the inclusion of QPVC effect further improves the description of widths as well as the evolution trend of dipole polarizability.

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Some aspects of the structure of neutron-rich F isotopes in the Particle-Rotor Model

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In this talk, we will discuss some aspects of the structure of neutron-rich F nuclei within the framework of the particle plus rotor model. Specifically, the low-lying structure of 25,27,29F can be understood in the rotation-aligned coupling scheme with their 5/2+ ground states as the bandhead of a decoupled band [1,2].

The excitation energies of the 1/2+ and 9/2+ states correlate strongly with the rotational energy of the effective core, seen by the odd proton, and allow us to estimate its 2+ energy. The Nilsson plus PRM picture suggests that the extra proton, with a dominant component in the down-sloping [220] ½ level polarizes the Oxygens and stabilizes its dynamic deformation. Thus, the effective cores could be interpreted as slightly deformed rotors with a modest ⍰2 ≈ 0.15, as compared to the weak vibrational quadrupole collectivity in the real Oxygens.

Relevant to this interpretation are the recent studies of the 25F(p, 2p) 24O and 25F(-1n KO)24O reactions carried out at RIBF/RIKEN [3] and NSCL/MSU [4] respectively. Derived spectroscopic factors suggest that the effective core of 25F significantly differs from a free 24O nucleus. The observed fragmentation of the πd5/2 single-particle strength agrees with the PRM calculations and arises from the effects of deformation and core overlap.

We will also present preliminary two-particles plus rotor model of the odd-odd 28,30F [5,6] and discuss some further experiments that can shed further light on the validity of our interpretation.

*This material is based upon work supported by the U.S. DOE, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC05-00OR22725

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Session 10 / 153

Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps

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An overview is given on recent mass and g-factor measurements with extreme precision on single or few cooled ions stored in Penning traps. On the one hand, mass measurements provide crucial information for atomic, nuclear and neutrino physics as well as for testing fundamental interactions and their symmetries. On the other hand, g-factor measurements of the bound electron in highly charged hydrogen-like ions allow for the determination of fundamental constants and for constraining Quantum Electrodynamics. For example, the most stringent test of CPT symmetry in the baryonic sector could be performed by mass comparison of the antiproton with H- and the knowledge of the electron atomic mass could be improved by a factor of 13.

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Observation of the radiative decay of 229mTh: En route towards the nuclear clock

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To be provided

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CRAB: Calibration by Recoils for Accurate Bolometry at the 100 eV scale using neutron capture – on the shore of particle, nuclear and solid state physics

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The detection of the coherent elastic neutrino-nucleus scattering (CEνNS) at reactors or of an hypothetical light dark matter (DM) particles will allow to test new physics beyond the standard model. In both cases their direct detection will lead to sub-keV nuclear recoils. This requires low energy thresholds of few 10 eV along with energy resolutions of few eV, which can be achieved by cryogenic detector operated at mK temperatures. Understanding the response of these detectors at a sub-keV energy scale is therefore crucial but remains a challenge. Up to now the calibrations have been only performed with X-rays sources leading to electronic recoils above keV energies. Recently the CRAB collaboration has proposed [1], based on the nuclear de-excitation FIFRELIN code predictions [2], to calibrate the cryo-detectors with pure nuclear recoils induced by thermal neutron radiative captures, mimicking the CEνNS or DM signals. In fact single-gamma cascades of several MeV produce nuclear recoil calibration peaks between 100 eV – 1 keV in a mm/cm-scale cryo-detector.
We discuss the first measurement performed with a CaWO4 cryogenic detector of the NUCLEUS

experiment [3] and with thermal neutrons produced with a 252Cf source showing a nuclear recoil peak at around 112 eV (182W(n,γ)183W) with a 3σ significance and evidence at the 6σ level of the nuclear recoil spectrum, in very good agreement with FIFRELIN-GEANT4 simulations [4]. This has been recently confirmed by the DM experiment CRESST [5], demonstrating the feasibility of this method as an in-situ non-intrusive calibration of cryogenic detectors.
Then we present the interplay between the nuclear de-excitation timing and atom recoil in matter timing which has recently been investigated in coupling the FIFRELIN and IRADINA [6] (binary collisation approximation) codes. It shows that the nuclear recoil spectrum shape can be significantly impacted, especially for germanium and silicone detectors [7], and so the calibration.
An up-coming high precision measurement will be performed at the TRIGA Mark-II reactor in Vienna where the gammas escaping the cryo-detector will be tagged in addition to the nuclear recoil. This will allow to get more calibration peaks to test the detector linearity response, to determine quenching factors and could also set constraints on nuclear models and solid state physics.

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Session 11 / 120

Advancements of γ-ray spectroscopy of isotopically identified fission fragments with AGATA and VAMOS++

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The utilization of nuclear fission as a method to investigate the nuclear structure properties has been widely employed for several decades. This approach offers an effective means of producing neutron-rich exotic nuclei, covering a broad region of the nuclear chart. By studying the properties of fission fragments, a diverse range of phenomena, including shell closure effects, collective excitation, and shape coexistence, can be explored. The γ-ray spectroscopy of fission fragments is a very powerful method to probe the evolution of nuclear structure properties as a function of excitation energy, angular momentum and neutron-proton asymmetry [1-3].

However, the multitude of isotopes produced during the nuclear fission process also presents a significant challenge. Identifying a specific γ-ray transition originating to a particular nucleus among all γ-rays emitted by hundreds of fission fragments produced in a single experiment is a non-trivial task.

Typically, two approaches are employed to address this challenge. The first one consists in utilizing a combination of known characteristic γ-rays from the fragment of interest or its complementary partner, along with high-fold γ-ray coincidence techniques [2, 3]. The second approach consists in using an experimental setup capable of detecting and isotopically identifying the fission fragments, thereby overcoming the requirement for knowledge of characteristic γ-rays [4, 5].

During the recent AGATA campaign at GANIL, a rich amount of fission studies experiments have been performed using the combination of the large acceptance VAMOS++ spectrometer and the state of the art γ-ray tracking array AGATA. This presentation aims to provide an overview of these experiments, highlighting selected results such as prompt and delayed γ-ray spectroscopy and short lifetime measurements of excited states.

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Study of fission products characteristic with the LOHENGRIN spectrometer

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Fission yields are one of the most used observables to describe the fission process. They are also mandatory for nuclear fuel cycle studies or nuclear reactor calculations. A collaboration between CEA, LPSC, and ILL has been working since 2010 on the LOHENGRIN spectrometer in order to better control the possible experimental biases and systematic uncertainties.
Different setups allow us to study some characteristics of fission products. In this talk, we will highlight the recent results obtained using γ spectroscopy. For instance, a new procedure has been developed in order to measure independent fission yields for shielded isotopes. For such isotopes, due to their low cumulated yield, their γ signals are very low in comparison to the γ–ray background at the measurement position. Therefore, the ions were collected by implantation of the mass-separated beam into Al foil placed inside a vacuum chamber. This foil was then removed and transferred to a low γ-ray background setup located at LPSC. The procedure is then repeated for different LOHENGRIN settings. The low γ-ray background setup features a considerably improved signal-to-background ratio compared to more conventional measurements in the online regime.
Fission product characteristics can be studied with the LOHENGRIN spectrometer such as their angular momentum. Usually, fission product angular momentum is studied through prompt γ emission or isomeric ratio measurement. The later observable is interesting because it preserves the initial angular momentum information resulting from the fission process just after the prompt particle emission. Recently experimental campaigns achieved at the ILL showed the kinetic energy dependence of isomeric ratios for numerous nuclei for 235U(nth,f) and 241Pu(nth,f) reactions. A Bayesian assessment of the angular momentum distribution is proposed according to calculations performed with the FIFRELIN code. The similar angular momentum distributions found for both reactions are interpreted with angular momentum generation models.

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Developments at the Nuclear Analytical Facilities at MLZ, Garching

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The prompt gamma activation analysis (PGAA) facility has continuously been developed at Heinz Maier-Leibnitz Center (MLZ). Four Compton-suppressed HPGe detectors equipped with modern cooling systems and 64k digitals spectrometers have been used for analytical and nuclear-physics experiments in the strongest cold neutron beam of the world. The standard PGAA setup consists of a 60-% and a low-energy HPGe detector both surrounded by BGO scintillators. A low-background chamber with a similar equipment has been added to count decay gamma rays of short-lived activation products thus enabling in-beam neutron activation analysis (ibNAA). [1]
NAA has recently been added to the instrument pool available to external users. The samples are irradiated in the highly thermalized channels of the reactor and a rabbit system transfers them to the counting labs where three HPGe detector equipped with digital spectrometers count them.
The planned upgrade project at MLZ, MORIS offers us a unique opportunity to initiate developments at our facility far beyond the standard implementation of gamma-ray spectrometry from neutron capture. The presentation summarizes also these plans.
The feasibility of Prompt Gamma Activation Imaging (PGAI) was shown in the frame of the ANCIENT CHARME projects several years ago [2]. It is based on the narrow collimation of the neutron beam to, and of the gamma rays emitted from predefined spots of complex objects. The method is highly time-consuming and after the first studies, there has never been enough beam time to use it routinely in spite of the obvious need for it. We plan to use a detector cluster consisting of seven HPGe detectors each of which would observe one voxel along the line activated by the neutron beam. This alone would speed up the experiment, but with applying multiple collimator channels within the gamma shielding, we hope to gain nearly two orders of magnitude in the duration of single scans.
To broaden the circle of the analyzed elements, our goal is to detect all possible particles emitted by the activation products, e.g. beta particles which in several cases are not followed by gamma radiation. This would be important e.g. in determination of the phosphorus dopant in silicon semiconductors. This requires a combination of a scintillator counting in 4π solid angle with a HPGe detector.
We also plan to test a new setup at the fast-neutron radiography station NECTAR. It would exploit imaging with inelastically scattered fast neutrons in coincidence with gamma rays identifying the emitter element.

