Shapes and Symmetries in Nuclei:
from Experiment to Theory
(SSNET'18 Conference)

Gif sur Yvette, November 5th – 9th, 2018

Book of Abstracts

Super- and hyperheavy nuclei in covariant DFT: recent results

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What are the limits of the existence of nuclei? What are the highest proton numbers Z at which the nuclear landscape and periodic table of chemical elements cease to exist? These deceivably simple questions are difficult to answer especially in the region of hyperheavy ($Z\geq126$) nuclei. In the beginning of my talk, I will present the review of the results obtained within covariant density functional theory for actinides and superheavy nuclei. This will serve as a starting point for further extrapolations to hyperheavy nuclei. Then, I will discuss the results of covariant density functional study of different aspects of the existence and stability of hyperheavy nuclei. For the first time, we demonstrate the existence of three regions of spherical hyperheavy nuclei centered around ($Z\sim138$, $N\sim230$), ($Z\sim156$, $N\sim310$) and ($Z\sim174$, $N\sim410$) which are expected to be reasonably stable against spontaneous fission. The triaxiality of the nuclei plays an extremely important role in the reduction of the stability of hyperheavy nuclei against fission. As a result, the boundaries of nuclear landscape in hyperheavy nuclei are defined by spontaneous fission and not by the particle emission as in lower Z nuclei. Moreover, the current study suggests that only localized islands of stability can exist in hyperheavy nuclei. The role of toroidal shapes in hyperheavy nuclei and how the nuclear landscape is built in the $Z>126$ region will be discussed in detail.

This material is based upon work supported by US Department of Energy, Office of Science, Office of Nuclear Physics under Award No. DE-SC0013037 and the Department of Energy, National Nuclear Security Administration under Award No. DE-NA0002925.

Shapes of Neutron-Rich Mo-Ru Isotopes from Coulex and Beta-Decay at CARIBU

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Collective shape degrees of freedom have been a major direction in the study of the nuclear finite many body problem for over 50 years. There is widespread evidence for quadrupole deformations, primarily of large prolate spheroidal deformation with axially symmetric rotor degrees of freedom. This naturally leads to the question of whether or not axially asymmetric rotor degrees of freedom are exhibited by any nuclei, with the implication of triaxial shapes. With respect to best cases for observation of triaxial shapes near the ground state, two regions stand out. The first is the Os-Pt region and the second is the neutron-rich Mo-Ru region, where low-energy 2^+_2 states are consistent with such an interpretation. Furthermore, the neutron-rich Mo-Ru region is expected to undergo a relatively rare instance of prolate-to-oblate shape evolution.

Recent results from Coulomb-excitation and beta-decay studies of ^{104,106}Mo and ^{110,112}Ru will be presented. These experiments were conducted at the CARIBU-ATLAS facility of ANL using GRETINA-CHICO2. A survey of the equipment, techniques, and results will be presented.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics.

Studies of semi-magic tin nuclei using large γ-ray spectrometers

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The tin isotopes with their magic number of 50 protons (Z) represent one of the most studied isotopic chain of nuclei. At extreme proton-to-neutron ratios the doubly-magic ^{100}Sn^{50} and ^{132}Sn$_{82}$ nuclei are benchmark nuclei for models of nuclear structure, while the mid-shell ^{116}Sn$_{66}$ nucleus is one of the best candidates for detailed spectroscopic study of intruder states. The neutron-rich tin nuclei allow for studies on the evolution of magic numbers across a wide range of masses, while the half-lives of isotones N = 82 nuclei below ^{132}Sn are key input parameters for astrophysical r-process calculations, and play an important role in the formation and shape of the second r-process abundance peak.

The low-lying energy states of the ^{116}Sn nuclear structure has been studied at TRIUMF with the 8π spectrometer [1], an array of 20 Compton-suppressed high-purity germanium (HPGe) detectors, through the β-decay of ^{116m}In. The 8π spectrometer was coupled to SCEPTAR, an array of plastic scintillators for β-particle tagging, PACES, an array of five lithium-drifted silicon detectors for high-resolution internal conversion-electron spectroscopy, and 8 $LaBr_3$ scintillators for fast -ray timing measurements. A collective rotational band originating from proton 2p-2h excitations across the proton Z = 50 shell gap has been re-examined in both γ-[2] and electron-spectroscopy [3]. The results of this experiment strongly suggest that the 0^+_3 state should replace the previously assigned 0^+_2 state as the band-head of the proton 2p-2h rotational band [2]. Conversion-electron spectroscopy and angular correlations were used to investigate the mixing among the 0^+, 2^+ and 4^+ states [3]. A subsequent experiment to study the structure of ^{116}Sn was performed at ILL Grenoble using ^{115}Sn(n_{ther},γ)^{116}Sn reaction [4] and FIPPS [5], an array of 8 HPGe clover detectors coupled with 16 LaBr3 detectors for fast timing lifetime measurements. The half-life of the 4^+_2 in ^{116}Sn of the proton 2p-2h band has been measured. The mixing of the 4^+ states in ^{116}Sn have been discussed and compared for the first time to *sd* IBM-2 calculations showing a remarkable agreement [4].

The ^{118,129,131,132}Sn isotopes have been studied at TRIUMF using the _-decay of radioactive indium beams and the GRIFFIN array [6], consisting of 16 large-volume HPGe clover detectors coupled to SCEPTAR for β-particle detection. The decay pattern of the 0^+ intruder states have been studied in ^{118}Sn [7], and angular correlations have been performed. The half-lives of the low- and high-spin isomers in ^{131}In [8], have been re- investigated, and the ^{131}Sn level scheme populated by the β decay of the two isomers has been resolved. A re-examination of the structure of ^{132}Sn has been performed [9], resulting in the identification of 23 new γ-ray transitions, and several angular correlation measurements being extracted.

Finally, the ^{116,118,120}Sn nuclei have been studied in (n_{ther},γ) reactions at ILL Grenoble using FIPPS. The data analysis of these experiments is underway. Angular correlations of selected transitions in ^{116}Sn will be presented.

The combination of these experiments collects complementary and detailed spectroscopic information on the Sn isotopic chain, which continue to be cornerstone nuclei for nuclear structure studies.

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[8] R.A. Dunlop et al., to be published
[9] K. Whitmore et al., to be published

Experimental study of the lifetime in neutron-rich nuclei around mass 100

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Rapid shape changes are observed in the region of neutron-rich nuclei with a mass around A=100. The simplest estimate of nuclear deformation can be obtained from the energy of the 2^+_1 state in even-even nuclei. For Sr (Z = 38) and Zr (Z = 40) isotopes it is observed to decrease dramatically at N = 60, while the evolution is much more gradual in Mo nuclei (Z = 42) [1]. Precise lifetime measurements are a key ingredient in the systematic study of the evolution of nuclear deformation and the degree of collectivity in this region.

Neutron-rich nuclei in the mass region of A = 100-120 were populated through the fusion-fission reaction of a ^{238}U beam at 6.2 MeV/u on a ^{9}Be target. The compound nucleus ^{247}Cm was produced at an excitation energy of ~45 MeV before undergoing fission. The setup comprises the high-resolution mass spectrometer VAMOS in order to identify the nuclei in Z and A, the Advanced γ-ray Tracking Array AGATA of 35 Ge detectors to perform γ-spectroscopy, as well as a plunger mechanism to measure lifetimes down to a few ps using the Recoil Distance Doppler Shift method [2]. The target was surrounded by 24 fast timing $LaBr_3$ detectors for the measurement of long lifetimes above 100 ps. The overlap between the two methods (RDDS and Fast-timing) will add better precision to the lifetime results.

In this contribution, we will report on the AGATA analysis and present preliminary results for the studied isotopes in zirconium and molybdenum chains.

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[2] A. Dewald *et al*. Progress in Particle and Nuclear Physics **67**, 3

Semiclassical Origin of the Asymmetric Nuclear Fission — The Pre-fragment Shell Effect in the Periodic-Orbit Theory —

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The asymmetric nuclear fission is only explained by taking into account the quantum shell effect. Theoretical analyses of the experimental results have revealed the importance of the deformed shell effect in the fission process as well as the fragment shell effect after scission. There are also indications that the deformed shell effect is associated with that of the nascent fragment (pre-fragment), but the ground for such relations have not been understood well.

In this talk, we propose a simple way of defining and evaluating the pre-fragment shell effect using the periodic-orbit theory (POT). In the semiclassical POT, oscillating component $\delta g(e)$ of the single-particle level density $g(e) = \sum_n \delta(e\text{-}e_n)$ is expressed as the sum over contributions of the classical periodic orbits [1]. In the fission deformation process, nucleus is elongated to one direction and a neck is formed which separate the system into two parts. We focus our attention on the appearance of the degenerate periodic orbits confined in each of the pre-fragments immediately after the neck formation. We classify the periodic orbits into three groups due to their spatial localization types: 1) those confined in the 1st pre-fragment, 2) confined in the 2nd pre-fragment, 3) none of them. By this classification, periodic-orbit sum in the semiclassical level density can be decomposed into three parts. According to this decomposition, the pre-fragment shell effect is naturally identified as the contributions of the orbits confined in each of the pre-fragments.

Using the trace formula which we have derived for the truncated spherical cavity [2], we analyze the cavity model with three-quadratic-surfaces shape parametrization and investigate the pre-fragment shell effect through the fission process. We found that the orbits confined in the pre-fragment have considerably large contribution to the shell effect already at the early stage of the fission process, and the pre-fragment magicity play significant role in formation of the fission path leading to the asymmetric scission [3].

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Fission dynamics of Fermium Isotopes using Langevin equations

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Fragment mass distributions in the fission of ^{246,264}Fm at low excitation energies are studied using the three dimensional Langevin equations with potential energy landscape of the two-center shell model. After overcoming the 1st saddle point, the large-amplitude shape motion along specific shape degrees of freedom is found in the 2nd minimum of the potential energy landscape due to the nature of the friction tensor in the Langevin equation. The 2nd-saddle points are found at two positions which links to the compact-symmetric scission and elongated-asymmetric scission, respectively, and they are located at both ends of the shape motion in the 2nd minimum. Height of the mass-symmetric 2nd saddle point relative to the asymmetric saddle point decreases toward heavier Fm isotopes. It was shown that not only the structure of the potential energy landscape but also the wide-range directive fluctuation of nuclear shape have a crucial role to understand the mechanism of the sharp transition of mass asymmetry.

The SOFIA experiments on fission yields: Recent results and perspectives

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Fission is a unique tool to study nuclear properties. The SOFIA collaboration takes advantage of the inverse kinematics technique to measure fission yields for a large range of systems, including exotic nuclei. Both fragments are fully identified in charge and mass, a unique feature. The use of Coulomb interaction as fission trigger results in a very low excitation energy in the fissioning system, allowing the study of the influence of nuclear structure on fission. Using samples of SOFIA results, this paper addresses some open questions of fission such as the evolution of elemental yields with mass, the partition of excitation energy between fragments or the transition between asymmetric and symmetric fission.

Shapes and Structures of Xe isotopes: Coexistence of Single Particle and Collective modes of excitations

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The variety of nuclear shapes and shape coexistences are the manifestation of the complicated interplay between the single-particle and the collective motions of the nucleus. The nuclear structures as a function of neutron number around the doubly magic shell closure of N=82 and Z=50 are one of the important areas to probe the both single particle excitations and collective modes of excitations. Isotopes with few proton particles and neutron holes about the shell closure gives us the unique opportunity to investigate the low lying single particle level structures, which in turn helps us to understand the effective nucleon-nucleon shell model residual interactions. Whereas, presence of unique parity h11/2 orbital in both proton and neutron shells generates the high spin collective structures. Particular interest in the A ~ 130 transitional mass region is that, at low spins, the nuclei show small axial deformation whereas at higher spins, shape coexistence may occur due to the competition between the proton alignment to the prolate side, and the neutron alignment near the h11/2 subshell, driving it to an oblate one. Transitional Xe isotopes with mass number near 130 are interesting to explore the structures at low spins as well as at high spins to explain the effect of various single particle orbitals. Xe isotopes are known for their smooth shape transition from spherical to deformed one as function of neutron number. At these mass regime ^{130}Xe is a potential candidate for investigation of E(5) symmetry breaking since its experimental R4/2 ratio is very close to theoretical predicted value. E(5) symmetry critical point is already identified in ^{128}Xe. The odd mass Xe isotopes in this mass region can be explained with deformed shape and are interesting to study. Experimental results on Xe isotopes at this mass region will be presented.

Exploring the Highly-deformed Band Structures in ^{123}Xe

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The nuclear structure exhibits transitional behaviour in the A$\sim$125 mass region as the nuclei lie between the spherical (Sn, Z=50) and strongly deformed (Ce, Z=58) structures. A wide variety of shape changes can be seen here even with the rearrangement of a few valence nucleons. This is because of the presence of a unique parity intruder subshell, $h_{11/2}$, which can be accessed by both the protons and the neutrons. These $h_{11/2}$ nucleons have opposite deformation driving effects and this conflict results in the exhibition of prolate, oblate or triaxial nuclear shapes [1].

Experiments conducted in the recent past have shown that when the angular momentum becomes roughly 25$\hbar$, non-collectivity is observed in the form of irregular structures [2]. At around the same spin region, high spin regular structures going up to $\sim$50-60$\hbar$ are reported to co-exist along with these single particle states [3]. Such long bands have been observed in ^{124,125,126}Xe [3, 4, 5]. These high spin bands have been found to have large deformation in ^{125}Xe [4], deformation parameters ϵ_2 $\sim$0.25-0.35 were calculated from lifetime measurements.

Proton excitations across the Z = 50 shell gap from the $g_{9/2}$ orbitals and neutron excitations within the 50-82 shell gap may have given rise to such long bands as have been reported by the band configuration assignments in [6,7,8,9]. Also, in the ^{125}I and ^{125}Xe nuclei [9, 10], the existence of these long bands have been attributed to the neutron excitations across the N = 82 shell gap along with proton excitations across Z = 50. As the spectroscopic data for low and moderate spins have been extensively studied for ^{123}Xe in the previous work [11], the present work has been motivated by the search for such long bands in the same. In order to populate the high spin states of ^{123}Xe, a heavy ion fusion evaporation reaction experiment was performed at the Argonne National Laboratory, USA. The ATLAS accelerator provided the 207 MeV ^{48}Ca beam at 4 pnA current which was bombarded on an Au-backed ^{80}Se target and the high spin levels of ^{123}Xe were populated in the ^{80}Se(^{48}Ca,5n)^{123}Xe reaction. The gamma ray coincidence data was recorded with the Gammasphere spectrometer array [12] consisting of 101 Compton-suppressed Ge detectors. In the present study, four new high spin band structures have been identified to feed the low lying levels. However, as the bands are weak, connections to these levels are yet to be established. Cranked Nilsson-Strutinsky calculations are being done in order to assign configurations to the bands. Tentative spin and parity values have been assigned based on the decay patterns of these bands to the lower spin levels.

