Shapes and Symmetries in Nuclei:

from Experiment to Theory Workshop

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Book of Abstracts

Nuclear Shapes in Covariant Density Functional Theory: Recent Results

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One of most interesting questions of nuclear structure is the existence of different nuclear shapes and their evolution with particle number and spin. In particular, a special attention is attracted to "exotic" ones, namely, the types of nuclear shapes which have not been studied extensively (or at all) in experiment. In my presentation I will focus on recent results obtained within the covariant density functional theory (CDFT) [1] which are related to the investigation of such shapes.

First, I will present the results of global studies of octupole deformation [2]. A new region of octupole deformation, centered around Z ~ 98, N ~ 196 is predicted for the first time. This region plays an important role in fission recycling in the mergers of neutron stars. In terms of its size in the (Z, N) plane and the impact of octupole deformation on binding energies this region is similar to the best known region of octupole deformed nuclei centered at Z ~ 90, N ~ 136. For the latter island of octupole deformed nuclei, the calculations suggest substantial increase of its size as compared with available experimental data.

Then, I will discuss the presence of large oblate deformations in superheavy nuclei [3]. It is interesting that some well tested covariant energy density functionals predict only very few spherical superheavy nuclei above Z = 110 and N = 172; the oblate ground states dominate the nuclear landscape here. Such an absence of "magic" spherical superheavy nuclei has never been discussed before and it is a consequence of the competition of the shell effects at spherical and oblate shapes.

Note that in those two investigations we pay special attention to the assessment of the accuracy of the description of existing experimental data and theoretical uncertainties for the prediction of the properties of unknown nuclei.

Finally, I will discuss super-, hyper- (HD) and megadeformed (MD) shapes and clusterization in the N ≈ Z A ~ 40 mass region [4]. Here, the rotation acts as a tool to bring these exotic shapes to the yrast line or its vicinity so that their observation becomes feasible with future generation of γ-tracking (or similar) detectors. The observation of the HD and MD structures at spin zero is basically impossible because they are located at high excitation energy with respect of the ground state. For several nuclei in this study (such as ^{36}Ar), the addition of several spin units above currently measured maximum spin of 16^- will inevitably trigger the transition to the HD and MD shapes.

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The GRIFFIN Facility for Decay Spectroscopy Experiments at TRIUMF

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GRIFFIN [1], the Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei is the new decay spectroscopy array located at TRIUMF, Canada's National Laboratory for Nuclear and Particle Physics, in Vancouver, Canada. GRIFFIN consists of 16 large-volume hyper-pure germanium clover detectors assisted by a custom-built digital data acquisition system. A suite of ancillary detector systems are coupled to GRIFFIN for comprehensive decay spectroscopy experiments with radioactive beams delivered by the TRIUMF-ISAC facility.

The early-implementation experiments with radioactive beams were performed with the GRIFFIN array, coupled to SCEPTAR [2], an array of plastic scintillators for beta-particle tagging, and PACES [2], an array of five lithium-drifted silicon detectors for high-resolution internal conversion-electron spectroscopy. Eight lanthanum bromide scintillators for fast gamma-ray timing measurements [2], and a neutron detector array for the detection of beta-delayed neutron-emitting nuclei called DESCANT [3], are also available for future experiments.

Results obtained with the GRIFFIN spectrometer near and far from stability using beta decay of beams of ^{115g,m}Ag [4], $^{128-130}$Cd [5]. ^{46,47}K [6,7], and ^{32}Na [8] will be presented along with a discussion of future opportunities, including the addition of the Compton and background suppression shields.

The GRIFFIN spectrometer is funded by the Canada Foundation for Innovation, TRIUMF, and the University of Guelph with matching contributions from the British Columbia Knowledge and Development Fund and the Ontario Ministry of Research and Industry. TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada. This research is supported by the Natural Sciences and Engineering Research Council of Canada.

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* and the GRIFFIN collaboration

Shape Coexistence in ^{70}Kr

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Nuclei in the vicinity of the N=Z line around A=70 exhibit very rapid shape changes due to the isospin symmetry breaking related to charge effects. This leads to differences in excitation energy between analogue states in isobaric multiplets. In this study we probed Coulomb energy differences in the T_z = -1 nucleus ^{70}Kr with respect to its mirror ^{70}Se. In ^{70}Kr, no spectroscopic information is available so far. We have performed a Coulomb excitation experiment of ^{70}Kr and ^{72}Kr isotopes to measure the $B(E2;0^+\rightarrow2^+)$ value. The experiment was performed at the Radioactive Isotope Beam Factory (RIBF). A ^{78}Kr primary beam at 345 MeV/nucleon was impinging on a ^{4}Be target. The BigRIPS fragment separator was used in order to deliver the ^{70}Kr and ^{72}Kr isotopes at around 150 MeV/nucleon to the secondary target for Coulomb excitation and inelastic scattering measurements. The emitted gamma-rays of the reaction were detected by the DALI2 array and recoils were identified by the ZeroDegree Spectrometer. Results will allow to make a direct comparison with the mirror nucleus ^{70}Se and will give an important new information about shape co-existence across the N=Z line.

Periodic-Orbit Bifurcations and Dynamical Symmetry Restorations in Spherical and Deformed Nuclear Mean Fields

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Shell structures in the single-particle spectra play essential roles in the microscopic description of nuclear shape stabilities and their preference for various types of deformations. Due to the quantum fluctuations caused by the non-uniform distribution of single-particle energy levels, nuclei show especially strong bindings when the numbers of constituent particles (protons and/or neutrons) coincide with the so-called magic numbers corresponding to the closed-shell configurations. One finds such magic numbers not only in the spherical mean fields but also in deformed potentials. In nuclear deformations, the most important shape degrees of freedom are quadrupoles ones. Observed superdeformed states which have large quadrupole deformations with axis ratio about 2:1 are attributed to the remarkable shell effect emerging around those shapes. Some exotic shapes with reflection asymmetries have been also suggested both theoretically and experimentally for ground and excited states in certain regions of the nuclear chart. One of the most exciting subjects among them might be the possibility of tetrahedral deformation.

In this talk, I will discuss the emergences of significant shell structures formed in spherical and various exotic-shape nuclear mean fields, and the studies on their semiclassical origins by means of the periodic-orbit theory (POT). In semiclassical trace formula, gross fluctuations in single-particle level density are described by the contributions of short classical periodic orbits. The magnitude of the contribution is strongly dependent on the stability properties of the orbit, which is quite sensitive to the shapes of the potentials. Notably, it often shows a remarkable enhancement around the bifurcation point of the orbit [1,2]. At the bifurcation points where new periodic orbits emerge in the system, the orbit accompanies a local family of periodic orbits around it which makes coherent contribution to the level density. The appearance of such degenerate family suggests a local restoration of dynamical symmetry around the periodic orbit.

Thus, the bifurcations of short periodic orbits give the foundations in the outstanding stabilities of certain many-fermion systems and the origins of their deformations. After an introduction to the POT for gross shell structures, I will present the results of numerical applications to several nuclear phenomena, employing the semi-realistic mean-field models with and without spin-orbit coupling:

- Semiclassical origin of nuclear magic numbers and the pseudospin symmetry [2]
- Superdeformed shell structures [1,2]
- Tetrahedral deformation and other types of octupole shapes [2,3]

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Beyond-Mean-Field Calculations Based on Time-Reversal-Invariance-Breaking HFB States - Prospects and Perspectives

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Recent progress in high-performance computing made it possible to push “beyond-mean-field calculations” for nuclear spectroscopy behind many of their past limitations. This presentation will report on the ongoing development of a fully microscopic approach that aims at the mixing of angular-momentum and particle-number projected time-reversal-invariance-breaking triaxial HFB states within a generator coordinate method (GCM). Projection restores the selection rules for electromagnetic transitions that are crucial for the interpretation of experimental data, and the GCM turns out to be necessary for a meaningful analysis of coexisting structures in a given nucleus. A new type of effective Skyrme interaction is used in order to carry out such calculations without formal ambiguities.

The breaking of intrinsic time-reversal invariance adds new degrees of freedom to this kind of approach that were completely absent in most earlier applications. In particular, it provides the means to model the coupling of single-particle states to collective motion. Examples to be addressed are the description of spectroscopic properties of odd nuclei in such a framework, and the role of non-collective degrees of freedom for low-lying states in even-even nuclei.

While first results obtained clearly show the potential of this kind of many-body method for the detailed description of spectroscopic properties, there remain open problems related to the set-up and phenomenological adjustment of a predictive effective interaction that can be safely used in such calculations.

Geometric Symmetries in Light Nuclei

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The role of discrete (or point-group) symmetries in alpha-cluster nuclei is discussed in the framework of the algebraic cluster model which describes the relative motion of the alpha particles. Particular attention is paid to the discrete symmetry of the geometric arrangement of the alpha-particles, and the consequences for the structure of the corresponding rotational bands. The method is applied to study cluster states in the nuclei ^{12}C and ^{16}O. The observed level sequences can be understood in a simple way as a consequence of the underlying discrete symmetry that characterizes the geometrical configuration of the alpha-particles, i.e. an equilateral triangle with D(3h) symmetry for ^{12}C, and a tetrahedron with T(d) symmetry for ^{16}O. The structure of rotational bands provides a fingerprint of the underlying geometrical configuration of alpha-particles.

Characterisation of the iThemba LABS Segmented Clover Detector

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The iThemba LABS segmented clover detector manufactured by Canberra France is made up of four front tapered n-type HPGe crystals packed closely together in the same cryostat. Each crystal has 60 mm diameter and is 90 mm long before shaping. The crystals have segmentation in depth at 35 mm. The outer contact of each crystal is electrically segmented into 8 contacts. This results in a total of 36 electronic channels of which 32 are associated with the outer contacts and 4 with the inner core contacts of the detector.

iThemba LABS acquired a Multi Geometry Simulation (MGS) and AGATA Detector Library (ADL) codes to simulate the pulse shapes for the iThemba LABS segmented clover detector. These codes are capable of simulating the pulse shapes for an arbitrary gamma-ray interaction position within the germanium. With these codes, the sensitivity of the iThemba LABS segmented clover detector to the exact position of the gamma-ray interaction was tested. The characterization of the detector in order to obtain realistic simulations of the pulse shapes is advancing well. The biased voltage and the impurity profiles for each crystal as given by the manufacturer are implemented into the codes. The orientation of the crystal lattice of one of the germanium crystal is measured and the results show that the fast <100> axis is at an angle of 47 degree. The measurements of the preamplifier response function for the core of one germanium crystal is performed and implemented into the ADL code. The analysis showed that the preamplifier response function of the core is different from that of the segments. A modified response function was used for the segments. The drift velocity of electrons is been measured and implemented into the ADL code. After including these properties of the germanium crystal into the ADL code, we found excellent agreement between the shapes of the simulated and measured charge collecting pulses.

In addition, the proportional cross-talk as a function of the deposited gamma-ray energy was determined. In some cases proportional cross-talk as large as 40keV was observed. The correction for the proportional cross–talk was successfully implemented and the full gamma-ray energies were recovered. Lastly the scanning of the detector for 90 degree Compton scattering is progressing well.

Parameter-Free Solutions of the Bohr Model with Modified Shape Phase Space

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A series of new parameter-free models based on a deformed shape phase space associated to a Bohr Hamiltonian is discussed. The modified shape phase space is achieved either by combining different collective conditions or by inducing an energy dependence of the potential energy. The former approach is applied in case of the critical point of the shape phase transition between spherical and axially symmetric shapes, while the latter is employed in exactly solvable gamma-unstable models where the energy dependence in the potential is easier to implement. The theoretical construction of the formalisms and the conditions realizing parameter-free energy spectra are dully explained. The new parameter-free models acquire or break various characteristics of associated dynamical symmetries, fact which provides strong spectral signatures for searching experimental candidates.

Shape Phase Transition with a Quasi Exactly Solvable Sextic Potential

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The quasi-exact solvability of the sextic potential with a centrifugal barrier is adapted for the gamma-rigid prolate regime of the Bohr-Mottelson model. The scaling property of the potential leads to a single parameter dependence of the normalized energy spectrum comprising the ground and beta vibrational bands with all the associated E2 transition probabilities. Through the variation of the free parameter, one can follow a shape phase transition between a spherical equilibrium shape and a well deformed one, crossing a critical point where the potential is maximally flat. Such a theoretically predicted transition is found to occur in the Ru isotopic chain, with ^{104}Ru identified as a critical nucleus.

The Dangers of Statistical Tests of Nuclear Structure Models

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It is common to assess the quality of nuclear models using statistical tests such as chi-square measures. Yet such tests, carried out without special care, can be extremely misleading. These dangers center on three issues: how to deal with data of differing precision, which observables to focus on, and theoretical uncertainties. These topics will be discussed with simple (idealized) examples. Time permitting, an application to a model of a partial dynamical symmetry based on SU(3), will be discussed, that illustrates the pros and cons of this model, the importance of valence nucleon number, and the issues of testing models mentioned above.

Neutron-Proton Correlation Phenomena in the Heaviest $T_Z \approx 0$ Nuclei

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Nucleonic pair correlations play an important role in many nuclear structure-related phenomena as well as for nuclear masses. Nuclei with N≈Z exhibit enhanced neutron-proton (np) correlations as the valence neutrons and protons occupy identical orbitals, although the details of these correlations are not well understood. In particular the consequences for nuclear pairing and superfluidity have been in the focus for a long time. In addition to the normal isovector (T=1) pairing mode based on like particle nn and pp Cooper pairs which have their spin vectors antialigned and occupy time-reversed orbits, neutrons and protons may here also form np T=1, I=0 pairs. Of special interest is the long-standing question of the possible presence of a BCS-type of np pairing condensate [1-3] predicted to be built primarily from isoscalar T=0, I≠0 np pairs, which still eludes experimental verification. The talk will review various, mainly experimental, aspects of enhanced neutron-proton correlation phenomena in nuclei along the N=Z line, approaching ^{100}Sn and beyond. In this unique region of the nuclear chart a rather complex picture of neutron-proton pair correlations with is beginning to emerge [4]. The search for isoscalar BCS-type pairing and investigations of the related "static" spin-aligned neutron-proton pair structure [5,6] in the A=90-100 mass region will be discussed. The talk will touch upon different experimental approaches and their future potential, with an emphasis on gamma-ray spectroscopic methods.