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Structural Evolution of the Neutron-Rich Calcium Isotopes

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Understanding the structure of atomic nuclei at the extremes of the Segre chart is of paramount importance in nuclear physics. In these nuclei, often termed exotic, new shell closures may emerge, while others may disappear. A crucial region is formed by the neutron rich Calcium isotopes, with striking appearances of new magic numbers at N = 32 and N = 34.
Within the SEASTAR (Shell Evolution And Search for Two-plus energies At RIBF) project at the RIBF, the most neutron-rich Calcium isotopes to-date and their neighboring isotones were studied by means of in-beam gamma-ray spectroscopy of fast moving nuclei, yielding new insight in to the driving mechanisms of shell evolution in the region (e.g [1, 2, 3, 4, 5, 6, 7, 8, 9]).
Besides providing a short description of the setup, my presentation will focus on the first spectroscopy of the neutron-rich Calcium isotopes 55,56,57,58Ca, as well as detailed spectroscopy of 54Ca, providing new insights into the possible new doubly magic nucleus 60Ca.

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Exploring the emergence of nuclear collectivity through moments and monopoles

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The emergence of collectivity in atomic nuclei is a primary research theme of the Australian National University Nuclear Structure Group. Through precision spectroscopy we aim to map emerging collectivity as valence nucleons are added to a doubly magic core, to elucidate the nature of weakly-collective nuclei, and to quantify the role of intruder configurations and shape-coexistence in weakly-collective nuclei.
Weakly collective nuclei are defined here as those that occur between nuclides that have a few valence nucleons outside a doubly magic core and those with many valence nucleons that show clear rotational bands. Highlights of recent research will be presented, with a focus on insights gained by confronting model calculations with experimental data on electromagnetic decays and moments [1-6].
There is increasing evidence that collectivity in nuclei emerges immediately as deformation and rotation, not vibration, and that the weakly deformed shapes tend to be triaxial. However, this evidence requires further investigation. The magnetic moments of weakly collective nuclei suggest that there is a class of nuclei, exemplified by the Te [2] and Xe [7] isotopes near 132Sn, that could be described as pre-collective, in that they begin to show collectivity in the low-excitation structure, but single-particle (seniority) structures also persist. Collectivity is emerging, but states that are 'more collective' exist along with states that are 'less collective'. Moreover, recent magnetic moment measurements on the Sn isotopic chain suggest emerging collectivity near N=60 that can be classified neither as vibration nor rotation [6]. In relation to models, important physics may be hidden by the

use of effective charges [1,4,6].
The above discussion applies to heavier nuclei, where the nearest doubly magic nuclides have N > Z. Shape coexistence in doubly magic shell-model cores with N = Z, namely the existence of relatively low-excitation deformed multiparticle-multihole states, has long been known. However, measured electric monopole transition strengths are only now determining the degree of shape mixing, with increasing evidence that these presumed inert, spherical shell-model cores are in fact deformed in their ground states [5]. We are striving toward more complete spectroscopy of such nuclei and their neighbours to map emerging collectivity, by measuring E0 transition strengths and magnetic moments, along with E2 transition strengths.

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Radiative Capture Reactions in Explosive Stellar Phenomena

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Recent multi-messenger observations of explosive astronomical events are generating exciting new challenges for nuclear physics and force a rethinking of old paradigms. In particular, advanced, space-based telescopes have provided unprecedented insight into the production of chemical elements across the Galaxy, while the detection of massive neutron stars have ruled out a variety of hypotheses regarding the nature of nuclear matter. Unfortunately, despite the wealth of observational data available, many broad and open questions relating to stellar nucleosynthesis throughout the cosmos still remain, owing to large uncertainties in the underlying nuclear physics processes that drive explosive stellar scenarios.

In this regard, exceptional advances in experimental nuclear physics, over the past few years, offer an exciting means to address this issue. Specifically, the latest generation of radioactive beam facilities can now act as terrestrial laboratories for the direct reproduction of astrophysical reactions, while state-of-the-art detection systems offer the possibility to study key unstable nuclei, that govern the pathway of nucleosynthesis in explosive astronomical events. In this talk, direct and indirect methods for studying astrophysical reactions will be discussed, with a specific emphasis on innovative techniques and advanced detection systems.

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Lifetime determination of excited states in ^{104}Ru and ^{130}Te via a new Doppler-shift attenuation approach

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The Doppler-shift attenuation method after proton scattering is a well-established technique to determine nuclear-level lifetimes in the range of sub-picoseconds [1,2]. In the last years, (p,p'γ) experiments have been performed using the combined detector array SONIC@HORUS consisting of 14 HPGe detectors and 12 Silicon detectors [3]. Measuring the emitted de-exciting gamma ray as well as the backscattered proton in coincidence provides complete knowledge of the reaction kinematics. To extract a lifetime the so called attenuation factor F(τ) has to be determined, which is linked to the continuously attenuating velocity of the recoiling nucleus. In the established analysis this is done by comparing the Doppler-shifted photon energy E_γ at different photon emission angles θ and using that F(τ) represents the slope of $E_\gamma(cos(\theta))$. Alternatively, the spectra measured at different angles can be corrected for their expected Doppler shifts assuming different F(τ) values. The optimal attenuation factor, which minimises the Doppler broadening of the analysed γ peak in the summed up spectra, yields the lifetime. First results on ^{130}Te, obtained via the new approach, are in good agreement with known level lifetimes. This procedure might be more efficient to determine lifetimes of weakly excited states leading to low statistics in the spectra.
Recently, a DSAM experiment on ^{104}Ru has been performed to further analyse systematics concerning the Ru-isotopic chain with increasing neutron number and to benchmark the new technique.
In this contribution, ongoing investigations on the new DSA approach will be presented as well as first results from the experiment on ^{104}Ru using this method.
Supported by DFG (ZI 510/9-1). A.B. is supported by the Bonn-Cologne Graduate School of Physics and Astronomy.

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Session 13B / 39

Understanding the Effect of the Chiral EFT Interaction on Nuclear Collectivity From an Ab Initio Symmetry-Adapted Perspective

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In this talk, I will discuss an *ab initio* approach which exploits symplectic symmetry in order to provide a physically informed basis that successfully describes collective and clustering features, including quadrupole moments, electromagnetic transitions, as well as alpha widths, in light to intermediate-mass nuclei [1, 2, 3]. Looking towards the high-precision physics era, we study uncertainties on collective observables computed with chiral effective field theory interactions by coupling the framework of the symmetry-adapted no-core shell model with the method of global sensitivity analysis [4]. Specifically, we generate large samples of the low-energy constants (LECs) that parametrize chiral potentials, in order to obtain distributions of observables such as the quadrupole moment in 6Li and 12C. We then compute Sobol sensitivity indices to determine the contribution of the variance in each LEC to the overall variance observed in these distributions. For the first time we determine the underlying forces to which collective observables are most sensitive. This study is a first step in the construction of high-precision nuclear interactions, which coupled with Bayesian analysis will aim to provide rigorous uncertainty quantifications on collective nuclear observables.

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Session 13A / 69

Lifetime measurements in ^{129}Sn

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The measurement of level lifetimes around the doubly closed shell nuclei carries extreme importance as they give direct insight into the transition probabilities and thus the understanding of the n-n interaction. The validity of the double shell closure near ^{132}Sn has been revealed from the study of low lying states of the nuclei which have few proton (neutron) particles (holes) about Z = 50 and N = 82 [1,2,3]. However, the availability of spectroscopic information around ^{132}Sn is comparatively scanty as compared to other double shell closure due to experimental difficulty in reaching this region by compound nuclear or transfer reactions using the available target-projectile combinations and fission being the most reliable pathways to access these nuclei.
The excitation spectra in Sn nuclei close to A=132 is specifically important as these nuclei provide information uniquely for the neutron single particle orbitals. Study of ^{129}Sn, with three neutron holes with respect to neutron shell closure at N=82, is thus worth pursuing in detail. The $d_{3/2}$, $s_{1/2}$ and the unique parity $\nu h_{11/2}$ orbitals play significant roles in the development of low lying level spectra and the isomers in isotopes of Sn with mass numbers close to A=132. In odd-A Sn nuclei, the $\nu h_{11/2}$ orbital becomes most relevant as one approaches N = 82 and proximity of only relatively lower spin (3/2 and 1/2) positive parity orbitals generate long-lived isomers at low excitation. Even the low energy higher spin positive parity states like $23/2^+$, $19/2^+$ and $15/2^+$ are generated with spin contribution from two neutron holes in $1h_{11/2}$.
In ^{129}Sn, the $\nu d_{3/2}$ orbital crosses the $\nu h_{11/2}$ orbital as observed from the nearly degenerate $11/2^-$ first excited level to the $3/2^+$ ground state. The evolution of B(E2) values corresponding to the decay of the positive parity isomers, viz. $19/2^+$ and $23/2^+$, in odd-A Sn nuclei show the effect of gradual filling of the νh11/2 orbital with the increase in neutron number [4]. The shell model calculation on the low lying negative parity excitations of ^{129}Sn shows that many of these levels have pure $\nu h_{11/2}{}^{-n}$ configurations with admixtures from the configurations involving $\nu d_{3/2}$ and $\nu s_{1/2}$ orbitals [5]. Out of these, the lowest $11/2^-$ and the 2553 keV, $27/2^-$ levels are isomers of 6.9 min and 217 ns, respectively. It is necessary to locate all the candidates of pure multiplets of νh11/2 structure and to estimate the possible configuration mixing in both the positive and negative parity levels.
Hence, the measurement of level lifetime for the low lying levels of ^{129}Sn is of substantial importance to understand the role of configuration mixing and neutron-neutron interactions around the N = 82 shell closure. With this motivation, the low lying excited states of ^{129}Sn have been populated from the combined route of IT decay of higher lying μs isomeric level viz, $19/2^+$ & $23/2^+$ and β-decay of ^{129}In . The neutron-rich Sn and In (A~129) isotopes were produced through thermal neutron-induced fission at Institut Laue Langevin (ILL), Grenoble, France. The recoiling fission fragments

