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The Many Facets of Nuclear Structure

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BOOK OF ABSTRACTS

INVITED TALKS

The routes towards the ”island of stability” – nuclear structure and synthesis

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Sign posts indicating the routes from the deformed nuclei in fermium-nobelium region towards the expected spherical species expected for the next closed proton and neutron shells beyond ^{208}Pb are nuclear structure features like *K* isomers or the single-particle structure probed, in particular, by unpaired nucleons in odd nucleon isotopes [1]. Synthesis methods alternative to the classical fusion-evaporation reaction, like multi-nucleon transfer (MNT) might promise access to the more neutron-rich region of those spherical superheavy nuclei (SHN) [2].
K isomers found in the region of the heaviest nuclei were typically meta-stable states of even-even isotopes like e.g. the first one, ^{254}No [3], or the heaviest ones, ^{266}Hs [4] and ^{270}Ds [5]. More recently, cases for even-odd and odd-even nuclei have been reported with e.g. ^{255}Rf [6], ^{255}No [7] and ^{249,251}Md [8], respectively. While for the even-even isotopes often 2-quasi-particle excitations across a shell gap lead to high K numbers, the meta-stable states in odd-mass nuclei are formed as 3-quasi-particle states where high K values are produced by 2-quasi-particle excitation coupled to the odd unpaired nucleon. No high-K isomer has yet been assigned to odd-odd nuclei in this region, possibly providing interesting quasi-particle configurations. Nuclei in the vicinity of shell gaps like ^{254}Lr and ^{258}Db [9], lying close to Z=100 and N=152 and having access to high-spin single-particle states (SPS), would be interesting candidates. The observation of low excitation energies for SPS, are observed to contradict theoretical predictions for SHN shell gaps, like in the case of the ^{247}Md → ^{243}Es decay [10].
Detailed nuclear structure of the heaviest nuclei as well as the synthesis of SHE are presently still hampered by the limited efficiencies of the existing experimental facilities. To overcome this restriction, various facilities promising highest beam intensities are presently coming online, like the SHE factory of FLNR/JINR in Dubna, Russia, delivering first promising results, or are under construction/commissioning like the linear accelerator facility SPIRAL2 at GANIL in Caen, France [11,1], equipped with the versatile separator spectroscopy set-up S3 [12].
As an alternative approach to the classical fusion-evaporation method, multi-nucleon transfer reactions, employing heaviest target and projectile combinations, are presently being discussed. As an attempt to populate neutron-rich actinide isotopes in the uranium region, we started to investigate the reaction ^{238}U+^{238}U at the combination GANIL's high-acceptance magnetic spectrometer VAMOS in combination with the highly efficient and highly granular germanium detector array AGATA and an additional x-ray detector array (ID-fix) in 2021.

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Covariant energy density functionals: physics content and performance improvement

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Ongoing studies of nuclear energy density functionals (NEDFs) are focused both on better understanding of their physical content and improving their global performance. Several studies of covariant energy density functionals (CEDF) have been performed by us within the framework of covariant density functional theory. They were dedicated to the understanding of parametric correlations between the parameters of CEDFs [1], systematic and statistical uncertainties in the description of physical observables [2,3] and the ways to improve their global performance in particle-particle (pairing) and particle-hole channels [4,5]. In the talk, brief review of early developments will be presented, and the major focus of the talk will be on the latter two issues. The results of in-progress studies will also be presented.

A systematic global investigation of pairing properties based on all available experimental data on pairing indicators has been performed for the first time in the CDFT framework in Ref. [4]. It is based on the separable pairing interaction of Ref. [6]. The optimization of the scaling factors of this pairing interaction to experimental data clearly reveals its isospin dependence in the neutron subsystem. However, the situation is less certain in the proton subsystem since similar accuracy of the description of pairing indicators can be achieved both with isospin-dependent and mass-dependent scaling factors. For a given part of the nuclear chart the scaling factors for spherical nuclei are smaller than those for deformed ones; this feature exists also in nonrelativistic density functional theories. Its origin is traced back to particle-vibration coupling in odd-A nuclei which is missing in all existing global studies of pairing. Although the present investigation is based on the NL5(E) CEDF, its general conclusions are expected to be valid also for other CEDFs built at the Hartree level.

The absolute majority of the NEDFs are fitted to experimental data in spherical nuclei. This represents a significant limitation since improving the penalty function in such fitting protocols leads to the reduction of the accuracy of the description of physical observables on the global scale. This is a consequence of the neglect of the information on deformed and transitional nuclei. A new anchor-based optimization method of defining the NEDFs is proposed by us in Ref. [5] which circumvents this problem and numerical cost of which remains relatively low. This approach leads to a substantial improvement in global description of binding energies for several classes of CEDFs.

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First physics results from DESPEC experiments in FAIR Phase-0

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The DESPEC experiment [1] is part of the NUSTAR (NUclear STructure, Astrophysics and Reactions) collaboration, which represents one of the four pillars that comprise the scientific program for the FAIR accelerator facility currently under construction in Darmstadt, Germany. The DESPEC setup will be installed at the focal plane of the future Superconducting FRagment Separator (Super-FRS), the central device of the NUSTAR experiments, where exotic ions from across the nuclear chart will be produced in projectile fragmentation reactions and delivered with event-by-event identification. The ions will then be implanted into a stack of detectors at the core of the DESPEC setup, where subsequent decay radiation will be detected, thus yielding information about the underlying nuclear structure.

As part of the FAIR Phase-0 program, the first physics commissioning of the DESPEC setup was carried out in early 2020 at GSI, where excited states in ^{94,96}Pd and ^{94}Ru (among others) close to doubly-magic ^{100}Sn were measured [2,3]. A full campaign comprising three experiments followed in 2021, wherein the prolate-oblate shape transition at A~190, quadrupole and octupole deformation in 220<A<230 Po-Fr nuclei [4], and ^{100}Sn core-breaking contributions in ^{102,103}Sn were investigated via fragmentation of ^{208}Pb, ^{238}U and ^{124}Xe, respectively. A further campaign comprising two experiments was performed in 2022 to investigate the region close to N=126 via high-resolution spectroscopy with the DEGAS array of HPGe detectors and high-efficiency beta-strength measurements with the DTAS total-absorption gamma-ray spectrometer.

This talk will provide details of the physics goals, first results of the program and an overview of the future plans leading to the start of FAIR operations.

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Shape effects and the search for pn pairing in the A=70 region

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In this talk I will present recent results of beta decay studies of the near drip line ^{70,71}Kr nuclei. The mass region around A=70 is considered of particular interest from the perspective of shape effects, configuration mixing, pn pairing in the T=0 channel and isospin symmetry (see [1,2,3] and references therein).

The larger production of the nuclides of interest at the RIKEN RIBF facility and the higher experimental sensitivity of the setup employed, allowed us to obtain a richer experimental information on the beta decay of ^{70,71}Kr [4,5] compared to previous studies.

In the beta decay of ^{70}Kr into ^{70}Br, fifteen gamma rays have been identified for the first time, defining ten populated states (previously no excited levels were known from the beta decay) [4]. One particular result in this case is an increase in the beta strength to the yrast 1+ state in comparison with the heaviest Z=N+2 system studied so far (^{62}Ge decay) [6,7] that may indicate increased np correlations in the T=0 channel.

Similarly in the beta decay of ^{71}Kr to ^{71}Br nine new levels have been identified preliminarily [5] solving some inconsistencies observed in the past [8].

The new results will be presented and discussed from the perspective of model calculations (QRPA and a pseudo-SU(4) model) [9,10].

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Recent highlights and perspectives for Nuclear Astrophysics at LUNA

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The Laboratory for Underground Nuclear Astrophysics, LUNA, located under the Gran Sasso Mountain in Italy, provides the ideal environment for nuclear reaction studies of astrophysical interest thanks to a millionfold reduction in the cosmic ray induced background compared to surface laboratories.

Since its first installation, almost 30 years ago, LUNA has allowed for pioneering measurements of key reaction cross sections at the lowest achievable energies, often for the first time. Studies of hydrogen burning reactions in the pp-chain, the CNO cycles, and NeNa-MgAl cycles have led to major improvements in our understanding of nuclear processes in various stellar environments, from our Sun, to Asymptotic Giant Branch stars and classical novae, and during Big Bang nucleosynthesis (see [1] a recent review).

In this talk, I will present an overview of past and recent achievements and highlight future opportunities to further explore the inner working of stars.

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Investigation of nuclear structure with resonant photon scattering at the HIγS facility

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Photon beams are a highly selective probe of the charge and current distributions of nuclei. The specific spin selectivity and strength sensitivity of this probe enables an almost model-independent spectroscopic study of dipole excitations at energies up to the particle emission threshold and investigations of the collective response of the internal degrees of freedom of the nucleus. In this talk, recent developments and experimental results obtained from photonuclear reactions with nearly-monoenergetic, polarized photon beams from the HIγS facility at TUNL will be presented and compared with those obtained with hadron-induced reactions.

Highlights from MUGAST and MUST2 campaigns at GANIL

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The MUGAST highly segmented silicon array [1] has been developed for the study of direct reactions induced by radioactive-ion beams by means of the combined detection of light charged particle and gamma-rays. A serie of experiments was performed on the VAMOS beam line at GANIL in which MUGAST was integrated into a 1π configuration of the AGATA array installed at VAMOS. The setup included the new ^{3,4}He target HeCTOR [2] developed at IJCLab. With this system, reactions of various interest for nuclear structure as well as astrophysics could be studied, of which I will present a survey. I will also present recent results obtained using the MUST2 array combined with the CRYPTA[3] cryogenic proton target.

A new version of the MUGAST array, is currently being integrated into the EXOGAM gamma detector at the LISE beam line of GANIL in view of forthcoming campaigns.

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Measuring the Impact of Nuclear Interaction in Particle Therapy and Radio Protection: the FOOT experiment

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Charged Particle Therapy is a highly effective method for treating deep-seated tumours, based on the energy loss pattern of charged particles, characterized by the Bragg peak at the end of range: the dose delivered to healthy tissues surrounding the tumour is therefore minimized. Beam-tissue nuclear interactions, though, produce low-energy, short-range nuclear fragments with a high Linear Energy Transfer (LET), that cause unwanted damage. In case of ion beams, projectile fragmentation produces longer-range fragments that release dose also in healthy tissues after the tumour. The same nuclear process is of increasing interest for radiation protection in human space flight, in view of deep space missions. Measuring differential fragmentation cross sections for beams (^{12}C, ^{16}O, etc.) of 200-400 MeV/u on graphite and polyethylene targets is the main goal of the FOOT (FragmentatiOn Of Target) experiment. Thanks to an inverse kinematics approach, the detection of beam fragments is possible and, by inverting the reference system, the data will provide an invaluable input to transport codes used for treatment planning and shielding simulations, thereby improving the accuracy of their predictions. FOOT aims at measuring differential cross sections with ~5% uncertainty with a portable setup that will collect experimental data in various facilities. The present status of the development and performance of its detector components will be discussed during the talk.

Insight into fission from the gamma probe: Going beyond current status with PARIS@VAMOS

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Fission corresponds to one of the most dramatic examples of a nuclear decay whereby a nucleus splits into two so-called fragments of about equal size. It plays a major role also in astrophysics and for many industrial and societal applications, like by example energy production, transmutation of nuclear waste, and medicine. Particularly crucial for both fundamental science and applications are the properties of the produced fragments, and their prompt decay by emission of neutrons and gamma-rays.

In the talk I will present recently performed an innovative experiment dedicated to the energetics of fission of a typical actinide, ^{247}Cm, at the GANIL facility in France. The coupling of the new-generation PARIS gamma-array with the powerful VAMOS++ heavy-ion spectrometer, made available in our experiment for the first time a rich set of observables. This include properties like: mass A, charge Z and kinetic energy E_{kin} of one of the fission fragments with unique precision, and approximate corresponding properties of its fragment partner, moreover we collected high-precision data of their decay by photon emission over the essentially whole gamma-ray energy dynamical range, as well as information on their cooling by neutron evaporation. The online preliminary insights of very encouraging experimental results will be presented.

Constraints on the nuclear EoS from nuclear structure and reactions

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Recent results connected to nuclear collision dynamics, from low up to intermediate energies, will be reviewed. Direct reactions can carry important information on yet unknown aspects of the nuclear effective interaction, relating for instance to the excitation of isospin and spin-isospin modes. On the other hand, dissipative heavy ion reactions offer the unique opportunity to explore, in laboratory experiments, transient states of nuclear matter under several conditions of density, temperature and charge asymmetry, thus allowing one to probe its Equation of State [1].

Transport models are an essential tool to undertake the latter investigations and make a connection between the nuclear effective interaction (and EoS) and sensitive observables of experimental interest. Comparisons of predictions of different approaches will be considered, to assess the robustness of the deduced constraints [2,3]. This analysis can be combined with recent investigations of the nuclear EoS in the context of nuclear structure and astrophysical scenarios.

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Activities and perspectives in nuclear astrophysics at TRIUMF

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TRIUMF hosts the Isotope Separator and ACcelerator (ISAC) facility which is a radioactive ion beam facility of the isotope separation on-line (ISOL) type. Rare isotopes are produced by spallation and fragmentation reactions in the ISAC production targets which are impinged by 500 MeV proton beams with up to 100 μA of current.

The radioactive beam production facilities at TRIUMF have been undergoing a major expansion over the past decade. The Advanced Rare IsotopE Laboratory (ARIEL) provides a new high-power superconducting electron linear accelerator (e-linac, up to 35 MeV, 10 mA, 350 kW) and the associated infrastructure. In 2026 and 2027, the parallel operation of the existing ISAC 500 MeV, 100 μA proton beamline, the high-power ARIEL e-linac photofission driver, and a second proton beamline to the ARIEL target stations, will establish a unique multi-user capability that will provide first two, and then three simultaneous radioactive beams, ultimately tripling the beamtime available to the suite of state-of-the-art research infrastructure at ISAC.

I will give an overview about the present experiments with astrophysical focus installed at the ISAC facilities and outline some recent results. Some future plans for experiments will be presented, including the proposed TRIUMF Storage Ring facility to perform direct neutron capture cross section measurements on short-lived nuclei.

Interplay between reaction dynamics and nuclear structure of light exotic beams

Alessia Di Pietro
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The region of the nuclear chart corresponding to light radioactive nuclei has, over the years, yielded many surprising results, among others the discovery of the halo structure in neutron and proton dripline nuclei. This region of the nuclear chart is also rich of many other phenomena like the appearance of molecular-like structures where α–particle-clusters are bound together by the exchange of neutrons or the existence of cluster configurations where at least one of the clusters is a weakly bound nucleus.

The availability of post-accelerated radioactive ion beams has opened the opportunity to study nuclear structure and reactions of such peculiar nuclei. Moreover, to be able to describe the physics observables extracted from experiments, state-of-the-art theory has to be used to advance our understanding of the nuclear structure and reaction dynamics. In this talk an overview of some of the new phenomena involving light exotic RIBs will be given and future perspectives discussed.

Indirect Measurements as a Probe of Explosive Nuclear Astrophysics

Daniel Doherty
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Despite significant advances in recent years, particularly with the advent of space-based telescopes significant questions remain concerning the production of chemical elements across our Galaxy. A number of broad, open questions relating to explosive nucleosynthesis remain due to the large uncertainties that currently exist in the underlying nuclear physics processes and reactions that drive these explosive events.

As these reactions often concern radioactive species relatively few have been studied directly in terrestrial laboratories and, therefore, indirect approaches are mandated. In this talk, I will describe some of the recent gamma-ray spectroscopy and charged-particle transfer studies that have been performed by the Surrey Group in recent years which cover a range of stellar phenomena. I will also mention some upcoming projects that take will take advantage of new opportunities at the latest radioactive-ion beam facilities.

Fine-structure energy scales of the IVGDR in the neodymium isotope chain

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High energy-resolution proton inelastic scattering experiments with E_p = 200 MeV were performed on $^{142, 144, 146, 148, 150}$Nd and ^{152}Sm in the excitation-energy region of the Isovector Giant Dipole Resonance (IVGDR) using the zero-degree mode of the K600 magnetic spectrometer at iThemba LABS. The effect of deformation on both the broad and the fine structure of the IVGDR in the rare-earth region was investigated. A goal of the present study was to extend, for the first time, the IVGDR measurements on these isotopes to high energy-resolution and confirm the *K*-splitting observed in previous photo-absorption measurements. Although the applicability of the low energy-resolution photo-absorption data to the present study is limited to broad structure comparisons only, techniques based on the continuous wavelet transform have been implemented in order to perform a fine-structure analysis on the high energy-resolution data obtained in the present study. Characteristic energy scales have been extracted from the experimental data and compared to those extracted from state-of-the-art theoretical predictions of the corresponding $B(E1)$ strength functions. The conclusions of these comparisons will be presented.

Towards precision nuclear physics from chiral EFT

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Chiral effective field theory is being advanced to a precision tool for analyzing few-nucleon systems, see [1,2] for review articles. I will outline the foundations of this theoretical framework, review state-of-the-art in the field and discuss selected recent and ongoing applications along this line.

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Recent applications of the Subtracted Second RPA for nuclear soft modes

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The subtracted second random-phase approximation, based on Skyrme functionals, is employed to investigate nuclear excitations. First of all, the Gamow-Teller resonances are studied in several nuclei, located in different regions of the nuclear chart [1,2]. The amount of Gamow-Teller strength is considerably smaller than in other energy-density-functional based calculations and agrees better with the experimental data. These important results, obtained without any *ad hoc* quenching factors, are due to the inclusion of two-particle–two-hole configurations. Their density progressively increases with excitation energy, leading to a long high-energy tail in the spectrum. This result may have implications for the computation of nuclear matrix elements for neutrinoless double-beta decay in the same framework. The same model is then applied for the study of low-lying energy excitations in the dipole [3] and monopole [4] channels. Their differences and analogies are discussed in terms of the isospin asymmetry and their impact on the equation of state is also investigated.

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Collectivity and Shape Coexistence in the Zr isotopes

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The Zr isotopes near N=60 present a fascinating laboratory in which to study shape coexistence. Proceeding from N=58 ^{98}Zr to N=60 ^{100}Zr, the excitation energy of the 2_1^+ states undergoes a dramatic drop, and a large decrease is also observed for the 0_2^+ state. This trend in the excitation energy has been linked with shape coexistence, with the configuration corresponding to the "deformed" 0_2^+ state in ^{98}Zr believed to become the ground state in ^{100}Zr, and the "spherical" configuration for the ground state of ^{98}Zr becoming an excited state in ^{100}Zr. The evidence supporting this view was provided through enhanced r^2(E0) values for $0_2^+ \rightarrow 0_1^+$ transitions (for a review, see Refs. [1,2]). Moreover, the recent determinations of B(E2) values for the 2_3^+®0_2^+ transitions in deformed excited bands in ^{94,96}Zr [3,4] demonstrated that shape coexistence persists in the lighter Zr isotopes. The trends of the ground and 2_1^+ state properties were reproduced well by Monte-Carlo Shell Model (MCSM) calculations, which also suggested that multiple shape coexistence occurs in the Zr isotopes and linked it to the so-called type-II shell evolution mechanism [5], i.e., reorganization of nuclear shells due to specific proton and neutron occupations.

We have pursued studies of the Zr isotopes along multiple fronts, including Coulomb excitation and b decay. Building on our successful b-decay study of ^{94}Zr [3], we have performed measurements of the b decay populating ^{96}Zr, ^{98}Zr, and ^{100}Zr using the 8p and GRIFFIN g-ray spectrometers at the TRIUMF-ISAC facility. These studies enabled the collection of very high levels of statistics, providing sensitivity to weak, low-energy g-ray decay branches that are needed to assign firmly the rotational-like bands. From our data for ^{98}Zr, for example, we can confirm the band built on the 0_2^+ state [1] and differentiate between the structural interpretations presented in Refs. [6,7]. Congruently, we have also studied the even-even stable Zr isotopes via Coulomb excitation using ^{12}C and ^{16}O beams and the Q3D magnetic spectrograph of the Maier Leibnitz Laboratory of the Technical University and Ludwig-Maximilians University Munich. These measurements have enabled us to extract systematically not only B(E2;$0_1^+ \rightarrow 2_i^+$) values, but also the $0_1^+ \rightarrow 3_1^-$ E3 strengths, solving some long-standing questions of the trend observed for the latter.