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Descriptions of Triaxial Band Structures in ^{133}La

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Since the chirality in nuclear physics was originally suggested 20 years ago, it has been one of the hot topics in nuclear physics.

Recently, experimental results on the odd-A ^{133}La nucleus have been obtained from a high-statistics experiment performed at the ATLAS accelerator facility with the Gammasphere array. Three new bands of quadrupole transitions and one band of dipole transitions are identified, and the previously reported level scheme is revised and extended to higher spins.

Here the focuses are mainly on the theoretical descriptions for the observed structures in ^{133}La. Firstly, the adiabatic and configuration-fixed constrained covariant density functional theory calculations were performed to search for the possible configurations and deformations. Potential energy surfaces in the β-γ plane are obtained. The configurations are tentatively assigned to all observed bands. With the obtained configurations and deformations, the particle rotor model calculations were carried out to calculate the experimental energy spectra and B(M1)/B(E2) ratios. Furthermore, the orientation of the angular momenta of the core and of the active particles is investigated. It is found that the chiral geometry exists in the nearly degenerate dipole bands, and the other dipole band can be interpreted as a magnetic rotation band.

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Shape Coexistence at the 40 Sub-Shell Closures

Emmanuel Clément
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Shape coexistence at the Z=40 and/or N=40 are examples of interplay between macroscopical and microscopical effects in nuclear matter leading to the competition between spherical normal state and intruder deformed configurations. How the nuclei change drastically its shape when adding or removing one or two pairs of nucleon remains an open subject in nuclear structure. Experimentally, the development of radioactive beams facilities and state of the art detections systems opened new avenues in the study of shape coexistence. In this presentation, the systematic study of shape coexistence in neutron deficient Se and Kr isotopes, neutron rich Sr and Zr and neutron rich Fe and Ni isotopes below ^{68}Ni will be discussed from both experimental and theoretical perspectives.

Shapes and Symmetries in Nuclei Studied with GRETINA*

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GRETINA [1], a first implementation of a gamma-ray tracking array, combines unparalleled position resolution, large Ge efficiency, and good P/T to provide a powerful tool for inbeam gamma-ray spectroscopy.

The commissioning in 2012 demonstrated the technical feasibility and unique capabilities of a gamma-ray tracking array, and successful physics campaigns have followed at NSCL/MSU (2013/14) and ATLAS/ANL (2014/15). New physics results have been shown in a broad range of topics, confirming the excellent performance of the array in both high and Coulomb barrier- energy environments, and in multiple configurations. GRETINA is again operating at NSCL for a second campaign coupled to the S800 spectrometer.

In line with the topic of this workshop, we will present selected highlights from these scientific campaigns that have focused on the studies of nuclear shapes, symmetries, and collectivity.

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Exotic Shapes and Exotic Symmetries

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Recently we have developed a new method for the determination of the shape isomers, which is based on the self-consistency of the quadrupole deformation [1,2,3]. We carry out Nilsson calculations in combination with the quasidynamical U(3) symmetry [4]. The advantage of this approach is that the connection of the deformed state with the possible cluster-configurations, and consequently with the reaction channels which can populate them (or in which they can decay) is determined by an U(3) selection rule. In the case of the hyperdeformed state of the ^{36}Ar [1] and the superdeformed states of the ^{28}Si [2] the experimental observations [5,6] seem to justify our theoretical predictions. For the description of the excitation spectrum, including the low-lying part, as well as the shape isomer, we apply [7] the semi microscopic algebraic quartet model [8]. This model is a symmetry governed truncation of the no-core SU(3) shell model [9].

The multichannel dynamical symmetry [10] connects the quartet (shell) model with the cluster description [11] (within the semi microscopic algebraic approach). In the cluster framework we apply Elliot's SU(3) model for the internal structure of the clusters, and the relative motion is also treated in terms of an algebraic model [12].

When the multichannel dynamical symmetry holds, then not only the cluster model states can be selected from the shell model basis, but the energies and the electromagnetic transition ratios are in coincidence as well. Therefore, a complete cluster spectrum can be projected out from the quartet description.

In the case of the ^{28}Si nucleus we were able to predict the ^{12}C+^{16}O cluster spectrum of the high-lying molecular resonances from the quartet-model description of the low-lying bands [7], in good agreement with the experimental finding.

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Lifetimes of Nuclear States in Proton-Emitting Nuclei from Differential Plunger Measurements

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Over the last few years, a programme of research performed at the University of Jyvaskyla, Finland has established the first measurements of the nuclear state lifetimes built above proton emitting states [1-5]. Lifetimes have been deduced in several nuclei; ^{109}I [1], ^{151}Lu [2,3] and ^{113}Cs [4] for the first time using a specially constructed Differential Plunger for Unbound Nuclear States (DPUNS) plunger [5]. The new experimental results have led to the development of a non-adiabatic quasi-particle code which has been required to explain proton emission based on the experimental deformations extracted from the lifetime measurements. This talk will show how the new lifetime values for the ground- and isomeric-state proton decays in ^{151}Lu are best interpreted by a mildly oblate deformation, settling a long-standing theoretical debate about the shape of ^{151}Lu. The very recent lifetime results for the more deformed proton emitter ^{113}Cs will also be discussed. In this case the wavefunctions extracted from the non-adiabatic quasi-particle code were used separately to evaluate both proton emission and gamma-ray transition rates as a function of deformation. In this study, a consistent quadrupole deformation was found to match both the experimental proton emission half-life and the lifetime of the electromagnetic state in ^{113}Cs. This deformation is in agreement with the earlier proton emission studies, but is now more firmly supported based on the measured electromagnetic transition rates. The perspectives for future measurements with a new differential plunger involving two degrader foils and its application to measuring lifetime in isobaric analogue states will also be discussed.

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Mathematical Modelling of the Nuclear Mean-Field: Woods-Saxon Potential as a Test Case

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We present the results of our pilot project which aims at establishing the uncertainties in reproduction of the single-nucleon levels within the spherically symmetric phenomenological nuclear mean-field Hamiltonian – here modelled with the help of the Woods-Saxon potential. This specific model Hamiltonian has certain advantages: it is relatively simple, but at the same time it contains all the mathematical features needed for testing the parametric instabilities. Therefore we believe it provides an excellent test-ground for the nuclear mean-field theories and the underlying Hamiltonians.

In our tests we use the set of experimental single-particle levels in the well-known spherical nuclei ^{16}O, ^{40}Ca, ^{48}Ca, ^{56}Ni, ^{90}Zr, ^{132}Sn, ^{146}Gd, ^{208}Pb. An important part of the information about predictive power can be obtained by an appropriate sampling within the full population: In our case the full population is composed of 8 nuclei and by selecting various sub-sets for which we optimize the parameters we are able to verify the quality of the predictions in the remaining elements of the population. The latter correspond to the borders of the population, in which case we talk about "prediction-mode extrapolation", in the opposite case: "prediction-mode interpolation". In parallel we perform the Monte-Carlo tests of the parametric correlations. According to the well-known theorems of the inverse problem theory of Applied Mathematics, the presence of the parametric correlation destabilizes the possibility of a reliable prediction in the extrapolation mode - the most important in the domain of the physics of exotic and superheavy nuclei. We present the illustration of the process of elimination of the parametric correlations and discuss the possible solutions in the nuclear context.

Mathematical Modelling of the Nuclear Mean-Field: A New Self-Consistent Multiphonon Approach to Odd Nuclei and its Application to the A=17 Isobars

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We extend to odd nuclei an equation of motion phonon method (EMPM) developed for even-even nuclei [1], which describes the detailed spectroscopic properties of neutron rich nuclei, including the fine structure of giant and pygmy dipole resonances [2, 3, 4]. Following closely the EMPM prescriptions [1], we derive and solve iteratively a set of equations of motion which yield an orthonormal basis of states composed of an odd particle coupled to orthonormal multiphonon core states in turn generated iteratively, starting from a Tamm-Dancoff basis, by the EMPM procedure. The basis so obtained is used to solve the eigenvalue problem in the full particle-phonon space. The formalism does not rely on approximations. These are, nonetheless, allowed naturally by the particle-phonon structure of the states. For way of illustration, we performed a self-consistent and parameter free calculation for A=17 isobars in space encompassing, for each spin ν, particle-core states $|(p \times \alpha n)\nu\rangle$ with n = 0, 1, 2, 3. Starting with a Hamiltonian composed of an intrinsic kinetic term and an optimized chiral nucleon-nucleon potential at next-to-next leading order ($NNLO_{opt}$), which minimizes the contribution of the three-body term [5], we derived a Hartree-Fock (HF) basis from a harmonic oscillator space including all the shells up to N_{max} = 16 and determined a TDA basis free of center of mass spurious admixtures [6]. We further included all particle-core two and three phonon states fulfilling the energy conditions $E\alpha 2 \leq 35$MeV and $\epsilon p + E\alpha 3 \leq 55$MeV, respectively. The coupling to the one phonon states brings the HF energies very close to the corresponding experimental levels. The particle-phonon energies enhance greatly the level density, consistently with experiments. They however, lie above ~ 11 MeV and do not get intermixed with the single-particle levels as the experiments would require. The two phonons leave the low energy spectrum unchanged and have the only effect of enhancing further the level density above ~ 8 MeV. Only once the three phonons are included, several particle-phonon intruders fill the low energy sector and reduce greatly the gap with experiments. The three phonons also induce a strong quenching and fragmentation of the electric dipole resonance in qualitative agreement with the experimental cross section. A further moderate quenching would be needed for a complete agreement. The phonon states have a weak quenching effect on the magnetic moment and the beta decay ground state transition, consistently with experiments. They also contribute significantly to approach the theoretical quadrupole moments to experiments but not sufficiently to reproduce the measured values. For a better agreement, it would be necessary to enhance the weight of the particle-core components.

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A Self-Consistent Equation of Motion Multiphonon Method for Even and Odd Mass Nuclei

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Several extensions of the random-phase approximation (RPA) have been adopted to study the fragmentation of the giant dipole resonance (GDR) and, in general, the anharmonic features of the nuclear spectra. Relativistic quasiparticle time blocking approximation (RTBA) [1], second RPA (SRPA) [2, 3], and the quasiparticle phonon model (QPM)[4] are some of them.

We have proposed an equation of motion phonon method (EMPM) [5, 6] which derives and solves iteratively a set of equations of motion to generate an orthonormal basis of multiphonon states built of phonons obtained in particle-hole (*p*-*h*) Tamm-Dancoff approximation (TDA).
Such a basis simplifies the structure of the Hamiltonian matrix and makes feasible its diagonalization in large configuration and phonon spaces. The diagonalization produces at once the totality of eigenstates allowed by the dimensions of the multiphonon space. The formalism treats one-phonon as well as multiphonon states on the same footing, takes into account the Pauli principle, and holds for any Hamiltonian.

The method was adopted mainly to investigate the dipole response in the heavy, neutron rich, ^{208}Pb [8, 9] and ^{132}Sn [10]. Fully selfconsistent calculations using a Hamiltonian composed of an intrinsic kinetic term and an optimized chiral potential $NNLO_{opt}$ [7] have emphasized the crucial role of the two-phonon basis in enhancing greatly the fragmentation of the GDR and the density of low-lying levels associated to the pygmy dipole resonance (PDR), consistently with experiments.

Recently, the method has been formulated in terms of quasiparticles and applied to the open shell neutron rich ^{20}O. A calculation using a Hartree-Fock-Bogoliubov basis derived from the same chiral Hamiltonian has shown that the low-lying spectrum can be reproduced only once the two-phonon basis is included. The two phonons have an important quenching effect on the dipole response, necessary for reproducing semi-quantitatively the experimental cross section in both GDR and PDR regions.

The method has been extended, now, to odd nuclei with one particle external to a doubly magic core. An analogous set of equations is derived and solved iteratively to generate an orthonormal basis of states composed of a valence particle coupled to n phonons (n = 1,2,…n…) generated within the EMPM.

A self-consistent calculation, using the same chiral potential in a space including up to two phonons and, under some simplifying assumptions, three phonons, has been performed for the A=17 nuclei. The multiphonon states enhance enormously the density of levels and compress the whole spectrum, consistently with the data. They contribute substantially to improve the agreement with the experimental moments and transitions strengths. Moreover, they exert a crucial quenching action on the dipole response, necessary for reproducing the cross section in GDR and PDR regions.

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Structure of Neutron-Rich Nuclei in the Vicinity of ^{78}Ni: The Case of N=51 Nuclei and of Ge and Zn Isotopes

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Recent experimental discoveries have revealed that the neutron effective single-particle evolution above ^{78}Ni (N>50) shows peculiar or unpredicted behaviours. The aim of this work is to determine the nature of the low-lying yrast or quasi yrast $7/2^+$ and $9/2^+$ states in 32 < Z < 40, odd-neutron N=51 nuclei, in order to assess their "collective" (core-particle coupled) or $\upsilon 1g_{7/2}$ and $\upsilon(2d_{5/2})^2(1g_{9/2})^{-1}$ single-particle origin and better constrain the relative position of the neutron single-particle states above a ^{78}Ni core. Calculations show that there is a difference of about two orders of magnitude between core-particle coupled state and single-particle state half-lives.

A Recoil distance Doppler-shift (RDDS) experiment has been performed at LNL (Italy). Neutron-rich nuclei were produced via multi-nucleon transfer with the ^{82}Se(@ 505 MeV) + ^{238}U system. The setup combined the AGATA demonstrator, the PRISMA fragment spectrometer and the Cologne plunger. The number of plunger distances was restricted to only two with the goal to provide the half-live domain (< 1 ps or several tens ps) of the states of interest. Half-lives of the lowest-lying 7/2 and 9/2 states of two N=51 nuclei, ^{87}Kr and ^{85}Se, as well as indications of higher lying state half-lives up to spin $19/2^-$ in ^{87}Kr have been measured. Structure analysis of these states will be discussed.