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Investigation of the nuclear structure of lowest ^{229}Th states

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The isotope ^{229}Th has seen increasing interest in these past years because of the few eV transition between its almost degenerate first isomeric state and its ground state. A highly precise nuclear clock could be designed exploiting such a transition. The recent direct experimental detection of the isomer and its nuclear structure is a new challenge for theoretical calculations. Employing the zero-range nuclear energy density functionals, with symmetry restoration, collectivity, pairing, and configuration mixing, we determine the energies and the transition rates in ^{229}Th and estimate uncertainties of the obtained results.

Single-particle levels in cluster potentials

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In analogy with the Nilsson model, we calculate the splitting of spherical single-particle levels in a deformed field, but for cluster potentials. We study applications to alpha-cluster nuclei with two, three and four alpha particles, in which the deformation parameter corresponds to the relative distance. The splitting of the single particle levels is studied as a function of the relative distance for the cases of a dumbbell, an equilateral triangle and a regular tetrahedron. The observed patterns may be used to gain insight into how the single-particle levels evolve with deformation, and what are the predominant interactions (quadrupole, octupole, etc.). This information can subsequently be used to extend the Algebraic Cluster Model (ACM) to odd-cluster nuclei by developing the Algebraic Cluster-Fermion Model (ACFM).

Matter distribution studies of Carbone isotopes $^{9-22}$C

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We systematically study the matter distribution from the reaction cross-section of Carbone isotopes with N=3-16 by using a modified version of the Glauber model. This model was modified to take into account the Coulomb distortion of the trajectory. We establish an empirically data basis of measured reaction cross sections with carbone target in a wide range of interaction energy from 30 to 950 A. We reproduce the experimental data of reaction cross section using the two-parameter density of Fermi. From the calculated cross section, we study the effective densities and the Root-Mean-Square (RMS) radii for the isotopes $^{9-22}$C. Evidence for a one-neutron halo structure is discussed for ^{15,17,19}C by a Glauber-model analysis.

Angular Correlation measurements with the iThemba LABS segmented clover detector

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Theoretical arguments predict that the distribution of the intensity of the gamma-rays emitted successively from the same nucleus should be anisotropic. The angular correlation functions, W(θ), for gamma-rays emitted from Ba-133, Bi-207, Cd-111, and Co-60 were measured experimentally using the iThemba LABS segmented clover detector. These measurements were to test the performance of the detector in reproducing and improving the previously measured mixing ratios of the gamma-ray transitions. Some of these mixing ratios were measured in the 70s, with few angles and very old detectors, e.g. Ge(Li), NaI. In addition, there are few polarization measurements, thus the mixing ratios are uncertain in some cases. From the measured W(θ), the multipole order of the gamma-rays and their mixing ratios can be correctly assigned. The iThemba LABS segmented clover detector has 32 segments which can be used as individual detectors. If γ1 is then detected in one segment and γ2 is detected in each of the remaining 31 segments, angular correlation information for 122 different angles can be obtained. With the source placed at 4 cm from the face of the detector, the opening angle is around 90 degrees hence it covers the whole range of angles needed for precise angular correlation measurements. The number of coincidences between γ1 and γ2 is determined as a function of θ (the angle between the two segments). In this presentation the results which shows that our detector can measure very precisely angular correlation functions, with large multipole order such as E3, M4, E4 and mixing ratios of M1+E2 will be discussed. In addition, the detector can distinguish between an unstretched dipole and a stretched quadrupole transition.

Nuclear shapes for the critical point of the U(5)-SU(3) nuclear shape phase transition

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The Bohr Hamiltonian [1,2] is solved for the critical point of the shape phase transition from the spherical vibrator to the prolate rotor, using a general sextic potential [3]. The parameters defining the potential are constrained such that its form to manifest two degenerated minima, a spherical and a deformed one, separated by a maximum (a barrier), which coincides with the energy surface predicted for this critical point by the Interacting Boson Model [4] using coherent state functions [5,6]. Even if a large number of solutions were proposed since the critical point model called X(5) [7] was introduced, trying different potentials for this critical point [8,9], none of these solutions took into account the barrier separating the two minima. From this point of view, this study presents a special interest for the field. The eigenvalue problem is solved by diagonalizing the Hamiltonian in a basis of Bessel functions of first kind, which in turn are obtained by solving the same problem but for an infinite square well. Both energies and wave functions depend on a single free parameter defining the height of the barrier. By analyzing the density distribution probability for the states of the ground band and of the first β band, one can understand how the shape of the nucleus is changing as the barrier is introduced and increased step by step. Doing so, new interesting results were obtained for the structure of the states in this critical point, properties which were not visible in the absence of the barrier.

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Fission in Inverse Kinematics: A New Window to Experimental Observables

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Experimentally, the understanding of the complex, long, and intricate process of nuclear fission is approached by collecting as many observables as possible and from all fissioning systems available. The measured properties of the fissioning system and of the fission products, and their correlations, has led to the current picture where, in a very simplified way, the fission proceeds according certain modes or channels centred around fragments with particular numbers of protons and/or neutrons, which emerge with specific deformations that also drive the sharing of part of the available energy.

Most of the information on fission was gathered so far in experiments that use direct kinematics, where the fissioning system can be considered at rest in the laboratory. However, these experiments suffer from two main drawbacks: few observables are measured simultaneously and the fragment atomic number is either absent or poor in resolution. The use of inverse kinematics, where the fissioning system is studied in-flight, opens a possibility to solve those issues and to add new information.

The correlation of the measured observables permits to recover properties such as the total kinetic energy or the neutron multiplicity that can be studied and compared with previous measurements. In addition, the measurement of the atomic number allows us to retrieve quantities such as the neutron-to-proton ratio of the fragments, the total excitation energy, with hints to the elongation of the system.

The discussion will mainly focus on the study of transfer- and fusion-induced fission of several systems, produced in inverse kinematics at GANIL (France).

Predictions of Proxy-SU(3) for gamma band to ground band B(E2) values

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B(E2) values for transitions between the gamma and the ground band are obtained within the framework of a simple, analytic, parameter free model, Proxy-SU(3). The results will be compared with experimental results and some other models as well.

Predictions of a new approximate Symmetry, Proxy-SU(3), for heavy deformed nuclei

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The new approximate symmetry, Proxy-SU(3), is briefly described, followed by a discussion of its predictions, most of which are parameter free and many analytic, for nuclear shapes, and shape transitions, as well as approaches to predicting relative B(E2) values from collective states.

Nuclear structure of N>150 Pu-Cf nuclei and outlook with AGFA

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High-spin spectroscopy of deformed A~250 nuclei currently offer the best laboratory to benchmark theories that attempt to understand the physics of the heaviest nuclei. Here, deformation and rotation pull down orbitals from above the neutron and proton spherical superheavy shell gaps into the valence domain. The talk will focus on the structure of trans-plutonium neutron-rich nuclei at high angular momentum, using inelastic and transfer reactions with heavy beams, radioactive targets and the Gammasphere array at the ATLAS facility at Argonne. These access the highest neutron orbitals up to N=154, and complement fusion evaporation reactions that can reach nuclei beyond Z =104. A brief update on the status and outlook for the spectroscopy of the heaviest nuclei with the Argonne Gas Filled Analyzer (AGFA) will also be presented.

Alpha Decay and Fission of High-K Isomers

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While the single-particle structure is vital to understanding the stability of the heaviest elements, the alpha decay and fission processes ultimately determine how long a nucleus will survive. Observations in the decay chains of ^{270}Ds [1,2] suggest that high-K isomeric states can decay via alpha emission where the metastable state is longer lived than the ground state of the same nucleus. Moreover, results on ^{254}Rf [3] suggest that high-K isomeric states can also have an unprecedented hindrance against fission. Such results have tremendous implications for how far we may be able to push the experimental studies of the heaviest elements.

In this contribution I describe recent efforts to gain a better understanding of alpha decay and fission of metastable states in the heaviest nuclei. In particular, the Superfluid Tunneling Model of Bertsch and co-workers [4] has been used to reproduce the alpha decay properties of the high-K isomers in ^{270}Ds and ^{266}Hs, including the unusual competition between $L \approx 10$ and $L \approx 0$ alpha transitions seen for the K—isomer in ^{270}Ds [5]. I will also discuss the possibilities of using the same model to look at the fission from high-K states.

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First Spectroscopy of ^{40}Mg

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The study of nuclei far from stability is one of the most active and challenging areas of nuclear structure physics. One of the most exotic neutron-rich nuclei currently accessible to experiment is ^{40}Mg [1, 2], which lies at the intersection of the nucleon magic number N=28 and the dripline, and is expected to have a large prolate deformation similar to that observed in the neighboring lighter isotopes $^{32\text{-}38}$Mg [3]. In addition, the occupation of the weakly bound low-l $p_{3/2}$ state may lead to the appearance of an extended neutron halo. ^{40}Mg offers an exciting possibility and a rare opportunity to investigate the coupling of weakly bound valence particles to a deformed core, and the influence of near threshold effects on collective rotational motion.

We will discuss the results of an experiment carried out at RIBF RIKEN to study low-lying excited states in ^{40}Mg produced by a 1-proton removal reaction from a ~240 MeV/u ^{41}Al secondary beam. ^{40}Mg and other final products were separated and identified using the Zero Degree Spectrometer, and prompt gamma rays were detected using the DALI2 array. Two gamma rays were observed, and the excitation spectrum shows unexpected properties compared to both neighboring Mg isotopes, and theoretical model predictions.

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Predicting Neutron Capture Cross Sections from Nuclear Masses

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The abundances of the elements in the cosmos are determined by a combination of astrophysical phenomena and nuclear physics. In particular, the creation of elements with A>60 is dominated by neutron capture reactions because the Coulomb barrier is generally too high for fusion reactions to be energetically favorable. Since neutrons are uncharged, neutron-induced reactions can take place over all Z ranges, and cross sections are large, even at low neutron energies. It has been known for some time that reliable determination of neutron capture rates is needed for understanding the astrophysical *s*-process, which takes place near stability; recent studies have shown that individual neutron capture rates also play a role elemental abundances from a range of environments under consideration as potential *r*-process sites, which take place on very neutron rich nuclei. In addition to neutron capture contributing significantly to nuclear astrophysics, capture cross sections are needed for a range of applied disciplines, from nuclear energy to nuclear medicine.

Unfortunately, many of the isotopes of highest interest are short-lived, exotic species, making them unsuitable for traditional measurements with a neutron beam impinging on a massive (>100μg) target. Instead, Hauser Feshbach reaction theory is typically used to predict these reaction cross sections. While the predictions agree to within ~30% where measurements exist, they quickly diverge by more than a factor of ten off stability where they are most critically needed.

Motivated by this, we have recently discovered a previously unrecognized correlation between the neutron capture cross-section, a tradition nuclear reaction quantity, and the two-neutron separation energy, which has typically been in the domain for nuclear structure. This offers several exciting possibilities. By parameterizing this simple correlation, we have been able to provide a new set of cross section predictions that can be used for nucleosynthesis studies. Continued work has indicated a path to generalizing this trend across energies and regions of the chart of nuclei. Further, because two-neutron separation energies are more straight-forward to study far from stability than neutron capture, we have the opportunity to provide capture cross sections based on S_{2n} rather than a direct capture measurement. Finally, this may offer hints into where traditional reaction theories have missed underlying physics that is needed to more accurately model the capture reaction process.

A new symmetry of shapes, shells, and clusters

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60 years ago Elliott established the connection between the quadrupole deformation and the spherical shell model [1]. In the same year Wildermtuth et al, revealed the relation of the clusterization and shell model [2,3]. In present day language one can say that the common intersection of the shell, collective and cluster models turned out to be an SU(3) dynamical symmetry.
This is true for a single major shell problem.

Many problems require the introduction of major shell excitations. In the meantime the fundamental structure models have been extended to many major shells. The corresponding symmetry-adapted models, based on the spherical shell picture, are: i) the symplectic (shell) model [4], ii) the contracted symplectic (collective) model [5], and iii) the semimicroscopic algebraic cluster model [6]. The common intersection of these models for a multi major shell problem is an Us(3) x Ux(3) > U(3) dynamical symmetry [7].

This symmetry turns out to be identical with the multichannel dynamical symmetry, which connects different cluster configurations [8], as can be seen by considering the shell (or quartet) state as a 1-cluster configuration [9]. Therefore, the symmetry is able to describe the detailed spectrum of different configurations in different energy-windows in a unified way [10]. As a consequence it has a remarkable predictive power [11].

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Charge radii in the region of Au-Po at ISOLDE

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The nuclei surrounding the $Z = 82$ shell closure are known to exhibit a rich variety of shape phenomena. In the neutron-deficient nuclei, cases for shape coexistence are found in abundance near the N=104 midshell, where spherical, prolate and oblate configurations are found in strong competition at low-excitation energies. On the neutron-rich side of the chart, evidence for octupole correlations can be seen.

Since 2007, an extensive in-source laser spectroscopy campaign has been undertaken by the Windmill – RILIS – ISOLTRAP – IDS collaboration at the CERN-ISOLDE facility, wherein isotope shift and hyperfine structure measurements of long chains of isotopes have been made. This talk will present results from these studies, along with the extracted changes in mean squared charge radii and their impact on modern nuclear theory.

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[*] *on behalf of the Windmill – RILIS – ISOLTRAP – IDS collaboration*

Empirical evidence of the super rigid structure of flat superdeformed bands

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A systematic study of the “flat” SD bands of Tl and odd-A isotopes of Pb is done by using the shape fluctuation model (SF model), vibrational distortion model, Nuclear softness (NS) formula, semi-classical particle rotor model (PRM) and exponential model with pairing attenuation. The least-squares fitting procedure is employed to extract the fitting parameters of the 11 flat superdeformed bands of the Tl and Pb isotopes which show an almost constant variation of the dynamic moment of inertia with rotational frequency. The intraband transition energies of the SD bands have been split into rotational and shape fluctuation energy, and its variation with the increasing rotational frequency is explored. Using these models, two distinct natures have been identified for the SD bands in the Tl and Pb isotopes. The effective pairing parameter Δ0, which may be analogous to the dynamic pairing parameter, obtained for the flat SD bands is almost negligible. The systematic study also revealed that smaller the Δ0 parameter is, more reduced is the increase of the dynamic MoI with increasing rotational frequency. The dynamic MoI is sensitive to the change in pairing correlations in the A≈190 mass region. Hence the almost constant dynamic moment of inertia as a function of rotational frequency observed for flat bands could be because of the almost negligible value of the pairing parameter and enhanced deformation. This in effect probably delays the proton alignment. Our study explores the role of shape fluctuations, vibrational effect, deformation and effective pairing correlations for the evolution of the dynamic moment of inertia with increasing rotational frequency in the flat SD bands.