The results from these studies will be presented in the context of shape coexistence in the region, with a focus on the evolution of both quadrupole and octupole collectivity in the Zr isotopes.

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Proton emission imaging with ACTAR TPC

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

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Nuclear physics uncertainties in the production of superheavy elements in neutron star mergers

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The rapid neutron capture process, or r process, is responsible for the production of about half of the elements heavier than iron found in nature, including the heaviest uranium and thorium [1, 2]. During the r process, several thousands of neutron-rich nuclei are synthesized in few seconds, powering an electromagnetic transient known as kilonova. Since most of such exotic nuclei have never been experimentally observed due to their exceedingly short half-lives, the estimation of abundances and kilonova light curves must rely upon the theoretical predictions of nuclear properties [3, 4].

During this talk, I will present calculations of nuclear properties and stellar reaction rates obtained within the energy density functional (EDF) framework. Several EDF parametrizations have been employed in order to asses the impact of systematic uncertainties in the r process nucleosynthesis. In particular, I will focus on the nucleosynthesis of translead elements in the merger of two neutron stars, and the role that nuclear masses, beta decays and fission play in shaping the r-process abundances and kilonova light curves [5].

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Ab initio prediction of $\alpha(d,\gamma)^6Li$ at BBN energies

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The radiative capture $\alpha(d,\gamma)^6Li$ is the dominant process in the Big Bang Nucleosynthesis (BBN) of ^6Li. It therefore strongly influences the abundance ratio of $^6Li/^7Li$, for which observational data are three orders of magnitude higher than BBN predictions. Because of the low cross section and the large experimental uncertainties, it is crucial to have accurate predictions. In this talk, I will present an *ab initio* calculation of $\alpha(d,\gamma)\,^6Li$, where all nucleons are active and interacting through chiral-EFT nucleon- and three-nucleon forces. After reviewing the *ab initio* no-core shell model with continuum method, I will show our results [1] which are in excellent agreement with the recent LUNA data [2]. I will also discuss the importance of each electromagnetic transitions on $\alpha(d,\gamma)\,^6Li$ at BBN energies.

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Nuclear structure studied via precision mass measurements at JYFLTRAP

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High-precision mass spectrometry provides important information on nuclear structure and how it evolves far from stability. The JYFLTRAP double Penning trap mass spectrometer at the Ion Guide Isotope Separator On-Line (IGISOL) facility has been utilized for mass measurements of around 350 ground-state masses and more than 60 long-lived isomeric states. In this talk, I will discuss recent highlights from JYFLTRAP. Ground and isomeric states in neutron-rich odd-odd rhodium isotopes have been studied with the phase-imaging ion cyclotron resonance (PI-ICR) technique and compared to the BSkG1 model predictions for these deformed nuclei [1]. Isomeric states in neutron-rich silver and indium [2] isotopes have also been recently studied at JYFLTRAP. Mass measurements close to ^{78}Ni [3] have given a quantitative estimation of the quenching for the N=50 neutron shell gap. In addition to nuclear structure, the measurements have provided important data for core-collapse supernova dynamics as well astrophysical r-process calculations.

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Shape coexistence and electromagnetic moments/transitions

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In neutron-rich nuclei, the quenching of the neutron shell gap induces the shape coexistence in their excitation spectra. We discuss how the shape coexistence are reflected in the electromagnetic properties. As an example, we discuss the N=28 nuclei (^{44}S, ^{42}Si and ^{40}Mg) and an N=20 nucleus ^{33}Al.

In nuclei neighboring ^{42}Si, different nuclear shapes coexist: The rigid shapes with different deformations coexist in ^{40}Mg and ^{42}Si, while ^{44}S exhibits large-amplitude collective motion and does not have rigid shape. These characteristics are reflected well in the monopole transition strengths.

For ^{33}Al, it is shown that the observed electromagnetic moments of the ground state are well reproduced if we assume the strong mixing of the spherical and deformed states. Furthermore, It is demonstrated that the ratio of the electromagnetic transition probabilities in an almost model-independent manner.

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The Nuclear Two-Photon Decay to study 0^+ Shape Isomers

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Shape coexistence occurs when the potential energy surface of the nucleus exhibits several minima as function of different degrees of deformation. Excited 0^+ states at low excitation energy are a clear indication of this phenomenon, but their existence can be hard to establish, in particular when they are the first excited state and below the pair-creation threshold of 1.022 MeV. Since a direct $0^+ \rightarrow 0^+$ decay cannot proceed via the emission of a single gamma ray, the only possible decay mode is internal conversion, which is often difficult to perform in-beam measurements. A typical example is the case of ^{72}Kr, for which it took more than 30 years between first speculations of shape coexistence and the confirmation of the existence of a 0^+ isomer by conversion electron spectroscopy [1]. Alternatively, low-lying excited 0^+ states can also be observed as fine structure in alpha-decay measurements, such as the famous triple shape coexistence observed in ^{186}Pb [2].

We have performed a pilot experiment at the GSI experimental storage ring (ESR) to establish a new technique to search for low-lying 0^+ isomers. The nuclei of interest are created in reactions at relativistic energies and completely stripped from their atomic electrons. Therefore, all first-order electromagnetic decays of a $0^+ \rightarrow 0^+$ transition (i.e. gamma decay, internal conversion, and pair creation if below 1.022 MeV) are forbidden and the 0+ state becomes a long-lived isomer, which can be stored in the ESR. The only possible electromagnetic decay is the simultaneous emission of two gamma rays, with individual energies adding up to the excitation energy of the excited state. This very rare decay was so far only observed in a handful of nuclei, but with excited 0^+ states at energies well above 1 MeV [3,4]. I will discuss the preliminary results of our experiment, in which we observed for the first time the nuclear two-photon decay of the low-lying 0^+ isomer in ^{72}Ge, as well as our future plans.

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

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

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

In this contribution, a dedicated setup for the implantation of a francium/radium/actinium-229 beam into large-bandgap crystals and the vacuum-ultraviolet spectroscopic study of the emitted photons will be presented. From the results obtained during a first measuring campaign using MgF_2 and CaF_2 crystals as host material it can be concluded that the radiative decay of the thorium-229 isomer has been observed for the first time, the excitation energy of the isomer has been determined with a factor of 5 improved uncertainty.

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Experiments for constraining

r-process neutron capture rates

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We live in a very exciting time, as we come closer and closer to unravel the mysteries of how half of the elements heavier than iron has been made in the Universe. A major breakthrough was achieved in 2017, when the electromagnetic transient, a “kilonova”, was measured following a neutron star collision, confirming that neutron star mergers are capable of producing lanthanides in significant amounts. However, we are still far from seeing the complete picture. It could well be that there are other possible sites where the rapid neutron capture process (*r* process) can take place, a complete end-to-end description of a neutron-star merger is still lacking, and the uncertainties connected to the needed nuclear input are substantial.

In this contribution, I would like to highlight one aspect of the nuclear physics uncertainties, namely the neutron-capture reaction rates. I will present some recent efforts to provide experimental constraints to these neutron-capture reaction rates [1], some new data on neutron-rich rare-earth nuclei measured this fall at Argonne National Laboratory, and some future prospects for detector development and experiments at existing and upcoming radioactive beam facilities.

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Precision Experiments at the Intersection of Atomic, Nuclear and Astro-Physics

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The storage of freshly produced radioactive particles in a storage ring is a straightforward way to achieve the most efficient use of the rare. 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. Until very recently, there were only two accelerator laboratories, GSI Helmholtz Center in Darmstadt, Germany (GSI) and Institute of Modern Physics in Lanzhou, China (IMP), operating heavy-ion storage rings coupled to radioactive-ion production facilities. The experimental storage ring ESR at GSI and the experimental cooler-storage ring CSRe at IMP offer beams at energies of several hundred A MeV. The ESR is capable to slow down ion beams to as low as 4 A MeV (β=0.1). Beam manipulations like deceleration, bunching, accumulation, and especially the efficient beam cooling as well as the sophisticated experimental equipment make rings versatile instruments.

The number of physics cases is enormous. The focus here will be on the most recent highlight results achieved within FAIR-Phase 0 research program at the ESR. Among them are the application of the new combined Schottky+Isochronous Spectrometry to investigate de-excitation of first excited 0+ states, measurements of proton-induced reaction rates, and studies of exotic decay modes appearing only in highly-charged ions.

The performed experiments will be put in the context of the present research programs at GSI/FAIR and in a broader, worldwide context, where, thanks to fascinating results obtained at the presently operating storage rings, a number of new exciting projects is planned. Experimental opportunities are being now dramatically enhanced through construction of dedicated low-energy storage rings, which enable stored and cooled secondary HCIs in previously inaccessible low-energy range. Thanks to the fascinating results obtained at the ESR and the CSRe as well as to versatile experimental opportunities, there is now an increased attention to the research with ion-storage rings worldwide.

Recent advances on the relativistic nuclear field theory

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Challenges and recent progress of the nuclear many-body problem on the fermionic correlation functions (CFs) will be reviewed. Starting from the ab-initio Hamiltonian, a consistent equation of motion (EOM) framework is formulated for the low-rank CFs and adopted for nuclear applications by approximations with minimal truncations, which keep the leading effects of emergent collectivity. A mapping of the EOM formalism to the relativistic nuclear field theory (RNFT) allows for extending the RNFT to higher configuration complexity in a systematically improvable framework.

The approach is implemented numerically for the nuclear response, on the basis of the relativistic effective meson-nucleon Lagrangian. The results obtained for medium-heavy nuclei show that the consistent inclusion of the emergent collective degrees of freedom refines the description of nuclear spectra, in both the high-energy and the low-energy sectors The approach confined by the leading ph$\otimes$phonon configurations beyond the standard random phase approximation has been extended to the case of finite temperature for both neutral and charge-exchange nuclear response. This has open new perspectives of building a consistent nuclear many-body framework for generating astrophysical input, that will be outlined.

The recent theoretical effort in reconciling superfluidity and deformation will be introduced. The theory is extended to superfluid systems with the quasiparticle-vibration coupling (QVC) unifying both the normal and pairing phonons, in the general Hartree-Fock-Bogoliubov basis. The QVC vertices are related to the variations of the Hamiltonian of the Bogoliubov's quasiparticles, which can be obtained by the finite amplitude method. First beyond-mean-field QVC applications to axially deformed nuclei will be presented and discussed.

The structure of ^{7,8,9}He in the rotational model

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Inspired by the recent results of Ref. [1] showing strong evidence for a deformed ^{8}He nucleus, we present a study of the structure of the odd-A ^{7}He and ^{9}He isotopes in the rotational model. While the *ab initio* calculations predict an oblate shape, in this work we consider two cases corresponding to an oblate and a prolate core with deformation $|\varepsilon2| \approx 0.38$ as inferred in [1].

A comparison of the experimental moment of inertia of ^{8}He, derived from the experimental 2+ energy, is in good agreement with the estimates from the Migdal formula [2], with the proton and neutron radii adjusted to reproduced experimental RMS charge and matter radii. At the adopted deformation, the relevant neutron Nilsson levels arising from the *p* and *sd* spherical shells are:

- ^{7}He: [101] 3/2,[110] 1/2 on the prolate and oblate side respectively, and
- ^{9}He: [101] 1/2, [220] 1/2 on the prolate and [220]1/2 and [202] 5/2 on the oblate side.

Particle plus Rotor Model calculations for both prolate and oblate configurations will be discussed and compared to available experimental data [3,4]. We will present predictions for electromagnetic properties and spectroscopic factors for the ^{8}He(p,d)^{7}He and ^{8}He(d,p)^{9}He reactions, which may stimulate further studies of these exotic nuclei. We also speculate on the structure of ^{7}H, seen as a proton-hole in the ^{8}He deformed core.

The rotational model offers an appealing and intuitive framework that appears to capture the physics at play in the low-lying structure of ^{7,8,9}He and is complementary to shell-model and *ab initio* approaches.

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Following the evolution of multiple shapes coexistence in even Ni isotopes and beyond

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The finding of a well-defined low-lying prolate 0+ state in ^{66}Ni few years ago represent the experimental observation of the most favourable case in what the recent Monte Carlo Shell Model calculations indicate as a gradual development of a prolate minimum with the increase of the number of neutrons in the even-even Ni isotopes. While the prolate structures are less and less energetically favoured, their identification becomes increasingly difficult. Definitely, a firm conclusion cannot be drawn following a single experiment, and an intensive campaign of experiments is carried on, combining gamma spectroscopy measurements following neutron capture and sub-barrier transfer experiments. The previous studies on ^{66}Ni and ^{64}Ni were extended with the spectroscopy of ^{62}Ni and the experimental image of the evolution of the prolate minima at Z=28 is gradually coming to light. Moreover, the proton-neutron complementary situation in the N=50 nucleus ^{84}Se might provide interesting experimental confirmations of the microscopic mechanism leading to deformed minima near closed shells.

This contribution will present the results obtained after a series of experiments performed during the last four years with ROSPHERE at IFIN-HH Bucharest and with FIPPS at ILL Grenoble.

Probing nuclear structure with slow neutrons: news from ILL

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Among the different approaches to study the structure of nuclei, thermal neutron induced reactions can be used to probe different phenomena. Capture reactions on (rare) stable or radioactive targets populate low-spin states below the neutron separation energy. With thermal neutron induced fission on actinides, neutron-rich nuclei are populated at moderately high spin. Those reactions are used at the Institut Laue-Langevin (ILL, Grenoble), at a high-resolution gamma-ray spectroscopy setup. FIPPS (*Fission Product Prompt gamma-ray Spectrometer*) has been used to study the structure of nuclei in different region of the nuclear chart, addressing phenomena as shape coexistence in different region of the nuclear chart.

After a general introduction about the nuclear physics activities at the Institut Laue-Langevin, recent results obtained in different experiments at FIPPS will be reported. Particular focus will be dedicated to the first fission campaigns, showing the innovative technique of *fission tagging* and first results. Preliminary results on the structure of neutron-rich Br isotopes will be shown as well as the ones already published about the structure of nuclei produced after neutron-induced reactions on beta radioactive targets. The future perspectives for the coupling of the existing FIPPS setup to a fission-fragment identification system will also be outlined.

Overview of nuclear structure activities at the Bucharest 9MV Tandem accelerator

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Since 2012, the ROSPHERE spectrometer is the main instrument to perform gamma-ray spectroscopy at the Bucharest TANDEM. The flexible configurations of ROSPHERE allows to perform lifetime measurements for excited nuclear states using the RDDS, DSAM and fast-timing methods, thus providing a niche thematic for the studies performed here. A second niche was the use of transfer reactions induced by heavy ions as a way to populate and study selectively specific states in the residual nuclei.

Recently, a new high energy configuration of ROSPHERE was introduced, making use of the large volume $LaBr_3$:Ce and CeBr3 detectors from ELIGANT instrument of the Extreme Light Infrastructure – Nuclear physics (ELI-NP) facility to perform gamma-ray spectroscopy studies with high efficiency and good resolution in an energy range up to 15 MeV.

Recent results from the 2022 experimental campaign will be shown with emphasis on the new opportunities available at the ROSPHERE spectrometer.

Gamma-ray spectroscopy at ATLAS

Claus Müller-Gatermann

Argonne National Laboratory

The ATLAS facility at Argonne National Laboratory offers a large variety of beams ranging from stable/long-lived to short-lived isotopes from fission or produced in-flight. The available tools for nuclear structure studies are as diverse, from ion traps and laser spectroscopy over a helical orbit spectrometer to large gamma-ray spectrometers coupled to recoil separators. After a short overview of the facility, I will present the status of the gamma-ray spectroscopy setups utilized at ATLAS. The local Gammasphere spectrometer and the US gamma-ray tracking array GRETINA can be coupled to the Fragment Mass Analyzer (FMA) or the Argonne Gas-Filled Analyzer (AGFA) as well as several ancillary detectors/devices. Brief highlights of the recent campaigns will be presented.

Applications of *Ab Initio* Nuclear Theory: Proton Capture on ^{7}Li and the X17 boson, Proton Emission in ^{11}Be β decay

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A realistic description of atomic nuclei, in particular light nuclei characterized by clustering and low- lying breakup thresholds, requires a proper treatment of continuum effects. We have developed an approach, the No-Core Shell Model with Continuum (NCSMC) [1,2], capable of describing both bound and unbound states in light nuclei in a unified way. With chiral two- and three-nucleon interactions as the only input, we can predict structure and dynamics of light nuclei and, by comparing to available experimental data, test the quality of chiral nuclear forces.

We will discuss applications of NCSMC to the proton radiative capture on ^{7}Li and the production of the hypothetical X17 boson [3] claimed in ATOMKI experiments [4]. We will also highlight our calculations of the proton emission in ^{11}Be β decay [5] that was observed in a recent TRIUMF experiment and disproves a hypothetical neutron decay to a dark matter particle [6].

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Prevailing triaxiality driven by the tensor force

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A large fraction of heavy nuclei are deformed from spherical to ellipsoidal shapes [1]. Such ellipsoidal shapes are considered to be of axial symmetry for most of deformed nuclei [1,2]. This traditional feature is presented in almost all textbooks of nuclear physics, while some questions have been raised from different viewpoints. Our recent Monte Carlo Shell Model calculation showed that this axial symmetry might not be universal [3]. The triaxiality was shown for ^{166}Er with gamma ~ 9 degrees, and level energies and E2 properties of the ground and low-lying states were described well with this triaxiality, in good agreement with experiment [3]. This structure differs from the conventional picture of Refs. [1] and [2] that the ground state is an axially-symmetric prolate equilibrium and the 2^+_2 state is a gamma vibration from it. The structure seen in our calculation is somewhat resembles that given by the rigid-triaxial-rotor model of Davydov and his collaborators [4], although the level energies may not be well reproduced by the Davydov model.

More recently, the question of the triaxiality has been further studied. I will present our findings. First, the triaxiality is not limited to ^{166}Er, whereas it was discussed only for ^{166}Er in [3]. In fact, this feature of the triaxiality prevails in many rare-earth nuclei, contradicting the picture of the dominant prolate shapes. Experimentally, quite a few (at least 22) nuclei around ^{166}Er in the nuclear chart exhibit the triaxial level schemes, while in the traditional picture, these nuclei were considered to have axially-symmetric ground states and gamma-vibrational 2^+ states.

The underlying mechanism for the triaxiality is of great interest, then. I will show that the tensor force, a crucial element of the shell evolution in exotic nuclei [5,6], indeed plays a key role for the emergence of triaxiality in the ground and low-lying states in many rare-earth nuclei. This unexpected finding makes the triaxiality quite robust, and seems to have impacts on the properties of heavy and superheavy nuclei. The possible experimental investigations of the shape of the ground state will be mentioned, for instance, from M1 excitation and relativistic heavy-ion collision.

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PAIN

In-beam γ-ray and electron spectroscopy at the MARA separator

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One of the goals of modern nuclear physics research is to understand the origin of coexisting nuclear shapes and exotic excitations and their relation to the fundamental interactions between nuclear constituents. Despite of huge amount of both theoretical and experimental efforts, many open questions remain [1 and references therein]. In order to verify and understand these subjects in more detail, complementary approaches are needed.

This talk will give an insight into shape coexistence studies around neutron-deficient Pb nuclei. In particular, it will focus on series of simultaneous in-beam electron and gamma-ray spectroscopy experiments employing the SAGE spectrometer [2] at JYFL, Finland. These experiments include studies of ^{185}Hg, ^{190}Pb and ^{196}Po nuclei.

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SpecMAT, the active target for transfer reaction studies at HIE-ISOLDE

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SpecMAT is an active target developed for studying the shell evolution in exotic isotopes and observing the fundamental aspects of the nuclear structure far from stability via transfer reactions carried in inverse kinematics. The SpecMAT is currently at its final developmental stage undergoing characterisation measurements at KU Leuven and ISOLDE, CERN. During the most recent characterisation, SpecMAT was installed in the ISOLDE Solenoidal Spectrometer, which generated a magnetic field of 2.5 T. This characterisation was performed off-line using a standard alpha source. In this measurement spiral tracks of alpha particles were successfully observed in the time projection chamber of the detector. Gamma rays emitted in the decay chain of ^{241}Am were detected in coincidence with the particle tracks by the scintillation array. With this characterisation, we demonstrated that all detector components could operate in the strong magnetic field and are ready for future on-line experiments.