were separated in mass and kinetic energy using the Lohengrin recoil fragment separator [6] and were detected with an ionization chamber (IC) placed at the focal plane. The IC provides a start signal for decay measurements of μs isomers. An array of four 1.5” X 1.5” $LaBr_3$(Ce) fast scintillator detectors placed at 90 degrees to each other and coupled with two Clover HPGe detectors were used for the detection of de-exciting γ radiations. The energy and time information from these detectors were obtained by digitizing the preamplifier outputs from the Clovers, the anode signals of the photomultiplier tubes (Hamamatsu 13435) connected to the LaBr3 crystals. The timing signals from the $LaBr_3$ detectors were also generated using analog CFD modules and the time differences were taken from the analog time to amplitude converter (TAC) modules. The TAC outputs were then digitized to get the time difference distributions required for lifetime measurements down to few picoseconds.
The gathered data are analyzed for the measurements of level lifetimes in picosecond range using generalized centroid difference(GCD) analysis [7]. The results from the present measurement in comparison with shell model calculations will be presented.

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Session 13B / 89

Nuclear structure and excited states of superheavy nuclei

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We present the first triaxial beyond-mean-field studies of super-heavy nuclei. They include the restoration of the particle-number and angular-momentum symmetries and the mixing of different shapes using the generator coordinate method. The importance of the γ degree of freedom is highlighted by comparing the triaxial to axial-symmetric calculations performed within the same framework. In the calculations, the effective finite-range density-dependent Gogny force is used.

Calculations for the even Flerovium isotopes towards the supposed N=184 neutron shell closure were performed [1]. For the three even Fl isotopes between the prolate {288}Fl and the oblate {296}Fl triaxial ground-state shapes are predicted, whereas axial-symmetric calculations suggest a sharp prolate-oblate shape transition between {290}Fl and {292}Fl. A novel type of shape coexistence, namely that between two different triaxial shapes, is predicted to occur in {290}Fl. Finally, the existence of a neutron shell closure at N=184 is confirmed, while no evidence is found for Z=114 being a proton magic number.

In the same framework, we present the study of the excitation spectra of super-heavy nuclei. As representative examples, we have chosen the members of the α-decay chains of {292}Lv and {294}Og [2,3], the heaviest even-even nuclei which have been synthesized so far using {48}Ca-induced fusion-evaporation reactions. Rapidly varying characteristics are predicted for the members of both decay chains, which are further accentuated when compared to the predictions of simple collective models. The calculations will be compared to the available experimental data [2] and the prospect of observing α-decay fine structures in future experiments discussed. Additionally, the excitation spectra along the α-decay chains of the odd-A nucleus {289}Fl is discussed [4].

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Microscopic aspects of γ-softness in atomic nuclei

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How the collective features emerge from the microscopic degrees of freedom is one of the main research themes in quantum many-body systems. Using the microscopic approach of the triaxial projected shell model (TPSM), the authors demonstrate that admixing few quasiparticle excitations into the vacuum configuration with a fixed triaxiality parameter γ provides a quantitative description of the shape fluctuations of the γ-soft nuclei.
This is demonstrated by a detailed study of ^{104}Ru, which reproduces a large set of experimental energies and $BE2$ matrix elements measured by COULEX [1].
The collective features are elucidated using the quadrupole shape invariant analysis, and also the staggering phase classification of the γ-band. A systematic study of twenty-two nuclei has been carried out by means of the TPSM. The experimental energies of the yrast bands and γ bands as well as the pertaining experimental $B(E2)$ values for intra and inter band transitions are very well reproduced. The signatures of triaxiality softness, as the position of the 2_2^+ state relative to the 4_1^+ state, the energy staggering of the γ band, the position of the 0_2^+ state and its
E2 decay are discussed.
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Session 13B / 116

Gamma-ray spectroscopy of neutron-rich Niobium isotopes: new insights into the sudden onset of deformation of the A~100 and N=60 region.

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Exotic nuclei, far from stability, are a perfect laboratory to probe the specific components of the nuclear interaction. The imbalance between the number of protons and neutrons can lead to the appearance of phenomena such as sudden shape transitions and shape coexistence. The nuclei with Z and N around 40 and 60, respectively, show one of the most remarkable examples of sudden nuclear shape transition between spherical and well deformed nuclei.
This work reports on new spectroscopic measurements for the neutron-rich Nb isotopes, produced in transfer and fusion-induced fission reactions at GANIL from two different experiments. The combination of the large acceptance VAMOS++, the new generation gamma tracking array AGATA along

with the EXOGAM gamma- ray spectrometer provide a unique opportunity to obtain an event-by-event unambiguous (A, Z) identification of one of the fission fragments, with the prompt and delayed gamma-rays emitted in coincidence with unprecedented resolution.
The level scheme of 99, 102, 104, 105, 106Nb have been significantly updated and a level scheme is presented for the first time for the 107Nb nucleus. The observation of a newly observed spherical/deformed shape coexistence in 99Nb will be presented, as the evolution of the nuclear deformation with the increasing neutron number. These results contribute to a better understanding of the nuclear structure of neutron-rich Niobium isotopes and provide very useful experimental data to constrain nuclear models in this complex island of deformation region.

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Neutron Elastic Scattering Differential Cross Sections on 13C

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Neutron elastic scattering cross sections on natural carbon serve as a reference standard in the incident energy range 10 eV to 1.8 MeV. The 2017 standards evaluation [1] is 0.5 to 2.0% higher in that energy range than the 2006 standards evaluation [2]. In addition the ENDF/B-VIII.0 and ENDF-VIII.1 releases split the natural carbon cross sections into the isotopes 12C, 13C, and 14C for the first time. These details call for the re-measurement of the 13C cross sections in sensitive regions. Ten elastic scattering angular distributions were recently measured for incident neutron energies between 0.5 and 3.25 MeV. Measurements were made at the University of Kentucky Accelerator Laboratory (www.pa.uky.edu/accelerator/), using nanosecond pulsed beams and time-of-flight techniques. An overview of neutron production and detection, the new digital data acquisition system, and data analysis will be presented.

Results are compared with data from previous measurements and data-base evaluations. This work was supported by the U.S. Department of Energy awards SC0021424, SC0021243, SC0021175, SSC000056, the U.S. National Science Foundation under grants PHY-1913028 and PHY-2209178, the U. S. Naval Academy Midshipmen Research Fund, and the Donald A. Cowan Physics Fund at the University of Dallas.

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Session 13B / 81

Nuclear studies with FSU Hamiltonian

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The empirical or semi-phenomenological nucleon-nucleon interactions that have been used in the traditional shell model studies for over half a century still play a key role in microscopic studies of nuclei. Progress has been made in connecting the empirical matrix elements of the Hamiltonian with the fundamental interactions coming from QCD, however full understanding is still missing. The research direction going from experiment to fundamental theory is of major importance.

In this presentation I will discussed the FSU shell model Hamiltonian developed in a collaborative theory-experiment effort at Florida State University [1]. The interaction covers a very broad mass region from light nuclei in the p-shell to those in the fp-shell. I will discuss some technical details and motivations related to the model hamiltonian, fit procedure, and experimental data used for the fit. I will highlight some important applications discussing binding energies, spectroscopy and complex many-body effects such as clustering. Some theoretical questions such as evolution of the mean field, inversion of the traditional shell structures, density of states and particle-hole configuration mixing will be briefly discussed.

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This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Nuclear Physics under Award Number DE-SC0009883.