Construction of nuclear effective interactions of new generation

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I will show the first results concerning new effective interactions with zero or finite-range. More specifically I will present the construction of a new Gogny-like interaction with three ranges, going from the determination of the ranges from microscopic considerations to the linear response formalism we developed recently to prevent unphysical unstabilities.

Test on N=50 neutron gap in the vicinity of ^{78}Ni and systematics of neutron-rich Ge nuclei

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In the case of N=50 isotopes from ^{90}Zr to ^{78}Ni, the first 0^+, 2^+ and 4^+ states are based on proton excitations inside the fp shell. The proton excitation to the $g_{9/2}$ orbital leads to negative spin states. However, the 5^+, 6^+ and 7^+ states correspond mainly to neutron excitations across the N=50 gap. Thus, the evolution of the excitation energy of these states (partially known in ^{82}Ge and unknown in ^{80}Zn) as a function of Z, allows to deduce the size of the N=50 gap in ^{78}Ni. A set of neutron-rich nuclei is produced in a fusion-fission reaction with ^{238}U beam on a ^{9}Be target. The several fission fragments are selected unambiguously (A and Z identification) by the VAMOS++ spectrometer. The prompt gamma rays are measured in coincidence with the fission fragments by the AGATA array composed of 8 triple-clusters. Preliminary results on the gamma rays assigned to various neutron-rich Ge isotopes will be presented.

Properties of ^{229}Th within the state-of-the-art nuclear DFT calculations

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University of York, United Kingdom

Employing the zero-range and finite-range nuclear energy density functionals, with symmetry restoration, collectivity, pairing, and configuration mixing, we determine energies and transition rates in ^{229}Th and estimate uncertainties of the obtained results.

Tri-axiality in ^{110}Ru from Coulomb excitation

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It has long been suggested, from both theoretical calculations and energy systematics, that the neutron-rich Ru/Mo isotopes may exhibit non-axially deformed (or triaxial) shapes at low excitation energy. However, direct measurements of these phenomena with Coulomb excitation have been hindered due to the refractory nature of these elements.

However, here we report on a recent multi-step Coulomb excitation measurement with the GRETINA and CHICO2 detector arrays was carried out with a 430-MeV beam of the radioactive neutron--rich 110Ru isotope produced at Argonne National Laboratory's CARIBU facility. This represents the first successful measurement following the post-acceleration of an unstable isotope of a refractory element. The reduced transition probabilities obtained for levels near the ground state provide strong evidence for a triaxial shape; a conclusion confirmed by comparisons with the results of beyond-mean-field and triaxial rotor model calculations.

In addition, new preliminary results from the summer 2018 experimental campaign will be presented.

Spectroscopy of neutron-rich Ca and Ni isotopes with SEASTAR

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The presentation will address nuclear structure and shell evolution at extreme isospin values, studied via in-beam gamma-ray spectroscopy at intermediate energies following knockout reactions on a thick liquid hydrogen target. Besides an introduction of the setup, key results will be presented that demonstrate the close cooperation between experiment and nuclear structure and reaction theory.

Particular emphasis will be laid on spectroscopy of the neutron-rich Ca isotopes ^{54,56}Ca, in which the significance of 3N forces can be studied, and the assumed doubly magic nucleus ^{78}Ni. The excitation spectrum of the latter provides first hints of the breakdown of magic neutron number N=50 and magic proton number Z=28 toward more exotic isotones and isotopes.

Study of the “α+^{208}Pb” Clusterization of the ^{212}Po Nucleus

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Atomic nuclei are made of protons and neutrons, which are normally uniformly distributed in the tiny volume of the nucleus. In some special cases, however, protons and neutrons organize themselves in cluster structures, as if the nucleus was a molecule made of smaller nuclei. A most famous example is the “Hoyle state” in the carbon-12 isotope, which is made up by 3 coupled α particles. If the Hoyle state did not exist, the fusion of 3 α particles could not occur in the Sun, and there would be no life on Earth. Among the large variety of cluster states, I focus on states which are made by one α plus a much heavier “core” nucleus: the α-^{208}Pb system in the 212 polonium nucleus.

Such cluster states were recently discovered in ^{212}Po in transfer reactions induced by ^{18}O at low energy. The rays emitted by these excited states display surprising electromagnetic properties which revealed a completely new mechanism: the vibration of the “α-core” distance around its equilibrium position [1,2].

At the JAEA Tandem laboratory in Tokai (Japan) we performed an experiment to understand how these special states are formed. Due to parity conservation, the direct population of these states -which have non-natural parity - is prohibited so we expect to discover and characterize a two step process. The measurements associated both particle and γ detections in order to get a complete feature of the mechanism and of the populated levels. Four different beam energies have been studied below and above the Coulomb barrier, and these results have been compared with TDHF calculations.

This experiment improved a lot our understanding of the transfer reaction at low energy in the lead mass region and is a first step to a systematic study of the alpha cluster states production by transfer.

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Nuclear structure studies close to shell closure N=126 using quasiparticle-phonon plus rotor method

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The study of structure of heavy and super heavy nuclei, need to produce a handful of events and therefore provide a detailed spectroscopic data. Owing to the extreme limit of current capabilities and weak production cross sections close to 1nb, the structure of heavy and very heavy nuclei could help us to understand the structure and stability of super heavy nuclei since such shell properties may be a consequence of nuclear deformation.

In this work, we aim to use the quasiparticle-phonon plus rotor model (QPRM) to study the nuclear structure of heavy elements in the region of N=126 isotones having $84 \leq Z \leq 92$, we focus our study with QPRM method to determine the microscopic configuration in terms of spin-parity and isomeric state at low-lying energies of excited states. As first step we show the structure at low lying states of ^{213}Ac populated via the alpha decay of ^{217}Pa.

Structure of neutron-rich N=46 and N=48 isotones

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Indication of triaxiality in ^{78}Ge has recently been presented from a low-energy sequence of strictly $\Delta J = 1$ transitions [1]. Neutron-rich N=46 and N=48 isotones were studied using the Gammasphere Ge-detector array at ANL. Beams of ^{76}Ge and ^{82}Se were incident upon thick ^{238}U and ^{208}Pb targets in deep-inelastic reactions.
New data in ^{82}Se will be presented to clarify β-decay studies [2, 3], and angular-correlation measurements are used to strengthen spin and parity assignments in some cases. These observations can provide insights into the single-particle and collective properties of these neutron-rich nuclei. NuShellX calculations for the N = 46 and N = 48 isotones will be shown to test the $p_{3/2}f_{5/2}p_{1/2}g_{9/2}$ proton and neutron subspace [4]. Additionally, new insight into the structure of isotonic nuclei will be discussed.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract Nos. DE-AC02-06CH11357 (ANL) and DE-AC02-98CH10886 (BNL), and grants No. DE-FG02-94ER40834 (Maryland). This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility.

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On shape coexistence and quantum phase transitions: lead and zirconium regions

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The shape coexistence phenomenon is related with the presence in the same energy region of eigenstates with different deformations. The lead region is considered as a paradigm for shape coexistence and several decades of experimental effort have supported this believe. In particular, long chains of the Pb, Hg, Pt and Po isotopes have been measured and a rich experimental body of data concerning, excitation energies, electromagnetic transition rates, radii, magnetic g-factors, alpha-hindrance factors and Coulomb excitation reactions, has been obtained.

In the case of Pb and Hg, the presence of intruder states is self-evident inspecting the parabolic energy systematics of the intruder states. However, in the case of Pt and Po, the presence and influence of intruder states is not obvious.

On the other hand, the concept of quantum phase transition (QPT), which has gained a lot of attention in nuclear physics, among other fields, during the last twenty years, appears when the Hamiltonian that describes the quantum system can be written in terms of two pieces, at least, each one with a given symmetry, and a Hamiltonian parameter, i.e., a control parameter, allows to pass from one to the other symmetry. This passing supposes a sudden change in a control parameter and a discontinuity in the ground-state energy or in some of its derivatives.

The rare-earth region around N=90 is very well known for containing examples of QPT's, in particular, the even-even isotope chains of Nd, Sm, or Gd show first order QPTs. In other regions, as in Ba or Ru even-even isotope chains, second order QPTs appear.

The goal of this contribution is to study the connection, if any, between shape coexistence and QPT, two seemingly unrelated phenomena, but that, once studied in deep, share common aspects: the rapid change in the ground state structure when going through an isotope chain or the presence in the mean-field energy surface of several minima. To illustrate the similarities and differences between both phenomena, we will focus in the zirconium and in the lead regions. The first region is known for the rapid change of the ground state deformation, with clear hints of the existence of a QPT. It is also known for the presence of intruder states coming from two-particle two-hole excitations across Z=40 shell closure. On the other hand, the lead region also shows up the presence of intruder states, in this case, corresponding to excitations across Z=82 shell closure, although here the precursors of a QPT are not present, at least, in an evident way.

Precision laser spectroscopy for nuclear structure studies

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Laser spectroscopy experiments provide a powerful tool to perform highly-efficient and precise measurements of the electromagnetic properties of exotic isotopes. These measurements provide access to observables that are key to our understanding of the nuclear many-body problem: nuclear ground-state spins, electromagnetic moments, and changes in the root-mean square charge radii.

This contribution will present recent results on high-precision laser spectroscopy experiments performed in the vicinity of the so-called doubly-magic isotopes ^{52}Ca, ^{68,78}Ni, ^{100}Sn and ^{132}Sn. The relevance of these results in connection with the recent advances in nuclear theory will be discussed.

Multiple shape coexistence in the Cd isotopes

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The long-standing view of the structure of the mid-neutron-shell Cd nuclei has been of nearly harmonic, vibrational states built on an approximately spherical ground state coexisting with deformed ‘intruder’ excitations. The two-phonon-vibration triplet of states appeared to be well established, and there were many searches conducted seeking the higher-lying multiphonon excitations, especially in ^{110,112}Cd which were considered as paradigms of harmonic vibration motion. There have been a number of studies, however, that have challenged this interpretation. Recently, we have examined the Cd isotopes via β decay measurements that have focused on the observation of weak, low-energy decay branches from levels at high excitation energy. Combined with level lifetimes determined by using the $(n,n'\gamma)$ reaction, $B(E2)$ values are available for a large number of transitions. We have observed bands in ^{110,112}Cd built on excited 0+ states, and have located candidates for pseudo-γ bands built on the ground states and the intruder bands. These results are interpreted through comparison with beyond-mean-field calculations that predict that the 0^+ states in ^{110,112}Cd possess shapes ranging from deformed prolate, oblate, triaxial, and the excitations built on them are rotational in nature.

Coriolis Mixing in 2qp isomer in ^{164}Gd and other N=100 isotones

Laurent Gaudefroy
CEA, France

I will report on two complementary delayed γ-ray spectroscopic studies on $^{164}Gd_{100}$, produced via spontaneous fission of ^{252}Cf used in selective experimental setups. We confirm the existence and the decay path of an isomeric state in ^{164}Gd at about 1100 keV with an half-life of about 600 ns. From comparison to other N=100 isotones and with calculations based on axially symmetric-deformed QRPA calculations using the Gogny interaction a 4^- spin and parity is proposed for the isomer. The state is interpreted as a 2^-qp neutron excitation and the variation of the lifetime of the isomer along the N=100 isotonic chain is interpreted in terms of Coriolis mixing implemented on top of the axially symmetric deformed QRPA calculations.

The DESPEC project at GSI/FAIR

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GSI Darmstadt, Germany

DESPEC-Phase0 experimental project at GSI and FAIR is under preparation. The goal is to investigate different modes of decay in exotic and heavy nuclei with spectroscopic means. The experimental detector-setup will be presented together with the plans for commissioning and physics campaigns.

New insights on evolution of collectivity in the vicinity of ^{168}Os

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Recently in the vicinity of $N = 92$ Pt-Os-W nuclei, dramatic differences in the nuclear structure have been observed through measurements of transition probabilities [1] carried out at the Accelerator laboratory of the University of Jyväskylä. The value of the $B(E2;4^+\rightarrow2^+)/B(E2;2^+\rightarrow0^+) < 1$, which is typical for the seniority scheme, appears in these even-even isotopes. Based on the level energies, these nuclei can be seen as collective, perhaps triaxial, at low spin. So far, this transition between collectivity and apparent single-particle regime has not been understood.

Some of the results have been presented in the previous editions of the SSNET conference. In the present contribution new insights based on the systematics of the data will be discussed.

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A beyond-mean-field description for nuclear excitation spectra: applications of the subtracted second random-phase approximation

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The second random–phase approximation (SRPA) is an extension of the standard random–phase approximation (RPA) where two particle–two hole (2p2h) configurations are included together with the RPA one particle–one hole (1p1h) configurations. This beyond mean– field model allows for reliable quantitative predictions to describe the widths and the fragmentation of excited states, due to the coupling between 1p1h and 2p2h elementary configurations.

I will present the formal developments and the practical applications that we have realized in the last years. One important recent achievement was the development of a substantial implementation of the SRPA model, based on a subtraction procedure. This subtraction method was tailored to cure double–counting problems encountered when effective interactions are used in beyond mean–field models, within energy–density functional theories. At the same time, this procedure cures all the instabilities and divergences present in the standard SRPA and produces renormalized single–particle excitation energies. The subtracted SRPA (SSRPA) provides a well–defined theoretical framework for quantitative predictions on nuclear excitation spectra.

Several applications to low–lying states and giant resonances will be shown: for instance, a systematic study on giant quadrupole resonances in medium-mass and heavy nuclei (centroids and widths) will be presented. In addition, a related topic will be discussed, namely the modification (enhancement) of the effective masses induced by the beyond-mean-field SSRPA effects.

Triaxiality, octupole correlation, and pseudospin symmetry in ^{131}Ba

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High-spin states in ^{131}Ba have been investigated via ^{122}Sn(^{13}C,4n) reaction in the Laboratori Nazionali di Legnaro. The level scheme has been significantly extended with several newly identified bands. Among them two nearly degenerate bands with negative parity and four nearly degenerate bands with positive parity have been established. A series of linking transitions among these bands are found. Among them, several E1 transitions link the bands with positive and negative parities.