In this talk recent Geant4 simulations of transfer reactions that can be studied with SpecMAT also will be presented. Using the newly developed simulation toolkit, SpecMATscint, we demonstrated the feasibility of studying the shell evolution in the chain of neutron-rich copper isotopes via a (d,^{3}He) transfer reaction.

Nuclear Josephson-like γ-emission

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Nucleon pair transfer processes between superfluid nuclei in heavy ion reactions are considered as possible analogues of the transfer of Cooper pairs [1] of electrons through Josephson Junctions (JJ) [2]. A particular signature of this analogy concerns the dependence of absolute pair transfer cross sections on the number of transferred pairs [3-11]. In this contribution we present a novel approach to the study of the above analogy, based on the alternating current (ac) Josephson effect and associated electromagnetic radiation emitted in the process (see e.g. [12] and references therein; see also [13]), for which the consideration of one nuclear Cooper pair transfer, together with the corresponding one-nucleon transfer process, leads to a direct identification of the nuclear Josepson-like effect. It is based on the nuclear Cooper pair coherence length and on the γ-radiation emitted in the transfer process.

Based on the seminal work of Montanari et al. ([14,15]; see also [16]) carried out at the Laboratori Nazionali di Legnaro (LNL), where the absolute transfer differential cross sections of the reactions $^{116}Sn + ^{60}Ni \rightarrow ^{62}Ni + ^{114}Sn$ and $^{116}Sn + ^{60}Ni \rightarrow ^{61}Ni + ^{115}Sn$ at a large variety of bombarding energies, from above the Coulomb barrier to well below it have been measured and analyzed in detail (G. Pollarolo) in terms of the semiclassical approximation and of microscopically calculated optical potential based on this last reaction formfactors, we will present predictions of the γ-angular distributions, analyzing powers and strength functions ([17, 18, 19, 20, 21]; see also [22]).

In this work we implement the quantum mechanical description of the coupling of the electric dipole associated with the (2n)-transfer reaction process with the electromagnetic field, establishing the connection between the dynamics of the collision process and the number and energy dependence of the emitted γ photons, thus providing a robust quantitative signature of the (ac) Josephson-like nature of the phenomenon. Two important quantities emerge as conserved properties: the Cooper pair coherence length, and the length and orientation of the effective dipole associated with the two transferred neutrons.

We will also comment on a most important result of our collaboration with the LNL (L. Corradi and S. Szilner), namely the recently approved by the PAC committee with high priority [23, 24], of the first experiment specifically dedicated to test our predictions.

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Laser spectroscopy of the Heaviest Elements at GSI

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The heaviest elements are of interest to nuclear and atomic physicists due to their peculiar properties. While nuclear shell structure effects are responsible for their very existence stabilizing them against spontaneous disintegration, the structure of their electronic shells is affected by strong relativistic effects leading to different atomic and chemical properties compared to their lighter homologs [1,2]. The atomic structure can be probed by laser spectroscopy which is a powerful tool to unveil fundamental atomic and, from the determination of subtle changes in atomic transitions, nuclear properties. The lack in atomic information on the heavy element of interest, the low production rates, and the rather short half-lives make experimental investigations challenging and demand very sensitive experimental techniques. In this contribution these challenges in laser spectroscopy of the heaviest elements will be discussed in view of the recent laser spectroscopic experiments. Nobelium (No, Z=102) became accessible in a pioneering experiment employing the RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) technique coupled to the velocity filter SHIP at GSI, Darmstadt. With this technique the identification and characterization of several atomic transitions in nobelium was possible for the first time [3]. Measurements of an atomic transition in the isotopes $^{251-255}$No as well as resolving the hyperfine splitting in ^{253,255}No gave access to nuclear moments and differential charge radii [4]. More recent measurements employ a novel mode of the RADRIS technique where the desired nuclides are bred by radioactive decay on the capture filament extending the reach of the method to ^{255}No and, for the first time, to on-line produced Fm isotopes. Recent results with dedicated experimental investigations were obtained for fermium (Fm, Z=100) and nobelium isotopes which will be discussed together with the perspectives for laser spectroscopy investigations in even heavier elements.

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Beyond mean field model and tensor interactions for nuclear collective motions

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I will discuss both natural parity and unnatural parity spin-isospin dependent collective motions in several doubly-closed shell nuclei by using a beyond mean field model, i.e., Subtract

Second Random-Phase Approximation (SSRPA) adopting the Skyrme energy density functional (EDF). The tensor forces are also included in SSRPA, especially to study the quenching effect in charge-exchange Gamow-Teller transitions and beta-decay life time.

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Isospin-symmetry breaking within charge-dependent DFT - formalism and applications

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I shall begin by introducing the single-reference charge-dependent nuclear Density Functional Theory (CD-DFT) developed recently by our group [1] which includes, in the isospin-symmetry-breaking (ISB) channel, both the Coulomb interaction as well the class-II and class-III contact terms up to next-to-leading (NLO) order and allows for proton-neutron mixing in particle-hole channel. I shall demonstrate that, after adjusting its six new low-energy coupling constants (LECs) to empirical data, our formalism is capable to account globally (irrespectively on atomic number) for various ISB related observables in N~Z nuclei. In particular, it is capable to account, with unprecedented accuracy, for the isovector and isotensor coefficients of the Isobaric Multiplet Mass Equation (IMME) or, alternatively, for the Mirror (MDE) and Triplet (TDE) Displacement Energies in nuclear binding energies. Even in the light nuclei, the quality of our results is surprisingly good, comparable with the Green Function Monte Carlo (GFMC) calculations of Ref. [2]. This, in turn, allows for detailed comparison between specific contributions to the IMME coefficients calculated using the CD-DFT (adjusted to finite nuclei) and GFMC (adjusted to two-body observables) theories. Such a comparison leads to a rather unexpected conclusion that our local correcting ISB potential accounts, predominantly, for the strong-force-rooted effects order by order.

Next, I shall present multi-reference CD-DFT - the variant that includes angular-momentum projection and rigorous treatment of the isospin breaking - calculations of the ISB corrections to the ground-state beta decay of T=1/2 mirror nuclei [3]. I shall demonstrate that, rather counter-intuitively, the local isovector potential surprisingly strongly influences the calculated Coulomb impurities and ISB corrections to the Fermi decay. This study is important in the context of precise testing of the electroweak sector of the Standard Model (SM). The mixed Fermi-Gamow-Teller decays of T=1/2 mirror nuclei offer an alternative way for such tests as compared to the pure superallowed $0^+ \rightarrow 0^+$ Fermi decays. Its precision is still too low for testing the SM but fast progress in β-decay correlation techniques makes such experiments very promising and keeps the field vibrant.

Eventually, I shall present the calculations of mirror energy differences (MEDs) obtained using DFT rooted No-Core Configuration-Interaction (DFT-NCCI) variant of our model. MEDs measure the differences in dynamics of changes of ISB effects in function of angular momentum along the rotational bands of mirror nuclei [4]. The calculated MEDs are in reasonably good agreement both with experimental data and the results of state-of-the-art shell-model calculations. It leads us to the conclusion that the theoretical methods based on CD-DFT allows to address quantitatively diverse isospin-sensitive observables and pseudo-observables in N~Z nuclei without a need for local tuning of the model's LECs.

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Probing single-particle structure with radioactive beams using the ISOLDE Solenoidal Spectrometer

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The ISOLDE Solenoidal Spectrometer (ISS) has been built for measuring direct reactions in inverse kinematics with radioactive beams (RIBs) from HIE-ISOLDE, with a focus on obtaining excellent charged particle resolution. ISS was fully commissioned in 2021 with a new silicon array developed by the University of Liverpool. This array makes use of double-sided silicon strip detectors, with ASIC readout, to determine the position of interaction and the energy of light ejectiles from reactions of RIBs with a light-ion target, when they return to the beam axis in the solenoid field. ISS has now completed two full physics campaigns focussing on measurements of the (*d,p*) reaction to probe single-neutron behaviour in various systems. This talk will give an overview of ISS and a summary of the physics campaigns from the last two years. These include, but are not limited to, the physics highlighted here.

The study of single-particle structure in light neutron-rich systems has led to discoveries of dramatic changes which are otherwise gradual near stability, leading to the weakening and appearance of shell closures. For example, the disappearance of N = 20 and emergence of N = 16 [1, 2] as well the emergence of N = 32, 34 in calcium isotopes [3]. Pronounced trends have also been observed in stable heavier nuclei, in the changes in high-j states as high-j orbitals are filling. Studies of chains of stable, closed-shell isotopes [4] and isotones [5] have pointed to robust mechanisms for these changes, such as the importance of a tensor interaction [6]. The beams available at ISOLDE allow an extension of these studies to N=126, with a focus on nuclei above ^{208}Pb, where monopole shifts arise due to the filling of the proton $h_{9/2}$ orbital. The evolution of single-neutron properties outside N=126 have been investigated, with a measurement of the ^{212}Rn(d,p) reaction, similar in scope on previous measurements south of ^{208}Pb in ^{207}Hg [7].

In light neutron-rich nuclei the monopole shifts of single-particle energies with changing proton occupancies have been investigated outside N=16 with a study of states populated in ^{28}Na, mapping out the relative behaviour of the intruder states above N=20 related to the evolution of structure here. A measurement has also been made of the fragmentation of single-particle strength in ^{31}Mg, inside the N=20 island of inversion, where a change in ground-state structures related to the weakening N=20 shell closure occurs. Both these data can be compared to that measured previously in ^{29}Mg [8] and ^{30}Al to understand the systematics along N=17 and across the border of the island of inversion.

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Recent studies on the shape evolution of medium-heavy nuclei and their impacts

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Nuclear shape is one of the fundamental properties of nuclear structure. As the number of protons or neutrons changes, the shape of the nucleus changes. In this talk, we discuss the shape coexistence of Ni isotopes and the shape transition from spherical to prolate in Nd and Sm isotopes.

We performed Monte Carlo shell model (MCSM) calculations for nuclei in Ni region and quasiparticle vacua shell model (QVSM) calculations for Nd and Sm isotopes. In the MCSM [1], a wave function is represented as a linear combination of angular-momentum- and parity-projected deformed Slater determinants. QVSM [2] is an extended method of MCSM and its wave function if represented as a linear combination of angular-momentum-, parity-, and number-projected quasiparticle vacua. QVSM is more suitable for calculations of heavier nuclei. We can study intrinsic shapes of nuclei by using quadrupole deformations of MCSM or QVSM basis states before projection. Nuclear shapes are represented by using "T-plot", a method to visualize the information of nuclear intrinsic shape of the states calculated by MCSM or QVSM.

Our MCSM calculations for Ni isotopes reproduce well their properties such as levels and transitions [3]. Shape coexistence of nuclei around ^{68}Ni is predicted by the calculations. Neutron-rich nuclei around N=50 were calculated by using extended model space.

Our QVSM calculations for Nd and Sm isotopes reproduce their properties related to the shape transition. The transitional nuclei ^{150}Nd and ^{150}Sm consist of two ingredients with small and large deformations. This property affects the nuclear matrix element of the neutrinoless double beta decay of ^{150}Nd.

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Clustering in heavy nuclei probed with knockout reactions

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Nuclear physicists know that the formation of clusters is essentially important at both edges of the nuclear chart: clusters pronouncedly develop in light nuclei such as ^{12}C, and (pre-)formation of clusters is essential in understanding decays of nuclei heavier than lead. What about in the other areas of the nuclear chart? We have to say that we have quite limited knowledge about it.

A recent result from the $^{112-124}$Sn(p,pα) knockout experiment led by RIKEN and TU Darmstadt groups shed new light on cluster structure in medium to heavy nuclei[1]. The excess-neutron (*N*-*Z*) dependence of the (p,pα) cross section shows a monotonic decrease with *N*-*Z*, which is in good agreement with mean-field predictions by S. Typel[2]. The results remind us of two things: nonnegligible cluster components exist in medium to heavy nuclei, and the (p,pα) cluster knockout reactions are useful in investigating clustering in those nuclei.

We have started a new research project named the ONOKORO project where we comprehensively investigate clustering in medium-to-heavy mass nuclei using (p,pX) cluster knockout reactions under normal and inverse kinematics. The project will probe d, t, ^{3}He, α clustering both in stable and unstable nuclei in the mass region of A=36 - 220.

At the conference, a physics background, research plans at RIBF, RCNP, and HIMAC facilities, and status of detector development for the inverse kinematics knockout experiments will be overviewed.

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Extreme Light Infrastructure - Nuclear Physics: Overview and Perspectives

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The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) combines fundamental and applied research in nuclear and laser-induced plasma physics. High-power laser and gamma beams with hitherto unreachable intensities can be provided at ELI-NP, spawning new research approaches at the interface of nuclear, atomic and plasma physics; as well as quantum electrodynamics and material science. New pathways in nuclear photonics with extremely intense photon beams for studying nuclear matter are of special interest to the community.

The flagship installation of the high-power laser system consists of 2 x 10 PW lasers providing fs-long pulses, which are predicted to reach the highest ever human-made intensities, of I~10^{23} W/cm^2. First experiments with the high-power lasers at ELI-NP aim at measuring the magnitude and scaling of the achievable laser intensity *I via* the laser-to-gamma conversion efficiency and to study new ion acceleration schemes to improve the control and quality benchmarks of laser-driven ion sources by understanding the complex laser-matter interaction.

A broad biomedical research program anchored in the unique ELI-NP capabilities is currently being developed at ELI-NP. It addresses topics, such as the production of nuclear beams relevant to radiotherapy, the radiobiological effects of laser and gamma beams, and medical imaging with laser-driven X-ray sources. Applications based on the use of intense, short-duration, mixed radiation pulses are also planned with the aim of studying the behaviour of materials under extreme conditions such as space environments.

Currently, ELI-NP is in a transition phase from implementation to operation as a user facility. Following the successful commissioning of the high-power laser system and the laser beam transport system, the commissioning of the experimental setups is now underway. The infrastructure will be gradually available to external user access by the end of 2023, with a first round of beamtimes already allocated to international teams.

An overview of the ELI-NP research infrastructure and selected research topics focused on nuclear projects to be investigated at ELI-NP will be given.

The gamma-ray tracking array AGATA at LNL

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Gamma-ray spectroscopy represents one of the most powerful methods to study nuclear structure since a large fraction of the de-excitation of the excited nuclear levels goes via gamma emission. The precise measurement of the gamma rays emitted from nuclear levels can provide a large amount of information of the nuclear structure of the specific nucleus under study. The continuous improvement in germanium gamma-array performances and in their associated instrumentation has allowed an enormous increase of the experimental sensitivity. The current forefront Ge gamma-array in Europe is AGATA [1] which is based on the new concept of gamma-ray tracking. It can identify the gamma interaction points (pulse shape analysis) and of reconstructing via software the trajectories of the individual photons (gamma-ray tracking). The state-of-the-art gamma-ray tracking AGATA array had it first implementation at Laboratori Nazionali di Legnaro (LNL) in 2009 with 5 AGATA triple Clusters, the so called AGATA demonstrator [2]. The AGATA gamma spectrometer has return to LNL with the new 2π solid angular coverage configuration [3]. The first physics campaign started in spring 2022 where AGATA has been coupled to the magnetic spectrometer PRISMA and other compatible ancillary detectors. In this presentation, the current physics campaign with the gamma-ray tracking AGATA at LNL will be discussed.

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Microscopic models of induced fission dynamics

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The dynamics of low-energy induced fission is explored using a consistent microscopic framework that combines the time-dependent generator coordinate method (TDGCM) and time-dependent nuclear density functional theory (TDDFT). While the former presents a fully quantum mechanical approach that describes the entire fission process as an adiabatic evolution of collective degrees of freedom, the latter models the dissipative dynamics of the final stage of fission by propagating nucleons independently toward scission and beyond. The two methods, based on the same nuclear energy density functional and pairing interaction, are employed in a study of the charge distribution of yields and total kinetic energy for induced fission [1]. The TDDFT is also used to model the saddle-to-scission dynamics, the formation of the neck between the nascent fragments, and the subsequent mechanism of scission into two or more independent fragments [2]. In the final phase of the fission process, the timescale of neck formation coincides with the assembly of two alpha-like clusters. At the instant of scission, the neck ruptures between the alpha-like clusters, which separate because of the Coulomb repulsion and are eventually absorbed by the two emerging fragments.

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Gamma-ray spectroscopy of nuclear fission with the nu-Ball2 hybrid spectrometer

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Gamma-ray spectroscopy is a versatile tool which can be used to study the decay of the excited fragments produced in the complex, dynamical process of nuclear fission. Gamma ray coincidence energy and time data can give important information on both the nuclear structure of exotic neutron-rich nuclei and the fission process itself [1]. In particular, spectroscopy and calorimetry of fragment de-excitation can probe the fission mechanism, giving information on the generation of angular momentum, the partition of energy, and the competition between emission of neutrons and gamma rays [2][3][4][5]. Moreover, the study of the population of isomeric states in fission fragments can give complimentary, independent information on fragment spins and their dependence on other observables [6]. A new experimental campaign with a major focus on gamma-ray spectroscopy of nuclear fission with the nu-Ball2 hybrid spectrometer has been underway for the last year at the ALTO facility of IJC Lab [7]. An overview of the emerging results from this campaign will be presented.

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Probing multiple shape coexistence in ^{110}Cd with Coulomb excitation

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The study of the properties of the shape-coexisting states enables to investigate the correlations of particles under different deformation conditions within the same nucleus, and provides one of the most demanding tests of modern nuclear theories. Nuclei assigned as possessing shape coexistence are now rather common (see, e.g., Ref. [1]), but examples of multiple shapes, i.e., more than two distinct shapes, are much rarer and have been largely restricted to the very neutron- deficient Hg or Pb isotopes. Recently, however, there have been suggestions of multiple shape coexistence occurrence in other regions of the nuclear chart, for example in the Ni [3, 4] and Cd isotopes [5–7]. The suggestion of multiple shape coexistence in ^{110}Cd was based on data obtained from high-statistics β-decay studies at TRIUMF-ISAC combined with level lifetime measurements using the DSAM technique following inelastic neutron scattering [5, 6, 8]. All these experimental findings lead to the fundamental question regarding the nature of collectivity of low-lying states in Cd nuclei, particularly the first excited 0^+ states, that were invariably interpreted as multi-phonon structures. Clearly, with the present knowledge of spectroscopic data, shape coexistence has to be invoked to account for them. Moreover, triaxiality is expected to play an important role in this mass region, as evidenced by Coulomb excitation studies in $^{96;98;100}$Mo [9,10]. In addition to this, recent results of beyond-mean-field calculations suggest that each of the first four 0^+ states in $^{110;112}$Cd presents four different and unique shapes [5].

Nowadays, the most critical needs are to establish the underlying structure of low-lying 0^+ states, particularly for ^{110}Cd, to validate the shape coexistence scenario and to reveal whether or not Cd isotopes possess a multi-phonon 0^+ excited states. The multi-step Coulomb excitation can provide essential data to advance our understanding of the nature of such low-energy states. A multi- faceted program of study to ascertain the shapes of the states in ^{110}Cd have been initiated. A series of multi-step Coulomb excitation studies have been recently performed at HIL, LNL and ANL laboratories using various Z–reaction partners. First preliminary results concerning the electromagnetic properties of low-lying 0^+ states in ^{110}Cd and their deformation will be presented and compared to the recent beyond-mean-field and generalized Bohr Hamiltonian predictions.