Session 13B / 102

Beta-decay study of the shape coexistence in ^{98}Zr

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Shape evolution in atomic nuclei has been a major area of research in nuclear physics. While throughout the nuclear chart the evolution of a spherical ground-state shape into a deformed one is usually a gradual process, in the Zr isotopic chain an abrupt shape transition is observed at N=60. Recent state-of-the-art Monte Carlo Shell Model (MCSM) calculations have successfully reproduced this dramatic onset of deformation in ^{100}Zr and predict that the same deformed configuration may coexist at higher excitation energies in lighter Zr isotopes [1, 2]. Of particular interest is ^{98}Zr, which is a transitional nucleus lying on the interface between both spherical and deformed nuclear phases. Based on the above, extensive experimental and theoretical research efforts have been made to study the shape coexistence phenomena in this isotope [3,4,5,6]. Although these studies provide an overall understanding of ^{98}Zr's nuclear structure, uncertainties remain in interpreting its higher-lying bands. Specifically, two recent studies utilizing MCSM [3] and Interacting Boson Model with configuration mixing (IBM-CM) [4] calculations have presented conflicting interpretations. The MCSM predicts multiple shape coexistence with deformed band structures, whereas the IBM-CM favours a multiphonon-like structures with configuration mixing.

To address these uncertainties, a β-decay experiment was conducted at TRIUMF-ISAC facility utilizing the 8π spectrometer with auxiliary β-particle detectors. The high-quality and high-statistics data obtained enabled the determination of branching ratios for weak transitions, which are crucial for assigning band structures. In particular, the key 155-keV $2_2^+ \rightarrow 0_3^+$ transition was observed, and its branching ratio measured, permitting the B(E2) value to be determined. Additionally, γ-γ

angular correlation measurements enabled the determination of both spin assignments and mixing ratios. As a result, the 0^+, 2^+, and $I = 1$ nature for multiple newly observed and previously known but not firmly assigned states has been established. The new results revealed the collective character of certain key transitions, supporting the multiple shape coexistence interpretation provided by the MCSM framework. These results will be presented and discussed in relation to both MCSM and IBM-CM calculations.

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Measuring and Simulating Capture γ-Ray Spectra using the RPI γ-Multiplicity Detector

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Accurate modeling of neutron induced capture γ-production is essential for reactor and shielding calculations, understanding γ-heating in critical systems, and non-proliferation applications. To determine the accuracy of nuclear data evaluations and simulation tools used to transport capture γ-cascades, the 16-segment γ-multiplicity NaI(Tl) detector at the Rensselaer Polytechnic Institute (RPI) Gaerttner Linear Accelerator Center (LINAC) has been upgraded to measure capture γ-ray spectra and multiplicity as a function of energy. Several samples including Fe, Mn, Co, Ta, and ^{235,238}U have been measured using the time-of-flight (TOF) method for incident neutrons in the low-energy region from 0.01 – 100 eV. A new method has been developed to model the event-by-event capture γ-cascade energy deposition in the detector array using DICEBOX and a modified version of MCNP-6.2. The method has been validated using ^{22}Na and ^{60}Co coincidence sources and the well-studied thermal ^{56}Fe(n,γ) capture γ-ray intensities. Additional measured samples will be used for further validation and analysis. The new modeling capabilities coupled with measured γ-ray spectra can be used to test transport codes and nuclear data evaluations of capture γ-rays used to simulate experimental results.

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Search for shape coexistence in the Selenium isotopes near the N=50 neutron shell closure

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In this contribution we discuss the investigation of the shape coexistence phenomenon in neutron-rich Selenium (Z=34) isotopes (^{83}Se and ^{84}Se), near the N=50 neutron shell closure, by gamma-ray spectroscopy. The shape coexistence phenomenon consists in the appearance of different shapes (spherical, oblate and prolate) within the same nucleus at comparable excitation energies [1], and it can be visualized through the Potential Energy Surface (PES, i.e., the potential energy of the system as a function of its deformation), which may present local minima associated with different shapes of the nuclear system. In the Selenium case, the excitation of neutrons beyond the N=50 neutron shell closure is expected to lead to a coexistence of shapes, similarly to what observed along the Ni isotopic chain [2,3] in agreement with the prediction from Monte-Carlo Shell Model calculations [4]. The ^{84}Se (N=50) and ^{83}Se (N=49) nuclei have been populated by a sub-Coulomb barrier transfer reaction at IFIN-HH (Bucharest, Romania) and by a neutron capture reaction at ILL (Grenoble, France), respectively. The decay schemes of both nuclei have been significantly extended and they are currently under investigation.
The gamma decay of ^{84}Se was detected by the HPGe ROSPHERE array, coupled with the SORCERER Silicon detector array. Two excited 0^+ states, already known from literature, have been confirmed at 2244 keV and 2654 keV excitation energy, and their gamma decay to the first 2^+ state has been observed for the first time. Preliminary results from lifetime analyses, performed with both the Doppler Shift Attenuation Method and the Plunger technique, indicate that the lifetime of the third 0^+ is of the order of 1 ps, while a longer lifetime is expected for the second excited 0^+ state. The analysis is currently ongoing. In the case of ^{83}Se, the gamma decay was detected by the HPGe FIPPS array, composed of a total of 16 clover detectors. Prior to the present (n, γ) measurement, very little information was available from the literature, with only few primary gamma rays placed in a tentative level scheme [7]. The current gamma-spectroscopy data allowed to significantly expand the decay scheme of ^{83}Se, through the observation of 28 new primary gammas, 68 new transitions (plus 20 tentative new transitions) and 16 new populated energy levels. The data analysis is still ongoing and firm spin and parity assignments of newly found states will be obtained from angular correlation investigation.
For both nuclei, comparison with theoretical predictions from Monte Carlo Shell Model calculations will be made in order to achieve a microscopic description of their structure. The aim is to clearly identify excited states which can be associated to different deformed shapes.

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Development of active neutron nondestructive assay system

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There is no acceptable and practicable single nondestructive method for the assay of Special Nuclear Materials (SNM) and Minor Actinides (MA) in highly radioactive nuclear materials, such as those found in spent fuel and MA transmutation fuel. The Japan Atomic Energy Agency (JAEA) and the Joint Research Centre (JRC) of the European Commission have been developing an active neutron nondestructive assay (NDA) system for nuclear non-proliferation and nuclear security [1]. We utilize four different NDA techniques, namely Differential Die-Away Analysis (DDA), Prompt Gamma-ray Analysis (PGA), Neutron Resonance Transmission Analysis (NRTA) and Delayed Gamma-ray Analysis (DGA) [2]. These are promising and effective active neutron techniques especially for nuclear material accountancy. The techniques give us different and useful analytical results, which could provide complementary information. We developed a combined NDA system, which enables the simultaneous measurements of DDA and PGA, at NUclear fuel Cycle safety Engineering research Facility (NUCEF) in the first phase of the collaboration. The conventional DDA utilizes a thermal neutron for the interrogation. The combined NDA system can be used an improved DDA. It has rather uniform sensitivity for fissile materials because fast neutrons are used for the interrogation. Moreover, it is possible to quantify a small amount of the fissile mass as low as 1mg(Pu-239) [3]. PGA is efficient adaptive NDA method to apply for the measurement of light elements and therefore is utilized for the quantification of neutron absorber and is particularly useful for the detection of explosives. The second phase of the project, launched in 2018, focuses on the development of the active neutron NDA system for highly radioactive materials. We conducted further study to improve the methodologies and developed an advanced NDA system which allows us to measure by NRTA as well as DDA and PGA. The third phase has started to study a compact NRTA system from 2022 for four years. NRTA can be used to quantify almost all medium and high-Z elements and considered as one of the most accurate NDA techniques to quantify the amount of SNM and MA. In addition, NRTA would be the most promising method in terms of the low-background measurements for highly radioactive nuclear materials because the detector can be set up farther away from the highly radioactive samples. An overview of the projects and the recent results will be presented, especially the details of new integrated NDA system.

This research was implemented under the subsidiary for nuclear promotion of MEXT (the Ministry of Education, Culture, Sports, Science and Technology of Japan).

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Investigation of excited states in 76As of interest for 0νββ decay

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Since many years the quest for experimental evidences for the neutrino less double beta decay is open.
Such measurement would imply the neutrino being identical to its antiparticle, therefore being a Majorana particle. A measurement of the lifetime for this process would lead to a precise estimation of the neutrino mass. However, very precise nuclear physics data are needed to achieve an accurate theoretical prediction.
Indeed, the predicted lifetimes and decay rates may vary by many factors depending on the nuclear interaction
chosen, and more and more precise nuclear physics information is needed to match the experimental sensitivity
of planned neutrino experiments. Large experimental efforts have been perform to study, theoretically [1]
and experimentally [2, 3], the double beta decay of 76Ge to 76Se. While a crucial role is played by the wave-functions of the mother ground state and the low-lying states of the daughter, theory shows that a non-negligible role can be played by the structure of the intermediate 76As [4]. An experiment is planned with the FIPPS apparatus at ILL, which aims at an unambiguous identification of the 1+ levels of 76As. Such identification would help theory constrain the matrix elements of the double beta decay. Such levels will be identified using γ-ray spectroscopy techniques after (n,γ) reactions on 75As. The spin and parity assignation of the excited levels will be possible thanks to angular correlation measurements.
Preliminary results from the FIPPS experiments will be shown as well as the characterization of the performance of the instrument.

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Systematic investigation of photon strength functions with monochromatic gamma-ray beams

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Following the main objective of the IAEA Coordinated Research Project on Photonuclear Data and Photon Strength Functions (Code F41032; Duration 2016-2019), new measurements of photoneutron and photofission cross sections in the Giant Dipole Resonance energy region have been performed at the laser Compton-scattering γ-ray source of the NewSUBARU synchrotron radiation facility. Nuclei in a wide mass range spanning from ^{9}Be to ^{238}U have been investigated. Quasi-monochromatic γ-ray beams with typical energy resolution 3% in FWHM have been employed. The neutron multiplicity sorting has been performed using an energy-dependent statistical treatment of neutron coincidence events associated with a flat-efficiency moderated neutron detection array. We report updates on the experimental technique and methodology and selected experimental results on photoneutron (^{197}Au, ^{208}Pb) and photofission (^{232}Th, ^{238}U) cross sections as well as average energies of neutron emission spectra.