This structure is an interesting realization of the multiple pairs of chiral doublet bands phenomenon (MχD) [1], which was previously observed experimentally in ^{133}Ce [2], ^{103}Rh [3] and ^{78}Br [4]. Especially in ^{78}Br, a series of E1 transitions were found linking two pairs of chiral doublets bands and interpreted as the result of octupole correlations. In ^{131}Ba, the two nearly degenerate bands with negative parity can be interpreted as chiral partner bands with the configuration $\pi h^2_{11/2}$-$\nu h^{-1}_{11/2}$, while the four nearly degenerate bands with the configurations $\pi h^1_{11/2}(g_{7/2}, d_{5/2})^1$-$\nu h^{-1}_{11/2}$. The octupole interaction between $h_{11/2}$ and $d_{5/2}$ proton orbitals can be the origin of the linking E1 transitions.

The pseudospin symmetry was discussed firstly in spherical nuclei, and extended to axially deformed nuclei later. Following theoretical studies suggested that the pseudospin symmetry remains an important physical concept even in the case of triaxiality [5,6]. However, the experimental proofs are still scarce. In ^{131}Ba, we are checking for the possibility to explain the four nearly degenerate bands with positive bands as pseudospin-chiral quartet bands, which may provide a crucial evidence for the existence of pseudospin symmetry in triaxial deformed nuclei.

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Study of superdeformation in ^{42}Ca with Coulomb excitation

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Superdeformed bands have been in focus of experimental nuclear physics studies for past decades. They have been reported in several regions of the nuclear chart and since then they also have become a new challenge for the nuclear structure theory. Recently, this phenomenon has also been discovered in the A~40 mass region. Unlike in the heavier nuclei, in calcium region the strongly deformed bands are linked to the normal deformed bands with the discreet gamma transitions, suggesting a possible mixing between these structures. Up to now the SD structures have been observed mainly in light-particle scattering and fusion-evaporation reactions, and the known B(E2) values were extracted from the lifetime measurements. However, recently also the Coulomb excitation technique has been hired to populate the SD structures in atomic nuclei.

A dedicated Coulomb excitation experiment aiming to investigate the properties of the superdeformed structure in ^{42}Ca was performed at INFN Laboratori Nazionali di Legnaro in Italy [1,2]. Gamma rays from the Coulomb excited ^{42}Ca beam on ^{208}Pb and ^{197}Au targets were measured by the AGATA HPGe spectrometer in coincidence with back-scattered projectile nuclei detected in the MCP detectors array. The level of acquired statistics was sufficient to extract a rich set of reduced matrix elements allowing to precisely describe the electromagnetic properties of low-lying yrast and non-yrast states in ^{42}Ca. The quadrupole deformation parameters of the ground state and the side bands in ^{42}Ca were determined from the measured matrix elements. The recently published results, indicating that two structures differing in overall deformation coexist in ^{42}Ca, were compared to state-of-the-art large-scale Shell Model and Beyond Mean Field calculations. In addition, the triaxiality parameter measured for the excited 0+ state provides the first experimental evidence for non-axial character of SD bands in the A~40 mass region.

In this talk I will present the benefits and the challenges of applying the Coulomb excitation method to study highly-deformed structures in atomic nuclei.

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High-K isomers in rare-earth neutron-rich nuclei by PNC-CSM Method

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Inspired by the newly discovered experimental data, high-K isomers in the rare-earth neutron-rich nuclei are investigated within the framework of the cranked shell model (CSM) with pairing correlation treated by a particle-number-conserving (PNC) method. The experimental multi-particle state energies and moments of inertia are reproduced quite well by the PNC-CSM calculations. A remarkable effect from the high-order deformation ε_6 is demonstrated. Based on the occupation probabilities, the configurations are assigned to the observed high-K isomeric states. More low-lying two-particle states are predicted. The pairing reduction due to the energy gap and the blocking effect of the multi-particle states are discussed in details. The systematics of the electronic quadrupole transition probabilities, $B(E2)$ values along the neodymium, samarium, gadolinium and dysprosium isotopes and N = 96, 98, 100, 102 isotones chains is investigated to reveal the midshell collectivities.

Coulomb excitation studies at TRIUMF-ISAC

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The versatile TIGRESS (HPGe) and BAMBINO (Si) setup at TRIUMF-ISAC enables Coulomb excitation measurements with accelerated radioactive ion beams produced using the ISOL method. Since being used for the first radioactive beam experiment with TIGRESS, the setup has been employed for a number of measurements. Data and results from three recent experimental Coulomb-excitation campaigns utilizing radioactive ion beams will be presented.

Neutron-deficient $^{21\text{-}23}$Mg were studied in order to provide precision $E2$ transition strengths with which to test nuclear structure models. The experimental data will be compared with calculations performed using the state-of-the-art ab initio in-medium similarity renormalization group and the microscopic symplectic no-core shell model, and the relative performance of these models assessed.

Data will be presented from an experiment in which ^{156,158,160}Er were studied to investigate transitional structure around $N = 88, 90$ in the rare-earth region. To-date, these are the heaviest radioactive ion-beams accelerated at the TRIUMF-ISAC facility and were provided at high intensity, with beam energies of 3.9 MeV/u and on-target intensities of approximately 1.10^8 pps (20-50% purity). An early analysis of the data taken in this experiment will be presented.

Finally, the Coulomb excitation of ^{82}Sr will be discussed. The goal of this experiment is to investigate the potential roles of shape coexistence and triaxiality approaching a region of exceptionally high deformation around ^{76}Sr, with future proposed measurements also presented.

Study of shape co-existence in mass 40 region

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Nuclei in mass 40 region are typical examples exhibiting shape coexistence. Ground states of mass 40 region near N=Z line have spherical shape due to the magic number of 20, while their excited states show deformed structure. Typical example is ^{40}Ca. In this nucleus, lowest excited state is 0^+ at 3.3 MeV and it is supposed to be normal deformed state and there is another 0^+ state at 5.3 MeV. This state is thought as a band head of superdeformed (SD) band and cascade transitions with large B(E2) values have been observed. In this region, such superdeformed bands are systematically observed and mass 40 region is one of the island of superdeformation.

In order to further understand the structural properties of mass 40 region, we have performed various experiments at RCNP using CAGRA gamma spectrometer and at ANU using super-e spectrometer, and data analysis is on-going.

Recent experimental results will be presented and discussed.

Electron-capture delayed fission in the heaviest nuclei

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Radioactive decays of the heaviest nuclei provide unique information on the limit of existence of nuclear matter. In this regards, the subsequent decays of the heaviest elements lead to the production of the most stable isotopes of the elements that exist in nature. A special interest is the so-called beta/electron capture (EC)-delayed fission process. EC delayed fission (ECDF) is a two-step process where first, an odd-odd mother nucleus undergoes EC decay, forming an excited even-even daughter one, which directly fissions instead of surviving. Despite this destruction of the nucleus, ECDF has a great impact on the understanding of nature, e.g., isotopic distribution of the astrophysical processes, gives access to fission from excited states, etc.

Presently, more than 30 cases of ECDF in isotopes of Tl, Bi, At, Fr, Np, Am, Bk, Es and Md are known. The ECDF process is often quantified by its probability (PECDF), expressed as the ratio of the number of initial EC decays to that of subsequent fissions from excited states of the daughter nucleus, which is still poorly describable by theory. Therefore, experimental PECDF values have mostly been used in theoretical work either for extraction of the fission barrier heights or for extracting partial ECDF half-lives. These approaches lead to interesting results, which help accumulating knowledge on the ECDF process. Despite these valuable results, still no conclusive picture of ECDF that provides a quantitative description of the experimental PECDF values is yet given. Accordingly, theoretical predictions of yet unknown cases of ECDF in wide ranges of Z and N do not currently exist.
I will present a semi-empirical estimate on ECDF probabilities of nuclei with Z=79-119 by inferring the theoretical QEC and Bf.

Nuclear structure studies at IGISOL

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The Ion Guide Isotope Separator On-Line (IGISOL) facility in the JYFL Accelerator Laboratory offers versatile possibilities for nuclear structure studies via high-precision mass measurements as well as via decay and laser spectroscopy. In this presentation, I will mainly focus on mass measurements recently performed with the JYFLTRAP Penning trap mass spectrometer at IGISOL. These include for example measurements on neutron-rich rare-earth isotopes close to N=100 as well as nuclides close to 78Ni. Many of the studied nuclides were measured for the first time and therefore provide essential information on nuclear structure far from stability.

Symmetry adapted SU(3) No-Core Shell model with importance sampling

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We apply the importance-truncation (IT) procedure based on the many-body perturbation theory [1] for the multi-shell SU(3) scheme basis of the ab initio symmetry-adapted no-core shell model (SANCSM) [2]. It will be shown that the IT method can yield a quantitative justification for the symmetry based truncation of the SANCSM approach. We will demonstrate a potential of the method via convergence rate of lowest eigen energies, B(E2) values and radii in ^{6}Li and medium-heavy ^{20}Ne. It will be shown that significant reduction of model space can be achieved in combined IT and SANCSM approach.

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Shapes and symmetries in fission of (super)heavy nuclei

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We study the role of different shapes and symmetries in fission of (super)heavy nuclei. Multidimensional energy landscapes are calculated within the MM model based on the deformed Woods-Saxon potential. The Strutinsky shell and pairing correction is taken for the microscopic part. For the macroscopic part we used the Yukawa plus exponential model. Main aim of our study is to improve the predictions for the fission saddles by simultaneously taking into account a large number of shape variables. It has been demonstrated that:
i) the effect of the mass asymmetry, known to lower the second, very deformed saddles in actinides, in the heaviest nuclei appears at the less deformed saddles in more than 100 investigated nuclei. It happens for those saddles in which the triaxiality does not play any role, which suggests a decoupling between effects of the mass asymmetry and triaxiality.
ii) the inclusion of triaxial shapes significantly reduces the fission barriers by up to 2.5 MeV; about 70 % of the found fission barriers correspond to triaxial saddles. Besides the quadrupole nonaxiality we checked also the effect of hexadecapole nonaxiality, which significantly lowers the fission barrier in Z ≥119 nuclei, especially neutron-deficient ones.
iii) for large elongations with which we are dealing in actinides, the dipole deformation (β_{10}) acquires a meaning of a real shape variable and the landscape modification obtained by including this deformation is decisive for the height and shape of the fission barrier.
We look also for the energy minima with a nonzero tetrahedral distortion, both absolute and conditional with the quadrupole distortion constrained to zero and we could not find any cases of stable tetrahedral shapes in heavy and superheavy nuclei.

Toroidal mode in nuclei

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Last years the toroidal dipole resonance (TDR) attracts a high attention [1-4]. This mode is located at the energy of the pygmy dipole resonance and forms the low-energy part of the isoscalar giant dipole resonance. The TDR has many remarkable properties. This is the only known dipole vortical mode in the family of intrinsic electric excitations. Various TDR properties were explored by our group within the self-consistent Skyrme Quasiparticle Random-Phase Approximation (QRPA), see [2-4]. Nevertheless, despite an impressive general theoretical and experimental effort, our knowledge on the TDR is still poor and even its experimental observation can be disputed [3].

In this connection, we propose a new route to study the toroidal mode: to switch the effort from TDR (embracing many states and masked by other multipole modes) to individual well-separated low-energy toroidal states. As was recently shown [4], such states can exist in low-energy spectra of light nuclei with a strong axial prolate deformation. For example, in ^{24}Mg, this state appears as the lowest dipole K=1 excitation. Here we discuss also the possibility to observe the toroidal individual states in inelastic electron scattering to back angles.

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Rotational bands in triaxial nuclei with particle-rotor model

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The yrare $\pi h_{11/2}$ band in ^{135}Pr was recently interpreted as transverse wobbling [1,2]. This novel idea [1] has attracted a lot of interest and raised several questions and discussions [3, 4, 5]. In particular, the freezing of the proton angular momentum along the short nuclear axis was questioned, as well as the stability of the transverse wobbling. We have examined the harmonic approximation in the particle-rotor Hamiltonian producing the harmonic wobbling equations [1]. It assumes that the rotation along the intermediate and along the long nuclear axes is small. In this contribution the harmonic wobbling approximation and in particular the nature of the predicted 1-quasiparticle rotational bands with and without this approximation will be discussed. We found that the predicted bands have distinctly different nature, that is transverse wobbling in the first case and (what we call) revolving rotation in the second. The implications for the interpretation of the yrare bands in some odd-mass triaxial nuclei, including ^{135}Pr, will be discussed.

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Partial dynamical symmetries for transitional nuclei

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Symmetries play a central role in characterizing the dynamics of nuclear shapes. The close relation between symmetry and geometry is clearly evident in algebraic models, where the shape-phases of the system are associated with dynamical symmetry (DS) limits. An Hamiltonian with DS is written in terms of Casimir operators of a chain of nested algebras, leading to complete solvability of its spectrum with exact quantum numbers for all eigenstates. A notable example is the interacting boson model (IBM), based on a U(6) spectrum generating algebra, where the analytic solutions corresponding to its DS chains with leading subalgebras: U(5), SU(3), $\overline{SU(3)}$ and SO(6), resemble known paradigms of nuclear collective structure: spherical vibrator, prolate-, oblate- and γ-soft deformed rotors, respectively. This identification is consistent with the geometric visualization of the model given by an energy surface, $E(\beta,\gamma)$, defined by the expectation value of the Hamiltonian in a coherent (intrinsic) state. The values, (β_{eq}, γ_{eq}), of the quadrupole shape parameters at the global minimum of $E(\beta,\gamma)$ define the equilibrium shape for a given Hamiltonian.

A dynamical symmetry corresponds to a single structural phase with a particular shape (β_{eq}, γ_{eq}). The DS Hamiltonians support a single minimum in their energy surface, hence serve as benchmarks for the dynamics of a single shape. The situation is more complex in transitional nuclei, whose spectra reflect a transition between different structural phases with possible coexistence of several shapes. The relevant Hamiltonians, by necessity, contain competing terms from different DS chains, with incompatible (non-commuting) symmetries and the corresponding energy surface accommodates multiple minima. In such circumstances, exact DSs are broken, and any remaining symmetries can at most be shared by only a subset of states. To address the persisting regularities, amidst a complicated environment of other states, one needs to enlarge the traditional concept of exact dynamical symmetry.

In the present contribution, we consider such an extended notion of symmetry, called partial dynamical symmetry (PDS). Hamiltonians with multiple PDSs, preserving the DS of only selected bands, are explicitly constructed and shown to provide suitable benchmarks for the dynamics of transitional nuclei at and near the critical-point, involving coexisting shapes.