A 14 days experiment combining AGATA and the VAMOS fragment spectrometer has been run last year with the aim to probe the medium spin structure of neutron-rich nuclei in the vicinity of ^{78}Ni, to experimentally determine the size of the N=50 gap as well as the $\pi f_{5/2}$-$\pi p_{3/2}$ spacing in ^{79}Cu. The fusion-fission mechanism in inverse kinematics for the ^{238}U (@ 6.2 MeV/A) + ^{9}Be reaction at an energy around the Coulomb barrier was used as it was earlier shown to be an efficient method to populate neutron-rich nuclei at relatively large angular momentum. AGATA in a compact configuration was coupled to VAMOS++, providing an event-by-event unambiguous (A,Z) identification of one of the fission fragments, and the prompt gamma-rays emitted in coincidence. The VAMOS++ and AGATA data presorting is completed. Excellent mass and atomic number resolutions have been obtained. Preliminary results on the gamma rays assigned to various neutron-rich Ge and Zn isotopes will be presented.

* On behalf of the AGATA-PRISMA and AGATA-VAMOS collaborations

Description of Nuclear Phenomena Associated with the Emergence of Broken Symmetries from an *ab initio* Perspective

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Based on the recent development of ab initio many-body calculations for medium mass nuclei, I will discuss how nuclear phenomena associated with the emergence of rotational and particle number symmetry breaking are described within first principle calculations.

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

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New excited states have been recently discovered in the ^{212}Po nucleus in the study of a transfer reaction of an α particle from a low-energy heavy-ion beam. These new states have surprising properties, such as extremely short lifetimes: thus their decay mode, which only proceeds via the emission of a dipole electric E1 transition, implies the existence of a large electric dipole moment of the system [1,2].

The ^{212}Po isotope is a heavy nucleus with 4 nucleons above the doubly magic stable nucleus ^{208}Pb. As such, its structure should be relatively easy to describe through the shell model, namely, 2 neutrons and 2 protons placed on the first available orbits, solutions of the potential created by ^{208}Pb. But this type of model cannot explain that the system would have an electric dipole moment at such low excitation energy. Only the assumption of a cluster-type structure "α+^{208}Pb", underlying in ^{212}Po, can explain the existence of these new states. Until now, "α+core" states had been reported only in light nuclei, and interpreted as arising from the collective rotation of the system around its center of mass. However, in the case of the "α+^{208}Pb" system, the collective rotation is prevented by the great mass of the spherical core. The states discovered in ^{212}Po have been interpreted by a completely new mechanism: the vibration of the "α-core" distance around its equilibrium position [1,2].

The population mechanism of these cluster states has been studied using data recorded in a dedicated experiment performed at Jyvaskyla. The influence of the dipole momentum of the projectile on the population of the cluster states has been characterized via the comparison of the ^{212}Po production yields obtained from two different beams.

In order to go further, an experiment –already accepted– will be performed at GANIL using a setup combining the AGATA γ array and a silicon particle detector [3].

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Octupole Deformation in the Nuclear Chart based on the 3D Skyrme Hartree-Fock plus BCS Model

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Breaking of the rotational symmetry is spontaneously induced by the coupling between the individual particle motions and the corrective motion, which was pioneered by Bohr and Mottelson [1]. Furthermore, the interplay between the spatial deformation and the pair deformation, which is the deformation in the gauge space, play important roles in nuclear structure. The deformation is a fundamental element to determine spectroscopic properties of nuclei. Systematic, non-empirical, and unrestricted studies of nuclear shape could provide useful insights into the nuclear structure.

We have performed a systematic study of the nuclear excited states with a self-consistent mean-field model employing Skyrme effective interaction [2]. Our calculation is based on the Hartree-Fock plus BCS model represented in the three dimensional Cartesian coordinate space which allows to describe any shape, such as non-axial octupole deformation while dealing with the pairing.

In this work, we calculate the ground states of nuclei over 1,000, and show the distribution for quadrupole (prolate, oblate and triaxial) and octupole deformed nuclei. Figure 1 shows the octupole deformed nuclei in the chart with respect to the octupole deformation parameter β_3. We can see a characteristic localization of the distribution, and we will discuss non-axial octupole deformation appeared in our results.

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A Symmetry Conserving Configuration Mixing Description of Odd and Even Exotic Nuclei with the Gogny force.

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Traditionally effective interactions like Skyrme, Gogny or relativistic interactions have been used in basic mean field approaches to describe with great success bulk properties of ground states of nuclei, such as masses, quadrupole moments, radii, etc. However, recent developments in beyond mean field calculations, with particle number and angular momentum projection in conjunction with the Generator Coordinate Method (with the deformations (β,γ), pairing gaps (ΔZ, ΔN) and angular frequency as generator coordinates) have shown that the Gogny force [1,2,3] is also able to provide high quality nuclear spectroscopy.

Applications to the description of the spectrum and transition probabilities of the nuclei ^{42}Si and ^{44}S as well as the odd and even Mg isotopes show that these calculations provide an accuracy comparable with state-of-the-art shell model calculations with tuned interactions. The advantages of the present approach as compared to the shell-model one are the added value of the intrinsic system interpretation and that the interaction, the Gogny force, is well known for its predictive power and good performance for bulk properties all over the chart of nuclides.

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Resonance Ionization Spectroscopy of Actinium Isotopes in a Supersonic Gas Jet

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The study of exotic nuclei at the limits of nuclear existence by laser spectroscopy requires the application of a technique with high efficiency and high spectral resolution. Laser ionization in the low-temperature and low-density supersonic gas jet from a de Laval nozzle installed at the buffer gas cell exit, results in a great reduction of the collisional broadening and thereby in a significant improvement of the spectral resolution [1] and the ionization efficiency. In-gas-jet laser spectroscopy studies on the neutron deficient actinium isotopes ^{214,215}Ac (at the N=126 shell closure) revealed a total spectral resolution down to ~400 MHz, enabling a 25-fold improvement in the extracted isotope shifts and hyperfine A- and B- parameters in comparison to former in-gas-cell spectroscopy studies [2]. Moreover, the results show that the total ionization efficiency in the gas jet is comparable to that in the gas cell (~0.5 %) and can potentially be improved by at least one order of magnitude by optimizing the duty cycle. Combining these results with state-of-the-art atomic calculations, nuclear properties such as spins, magnetic dipole and electric quadrupole moments, and differences in mean charge radii have been obtained for a number of actinium nuclei around the N=126 neutron shell closure. A comparison to large-scale shell-model calculations provides new evidence to the extent of magicity in this region.

Further characterization and optimization of the in-gas- jet technique is ongoing at the off-line IGLIS laboratory at KU Leuven, where the physical and technical limits of the technique are being explored. This will ensure the best performance in spectral resolution and ionization efficiency for the future IGLIS setups [3] that will be coupled to the in-flight mass separator MARA, at the Department of Physics in the University of Jyväskylä, and to the Superconducting Separator Spectrometer (S3) at the new radioactive ion beam facility SPIRAL2 (GANIL).

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Simple Nuclear Systems around the Doubly Magic ^{132}Sn Studied via Fast-Timing Measurements

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Changes in nuclear structure are expected in nuclei around neutron-rich shell closures at ^{78}Ni and ^{132}Sn with a large neutron to proton ratio. Unexpected features appear and collective phenomena may arise in the vicinity of these exotic shell closures. Relevant experimental information may be obtained from gamma spectroscopy in combination with excited-level half-life measurements.

The Advanced Time-Delayed Method (fast-timing) has been used to measure level lifetimes in several Sn, Sb and Te nuclei around the doubly magic ^{132}Sn nucleus. Complementary production techniques were employed. Firstly, beta-decay studies have been performed at the ISOLDE facility at CERN.

In one experiment high-purity Sn beams have been extracted by means of SnS^+ molecular ions. In a second experiment pure, isomer selective, In beams where laser-ionized. Secondly, prompt-fission γ-ray measurements have been performed at the PF1B beam line of the reactor of the Institut Laue–Langevin (ILL), where fission was induced by cold-neutrons, and measurements were carried out with a mixed array of Ge and $LaBr_3$(Ce) detectors.

Information on several nuclei around ^{132}Sn will be provided. We will discuss single-particle states in the odd ^{131}Sn and ^{133}Sn, where the isomer selective of the beta-decaying In parents help disentangle the decaying patterns. We will also report on transition rates in ^{135}Sb, where the low-lying $1/2^+$ state had been earlier identified in beta-decay. The collective E2 transition can be compared with the $11/2^+$ ground-state transition. We will also address the ^{136}Te B(E2; $2^+ \rightarrow 0^+$) puzzle, where the reduced transition rate (in combination with the increased 2^+ energy) is not consistent with the empirical rule for quadrupole collectivity, nor with the enhanced E2 transitions in neighbouring Sb isotopes. The measurements at low energy from beta-decay will be put in context in comparison with lifetimes of higher spin states obtained in the fission experiment at ILL. A comparison of to ^{138}Te will be provided.

The Study of Neutron-Rich Nuclei at HRIBF – Lessons Learned

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I will describe highlights of experiments done at the Holifield Radioactive Ion Beam Facility (HRIBF) using pioneer techniques, methods and instrumentation developed specifically for this purpose during the last decade and a half. These experiments were aimed to the study of neutron-rich nuclei primarily at or near the magic numbers. HRIBF was a premier ISOL facility for the production of high quality and purity radioactive ion beams. Measurements of energies, B(E2), Q, g factors of low-lying states along important isotopic and isotonic chains using new particle-gamma instrumentation and techniques. Our approach has been to reduce the risk of unknown systematic errors with appropriate experimental design and simplicity of experimental procedures and analysis. Progress in the development of a new charged particle array, and on the use of polarized targets will be discussed. Finally, I will briefly discuss the possibility of experimentally studying shapes of large clusters of atomic ions.

Goodness of Isospin in Neutron Rich Systems and Fission Fragments

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The concept of isospin has been widely used in lighter N≈Z nuclei where it is a reasonably good quantum number [1-2]. It is, however, interesting to note that the purity of isospin may be restored in neutron-rich systems, which are now becoming more accessible in labs [3-4]. Besides, the neutron-rich fragments emitted in nuclear fission present a good opportunity to test the goodness of isospin [5-6].
In this paper, we present the results of our calculations for the relative yields of neutron-rich fission fragments emitted in $^{208}Pb(^{18}O, f)$ by using conservation of isospin and compare [7-8]. We fix the isospin of the compound nucleus first and assume that the neutron evaporation leaves us with a residual compound nucleus which breaks into fission fragments. We take into account all the possible isospin values allowed by algebra and the fact that the fission fragments arise as Isobaric Analog States. We then write the isospin wavefunction in terms of the fragments and the Isospin Clebsch Gordon Coefficients are used in calculating the fragment yields. We also use the neutron multiplicity data for various n-emission channels in each partition, and use them to obtain the weight factors in calculating the yields. We then calculate the relative yields of fission fragments. Our calculated results are able to reproduce the experimental trends reasonably well. This establishes that isospin conservation may prove a very useful concept in neutron-rich systems.

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Effectively-Truncated Large-Scale Shell Model Calculations and Nuclei around ^{100}Sn

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Large-scale shell-model calculations have become a well-established approach to microscopically investigate medium- and heavy-mass exotic nuclei, whose description, especially when concerning collective properties, requires very large model spaces with many valence nucleons. However, in spite of the progress in solving eigenproblems of considerable complexity the dimensions of the energy matrices to be diagonalized are in some cases still too large to be exactly addressed also with up-to-date shell-model codes. One is therefore forced to adopt truncations of the shell-model basis, which are usually based on allowing only a limited number of particle-hole cross-shell excitations.

Here, a new procedure, developed within the framework of realistic shell model, is proposed to reduce the computational complexity of large-scale shell-model calculations [1,2]. First, we derive an effective "mother" Hamiltonian within a large model space, starting from the free nucleon-nucleon potential.

As a second step, we find out the single-particle orbitals relevant to describe the class of isotopes or isotones under investigation by studying the effective single-particle energies (ESPE) of this Hamiltonian. Finally, a new effective Hamiltonian, defined in the truncated model space including the identified reduced number of orbitals, is constructed by way of an unitary transformation of the "mother" Hamiltonian. This double-step approach provides a truncation procedure by effectively preserving as much as possible the role of the rejected degrees of freedom. As an application, we consider nuclei around 100Sn, i.e. even-even $^{90\text{-}98}$Zr, $^{92\text{-}98}$Mo, $^{94\text{-}98}$Ru, $^{96\text{-}100}$Cd, $^{98\text{-}102}$Pd, $^{100\text{-}104}$Sn nuclei. Our aim is to check the reliability of our double-step truncation approach and investigate the role of the Z = 50 cross-shell excitations in explaining the quadrupole collectivity observed along these isotopic chains. Our starting effective Hamiltonian is defined within a model space spanned by seven $1p_{1/2}$, $0g_{9/2}$, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$ proton orbitals and by five $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$ neutron orbitals, considering ^{88}Sr as inert core. The one- and two-body terms of this Hamiltonian, as well as the effective charges for electric quadrupole transition operator, are derived from the high-precision CD-Bonn nucleon nucleon potential [3] by way of many-body perturbation theory [4]. By following the evolution of the neutron and proton ESPE, two reduced model spaces are identified and the corresponding Hamiltonians constructed. Then, the excitation energies of the yrast 2^+ states and the $B(E2; 0^+ \rightarrow 2^+)$ transition rates are calculated using the three Hamiltonians, whenever possible, showing the ability of the truncated Hamiltonian to reproduce eigenvalues and electromagnetic transition rates of the original Hamiltonian, especially when the ESPE provide a neat separation in energy between the new model subspaces. The comparison of experimental and calculated results is also discussed.