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Systematics of the dipole polarizability

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The electric dipole polarizability is a key observable to set constraints to the symmetry energy parameters of the equation of state and the neutron skin thickness of nuclei. The electric dipole response of a nucleus can be probed with inelastic proton scattering at very forward angles and intermediate proton beam energies, where relativistic Coulomb excitation dominates (1). This kinematics is furthermore suited to measure the isovector spin-flip M1 resonance.
Over the last decade the electric and magnetic dipole response in numerous nuclei has been measured with inelastic proton scattering at the Research Center for Nuclear Physics in Osaka, Japan. Proton beam energies of 295 MeV were used and scattered protons were measured with the Grand Raiden (GR) magnetic spectrometer. With the GR placed at 0°, measurement of scattered protons at extreme forward angles can be realized (2). Measured spectra are deconvoluted into contributions of different multipolarities by performing a multipole decomposition analysis based on DWBA calculations.
In this talk new results about the dipole response and dipole polarizability of ^{58}Ni and ^{90}Zr will be presented. Forthermore the now available systematics of the dipole polarizability will be discussed: from light and medium-mass to heavy nuclei, as well as the evolution within isotopic chains (3,4,5,6).

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Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 279384907, SFB 1245.

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Fast Neutron-induced Gamma-ray Spectrometry (FaNGaS)

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Fast Neutron-induced Gamma-ray Spectrometry (FaNGaS)

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Keywords: Inelastic scattering, Fast neutron, Cross section, Gamma ray, Detection limit

Prompt Gamma Neutron Activation Analysis (PGNAA) based on cold or thermal neutron capture is a powerful technique for non-destructive elemental analysis of small and thin samples. However, due to limited penetration and attenuation effects, PGNAA is not suited for a precise investigation of large objects. The feasibility to analyse large samples by measuring prompt gamma rays from fast-neutron-induced reactions was already demonstrated several decades ago [1]. The FaNGaS (Fast Neutron-induced Gamma-ray Spectrometry) instrument, installed at Heinz Maier-Leibnitz Zentrum (MLZ) in 2014, advances this technique in nuclear analytical chemistry and makes it available for a broad community of industry and research [2-8]. Using the intense fission neutron beam delivered by the research reactor FRM II (Forschungs-Neutronenquelle Heinz Maier-Leibnitz) to investigate fast-neutron induced prompt gamma-ray emission, it offers new possibilities for the chemical analysis of large or small samples as a complementary method to conventional thermal- or cold-neutron based PGNAA. The predominant reaction channel of fast neutrons at FaNGaS is the (n,n'γ) inelastic scattering reaction, currently with only one existing database: the "Atlas of Gamma-rays from the Inelastic Scattering of Reactor Fast Neutrons", published in 1978 by Demidov et al. [9]. This data compilation is valuable and a relational database has been recently developed based on this Atlas [10]. However, it was yet never validated and previous measurements with FaNGaS show the need for a critical and meticulous validation [3-6,8]. Apart from building up a comprehensive catalogue of (n,n'γ) reactions another main objective is a continuous optimization of the instrument to achieve a further peak-to-background reduction.
In this talk the experimental set-up and technical specifications of FaNGaS will be given. Relative intensities and partial gamma-ray production cross sections of fast-neutron-induced prompt gamma rays derived from the measurement of various elements will be presented along with literature comparisons.

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Evolution of low-lying M1 modes in germanium isotopes

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Magnetic dipole strength functions are determined for the series of germanium isotopes from N = Z = 32 to N = 48 on the basis of a large number of transition strengths calculated within the shell model.
The evolution of the strength with increasing neutron number in the g9/2 orbital is analyzed. A bimodal structure comprising an enhancement toward low transition energy and a resonance in the region of the scissors mode is identified. The low-energy enhancement is strongest near closed shells, in particular at the almost completely filled g9/2 orbital, while the scissorslike resonance is most pronounced in the middle of the open shell, which correlates with the magnitude of the also deduced electric quadrupole transition strengths. The results are consistent with previous findings for the shorter series of iron isotopes [1] and prove the occurrence and correlation of the two low-lying magnetic dipole modes as a global structural feature [2].
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A novel projected shell model method for nuclear level density

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Nuclear level density (NLD) is a basic property of atomic nuclei and is a crucial ingredient in nuclear reaction theories. For a quantitative, microscopic description of NLD, one should solve the exact many-body eigenvalue problem, $H |\Psi\rangle = E |\Psi\rangle$, and obtain all energy levels in the Hilbert space. However, this has turned out to be an impossible task for mid-mass and heavy nuclei if the discussion is confined in the conventional shell model. One has to develop novel shell-model methods by applying modern many-body techniques.

There is overwhelmingly experimental evidence indicating that excited nuclear states are dominated by quasiparticle (qp) excitations, which form many-body configurations with broken nucleon-pairs from different orbitals. By taking these multi-qp states as building blocks for shell-model basis, we propose a novel shell-model method for calculation of NLD in deformed nuclei. The shell-model diagonalization with two-body residual interactions yields a large ensemble of eigenstates of angular momentum and parity. We demonstrate that NLD as a statistical quantity depends sensitively on structure of deformed single-particle states.

As the first example to introduce this method, we take a well-deformed rare-earth nucleus, 164Dy, for which NLD has been studied extensively by the Oslo method. By a quantitative comparison with discrete levels from spectroscopic measurements, we show that while the pronounced step-wise structure in the low-energy NLD curve can be understood as the collective excitation and nucleon-pair breaking, the exponential growth of levels in the higher-energy NLD can be described by combination of the broken-pair states, subject to the Pauli Principle. According to the nature of NLD with increasing excitation, we divide the entire NLD curve into (1) collective regime, (2) pair-breaking regime, and (3) multi-qp regime. We discuss the formation mechanism and characteristic features of

NLD for the three regimes. In addition, the parity dependence and angular-momentum-dependence in NLD are discussed with a strong emphasis of the structure effect.

A shell model calculation for NLD up to the highest excitations requires heavy computational effort. The numerical effort can be greatly reduced if we just use the full set of multi-qp configurations in the shell-model space to count levels, without carrying out configuration mixing in very large matrices. Our preliminary results show that in this way, we can obtain an NLD curve qualitatively similar to realistic calculations, and can easily extend the calculation up to the neutron separation energy to compare the result with the NLD from the neutron-resonance spacing data, for arbitrarily heavy, deformed nuclei.

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New results from in-beam and decay spectroscopy in the region around doubly-magic 132Sn performed at the Radioactive Isotope Beam Facility

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In the last decade, a considerable progress in the understanding of the structure of nuclei in the vicinity of 132Sn, the heaviest doubly-magic nucleus far-off stability accessible for experimental studies, was achieved. The vast amount of results obtained in several experimental campaigns performed at the Radioactive Isotope Beam Facility (RIBF) in Japan, in combination with state-of-the-art theoretical investigations, contributed in a significant way to this progress. In the present contribution, we will discuss unpublished results from several different experiments. We will start with new (and maybe last?) results from an experiment which was dedicated to decay spectroscopy in the 132Sn region and performed during the EURICA campaign in 2014. This experiment already delivered a lot of very valuable information giving rise to the publication of numerous articles over the last years. Some examples are the first observation of the decay of the isomeric 6+ states in 136,138Sn or the identification of the p3/2 proton single-hole state in 131In. Regarding in-beam g-ray spectroscopy, exciting new results from various experiments performed with the DALI2+ spectrometer consisting of NaI scintillator detectors as well as with the HiCARI array, which is based on both segmented and unsegmented Ge detectors, will be discussed. The talk will close with a glance at the exciting future perspectives in the region around 132Sn.

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Ab-initio description of monopole resonance in light- and medium-mass nuclei

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Giant monopole resonances have a long-standing theoretical importance in nuclear structure. The interest resides notably in the so-called breathing mode that has been established as a standard observable to constrain the nuclear incompressibility [1]. The Random Phase Approximation (RPA) within the frame of phenomenological Energy Density Functionals (EDF) has become the standard tool to address (monopole) giant resonances and extensive studies, mostly in doubly-closed-shell systems, have been performed hroughout the years, including via the use of so-called sum rules [2]. A proper study of collective excitations in the ab-initio context is, however, missing.

In this perspective, the rst systematic ab-initio predictions of (giant) monopole resonances will be presented [3, 4, 5]. Ab-initio Quasiparticle-RPA (QRPA) [6] and Projected Generator Coordinate Method (PGCM) [7] calculations of monopole resonances are compared in light- and mid-mass closed- and open-shell nuclei, which allows in particular to investigate the role of super uidity from an ab-initio standpoint.

Sum rules are also employed within both many-body chemes to characterize the fragmentation of the monopole strength. The study further focuses on the dependence of the results on the starting nuclear Hamiltonian derived within the frame of chiral effective field theory.