A new method for calibrating two-dimensional ΔE-E without radioactive source

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A new method with high accuracy has been developed for calibrating two-dimensional ΔE-E spectra of charged particles without radioactive source. Calibration parameters are deduced by fitting the ΔE-E curves to those simulated by LISE++. This method has been tested and the errors have been evaluated by comparing with calibrated projectile fragmentation of ^{9}Li delivered by the First Radioactive Ion Beam Line in Lanzhou. It provides an alternative way to get precise energies and sort the data from different pairs of ΔE-E silicon detectors into one figure, in case the usage of radioactive sources is restricted. We therefore apply this method in the analysis of emitter channels of charged particles recorded in the measurement via ^{9}Be+^{122}Sn reaction in LNL, Legnaro, where fifty pairs of ΔE-E silicon detectors were employed. Adding back the energy loss in the aluminum absorber, the precise emitting energy of charged particles can be deduced to further investigate the reaction system.

Relativistic effects in triggering the N=34 magic shell of Ca-54

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In recent time, lots of efforts have been devoted to understanding the occurrence of the new magicities N=32 & 34 in Ca-52 & Ca-54, which have been confirmed both from the experimental and theoretical sides. While under the frame of covariant density functional (CDF) theory, only the CDF with Fock terms PKA1 can provide appropriate description on the emergence of the new magicities N=32 & 34. In the prior study, it has been illustrated that within CDF, the isovector pion and tensor rho couplings play the crucial roles in the occurrence of N=32 magic shell in Ca-52, from the aspect of the evolution along the N=32 isotonic chain, and the tensor force components introduced by pion and tensor rho fields are also significant. While the isovector couplings cannot explain the emergence of N=34 magicity with two more neutrons, which remains some mystery.

In this talk, the emergence of magic shell N=34 will be studied from the aspect of the evolution along the calcium isotopic chain. It is found that from Ca-48 to Ca-52, the neutron 2p orbital splittings are continuously enlarged, leading to the occurrence of N=32 magicity in Ca-52. While with only two more neutrons, namely Ca-54, the 2*p* orbital splitting is reduced distinctly and meanwhile the 1*f* orbital splitting remains unchanged. Both trigger the N=34 magic shell in Ca-54. To understand such dramatic evolution, the density profiles as well as the contributions to the spin-orbital splittings are analysed. It is shown that consistent with evolution of 2*p* orbital splittings, the central density profile represents atypical evolution, from a slightly central-bumped shape in Ca-48 to completely central-bumped one in Ca-52, and to the fairly distinct bubble-like shape in Ca-54. Further analysis shows that such dramatic changes can be traced back to the couplings between the *s* and 2*p* orbits. It is found that due to the relativistic effects in the couplings, namely the contributions from the small components of Dirac spinors, the couplings between *s* and $2p_{1/2}$ orbits represent distinct repulsion, which is also common in other nuclei. Compared to Ca-52, two valance neutrons fill in $2p_{1/2}$ orbit, which bring about the repulsive couplings with the *s* orbit. Such that the *s* orbits are distinctly central-depressed, leading to the neutron bubble-like structure in Ca-54. Because the 2*p* orbits have fairly large overlap with the interior region, the evolution of central density profile will bring the consistent changes on the 2*p* orbit splittings, which account for the emergence of the magicity N=32 & 34.

Decay-spectroscopy and lifetime measurements of superheavy nuclei

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The study of super heavy nuclei addresses the question of nuclear stability and nuclear structure under extreme conditions of charge and mass. Several axes of research are pursued in this domain at CSNSM. One of them consists in the decay studies of super heavy nuclei with the GABRIELA multi-detector array at the focal plane of the Separator for Heavy Element Studies (SHELS) in Dubna. The second is the R&D on the feasibility of spectroscopy and lifetime measurements of trapped super heavy nuclei in the Maier Leibnitz Laboratory (MLL) Penning trap currently installed at the ALTO facility. In this talk, results concerning the interplay between single-particle and collective degrees of freedom in ^{251}Fm will be presented as well as the status of simulations and mechanical design of the spectroscopy tower of the MLL trap.

Chirality in the even-even nucleus ^{136}Nd

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Chirality in nuclei is a dynamic collective mode that may appear in a triaxial nucleus which rotates about an axis out of the three principal planes of the ellipsoidal nuclear shape. Evidence for chiral doublet bands has been observed for the first time in the even-even nucleus ^{136}Nd. One chiral band was firmly established. Four other candidates for chiral bands were also identified, which can contribute to the realization of the multiple pairs of chiral doublet bands (MχD) phenomenon. The observed bands are investigated by the constrained and tilted axis cranking covariant density functional theory (TAC-CDFT). Possible configurations have been explored. The experimental energy spectra, angular momenta, and B(M1)/B(E2) values for the assigned configurations are globally reproduced by TAC-CDFT. Calculated results support the chiral interpretation of the observed bands, which correspond to shapes with maximum triaxiality induced by different multiquasiparticle configurations in ^{136}Nd.

Nuclear matrix elements to unveil the nature of neutrinos and dark matter

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The fundamental nature of neutrinos and dark matter are among the biggest puzzles on physics. Low-energy experiments using atomic nuclei play a crucial role to solve these questions, and the interpretation of these measurements requires reliable nuclear matrix elements. Prominent examples of experiments testing fundamental symmetries are searches of the neutrinoless double-beta decay, and the direct detection of dark matter.

I will discuss the latest developments in the calculation of the nuclear matrix elements that govern double-beta decay and the interaction of dark matter with nuclei, with emphasis on the role of nuclear correlations. In addition, I will also discuss possible ways to constrain the matrix elements in nuclear structure experiments, such as charge-exchange reactions.

Point symmetry and nuclear octupole bands

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We discuss the application of a model formalism capable to describe nuclear alternating-parity spectra in the mass regions of pronounced octupole deformation. The model describes rotations of the quadrupole-octupole (QO) shape determined by a point-symmetry based Hamiltonian [1] and oscillations in a double-well octupole potential which together provide an explanation of the “beat” staggering structure observed in the octupole bands of light actinides Rn, Ra, Th [2] and nuclei in the region of Ba and Ce [3]. The approach allows us to study the evolution of nuclear collective motion from the low-energy soft-octupole mode to the higher-spin regime of QO rotations. The latter is associated with the irreducible representations of the octahedron point-symmetry group which take into account the contribution of different QO shapes to the rotation motion. The model provides a detailed test for the presence of octupole collectivity especially in less studied regions. This is demonstrated for spectra in the region of Nd isotopes.

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Neutron rich nuclei through microscopic nonadiabatic quasiparticle approach

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Neutron rich nuclei with A ~ 100 and Z ~ 50, exhibit specific features such as shape coexistence and shape variation from spherical to large quadrupole and triaxial deformation with increasing neutron numbers [1, 2]. Investigating the structural properties of these nuclei is also crucial since they participate in astrophysical nucleosynthesis through rapid neutron capture process (r-process). We have developed a nonadiabatic quasiparticle approach where the rotation-particle coupling is treated microscopically [3]. A neutron rich nucleus ^{111}Tc with its rotor ^{110}Mo is investigated by utilising our microscopic approach. This nucleus possess axial asymmetry according to the result of rigid triaxial rotor-plus-particle model [1]. With our model, we have reproduced the spectra of ^{111}Tc and its rotor ^{110}Mo at $\gamma = 25^\circ$. The quadrupole deformation is calculated as $\beta_2 \sim 0.35$, where the best agreement with the data is obtained. We have unambiguously identified that $1g_{9/2}$ and $2d_{5/2}$ single-particle orbitals are predominantly contributing in the configuration of ground and side bands of ^{111}Tc.

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Correlation between the average number of emitted neutrons and the mass yield of fragments from thermal neutron induced fission of ^{235}U

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Using the Monte Carlo method, the measurement of the number of emitted neutrons as a function of the mass of the final fragments of the fission induced by thermal neutrons of the ^{235}U was simulated. As input data for the average number of neutrons emitted as a function of the primary mass, a perfect sawtooth function, composed of three line segments close to the experimental curve obtained by several authors [1-3], is assumed. The output curve gives the number of neutrons emitted as a function of the final mass of the fragments. This curve oscillates around the first curve, similar to what the experimental curves oscillate with respect to its sawtooth curve approach. In particular, with respect to the sawtooth curve, the resulting simulation curve presents high values for the lightest masses, low values for the heavier ones and a widening in the form of a peak around m = 110. These results are due to the conjugate interplay of the number of neutrons and the yield of mass curve in regions where it has a rapid variation depending on the mass of the fragments. The double energy and the flight time techniques are also simulated to demonstrate that the result depends on how the mass of the fragments are measured.

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Nuclear structure of long lived isomer of ^{217}Pa using the QPRM model

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The analysis of the heavy and very heavy nuclei with, particularly, an extension into the domain of exotic and superheavy nuclei is in the center of the contemporary research in low energy subatomic physics. This research program, currently going on the biggest laboratories in the world, is motivated from the theoretical calculations which predict the existence of an island of stability for superheavy nuclei beyond Z=82 for proton and N=126 for neutrons. To study the structure of heavy and superheavy nuclei, we need to produce a handful of events and therefore provide a detailed spectroscopic data. Owing to the extreme limit of current capabilities and weak production cross sections close to 1nb, the structure of heavy and very heavy nuclei could help us to understand the structure and stability of superheavy nuclei since such shell properties may be a consequence of nuclear deformation

In this work, we aim to use the quasiparticle-phonon plus rotor model (QPRM) to study the nuclear structure of heavy elements in the region of N=126 isotones having $84 \leq Z \leq 92$. We show the experimental levels scheme of ^{213}Ac populated via the alpha-gamma decay of ^{217}Pa. Then, we focus our study QPRM method to determine the microscopic configuration in terms of spin-parity and isomeric state at low-lying energies of excited states.

Study of exotic excitations in nuclei near spherical and deformed shell gaps using INGA

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Understanding of the excited states in nuclei is a fascinating field of study in nuclear structure physics. The shell gaps, both spherical and deformed, play significant role in determining the excited states and high spin structures in nuclei. In general, the single particle and collective excitation are favored for the nuclei near the spherical shell closures and in the mid-shell nuclei, respectively. However, shape driving effect of some of the high-j nucleon orbitals (e.g $h_{9/2}$, $i_{13/2}$) near the spherical shell closures (Z = 82 and N = 126), induces deformation and thereby, collective rotational states in nuclei. Moreover, the involvement of such high-j orbitals produce novel and interesting modes of excitation in nuclei, such as magnetic rotation and chirality. We have studied several isotopes of Tl (Z = 81) and Bi (Z = 83), the proton Fermi level of which lie just below and above the Z = 82 magic number. The level schemes of these nuclei have been extended considerably from our study and we have observed some of the above interesting aspects of nuclear excitation in these nuclei. On the other hand, the identification of the band crossing in the mid-shell nucleus ^{169}Tm, which lie right on the stability line, from our study and its comparison with its neighboring isotopes brought out an interesting aspect of the effect of the N = 98 deformed shell gap on the band interaction strength. Some of these nuclei are predicted to be triaxial at higher excitation energies from the total Routhian surface calculations. All these experimental investigations were performed by gamma ray spectroscopic method and using the Indian National Gamma Array (INGA) which is an array of up to 22 number of Compton suppressed clover HPGe detectors. The data and the results of our investigations along with our understanding will be presented.

From Quark Correlations to Nuclear Drip line

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We propose a quark model of nuclear structure where quark correlations lead to nucleon--nucleon correlaions and arrangement of them into lattice--like structure.

The model is based on the quark model of nucleon structure in which valence quarks are strongly correlated within a nucleon [1]. Nuclei are built by junctions of SU(3) color fields of two quarks of neighboring nucleons. At any junction two quarks should be of different color (r,g,b), different flavor (u,d), and have parallel spins.

Application of the model to larger collections of nucleons reveals the emergence of the face-centered cubic (FCC) symmetry at a nuclear level where nucleons are arranged in alternating spin--isospin layers [2]. The model of nuclear structure becomes isomorphic to the shell model and, moreover, composes the features of the liquid drop and cluster models. Binding of nucleons in stable nuclei are provided by quark loops which result in three and four nucleon correlations. There are two essential differences from the shell model. First, on a quark level the nuclear shell closures correspond to the octahedral symmetry. Thus all nuclei even with closed shells are non-spherically symmetric. Second, closure of shells in our model is strongly dependent from the relative numbers of protons and neutrons, because they are strongly correlated. It turns out that a building blocks of the nuclear structure are three-nucleon (triton and helium-3) and and four-nucleon (helium-4) like configurations. The quark loop that can be identified with three nucleon force results in a "pairing" effect. And namely quark loops leading to four-nucleon correlations are responsible for the binding energy enhancement in even-even nuclei which are formed by virtual alpha-clusters. Closure of *p-, d-, f-, ...* shells rearranges inner *s-, p-, d-, f-, ...* shells correspondingly in such a way, that the inner nucleons become the common ones for neighbouring virtual alpha-clusters binding them, at the same time [3]. For medium and heavy nuclei the arrangement of nucleons is modified by Coulomb repulsion of protons. This effect together with quark/nucleon correlations leads to deviation from the shell model expectations. The model can predict the boundary of the maximal numbers of proton and neutron excess, i.e. proton and neutron drip lines.

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Coulomb excitation at LNL with the SPIDER-GALILEO setup and opportunities at SPES

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Low-energy Coulomb excitation is one of the simplest and well known tools to study the nuclear shape, for this reason is widely used at radioactive beam facilities. In particular in the case of ISOL facilities the energy and the intensity of the available beams is suitable for low-energy Coulomb excitation. The SPES facility for the acceleration of radioactive beams will soon provide the first exotic beams at the National Laboratories in Legnaro.

To this aim the gamma spectroscopy group in Florence has developed and assembled a new particle detector to be used for Coulomb excitation studies of both for stable and radioactive beams at LNL. The Silicon PIe DEtectoR (SPIDER) has been coupled to the GALILEO array of germanium detectors, and different experiments have been already performed.

In this talk the performances of the setup, a brief summary of the experiments already performed and the future perspectives with both the available stable beams at LNL and the future radioactive beams by SPES, will be presented.

Nuclear structure and dynamics from *ab initio* theory*

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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 a new 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 are able to predict structure and dynamics of light nuclei and, by comparing to available experimental data, test the quality of chiral nuclear forces. I will present latest NCSMC calculations of halo nuclei, unbound nuclei such as ^{9}He and structure of A=7 nuclei considering their multiple breakup channels. Further, I will present our study of beta decays and the role of the two-body currents. Finally, I will discuss polarization effects in the ^{3}H(d,n)^{4}He fusion and its mirror reaction ^{3}He(d,p)^{4}He.

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* Supported by the NSERC Grant No. SAPIN-2016-00033. TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada.