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SUBMITTED TALKS

Radioactive Ion Beams at SPES for nuclear physics and medical applications

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Around the world, many facilities producing Radioactive Ion Beams (RIBs) using the Isotope Separation On Line (ISOL) technique have been or are under construction. SPES (Selective Production of Exotic Species) is the facility in the installation phase in these years in the Laboratori Nazionali di Legnaro (LNL). At SPES, the radioactive atoms are produced using a 40 MeV-200 μA proton beam impinging the Uranium Carbide (UCx) target composed by seven disks in order to dissipate the 8 kW beam power. The formed RIB will be subsequently directed and focalized using different electromagnetic systems and purified in order to have a pure isotope beam without contaminants. The RIBs can be sent directly to the low energy experimental area and, afterwards, to the post-acceleration stage.
Currently the installation program concerning the RIB source provides the set-up of the apparatus around the production bunker. The main objective is to provide in the next years, the first low-energy radioactive beams for beta decay experiments using the b-DS (beta Decay Station) set-up and for radiopharmaceutical applications by means of the IRIS (ISOLPHARM Radioactive Implantation Station) apparatus. The goal of the ISOLPHARM project is to provide a feasibility study for an innovative technology for the production of extremely high specific activity beta emitting radionuclides as radiopharmaceutical precursors.
In this presentation, all the specific issues related to the SPES RIB and the Low Energy beam lines will be appropriately presented and commented, showing the results obtained in the last years. The main RIB systems, such as ion source systems, target-handling devices and the installation of low energy transport line, will be presented in detail.

A study of two special properties in t+p reaction by using an ab-initio four body reaction calculation

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The $J=0^+$ and 0^- continuum structures in ^4He are investigated by using an ab initio reaction theory with the microscopic R-matrix method[1-3]. In the $E_x > 20$ MeV excitation energy region of 4He, the continuum states are mainly described by the t+p, h+n and d+d channels. The difficulty of the observation of third 0^+ state and second 0^- state is originating from the magnitude of the S-matrix for the elastic channel which is almost zero. This reason why no observation or the zero S-matrix is explained by the Wildermuth mechanism[1].

Furthermore, the ab-initio calculation shows almost 100% of the tritium is transformed into ^3He or deutron[1] when the proton is irradiated in low energy (3-10MeV) with the total spin J=0. It may be important for a fundamental research for the Fukushima tritium contaminated water problem, where tritium can not be removed from the normal water.
In the workshop, I will explain two special properties in t+p reaction.

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Lifetime measurements via the Doppler-shift attenuation method using particle-γ coincidences

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Nuclear level lifetimes are important observables to gain insights into nuclear structure phenomena. In combination with $\gamma\gamma$-decay branching ratios and multipole mixing ratios, they give access to absolute transition strengths and probabilities. To further increase sensitivity, experimental setups, data acquisitions and analysis methods are constantly improved. A powerful tool to determine lifetimes in the sub-picosecond regime is the coincidence Doppler-shift attenuation method (DSAM) [1,2]. At the University of Cologne, the 10 MV FN Tandem accelerator provides the particle beam, typically consisting of protons or alpha particles. It impinges on a thin target which is positioned inside the combined particle-γ detector array SONIC@HORUS [3]. Measurements of particle-γ and particle-γ-γ coincidences provide knowledge about the complete reaction kinematics. Hence, feeding contributions from energetically higher lying states to the transitions of interest can be eliminated, enabling the measurement of real lifetimes instead of effective ones. For this, the Doppler shift is used resulting from the motion of the target nucleus which is continuously decelerated. The deexciting γ-ray energies are measured by the HPGe detectors of HORUS for several emission angles θ relative to the direction of motion of the recoiling target nuclei. These energies give the corresponding Doppler shift and, therefore, the recoil velocity at the moment of deexcitation. By simulation of the stopping process inside the target material, this velocity can be linked to the respective level lifetime. Within one experiment several dozens of lifetimes can be determined, and extensive spectroscopy can be performed.

In recent years, DSAM experiments on several stable isotopes have been performed in Cologne, concentrating on the regime from the shell closure at N=50 to Z=50 along the valley of stability. Systematic studies are performed along isotopic chains [4-7], including Zr, Ru, Sn, and Te, tracing the evolution of symmetry mixing and shape coexistence. While the well-established analysis method is based on the fact that the deexciting γ-ray energy depends linearly on the cosine of the emission angle θ, a new complementary method makes use of a peak-shape optimization process, applying several Doppler corrections to determine the recoil velocity. It enables the analysis of weak transitions, which are suffering from low statistics, allowing the determination of additional nuclear level lifetimes [7].

Within this contribution, the experimental setup and the analysis procedure performed in Cologne will be introduced, as well as recent results obtained via the DSA method and by spectroscopy benefitting from coincidence measurements.
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Transfer Reaction on ^{68}Ni

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The shell model [1] is a widely applied framework used to assess and predict nuclear structure. This model groups nucleons into shells corresponding to a certain energy and quantum numbers. Following this, it predicts the existence of the well-known magic numbers in nuclei close to stability (2, 8, 20, 28, 50 & 126). However, moving closer to the edges of the nuclear chart a number of interesting phenomena have been found, such as the appearance of new magic numbers [2] or the coexistence of deformed configurations in nuclei [3]. The semi-magic nucleus 68Ni is an interesting case, having a magic number of protons (Z=28) and N=40 neutrons which corresponds to a harmonic oscillator shell closure. Whether this nucleus does exhibit a strong shell closure is debated, with the low value for B(E2) measured in transfer reactions [4] pointing towards a shell closure, whereas mass measurements of ^{68}Ni and surrounding nuclei [5] support the contrary.

One neutron transfer reactions are a powerful tool to investigate nuclear structure. The ^{68}Ni(d,p)^{69}Ni reaction (with a Q-value of 2.362MeV) will populate states corresponding to configurations with one neutron outside the ^{68}Ni core; in particular, states with a strong νg9/2 and νd5/2 single-particle strength. This study will help us evaluate the existence of a N=40 shell closure and will provide experimental feedback for the use in shell model calculations. Especially the location of the νd5/2 has a profound impact on the results as it is responsible for the large quadrupole collectivity in this region [6]. This reaction has been studied previously using a fragmentation beam at a higher energy at GANIL [7], but the current setup will improve on the energy resolution and the angular sensitivity, leading to a better identification of the populated states. This measurement will also expand on the information gained during a previous experiment using the ^{66}Ni(d,p)^{67}Ni reaction [8].

The experiment [9] will be carried out in November 2022 at ISOLDE, CERN using the Isolde Solenoidal Spectrometer setup. A beam of ^{68}Ni will be created and accelerated to 8MeV/u. It will be fired upon a CD_2 target where the transfer reaction occurs. The outgoing proton will be bent by the magnetic field and end up back at the beam axis after a single revolution. There it is detected by the segmented silicon array detector. Using the energy and position it is possible to reconstruct the excitation energy of the ^{69}Ni. In addition, the setup will feature for the first time the inclusion of the SpecMAT scintillator array [10], allowing for the detection of gamma rays emitted during the reaction. The use of particle-gamma coincidences will allow for a more accurate determination of the level scheme of ^{69}Ni.

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Decays of stretched states in light nuclei as a probe for the open nuclear quantum system description

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The structures of stretched excitations are dominated by a single particle-hole component for which the excited particle and the residual hole couple to the maximal possible spin value available on their respective shells. In light nuclei they appear as high-lying excitations resulting from the $p_{3/2} \rightarrow d_{5/2}$ stretched transitions [1]. Due to the expected low density of other one-particle-one-hole configurations of high angular momenta in this energy region, their configurations should be relatively simple. Therefore, their theoretical interpretation could provide clean information about the role of continuum couplings in stretched excitations.
The decays of stretched resonances are expected to be dominated by the proton and neutron emission, however, their decay patterns are poorly known experimentally, thus far. The direct measurement of stretched states decay paths should provide data which can be used as a very demanding test of state-of-the-art theory approaches, like for example, Gamow Shell Model (GSM) [2] which is an adequate tool for the theoretical description of these excitations.

The results of the first experimental studies on the decay of the 21.47-MeV stretched resonance in ^{13}C will be presented. It was investigated in a ^{13}C(*p,p'*) experiment at 135 MeV proton energy, performed at the Cyclotron Centre Bronowice (CCB) at IFJ PAN in Kraków. The information on the proton and neutron decay branches from the 21.47-MeV state in ^{13}C was obtained by measuring the protons inelastically scattered on a ^{13}C target in coincidence with γ rays from daughter nuclei and charged particles, from the resonance decay.
The experimental results were compared with theoretical calculations from the GSM, extended to describe stretched resonances in *p*-shell nuclei. A very good agreement obtained between the measured and predicted properties of the 21.47-MeV state in ^{13}C was obtained.

In a similar measurement at CCB, the decays of stretched resonances in ^{16}O nucleus were also investigated. A triplet of close lying states at ^{16}O, namely at 17.79, 18.98, and 19.80 MeV, was populated. The decay channels via proton and alpha emission were identified by studying the γ rays from daughter nuclei in coincidence with scattered protons. The quantitative information on the decay branching ratios could be extracted from a systematic analysis of the proton-γ matrix. The physical interpretation of the results would largely profit from theoretical calculations, which are not available at the moment. However, the obtained results support the extension of the investigation of the stretched resonances decays in other nuclei such as ^{14}N, using the present method.

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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 n/s/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 $LaBr_3$ 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 ^{252}Cf spontaneous fission source will be outlined.

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Exotic decay of ^{115}Cs near the proton drip line

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The study of nuclei at the limits of stability has recently become a central focus of nuclear structure research. The study of exotic decay mode of the neutron-deficient, proton and alpha unbound nucleus, ^{115}Cs, close to upper mass limit of the *rp-process* nuclei, provides many interesting and new information on n-n interactions [1–3] , which is important for understanding the limits of existence of the nuclei. Many interesting properties have been observed in the nuclei around the drip line. The observation of the breakdown of traditional magic numbers in exotic nuclei [4–6] far from stability has been an important issue in nuclear structure physics. Other properties are appearance of new magic numbers, exotic decay [7–9], cluster structure [10–12] etc. In respect of these, the measurement was performed at the ISOLDE decay station (IDS), where secondary beam of ^{115}Cs was sent to the experimental hall and implanted on a 20μg/cm^2 carbon target. The IDS setup consisted of five DSSD (Double Sided Silicon Strip Detectors), four PAD detectors behind the DSSD (behind the lower DSSD there was no PAD) functioning as ∆E-E telescopes. Those DSSDs were of different thickness. Four High-Purity Germanium(HPGe) clover detectors surround the chamber to provide high gamma-ray detection efficiency. The solid angle coverage of all DSSDs is nearly 45.8% of 4π. By applying proper coincidence and anti-coincidence condition we have differentiated protons alpha and beta events from ∆E-E spectrum. We have added the deposited energies of high and low energy delayed protons. The delayed proton spectrum has been further converted into the reference frame of ^{115}Xe. For obtaining the proton unbound excited states of ^{115}Xe, the proton separation energy has been added with the spectrum. We have fitted the peaks of proton unbound states of ^{115}Xe with the Gaussian shape with width as a variable parameter via χ^2 minimization, several proton unbound states of the nucleus have been obtained. We have also fitted the proton unbound states by Bayesian method of analysis. Both methods show that excitation energies of proton unbound states of ^{115}Xe are distributed from 3.8 MeV to 7.8 MeV. The measured lifetimes of those proton unbound states are of the order of zeptoseconds. We have also measured the half life of ^{115}Cs from delayed proton events [13] and which is in agreement with the previously reported value[14]. We have also measured the decay branching ratio of delayed proton which is more than the previously reported value[14]. New delayed α-branching ratio and several newly reconstructed particles unbound excited states of ^{115}Xe are being reported for the first time. The measured delayed γ-rays are in agreement with the bound excited states of daughter nucleus, ^{115}Xe obtained from the previous measurement. Now we are trying to produce the beta delayed two proton spectrum, we hope in future we will produce more interesting results.

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About proton-neutron mixing in the energy density functional

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Traditional EDF mean field methods neglect the proton-neutron mixing for the wave function implementation, considering only the action of the particle-like channels. Having protons and neutrons interacting should lead to an effect with respect to the results obtained from models that set them apart.

The effective interaction used for the calculation is the Gogny D1S [3], which was not fitted for this condition. We are interested in the effects of the p-n pairing for this interaction using the HFB variational method, then see the aftermath yielded by the parametrization.

Preliminary mean field analysis, using Taurus code, shows that the results, for proton-neutron mixed states on the interaction, do not diverge, however, it is relevant for the pairing coupling and energies compared with p-n separated wavefunctions.

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Exploration of single-particle and collective modes of excitations in nuclei with $A \sim 90$

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Excited states in atomic nuclei can be generated by two extreme modes of excitations connected to the single-particle and collective degrees of freedom [1]. Due to the spherical ground state of even-even Zr isotopes around $A \sim 90$, with $Z = 40$ semimagic proton number, quadrupole collectivity is seen to be less compared to the neighbouring nuclei [2]. It remains a question that up to which excitation energy and spin, the single-particle excitations dominate over the quadrupole collectivity. In contrast, large octupole collectivity has been observed through the measurement of enhanced $E3$ transition probability, $B(E3)$ [3], with the value for ^{96}Zr being one of the largest across the nuclear chart [4]. Thus, an intriguing aspect of studying these nuclei is the manifestation of single-particle excitations and the evolution of collectivity. Additionally, the coupling of a valence particle with an octupole phonon can induce octupole collectivity in the neighbouring odd-A nuclei having one particle outside the even-even core by acquiring a permanent octupole deformation [5].

To explore such features, a series of new measurements have been performed on ^{90,91}Zr using a hybrid array of clover HPGe and $LaBr_3$(Ce) detectors. The level scheme of ^{90}Zr has been studied up to an energy of ~ 13 MeV and spin of ~ 20$\hbar$ [6]. Shell-model calculations, with extended model space across the $N = 50$ shell gap, provide good description of both positive- and negative-parity states. In a separate experiment, low-lying octupole collectivity in this nucleus is being probed with Coulomb excitation technique. Also, new lifetime measurement for the $11/2^-_1$ state in ^{91}Zr employing electronic fast-timing technique leads to a value of $B(E3;\ 11/2^-_1 \rightarrow 5/2^+_{g.s.}) = 19.5 \pm 1.5$ W.u., indicating significant collective enhancement of the $E3$ transition [7]. The above results will be presented in this contribution.

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SiPM-based $LaBr_3$ readout module for PMTs replacement in gamma spectroscopy: first results of in-beam measurements

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We present the first results of in-beam measurements performed with the GAMMA spectrometer, a 144-ch SiPM-based readout system for large scintillation crystals in gamma spectroscopy with high dynamic range and high resolution.
A SiPM-based indirect conversion gamma detector is used for the first time to detect energies up to 15.1MeV with state-of-the-art energy resolution.

The system [1] is based on a 3" co-doped lanthanum bromide (LaBr3(Ce+Sr)) crystal (73ph/keV conversion efficiency, 25ns decay time) coupled to 144 NUV-HD Silicon Photomultipliers (SiPMs) from Fondazione Bruno Kessler (30um cells, 1100cells/mm2 density, 100 kHz/mm2 dark count rate). Nine custom GAMMA ASICs (16 channels, 84dB dynamic range) [2] provide the 144 channels for the SiPMs readout with programmable integration time. A custom bias module with temperature compensation assures the gain stability of the SiPMs.

The module achieves excellent spectroscopic results (2.6% energy resolution at 662keV, the 137Cs emission peak), in line with or better than those expected from PMTs, and 80keV - 30MeV energy dynamic range thanks to the custom ASIC with automatic gain adaptation. High-rate acquisition (above 30kHz) can also be achieved without degrading the performance. Also, position sensitivity for reconstructing the position of interaction inside the crystal at this energy will be investigated to compensate for relativistic Doppler broadening effects. Previous measurements with a Cs collimated source and machine learning approach achieved ~1cm resolution.

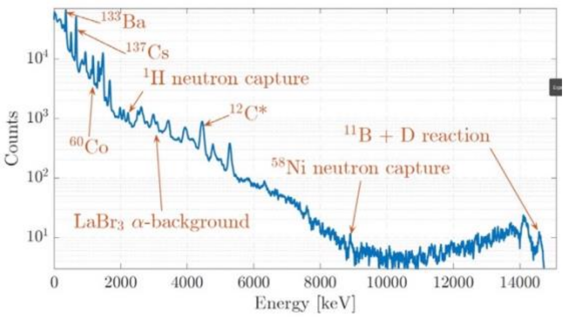

Figure 1: ^{133}Ba, ^{137}Cs, ^{60}Co, AmBeNi and ^{11}B on ^{2}H reaction spectrum.

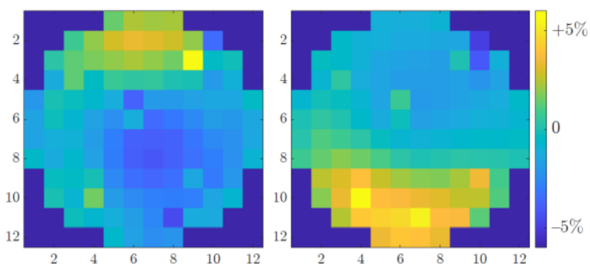

Figure 1: Heatmap of the SiPMs signal when irradiating the crystal from the front with 1cm collimation at two opposite sides.

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Multinucleon transfer reactions in $^{206}Pb + ^{118}Sn$ studied with PRISMA spectrometer

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Multinucleon transfer reactions among heavy ions at energies close to the Coulomb barrier constitute a link between quasi-elastic (QE) processes, characterised by the transfer of few nucleons and small kinetic energy losses, and deep inelastic (DIC) processes, where massive transfer and large kinetic energy losses take place [1]. Interest in the study of these processes has been motivated by advances in two main areas. The first one is production of exotic species, especially the heavy neutron-rich one, where multinucleon transfer reactions have been recognised as a promising production tool [2]. The second one is the nucleon-nucleon correlations. It has been shown that nucleon-nucleon correlations can be quantitatively probed at energies far below the Coulomb barrier, where QE processes dominate [3, 4].

The multinucleon transfer reactions for the $^{206}Pb + ^{118}Sn$ system have been measured at E_{lab}=1200 MeV, with detecting angle initially set around grazing angle, at Θ_{lab}= 35°, and then at 25°, which allows to obtain angular range of ~20°. The experiment was performed at LNL-INFN with large solid angle magnetic spectrometer PRISMA.

The obtained differential and total cross sections, and *Q*-value distributions for a variety of neutron and proton pick-up and stripping channels, will be presented and discussed. Behaviour of *Q*-value distribution of different nucleon-transfer channels indicates the presence of transition from the QE to DIC processes, especially when multinucleon transfers are involved. The corresponding differential and total cross sections have been compared with calculations performed with the GRAZING code [5]. An overall good agreement is found for most of few nucleon transfer channels. The data is underestimated for the channels involving a large number of transferred nucleons, which indicates that more complex processes are present.

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Reconstruction techniques for nuclear reactions measured with ACtive TARget TPC

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Tracking detectors for low-energy nuclear physics experiments acting at the same time as reaction targets are very promising devices in a wide range of research topics. The ability to measure and reconstruct the trajectory of all reaction products with high efficiency and good geometrical resolution allows particle spectroscopy studies under experimental conditions below the sensitivity threshold of standard techniques. The features of these detectors, such as the large dynamic range, the possibility of recording multiple tracks in coincidence, and the efficiency gain achieved due to interaction vertex tracking, make them suitable for a wide range of physics cases [1,2]. In addition, the use of these detectors is crucial to investigate peculiar effects in the nuclear physics landscape, such as 2p radioactivity [3] and triple-alpha clustering of ^{12}C, or to study reactions induced by an exotic beam of very low intensity. The precise reconstruction of the events is among the most important steps to achieve clear measurements and to shed light on the nuclear structure underlying the measured reaction channels. However, reaching such conclusions is only possible if robust, efficient, and computationally fast reconstruction codes are implemented and validated. In this work, clustering routines and classification techniques were developed to process experimental data from the ACTAR active target, with the goal of providing accurate information on track geometry, particle energy, and identification. Data from a $^{20}O(d,^{3}He)^{19}N^{*}$ reaction measured at GANIL were analyzed to compare different clustering algorithms [4,5]. In addition to this analysis, convolutional neural networks were used to obtain a quick and general classification of acquired events, distinguishing between spurious acquisitions related to trigger settings and events containing interesting reaction vertex. The algorithms and techniques developed in this work will be implemented in the standard analysis routine of the ACTAR data processing.