Monopole resonance represents, thus, the first step towards the investigation of higher multipolarities.
Eventually, the mid-term goal to establish PGCM as a new method to study resonances in the light- and medium-mass region of the nuclide chart will be discussed: interpretation and analysis of resonance data in lighter nuclei is a very demanding task on which ab-initio PGCM could shed new promising light.

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Electromagnetic dipole response studies at the southern tip of Africa

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 Photon Strength Functions (PSFs) and associated resonances 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 including iThemba LABS in South Africa. These range from significant increases in efficiencies of gamma-ray detector arrays, 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 presentation, I will provide an overview of the recent experimental (inverse-Oslo method [1]) and analytical (Shape method [2]) advances and how these have laid the foundation for novel and ambitious measurements at radioactive and stable ion beam facilities. Recent progress in exploring the underlying nuclear structure of resonances with a particular focus on the Pygmy Dipole resonance will also be discussed. In addition, I will introduce the low-energy nuclear physics beam line at iThemba LABS' Tandetron laboratory and the measurements of PSFs in neutron deficient isotopes.
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This work is supported by the National Research Foundation of South Africa under grant number 118840.

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Evidence for a toroidal electric dipole mode in nuclei

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A multipole expansion of electromagnetic fields shows that besides the well-known electric and magnetic terms a toroidal dipole mode must exist, where the electric current is bent on the surface of a torus (1). Such modes appear in a wide variety of fields ranging from solid-state physics, quantum and nonlinear optics, to particle physics and astronomy. A toroidal electric mode should also appear in all nuclei as response to an external dipole field, like the isovector giant dipole resonance or the isoscalar compression resonance due to nuclear density variations. Such a mode was predicted more than 50 years ago, but clear experimental evidence is lacking so far (2). Using a combination of high-resolution inelastic scattering experiments with photons (3), electrons (4) and protons (5), we identify for the first time candidates for toroidal excitations in the nucleus ^{58}Ni and demonstrate that transverse electron scattering form factors represent an unique experimental observable to prove their nature (6). While the present case refers to a nucleus with almost equal proton and neutron number, toroidal excitations might also offer an explanation for the observation of the pygmy dipole resonance at low energies in nuclei with neutron excess (7).

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Supported by DFG under contract SFB 1245 (Project ID No. 79384907)

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Shape coexistence and mixing behind the isomers of 94Pd

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The heaviest nuclei around the N = Z line offer new insights into the coexistence phenomena and the fundamental
symmetries. These exotic nuclei are of particular interest due to the open questions concerning the nature of the
observed isomers, the irregularities in the excitation spectra, and their feeding by the β decay of the neighboring nuclei. We investigated the evolution of shape coexistence and mixing in the structure of ^{94}Pd
positive parity states and the nature of the isomeric states at spin 8^+ and 14^+ within the beyond-mean-field
$complex$ Excited Vampir model using an effective interaction derived from a nuclear matter G matrix based on the
charge-dependent Bonn CD potential in a large model space. Within the same theoretical framework we studied
the Gamow-Teller β decay of the 7^+ isomer and the superallowed Fermi β decay of the 0^+ ground state of ^{94}Ag to ^{94}Pd. Results on the structure and electromagnetic properties of positive parity states
up to spin 14^+ in ^{94}Pd as well as the strength distributions for the ^{94}Ag β decay feeding the investigated states in ^{94}Pd will be discussed and compared with the available experimental data [1].

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Configuration mixing and quantum phase transitions in odd-mass nuclei around ^{100}Zr

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Configuration mixing and quantum phase transitions in odd-mass nuclei around ^{100}Zr

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Abstract

Several N = 60 isotones around ^{100}Zr show rotational structures based on a deformed ground state. The shape transition from spherical single-particle structures of the N = 50 closed-shell isotones to quadrupole deformation at N = 60 can be described in terms of Quantum Phase Transitions (QPT). Recently, calculations using the Interacting Boson Model with configuration mixing (IBM-CM) of the ground and the 2p-2h intruder states could very well describe the experimentally observed sudden (sharp) shape transition in the even-Zr isotopes going from N = 58 to N = 60 as an abrupt configuration crossing (type II QPT) [1]. The calculation revealed that the type II QPT is accompanied by a type I QPT of the intruder state as gradual spherical-to-deformed shape transition of this configuration [1]. The calculations have been extended to the odd-Nb isotopes with N = 52-64 using the IBFM-CM by coupling the $\pi(1g_{9/2})$ orbit to the Zr boson core [2]. Similarly to the even-Zr isotopic chain, the odd-Nb disclose a Type II QPT at N = 60 accompanied by a type I QPT of the intruder configuration and which is the feature of an intertwined QPT [1,2].

We are reporting on further investigation on QPTs by presenting results of γ-γ lifetime measurements of the lowest excited states in the odd ^{99}Zr and ^{99}Nb nuclei. Highly effective and precise γ-γ fast-timing experiments have been performed at the LOHENGRIN fission-fragment separator of the Institut Laue-Langevin [3]. The deduced transition rates are compared with newest calculations on ^{99}Nb within the IBFM-CM framework. Experimental results of transition rates in ^{99}Zr [3] have been used to investigate QPTs by comparing with the IBFM constructed with deformation constrained self-consistent mean-field calculations based on the relativistic Hartree-Bogoliubov model with a choice of a universal energy density functional and pairing interaction [4].

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Session 16 / 111

Investigation of γ-softness: Lifetime measurements in ^{104,106}Ru

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Lifetimes of the 2^+_1, 4^+_1, 6^+_1, 2^+_γ and 3^+_γ states in ^{104,106}Ru were measured using the recoil-distance Doppler shift technique and the Cologne Plunger device [1]. Low-lying excited states in both nuclei were populated in a ^{104}Ru(^{18}O, ^{18}O\textquotesingle)^{104}Ru* inelastic scattering and in a ^{104}Ru(^{18}O, ^{16}O)^{106}Ru two-neutron transfer reaction at the Cologne FN Tandem accelerator. The experimental energy levels and deduced electromagnetic transition probabilities are discussed in the context of γ-softness and the mapped interacting-boson model with input from the microscopic self-consistent mean-field calculation using a Gogny interaction [2]. The newly obtained results for the γ band, give a more detailed insight about the triaxial behavior of ^{104,106}Ru. The results will be discussed in the context of γ soft and rigid triaxial behavior which is present in the neutron-rich Ru isotopes [3].

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Structure of ^{50,52,53,54}Cr from inelastic neutron scattering: Implications for shape coexistence and E0 strengths

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Nuclear shape coexistence occurs when an atomic nucleus exhibits low-lying excited states with dramatically different shapes than the ground state [1]. Electric monopole (E0) transitions are a particularly sensitive probe of shape coexistence with the E0 transition strength directly related to the change in the mean square charge radius and degree of mixing between two states.

Shape coexistence in the N=28 region is poorly studied from the perspective of E0 transitions [2], but it is expected in ^{52}Cr from neutron 2p-2h excitation across the N=28 shell gap. The first E0 spectroscopy on the Cr isotopes was performed at the Australian National University [3], but insights were hampered by missing and imprecise data on the key spectroscopic quantities for the determination of the E0 transition strengths, such as level lifetimes and transition mixing ratios.

To address these deficiencies, the low-lying states in ^{50,52,53,54}Cr were investigated at the University of Kentucky Accelerator Laboratory with inelastic neutron scattering. Gamma-ray spectroscopic measurements were carried out following the scattering of quasi-monoenergetic neutrons from a natural chromium rod target. Neutron energies of 2.9 and 3.4 MeV were used to determine level lifetimes via the Doppler-shift attenuation method (DSAM), and gamma-ray angular distributions yielded transition mixing ratios and information on transition multipolarities. Excitation functions were recorded for neutron energies from 2.6 to 4.5 MeV.

We present level lifetimes, transition multipolarities, and spin-parity assignments for states in ^{50,52,53,54}Cr, along with their implications for E0 transition strengths and shape coexistence in these nuclides and this region of the nuclear chart.

This material is based upon work supported by the U. S. National Science Foundation under Grant No. PHY-2209178.

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In-beam γ-ray spectroscopy of 94Ag

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The concept of isospin has been introduced to explain the apparent exchange symmetry between protons and neutrons. However, if the nuclear force were the same for neutrons and protons properties such as excitation energies and masses would depend only on the mass number A. Naturally, the Coulomb force will break this degeneracy, although the underlying wave functions are expected to retain their isospin symmetry.

Isospin symmetry implies that states with the same isospin number T in mirror nuclei, are remarkably similar. Energy differences between mirror analog states arise from isospin-non-conserving interactions, such as the Coulomb interaction. The study of these energy differences has gathered attention in recent years [1-3 and references therein]. These studies have shown that electromagnetic effects within the shell model alone cannot explain all these energy differences, suggesting other effective isospin-non-conserving (INC) interactions are missing from current models [4].

In addition, pairing correlations have a significant importance in the description of the nuclear structure of N=Z nuclei, where protons and neutrons are arranged occupying the same orbits, allowing T=0 np pairing in addition to the normal T=1. It was recently suggested that spin-aligned T=0 np pairs dominate the wavefunction of the y-rast sequence in 92Pd [5]. Subsequent theoretical studies were devoted to probe the contribution of np pairs in other N=Z A>90 nuclei [6-7], suggesting that a similar pairing scheme strongly influences the structure of these nuclei.