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Studies of Shape Coexistence at TRIUMF-ISAC

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The phenomenon of shape coexistence in atomic nuclei has now been established as a relatively common behaviour across the nuclear chart. The appearance of these structures seems to depend on the delicate interplay between the occupation of different single-particle orbitals and the strength of the proton-neutron interactions. A range of experimental setups have been developed at ISAC to study shape coexistence effects.

Shape coexistence between low-lying structures of different shape has been established in the neutron-deficient krypton isotopes. In the case of ^{78}Kr which lies at the boundary of this region of coexistence, there are discrepancies in the B(E2) transition strengths reported in literature between measurements using beta decay and Coulomb excitation. At ISAC, ^{78}Kr has been studied through the beta decay of ^{78}Rb using the 8pi spectrometer with the PACES electron detectors. In addition, a Coulomb excitation study will be performed at TIGRESS with the SPICE detector.

In the neutron-rich Sr isotopes there is a dramatic change in ground-state structure that occurs at neutron number 60. A series of transfer reaction studies with accelerated radioactive beams has been performed with the SHARC silicon barrel coupled with the TIGRESS array to examine the evolution of single-particle orbitals around this transition point.

The details of these studies and other recent experiments will be given and a look to future opportunities at ISAC.

Nuclear Structure with NUSTAR at GSI and FAIR

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NUSTAR comprises the current nuclear structure, astrophysics and reactions programme at GSI and its proposed continuation and extension at FAIR. NUSTAR relies on the availability of exotic rare isotope beams produced by fragmentation reactions and fission of relativistic heavy ions.
The fragment separator FRS and a versatile set of instruments, including gamma arrays, particle spectrometers and a storage ring enable unique experiments at GSI. The Super-FRS at the FAIR facility will provide several orders of magnitude stronger beams, providing access to the extremes of nuclear stability. To exploit these opportunities novel experimental set-ups are in preparation. R&D efforts result already now in improved detectors and enables the NUSTAR collaboration to steadily enhance the sensitivity and selectivity limit of their experiments. Current NUSTAR physics highlights will be discussed as well as plans for the Phase-0 programme starting in 2018 with the powerful FAIR injectors and the Phase-1 programme at the final FAIR facility.

Recent Results in the ^{100}Sn Region

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The nuclear structure in the ^{100}Sn region will be presented. State-of-the-art experimental techniques involving stable and radioactive beam facilities have enabled access to exotic nuclei in its next neighbourhood. The analysis of experimental data has established the shell structure and its evolution towards N = Z = 50, seniority conservation and proton–neutron interaction in the $g_{9/2}$ orbit, the super-allowed Gamow–Teller decay of ^{100}Sn, masses and half-lives along the rp-path, and super-allowed α decay beyond ^{100}Sn. The status of theoretical approaches in shell model and mean-field investigations will be discussed and their predictive power assessed. Selected structure features of 100Sn and its doubly-magic neighbours ^{56}Ni at N = Z, ^{132}Sn and ^{78}Ni at $N \gg Z$ are compared.

Transition Rate Measurements at Extremes of Shape Coexistence

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The region of the nuclear chart around neutron-deficient Pb nuclei is of great interest in modern nuclear structure physics as intriguing phenomena such as the coexistence of multiple shapes have been observed. The relation between these configurations and underlying microscopic nuclear structure can be studied by measuring transition energies, and transition probabilities between the coexisting structures. In nuclei close to the Z = 82 shell gap and the neutron mid shell at N = 104, large valence neutron space together with the relatively small proton shell gap provides us with an excellent laboratory for such studies.

Reduced transition probabilities, B(E2) values, give particularly precise information of the collectivity and its development in atomic nuclei as a function of N and Z. Measurements of the B(E2) values have been carried out through mean lifetime measurements of the neutron-deficient Hg, Pb and Po nuclei close to the neutron mid shell at the Accelerator Laboratory of the University of Jyväskylä [1]. These studies at the extremes of the proton and neutron ratio have utilised selective tagging methods by employing the JUROGAM I & II γ-ray spectrometers and the RITU gas-filled recoil separator. Experimental methods and the results of these studies, and their impact on the theory development will be discussed.

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Magnetic Dipole Moment of Chiral Bandhead in ^{128}Cs

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Magnetic dipole moment measurements may provide an essential data for spin orientation in a three component systems like doubly-odd nuclei with core rotation included. Semi classical additivity formula for the g-factor of a three component system has a term sensitive to mutual orientation of the three angular momenta vectors of the components. In a semi-classical picture, this dependence may be used to recognize whether the three angular momenta vectors of components are located in one plane (planar configuration) or span the three-dimensional space (aplanar configuration). This is particularly interesting in case of nuclear chirality where aplanar configurations are expected. Even more interesting observation gives the quantum picture of a single coupling scheme. Such coupling scheme is defined as the unique set of expected mutual angles between each pair of the angular momenta vectors. The expected angles are always maximally chiral as a result of spin precession in quantum angular momentum algebra. Therefore, if the wave function of a nuclear state is close to a pure coupling scheme it will always have observables with maximum chirality although the nuclear chirality may not be defined in such a system due to spin precession. However, the real nuclear states are wave packets built of superpositions of many coupling schemes in a spherical basis. This gives the transition to semi-classical picture where orientations of the three angular momenta vectors are well defined and the planar configuration may be formed and observed by the measured g-factor values. Results of the TDPAD experiment performed at IPN Orsay will be used to discuss the above features. The g-factor of the $\pi h_{11/2} \otimes \nu h_{11/2}$ chiral bandhead has been determined indicating significant component of non-chiral spins configurations.

Breaking of Axial Symmetry in Excited Heavy Nuclei as Identified by Experimental Data

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During investigations performed at HZDR and TU-Dresden on photon scattering and a study of recently reviewed [1,2] experimental results from radiative neutron capture a remarkable effect of symmetry breaking in excited heavy nuclei was realized. Such symmetry breaking was predicted recently by CHFB-calculations performed at CEA-DAM [3], and the Dresden work was mainly based on the deformation values from these calculations. Their impact on predictions for photon strength functions and nuclear level densities was investigated; for the latter the following points are of importance:

When axial (or spherical) symmetry is not assumed ad hoc, the collective enhancement of level densities leads to good agreement of experimental data to Fermi-gas predictions without the usually applied quasi arbitrary increase of the level density parameter. One can then stick to the prediction obtained from the Fermi-energy and an only small correction for surface effects is needed. The agreement was shown to be equally good for heavy nuclei in the range of 60<A<240 independent of their distance from nuclear shells. Respective results for spin 1/2 states in nuclei in the valley of stability were published as Phys. Lett. [4]; a full paper is expected to appear soon [5]. As shown there, a considerable improvement of predictions for average neutron capture resonance spacings by a modified back-shifted Fermi-gas model (BSFM) was found.

This BSFM closely follows the basic principles for a gas of weakly bound Fermions including:

(1) a phase transition at a temperature defined by statistical theory,
(2) pairing condensation quasi-independent of nucleon number A,
(3) the level density parameter fixed by the Fermi energy;
(4) in finite nuclei the back-shift energy is defined by shell effects [6] and
(5) the collective enhancement is considerably enlarged, when the projection onto fixed angular momentum allows for a broken axial symmetry [4,7].

Nearly no parameter fitting is needed to arrive at a good reproduction of average resonance spacings [2] for spin-½ in a large number of nuclei as reached by neutron capture into spin-0-targets, including Maxwellian averaged cross sections [1]. A wide range of E_x was covered by complementing the modified BSFM by a constant temperature approximation below the phase transition point [8,9].

The unexpected finding [4] of broken axial symmetry in a wide range of nuclei with A>50 finds additional support by a detailed study [5] of experimentally determined IVGDR shapes: Here only one global width parameter suffices and the consequent use of three poles leads to a surprisingly good agreement of the data to triple Lorentzians with perfect accordance to the classical TRK sum rule.

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Studies of Superdeformed States in Atomic Nuclei Using the Coulomb Excitation Method

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A Coulomb excitation experiment to study electromagnetic properties of the strongly-deformed band in ^{42}Ca and its coupling to yrast states was performed at the Laboratori Nazionali di Legnaro in Italy using the γ-ray spectrometer AGATA Demonstrator and the DANTE charged particle detector array.

The motivation for this measurement was the observation of a rotational structure in ^{42}Ca, which is similar to previously identified super-deformed bands in several A~40 nuclei, such as ^{40}Ca, $^{36,38}Ar$, ^{44}Ti. Lifetime measurements in ^{42}Ca using the Doppler-shift attenuation method suggest a smaller deformation of the band built on the second 0^+ state (1837 keV) than in the case of ^{40}Ca. On the other hand, the moment of inertia of this band was found to be very similar to the one of the super-deformed band in ^{40}Ca. Another argument for the highly-deformed character of this band was the observation of its preferential feeding by the low energy component of the highly split GDR decaying from ^{46}Ti.

In the present experiment, Coulomb excitation was used for the first time to populate the highly-deformed band and to study its decay. Shape parameters of a weakly-deformed ground-state band and highly-deformed slightly triaxial side band in ^{42}Ca were determined from E2 matrix element measured in the first low-energy Coulomb excitation experiment performed with AGATA. The picture of two coexisting structures is reproduced by new state-of-the-art large-scale shell model and beyond-mean-field calculations. In this talk the super-deformed and slightly triaxial character of the band built on 0^+_2 will be discussed.

Single-Particle and Collective Rotational Properties of the Light Deformed Superheavy Nuclei in a PNC-CSM Method

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Inspired by the increased experimental observations and theoretical interest to a detailed spectroscopic study of the light superheavy nuclei, the single-particle and rotational properties of nuclei with Z ~ 100 are investigated systematically by the Cranked Shell Model (CSM) with pairing correlations treated by a Particle-Number Conserving (PNC) method [1, 2], in which the Pauli blocking effects are taken into account exactly.

By fitting the experimental bandhead energies in more than 30 odd-A nuclei with Z ~100, a new set of Nilsson parameters (and μ) is proposed [3]. The experimentally observed variations of moment of inertia (MOI) for the even-even, odd-A, and odd-odd nuclei are reproduced very well by the PNC-CSM calculations. The upbending mechanism in this region is understood clearly. Taking Cm and Cf isotopes for example, the upbendings in the ground state bands are mainly caused by the intruder proton (N = 6) $i_{13/2}$ orbitals. The rotational properties of odd-odd nuclei ^{251}Md and ^{255}Lr are investigated in detail [4, 5]. Note that for the odd-odd nuclei in this mass region, the rotational bands up to high spin have been observed only in these two nuclei. For the first time, the effect of the proton N = 7 major shell in this mass region is tested. The intruder of the proton high-j low-$1j_{15/2}$ (1/2[770]) orbital could lead to band-crossings at frequency region $\hbar$w = 0.15 - 0.25 MeV which is quadrupole deformation dependent. The high-K isomeric states observed in experiment are studied systematically [6]. The including of the high order deformation 6 leads to a strengthened deformed shell gaps at N = 152 and Z = 100, and a better reproduction of the isomer energies [6]. Paring reduction of the high-K isomer states in ^{254}No and the systematically observed K = 8^- isomer states in N = 150 isotones are discussed in detail. Recently, PNC-CSM is further developed to describe the properties of the reflection asymmetric nuclei [7]. The microscopic mechanism of the frequency variation of the alternating-parity bands in even-even ^{236,238}U and ^{238,240}Pu and the parity doublets in odd-A nuclei ^{237}U and ^{239}Pu will be presented.

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Beta-NMR/NQR Studies of the Neutron-Rich Al Isotopes at the Border of the Island of Inversion

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In the last decades, the changing structure of nuclei far from stability has attracted a considerable amount of attention both experimentally and theoretically. One of the oldest examples is the island of inversion around N = 20, where deformed intruder configurations become the ground state below the conventionally expected spherical configurations. Since the structure of the nuclei at the edges of the island of inversion results from the subtle balance between stabilizing shell gaps and proton-neutron correlations, their study is imperative to improve our understanding of the drivers of the sudden structural changes in this region.

Located above the deformed Mg isotopes, the neutron-rich Al isotopes (Z = 13), constitute the northern border of the island of inversion. The results of two β-NMR/NQR experiments on ^{33}Al and ^{34}Al will be presented [1]. The high-precision of the quadrupole moment of ^{33}Al reveals a significant amount of intruder configurations in its ground state, placing it inside rather than outside the island of inversion. Furthermore, the g-factor and quadrupole moment of the recently discovered 1^+ state in ^{34}Al [2] is discussed. This state is proposed to have a 1p-1h intruder configuration, so far unique in the island of inversion where 2p-2h (and 4p-4h) excitations are found to dominate the wave functions. Its g-factor and quadrupole moment, in comparison with the 1^+ normal ground state of ^{32}Al, enables the confirmation of the proposed intruder nature and offers the exceptional opportunity to study the increase in deformation due to these particular 1p-1h excitations.

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Spectroscopy of Neutron-Rich ^{96}Y Isotope Produced in Fission Induced by Cold Neutrons

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The onset of the deformation in neutron-rich nuclei around A = 100 mass region has for many years remained one of the most interesting subjects for nuclear spectroscopy study. For the neutron number N = 60, a sudden onset of the deformation has been observed at the ground state, which is manifested by the presence of rotational bands (e.g. [1]). On the other hand the occurrence of shape coexistence in nuclei with N = 58 and 59, in this region (e.g. [2]), suggests that the evolution of the deformation is a more gradual process. In the yttrium isotopic chain, a rotational band above the 4-, 496-keV K-isomer has been observed in the N = 59, ^{98}Y nucleus, while there was no evidence of the deformed structure in the Y isotopes with neutron number less than N = 59. Our goal was to investigate N = 57, ^{96}Y isotope where only a few states were known from beta decay study of ^{96}Sr [3] as well as the long 9.6-s (1140-keV) isomer [4].