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Measurement of the cross section for light fragment production at large angle in the ^{12}C collision on C, O, and H in 100-350 MeV/u energy range

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Nuclear inelastic interactions in carbon ion particle therapy treatments can lead to the fragmentation of the projectile, producing a non negligible amount of dose deposition outside the planned target volume [1]. In order to improve the Monte Carlo simulation models adopted in the clinical treatment planning systems and to investigate the possibility to employ light charged fragments for range monitoring purposes, in the framework of the FOOT experiment of INFN [2] we measured the cross sections for the production of protons, deuterons and tritons of a 12C beam at 100-350 MeV/u on C, O and H targets at large detection angles (>45°). The experimental setup included a time-of-flight measurement system and LYSO crystals to perform particle identification and to measure their kinetic energy. We made use of different targets: graphite (C), PMMA (C2O5H8) and polyvinyl-toluene (plastic scintillator, CbHa). The cross sections for the reactions on H, C and O where extracted by performing a stoichiometric subtraction of the results obtained for the three composite targets. An overview of the methods and the results about the measurements at 60 and 90 degrees, as published in [3], will be shown, together with some preliminary comparison to Monte Carlo simulations.

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Systematic ISGMR measurement project with CNS Active Target (CAT-M)

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The nuclear matter incompressibility (K0 and Kτ) can be directly determined from the nuclear incompressibil- ity KA measured from the isoscalar giant monopole resonance (ISGMR), and they play an important role in the nuclear matter equation of state. Previous studies have reported K0 = 240 ± 20 MeV and Kτ = −550 ± 100 MeV, and the error of Kτ is as much as 20 % [1]. Also, recent ISGMR measurements in Mo isotope have reported K0 = 202 MeV [2]. The errors in K0 and Kτ can be attributed to surface effects Ks and Kτs, respectively. Therefore, it is important to perform systematic ISGMR measurements with various nuclei, in- cluding unstable nuclei, and to evaluate the surface effects quantitatively.

We plan to systematically measure the ISGMR of various isotopes including unstable nuclei to derive K0 and Kτ with high precision. In this project, A dipole magnet was introduced to the active target, CAT-M, as an upgrade to CAT-M. for systematic measurement of ISGMR. The magnets prevent δ-rays generated during high-intensity beam irradiation from entering the active area in CAT-M. As a result, the SN ratio is improved by a factor of 100. This is expected to make it possible to measure recoil particles at forwarding angles with high accuracy. On the other hand, the introduction of the magnet has made it impossible to measure beam particles with CAT-M. Therefore, a compact TPC (Beam TPC), which can be installed near the reaction point, has been newly developed. This detector is capable of measuring the position of the beam particles can be determined with an accuracy of 600 μm.

We have completed ISGMR measurements for ^{132}Sn, ^{136}Xe, and $^{80-86}$Kr by this year. We will give an overview of the project and the most recent ISGMR measurement using the ^{86}Kr (d, d′) reaction.

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Lifetime measurements to investigate γ-softness and shape coexistence in ^{102}Mo

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Lifetimes of low-spin excited states in ^{102}Mo populated in a ^{100}Mo(^{18}O,^{16}O)^{102}Mo two-neutron transfer reaction were measured using the recoil-distance Doppler-shift technique at the Cologne FN Tandem accelerator. Lifetimes of the 2^+_1, 4^+_1, 6^+_1, 0^+_2, 2^+_γ, 3^+_γ states and one upper limit for the lifetime of the 4^+_γ state were obtained. The energy levels and deduced electromagnetic transition probabilities are compared with the ones obtained within the mapped interacting boson model framework with microscopic input from Gogny mean field calculations. With the newly obtained signatures a more detailed insight in the γ-softness and shape coexistence in ^{102}Mo is possible and discussed in the context of the Z≈40 and N≈60 region. The nucleus of ^{102}Mo follows the γ-soft trend of the Mo isotopes. The properties of the 0^+_2 state indicate, in contrast to the microscopic predictions, shape coexistence which also occurs in other N = 60 isotones [1].

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Measurements of the ISGMR in Kr Isotopes with CAT-M Active Target

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The active target CAT-M (CNS Active Target - Medium/Manul) is being used in an experimental campaign at HIMAC (Chiba, Japan) for the study of the ISGMR (Isoscalar Giant Monopole Resonance). This nuclear collective mode, also called "Breathing Mode", is a compression mode which consists in an in-phase (protons and neutrons) expansion and compression of the nucleus around the equilibrium radius/density [1].

The ISGRM energy is directly connected to the finite nuclear incompressibility K_A , which can then be linked to the incompressibility of the nuclear matter K_∞, an important parameter of the nEoS (nuclear Equation of State) [2]. The estimate of the incompressibility of the nuclear matter suffers from a large uncertainty K_∞ = (230 ± 40) MeV [3], significantly driven by the poor knowledge on the asymmetry term K_τ = (−550 ± 50) MeV [4]. To better constrain this parameter, measurements along nuclear isotopic chains are necessary, including unstable nuclei.

Active Targets are particularly suited to the study of the ISGMR, the excitation energy of the isotope under study can be inferred from the measurement of the recoiling particle following inelastic scattering. In this campaign the active target CAT-M was used in combination with lateral Si detectors to stop and identify the recoiling particles with enough energy to leave the TPC. Several experiments have been already performed along the Kr isotopic chain, and the most recent took place in September 2022 on the ^{84}Kr nucleus. In this measurement, we combined for the first time CAT-M with the Si array detector of Leuven. This array consists of 12 DSSSD (Double-Sided Silicon Strip Detectors) 100x100mm2, covering a large portion of the solid angle, which grants a good energy resolution, and a precise reaction angle reconstruction (64 strips per detector). A report of this experiment will be given, as well as some preliminary results on the ongoing analysis of the ^{80}Kr measurement.

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One-neutron removal cross sections for the ^{16}N isomeric state

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The enhancement of halo neutron removal cross sections in neutron halo nuclei is well known and is one of the evidences for the neutron halo structure. We have measured neutron removal cross sections for several exotic light nuclei to reveal their characteristic neutron-halo-like structures. [1]

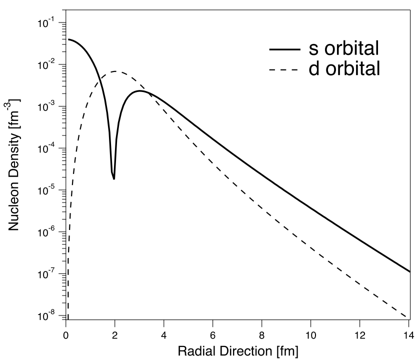

Figure 1. Single particle model densities calculated with (a neutron + ^{15}N core) model.

The difference in the nuclear structure between the ground and the isomeric state of ^{16}N can be explained by the orbitals in which the valence neutron is sitting. Considering the spin and parity, the valence neutron is considered to be mainly occupying the $1d_{5/2}$ orbital in the ground state and the $2s_{1/2}$ orbital in the isomeric state. Therefore, the valence neutron in the ^{16}N isomeric state, with effects of $2s_{1/2}$ orbital and its relatively small neutron-separation energy of 2 MeV, can be distributed more broadly in the radial direction. Figure 1 shows the calculated nucleon density distributions of ^{16}N valence neutrons using the single-particle model. The spread of the density distribution depends on which orbital the valence neutron resides in. Therefore, the ^{16}N isomeric state is a candidate for neutron halo nucleus. The halo nucleus in the excited state has not been observed directly with experimental evidences.

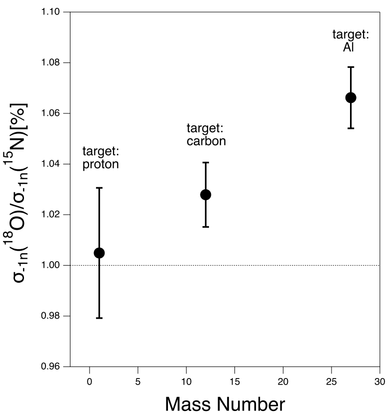

Figure 2. Ratio of one-neutron removal cross sections plotted against mass number.

In the present study, we measured one-neutron removal cross sections using secondary beams of ^{16}N with a mixture of ground and isomeric states. We used two types of primary beams, ^{15}N and ^{18}O, to produce ^{16}N beams with different isomeric ratios, and compared the one-neutron removal cross sections measured with each secondary beam. The experiments were carried out at the HIMAC heavy ion synchrotron facility at National Institute for Radiological Sciences (NIRS), Japan.

The experimental results (Fig. 2) show that the neutron removal cross section obtained from a ^{16}N beam with a large isomeric ratio, which was produced from ^{18}O, is large compared to that obtained with a ^{16}N beam with a small isomeric ratio produced from ^{15}N. This results suggest that the ^{16}N isomeric state is considered to have a neutron-halo-like structure.

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Shell model nuclear level densities using spectral distribution method

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Radiative neutron capture processes are crucial for complete understanding of nuclear astrophysical network calculations like, r-process. Within a statistical framework, the radiative neutron capture cross-sections and relevant reaction rates calculations primarily require (i) neutron-nucleus optical model potential (OMP), (ii) γ-ray strength function (γSF), and (iii) nuclear level density (NLD). The NLDs have been calculated using various methods which ranges from simple phenomenological models based on non-interacting degenerate Fermi gas [1–4] to more complex microscopic mean-field models [5, 6]. The collective effects in these models are included through the rotational and vibrational enhancement factors. Further normalization are done with the experimental data at low energy and neutron resonances.

More realistic values of NLDs are obtained using the framework of shell model which naturally incorporates for the collective excitations through the residual interaction. There are few different approaches to calculate the NLDs within the framework of shell model. One of them is the shell model Monte Carlo [7] which utilizes auxiliary fields to compute the thermal trace for the energy and further inverse Laplace transform to obtain the NLDs. Another efficient way to construct the NLDs is based on the spectral distribution method (SDM) for many-body shell model Hamiltonian in full configuration space, which avoids the diagonalization of huge dimensional matrices. The SDM has further been extended for the construction of the NLDs for many body shell model Hamiltonian using calculation of the first and second moments of Hamiltonian for different configurations at fixed spin and parity[9]. We have calculated NLDs and s-wave neutron resonance spacings using SDM and employing these NLDs, we have computed reaction cross-sections and astrophysical reaction rates for radiative neutron capture in few Fe-group nuclei[8]. We compare our results with those obtained with NLDs from other phenomenological and microscopic models as commonly employed and found to be in harmony with experimental data compared to other models, particularly for the incident neutron energies of astrophysical interest. Since the present method is quite general, can be explored in various model spaces and other reactions of astrophysical interest.

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Search for the Anomalous Internal Pair Creation in ^{8}Be

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In 2016, A. J. Krasznahorkay et al. [1] announced the finding of anomalies in the internal pair creation decay of specific excited states of ^{8}Be. The Hungarian group measured the $e^{+}e^{-}$ angular correlations for two transitions: the isovector magnetic dipole 17.6 MeV ($J^{\pi}=1^{+}$, T=1) state → ground state ($J^{\pi}=0^{+}$, T=0) and the isoscalar magnetic dipole 18.15 MeV ($J^{\pi}=1^{+}$, T=0) state → ground state. According to the expected behavior for the Internal Pair Creation, the production cross section drops quickly with the separation angle [2]. In contrast, the authors observed a peak-like behavior at large angles (centered at ~140º). The authors declared that this anomaly is "possibly due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of 16.70±0.35(stat)±0.5(Syst) MeV/c2 and $J^{\pi}=1^{+}$ was created" [1]. This result is of great importance in the physics branches of the standard model, dark matter, quantum field theory, and nuclear physics. There are worldwide efforts to independently reproduce the Hungarian experiment, and we are convinced that the repetition of the experiment is crucial.
For this purpose, we developed a dedicated setup to be operated at Legnaro National Laboratories of INFN. The setup consists of 2 ΔE−E detector telescope clovers placed perpendicularly to the beam direction. The material used to build the detectors is the plastic scintillator EJ-200 and the light emitted is read out by SiPM. The ΔE layer is made up of 20 thin bars with dimensions of 0.2 cm x 5.0 cm x 0.5 cm. Furthermore, this layer will be used to determine the $e^{+}e^{-}$ incidence positions on the detector. To be able to do this, the bars are placed in an orthogonal configuration in two sub-layers; 10 bars in the x-axis direction and 10 bars in the y-axis direction. The E layer is made up of a calorimeter of 10 cm x 5 cm x 5 cm. A complete clover consists of 4 ΔE−E detector telescopes in a square configuration (2 x 2). To characterize the setup, Geant4 simulations were done [4]. These simulations allowed us to calculate a detection threshold energy for electrons of 3.6 MeV (in the three layers: two thin bars and a calorimeter). Such values showed that conventional static electron sources (for instance, a ^{90}Sr/^{90}Y) are not useful for detector response characterization. Therefore, only cosmic radiation or reaction products were used for this purpose. These simulations also were used to calculate a maximum detection efficiency at ϵ^{max}_{pair} ~ 2.5%, in a similar detector arrangement as the one reported in the reference [3]. Several experiments were done to determine the best material configuration to cover the plastic scintillators and to test the electronic setup for data acquisition.

In this work, the first in-beam experiment is presented. It was done at the CN accelerator (INFN-LNL). We used a LiF on Cu backing as a material target. In analogy with the experiment reported in the reference [1], the nuclear reaction ^{19}F(p, α)^{16}O is used as a calibration reaction and the population of the ^{8}Be* was done via the irradiation of ^{7}Li with 1 MeV protons (^{7}Li(p,$e^{+}e^{-}$)^{8}Be). The aim of this setup is the measurement of the $e^{+}e^{-}$ angular correlation distribution in the internal pair creation decay of ^{8}Be to compare it with the one of the Hungarian group.

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Evolution of triaxiality in neutron-rich Ruthenium isotopes: lifetime measurements of excited states

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Neutron-rich nuclei close to mass 100 exhibit changes in deformation which are highly sensitive to variations in proton and neutron number. Among these are ruthenium isotopes with pronounced triaxial deformation in the ground state [1]. The shape evolution in this mass region has been studied through lifetime measurements of excited states. In an experiment at GANIL, a wide array of neutron-rich nuclei were produced in fusion-fission reactions between a ^{238}U beam accelerated to 6.2 MeV/u and a stationary ^{9}Be target. The mass, charge, atomic number and velocity of the fission fragments were measured in the Variable Mode Spectrometer on an event-by-event basis. The combination of the Advanced Gamma Tracking Array placed at backwards angles with a magnesium degrader foil mounted in the Orsay Universal Plunger System was employed to measure picosecond lifetimes with the recoil-distance Doppler shift method [2]. The precise event-by-event measurement of velocity has made possible the development of a new variant of the RDDS method with increased range, where gates applied to the velocity provide multiple data points for each target-degrader distance.

An overview of the lifetime measurements shall be presented, focusing on odd and even ruthenium isotopes. For ^{110}Ru and ^{112}Ru, lifetimes could be measured in both the ground-state and one phonon gamma bands. The experimental results will be compared to either local triaxial rotor or particle-rotor models, and to current global theoretical calculations.

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Measurement of Half-Lives of Alpha-Decaying Francium and Radon Isotopes using the DESPEC setup

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The isotopes ^{217}Fr, ^{218}Rn and ^{219}Rn are short-lived alpha decaying isotopes present in natural radioisotope decay series. The half-lives of these isotopes have been measured a few times in the past, from the time difference between alpha-particles producing the isotope and from it decaying. In all cases the isotopes are produced indirectly from the decay of radioactive sources. These results have inconsistencies and do not fully evaluate systematic components to the uncertainties [1].

In 2021 data was taken for the isotopes using the DESPEC [2] setup at GSI. From this data, the isotopes were directly produced in fragmentation reactions at the FRS target and implanted into the silicon implantation detector AIDA, which subsequently can also measure the alpha decays of the isotope and its daughters. The half-lives can be directly measured from the timestamped data. The direct production, separation and identification from the FRS [3] allows reduced systematic uncertainty compared to prior measurements.

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Study of deformed structure in ^{254}Es and ^{249}Cf via Coulomb excitation gamma-ray spectroscopy

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Exploring the new elements toward the high end of the nuclear chart is one of the most interesting topics in nuclear physics. Currently a search for new element in so-called super-heavy region is on- going. Key ingredient to stabilize nucleus in this region is a nuclear shell structure and Z=114, 120, N=184 [1-4] are predicted to be new magic numbers. However, the access to such nucleus and study the shell structure are limited by the very low cross sections. To investigate the shell structure, we are focusing on the deformed nucleus of the A~250 heavy mass region including ^{254}Es, ^{249}Cf isotopes. By studying the excited states, spin and parity, and deformation, we will be able to access the single-particle orbital which is supposed to generate new shell structure at Z=114, 120, N=184 and try to investigate nuclear shell structure in the super-heavy mass region.
In A~250 nuclei, experimentally observed rotational bands indicate the existence of deformed structure in this region, however the studies of deformation, such as determination of quadrupole moment, are not performed well. To understand single-particle structure, it is important to determine the size of ground state deformation systematically.

In order to study nuclear deformation in A~250 region, we have performed Coulomb excitation experiments to determine the deformation of low-lying states of ^{254}Es and ^{249}Cf. The experiment was performed at the JAEA-Tokai Tandem accelerator using ^{58}Ni beam with an energy of 250MeV. The very rare ^{254}Es was produced at the High-Flux Isotope Reactor at ORNL, USA, and it was separated at the ORNL's Radiochemical Engineering Development Center. The ^{254}Es target was produced at JAEA using less than a microgram of material. Particle-gamma coincidence measurements were conducted using segmented CD-silicon detectors placed backward and forward from the target and the Ge and LaBr3 detectors placed around the target. From the gamma-ray spectrum analysis, rotational band structures in both ^{254}Es and ^{249}Cf were observed.
In the presentation, recent experimental results will be discussed.

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Gamma spectroscopy of neutron-rich Y isotopes: Identification of new multi-quasiparticle isomers

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For the neutron number N = 60, a sudden onset of the deformation has been observed in Y isotopes at the ground state, which is manifested by the presence of rotational bands (e.g. [1]). On the other hand, the occurrence of shape coexistence in nuclei with N = 58 and 59, in this region (e.g. [2]), suggests that the evolution of the deformation is a more gradual process. Our recent research has shown that already in the N = 57, ^{96}Y isotope the coexistence of spherical and deformed structures are present and a rotational band is built on the top of a new (6$^+$), 181-ns isomer [3]. For N = 60, i.e., in ^{99}Y, in addition to the ground state rotational band, two other bands were found above the 11/2$^+$ (1.6 ns) and 17/2$^+$ (8 µs) isomers. These isomers have been interpreted as three-quasiparticle states with π5/2[422]ν3/2[411]ν9/2[404] configuration. In both ^{98}Y and ^{99}Y, the special role of the $g_{9/2}$ neutron extruder in stabilizing the deformed minimum was recognized. Our goal is to search for similar isomers at relatively high-spin in Y isotopes beyond the N = 60 boundary.

The neutron-rich ^{100}Y and ^{101}Y isotopes have been produced in the fission of a ^{235}U active target induced by thermal neutrons from the reactor at Institut Laue-Langevin. The level scheme up to excitation energy of 2.5 MeV has been established based on multi-fold gamma-ray coincidence relationships measured with the new highly efficient HPGe array - FIPPS [4]. Additionally, the low-spin structures in ^{101}Y have been examined using a dedicated measurement where gamma rays from the fission products separated by the LOHENGRIN spectrometer were measured with HPGe and Si(Li) detectors .

By exploiting gamma delayed- and cross-coincidence techniques [5], new isomeric states at higher excitation energy have been located in ^{100}Y and ^{101}Y. It was also possible to identify new rotational bands above the isomers in ^{100}Y and ^{101}Y. As in the case of ^{99}Y isotope, the isomeric states could be interpreted as multi-quasiparticle type. It should be emphasized that this is in contrast with other isotopic chains with N > 60 and Z = 38-44, where the bandheads of the higher-located rotational structures are not isomeric. The configurations of the new structures will be discussed based on the observed decay patterns, as well as Hartee-Fock-Bogoliubov calculations. The results suggest that 9/2$^+$[404] neutron orbital is no longer involved in the configurations of the isomers.