In an effort to answer these questions, a recoil beta tagging experiment has been performed to try and identify the excited T=0 and T=1 states in odd-odd N=Z 94Ag using the 40Ca(58Ni,p3n)94Ag reaction. The experiment was conducted using MARA recoil separator and JUROGAM3 array at the Accelerator Laboratory of the University of Jyväskylä. The identified transitions, experimental CED and nuclear shell model predictions will be shown in this presentation. A preliminary interpretation of the experimental results will also be discussed.

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Study of the transition from single-particle to collective behaviour in Po isotopes

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Single-particle motion and nuclear collectivity are the two extremes which have shaped our understanding of the dynamics for the nuclear many-body system. A suitable region for studying the evolution of the nuclear states with the number of valence nucleons from single-particle configurations towards multiconfigurational mixture are the neutron-deficient Po isotopes in the vicinity of the doubly-magic nucleus ^{208}Pb. To fill the gap in the evolution between the states of seniority-type character in ^{210}Po [1] and those of collective nature in ^{204}Po [2], we have studied the low-lying states of the even-even ^{206,208}Po isotopes as well as the low-lying negative-parity states of ^{209}Po. The results for the low-lying negative-parity states of ^{209}Po show that the removal of one neutron from ^{210}Po does not induce any additional quadrupole collectivity. If we remove further neutrons from the closed shell, the experimental results indicate that in Po isotopes the transition from single-particle to collective excitations has a pronounced spin-dependent behaviour. The nature of the

6_1^+ and 8_1^+ states remains of the seniority-type regime and the transition to collectivity occurs at N≤120 since the structures of the 4_1^+ and 2_1^+ states of Po isotopes have already collective nature below N=124. In the present study will be summarized results from our previous studies for ^{208}Po [3] and ^{209}Po [4] as well as new results for the $B(E2; 2_1^+ \to 0_1^+)$ of ^{206}Po will be presented.

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Collectivity in Dysprosium

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As basic building blocks of matter, nuclei show some emergent collective behavior across isotopic and isobaric chains and are known to be deformed in shape in regions of the chart of nuclides away from closed shell. One mode of collective behavior is the existence of vibrational degrees of freedom superimposed on rotational and is one of the open questions in nuclear structure physics today. One method of characterizing these modes of behavior is by the measurements of lifetimes and the use of the resulting reduced transition probabilities, B($E2$) values, a measure of the collectivity connecting states. Although ^{162}Dy has been extensively studied in the past, we have examined ^{162}Dy with the $(n, n'\gamma)$ reaction and neutron energies up to 3.1 MeV to confirm known 0^+ states and provide level lifetimes through DSAM measurements to over fifty levels including both positive and negative parity level lifetimes. We will present the results of these measurements and the implications for collectivity in the rare-earth region.

This material is based upon work supported by the National Science Foundation (NSF) under grant numbers PHY-2011267, PHY-2209178, and PHY-2011890. The enriched isotope used in this research was supplied by the United States Department of Energy Office of Science by the Isotope Program in the Office of Nuclear Physics.

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Conclusion

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The nuclear physics of r-process observables

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Over five years ago the groundbreaking gravitational wave event GW170817 provided the first direct proof that neutron star mergers produce heavy elements via rapid neutron capture (r-process) nucleosynthesis. Still, the extent of the element synthesis in this environment and the role of neutron star

mergers in contributing to the galactic tally of r-process elements have yet to be clarified. Interpreting clues from r-process observables such as light curves, abundance patterns, and isotopic ratios currently suffers from large uncertainties due in part to the unknown nuclear physics of the unstable species which participate in the r-process. Here we discuss quantifications of these uncertainties and what we can learn from observables despite them. We will also consider the prospects for reducing nuclear uncertainties via advances in nuclear theory and experiments at AMS and radioactive beam facilities.

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A new technique to determine gamma emission probability above the neutron threshold without gamma-ray detectors

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Evaluation of the neutron-capture reaction rates on radioactive isotopes is still challenging. Several indirect methods have been proposed to evaluate the cross sections. We recently developed a novel technique to determine the gamma emission probabilities of the unbound states in a nucleus without detecting gamma-rays. By employing the idea of the surrogate reaction, the neutron capture reaction cross section can be evaluated with the gamma emission probability.

We applied the technique to 79Se and 130Sn to evaluate the neutron capture cross section on these nuclei. The experiment was carried out at a new beam line named OEDO which can provide the energy-degraded and focused RI beam at RIBF. The (d,p) reaction was measured in inverse kinematics and outgoing residual nuclei were also measured by the SHARAQ spectrometer in coincidence with the recoiled protons. In this talk, we will introduce the OEDO beam line and discuss the experimental result of 79Se.

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Shape evolution, mixing and coexistence around Z=30-48 studied with beyond-mean-field methods

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Nuclei in the region of the nuclear chart between Z = 28 and 50 magic numbers show a collective behavior that can be attributed to the appearance of quadrupole shape mixing and/or coexistence. Advanced energy density functional (EDF) methods, including symmetry restorations and axial and triaxial shape mixing, are the perfect tools to study these phenomena from a microscopic point of view. In this contribution I will present recent systematic calculations performed with the Gogny EDF, comparing with the available experimental data and shell model calculations. Furthermore, I will focus on specific examples of static and dynamic shape coexistence.

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Magnetic moments of microsecond isomeric states at N=59 shape transition region – nuclear alignment in abrasion-fission reaction

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Nuclear moments are an important ingredient of our knowledge and understanding of the nuclear structure far from the beta-stability line. The nuclear magnetic moments are very sensitive probes of the single particle structure of the nuclei where the investigated states provide information on valence nucleons occupancy and on configuration mixing. They can serve as a test of the purity of their nuclear wave functions and to the theoretical models predictive power.

After the discovery of a possible large amount of nuclear spin-alignment in projectile fragmentation reactions several experiments were successfully performed in the neutron-rich exotic region. A powerful method to study isomeric states is the well-known Time Dependent Angular Distribution (TDPAD) technique, usually applied to isomers produced by fusion evaporation. Isotopes produced in abrasion-fission reaction at the BigRIPS spectrometer from the RIKEN Nishina center are mainly only accessible in the present facility.

Measurement of nuclear magnetic moments of more exotic isomers requests the knowledge of the behaviour of the spin-alignment arises from abrasion-fission reactions. To bring useful data on the dependence of the amount of the nuclear spin-alignment with respect to the momentum distribution an experiment was performed at RIBF. Reaction mechanism results and magnetic moments of yrast 98mY and 99mZr states will be presented. Rapid onset of collective behaviour in the neutron-rich N=60 region will be discussed.

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Electromagnetic Dipole Response of Nuclei

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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.

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

Poster Session / 74

Linking fundamental interactions and nuclear structure via spectroscopy

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Over the past several decades, the spectroscopy of atomic nuclei provided invaluable information towards our current understanding of nature at the most fundamental level. More recent state-of-the-art experiments have placed critical bounds on beyond the standard model (BSM) physics, while also offering important benchmarks for related theoretical calculations.

This work presents recent spectroscopic studies related to the above. These include experiments to perform precision tests of isospin-symmetry-breaking in the sd-shell [1] and to benchmark ^{136}Xe neutrinoless double beta decay ($0\nu\beta\beta$) matrix element calculations [2,3]. The latter studies were extended to ^{136}Cs [4], whose nuclear structure is also important for the detection of solar/supernova neutrinos and dark-matter events in large-scale xenon detector experiments.

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Poster Session / 80

Proton optical model potential for p-process study

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The stable neutron deficient nuclei with mass number of 74<A<196 (nearly 30-35 nuclei) not produced via the s- or r- process are known as p-nuclei. Their isotopic abundances are considerably lower than the other stable isotopes of the same element. Generally accepted that s- or r- isotopes are serves as seed nuclei for the p-nuclei production.
In the stellar explosive site, the series of (γ,n) reactions on s- and r- seed nuclei synthesized the proton rich stable isotopes. Hence the neutron separation energy is increasing and at the same time the proton and alpha separation energy is decreasing, then (γ,p) and (γ,α) reactions starts to play an important role for p-nuclei production.
The γ-disintegration reactions by gamma-beam is difficult to perform in laboratory and hence it can be studied from inverse reactions by the principle of detailed balance. Investigation of the Experimental charge particle capture reactions with the theoretical prediction one have to use the Hauser-Feshbach statistical model.
The choice of proton optical model potential is one of important input parameters for Hauser-Feshbach

calculation. In this work, the published proton elastic scattering on the p-nuclei in the energy near coulomb barrier were studied for obtaining proton optical potential. ^{76}Se, ^{86}Sr, ^{92,94}Mo, ^{104}Pd, ^{106,108}Cd, ^{115}In, ^{112,116}Sn, ^{134}Ba, ^{148}Sm, ^{171}Yb nuclei were used. Optical potential search code SFRESCO was used to calculate the Wood-Saxon proton potential.

Poster Session / 109

Nuclear data for basic sciences and applications

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Up-to-date recommended nuclear data are key to new and successful developments in basic research and applications. In this paper we present international efforts to collect and assess available experimental data with the goal to provide recommended data. We discuss trends observed through systematic comparisons of the data and present online databases with versatile retrieval interfaces and web APIs developed at the IAEA.