Nuclear structure studies based on energy density functionals

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The microscopic self-consistent mean-field (SCMF) framework based on universal energy density functionals provides an accurate global description of nuclear ground states and collective excitations, from relatively light systems to super-heavy nuclei, and from the valley of beta-stability to the particle drip-lines. Based on this framework, structure models have been developed that go beyond mean-field approximation and include collective correlations related to restoration of broken symmetries and fluctuation of collective variables. In particular this includes i) generator-coordinate method with projections on particle number, angular momentum and parity, ii) implementations for the solution of the collective Hamiltonian for quadrupole and octupole vibrational and rotational degrees of freedom, iii) microscopically determined interacting boson model. These models have become standard tools for nuclear structure calculations, able to describe new data from radioactive-beam facilities and provide microscopic predictions for low-energy nuclear phenomena of both fundamental and practical significance.

In this talk some of the recent applications of the SCMF framework will be highlighted: studies of shape evolution and coexistence, quadrupole and octupole shape transitions in various systems, shape transitions in odd-mass nuclei and SCMF based analysis of the dynamics of spontaneous fission process. Finally, perspectives for future calculations will be discussed.

Fission studies using multi-nucleon transfer reactions

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We are promoting a program of fission studies using multi-nucleon transfer reactions [1-3]. This approach allows us to investigate fission of neutron-rich nuclei, which cannot be populated by particle capture reactions. From the measurement of fission fragment mass distributions (FFMDs) for various nuclides and their evolution with initial excitation energy, the role of multi-chance fission, i.e. neutron emission prior to fission, on FFMD was investigated [3]. The obtained large data set of FFMDs was used to improve the Langevin model to describe low-energy fission [4], which was applied to the fissions of fermium isotopes. The results explain the origin of the onset of sharp symmetric fission appearing in neutron-rich fermium isotopes. In the presentation, we will also discuss other data obtained in our setup, such as fission barrier height and prompt neutrons in correlation with fission fragments.

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Shape coexistence studies at JYFL and ISOLDE

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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 the 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. For example, the experimental program carried out at JYFL has included in-beam electron and γ-ray spectroscopy and lifetime measurements [2]. The post-accelerated radioactive ion beams available at REX-ISOLDE [3] have allowed the Coulomb excitation experiments to be performed using the MINIBALL γ-ray spectrometer [4].
This talk will give an insight into shape coexistence studies around neutron-deficient Pb nuclei carried out JYFL and ISOLDE. The advantages of different techniques will be discussed.

The Academy of Finland and the EU 7th Framework Programme for Research are gratefully acknowledged.

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Shape coexistence in neutron deficient Hg isotopes

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In a recent experiment, neutron-deficient $^{177\text{-}185}$Hg isotopes were studied using in-source laser resonance-ionization spectroscopy at the CERN-ISOLDE radioactive ion-beam facility in an experiment combining different detection methods tailored to the studied isotopes The experimental data show an interesting odd-even staggering in the evolution of charge radii in the region $^{180\text{-}184}$Hg.

Using Density Functional Theory, we have performed extensive calculations in this region of the nuclear chart observing that the staggering can be explained as a change in shape: going from the even (prolate) to the odd (oblate) nucleus. The calculations turn out to be extremely sensitive to some particular terms of the functionals as pairing strength and surface properties. The calculation give a reasonable description of the data. However, the prediction of the staggering is two neutron numbers off compared to experiment and the ground-state spins of odd isotopes are not correctly reproduced. Despite this lack of predictive power, the knowledge we gained in this study may still be very useful in the construction of new functionals paying thus more attention to properties of deformed nuclei.

Octupole vibrations in super heavy nuclei and K-mixing for isomeric with the QRPA formalism

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Known to be well adapted for the description of giant resonances, the QRPA formalism can also, with the same accuracy, describe low energy vibrational states whether with a highly collective or with a single-particle character. The QRPA approach based on the Gogny interaction developed in Bruyères-le-Châtel [1] can be applied to spherical as well as to axially deformed nuclei, from light (i.e. oxygen) to superheavy elements [2]. At the end of the calculation the transition probabilities for the decay of the QRPA excited states toward the ground state are obtained, regardless of the transition multipolarity. In addition, recent developments allow us to study odd nuclei.

In this talk I will present recent successes obtained by the QRPA approach in the reproduction of two experimental findings: octupole excitations around ^{249}Cf [3], and K=4 isomeric states in N=100 isotones [4].

In superheavy odd nuclei our approach is able to produce low energy octupole excitations in agreement with recent experimental data on ^{251}Fm [3]. After specifying some points of the odd system treatment, the octupole electric B(E3) and quadrupole magnetic B(M2) transition probabilities will be discussed with respect to data along the N=150 chain.

Our axially-symmetric-deformed QRPA approach has also been applied to the N=100 isotones in order to describe the J=4 isomeric states. Since calculated half-lives for pure K=4 states are too large by several orders of magnitude, Coriolis coupling between QRPA states has been introduced [4]. The formalism related to the induced K-mixing will be explained, and results about the mixing amplitudes in isomeric states will be used to interpret the variation of the lifetime along the isotonic chain [4].

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Coexistence phenomena in neutron-rich A~100 nuclei within the beyond-mean-field approach

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Structure and dynamics of neutron-rich nuclei in the A~100 mass region manifesting dramatic changes in some isotopic chains and sudden variations of particular nuclear properties are relevant for the astrophysical r-process and nuclear reactor related issues.

Our recent investigations represent an attempt to a comprehensive understanding of shape coexistence phenomena suggested by the experimental data at low spins and the richness of various structural effects at intermediate spins in neutron-rich A~100 nuclei within the beyond-mean-field complex Excited Vampir variational model with symmetry projection before variation using a realistic effective interaction obtained from a nuclear matter G-matrix based on the charge-dependent Bonn CD potential and a large model space. Results will be presented concerning effects of shape coexistence and mixing on structure and electromagnetic properties as well as beta-decay properties around the neutron number N=58.

Continuum shell model for nuclear structure and reactions

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Loosely bound nuclei are currently at the center of interest in nuclear physics in problems related to the limits of stability of nuclear matter and nucleosynthesis. Since nuclear properties are profoundly affected by environment of the many-body continuum representing scattering and decay channels, a simultaneous understanding of the structural and reaction aspects is crucial for understanding of short-lived nucleonic matter.

Attempts to reconcile the nuclear shell model with the reaction theory have led to the development of the continuum shell model. I will review recent progress in the shell model description of nuclear open quantum systems and, in particular, the understanding of near-threshold collectivity/ clustering in terms of the coupling of shell model states via the decay channel(s). This anti-Hermitian coupling leads to the formation of the ’aligned state’, the eigenstate of the continuum shell model which captures most of the continuum coupling, and, above the decay threshold, exhausts most of the decay width.

Various applications of the continuum shell model in studies of nuclear spectra and binding energies, exotic particle decays, and reaction cross sections will illustrate some of the generic open quantum system phenomena in the context of nuclear physics.

Neutron-rich nuclei with N>=126

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Information gained on neutron-rich N~126 nuclei is essential for the understanding of nuclear structure in heavy nuclei. Studies around doubly magic systems allow direct tests of the purity of shell model wave functions. From a longer-term perspective, experiments in this region pave the way toward the proposed nuclear-astrophysical r-process waiting point nuclei along the N = 126 shell closure. In the case of the beta decay of N~126 nuclei there is a competition between allowed and first-forbidden transitions. This is the mass region where first-forbidden (FF) transitions can be dominant, which can have profound implications on their half-lives and therefore on the r-process (A~195 abundance peak). Recently several experiments were performed at ISOLDE with the aim to study neutron-rich nuclei around ^{208}Pb.

(i) Structure of ^{208}Tl from the beta decay of ^{208}Hg. ^{208}Tl being a one-proton-hole one-neutron-particle nucleus, its excited levels give direct information on the proton-neutron interaction in the Z<82, N>126 quadrant. In addition, the existence of both negative and positive parity states at low excitation energy makes this nucleus an ideal testing ground for the study of the competition between first-forbidden and allowed beta decay.

(ii) Structure of ^{207}Tl from the beta decay of ^{207}Hg. A large number of excited states, several of them of octupole character were observed and compared with calculations.

(iii) Coulomb excitation of ^{206}Hg at safe energies. This gives information about both quadrupole and octupole collectivity.

The presentation will report on recent results and their relevance on the structure of neutron-rich nuclei around ^{208}Pb.

Ground-State Rotational Bands in Even-Even Heavy and Super-Heavy Nuclei

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The macroscopic-microscopic model with the Lublin-Strasbourg drop [1] and the Yukawa-folded single particle potential [2], the Strutinsky shell-correction method [3], and the GCM+BCS approach for pairing correlations [4] is used with the cranking model to describe the ground-state rotational bands in even-even actinide and trans-actinide nuclei. The 4D Fourier shape parametrization was used to find the ground-state shape of investigated nuclei [5]. The strength of the monopole pairing force is adjusted to reproduce the experimentally known rotational E_{2+} state within the cranking model. It is also shown that the rotational states with $L \leq 10$ in Ra to No nuclei evaluated using a simple rotational formula agree quite well with the data. We propose a simple mechanism which takes into account a dynamical coupling of rotation with the pairing field [6] what allows to obtain a good agreement with the data up to the states with the largest angular momenta ($L \leq 30$) measured in this mass region [7,8].

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Nuclear properties of nobelium isotopes from laser spectroscopy

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Laser spectroscopy is a versatile tool to precisely measure properties of an elements electron shell and moreover to deduce properties of the nucleus. This is of particular importance for the heaviest elements where the electron shell is strongly influenced by electron-electron correlation and relativity changing the electron configuration and thus, the chemical behavior [1,2]. By resolving subtle changes in the center position and the structure of an optical resonance, laser spectroscopy enables to infer information on the deformation and the intrinsic moments of the atomic nucleus.
The study of nuclear properties for nobelium (No, Z=102) isotopes became possible after the first identification of a strong 1S0 → 1P1 ground state transition in pioneering experiments at GSI, Darmstadt where the sensitive RAdiation Detected Resonance Ionization Spectroscopy (RADRIS) technique was applied [3,4]. Nobelium ions are produced in a fusion-evaporation reaction with a ^{48}Ca primary beam impinging on a lead target. The recoils were separated from the primary beam by the velocity filter SHIP, stopped in high-purity argon gas and collected onto a thin tantalum filament. After re-evaporation the neutral atoms were probed by laser light applying two-step resonance ionization and the created photo-ions were detected by their characteristic alpha decay. Here, the isotope shifts of the ground-state transition were measured for the isotopes $^{252\text{-}254}$No as well as the hyperfine splitting in ^{253}No. In combination with atomic calculations, we determined the evolution of the deformation of the nobelium isotopes in the vicinity of the deformed shell closure at neutron number N=152 and extracted the magnetic moment and the spectroscopic quadrupole moment of ^{253}No [5]. These results will be discussed and the prospects for extending laser spectroscopy to heavier elements and towards high-resolution laser spectroscopy of nobelium isotopes and isomers will be given.

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Configuration assignments for the extensive level scheme of ^{167}Lu

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An extensive level scheme including some 630 γ-ray transitions has been observed [1] in $^{167}_{71}\mathrm{Lu}_{96}$. Configurations have been assigned to the different band structures using the Cranked Nilsson-Strutinsky (CNS) [2,3] and the cranked Nilsson-Strutinsky-Bogoliubov (CNSB) [4, 5] models, i.e. with pairing neglected (CNS) and pairing included (CNSB). The advantage of the unpaired formalism is that it is possible to fix configurations in a much more detailed way. Assignments have been given to all linked bands which are observed in an extensive spin range. In many cases, we find an improved understanding of the bands compared to the assignments in the experimental paper [1], which are mainly based on identification of 'paired' band-crossings. Our calculations suggest that the only important paired band-crossings are those which are observed below $I \simeq 30$ in high-j shells with the Fermi level in the lower part of the shell. Indeed, it is only such crossings which are discussed in the original paper by Bengtsson and Frauendorf [6]. Starting at rather low spin values, the structure of the rotational bands calculated in CNS and CNSB are very similar, indicating that the spin is mainly built from the gradual alignment of the spin vectors of the valence particles. Thus, the labelling of the bands according to the number of particles with 'aligned spin' becomes strange at high spin and it becomes more appropriate to label the bands according to the filling of particles in different j-shells or groups of j-shells independent of their alignment. For example, typical yrast configurations for low spin positive parity proton states in ^{167}Lu are based on $\pi(h_{11/2})^8$ while $\pi(h_{11/2})^6$ configurations are generally more favoured in energy at high spin (cf. Fig. 12.11 in Ref. [7]).

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Towards ultra-cold gases of caesium isomers: progress and perspectives

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University College London and IGISOL have recently commissioned a facility for the production, laser cooling, and trapping of ultra-cold Caesium isotopes and isomers at the Accelerator Laboratory of the University of Jyväskylä (Finland). In this talk, we will report on the design, installation, and test of the experimental facility, and on its latest results. The desired ^{A,Am}Cs species is produced by proton-induced fission or fusion evaporation in the IGISOL-4 facility [1]. ^{A,Am}Cs^{+} are electrostatically extracted, accelerated to 30 keV, mass separated, and routed to the "cold" experimental chamber. Here, thin foil implantation allows creation of a stable thermal vapour of neutral ^{A,Am}Cs atoms, which are then laser cooled and trapped in a magneto-optical trap. At the current stage ^{A,Am}Cs is brought from 104 eV to 10-8 eV in around 5 s, at full capacity. Availability of ultra-cold ($\leq 10^{-4}$ K) samples of unstable Cs isotopes and isomers opens new perspectives for a deeper insight into the nuclear structure and for the investigation of multi-body physics at the nuclear level. In particular, direct comparison of optical transitions shifts in ^{A}Cs/ ^{Am}Cs pairs provides novel data for investigating the charge radii variations and the nuclear shape. Furthermore, the possibility of selectively trapping and detecting small traces of given Cs isotopes constitutes the building block of a new, highly sensitive approach to nuclear forensics, and related applications in environmental control and security. Finally, perspectives on the realisation of an isomeric Bose-Einstein condensate and of the long-awaited experimental demonstration of coherent gamma photons generation will be also presented [2].

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Fission study project in RIKEN RIBF: towards the complete measurement of fission observables

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Fission is one of the most dynamical process that can occur in nuclei and related to a variety of topics of nuclear physics. Despite of the fact that the fission is one of the phenomena having longest history of studies, it is still very difficult to describe this process theoretically. This is partly because, in terms of nuclear shapes and symmetries, the fission relates the initial state to final states having totally different shapes and symmetry, i.e. two split nuclei having individual shell structures. Obviously, it is of great importance to experimentally pin down the properties of the initial and final states simultaneously for the understanding on the process. In RIKEN RIBF project, we are planning to determine the complete information on the initial and final states by using the (p,2p) reaction in inverse kinematics with an RI beam in conjunction with the SAMURAI spectrometer at RIBF. The missing mass spectroscopy of the reaction and its combination with an RI beam provided at BigRIPS is a powerfull approach to control the initial state of the fission nucleus, while the use of the SAMURAI spectrometer gives the information on the fission fragments in a complete manner. Therefore, combining these two, one can obtain a complete information on the fission. In this talk, we will present the present status of this project.