The yttrium-96 isotope has been produced by fission of both ^{235}U and ^{241}Pu targets induced by cold neutron from the reactor at Institut Laue-Langevin. The level scheme up to excitation energies in excess of 5 MeV has been established based on multi-fold gamma-ray coincidence relationships measured with the EXILL spectrometer [5] which consists of up to 46 HPGe detectors. By exploiting delayed- and cross-coincidence techniques, extensive structure has been delineated. During the analysis, over 50 new gamma transitions which feed previously known low-spin states as well as the long 9.6-s, 8^+ isomer have been identified. Moreover, a new isomeric state at 1655-keV excitation energy has been located with half-life of 175 ns. Angular correlation analysis allows to define spin-parity assignment for most of the identified levels, in particular (7^+) for new isomer. By using the delayed-coincidence method it was possible to identify above the 175-ns state a few weak transitions, which seem to form a rotational band, in analogy to the structure above the 4^- isomer in the ^{98}Y isotope.

The existence of the new isomeric state and the possible deformed band built on that isomer in the N = 57 ^{96}Y isotope shed new light on the study of the onset of deformation in neutron-rich nuclei around N = 60. It shows that the deformed structures appear just after the subshell closure at N = 56 and evolve smoothly when passing through N = 57-59 isotopes, to became a ground state structure in the ^{99}Y isotope, i.e., at N = 60.

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Medium and High Spin Structure in the ^{94}Y Isotope Produced in Fission Induced by Cold Neutrons

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The shape of a particular nucleus results from an interplay between the collective (macroscopic) and single-particle (microscopic) energies and, therefore, highly depends on both the atomic number Z and the neutron number N. The neutron-rich nuclei around Z=40 and N=60 provide one of the best territories for the exploration of this sensitivity. Indeed, the sudden onset of deformation observed for neutron-rich nuclei with Z = 36–40 nuclei near N=60 is considered the most dramatic shape change in the nuclear chart. Nevertheless, the resent study of the yttrium isotopic chain reveal occurrence of shape coexistence in the ^{98}Y isotope [1] and possible rotational band above the 6^- isomeric state in the ^{96}Y nucleus [2]. This suggests that the evolution of the deformation is a more gradual process. Therefore, we decided to investigate whether deformed structures are still present in the ^{94}Y nucleus which lies 5 neutrons away from the N=60 boundary. So far, very little spectroscopic information has been gathered on ^{94}Y – what regards higher spin yrast excitations established was only the presence of the 1.35-μs, (5^+) isomer at 1202 keV excitation energy [3]. This isomer could be used as a starting point for the identification of structures on top of it.

The ^{94}Y isotope has been produced by fission of ^{235}U target induced by cold neutron from the reactor at Institut Laue-Langevin. The level scheme up to excitation energies of about 7 MeV has been established based on multi-fold gamma-ray coincidence relationships measured with the EXILL spectrometer [4] which consists of up to 46 HPGe detectors. During the analysis, over 30 new gamma transitions, which feed the previously known (5^+) isomer, have been identified. Angular correlation analysis allows to define spin-parity assignment for most of the identified levels. The identified transitions don't show any pattern characteristic for deformed structures. Furthermore, no higher located isomer has been found, similar to the ones known in heavier yttrium isotopes on which the rotational bands are built. Those findings are in line with the expectations that in ^{94}Y only spherical structures are present at low excitation energy.

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Lifetime Measurements with GRETINA at NSCL Magnetic Response of Halo Nuclei

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Collective motions in atomic nuclei at low excitation energies have often been described in terms of rotation and vibration with respect to the ground-state shape. This picture can be altered in exotic nuclei with unusual proton-to-neutron ratios, where shape and shell effects can induce a delicate interplay between different structures. In self-conjugate nuclei at N=Z, proton and neutron shape (deformed shell) effects can be amplified, leading to shape coexistence phenomena pronounced in the A=70-80 region. On the neutron-rich side with large isospin asymmetry ($N \gg Z$), the shell structure is significantly modified, which results in a competition between the normal and intruder configurations at the conventional magic numbers and sometimes induces the halo formation in weakly-bound nuclei.

As a way to observe unique forms and dynamics of exotic isotopes which are often produced in very low amounts, the advanced gamma-ray array GRETINA (Gamma-Ray Energy Tracking In-beam Nuclear Array) has been employed in the lifetime measurement program with fast rare isotope beams at NSCL. This talk will provide an overview of the program and highlight physics results obtained for self-conjugate nuclei as well as very neutron-rich nuclei close to the drip-line. Recent studies on magnetic properties of halo nuclei will be presented and impacts due to spherical and deformed configurations on the transition strengths will be discussed.

Nuclear Isomers: What we Learn from Tin to Tin

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In recent times, nuclear isomers have taken a centre stage in nuclear physics as they provide a useful handle to study various nuclear structure properties in unusual situations. We have recently presented a detailed tabulation of more than 2450 nuclear isomers [1]. In this talk, we mainly focus on the nuclear isomers in semi-magic nuclei with specific emphasis on the Sn isotopes. The Sn isotopes present the longest chain of isotopes with experimental data available from the doubly magic ^{100}Sn to the doubly magic ^{132}Sn and beyond up to ^{138}Sn. This range of isotopes covers many sub-sets of active valence orbitals leading to significant changes in nuclear structure as we move from ^{100}Sn to ^{138}Sn. The concept of seniority, a beautiful symmetry arising from the pairing of nucleons in nuclei, has proved very useful in understanding the behavior of semi-magic nuclei. We use a generalization of this concept, known as the generalized seniority, and show that it behaves almost as a good quantum number throughout the Sn-isotopic chain.
It is generally believed that the seniority isomers arise only due to E2 transitions, as the odd-tensor decays conserve the seniority and show a particle number independent behavior in a single-j scheme [2]. By extending the seniority picture to the multi-j degenerate orbitals i.e. the “generalized seniority”, we could establish that the decay properties are similar for both even and odd tensor electric transitions [3]. We have used this result to understand the decay trends of isomeric states as well as other excited states in the multi-j environment. For example, we have shown for the first time that the isomers from the Sn-isotopic chain display a similar behavior for E1 decaying 13^- Sn-isomers, and E2 decaying 10^+ and 15^- Sn-isomers [3]. These findings have opened up the way to find a new kind of seniority isomers decaying via odd-Electric transitions. To further extend the results for seniority changing transitions, we study the first excited 2^+ and 3^- states in Sn-isotopes, and found that our scheme successfully explains the asymmetric double parabolic trend of B(E2) values and the inverted parabolic behavior of B(E3) values [4, 5]. We also extend these calculations to the 6^+ isomers in $^{134-138}$Sn isotopes [6]. To conclude, we are able to describe the decay properties of both the isomeric states and other excited states using a simple microscopic generalized seniority scheme. These results are supported by shell model calculations based on the most useful truncated space guided by the generalized seniority scheme.

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Characterization and Calibration of Radiation-Damaged Double-Sided Silicon Strip Detectors

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Double-sided silicon strip detectors (DSSSD) are commonly used for event-by-event identification of charged particles as well as the reconstruction of particle trajectories in nuclear physics experiments with both stable and radioactive beams. Intersecting areas of both p- and n-doped front- and backside sectors form individual virtual pixel segments allowing for a high detector granularity. DSSSDs are employed in demanding experimental environments and have to withstand high count rates of impinging nuclei. The illumination of the detector is often not homogeneous, consequently, radiation damages of the detector are distributed non-uniformly. Position-dependent incomplete charge collection due to radiation damage limits the performance and lifetime of the detectors, the response of different channels may vary drastically. Position-resolved charge-collection losses between front- and back-side sectors are investigated in an in-beam experiment and by performing radioactive source measurements. A novel position-resolved calibration method based on mutual consistency of p-side and n-side charges yields a significant enhancement of the energy resolution and the performance of radiation-damaged parts of the detector.
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A Self-Consistent Equation of Motion Multiphonon Method for Even Mass Nuclei

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In last years, several methods for microscopic calculations of the fine structure of giant and pygmy resonances were developed [1-3]. Among them, the Equation-of-Motion Phonon Method (EMPM) in particle-hole formulation was applied for the investigation of fine structure of E1 strength in ^{16}O and heavier nuclei ^{132}Sn, ^{208}Pb [4-8]. Recently, EMPM was extended for open shell systems and applied to neutron-rich nucleus ^{20}O [9]. It was shown, that multiphonon states enhance enormously the density of levels and fragment E1 strength, consistently with the data. The method is fully self-consistent and designed for general two-body Hamiltonian. We will review recent results based on modern chiral nucleon-nucleon interaction NNLOopt [10]. Further, we will discuss the importance of two-phonon components in the description of ground states of spherical closed-shell nuclei within EMPM.

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Multipole Modes within the Finite Amplitude Method and Application to the Nuclear Photo Absorption Cross-Section

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The response of the atomic nucleus to gamma radiation provides crucial information about its structure and the forces acting between constituent nucleons. To access these excited modes, within the framework of superfluid nuclear density functional theory, the linear response is one of the commonly used methods. Traditionally, the linear response, or the quasiparticle random phase approximation (QRPA), has been formulated in the matrix form. However, the matrix QRPA becomes computationally very demanding with deformed nuclei, resulting usually truncations in the used model space.

To circumvent the large CPU and memory cost of the matrix QRPA, the finite amplitude method (FAM) solves the QRPA problem iteratively. We have developed recently a FAM-QRPA module which allows to handle non-axial multipole modes [1], without any truncations. This work demonstrated the first practical application of the iterative QRPA method for deformed superfluid nuclei, with an arbitrary multipole transition operator.

As an application of the FAM-QRPA, we have done a systematic computation of the nuclear photo absorption cross sections for the heavy rare-earth nuclei [2]. The computed results show that for isotopes heavier than erbium, there is some deficiency in the cross section, when compared to experimental data. A simple modification of the Thomas-Reiche-Kuhn sum rule enhancement factor cannot cure this deficiency.

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Lifetimes of the 2^+_1 and the 4^+_1 States of ^{148}Ce and its $B_{4/2}$ Ratio from EXILL&FATIMA Experiment

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The even-even N=90 isotones with Z=60-66, present an interesting phase transition. This phase transition in nuclei is characterized by a sudden change of the shape of the nucleus [1]. ^{148}Ce lies on the downboundaries of the phase transition region and therefore further elucidate the underlying mechanisms that lend the shape phase transition behavior.
^{235}U and ^{241}Pu fission fragments were measured by a mixed spectrometer consisting of high-resolution Ge and fast $LaBr_3$(Ce)-scintillator detectors at the high-flux reactor of the ILL. Prompt γ-ray cascades from the nuclei of interest are selected via Ge-Ge-$LaBr_3$-$LaBr_3$ coincidences. The good energy resolution of the Ge allows precise gates to be set, selecting the cascade, hence, the nucleus of interest. The excellent timing performance of the LaBr3 detectors in combination with the General Centroid Difference method [2] allows the measurement of lifetimes in the ps range in preparation for the FATIMA experiment at FAIR. The first results on neutron-rich ^{148}Ce are presented.

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Theoretical Description of E0, E1, E2 and M1 Giant Resonances

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Self-consistent RPA+Skyrme BCS approach is used for the description of E0 [1,2], E1 [3,6], E2 [2], M1 [4,5] giant resonance positions and shapes. Comparison of the calculated E0 strength functions with experimental data demonstrates a known fact that there is not possible to describe experimental GMR in all isotopes with one parametrization of effective nucleon-nucleon interaction. It is also manifested how the coupling between E0 and E2 modes leads to the double-peak character of the GMR observed in deformed nuclei. A toroidal character of the nucleon flow in the E1 excitations in the pygmy E1 resonance energy region is shown. This leads to the new interpretation of the pygmy resonance (pygmy resonance is not connected only with a vibration of the neutron skin versus N=Z core). Comparison of the Skyrme RPA results with other theoretical approaches and with corresponding experimental data on the giant M1 resonance demonstrates a good RPA description of the scissor (orbital) part of the M1 resonance while for a good description of the spin-flip part of the M1 resonance it is necessary to go beyond the RPA. Calculated neutron and proton flows in the excited states of deformed nuclei with energies ~3 MeV (scissor mode energies) are in agreement with the standard interpretation of the scissor M1 resonance (angular oscillation of the axially deformed proton system versus neutron system around an axis perpendicular to the nucleus symmetry axis). The shapes of the nucleon flow in other giant resonances are discussed as well.

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Variety of Shapes and a Complex Shape Coexistence in ^{187}Tl

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The region of neutron-deficient nuclei near the Z=82 closed shell provides some of the clearest and most extensive examples of shape coexistence, a phenomenon where the atomic nucleus exhibits level structures characteristic of different nuclear shapes at low (similar) excitation energies. The most recent review [1] has summarized the status of shape coexistence in this region, describing a systematic picture of spherical, oblate and prolate shapes based on multiple particle-hole excitations across the Z=82 shell gap, with the deformed structures reaching their lowest excitation energies around the middle of the neutron shell at N=104.

This contribution considers the case of ^{187}Tl with N=106, where the typical picture of spherical, prolate and oblate shapes was first established from the observation of characteristic level structures associated with $h_{9/2}$ and $i_{13/2}$ protons coupled to prolate and oblate shapes, giving decoupled ΔI=2 and strongly-coupled ΔI=1 sequences, respectively [2,3]. Subsequent investigations determined the magnitudes of the deformations from lifetime measurements [4] and identified possibly deformed isomeric states based on three-quasiparticle excitations [5]. The latter study hinted at a more complex manifestation of shape coexisting states in this nucleus and motivated a more sensitive experiment using Gammasphere that was performed at Lawrence Berkeley National Laboratory, using a heavy-ion fusion-evaporation reaction involving a beam of 154 MeV ^{32}S ions incident on a 1.2 mg/cm^2 ^{159}Tb target, backed with 4.5 mg/cm^2 of ^{197}Au. The beam from the 88-inch cyclotron was pulsed at 60 ns intervals, enabling the separation of both in- and out-of-beam events. Preliminary results were presented in Ref. [6].