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Development of a mobile gamma-ray $LaBr_3$:Ce detector system for in situ radionuclide analysis

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The spillage of polluted process water from the Bosveld Phosphates mine adjacent to the Kruger National Park, South Africa during December 2013/January 2014, led to the investigation of possible radiation pollution in the Olifants River. The river runs directly into the park. An environmental impact study has been planned together with South Africa National Parks for in situ measurements, to evaluate the current situation in terms of pollution from a radiation and chemical perspective. The study will be extended upstream from the Olifants River to create a footprint of the current state of radiation contamination and the determination of disequilibrium by investigating the chemistry related to U, Th and the relevant gamma-ray emitting isotopes.

A mobile gamma-ray detection unit equipped with a $LaBr_3$:Ce detector has been designed and built in the form of a portable backpack that can be used for in situ measurement of radionuclide activity. Real-time activity data are collected and synchronised with GPS coordination. In addition to these measurements, grab samples (soil and water) are taken and analysed in the laboratory using a gamma-ray spectrometer equipped with an HPGe-detector.

A comparison of in situ results obtained by the mobile device and the more sensitive laboratory spectrometer will allow the determination of the sensitivity, effectiveness and practicality of the mobile system. Grab samples will be analysed chemically to determine radioactive decay disequilibrium and fate and transport of radioactive elements. These results will be used for environmental impact study purposes in the designated areas affected by the mine spillage as mentioned earlier.

Proof-of-principal of the measurement system was undertaken at iThemba LABS with radioactive sources and at the South African Nuclear Energy Corporation. In situ measurements at two sites in the Kruger National Park have been performed.
An overview of these measurements and preliminary results will be presented.

Innovative material developments for target backings

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A new generation of instruments dedicated to the study of heavy and superheavy elements has just been commissioned in many laboratories around the world. One can cite the SPIRAL2 accelerator in GANIL, the SHE Factory in FLNR and the new RILAC2 in RIKEN which are designed to reach beam intensities up to 10 pμA with heavy ions as ^{48}Ca, ^{50}Ti, ^{51}V or ^{54}Cr. Under these conditions, with more than 6.10^{13} ions per second interacting with the target, the beam spot power will be unsustainable for the usual target backings used in such experiments. For decades, we were using a classical Titanium backing which is no longer relevant for such intensities. The development of a new generation of materials especially designed for these specific conditions become of paramount importance for the future of SHE studies.

With the support of an USIAS (University of Strasbourg Institute for Advanced Study) grant, we are exploring the current possibilities at IPHC. For these developments, we face two major problematics : the heat dissipation and the structure faults induced by high dose effects. Moreover, we are still constrained by the required properties of a target backing such as the thickness of the foil (in the μm order of magnitude) and the mass (low Z) of the chosen material. These requirements has pushed us to consider Carbon-based foils as very promising leads, and espe- cially graphite, diamond-like carbon and graphene. We studied these different materials with a special interest for the graphene structure. This pure Carbon material consisting of a single layer of atoms arranged in a two-dimensional honeycomb lattice nanostructure shows amazing thermal and mechanical properties. Its thermal conductivity constant can reach 5 000 W/mK against 17 W/mK for pure Titanium and it is considered as the strongest material ever tested, with an incredible 130 GPa tensile strength (20 to 100 times more than Titanium). Although this innovative material seems to be very promising, the production of foils with a few μm thickness requires a state of the art collaboration between chemistry, material physics and nuclear physics, strongly supported by the pluridisciplinarity of IPHC. This helped us to shape three types of graphene foils made with three different methods which are currently under study to measure their mechanical properties. Nevertheless, it will be mandatory to test these foils under real conditions to measure the dose effects induced under irradiation.

In parallel, we are also considering to test different alloys with a Titanium base or not, which are widely used, as an instance in the aerospace industry, but in totally different conditions. In this context, we are building a laboratory fully dedicated to these studies in IPHC with the ambition to produce and characterize these alloys with different compositions, crystalline phases and cooking methods. These alloys show multiple axis of interest : they have been studied for decades, they are available in large quantities and they are much easier to handle and to produce than graphene. Moreover, the design of an alloy especially dedicated to our studies could allow us to customize it on purpose. As an instance, it can be possible to add specific elements or even to dope it or to cover it with light elements as Boron in order to take the benefit of their mechanical properties (tensile strength, flexibility, thermal conductivity...).
The first part of this talk will be dedicated to the characterization of the extreme conditions these materials will encounter at the target plane. Then, our first materials and some preliminary results will be presented and we will finish by a discussion on the possibility to test these innovative foils under real conditions ; as close as possible to the operational conditions of the future experiments that will be performed with such intense beams.

Development of a new γ - γ angular correlation analysis method using a symmetric ring of clover detectors

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A new method for γ - γ angular correlation analysis using a symmetric ring of HPGe clover detectors is presented. Pairwise combinations of individual crystals are grouped based on the geometric properties of the spectrometer, constrained by a single variable parameterization based on symmetry considerations. The corresponding effective interaction angles between crystal pairs, as well as the attenuation coefficients are extracted directly from the measured experimental data. Angular correlation coefficients, parameter uncertainties and parameter co-variances are derived using a Monte-Carlo approach, considering all sources of statistical uncertainty. The general applicability of this approach is demonstrated by reproducing known multipole mixing ratios in ^{177}Hf, ^{152}Gd and ^{116}Sn, populated by either β-decay or (n,γ)-reactions, measured at the Institut Laue-Langevin, using the EXILL&FATIMA spectrometer and different configurations of the FIPPS instrument. The derived mixing ratios are in excellent agreement with adopted literature values with comparable or better precision [1].

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Missing mass spectroscopy of proton-rich N=2 isotone

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While more and more experimental results are accumulated for the neutron-richnuclei, the experimental result of the proton-rich nuclei is still limited sincethey are more unbound than their mirror nuclei by the Coulomb repulsive force. Theproton-rich N=2 isotone is a unique system since all of them ever observed, ^{5}Li, ^{6}Be, ^{7}B and ^{8}C are particle unbound relative to alpha and 1 to 4 proton emissionthough some of their mirror partners, neutron-rich He isotope ^{6}He and ^{8}He, havebound ground states. Almost only the ground states have been confirmed for theseproton-rich N=2 isotone and the experimental investigation of the excited resonancesof them is interesting.We performed the experiment at GANIL. A ^{9}C secondary beam containing N=3 isotone ^{8}B, ^{7}Be and ^{6}Li was produced by the LISE spectrometer. Unbound states in N=2 isotone ^{8}C, ^{7}B, ^{6}Be and ^{5}Li were populated via the (p,d) reaction with a thin liquidhydrogen target. An array of MUST2 telescopes was used to detect recoil deuteronsfrom the target and decay fragments. The excitation energy and angular distributionwere reconstructed by the missing mass method. We will report on the experimentalresult of newly observed resonances.

Level-lifetime measurements using inelastic nuclear collisions: addressing the $B(E2)$ disparity in Sn isotopes

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There has been a considerable interest focused on the study of enhancement or suppression in low-lying quadrupole collectivity in the even-even Sn isotopes. Multiple independent studies have investigated the collective nature of the first-excited 2^+ state through experiments on Coulomb excitation [1, 2], heavy-ion scattering [3] and lifetime measurements for the 2^+ level [4]. In particular, the existing lifetime estimates for the stable Sn isotopes indicate significantly reduced collectivity, with different trends in the regions prior to and post the midshell (^{116}Sn) between the N = 50 and N = 82 double-shell closures. A re-examination of the same has been carried out via a series of fresh experiments, on two of the stable isotopes − one prior to and one post the midshell - ^{112,120}Sn, as reported in this contribution. Low-lying levels in the ^{112,120}Sn isotopes have been populated by inelastic scattering with heavy-ion beams. Using an array of HPGe clover detectors, new lifetime values are extracted with the Doppler shift attenuation method (DSAM), implemented using updated methodologies [5,6].

The transition characteristics are inferred through the $B(E2;\, 0^+_{g.s.} \rightarrow 2^+_1)$ values, which confirm the presence of signatures of enhanced quadrupole collectivity, and are in compliance with systematic Coulomb excitation measurements on the Sn isotopes, thereby addressing the long-standing discrepancy. Good agreement is also seen with generalized seniority model [7] as well as state-of-the-art Monte Carlo shell model [8] calculations. In particular for ^{112}Sn [6], both the $0^+_{g.s.}$ and 2^+_1 states are seen to have oblate deformations, leading to the highest $B(E2;\, 0^+_{g.s.} \rightarrow 2^+_1)$ value across the Sn chain. The results will be presented and discussed. To expand the scope of this work, similar attempts are underway to implement DSAM in other avenues such as transfer reactions, to probe the 2^+ lifetime for the unstable ^{110}Sn nucleus, populated by 2*n*-transfer from ^{112}Sn.

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Italian National Repository: research opportunities at the Technology Park

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The National Repository for the Italian Radioactive Waste will be realized, as for Legislative Decree n° 31/2010, within a Technology Park, a centre of excellence to be designed for advanced R&D on nuclear matters and sustainable development and to provide information and training. National and International scientific communities will be engaged in the development of the research laboratories together with the local communities.

Among the research equipment and facilities planned for the Technology Park the ones involving neutrons and gamma rays are expected to play a major role in the scientific programme.

This presentation is intended to give a brief illustration of the state of the art and perspectives for this project.

Energy functionals from *ab initio* nuclear matter calculations

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Density functional theory (DFT) is a powerful and versatile method in nuclear structure theory [1], with wide-ranging applications such as ground states and collective excitations of nuclei over the whole nuclear chart and infinite nuclear matter. The predictive power of DFT is tied to the accuracy of the nuclear energy density functional (EDF) on which it is based on. Current phenomenological EDFs, which are constrained by experimental measurements of nuclei close to magicity, are rather successful in reproducing stable nuclei. However, in order to overcome their known shortcomings that are visible e.g. when they are applied to nuclei far from the stability valley, new strategies are called for.

On the other hand, *ab initio* holds the promise of allowing us to determine the structural properties of nuclei and nuclear matter in a fundamental and unbiased way, starting from the individual interactions between the constituent protons and neutrons [2]. At the same time, *ab initio* methods are rather demanding computationally and cannot be routinely applied to heavy nuclei.

In this contribution, we would like to describe our approach to constructing EDFs based on *ab initio* nuclear theory [3]. Our key idea is to constrain the EDF on *ab initio* predictions for the equation of state (EOS) of infinite nuclear matter and its response to an external static potential [4]. We will present our results obtained with the Quantum Monte Carlo and the Self-consistent Green's functions *ab initio* approaches. Then, we will discuss how the former can be compared to DFT calculations of the static response in order to constrain the gradient terms of the EDF [5].

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Experimental study of the pygmy dipole resonance and its evolution in Sn isotopes

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The electric dipole response of neutron-rich nuclei below the neutron threshold often reveals presence of the pygmy dipole resonance (PDR), superimposed on the low-energy tail of the giant dipole resonance (GDR). As the PDR is usually interpreted in relation to the neutron excess, a multifaceted experimental and theoretical study of this feature may have a significant impact on studying both the nuclear structure properties in general and the astrophysical r- and s-processes of element production.

This work presents a systematic study of the dipole γ-ray strength functions (GSF) below the neutron threshold in eleven Sn isotopes ($^{111-113}$Sn,$^{116-122}$Sn and ^{124}Sn) with a primary goal of investigating the evolution of the pygmy dipole strength with an increasing neutron number in the Sn isotopic chain. The experimental GSFs have been extracted from the particle-γ coincidence data by applying the Oslo method [1], primarily used for the simultaneous extraction of statistical properties of nuclei, such as the GSF and nuclear level density. The most recent (p, p' γ) experiments on ^{117,119,120,124}Sn have been performed at the Oslo Cyclotron Laboratory with a new array of 30 $LaBr_3$(Ce) scintillator detectors (OSCAR). This provides an improved energy resolution and timing properties for the selection of p-γ events as compared to the earlier experiments with the NaI detector array CACTUS. The shapes of the strengths in these nuclei have been additionally constrained by applying the novel Shape Method to the coincidence data [2]. The previously published strengths in $^{116-119,121,122}$Sn [3] have been reanalyzed in order to provide a coherent analysis of the strengths in the studied nuclei.

All experimental strengths were compared to the GSFs extracted from relativistic Coulomb excitation in forward-angle inelastic proton scattering below the neutron separation energy [4] and were found to be in excellent agreement within the experimental error bands in the regions where the data overlap. The Oslo method strengths below the neutron threshold, combined with the inelastic proton scattering data above the neutron threshold provide an exhaustive picture of the nuclear response, covering the GDR, the PDR and the low-lying M1 strength. The evolution with an increasing neutron number of parameters characterizing the PDR as well as the fraction of the corresponding classical Thomas-Reiche-Kuhn sum rule will be presented together with the study of the effect of the pygmy dipole strength on the radiative neutron capture cross-sections is these nuclei. The increasing number of neutrons was found to lead to the increasing low-lying dipole strength towards the heaviest studied ^{124}Sn isotope. This trend may be expected to be the case for even heavier nuclei and play a noticeable role in various astrophysical scenarios.

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Optimizing the number of states in the Generator Coordinate Method

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The Generator Coordinate Method (GCM) is a widely used beyond-mean-field technique providing variational solutions to the many-body problem. This method is based on the mixing of different intrinsic (non-orthogonal) configurations along generating coordinates, such as mass multipole moments and pairing correlations.

In order to obtain the energy spectrum, we have to solve the Heel-Wheeler-Griffin equation as a generalized eigenvalue problem, which requires the construction of an orthonormal basis. This so-called 'natural basis' can be prone to numerical instabilities due to the presence of (approximate) linear dependencies in the set of states included in such basis.

We propose a new method for reducing such numerical instabilities based on the orthonormal property of the natural basis norm overlap matrix. By exploiting the saturation in the number of states in the natural basis, we are able to optimize in a sensible way the number of both intrinsic and natural basis states needed for the calculations, with a corresponding reduction of computational time cost and improved numerical stability.

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Lifetime measurement of first 4^+ state in ^{102}Sn

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The long chain of Sn isotopes is a formidable testing ground for nuclear models studying the evolution of shell structure and interplay between pairing and quadrupole correlations. A transition from superfluid nuclei at midshell to spherical nuclei is also expected approaching the neutron shell closures at N = 50, where the seniority scheme can be adopted to describe the energy spectra. However, the corresponding B(E2: $0^+ \rightarrow 2^+$) values have shown a presumed deviation from the expected parabolic behavior. From a theoretical point of view, various attempts have been done to explain the experimental results, in particular by including core-breaking excitations in the shell-model calculations by activating protons and neutrons from the g9/2 orbital to he higher ones.

From experimental side, limited data are available beyond ^{104}Sn on this very neutron deficient region, leading to a diffculty in a firmly establishment of core-braking effect. In this presentation, we will report on the first lifetime measurement for the 4^+ state in ^{102}Sn which is sensitive to the balance between the pairing and quadrupole terms in the nuclear interaction. The experiment is performed at GSI based on the use of hybrid AIDA+HPGe+$LaBr_3$(Ce) array, made available by the HISPEC/DESPEC collaboration. The nuclei of interest were separated and identified through the FRS separator, following the production via fragmentation reaction of ^{124}Xe beam incident on a ^{9}Be target. The ^{102}Sn ions are stopped by AIDA array and γ rays emitted from the 6^+ seniority isomer are collected by FATIMA array which allows a direct lifetime measurement with a precision up to few tens of ps. The obtained experimental data would be compared with theoretical predictions, shedding light on the detailed wave function and the core-breaking contribution.

Measurement of nuclear transmutation via muon capture reaction for Si isotopes

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The muon capture reaction is a capture of a negative muon by a proton in the nucleus via the weak interaction. This reaction produces an excited Z-1 nucleus having the same mass as the original nucleus. Although the existence of the muon nuclear capture event has been well known since the 1950s, the measurement data of the excitation energy of the nuclei or the branching ratio of particle emissions from this excited state are sparse, and there is no established model of muon capture. The production branching ratio of each daughter nucleus produced by the muon capture of Si isotopes, which gives information on the energy distribution of the excitation states populated by the muon nuclear capture, was measured with some methods [1-4]. But these methods contain some assumptions, and they show some discrepancies in the production branching ratio. Therefore, to obtain accurate data and evaluate the excitation state of the nuclei after the muon capture, we measured the absolute production branching ratio of the muon capture of Si isotopes with a new method, the *in-beam* activation method.

The experiment was performed at the Materials and Life Science Experimental Facility (MLF), J- PARC [5]. In the facility, the pulsed muon beam is produced by decay of pions, which are generated by irradiating the graphite target with the 3-GeV proton beam. The pulsed beam has a quiet time period between any neighboring pulses, suited for the β-decay measurement without beam background. In the *in-beam* activation method, β- delayed γ-rays are simultaneously measured during the beam irradiation thanks to the time structure of the pulsed muon beam. The negative muon beam at 38 MeV/c irradiated targets at 25 Hz. The targets were enriched ^{28,29,30}Si powders and a natural Si plate. Two Ge detectors were used for gamma-ray detection, and a thin plastic scintillator was used for the muon counter. The response function of the plastic scintillator was also measured with the in-beam activation method of the Al target by changing the intensity of the muon beam.

From this experiment, some β- delayed γ-ray peaks from Na, Mg, and Al isotopes were observed. The absolute production branching ratio of muon capture of Si isotopes is obtained from the counts of these gamma-ray peaks and the number of irradiated muons. This result is also compared with the PHITS simulation. The result of the experiment will be reported in this presentation.

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The low-lying dipole response in ^{64}Ni

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The Pygmy Dipole Resonance (PDR) is an electric dipole excitation mode located below and around the neutron-separation threshold and has attracted considerable attention for the last dec- ades [1,2]. Although some experimental and theoretical effort was put in its investigation, there are still some open questions concerning this excitation such as its origin and degree of collectivity. Besides comparing results when the same nucleus is irradiated with different probes (multi- messenger investigations) [3], studies within isotopic and isotonic chains using the same probe help to deepen our understanding of the low-lying electric dipole response of atomic nuclei. The nickel (Z = 28) isotopic chain is well suited for this purpose because it consists of four even-even, stable isotopes with N/Z ratios between 1.07 and 1.29. The dipole response of ^{58,60}Ni has already been investigated in real photon-scattering experiments [4-6], also denoted as Nuclear Resonance Fluorescence (NRF) experiments [7-9]. In addition to these studies of stable nuclei, the unstable isotopes ^{68,70}Ni were measured in Coulomb-excitation experiments in inverse kinematics to investi- gate the low-lying dipole response [10-12].

One missing link to complete the systematics in the Z = 28 isotopic chain is the dipole response of ^{64}Ni. Therefore, two complementary NRF experiments, using on the one hand an unpolarized, en- ergetically continuous photon-flux distribution and on the other hand a polarized, quasimonoener- getic γ-ray beam, were performed on this isotope. These enable the determination of, e.g., abso- lute transition strengths, spin and parity quantum numbers, and photoabsorption cross sections in a model-independent way.
In this contribution, the NRF technique will shortly be explained and first results of the experiments on ^{64}Ni will be presented.

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Theoretical interpretation of some special aspects in the ^{132}Sn and ^{208}Pb masses region

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In the last decades several advances have been made in the ^{132}Sn and ^{208}Pb masses region, by the measurements of many spectroscopic properties of nuclei from the two regions. Whereas some of these observations were unexpected experimentally such as: the isomeric transitions, the excited states in ^{212}Po, the transitions in ^{136}Te and ^{210}Po, ...

Within the shell-model framework, I will discuss some of these results by giving the theoretical interpretations reinforced by the calculations using our effective interactions N3LOP [1] and H208[2] developed respectively, for the ^{132}Sn and ^{208}Pb masses regions.

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Isospin symmetry breaking in the nuclear ground state

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Isospin symmetry of atomic nuclei is broken due to the Coulomb interaction and the isospin symmetry breaking (ISB) terms of the nuclear interaction. Although the ISB terms are a tiny part of the whole, attention has been paid, for instance, to the mass difference of mirror nuclei and the isobaric analog states.