IMME within isospin-symmetry-breaking DFT

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In the recent article [1] we have demonstrated that the extended nuclear Density Functional Theory (DFT) that includes isospin-symmetry-breaking (ISB) leading-order (LO) contact terms and proton-neutron mixing in the particle-hole channel is capable to account globally (irrespectively on atomic number) for the ISB in nuclear masses of N ≈ Z nuclei. It is, however, not obvious whether the introduced ISB contact terms are due to the strong forces, beyond mean-field Coulomb effects or both. In this talk, I shall address this fundamental for our understanding of the ISB in atomic nuclei question by performing systematic study of the Isobaric Multiplet Mass Equation (IMME) in light nuclei. I will delineate contributions to the isovector and isotensor IMME coefficients coming from the electromagnetic, isoscalar, and ISB terms of the functional and compare them to the available *ab initio* calculations what, in turn, will allow me to evaluate and quantify the role of many-body ISB contributions. I will demonstrate that, after including next-to-leading (NLO) surface-sensitive isovector and isotensor gradient terms, our DFT results agree reasonably well with the Green Function Monte Carlo results of Ref.[2] in light nuclei what leads to a rather unexpected conclusion that the nuclear DFT properly takes into account the contribution of the Coulomb interaction and that the local correcting ISB potential accounts, predominantly, for the strong-force-rooted effects order by order. Comparison of isotensorial IMME coefficients calculated using the extended DFT to the shell-model-based *ab initio* results of Ref. [3] in the pf-shell triplets is, at the moment, inconclusive due to problems with convergence in the latter theory.

Superallowed $0^+ \rightarrow 0^+$ Fermi decays allow for stringent verification of the conserved vector current hypothesis and are currently the most precise sources of our knowledge concerning the Fermi coupling constant GF and the V_{ud} element of the Cabibbo-Kobayashi-Maskawa matrix. The mixed Fermi-Gamow-Teller decays of T=1/2 mirror nuclei can be also used to test the electroweak sector of the Standard Model provided that, apart of half-lifes, branching ratios, and Q-values, another observable like the neutrino-beta correlation, beta-asymmetry or neutrino-asymmetry is also measured, see Ref. [4,5]. The precision of these experiments is still too low for testing the Standard Model but fast progress in β-decay correlation techniques makes these experiments very promising and keeps the field vibrant see, for example, Ref. [6] for the recent β–asymmetry measurement in ^{37}K decay. Similar to the superallowed 0+ → 0+ Fermi decays, the analysis of T=1/2 transitions and, in particular, the extraction of V_{ud} depends on theoretical calculation of radiative and many-body ISB corrections. In the second part of the talk, I shall present multi-reference DFT calculations of ISB corrections to beta decay of T = 1/2 mirror nuclei that involve for the first time both the Coulomb interaction and the local isovector interaction at LO and NLO fitted to reproduce mirror energy displacements. I will demonstrate that, counterintuitively, the local isovector potential surprisingly strongly influences the calculated ISB corrections.

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Nuclear Semi-Bubbles in the Heaviest Elements

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Density distributions of atomic nuclei are an intriguing and important subject of current research. In most nuclei the density distribution reaches nuclear saturation density in the center and smoothly decreases to zero in a surface region. However, in superheavy nuclei the Coulomb repulsion between protons becomes so strong that an appreciable depression in the central density results. Our nuclear density functional theory (DFT) calculations indicate that the so-called nuclear semi-bubbles are already visible in elements heavier than Pb and the newest addition to the periodic table, Og, presents already a strong central proton density depression.

The consequences of central density depression are many-sided. High nucleon j-orbits become lower in energy, low-j orbits become higher. On the other hand rms radii become much larger. Our results show that isotopic shifts in Nobelium isotopes can be well reproduced with the central depression.

Recent progress of nuclear dynamics studies with TDDFT

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Time-Dependent Hartree-Fock (TDHF) theory has been a versatile tool to study a variety of dynamic phenomena in nuclear systems. It has also been referred to as Time-Dependent Density Functional Theory (TDDFT) in conjunction with the theories developed for electronic systems [1-3].

In this talk, I will digest recent progress of our studies with TDDFT.

To access yet-unknown territories in nuclear chart far away from stability, reliable theoretical predictions of heavy-ion reactions are mandatory to lead future experiments. To this end, a method to evaluate production cross sections has been developed [4], which utilizes the particle-number projection method as well as a statistical-decay model, based on TDDFT results. Besides, friction coefficients can be deduced from TDDFT employing Dissipative-Dynamics TDHF (DD-TDHF) method [5], and it has been applied for reactions leading to the synthesis of superheavy nuclei.

Moreover, with the usage of top-tier supercomputers, effects of pairing correlations on nuclear dynamics can nowadays be studied with TDDFT extended for superfluid systems, called Time-Dependent Superfluid Local Density Approximation (TDSLDA) [6] (formally equivalent to TDHFB). Its application started only very recently: e.g. giant resonances [7,8], fission [9,10], heavy-ion reactions [11], and superfluid vortices in the inner crust of neutron stars [12]. In this talk, I will also review the study of nuclear superfluid dynamics with TDSLDA.

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Shell model description of dipole strength at low energy and its impact on reaction rates

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In this talk, I will review recent shell-model calculations of dipole radiative strength functions in several regions of nuclei. Both E1 and M1 radiation will be addressed with a special emphasis on the description of the low-energy enhancement of strength functions discovered in (n, gamma) experiments. Systematic trends revealed in various shell model calculations will be presented. Finally, it will be shown how a phenomenological correction of strength functions at low energy inspired by shell model can impact the calculations of averaged radiative widths and of (n, γ) cross sections.

Shape evolution in neutron-rich Zr nuclei

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The study of various modes of excitations and the associated evolution of nuclear shapes along spin and isospin axes in atomic nuclei is one of the fundamental quest in nuclear physics. In this regard, the neutron rich nuclei with Z~40 and N~60 have attracted considerable attention. While the ground states of Sr and Zr isotopes with N ranging from the magic number N = 50 up to N < 60 are weakly deformed, they undergo a rapid shape transition from nearly spherical to well deformed prolate deformations as N = 60 is approached. In isotopes with Z ≥ 42 the shape change is rather gradual showing characteristic signatures of triaxiality. This strong dependence of observed spectroscopic properties on the number of protons and neutrons, makes the neutron-rich A~100 nuclei a very good region for testing various theoretical models. Several experimental and theoretical efforts have been made to investigate the structural evolution in these nuclei, however, a satisfactory description is still far from being complete. Further experimental information, especially lifetime and static quadrupole moments of these nuclei is an important step towards providing a firmer understanding of their properties through comparisons with modern theoretical models. Some recent results from our experimental program to study these nuclei using fusion-fission experiment performed at GANIL will be presented and the future prospects will be discussed.

Shape coexistence and collective low-spin states in ^{112,114}Sn studied with the (p,p′γ) DSA coincidence technique

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The semi-magic Sn (Z = 50) isotopes have been subject to many nuclear-structure studies. Signatures of shape coexistence have been observed and attributed to two-proton-two-hole (2p-2h) excitations across the Z = 50 shell closure [1]. In addition, many low-lying nuclear-structure features have been observed which have effectively constrained theoretical models in the past. One example are so-called quadrupole-octupole coupled states (QOC) caused by the coupling of the collective quadrupole and octupole phonons [2]. In fact, identifying multiphonon structures in the semi-magic Sn nuclei has been named as an important step to answer the question as to whether pure vibrational modes can be observed in the Z = 50 region at all [3].

We have performed two proton-scattering experiments followed by the coincident spectroscopy of gamma rays at the Institute for Nuclear Physics of the University of Cologne to excite low-spin states in ^{112}Sn and ^{114}Sn. We determined their lifetimes via the (p,p′γ) DSA coincidence technique [4] using the combined spectroscopy setup SONIC@HORUS [5] and extracted reduced electromagnetic transition strengths.

The gamma-decay branching ratios and E2 transition strengths deduced allowed the investigation of the intruder configuration in both Sn nuclei. The collectivity in this configuration is comparable to the one observed in the Pd nuclei, i.e. the 0p-4h nuclei. Strong mixing between the 0^+ states of the normal and intruder configuration might be observed in ^{114}Sn. sd IBM-2 mixing calculations were added which support the experimental results [6]. For the first time, members of the expected QOC quintuplet are proposed in ^{114}Sn. The previously unknown 1^- candidate in ^{114}Sn fits perfectly into the systematics observed for the other stable Sn isotopes [6].

In this contribution, we will discuss our present results and point out future challenges for studying shape coexistence and multiphonon states close to the Sn isotopes.

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Resonances and halos in exotic nuclei in covariant density functional theory with Green's function method

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The exotic nuclei with unusual N/Z ratios have become one of the most important frontiers. Many novel phenomena such as halos, new magic number and new excitation mode have been found. Theoretically, to describe those exotic nuclei, one has to deal with pairing correlation and continuum properly. Especially, the single-particle resonant states in the continuum are found very essential for the structures and features of exotic nuclei. Green's function method is one of the most effective tools for describing the continuum. Besides, the covariant density functional theory has achieved great successes in the description of nuclear structure and becomes one of the most important microcosmic approaches nowadays.

In this report, firstly, I will talk the single-particle resonant states, both in the spherical and deformed nuclei, in the Green's function relativistic mean field (GF-RMF) theory, where how to extract the energies and widths by Green's function method will be shown, the Nilsson levels for bound and resonant orbitals in the p-wave halo candidate nucleus ^{37}Mg will be given and the mechanism of its deformed halo will be analyzed; Secondly, I will talk the giant halos in the neutron-rich Zr isotopes by the Green's function relativistic Hartree-Bogoliubov (GF-RHB) theory, in which the extended density distribution, quasi-particle spectrum, as well as the energies and widths of the resonant states playing important roles for giant halos will be shown.

Nuclear shell model starting from deformed bases

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Our understanding of angular–momentum-projection goes beyond quantum-number restoration for symmetry-violated states. The angular–momentum-projection method can be viewed as an efficient way of truncating the shell-model space which is otherwise too large to handle. It defines a transformation from the intrinsic system, where dominant excitation modes in the low energy region are identified with the concept of spontaneous symmetry breaking, to the laboratory frame with well-organized configuration states according to excitations. An energy-dictated, physically-guided shell-model truncation can then be carried out within the projected space and the Hamiltonian is thereby diagonalized in a compact basis.

We demonstrate that angular momentum projection emerges naturally if a deformed state is treated quantum-mechanically. It is independent of effective interactions. With the Projected Shell Model as example, we discuss several truncation schemes: truncation in a deformed basis with axial symmetry, that with triaxiality, and that including Slater determinants corresponding to different deformations. The efficiency of the method is shown by the recent Gamow-Teller transition calculation for highly-excited states in heavy, deformed odd-mass nuclei.

Extending applicability of large-scale shell-model calculations

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The shell model, or configuration interaction method, directly solves many-body problems, and its applicability to actual problems should be in principle rather wide. However, due to the limitation of numerical computation the shell model was applied predominantly to low-lying spectra of light nuclei or those around the closed shell. Recently, methodological and numerical advances in the shell model enable extending its applicability. In this talk, I will provide a brief overview of recent advances of the shell model from this viewpoint. One direction is the mass region. While the full pf shell was the frontier of the shell model until the beginning of the 2000s, one can now calculate neutron-rich Ni nuclei, rare-earth nuclei etc. Another direction is the excitation energy. Using large valence shells, E1/M1 and Gamow-Teller strength distributions and level densities can be calculated. We will show some examples of those recent developments.

A Seniority and the Pandya relation

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Seniority refers to the number of nucleons that are not in pairs coupled to angular momentum zero. It arises as an exact quantum number for like nucleons interacting through pairing [1] or, more generally, for a manybody system with a (unitary) symplectic symmetry Sp( ) [2]. Another symmetry of the shell-model is related to particle-hole conjugation [3], leading to the so-called Pandya relation [4], which connects the (two-body) interaction between nucleons to that between a nucleon of particle and one of hole character. This relation is used extensively to correlate spectra of pairs of nuclei, e.g. ^{40}K and ^{38}Cl [5]. Many other examples are known [6, 7].

In this talk the merger of these two symmetry concepts is proposed. The action of particle-hole conjugation on configurations with definite seniority is investigated, leading to a generalised Pandya relation in terms of 3nj symbols. Examples of its application in nuclei are presented.

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A microscopic treatment of correlated nucleons: Collective properties in stable and exotic nuclei

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Collective excitations are observed and analyzed in several many-body systems such as, for instance, atomic nuclei, trapped atomic gases or metallic clusters. A model which is widely used to describe collective excitations is the random-phase approximation (RPA), where the excited modes are superpositions of 1 particle-1 hole configurations only. The RPA allows in general for a satisfactory description of excited states in nuclei, both low-lying ones and giant resonances.

However, being based on a mean-field or independent-particle picture, the RPA model fails in reproducing the fragmentation and the spreading width of excitations. For example, if one wishes to describe the spreading width of resonances, which can be observed experimentally, one has to go beyond this simple mean-field-based model. A possible way to do it is to add 2 particle-2 hole configurations in the model, which is known as Second RPA (SRPA). Yet the standard SRPA model presents some severe limitations related to instabilities and ultraviolet divergences. Several directions may be followed to handle and cure such instabilities.

One of them is based on a subtraction procedure. Some results based on this procedure will be presented, namely a systematic study on the giant quadrupole resonances of several nuclei, from ^{30}Si to ^{208}Pb, with special emphasis on the description of the spreading widths.
Some perspectives will also be illustrated, based on the extension of the present SRPA code (with subtraction) to treat pairing correlations in the ground state. These correlations are captured by renormalizing the SRPA matrix elements, using beyond-Hartree-Fock occupation numbers.

A beyond-mean-field description for nuclear excitation spectra: applications of the subtracted second random-phase approximation

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In this work we outline briefly a microscopic multiphonon approach known as equation of motion phonon method (EMPM) [1] and its reformulation in the quasiparticle formalism [2]. This method was recently applied on various neutron-rich nuclei in the oxygen and calcium regions. We show the effect of multiphonon (i.e. multi particle-hole) configurations on the energy spectra and collective modes (giant and pygmy dipole resonances) in the studied nuclei.