We will discuss the full level scheme now deduced for ^{187}Tl and make comparisons with new potential energy surface calculations (similar to those in Ref. [7]) that can be used, in conjunction with spectroscopic information and observation of characteristic level structures, to deduce the nature of the various shapes that are manifest in ^{187}Tl. A rich structure of shape coexisting states is now identified beyond the usual spherical, oblate and prolate shapes. These include a well-deformed triaxial band based on the 11/2$^-$[505] proton state, deformed isomeric states based on multi-particle excitations, and an $i_{13/2}$ proton band with an enhanced deformation mid-way between the usual prolate shape and the superdeformed shape (see, for example, Ref. [8] for the neighbouring case of ^{189}Tl) that is observed in heavier Tl isotopes.

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Measuring Entry Distributions with and Unfolding Spectra from Detector Arrays

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For escape-suppressed detector arrays such as Gammasphere, techniques have been developed to unfold spectra and, thus, to extract the true quasi-continuum of gamma rays emitted in fusion evaporation reactions [1]. This makes it possible to perform quasi-continuum spectroscopy at very high spins and finite temperatures (known as QC and Ridge spectroscopy, see [2]). Furthermore, by removing the heavimet shields from the BGO Compton suppressors of Gammasphere, it is possible to directly determine entry distributions for heavy ion reactions using the spectrometer as a calorimeter [2].
With the advent of tracking detector arrays, it should be possible to measure the quasi-continuum of gamma rays as well as entry distributions with superior precision. However, the techniques for doing so are significantly more elaborate. We will propose some new techniques and discuss the first results from unfolding of an ^{152}Eu spectrum measured in a tracking array.
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Chiral Symmetry in the Tl Isotopes

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When a left-handed and a right-handed nuclear system form in angular momentum space, a pair of nearly degenerate rotational bands is observed [1]. A good chiral symmetry is revealed by an observation of close near-degeneracy in all properties of the partner bands. Search for chiral symmetry systems was performed in ^{193,194}Tl isotopes using the AFRODITE array at iThemba LABS.
In ^{194}Tl a pair with excellent near-degeneracy was discovered [2,3]. The close similarity of the bands was also confirmed by DSAM lifetime measurements [4]. A third partner band was found in this nucleus [3]. This observation hints at a possible formation of a second chiral system associated with the same configuration. This makes ^{194}Tl a very interesting case for studying chiral symmetry.
The analysis of the ^{193}Tl data revealed the presence of three partner bands [5]. Spin and parity were assigned to these bands. A very interesting feature is that two of these bands cross each other. A tentative fourth band was observed, but could not be linked to known levels.
The studies in the ^{193,194}Tl isotopes will be presented and discussed.

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The iThemba LABS Rare Ion Beam Project

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The iThemba Laboratory for Accelerator Based Sciences has been operating a K=200 Separated Sector Cyclotron for nuclear physics research, isotope production and hadron therapy since about 1986. The conflicting demands of these diverse application place severe restrictions on research capacity and on the possibility to respond to future demands.

iThemba LABS plans to acquire a high current 70 MeV cyclotron that would serve the needs of radioisotope production, thus allowing the SSC to be used primarily for research. In addition an ISOL based Radioactive-ion beam facility using 66 MeV protons is planned.

The first step towards a RIB facility is to install and test a suitable production target/ion source. We have a collaboration with INFN Legnaro, who will supply the "front-end' which is a copy of the SPES target and ion source. The design can accommodate various target materials. With a uranium–carbide target and 70 MeV protons at 150 μA the expected yield is 2×10^{13} fissions/s, however initial tests will be limited to 50 μA. The design of low-energy beam lines and end-stations are well advanced and it is expected that low-energy fission fragment beams could be available for experiments after 2018.

Various options for the post-acceleration and experimental facilities are under consideration.

Partial Dynamical Symmetries and Prolate-Oblate Coexistence in Nuclei

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We present a symmetry-based approach for describing prolate-oblate and spherical-prolate oblate shape coexistence in nuclei [1]. The proposed number-conserving rotational-invariant bosonic Hamiltonian involves three-body terms. It preserves two different variants of SU(3) symmetry for the prolate and oblate ground bands and the U(5) symmetry for selected spherical states. Quadrupole moments and B(E2) transition rates, involving these states, are calculated in closed form and isomeric states are identified by means of selection rules. The purity of particular subsets of states, in the presence of other mixed states, demonstrates the relevance of partial dynamical symmetries to shape-coexistence in nuclei.

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On the Structure of ^{32}Mg*

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The N=20 Island of Inversion has been the subject of intense work, both experimentally and theoretically [1]. As protons are removed from ^{40}Ca, changes in the balance between the monopole shifts of the single-particle levels and the pairing plus quadrupole correlations erode the N=20 shell gap, leading to deformed (*2p2h*, *4p4h*) ground states in these nuclei, expected *a-priori* to be semi-magic and spherical. The nucleus ^{32}Mg takes center stage in this region where neutron pairs promoted from the *sd* to the *fp* levels across the narrowed *N*=20 gap are energetically favored. The enhanced occupation of these deformation-driving *fp* orbitals causes the nucleus to deform [2,3].

While there is evidence for the existence of deformed ground states, band structures, which are considered the fingerprints of rotational motion, have not been observed and a basic question on what exactly are the excitation spectra and collective modes remains largely unanswered. We will present results from a measurement with GRETINA [4] at the S800, studying the yrast band in ^{32}Mg populated via a fragmentation reaction [5], and discuss the results, within a rotational description.

In parallel, and contrary to the accepted interpretation and the results above, Fortune [6] carried out a two-level model analysis of the reaction ^{30}Mg(t,p)^{32}Mg, studied by Wimmer et al. [7] at CERN/ISOLDE and put forward the puzzling conclusion that in ^{32}Mg the 0^+_1 appears to be dominated by the *sd*-shell components (≈80%) and the excited 0^+_2 by the *fp*-shell two-particles two-holes intruder. Inspired by Large-scale Shell Model calculations [5,8] that predict the coexistence of *0p0h*, *2p2h* and *4p4h* states in the low-lying excitation spectra, we have reexamined the phenomenological analysis of Fortune extending it to a 3x3 level mixing. The results agree well with those of the Shell Model, and provide a simple framework that captures the main structure ingredients and solves Fortune's puzzle.

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High-Spin Seniority Isomers in Z=50 and Z=82 Chains

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The semi-magic nuclei are a fertile ground to look for good seniority states and a significant amount of work already exists in this area, more so for the Z = 50, Sn-isotopes. Seniority isomers arise due to the selection rules, generally relating to the E2 decays. In this paper, we present a comparative study of the identical and mirror behavior of the high-spin seniority isomers in the Z = 50 and the Z = 82 chains. The behavior of these isomers has been qualitatively discussed by many groups in terms of the single-j seniority ν = 2 and 3 states in the even-even and even-odd isotopes respectively, for both the chains. The high-j $h_{11/2}$ and $i_{13/2}$ intruder orbitals play an important role in these isomers. In this paper, we study the B(E2) variation of these isomers by using the generalized seniority scheme, applicable to many-j degenerate orbitals [1]. We show that the isomers known to arise mainly from the high-j intruder orbitals, do require the configuration mixing and the generalized seniority as an essential requirement. The large scale shell model calculations also support these results.

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Shape Evolution of Hot Rotating Nuclei Observed via the GDR Gamma-Decay

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The study of properties of the giant dipole resonance (GDR), especially its gamma decay, at high temperature and angular momentum is one of the central topics in nuclear structure as it provides insight into the behaviour of nuclei under extreme conditions. Of special interest are shape changes induced by high angular momentum leading to very elongated nuclear shapes, particularly the predicted Jacobi and Poincare shape transitions. The former one has been experimentally observed in number of nuclei up to mass 90 [1-5]. The latter is predicted [6,7] to occur at extremely very high spins in exotic neutron-rich nuclei formed in fusion-evaporation reactions induced by high-intensity radioactive beams

In the talk the status of experimental findings, their interpretation, and possible connections to the superdeformed and hyperdeformed structures at low temperatures will be overviewed. In addition the outlook of this type of studies will be discussed in the context of soon available radioactive beam facilities. In addition, the concept and status of construction of the novel gamma-ray calorimeter PARIS [8] and its role in such investigations will be discussed.

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Measurement of Prompt Gamma-Rays from Neutron Induced Fission of U-235

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The measurement of prompt fission γ-ray spectrum (PFGS) is quite important to study de-excitation process of neutron-rich fission fragments, since the PFGS include information on sharing the total excitation energy between two fragments, and quantities such as level density parameters to describe de-excitation process of the fragments. The PFGS measured for spontaneous fission of ^{252}Cf shows a broad bump at energies more than 8 MeV. This interpreted as a giant dipole resonance (GDR) of the fragments centered around 15 MeV. For neutron induced fission, however, no data are available in the energy range larger than 7 MeV. This prompted us to make a new measurement to extend the known PFGS for ^{235}U(n,f) up to 20 MeV. An experimental apparatus consists of two multi-wired proportional counters to detect fission fragments and two large volume $LaBr_3$(Ce) scintillators to measure the γ–rays from the fragments. The measurement has been carried out at the PF1b beamline of the Institut Laue Langevin. Scintillators enable us to increase the detection sensitivity for the PFGS by about 5 order of magnitude, which is high enough to take data at energies more than 15 MeV. In this contribution, we will present the results obtained the measurement. We also present our recent activities on fission study using multi-nucleon transfer reactions, and future radioactive beam facility planned to be developed at Japan Proton Accelerator Research Complex (J-PARC).

Backbending in the Pear Shaped ^{223}Th Nucleus

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An experiment has been realized using the EUROBALL IV array at Strasbourg to study the fission products produced in the reaction ^{208}Pb(^{18}0,fγ). Nevertheless, the experiment also led to the production of ^{223}Th in the fusion-evaporation channel, with three neutrons evaporated. The structure of thorium isotopes is known to present features of octupole collectivity. The aim of the present talk is to report new results about the structure of ^{223}Th, with possible consequences on the characterization of its octupole properties. Indeed, the quality of the data allowed us to establish more than 25 new levels and extend the yrast band up to $49/2^+$. This observation has brought to light a sharp backbending occurring at the highest spins promoting the ^{223}Th as the heavier thorium isotope having an accident observed in its moment of inertia. The interpretation of this phenomenon in terms of band crossing will be discussed. Moreover, a new non-yrast structure was discovered showing very different features and further details will be presented.

Dynamical Description of the Poincaré and Jacobi Shape Transitions in Nuclei: Rotation Induced Symmetry Breaking Phenomena

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The Jacobi and Poincaré shape transitions, during which the shape is changing, correspondingly, from oblate through tri-axial to prolate, and from left-right symmetric to the left-right asymmetric shapes, have been originally predicted to occur in gravitational objects such as stars [1, 2]. The Jacobi shape transition was also predicted to exist in fast rotating atomic nuclei [3,4]. The presence of the latter was confirmed experimentally [5] in fast rotating nuclei. It then turns out that an atomic nucleus, similarly to the rotating stars, can change its shape from oblate via tri-axial to prolate (Jacobi transition) [1] and/or from left-right symmetric to the left-right asymmetric shapes (Poincaré transition) [2].
Recently we have examined [6,7] a competition between the Jacobi-, and Poincaré-type shape transitions taking place in hot nuclei when angular momentum, L, increases. The analysis was focused on nuclei in which according to our predictions both of these transitions take place for the angular momenta below the critical fission limit value. We applied the LSD-C (Lublin-Strasbourg Drop - Congruence) model [7] for the macroscopic-energy expression, studied and optimized in a preceding article. We have examined systematically the properties of the transitions as well as the associated critical spin values defined as spins at which the onsets of the Jacobi and/or Poincaré transitions studied take place. We explicitly exploited the fact that the total energy landscape becomes flat gradually as function of certain deformation degrees of freedom when the angular momentum increases and the nuclei undergo large amplitude oscillations already for L much lower than their critical values. We calculated the most probable deformations corresponding the LSD-C model potentials by solving the associated collective Schrödinger equation exactly. Predictions related to various nuclei (Z=8 - 100) are discussed and illustrated. The highest chance to see the Poincaré shape transitions are in the neutron rich nuclei, which might be accessible using the beams from the Eurisol facility.

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Collective Hamiltonian Based on Density Functional for Chiral Mode

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Regarded as the evidence of stable triaxiality of nuclei, the chirality and wobbling have become hot topics in nuclear physics. Theoretically, it is extensively investigated by particle rotor model and tilted axis cranking approach. Recently, a collective Hamiltonian method was constructed based on the tilted axis cranking single-j shell model, and was successfully applied for investigating the chiral and wobbling modes. Its successes guarantee its application for realistic TAC calculations.

During the past several decades, covariant density functional theory (CDFT) has achieved great successes in describing many phenomena in stable as well as exotic nuclei. In particular, the tilted axis cranking covariant density functional theory (TAC-CDFT) has been widely used to investigate the phenomena of magnetic rotation and antimagnetic rotation. Therefore, it is of interest to construct the collective Hamiltonian based on the TAC-CDFT to investigate the chiral mode.
For describing the chiral mode, a three dimensional TAC-CDFT is necessary. Such a calculation is time-consuming. The current status of such attempt is introduced. Including the first step the collective Hamiltonian based on a two dimensional TAC-CDFT and the developed collective Hamiltonian to study the wobbling bands in 135Pr, and the progress of the collective Hamiltonian based on a three dimensional TAC-CDFT will be constructed.

Fission Product Prompt Gamma-Ray Spectrometer, A New Instrument for the ILL

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FIPPS (Fission Product Prompt gamma-ray Spectrometer) is a new instrument under construction at the ILL in the context of ILL ENDURANCE program. FIPPS addresses two fundamental domains of nuclear physics: fission of heavy elements and structure of neutron rich matter. Neutron capture induced reactions provide a suitable way to investigate these domains. FIPPS will complement the existing Nuclear Physics instrument suite at the ILL.