Poster Session / 85

Quantum computing with schematic nuclear models

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A quantum simulation of the Agassi model from nuclear physics is proposed so as to be implemented within a trapped-ion quantum platform [1]. Numerical simulations and analytical estimations illustrate the feasibility of this simple proposal with current technology, while our approach is fully scalable to a larger number of sites. The use of a quantum correlation function is studied as a signature of the quantum phase transition by quantum simulating the time dynamics, with no need of computing the ground state. The use of machine learning procedure to determine the quantum phase diagram of the model is also explored [2].

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Session 2 / 94

Nuclear structure calculations with the projected generator coordinate method

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The Generator Coordinate Method (GCM) provides a general framework to give variational solutions to the many-body problem. It is based on the definition of the variational trial wave functions as the linear mixing of different intrinsic configurations defined along the so-called generating coordinates. This beyond-mean-field method can give ground and excitation energies, decay probabilities, and interpretations of the results in terms of collective and single-particle degrees of freedom. In nuclear physics, the most common (and involved) realizations of the GCM formalism nowadays is the mixing of symmetry-restored (particle-number, parity and angular momentum projected) intrinsic quasi-particle states obtained from self-consistent mean-field calculations, the so-called Projected-GCM (PGCM).

In this contribution I will show some recent results obtained with the PGCM method that can be compared with experimental data (shape evolution/coexistence/mixing in atomic nuclei, weak decays nuclear matrix elements, etc.).

Poster Session / 95

On the missing yield of in-beam radiative proton-capture cross section measurements relevant to the p process

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The p process nucleosynthesis is responsible for the creation of around 35 low-abundant nuclides which lie in the neutron-deficient side of the isotopic chart [1]. The modeling of the p process consists of around 20,000 reactions involving around 2,000 nuclides, including photodisintegration reactions such as (γ,p), (γ,a) and (γ,n). Their inverse reactions, related by the reciprocity theorem, can be studied in accelerator facilities to estimate relevant reaction rates. Thus, accurate cross section measurements of radiative-capture reactions inside the astrophysically relevant energy range (Gamow window) are particularly important for the estimation of the corresponding reaction rates in stellar environments. One of the methods, called the in-beam angular distribution method [2,3] has been extensively used for the determination of such cross sections. While the method provides a very good means of measuring the cross sections, transitions that are beyond the detection limit of each setup are not considered in the analysis, which results in a missing yield on the final value of the measured cross section. In this work, an attempt to quantify this missing yield is presented using the FIFRELIN code [4] for the reaction 112Cd(p,γ)113In [3]. FIFRELIN employs a Monte Carlo Hauser-Feshbach framework based on Bečvár's algorithm [5] and is able to model the de-excitation of every isotope from an initial excitation energy and provide an estimate for both the discrete and the continuous part of the de-excitation spectrum. The corrected results are compared with results measured by the more accurate activation method [6].

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Poster Session / 100

Odd-even splitting in scissors bands

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The rotational band based on the scissors mode is investigated by an angular-momentum-projected method, which introduces the scissors degree of freedom by projecting protons and neutrons independently. An odd-even splitting of the rotational energy is found as a characteristic feature of these bands, which can be amplified by mixing with K=1 two-quasiparticle excitations. The odd-even splitting found here provides a quantitative explanation for the observed 2+ member of the scissors band in 156Gd, which stays unexpectedly close to the 1+ band head. The splitting in the scissors band can be attributed to the flipping of the rotational axis between odd and even spins, as well as the signature splitting of the two-quasiparticle band mixed with it.

Poster Session / 105

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

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Determination of the true feeding intensities (Iβ) 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 effi- ciency, is an ideal spectrometer to determine not only the true β feeding intensities free from Pande- monium 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 107Tc and 107Mo, which have incomplete data in current nuclear dataset, is determined experimentally using MTAS. We found the Pandemonium Effect in the β-decay measurements of 107Tc and 107Mo. 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 107Tc and 107Mo towards lower energy.

Session 3 / 126

The ISOLDE Decay Station: recent activities and perspectives

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

Following the end of the CERN Long Shutdown 2 development campaign, ISOLDE has resumed the experimental campaign in June 2021 and implemented a major upgrade for the support structure of the detectors in April 2023. There have been several new decay spectroscopy experiments performed at IDS that will be highlighted in the current presentation, including the May 2023 fast-timing campaign, alongside a detailed description of the setup and future development plans.

Session 8 / **127**

Cross section measurements for Nuclear Astrophysics using the Trojan horse method

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I discuss the basic concepts of the Trojan Horse Method in nuclear astrophysics and the opportunity it offers to determine the cross sections of various stellar burning reactions when it is difficult to perform the corresponding direct measurements. I will focus on recent results to investigate carbon burning and primordial nucleosynthesis.

Session 4 / **157**

Triaxiality and shape coexistence as basic modes of collective bands of heavy nuclei.

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Many of deformed heavy nuclei, such as 166Er and
their neighbors in the nuclear chart, are shown to have
triaxial ground and gamma bands with gamma equal to about
10 degrees, with gamma stretching in the gamma bands.
Some other nuclei, like 154Sm, show prolate ground bands,
but their side bands are produced by the shape coexistence of

triaxial shapes with gamma equal to about 15 degrees.
Monopole interactions containing tensor force contributions are essential for these structures. If time permits, M1 excitations from these ground states may be discussed, with a possible mode specific to triaxial ground states.
The calculated results are obtained by the advanced version of the Monte Carlo Shell Model (MCSM), called the Quasiparticle Vacuua shell model.

Session 15 / 151

Neutron captures in the stellar slow and rapid process regimes probed in the laboratory

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eutron capture experiments in the laboratory help us understanding the stellar production of heavy elements in nature. Measurements of capture cross sections in the stellar slow (s-) process energy regime were measured for neutrons produced by the 7Li(p,n)7Be reaction with the high-intensity Liquid-Lithium Target (LiLiT) at the Soreq Applied Research Accelerator Facility (SARAF, Israel). The NIF (National Ignition Facility) at Lawrence Livermore National Laboratory (USA) produces a neutron field with a density well into that of the rapid (r-) process regime by imploding a DT-filled capsule with high-power lasers. First experiments performed recently will be described.

Session 13B / 50

Half-life determination of isomers produced by spontaneous fission of 252Cf using the VESPA setup

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At EC-JRC Geel, the VESPA setup [1], made of a position-sensitive double Frisch-grid ionization chamber surrounded by $\mathrm{LaBr_3}$(Ce) scintillation detectors, is dedicated to multi-parameter measurements on ^{252}Cf(sf). The fission process generates highly excited nuclei. These nuclei will dissipate their excitation energy and angular momentum through the emission of neutrons, photons and conversion electrons. During this de-excitation process, they may populate an isomeric state characterized by its half-life.
Using five $\mathrm{LaBr_3}$(Ce) detectors, several gamma-ray transitions, originating from isomeric states, were detected and their associated half-lives were measured. As lanthanum-bromide detectors are fast scintillators [2], they are well suited to perform such measurements. However, many gamma rays are emitted during the fission process, and the resolution of such scintillators is not sufficient to discriminate background from the gamma rays of interest. Thus, coincident γ-γ events were considered in order to lower the background.
The identification of the emitting nuclei was performed using the mass information that is obtained from the ionization chamber signals, together with the spectral characteristics of the gamma rays,

namely their energy and time distribution relative to fission. In the end, the half-life of several isomeric states were measured, including the 830.83 keV state of ^{97}Sr, where previous measurement lead to discrepant data [3]. The range of measured half-lives in this work goes from a few nanoseconds up to a few microseconds.

Session 3 / 83

Intertwined quantum phase transitions in odd-mass Nb isotopes

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Structural changes induced by variation of parameters in the Hamiltonian, called quantum phase transitions (QPTs), are currently a topic of great interest in nuclear physics. In this field, most of the experimental and theoretical attention has been devoted to the evolution of structure with nucleon number, exhibiting two types of phase transitions. The first, denoted as Type I, is a shape-phase transition within a single configuration, as encountered in the neutron number 90 region [1]. The second, denoted as Type II, is a phase transition involving a crossing of different configurations, as encountered in nuclei near (sub-) shell closure [2]. If the mixing between configurations is small, the Type II QPT can be accompanied by a distinguished Type I QPT within each configuration separately. Such a scenario, referred to as intertwined QPTs, was recently shown to occur in the $^{92-110}$Zr (Z=40) isotopes [3,4].

QPTs have been studied extensively in even-even nuclei, but far less in odd-even nuclei due to their complexity. For the latter, fully microscopic approaches, such as the large-scale shell model and beyond-mean-field methods, are computationally demanding and encounter difficulties. Alternative approaches involving particle-core coupling schemes, employing algebraic modeling and density functionals-based mean-field methods, have been proposed. So far these approaches were restricted to Type I QPTs in odd-mass nuclei without configuration mixing. In the present contribution, we present a general Bose-Fermi framework for studying spectral properties, QPTs and coexistence phenomena in odd-mass nuclei, in the presence of configuration mixing [5]. An application to the $^{93-105}$Nb (Z=41) isotopes, discloses a Type I QPT (gradual evolution from spherical to deformed core shapes and transition from weak to strong coupling within the intruder configuration), superimposed on a Type-II QPT (abrupt crossing of normal and intruder configurations). The pronounced presence of both types of QPTs demonstrates the occurrence of intertwined QPTs in odd-mass nuclei. This work done in collaboration with N. Gavrielov (Yale, HU) and F. Iachello (Yale).

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