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Transfer reactions in transitional region

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Two-particle transfer reactions offer the possibility of clarifying the nature of the phase transitions that appear in chains of nuclei as a function of the number of protons or neutrons. This information can be viewed as a necessary complement to the one coming from the evolution of B(E2)'s values and energies of the first 2^+ state. Pair-transfer processes are known to be strongly influenced by the pairing interaction and therefore the information will come essentially from the population of the 0^+ states. The evolution of the population of these states will signal the position of the critical points and, even more important, the nature of the phase transitions (first order vs second order vs shape coexistence). Different structure approaches, ranging from the fully microscopic ones to those based on collective algebraic models, coupled to a proper description of the reaction mechanism are essential to reach this goal. As a specific example I will discuss the shape phase transition in Zirconium isotopes.

Towards comprehensive mass measurements with MRTOF Mass Spectrographs at RIKEN RIBF

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The exotic isotopes $^{249\text{-}253}$Md [1] as well as many other rare isotopes of heavy- [2,3] and intermediate-mass nuclei [4] – 80 isotopes in total – have successfully been measured with a multi-reflection time-of-flight mass spectrograph (MRTOF-MS) at the GARIS-II facility of RIKEN RIBF in 2016-2017. In the series of experiments, we showed that the mass spectrograph can precisely and accurately measure atomic masses with high efficiency even for very short-lived isotopes having a half-life of 10 ms. After successful completion of the first campaign, we are expanding to have mass spectrographs at multiple facilities of RIBF such as the new GARISII, KISS, and BigRIPS+SLOWRI, to perform comprehensive mass measurements of all available nuclides at RIBF. The flagship experiment will be for hot-fusion superheavy nuclides, in particular ^{288}Mc and ^{284}Nh.

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t-bands in the mass 130 region

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In the mass 170 region, the rotation alignment of two i13/2 neutrons gives rise to low-K s-bands, which can cross the corresponding ground-state band and cause the well-known "backbending" rotational discontinuity. However, when the neutron Fermi level is above mid-shell, there is competition from the high-K coupling of the two $i_{13/2}$ neutrons, forming t-bands [1]. The first example was found in ^{179}W [2] with N=105, where the spectator 7/2[514] neutron gives residual interactions that are favourable for the high-K coupling of the {7/2[514],7/2[633],9/2[624]} three-quasineutron t-band configuration.

The present work considers equivalent t-band structures in the mass 130 region, where the neutron Fermi level is in the upper half of the $h_{11/2}$ orbitals. In ^{129}Ba, with N=73, Byrne et al. [3] reported a high-K band with a 16ns bandhead half-life and assigned the {7/2[404],7/2[523],9/2[514]}, K=23/2 three-quasineutron configuration. Recently, Chakraborty et al. [4] found the same structure in the isotone ^{127}Xe, with a 28 ns bandhead half-life. As with ^{179}W, residual interactions lead to favouring of the t-band configuration with high K. However, in the neighbouring even-even nuclei, the parallel intrinsic spins of two $h_{11/2}$ neutrons are not favourable for t-band formation. Nevertheless, as we now report, experimental evidence for a two- $h_{11/2}$ neutron t-band has been newly found in ^{130}Ba, contrasting with the other known structures based on two $h_{11/2}$ neutrons and, alternatively, on two $h_{11/2}$ protons.
The t-band data in the mass 170 and 130 regions will be compared.

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Quadrupole shape fluctuations in nuclei and collective Hamiltonian method within Skyrme EDF

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To study large-amplitude shape fluctuation and mixing in nuclei in transitional regions, our goal is to construct the five-dimensional quadrupole collective Hamiltonian as functions of deformation parameters β and γ from constrained Hartree-Fock-Bogoliubov (CHFB) for the collective potential plus local quasiparticle random phase approximation (LQRPA) for the inertial functions within Skyrme energy density functional. As the first step toward the goal, we have developed a QRPA code in three-dimensional (3D) space [1] that can handle multipole modes of excitation in triaxial superfluid nuclei with a help of the finite amplitude method (FAM) [2] for a few and efficient computations. As the next step, we have developed our 3D-FAM to computing rotational moments of inertia on top of β-γ-constrained HFB states [3]. To do so, we follow the framework of computing the collective inertia of the Nambu-Goldstone mode by FAM in [4]. For vibrational masses, solutions of discrete low-lying collective modes are necessary, and a contour integral technique developed in [5] is useful for our purpose.

In this contribution, we will present recent progress of 3D FAM-QRPA and show results of multipole strength functions of triaxial superfluid nuclei. Then, we will show our attempt to computing rotational moments of inertia on β-γ plane and vibrational masses toward constructing quadrupole collective Hamiltonian based on Skyrme energy density functional.

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Recent experiments performed with GRETINA

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The gamma-ray tracking array GRETINA coupled with the S800 magnetic spectrograph has finished its second campaign at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University in 2017. It was then shipped and set up at the ATLAS and CARIBU facilities at Argonne National Laboratory where it is currently utilized in its second campaign there. An overview of the experimental programs and selected results covering broad ranges from nuclear structure physics to nuclear astrophysics will be presented.

Prolate-oblate shape coexistence in neutron-rich Se isotopes

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Isomer spectroscopy has been performed on the N~60 ^{92,94}Se isotopes. Gamma-rays were recorded by the EURICA HPGe array, placed around the AIDA implantation detector behind the ZeroDegree spectrograph at RIKEN-RIBF. A cocktail beam of ^{92,94}Se and neighboring isotopes was produced by a uranium beam impinging on a ^{9}Be target, and then separated by the BIGRips spectrograph. The isotopes of interest then partially reacted on the 1H target of the MINOS device. Hence, the ^{92,94}Se isotopes were either unreacted secondary beam or resulted from reactions of other beam components with the proton target. An isomer was identified for each isotope, and is found to be most likely of oblate nature. The decay behaviors of the respective isomers are very different, decaying into different band structures. This decay behavior is taken as a hint to the coexistence of and the switch from prolate to oblate deformation in the ground states of ^{92,94}Se.

New aspects of shape coexistence in nuclei

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Shape coexistence has emerged as, potentially, a universal feature of nuclear structure (see, e.g., [1,2]). The mass regions where this has been established or suggested expand progressively. Some recent possibilities are excited spherical structures in deformed nuclei [3] and deformed structures in very neutron-rich closed-shell nuclei [4].

The question to be addressed is what other mass regions are expected to exhibit shape coexistence. Two regions that will be considered, based on data, are the N = 50 and N = 82 closed shell nuclei. Further, the issue of multiple (i.e., more than two) coexisting shapes will be addressed and regions where this has been identified will be presented.

A wider (theoretical) view will be introduced based on the symplectic shell model [5,6]. This view provides the explanation of the shape coexistence occurring in ^{12}C (the Hoyle state). It also points to a need to reshape the language of intruder states and particle-hole excitations.

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Deformation and shape coexistence studied with the Coulomb excitation in neutron-deficient Po and Hg isotopes

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The neutron-deficient mercury isotopes (Z=80) serve as an illustrative example of shape coexistence [1], whereby at low excitation energies near-degenerate nuclear states are characterized by different shapes. The first observation of a dramatic change in the ground-state mean-square charge radii was carried out through the isotope shift measurements in ^{183}Hg and ^{185}Hg, when comparing to heavier-mass mercury isotopes [2]. Since then a large amount of information has been collected for nuclei around N=104 midshell using different experimental techniques supporting shape coexistence in this region.

In the neutron-deficient mercury isotopes with neutron number around mid-shell (N=104, ^{184}Hg) the intruding deformed states come low in excitation energy and mix with the normal more spherical states. The mixing between the states of the coexisting configurations gives rise to transitions with a strong electric monopole component. In the Po isotopes, above Z=82, low-lying intruder states have also been identified. Early theoretical studies concluded that the ground state of the heavier $^{194-202}$Po isotopes remains spherical, with the first (oblate-like) deformed ground state appearing in ^{192}Po [3]. A prolate deformation in the ground state was suggested for the lightest polonium isotopes with mass $A < 190$.

Among a large number of different complementary techniques used to study nuclear structure, Coulomb excitation brings substantial and unique information detailing nuclear deformation and shape coexistence. An extensive program of Coulomb-excitation experiments has been undertaken at the REX-ISOLDE facility on even-mass, neutron-deficient Hg, Po isotopes [4,5]. Results from these measurements obtained for $^{182-188}$Hg and $^{196-202}$Po isotopes will be presented and compared with various theoretical predictions, i.e., the interacting boson model with configuration mixing, the beyond mean-field approaches, and the General Bohr Hamiltonian. An interpretation of the results within the two state mixing model will also be given. The future Coulomb excitation and decay spectroscopy experiments at ISOLDE will also be discussed.

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Calculations of Iso Spin triplet states in the Mass A~60-80 region

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This paper presents extended TRS calculations of the T=1 bands in deformed nuclei with focus on A~60-80 region. The odd-odd T=1, Tz=0 bands are compared to their even-even neighbours. It is shown that the symmetry breaking of the T=1 pairing enables an unified description of the iso spin triplet states and their rotational properties. The iso spin breaking effect as a function of the T=1 pairing strength is shown. Shapes and moments of inertia are calculated and compared to experiment.

Nuclear Structure of the Transitional Xe Isotopes from Inelastic Neutron Scattering

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The nuclear structure of the stable Xe isotopes is of interest for several reasons. For example, these isotopes span a transitional region and, in general, have been poorly studied due to the lack of suitable targets. Additional information is required in order to understand their character. Moreover, these nuclei play prominent roles in the ongoing searches for neutrinoless double-beta decay ($0\nu\beta\beta$). ^{136}Xe is a candidate in the search for $0\nu\beta\beta$, ^{134}Xe is a contaminant in these experiments providing additional backgrounds [1], and ^{130}Xe is the daughter nucleus in the double-β decay of ^{130}Te. Comprehensive structural information provides crucial tests for the nuclear structure models used in calculating the nuclear matrix element for $0\nu\beta\beta$ and the neutrino mass, if this exotic decay process is observed.

To obtain relevant information for providing insight into the structure of these nuclei, we have examined ^{130,132,134,136}Xe at the University of Kentucky Accelerator Laboratory using inelastic neutron scattering (INS). For each of these isotopes, highly enriched Xe gases were converted to approximately 10 grams of solid XeF_2 and γ-ray spectroscopic measurements were performed following INS with nearly monoenergetic neutrons. The γ-ray angular distribution and excitation function measurements yielded new levels and spin assignments, branching ratios, multipole mixing ratios, and level lifetimes (from the Doppler-shift attenuation method [2]), which allowed the determination of reduced transition probabilities.

In addition to these measurements, shell model calculations were performed. The comparison with experimental data is quite good overall and lends further information for elucidating the structure of these nuclei.

This material is based upon work supported by the U. S. National Science Foundation under Grant No. PHY-1606890.

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Shape transition with temperature of the pear-shaped nuclei in covariant density functional theory

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The shape evolutions of the pear-shaped nuclei ^{224}Ra, even-even $^{144–154}$Ba, and even-even $^{286–304}$Cm with temperature are investigated by the finite-temperature relativistic mean field theory with the treatment of pairing correlations by the BCS approach[1,2]. The free energy surfaces as well as the bulk properties including deformations, pairing gaps, excitation energy, and specific heat for the global minimum of the isotopes are studied. For ^{224}Ra, three discontinuities found in the specific heat curve indicate the pairing transition at temperature 0.4 MeV and two shape transitions at temperatures 0.9 and 1.0 MeV, namely one from quadrupole octupole deformed to quadrupole deformed, and the other from quadrupole deformed to spherical. Furthermore, the gaps at $N = 136$ and $Z = 88$ are responsible for stabilizing the octupole-deformed global minimum at low temperatures. Similar pairing transition at $T \sim 0.5$ MeV and shape transitions at $T = 0.5–2.2$ MeV are found for even-even $^{144–154}$Ba.

A proportional relation between the critical shape transition temperature and the deformation at zero temperature $T_c = 6.6\beta(0)$ or $T_c = 44A^{-1/3}\beta(0)$, where A is the mass number, is found for both octupole shape transition and quadrupole shape transition. Through this study, the formation of octupole equilibrium is understood by the contribution coming from the octupole driving pairs with $\Omega[N; n_z; m_l]$ and $\Omega[N+1; n_z \pm 3; m_l]$ for single-particle levels near the Fermi surfaces as it provides a good manifestation of the octupole correlation.

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High-spin level structure of the near-spherical nucleus ^{95}Tc

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High-spin level structure of the near-spherical nucleus ^{95}Tc has been reinvestigated via the ^{90}Zr(^{12}C,αp2n)^{95}Tc reaction at a beam energy of 78 MeV in HIRFL. The emitted γ-rays from the reaction products were detected by a new multidetector array which has been installed in 2017. The previously reported spins and parities have been partly modified by the use of standard in-beam spectroscopic methods. The new level structures can be well interpreted by the central and tensor interactions between valence protons and neutrons in the $\pi(p_{1/2},g_{9/2})$ and $\nu(d_{5/2},g_{7/2})$ orbitals.

Investigation of the N=60 shape transition with low-energy Coulomb excitation

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Neutron-rich nuclei in the A~100 mass region have been under extensive investigation in the last four decades, from both theoretical and experimental points of view, due to observation of a sudden onset of deformation when moving from N=58 to N=60. This effect was initially observed in mass measurements and later confirmed by laser-spectroscopy studies of ground-state quadrupole moments (e.g. in the Rb isotopes) as well as by significant amount of experimental data on low-lying excited states in neutron-rich Sr and Zr isotopes. Recent mass measurements and Coulomb-excitation experiments of Kr isotopes have shown a more gradual shape transition in this isotopic chain as compared to what is observed for heavier elements, including the neighbouring Rb nuclei.

Recently, neutron-rich Sr and Rb isotopes were investigated using low-energy Coulomb excitation of radioactive beams at the REX-ISOLDE facility [1,2]. The transition probabilities and spectroscopic quadrupole moments measured in ^{96,98}Sr (N=58,60) [1] allow drawing definite conclusions about the coexistence of highly-deformed prolate and spherical configurations that interchange at N=60. In particular, a very small mixing between the coexisting states is observed, contrary to other shape-coexistence regions where strong mixing is the rule.

In another series of Coulomb excitation experiments, the southern border of the highly-deformed region has been established in the Rb isotopic chain [2] thanks to observation of regular rotational bands in ^{97,99}Rb (N=60,62). Transition probabilities between these states confirm that the ground-state deformation of ^{97,99}Rb is essentially the same as those determined for N>58 Sr and Zr nuclei.

The shape transition in neutron-rich Kr isotopes, although much more gradual than what is observed for Z=37-40 nuclei, is expected to give rise to shape coexistence of states corresponding to different configurations. The possibility to explore these structures in low-energy Coulomb excitation at SPES will be shortly discussed.

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