FIPPS consists of a high efficiency Ge detector array surrounding a fission target with a thick backing, coupled to a fission fragment spectrometer based on a gas filled magnetic (GFM) device. The new instrument will be positioned at a finely collimated halo-free thermal neutron beam at the ILL. The combined spectrometer will give access to new nuclear spectroscopy information of neutron-rich nuclides by tagging the complementary fragment and new insight into the fission process via combined measurements of mass A, nuclear charge Z, kinetic energy E_k and population of excited states.

The status of the future instrument will be presented.

The Role of NonAxial Shapes in Neutron-Rich Ba Isotopes

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The transition of nuclei from spherical to deformed shapes has always been an interesting, yet controversial, topic in nuclear structure. Dramatic emergence of deformed ground-state structures in stable rare-earth nuclei between N = 88 and N = 90 has often been discussed in terms of a 'phase transition' [1]. One way to clarify the discussion is to expand the scope of investigation to heavier and lighter members of the sequence. However, the lighter isotones are quite neutron rich and inaccessible by conventional fusion-evaporation reactions. Nuclei in this region are also expected to exhibit strong octupole correlations [2] as polarisation of spin-orbit partners appears to quench the Z = 64 subshell closure, resulting in strong couplings between $\Delta j = \Delta l = 3$ nucleon orbitals ($\pi d_{5/2} - \pi h_{11/2}$ and $\nu f_{7/2} - \nu i_{13/2}$).

Neutron-rich barium isotopes (Z = 56) have been the subject of recent investigation into the onset of nonaxial deformation [3]. This presentation will focus on detailed b–g spectroscopy of low-spin structures in the N = 90 nucleus, ^{146}Ba, which was performed at the CARIBU facility [4]. Experimental observations are compared to predictions from the interacting boson model, which suggest that the role of the γ degree of freedom has previously been underestimated. Possible evidence of octupole correlations, which have been observed directly in ^{144}Ba [3], will also be discussed.

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β-γ Decay Spectroscopy of Neutron-Rich exotic Nuclei at the CARIBU Facility

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Major strides have been taken in recent years to access exotic neutron-rich nuclei through fission of heavy actinides. The CARIBU [1] radioactive ion-beam facility at Argonne National Laboratory exploits the spontaneous fission branch of ^{252}Cf to deliver low-energy and re-accelerated beams for a variety of experiments. Fission fragments extracted from a ~1-Ci source are rapidly thermalised in a gas catcher. The resulting low-emittance beam is purified in the isobar and MR-TOF separators, before delivery to the experimental area. The X-Array (a highly efficient HPGe clover array) and SATURN (plastic scintillators and tape-transport system) decay-spectroscopy station [2] has been commissioned to perform detailed β-γ decay spectroscopy of un-accelerated (<10 keV) beams. Flexibility in design allows the needs of a variety of experiment to be met. The X-Array can be operated with one clover replaced by auxiliary detector arrays, such as fast-timing $LaBr_3$ detectors or the UMass Lowell SCANS array of Cs_2LiYCl_6 scintillators [3]. Many new research projects are underway, including investigations into nuclear structure in the vicinity of ^{132}Sn, shape changes in the A =100 mass region, and the shape of β-delayed neutron spectra. This presentation will review capabilities and first physics cases approached with the low-energy decay-spectroscopy program.

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Description of Superdeformed Nucleus ^{194}Tl by Soft Rotor Formula

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Six superdeformed rotational bands in ^{194}Tl, which shows the pronounced increase in the dynamic moment of inertia ($\Im^{(2)}$) with rotational frequency ($\hbar\omega$) in A~190 mass region, are studied using soft rotor formula (SRF) [1]. The SRF formula has been used to assign band head spins (I_0) of six rotational superdeformed bands in even-A (odd-odd) ^{194}Tl nucleus. The least-squares fitting method is employed to obtain the band head spins of these six bands in A~190 mass region. The present approach profits from the comparison of the calculated transition energies with the experimental transition energies. Model parameters are extracted by fitting of intraband γ-rays energies, so as to obtain a minimum root-mean-square (rms) deviation between the calculated and the observed transition energies. The excellent agreement between the calculated and observed transition energies gives good support to the model. The dynamic moment of inertia ($\Im^{(2)}$) is also extracted and its variation with rotational frequency ($\hbar\omega$) is investigated.

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Study of Multiphonon Band of ^{168}Er Nucleus

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The nuclear structure of multiphonon γγ-band of ^{168}Er is investigated by using the Modified Soft Rotor Formula (MSRF) proposed by Gupta *et al.* [1]. The moment of inertia parameters along with softness parameter and constant energy parameter *EK* so obtained are considered to study the nuclear structure. We further calculate the excitation energies of ^{168}Er nucleus using these parameters and compared the results with experimental data and discuss their systematic. This provides very interesting results about the nature of the nucleus and its relation with deformation. The values of the softness parameter and positive values of moment of inertia are obtained for multiphonon γγ-band. The constant energy parameter *EK* in the MSRF formula is also illustrated. The staggering patterns in these bands are also studied in detail.

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Nonadiabatic Approach with Microscopic Rotation Particle Coupling for Triaxial Proton Emitters

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Nuclei at the drip line are weakly bound and decay through various channels. Near the proton drip, for 80 > Z > 50, proton emission is the dominant decay process. Studies in this regard yield rich information about the structure and decay of such exotic nuclei [1]. In our approach [2-4], the proton emitters are considered as system of even-even core coupled to the valance particles. In a microscopic way, the Hamiltonian of the proton emitters can be evaluated through a coupling matrix which considers the coupling between the particles and the spectrum of the core. This model allows us to calculate the energies and the wave functions of the proton emitters without assuming a fixed moment of inertia for the core. We consider a nonadiabatic approach [2, 3] where we consider the Coriolis mixing of quasi-particle states near the Fermi energy, instead of assuming the (Nilsson) orbital from which the proton is emitted. We have tested the precision of rotational spectra obtained within our approach for nuclei near the beta-stability region and then applied it for nuclei around the proton drip line where we can calculate the decay widths also. Application of our approach to the deformed proton emitters ^{109}I and ^{147,147m}Tm with triaxial shape degree of freedom reveals that the triaxial shapes are not important in the former but quite crucial in the latter. We could explain the decays of ^{147,147m}Tm and their rotational spectra in a unified way without any ambiguity in the choice of parameters.

Reliability of Information in Nuclear Databases through Comprehensive Tests: The example of β Decays

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Evaluation of nuclear structure and decay data is the ultimate step for broadly disseminating the results of fundamental research conducted over many years. These recommended data and their associated uncertainties are entered into databases such as ENSDF (Evaluated Nuclear Structure Data File) and are the cornerstones for current and future research. In order to build the decay scheme of a radionuclide, a critical review of every related publication is necessary. However, experimental information is always missing and theoretical models are mandatory for filling in the blanks. Beyond the huge effort to ensure the comprehensive nature of the databases, only limited testing is performed on a systematic basis. Such testing is essential in understanding the quality of the evaluated nuclear data stored therein.

Regarding β decays, the LogFT program written in the 1970s has been used by evaluators ever since in order to calculate mean energies of β spectra, log *ft* values and intensities of electron capture transitions. Due to the limited computing power at that time, this code was implemented with very simple analytical models and tabulated parameters to ensure fast calculations. Aiming for better recommended data, the BetaShape program has been developed for the calculation of β spectra with the ultimate intention of broadly disseminating it, beyond the data evaluation community. Ensuring fast computation is still mandatory nowadays when calculating thousands of transitions. An almost analytical model has thus been developed based on Behrens and Bühring formalism [1]. Allowed and forbidden unique transitions are calculated specifically and no limitation exists on the transition order, while forbidden non-unique transitions are determined using the ξ approximation. The Fermi function and the λ_k parameters involved in the definition of the theoretical shape factor are determined from the Coulomb amplitudes of the relativistic electron wave functions. These wave functions are calculated for the Coulomb potential of a uniformly charged sphere, which means that the finite nuclear size effect is intrinsically taken into account. Dirac equations are solved numerically as no analytical solution exists even for such a simple potential. Radiative corrections that account for virtual photon exchange and internal bremsstrahlung were also implemented. The usual but very approximate screening correction from Rose was kept as an option but a new one adapted from Bühring [2], exhibiting no breakdown at low energy and being theoretically more refined, was also implemented. A database of measured shape factors has been included and experimental information is always preferred if present. The correlated ν spectrum is also calculated. Most of the formalism has been described in a recent publication [3], except the Bühring screening correction, together with a systematic comparison of these calculations with experimental shape factors gathered in the database.

The BetaShape program can be used with a bespoke interface which extracts the data from ENSDF files to determine the parameters required for the calculation of each transition. All the transitions within the ENSDF database have been calculated using both LogFT and BetaShape. A comparison of the results highlights the strengths and weaknesses of the current nuclear data, stressing the need for an effort from all walks to improve the reliability of the nuclear structure databases. This statement is particularly true for nuclei sparsely studied by experimentalists where reliable theoretical predictions with firmly established uncertainties would be essential to improving the quality of the nuclear data.

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Collectivity in Neutron Rich Nuclei above ^{132}Sn Core

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New era for theoretical and experimental nuclear structure is dawning due on the one side to the number of successful approaches ranging from empirical fits of the interactions, to deriving them microscopically from the bare *NN* potential, and on the other side to the experiments progress by the availability of radioactive ion beams, which may provide a stringent test for the validation of various theoretical models.
Within the shell model, special attention has been focused to the neutron rich nuclei beyond ^{132}Sn, where many studies have been achieved by the calculations of the low-lying state energies and isomeric transitions of tin isotopes ^{134,136,138,140}Sn.
In the same context, making use of a realistic interaction derived from N3LO and including the model space above the closed core ^{132}Sn, the energy levels and the electromagnetic transition rates of chain of even-even nuclei with $52 \leq Z \leq 60$ will be presented and compared to the experimental data. I will mainly focus to the appearance of a deformation and the evolution of the collectivity in the chain of isotones N=86, where several signatures support the presence of triaxial γ-band in this mass region.
These applications constitute a stringent test of our effective interaction, and our predictions can be provided as benchmark for future experimental measurements.

On Shape Isomers in Hg to Po Region of Nuclei

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New super and hyper-deformed shapes isomers in even-even Hg to Th isotopes are foreseen [1-5]. The calculation bases on the macroscopic-microscopic model where the macroscopic energy is evaluated using the Lublin-Strasbourg-Drop method and the microscopic, shell plus pairing corrections are calculated with the Yukawa-folded single particle potential. The quadrupole moments and the energies of the lowest rotational state 2^+ in all local minima of the potential energy surfaces are evaluated. They are in good agreement with experimental data in the ground states [3,5,6]. The obtained potential energy surfaces explain the main features of the fragment partition as measured in low-energy fission along the isotope chains which lie in a transitional region of the nuclear chart, and shall be essential to consistently understand the evolution of fission properties from neutron-deficient Mercury to heavy actinides. The ability of our method to predict fission observables over such an extended region looks promising.

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Laser Spectroscopy as a Tool to Study Shapes and Symmetries

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Collinear laser spectroscopy is a very powerful tool to study the spin, electromagnetic moments and charge radii of exotic isotopes in a model-independent way. At ISOLDE-CERN two collinear laser beam lines are currently operational, one dedicated to the optical detection of hyperfine structures from resonantly excited atoms or ions (COLLAPS) [1,2] and one dedicated to Collinear Resonance Ionization Spectroscopy (CRIS) with ion detection [3,4,5]. In this presentation I will explain the complementarities of both techniques and address some recent scientific highlights, with a focus on the study of shape changes (with possible examples on Mn, Cu, Zn, Cd and Fr isotopes).

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Nuclear Shapes and Excitations in the Microscopically-Guided Algebraic Theory

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The advent of new radioactive-ion-beam facilities worldwide has allowed access to new nuclear shapes and excitations in thus far unexplored nuclei, and a microscopic interpretation of these phenomena is a challenging task. Among the contemporary nuclear structure theories, the nuclear density functional theory (DFT) provides a global and reliable description of nuclear matter and bulk properties. The calculation of spectroscopic properties within the DFT requires one to go beyond the mean-field level to restore broken symmetries by projecting a mean-field solution onto state with good symmetry quantum numbers and to include quantum fluctuations for collective coordinates. Such a calculation presents a major computational challenge for heavy-mass system especially when several deformations, e.g., axial asymmetry, reflection asymmetry, etc., have to be considered, and often requires an alternative approach that drastically reduces the computational cost while keeping essence of low-energy nuclear structure.

I will present a recently developed method [1,2,3] allowing an accurate and computationally feasible description of spectroscopic properties of nuclei, that is constructed by merging the microscopic framework provided by the DFT with the algebraic model of interacting bosons. This is based on mapping the potential energy surface in the relevant deformation space, calculated within the constrained self-consistent mean-field methods within the DFT, onto the corresponding interacting boson model (IBM) Hamiltonian. The method exploits the merits of both DFT and IBM – the DFT provides the IBM with the microscopic input, while the IBM acts as an effective theory able to calculate spectroscopic properties of a wealth of medium-mass and heavy nuclei immediately comparable to experiment. In this talk, I will highlight the recent calculations using the proposed DFT-based IBM approach - the octupole deformation in radioactive nuclei around actinide region [4], shape transition and coexistence in neutron-rich A~100 nuclei [5], and the implementation of the method into the calculation of odd-mass nuclei [6].

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Model Stability from Shell Far

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In this presentation, we will expose some of the last developments in microscopic nuclear structure calculations for exotic nuclei far from stabilitity. In a first part, we will expose recent study on the development of collectivity in neutron-rich nuclei around N=40, where recent experimental evidence suggest a rapid change from the spherical to rotational regime, in analogy to the island of inversion known at N=20 [1] and extension of the island of collectivity towards N=50 [2]. Our recent algebraic Nilsson SU3 self-consistent model will be used to describe the intruder relative evolution in the vicinity of ^{78}Ni [3].