In this talk, first, the effects of ISB terms on the neutron-skin thickness of both $N = Z$ and $N > Z$ nuclei and the charge radii difference of mirror nuclei will be discussed. Then, the effect of the ISB terms on the estimation of the density dependence of the symmetry energy (L) using these observables will be discussed. At last, we will show a new way to pin down the strength of the charge symmetry breaking term, which is a part of the ISB terms, and a related puzzle.

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Internal conversion electron spectroscopy of even-even nuclei

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Spectroscopy of electrons originating from nuclear processes provides an important tool for nuclear structure investigations. Electron measurements are particularly relevant in the study of electric monopole (E0) transitions connecting 0^+ states since they cannot proceed via gamma-ray emission.

The E0 transitions are an ideal tool to investigate specific nuclear structure phenomena because they are related to the radial distribution of the electric charge inside the nucleus therefore the monopole transition strengths are sensitive to changes in the shape of the nuclear states.

We have performed electron conversion measurements at the National Legnaro Laboratory of INFN, with the aim of study the O(6) symmetry breaking in the even-even ^{126}Xe isotope. The isotopes $^{124-132}$Xe have been for many years considered as good examples of O(6)-like nuclei in the framework of the IBM model. This interpretation was later questioned by measurements of B(E2) strengths in ^{124,126,128}Xe [1,2]. The absolute B(E2) values seem to indicate that the O(6) symmetry is broken. This result has been recently confirmed by a study of the validity of the O(6) $\supset$ O(5) symmetry in the various vibrational bands of the ^{126}Xe isotope.

Since in the O(6) limit E0 transitions obey different selection rules than E2 transitions, the study of E0 transitions between states having the same spin and parity can give important information on the level structure and therefore can help testing the proposed O(6)-symmetry breaking.

We will report on the results we obtained concerning internal conversion coefficients and electric monopole strength. A comparison with the predictions of the interacting boson model will also be presented.

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Heavy-baryon ChPT with vector mesons and a novel NN force

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We extend chiral perturbation theory to include vector mesons as well as pions and nucleons. By counting the vector meson mass as heavy while treating the associated momentum as light, a consistent scheme can be obtained with a well-defined power counting rule.

In the resulting theory, contrary to usual vector-meson dominance (VMD) model, the vector mesons appear as auxiliary fields that can be completely integrated out at the leading order, and the genuine vector meson contributions are taken into account as the loop corrections at higher orders.

We find that the extended theory can describe the electromagnetic form factors of pions and nucleons far better than the conventional ChPT does, achieving the so-called vector-meson dominance in a systematic way.

The resulting chiral nuclear force up to next-to-next-to-leading order (N2LO) has been obtained and applied to NN phase shifts, which shows improved accuracy compared to the conventional ChPT forces, revealing the role of vector mesons in low-energy nuclear dynamics.

Spectroscopy of ^{126}Sn following two-neutron transfer: Evidence for a 0^+ intruder state

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The chain of Sn isotopes provides a special benchmark for nuclear structure studies as it contains two doubly-magic nuclei, ^{100}Sn and ^{132}Sn, and 10 stable isotopes in between. The enhancement of the $B(E2,2^+\rightarrow0^+)$ values for the lighter Sn isotopes near N=60, which has been a challenge for theoretical models for a long time, was recently explained by large-scale Monte Carlo shell model calculations as due to the breaking of the Z=50 core and associated deformation [1]. The spectroscopic quadrupole moments for the first 2^+ states, on the other hand, show a maximum at mid-shell [2]. Deformed intruder states, manifested as excited 0^+ states with rotational bands on top, are also lowest at mid-shell [3]. These 2p-2h states and their mixing with the ground and first excited 2^+ states play an important role for understanding the electromagnetic moments in the chain of Sn isotopes. The heaviest Sn isotope for which an excited 0^+ state is known, is ^{124}Sn.

To extend the systematics of intruder states in the chain of Sn isotopes, we have studied ^{126}Sn in a two-neutron transfer reaction experiment. Excited states in ^{126}Sn were populated by the ^{124}Sn(^{18}O,^{16}O)^{126}Sn reaction with a beam energy of 56 MeV, slightly below the Coulomb barrier. The experiment was carried out at IFIN-HH in Bucharest using the ROSPHERE array comprising 25 Compton-suppressed HPGe detectors coupled to an array of 6 silicon detectors under backward angles. A new excited 0^+ state was observed and unambigously assigned by gamma-gamma angular correlations of the 0^+-2^+-0^+ cascade. Doppler-broadened line shapes from the stopping of the recoils in the 8 mg/cm^2 thick target allow lifetime measurements for several states using the Doppler shift attenuation method.

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Exploring the Pygmy Dipole Resonance in deformed nuclei

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Studies on the Pygmy Dipole Resonance (PDR) are currently almost exclusively focused on spherical nuclei [1-3]. For deformed nuclei several theoretical and experimental studies have been performed to investigate the response of the Giant Dipole Resonance (GDR) while only few focused on the PDR. Results from a (p,p') inelastic scattering experiment on ^{154}Sm performed at RCNP (Japan) [4] showed evidence of a double-hump structure similar to the one predicted for the GDR where the deformation gives rise to a splitting in the dipole strength related to longitudinal and transversal oscillations against the symmetry axis [5]. This double structure could also be explained by the isospin mixing of the pygmy states that in spherical nuclei have shown to generate a splitting of the strength when excited with isovector or isoscalar probes. In order to have a better understanding on the role of deformation in the excitation of the PDR, a systematic investigation must be performed. Experiments to study the isoscalar response of spherical and deformed nuclei were performed at iThemba LABS (South Africa) using inelastic scattering of α- particles at 120 MeV. The scattered particles were detected by K600 magnetic spectrometer, while the subsequent gamma decay was measured by the BaGeL (Ball of Germanium and LaBr detectors) array. The results of these studies will be presented in this talk.

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Study of intruder states towards ^{78}Ni by performing lifetime measurements in ^{83}Se

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Quadrupole interaction between protons and neutrons drives the nucleus into deformed configurations at low excitation energies. Around the N=50 shell gap, intruder states with spins $1/2^+$ and $5/2^+$, originating from the $s_{1/2}$ and $d_{5/2}$ orbitals were first observed in ^{83}Se and, later on, in the other N=49 isotones. In this nucleus, intruder states reach energies of around 500~keV, the lowest among the other N=49 isotones. The ^{83}Se nucleus is at the mid of the proton fp-shell and it should have the maximum quadrupole correlations which makes it a good candidate to understand the collectivity of the particle-hole intruder states in this region, lowered in energy by large quadrupole correlations. Indeed, large-scale shell-model calculations predict a quenching of the energy of the intruder states in ^{83}Se, at variance with the experimental data [1]. Lifetime measurements of the intruder states of ^{83}Se would give an indication of their wave function and would allow estimating the degree of the N=50 core breaking in the ground state of Se isotopes. Moreover, such measurements could shed light on the behavior of the N=50 shell gap towards ^{78}Ni, a double-magic nucleus in which intruder configurations competing in energy with the spherical ones have also been found [2].

We will report on the results obtained from a recent experiment performed in Laboratori Nazionali di Legnaro, where lifetimes of the intruder-state band were measured using RDDS and DSAM techniques. A beam of ^{82}Se, with intensity 0.02 pnA, accelerated at 270 MeV by the ALPI-TANDEM accelerator at LNL-INFN, impinged into a deuterated polyethylene (C_2D_4) target which was evaporated on a 6 mg/cm^2 thick gold layer. The GALILEO γ-array was coupled to the SPIDER silicon-array, allowing to obtain the needed channel selectivity through coincidence measurements between γ rays and protons coming from the (d,p) transfer reaction. The results on lifetimes will be discussed in the framework of large-scale shell-model calculations and mean-field approaches, pointing out the role of the collectivity of low-lying intruder configurations.

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First spectroscopy of the T=3/2 p-unbound ^{55}Cu

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Mirror energy differences provides a powerful tool to investigate the evolution of the nuclear structure as a function of angular momenta. In the latest years detailed studies aimed to probe the influence of isospin non-conserving interaction [1] and the effects of halo orbits and their occupation [2–4] on the displacement of analogue excited states of mirror partners were performed, showing excellent agreement between data and large scale shell model calculations. Moreover with the nowadays intensities of radioactive ion beam, the validity of the shell model and, in general, of our knowledge of nuclear structure, can be challenged towards the proton drip line. In this presentation, we will report on some preliminary results from in-beam γ-ray spectroscopy studies of excited states in the T_Z=-3/2 ^{55}Cu carried out at the Radioactive Isotope Beam Factory, RIKEN (Japan). The mirror energy differences are interpreted within the shell model framework where Coulomb and isospin breaking terms have been included. In this work we will extend the investigation on the structure of proton-rich nuclei to the middle of the fp shell and beyond the proton stability. Finally we will try to address how the competing processes of proton decay and γ-ray de-excitation can impact on cross section estimations.

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Nuclear physics in the N~126 region relevant for the r process

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Half of the nuclei heavier than iron were synthetized in the r process. The r-process yield peak at A~195 is linked to the N=126 closed neutron shell. In contrast to lighter mass regions, the r-process waiting point nuclei at N=126 still cannot be studied experimentally, and the yield calculations rely entirely on theoretical nuclear physics properties.

The most neutron rich N=126 nuclei for which basic observables such as the ground-state lifetime and mass were determined are ^{204}Pt (Z=78) and ^{206}Hg (Z=80), respectively. Therefore information on features which determine these values, single-particle energies and nucleon-nucleon interactions are crucial in order to increase the predictive power of nuclear theories. Nuclear structure information, like excited state energies, gamma-ray transition energies and transition strength are known "down" to ^{203}Ir (Z=77).

The neutron-rich N~126 region is different in two ways when compared to lighter nuclei.

i. In this heavy region the first-forbidden (FF) beta decays are expected to compete against allowed ones, and even to dominate, with profound implications on their half-lives and therefore on the r-process [1]. And FF transitions are notoriously difficult to calculate. The beta decay of ^{208}Hg into ^{208}Tl was studied at ISOLDE Decay Station at CERN. Three negative parity excited states in ^{208}Tl were populated directly in beta decay. In contrast none of the positive parity states were populated. This latter can be understood by considering the properties of the single proton and neutrons involved [2]. Similarly to ^{208}Hg, ^{207}Hg also decays predominantly via first-forbidden decays [3].
ii. A less well-known selection rule for the otherwise allowed beta-decays is that the number of nodes (n) in the radial wave functions of the initial and final states has to be the same. If the selection rule is strictly obeyed, beta decay between them is forbidden, resulting in longer lifetimes. The greatest impact is on nuclei where the Fermi level lies high above N=126 and/or much below Z=82, e.g. nuclei on the astrophysical r-process pathway, influencing the nucleosynthesis of heavy elements. This selection rule has little effect on isotopes which are proton-rich or close to the stability line, making the experimental investigation of its validity difficult. The most stringent test on the validity on this selection rule was provided by the beta decay of ^{207}Hg, where the level of forbiddeness of the Δn=1 1g9/2 -> 0g7/2 was recently investigated at ISOLDE. An upper limit of 3.9×10^{-5} was obtained for the probability of this decay, corresponding to a log(ft)>8.8 (95% confidence limit) [4].

In conclusion, the status of nuclear physics knowledge in the N~126 region relevant to the r-process will be presented, with emphasis on phenomena specifically relevant to this region: the large role of first-forbidden beta decays, and that of the Δn=0 selection rule in Gamow-Teller decays.

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^{166,167}Ho: *M1* scissors modes, (n,γ)-rates and their implications to the astrophysical s-process

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The γ-strength functions and the nuclear level densities for the rare-earth nuclei ^{166}Ho and ^{167}Ho have been extracted from the ^{163}Dy(α,pγ)^{166}Ho and ^{164}Dy(α,pγ)^{167}Ho data using the Oslo method [1].

A structure at ≈ 3 MeV in the ^{166}Ho γ-strength function is interpreted as the *M1* scissors mode. By employing three different methods we find that its strength depends rather strongly on the modelling of the *E1* strength, while its centroid does not. The ^{166}Ho scissors resonance parameters are consistent with previous results on other rare-earth nuclei.

From the level density and the strength function we can calculate the neutron-capture rate for the A-1 nucleus, this being important for astrophysical applications such as nucleosynthesis network calculations and the correct estimation of final abundances.

While the ground state of ^{166}Ho has a half-life of about one day, its first excited state has an energy of 6 keV, a spin of 7^- and a half-life of about 1200 years before β-decaying to Er [2]. This makes the timescale of its decay comparable to that of the s-process, and the (n,γ)^{167}Ho reaction possible during the s-process. The experimentally constrained (n,γ)^{166}Ho and (n,γ)^{167}Ho reaction rates are important for the correct estimation of the production of different Er isotopes, and their impact to the s-process is investigated.

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New beta decay studies in A~225 Po-Fr nuclei

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The island of octupole deformation around A~222 is the region where the strongest octupole deformations are expected to manifest [1], however very few experimental information is presently available on the 220<A<230 Po-Fr nuclei. Our experimental study aims at providing a systematic study of the β-decay properties of the mentioned nuclei. This will help to probe the predictions of global nuclear models in more exotic nuclei with N>126, of relevance to understand the formation of the heaviest chemical elements through the r process of explosive nucleosynthesis [2]. Moreover, we aim at finding evidence of octupole deformation in the populated nuclei, as octupole correlations were measured only in few selected cases: ^{220}Rn, ^{224}Ra [3] and ^{228}Th [4], highlighting also a typical de-excitation pattern.

In order to attack this hard-to-reach region, an experiment was performed at GSI-FAIR (Darmstadt, Germany) in April 2021, within the experimental campaign of the HISPEC-DESPEC collaboration. The ions of interest were produced in in-flight fragmentation reactions, selected and identified using the Fragment Separator (FRS) [5] and implanted in the DEcay SPECtroscopy (DESPEC) station [6]. The DESPEC station is composed of a stack of Double Sided Silicon-Strip Detectors (DSSD) for ion implantation and beta detection, sandwiched between two plastic scintillator detectors for beta timing measurements and a hybrid γ-detection array consisting of HPGe and LaBr3(Ce) detectors. The ions implanted in the DSSDs are let decay and the internal structure of the daughter nuclei is performed with ion-beta-gamma correlation and fast timing techniques.

Recent results on new beta decay half-lives will be reported on.

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Ab-initio description of the 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 throughout 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 first 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 (P-GCM) [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 superfluidity from an ab-initio standpoint. Sum rules are also employed within both many-body schemes 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 P-GCM 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 P-GCM could shed new promising light.

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Lifetime measurement of the first excited state in ^{84}Mo

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In nuclei along the N = Z line, as protons and neutrons occupy the same valence orbitals, proton- neutron correlation properties and quadrupole-quadrupole interactions emerges. In heavy even N = Z nuclei the competition between prolate and oblate quadrupole coherence is hitherto not measured. Well-developed deformation in the upper ***fpg*** shell starts from ^{68}Se. In ^{68}Se, the intrinsic deformation of the ground-state band has been interpreted as oblate, while a prolate deformation is assigned to the excited band that soon becomes yrast. The tendency leads to the emergence of shape coexistence, which are predicted in the strongly deformed ^{72}Kr, ^{80}Zr and ^{84}Mo [1].

In this study, exploiting an ^{86}Mo radioactive beam produced at NSCL, we measured the lifetime of the first 2^+ state in ^{84}Mo and ^{86}Mo using the GRETINA array and a plunger setup. The reduced transition probability B(E2; $2^+ \rightarrow 0^+$) of the Mo isotopes were deduced, thereby understanding their quadrupole collectivity and deformation.

The experimental results will be presented along with their interpretation with state-of-the-art calculations using ZBM3 effective interaction

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Decay spectroscopy of ^{225}Pa: Toward laser spectroscopy of neutron-deficient actinides

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The study of the structure of neutron-deficient actinides is of particular interest since several theoretical calculations predicts strong octupole deformation in this region of the nuclear chart [1, 2, 3]. In addition, this region includes ^{229}Th whose study of the low-lying isomeric state is of great interest [4]. However experimental data are scarce due to very low production rates. There is an ongoing program at IGISOL, University of Jyväskylä, to study actinide isotopes, including a study of the production and decay spectroscopy of neutron-deficient actinides through proton- induced fusion-evaporation reactions on a ^{232}Th target. A successful experiment was performed in July 2020 where short-lived actinide isotopes were produced, mass separated and guided to a decay spectroscopy station. Using an experimental setup composed of Ge, Si and Si(Li) detectors, α, γ and electron decay spectroscopy of the selected nuclei can be performed to extract the decay schemes that are missing or incomplete in this region of the nuclear chart. In this presentation, I will show results focusing on ^{225}Pa, for which very little decay information was available before this experiment, as well as its daughter nucleus ^{221}Ac. Reconstruction of the decay scheme and measurement of α hindrance factors point toward a static quadrupole-octupole deformation of both 225Pa and 221Ac. A second goal of this experiment is to measure production yields in order to consider a laser spectroscopy program in the future. Indeed laser ionisation spectroscopy is well established as a powerful tool in nuclear structure studies [5]. It allows the measurement of spins, magnetic dipole moments, electric quadrupole moments and changes in the mean-square charge radii independently of nuclear models.

In the near future, the possibility to perform laser ionisation spectroscopy at S3-LEB of neutron- deficient actinides produced and selected by S3 will allow to continue this program towards nuclei further from stability. In particular the SEASON (Spectroscopy Electron Alpha in Silicon bOx couNter) detector will enable the coupling of two approaches : laser ionisation spectroscopy and decay spectroscopy. I will conclude my talk discussing perspectives offered by SEASON at S3-LEB.

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Probing the isospin symmetry in the 43Sc-43Ti mirror pair via cross-shell excitations

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Studying the nuclei along and near the N = Z line is the best way to find answers to some fundamental questions in nuclear structure, such as charge-dependence of the nuclear interaction or the role of the proton-neutron pairing. The differences between the excitation energy of isobaric analogue states (IAS), called mirror energy differences (MED), are signatures of isospin symmetry breaking (ISB) in mirror nuclei [1]. In spite of our deep understanding of the electromagnetic interaction, the differences in the experimental binding energies in mirror nuclei cannot be reproduced theoretically [2], thus pointing that the ISB could arise also from the residual nuclear interaction [1].

Cross-shell particle-hole excitations from the *sd* to the *fp* shells in the mid-shell 42≤A≤54 nuclei generate rotational bands of non-natural parity which are particularly sensitive to the electromagnetic spin-orbit interaction. In the ^{43}Sc-^{43}Ti mirror pair such positive-parity bands should extend up to $27/2^+$. There is a competition between proton-hole and neutron-hole excitations from the sd orbitals and the MED are very sensitive to cross-shell single-particle excitations and can be used to understand which type of nucleons are excited across the shell gap.

To explore this phenomena, we performed spectroscopic studies extending the level scheme of ^{43}Ti up to the $25/2^+$. Excited states of ^{43}Ti were populated in a fusion-evaporation reaction in JYFL, Jyvaskyla. The prompt γ-rays were detected with JUROGAM 3 spectrometer while the evaporation residues were selected with MARA separator. Comparison of the IAS in the A=43 mirror pair allowed us to pinpoint the isospin dependence that has a strong effect on the band structures. Indeed, we find that the competition between protons and neutrons promoted from the $d_{3/2}$ orbital yields MED as high as 250 keV. This can be interpreted within the Shell Model as the effect of ISB nuclear force, found to be as strong in this mass region as that of the Coulomb component [1,3].

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First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the N = 40 Island of Inversion

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

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

Electro-Mechanical Advances for the N3G Experiment

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In the framework of modern gamma spectroscopy, the high-flux and high-damage experiments highlight the need for a new generation of detectors, based on electrons-collecting electrodes. The N3G (Next Generation Germanium Gamma detectors) experiment was born in order to achieve this goal, applying the PLM (Pulsed Laser Melting) doping-technique [1] to hyper-pure germanium (HPGe) detectors. In parallel to the development of innovative segmented HPGe crystals, this experiment is also aimed at the development of a detector containment system complete of contact structures and front-end electronics.

The electrodes of the detector are connected to the readout electronic chain through a two-steps system. It consists of a flexible printed circuit board (PCB) realized on a Kapton substrate, which wraps the detector itself, connected to a second PCB, that is rigid. The system described is placed inside a canister which is set on vacuum. The canister, made of aluminum, is closed by a specifically designed flange. This mechanical component is equipped with six feed-through connectors for the signals, high-voltage rod and vacuum inlet. The design of the entire canister has been thought to be compatible with the cryostats available at LNL. For the preliminary tests a dummy detector has been designed and 3D printed. This one has the same geometry of the first detector prototype. On the outer surface it presents copper contacts that are connected internally to test capacitors. In this way it is possible to use such dummy to inject current pulses into the charge sensitive pre-amplifiers (CSPs) and test the whole contact system and front-end electronics (FEE).

The N3G FEE is based on an ASIC (Application-Specific Integrated Circuit) pre-amplifier realized in AMS C35B4C3 (350 nm) technology. This CSP is being designed in two different configurations. The first one is fully integrated and has a MOS input transistor. The second one is designed to be coupled with an external JFET transistor. The CSP was tested on a dedicated testbench. It is characterized by 8MeV dynamic range, which can be extended up to 40MeV thanks to an innovative fast-reset system [2]. Below the saturation threshold, set by the power supply voltages, the pre-amplifier shows an excellent linear behavior and a leading-edge fall-time in the order of 20 ns. Its energy resolution performances were tested filtering its output signal through a quasi-Gaussian shaping amplifier and simulating the detector with a 15 pF capacitor. The Equivalent Noise Charge (ENC) and the energy resolution for 1MeV energy signals were measured for different shaping times: the best resolutions of 1.08 keV were obtained with 6 μs and 10 μs shaping-times. The energy information on the events that cause the pre-amplifier saturation can be retrieved thanks to an innovative fast-reset circuit and time-over-threshold techniques. The duration of the reset phase is directly proportional to the charge removed from the input node of the CSP and, as a consequence, to the energy released by the interactions that bring the CSP itself in saturation. The resolution expressed as FWHM for interactions of energies greater than 15MeV is better than 0.11%, which is an excellent result.

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Probing the tensor force by looking at changes in spin-orbit splittings in atomic nuclei

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The short-range strong nuclear force binds the nucleons in the nucleus and drives the emergence of a nuclear shell structure. The description of the atomic nucleus, a quantum system composed of interacting nucleons (protons and neutrons), requires the combination of three of the four fundamental forces: electromagnetic, weak and strong. The latter binds the nucleons in the nucleus and drives the emergence of a nuclear shell structure and shell gaps.

A rare fraction of nuclei, called magic, exhibit enhanced stability and play a crucial role on earth and in the fate of exploding stars, owing to the large energy gap between occupied and valence orbitals. Recent experimental achievements in nuclei with a large neutron to proton imbalance have revealed the weakening of the energy gaps associated with several traditional magic numbers. The precise mechanism behind this evolution remains however elusive, because of the complex interference between the various components of the nuclear force, such as the central, spin-orbit and tensor parts.

After a general introduction, I will show that the impact of the tensor part on spin-orbit splittings can be characterized in only few places of the chart of nuclides, with the effect of increasing or decreasing their amplitude, depending on the orbitals considered.

A special emphasis will be given to a recent experiment carried out at the Ithemba-Labs facility using the (p,d) neutron removal reaction at 66 MeV using a $^{36}S_{20}$ target. We observe a decrease by about 400 keV of the neutron $0d_{5/2}$ - $0d_{3/2}$ spacing between $^{40}Ca_{20}$ and $^{36}S_{20}$, as compared to an expected increase by about 450 keV, from the sole action of the spin-orbit force. This example is the first to demonstrate that tensor forces partly counterbalance the effect of spin-orbit forces.

This observed reduction is opposite to predictions of most mean-field approaches that ignore tensor interaction. Many-body methods that include tensor force observe the good trend, but globally overestimate its impact, as for interactions derived from the bare nucleon-nucleon interactions, in which a reduction by as much as 2.4 MeV is predicted. The present result is expected to give unprecedented constraint of theoretical models, aiming at better predictions of shell evolution over the whole chart of nuclides.

Accessing the Single-Particle Structure of the PDR

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In atomic nuclei, the term pygmy dipole resonance (PDR) has been commonly used for the electric dipole (E1) strength around and below the neutron-separation energy. It has been shown that the PDR strength strongly impacts neutron-capture rates in the s- and r-process, which synthesize the majority of heavy elements in our universe. A precise understanding of the PDR's microscopic struc- ture is essential to pin down how it contributes to the gamma-ray strength function (γSF) often used to calculate the neutron-capture rates. In fact, the different responses to isovector and isoscalar probes highlighted the complex structure of the PDR and emphasized that different underlying structures would indeed need to be disentangled experimentally if stringent comparisons to microscopic models wanted to be made.

Featuring our recent study of ^{208}Pb [1], I will present how the neutron one-particle-one-hole struc- ture of the PDR can be studied with high-resolution magnetic spectrographs. The data on ^{208}Pb were obtained from (d, p) one-neutron transfer and resonant proton scattering experiments performed at the Q3D spectrograph of the Maier-Leibnitz Laboratory in Garching, Germany. In this contribution, the new data will be compared to the large suite of complementary, experimental data available for ^{208}Pb highlighting how we established (d, p) as an additional, valuable, experimental probe to study the PDR and its collectivity. Besides the single-particle character of the states, different features of the strength distributions will be discussed and compared to Large-Scale-Shell-Model (LSSM) and energy-density functional (EDF) plus Quasiparticle-Phonon Model (QPM) theoretical approaches. The comparison clearly points out the importance of understanding both the population of the PDR in nuclear reac- tions and its γ-decay properties.

To highlight future possibilities, I will also present first results from a new experimental program with the Super-Enge Split-Pole Spectrograph at Florida State University. Here, particle-γ coincidence capabilities have been recently added to study the PDR around the N = 28 shell closure, where the dipole-type neutron-skin mode is expected to develop.

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Study of Giant Monopole Resonance in ^{58,68}Ni with ACTAR@GANIL

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A Giant Resonance corresponds to the collective motion of a high number of nucleons composing the nucleus. In particular the Isoscalar Giant Monopole Resonance (GMR) consists in a compression/dilatation mode of the nucleus, the so-called breathing mode, with all the nucleons in phase. Its characteristics can be related to the nuclear matter incompressibility used in the equation of state, the latter used to describe the neutron stars for example. The systematic study of this type of resonance in exotic nuclei allows to evaluate the dependence of neutron/proton asymmetric effects on the incompressibility and also to investigate the emergence of new mode, like the soft monopole mode at lower energy.

One way to populate the resonances in nuclei is the use of inelastic scattering reactions. The choice of the probe and the energy of interaction allows to select the kind of resonance that is mainly populated. It has been shown that the use of active targets is well suited for the study of GMR in exotic nuclei [1-4].

In 2019, an experiment has been held at the GANIL facility to probe the GMR in both ^{58}Ni and ^{68}Ni with ACTAR [5], a new generation active target. The ^{58}Ni(α, α')^{58}Ni* reaction has been used to validate the experimental method, comparing to the results obtained in direct kinematics [6]. The case of ^{68}Ni is particularly interesting as it will allow to validate the results obtained previously with the active target MAYA and investigate the soft monopole mode, as the energy and angular resolution of MAYA was not sufficient to characterize it.

This talk aims to show the preliminary results obtained during this experiment.

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Are the ground states of randomly interacting bosons random?

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Bosonic degrees of freedom describe collective nuclear dynamics, clustering, and phase transitions. In this work we present a systematic study of chaotic many-boson systems governed by random interactions. Our findings show that ground states of randomly interacting bosonic systems are not random, being dominated only by a few collective configurations containing condensates of clusters. Related topics pertaining to general questions of quantum chaos, eigenstate thermalization, symmetries, clustering, and emergence phenomena will be discussed.

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The first result of electron scattering from online-produced unstable nuclear target at the SCRIT facility

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Electron scattering is one of the most important tools for studying the internal structure of nuclei, because it is the only method that can accurately determine the charge density distribution. That of which is a fundamental physical quantity directly reflecting the wave function of the proton. However, the electron scattering experiment for unstable nuclei had not been performed so far. Mainly due to the fact that it is very difficult to prepare the target for short-lived and rare unstable nuclei.

We developed the SCRIT (Self-Confining Radioactive-isotope Ion Targets) method[1] and constructed the SCRIT electron scattering facility at RIKEN, RI Beam Factory. The SCRIT method enables us to produce electron scattering experiments with a small number of unstable nuclear targets. The luminosity of 1027 [$cm^{-2}s^{-1}$] required for determining the charge density distribution of medium heavy nuclei by electron scattering is only achieved with 10^8 particles, as it has been demonstrated already[3].

Recently, we succeeded in creating the world's first electron scattering procedure online-produced unstable ^{137}Cs nuclei at our facility. The ^{137}Cs beam was produced via photo-fission of uranium by irradiating 28-g uranium disks with a 15-W electron beam at an isotope separation online system (ISOL)[2]. The ion beam was bunched at the cooler buncher system[4] with a frequency of 0.25 Hz. Then, the luminosity of 1026 $cm^{-2}s^{-1}$ was achieved by introducing 10^7 particles/pulses into the SCRIT system. The electron beam energy was 150 MeV and the accumulated beam current was 200 mA. The elastically scattered electrons were measured and it was found that the obtained angular distribution is consistent with a theoretical calculation. This success marks the realization of the long-awaited method to elucidate the structures of unstable nuclei.

In this contribution, we will report the world's first result of electron scattering from online-produced unstable nuclei and future prospects of the SCRIT facility.

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The Many Faces of the Low-Energy Electric Dipole Response of ^{120}Sn

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A concentration of electric dipole strength below the neutron separation threshold (Low-energy Electric Dipole Response, LEDR) is known to be common in medium to heavy mass nuclei and has been studied for decades. While early observations showed the genuine existence of this type of nuclear excitation, a variety of complementary experiments uncovered intricate details of the LEDR in recent years. Unprecedented access to the microscopic structure of individual states in the LEDR of ^{120}Sn was gained recently by a consistent comparison of the population of said states in ^{119}Sn(d,pγ) and ^{120}Sn(γ,γ') from both experiment and theory [1]. The (d,pγ) transfer experiment was performed with the SONIC@HORUS setup at the University of Cologne and allowed to unambiguously investigate the response of the LEDR states to this very selective probe. Nuclear structure calculations were performed within the Quasiparticle-Phonon-Model (QPM) and realistic observables were determined via dedicated reaction theory based on the QPM input. The combined experimental and theoretical effort showed that *i*) a handful of strong single-particle configurations generate the LEDR strength of ^{120}Sn below approx. 7.5. MeV and *ii*) that only two of these configurations are responsible for the pronounced response found in ^{119}Sn(d,pγ). Furthermore, the QPM reproduces several experimental observables, e.g., the summed B(E1)↑ strength below the neutron threshold, to a satisfactory degree. Especially, the expected structural change to more complex configurations towards higher excitation energies is observed in the QPM calculations, which is believed to cause the discrepancy between (p,p') Coulomb-excitation experiments and (γ,γ') data [2].

Very recently, results from a ^{120}Sn(α,α'γ) experiment performed with the CAGRA+GR setup at the Research Center for Nuclear Physics in Osaka, Japan, could be added to the list of data available on ^{120}Sn. The determined average excitation cross sections suggest a rather flat isoscalar response to high energy α-scattering throughout the excitation energy range and no pronounced concentration of the cross sections. The latter was, however, observed in the similar nucleus ^{124}Sn in ^{124}Sn(α,α'γ) and ^{124}Sn(^{17}O,^{17}O'γ) experiments [3]. Interestingly, theoretical cross sections obtained from the QPM calculations and dedicated reaction theory exhibit the same flat response of ^{120}Sn to (α,α'γ). In any case, a considerable amount of isoscalar electric dipole strength was observed in ^{120}Sn(α,α'γ), which suggests a connection between the microscopic nature of excited states probed in (d,pγ) and the surface-mode character probed in (α,α'γ).

This contribution will present the recent study on the microscopic nature of the LEDR in ^{120}Sn and benchmark the QPM calculations against several available experimental data sets. The analysis progress on two new ^{115,117}Sn(d,pγ) data sets will be shown. Finally, the current status of the puzzling results on ^{120}Sn(α,α'γ) will be discussed.

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Relativistic exact-exchange density functional theory for finite nuclei

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The relativistic density functional theory (RDFT) has been successfully used to describe the static and dynamic properties of nuclei throughout the nuclear chart [1-3]. Most of the successes are benefited from the functionals that depend only on local densities and currents. Without considering the nonlocal exchange terms, the computational costs are low. However, these functionals have a few common problems when they are applied to describe the nuclear shell structure and spin-isospin excitations. Recent studies based on the relativistic Hartree-Fock (RHF) theory show that these problems can be solved by including the exchange terms [4-7]. But the RHF theory introduces nonlocal exchange potentials and becomes much more involved. It is therefore desirable to stay only with local potentials and keep the exchange terms simultaneously. In this work, we develop the relativistic exact-exchange density functional theory (REXX DFT) for finite nuclei, in which local exchange potentials are obtained with the relativistic optimized effective potential (ROEP) method [8,9,10]. The REXX calculations are performed for the doubly magic nuclei with a RHF effective interaction PKO2. The ground-state energies and charge radii calculated by the REXX DFT are in a good agreement with the RHF results, which verifies the validity of the ROEP method in nuclear studies. Compared to the complicated integro-differential RHF equation, the REXX DFT only needs to solve a much simpler differential Dirac equation. This reduces the REXX computational time to about third of the time cost by the RHF calculations. It is expected that the REXX DFT can be further applied to deformed nuclei.

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POSTER ABSTRACTS

Testing the predictive power of realistic shell model calculations via lifetime measurement of the $11/2^+$ state in ^{131}Sb

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We present recent results [1] on the lifetime of the $11/2^+$ state in ^{131}Sb measured at LOHENGRIN with fast-timing techniques [2]. The measured value of $T_{1/2}$ = 3(2) ps, at the limit of the experimental technique, and the corresponding B(E2) transition probability point to a non-collective nature of this state. Experimental data are discussed within the shell-model framework [3] and consequences on the emergence of collectivity around ^{132}Sn are addressed.

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The ELI-NP $LaBr_3$:Ce/$CeBr_3$ detectors at ROSPHERE

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At the beginning of 2022 an experimental campaign using more than 20 $LaBr_3$:Ce or $CeBr_3$ (size 3"x3") was performed at IFIN (Magurele, Romania). The Lanthanum/Cerium Halide scintillators and the used digital DAQ were developed for several ELI-NP setups, mainly ELIADE and ELIGANT-GN [1,2,3] array which is planned to be used at ELI-NP (Magurele, Romania) [4]. The poster will present the general performances of the array and the winter 2022 campaign [5].
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Search for shape coexistence in the Se isotopes near the N=50 neutron shell closure

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The shape coexistence phenomenon, i.e., the appearance of different shapes of the nucleus at similar excitation energies [1], is studied by gamma-ray spectroscopy in neutron rich Selenium isotopes. The ^{84}Se (Z=34, N=50) and ^{83}Se (Z=34, N=49) nuclei have been populated by transfer reaction at IFIN-HH (Bucharest) and neutron capture at ILL (Grenoble), respectively. The decay scheme of both nuclei has been significantly extended and it is currently under investigation.

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γ decay from near-neutron-threshold state in 14C: a probe of collectivization phenomena in light nuclei

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The γ decay of the 2^+ near-threshold resonance, located 142 keV above the neutron separation energy (S_n = 8176 keV) in the continuum of ^{14}C was investigated to study the onset of collectivization phenomena in light nuclei, as predicted by the Shell Model Embedded in the Continuum [1]. Preliminary results from the experiment, performed at Argonne National Laboratory with the GRETINA γ-ray spectrometer coupled to the ORRUBA Si detectors, are here presented.

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The structure of low-lying 1^- states in $^{90,94}Zr$ from $(\alpha,\alpha'\gamma)$ and $(p,p'\gamma)$ reactions

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The low-lying dipole strength was investigated in $^{90,94}Zr$ via $(p,p'\gamma)$ reaction at 80 MeV and via $(\alpha,\alpha'\gamma)$ reaction at 130 MeV. These experiments were performed at RCNP (Osaka University) and made combined use of the high-resolution magnetic spectrometer Grand Raiden and the CAGRA HPGe gamma array [1]. Angular correlation plots allowed to identify the multipolarity of the γ transitions. To this aim, experimental data were compared with calculated angular correlation curves, obtained following the prescriptions given in [2]. The comparison of our results with existing (γ,γ') reaction data shows differences in the excitation patterns. In the present experimental conditions, in fact, both α and p probes are exciting the investigated 1^- states mainly through the short-range nuclear force, expected to favor the population of surface excitations. DWBA calculations were made using form factors built assuming specific transition densities, characterized by a strong neutron component at the nuclear surface and based on RPA. A combined analysis of the $(\alpha,\alpha'\gamma)$ and $(p,p'\gamma)$ data was performed to investigate the Isoscalar character of the 1^- states in $^{90,94}Zr$ [3].

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The Origin Project: a 16-channel system for brachytherapy in-vivo dosimetry

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The ORIGIN project addresses the urgent need to deliver more precise and effective Brachytherapy treatments for prostate and gynaecological oncology. The project targets the development of two innovative single-point optical fibre dosimeters with inorganic scintillators on the tip.

This work presents the compliance of a one-channel dosimeter to TG43-U1, the laboratory commissioning, and the qualification in a clinical environment of the 16-channel system for HDR brachytherapy.

The ORIGIN project is an initiative of the Photonics Public Private Partnership (www.photonics21.org) and has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement n. 871324.

Microscopic calculation of the pinning energy of a vortex in the inner crust of a neutron star

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The structure of a vortex in the inner crust of a pulsar is calculated microscopically in the Wigner-Seitz cell approximation, simulating the conditions of the inner crust of a cold, non-accreting neutron star, in which a lattice of nuclei coexists with a sea of superfluid neutrons.

The calculation is based on the axially deformed Hartree-Fock-Bogolyubov framework, using effective interactions. The present work improves previous studies in three ways:

i) it allows for the axial deformation of protons induced by the large deformation of neutrons due to the appearance of vortices;
ii) it includes the effect of Coulomb exchange;
iii) it improves the numerical treatment.

We also demonstrate that the binding energy of the nucleus-vortex system can be used as a proxy to the pinning energy of a vortex and discuss in which conditions this applies.
From our results, we can estimate the mesoscopic pinning forces per unit length acting on vortices.
We obtain values in the order of 10^{14} to 10^{16} dyn/cm, consistent with previous findings.

Changing configurations along the yrast line in ^{138}La

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The hybrid array consisting of detectors of good energy resolution (Clover HPGe) and good time resolution ($LaBr_3$(Ce)) has paved a new dimension of studying spectroscopy and transition probabilities of nuclei [1,2,3]. A fusion-evaporation reaction ^{130}Te(^{11}B, 3n) at 40 MeV beam energy has been used to study the excited states of the odd-odd ^{138}La nucleus. The measurements were carried out using the Indian National Gamma Array (INGA) consisting of eleven Compton-suppressed clover HPGe detectors and 14 $LaBr_3$(Ce) detectors coupled with a Digital Data Acquisition (DDAQ) system. The half lifes of the 739.4-, 837.5-, and 2354.0-keV states in ^{138}La have been measured. The experimental results have been compared with large-scale shell model calculation. The measured lifetimes suggest the phenomenon of changing configuration of yrast states in ^{138}La. A detailed result on spectroscopy and lifetime measurements in ^{138}La will be presented in the workshop.

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Electro-Mechanical Advances for the N3G Experiment

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N3G (Next Generation Germanium Gamma detectors) is an INFN experiment aimed at developing a new generation of HPGe detectors based on electrons-collecting segments. Beside the application of the innovative PLM (Pulsed Laser Melting) doping-technique [1] to the HPGe crystals, the experiment involves the design of a dedicated containment system, complete of contact structures and front-end electronics. A low-noise ASIC pre-amplifier, including a fast-reset circuit [2], has been designed and tested.

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