Then new theoretical calculations for the very region of ^{78}Ni will be presented for the first time within the interacting shell model framework using an enlarged model space outside a ^{60}Ca core comprising *pf* shell for the protons and *sdg* orbits for neutrons. Besides, the surprising spectrum of ^{78}Ni, we predict development of deformation below ^{78}Ni for iron and chromium isotopes, leading to the idea of merging islands of collectivity from N=40 to N=50, as already observed from N=20 to N=28 [3]. Finally, discussion of the underlying mechanism in terms of Spin-Tensor components will be exposed and compared to other neutron-rich regions of the nuclear chart.

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Shell Evolution, Shape Transition and Shape Coexistence with Realistic Nuclear Forces

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We will overview recent developments (i) on the structure of neutron-rich exotic nuclei based on modern nuclear forces and (ii) on the shape transition/coexistence driven by the shell evolution. The type I shell evolution, which is the change of shell structure within a chain of isotopes, will be discussed in terms of the effective interaction derived from the N3LO chiral-EFT two-body and appropriate three-body forces. The newly developed EKK method enables us to derive an effective interaction for two major shells, *e.g.*, sd+pf. Z=10-14 (Ne-Si) isotopes around the island of inversion will be described focusing on intruder mixture in transitional nuclei. Another example is Ca-Ni isotopes with the pf-sdg shells, clarifying magicity at ^{52,54}Ca and ^{68,78}Ni as well as strong deformation in ^{62,64}Cr.

The shape transition and shape coexistence will be discussed by using the state-of-the-art large-scale Monte-Carlo shell-model, describing spherical and extremely deformed states on the same footing. The shape coexistence in exotic Ni and its neighbours will be explained in terms of type II shell evolution where the shell structure is reorganized due to multiple particle-hole excitations for particular orbits, resulting in strongly deformed states at very low energy. This idea is extended to $^{90\text{-}110}$Zr, reproducing the sudden drop of the 2^+ level at ^{100}Zr, as an evidence of the first-order quantum phase transition. Here, type II shell evolution is driven cooperatively by the monopole components of tensor and central forces. They weaken the resistance against deformation. This mechanism, which may be interpreted in terms of Dual Quantum Liquid, can be relevant for superdeformation and fission.

Shapes and Collectivity in Neutron-Deficient Pb Nuclei

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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 g-ray spectrometer [4]. This talk will give an insight into shape coexistence studies of neutron-deficient Pb nuclei carried out JYFL and ISOLDE. The advantages of different techniques will be discussed.

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Rotational Features of Triaxial Nuclei

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Study of band structures of nuclei from symmetry consideration plays an important role in understanding different phenomena in nuclear structure. In selected regions of nuclear landscape, axial symmetry is broken and these nuclei are described using the triaxial deformed mean-field. The novel characteristic rotational features of triaxial nuclei are chirality and wobbling. Selected results on these excitation modes will be presented from gamma-spectroscopy studies of nuclei in $A \sim 110$ and 130 regions carried out using the Indian National Gamma Array (INGA) consisting of 24 Compton suppressed clover detectors coupled to a digital data acquisition system.

Microscopic Neutron Emission and Fission Rates in Compound Nuclei

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For productions of superheavy nuclei, one of the key issues is the survival probabilities of compound at high excitation energies. However, conventional studies are based on statistical models with many parameters. We studied the thermal excited nuclear properties, neutron emission rates [1], and fission rates [2] based on the finite temperature Hartree-Fock-Bogoliubov theory, in which quantum effects self-consistently fade away.

Within the deformed coordinate spaces, the thermal neutron gas can be obtained self-consistently, which produces the thermal equilibrium pressure. The neutron emission rates can be calculated with the neutron gas density. With the temperature dependent fission barriers and mass parameters, the thermal fission rates can be calculated from low to high temperatures in a consistent picture, based on the imaginary free energy approach.

These studies are based on microscopic density functional theory and are free of level-density parameters, in contrast to the conventional statistical models. The microscopic descriptions of thermal decays will be very useful for studying various fissions in reactors and r-process, and the survival of compound superheavy nuclei.

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When Odd Nuclei Break Symmetry of the Mean Field

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The description of odd nuclei within the mean field framework implies to break symmetries that are conserved for even nuclei. I will define symmetries of HFB calculations and specify those which need to be broken in order to describe the nuclear deformation (in HFB calculations with constraints), the nuclear vibration (in QRPA approach) and the nuclear rotation (in cranked HFB calculation).

Whatever the shape of the ground state, the QRPA approach is able to describe excited states, for any multi-polarity and parity, excepted those of the rotational bands. Nevertheless, to calculate Gamma strength functions for odd nuclei, all K projections of the total angular momentum, including negative ones, have to be considered: the time reversal symmetry is for odd nuclei but it is conserved in underlying HFB equations. Rotational degree of freedom can be investigated within HFB formalism including constraint on angular momentum. As an example the description of rotational band of ^{251}Md will be presented. This latter calculation in an odd-even nucleus implies not only to break Time reversal symmetry but also the "Signature" one.

Exact projections for symmetry restauration applied to QRPA and cranking HFB will be mentioned in perspectives.

Shape Coexistence, Isospin Symmetry, and Stellar Weak Processes within Beyond-Mean-Field Approach

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Shape coexistence and mixing, competing like-nucleon and neutron-proton pairing correlations, and isospsin-symmetry-breaking interactions generate exotic structure and dynamics around N=Z line in A~70 region. Beyond-mean-field approaches are needed to describe realistically the experimentally accesible properties of these proton-rich nuclei and to predict properties of isotopes that play a role in astrophysical environment. In particular, beta-decay properties of low-lying excited states of nuclei situated on the rp-process path are expected to influence their effective half-lives at the temperatures of X-ray bursts. Recently obtained self-consistent results on isospin-related phenomena in A~70 nuclei within complex Excited Vampir beyond-mean-field model using an effective interaction derived starting from Bonn CD potential will be discussed [1]. Weak interaction rates under terrestrial and stellar conditions have been investigated within the same approach [2,3]. The influence of shape coexistence and mixing in the structure of the parent states as well as in the independently calculated daughter states on terrestrial and stellar weak interaction rates will be presented.

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Multi-Particle Multi-Hole Configuration Mixing Approach with the Gogny Force

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In my presentation, I will present and review the state of the art of the Multiparticle-Multihole configuration mixing approach. I will present recent applications in structure and reactions, using the Gogny force [1-4]. Then, I will discuss some perspectives and extensions.

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Fourier Description of Exotic Shapes of Deformed and Fissioning Nuclei

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Proper and low dimensional description of shapes of deformed nuclei is one of the most difficult task with which nuclear physicists have fought since the first paper of Bohr and Wheeler on nuclear fission theory [1]. It is rather well known that classical expansion of liquid drop surface in spherical harmonics serious, proposed by Lord Rayleigh in 19th century, is not rapidly convergent when a nucleus is very elongated. It was shown in Ref. [2] that one needs at least 14 first terms of the expansion in order to obtain an accurate profile of the liquid-drop fission barrier from the ground state, through the saddle up to the scission point.
A reasonably good description of the fission barrier was obtained using the Funny-Hills (FH) parametrisation developed by Brack at al. in Ref. [3] and its extended version called the Modified Funny-Hill (MFH) nuclear shape description [2]. Unfortunately it is very difficult to estimate an inaccuracy of the energy of a very deformed nucleus due to limited class of shapes produced by these both above shape parametrizations. One can do it using an extended version of the FH parametrisation proposed by Trentalange, Koonin and Sierk (TKS) [4], where one expands the square of the distance from the symmetry axis 'z' to a point on the nuclear sharp surface in serious of the Legendre polynomials. The TKS expansion is well convergent but rather difficult to handle because of strong limitations onto available deformation parameter space [2]. An alternative description of nuclear shapes by expansion of the square of the distance from the symmetry axis to the surface in a Fourier series was proposed Ref. [5]. This new method is also rapidly convergent and easy to handle. We are going to show that it gives a new alternative way of of description of exotic shapes of deformed atomic nuclei.

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Shape Coexistence and Band Terminations in the I~60 Spin Range

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High-spin bands in nuclei with A»130-170 are interpreted using the cranking formalism where pairing is either neglected (CNS [1,2]) or included in the cranked Nilsson-Strutinsky-Bogoliubov (CNSB) formalism [3]. The advantage of the unpaired formalism is that different rotational bands can be understood in a much more detailed way. The combination of these two methods [4] is a very powerful way to get a detailed understanding of observed high-spin states. In this talk, we will point out the difficulty to distinguish between strongly deformed configurations and configurations approaching termination. It is of special interest that terminating states with up to 18 particles or particles+holes outside closed shells have been observed and more of them should be reasonably straightforward to observe. The possibility to exhaust the spin content in major shells will be discussed.

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Lifetime Measurement in the Even-Even Neutron-Rich Molybdenum Isotopes with the PresPEC-AGATA Setup

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The energies of the excited states of the mid shell nuclei with mass 100 < A < 110 indicate collective behaviours. In particular, the neutron rich molybdenum and zirconium isotopes show a rapid shape transition. In addition, shape-coexistence behaviours and triaxiality are expected in this region. In order to have a better understanding of the collectivity in this region, lifetimes of excited states in even-even molybdenum isotopes were measured by an in-flight-gamma-ray spectroscopy experiment using the PreSPEC-AGATA setup. The coupling of AGATA with LYCCA detectors provided with a high resolution the ion positions at the target level and the emission angles of the gamma rays, which allow the use of a Doppler Shift Attenuation Method for the lifetime determination. After a detailed analysis, several transitions associated with the decay of the ground state band in even-even molybdenum isotopes from A=100 to A=108 have been observed and there lifetime were measured. A good agreement was obtained between our results and the adopted values. A comparison of the results with beyond mean-field calculations indicates a triaxial behaviour in the neutron rich molybdenum isotopes. The key elements of the data analysis that allowed to estimate the lifetime of even-even molybdenum isotopes together with the results will be presented in this talk.

Towards Lifetime and g-Factor Measurements of Short-Lived States in the Vicinity of ^{208}Pb

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CSNSM, IN2P3-CNRS and Université Paris-Sud, Orsay, France

The present poster reports on the present status of the analysis of the E672 experiment that was performed in July 2015 at GANIL. The aim of the experiment was to measure lifetimes of excited states in the ^{208}Pb region, focusing mainly on the lifetime of the 2^+ states of $^{204\text{-}206}$Hg. The nuclei of interest were populated with multi-nucleon transfer reactions. The beam-like recoils were identified with the VAMOS spectrometer while the gamma rays were detected in AGATA. A Plunger device was used for the lifetime determination based on the RDDS technique.

Due to complications during the experiment, we can rely only on the mass of the fragments detected by VAMOS in order to identify the reaction products. The challenge of the analysis is to reach a mass resolution for mass A~200 that is sufficient to clearly identify the fragments reaching the focal plane of VAMOS. The progress on the analysis that focuses on the identification of the reaction products will be highlighted in the poster.

Although at the present stage of the analysis it is not clear yet which part of the statistics we will be able to use to reconstruct the mass of the beam-like product, the near-line results showed promising possibility for the lifetime determination of the $19/2^-$ state of ^{207}Pb, located above the $13/2^+$ isomeric state. This preliminary result will also be presented in the poster.

Exactly Solvable Models of Extending Interacting Boson Model

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The interacting boson model (IBM) is extended by including the g-boson degree of freedom. By recent measurements of E2 and E4 transitions in some nuclei which cannot be explained in the sd boson models, this extension become necessary. Transitional sdg interacting boson model Hamiltonian is estimated for spherical to gamma-unstable nuclei shape- phase transition in even-even nuclei by employing the affine SU(1, 1) Lie algebra. This algebraic method offer simpler and also easier way in compare to other numerical methods for complicated sdg Hamiltonian. Energy spectra, B(E2) and B(E4) are determined via the Bethe-Ansatz method. Using the accessible empirical data for the chain of Ru Isotopes, a satisfactory description of B(E2) and B(E4) properties is obtained, which also predicts dynamic shape transitions in these nuclei. An acceptable degree of agreement was achieved.

Low-lying Nuclear Shape Evolution from the Dysprosium Valence Maximum to Gamma-Soft Neutron-Rich Osmium Isotopes

Patrick Regan
University of Surrey and NPL, Guildford, United Kingdom

This talk will present a range of experimental results studying the evolution of deformed nuclear shapes ranging from the valence maximum system, ^{170}Dy (Z=66, N=104) to heavy, neutron-rich osmium (Z=76) isotopes which have been carried out over the last five years. These rather exotic, neutron-rich nuclear systems have been investigated using (a) delayed gamma-ray spectroscopy following high-energy projectile-fission and fragmentation using the Cluster germanium gamma-ray arrays RISING at GSI and EURICA at RIKEN and (b) coincidence fast-timing measurements of relevant B(E2: $2^+ \rightarrow 0^+$) decay rates using hybrid HPGe-$LaBr_3$(Ce) gamma-ray arrays at IFINHH, Romania. The wide range of experimental results are compared with competing theoretical predictions of nuclear shape using both mean-field calculations and extended IBM-style spectroscopic predictions which result.

MINIBALL - Status and Perspectives of the Nuclear Structure Experiments at ISOLDE

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The MINIBALL spectrometer utilizes successfully the huge variety of post-accelerated radioactive ion beams provided by REX-ISOLDE and since last year by HIE-ISOLDE at CERN. In-beam gamma-ray spectroscopy after Coulomb excitation or transfer reactions is performed with optimized setups of ancillary detectors for particle detection. The physics program is covering a wide range of shell model investigations from the light sd-shell nuclei up to the Ra region. Especially the enlarged availability of exotic heavy ion beams enables unique studies of collective properties up to the actinide region. First data taking with HIE-ISOLDE beams started very recently. The higher energies and intensities of the new post-accelerator provides a promising perspective for a new generation of MINIBALL experiments. An overview of the MINIBALL program with specific highlights from the REX-ISOLDE period will be given. Results from the first HIE-ISOLDE experiments, which will focus on Coulomb excitation measurements, will be presented.

The Evolution of Shapes and Collectivity with Increasing Angular Momentum

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The light rare-earth nuclei near N = 90, are textbook examples of the evolution of nuclear structure with excitation energy and angular momentum. They display a variety of different phenomena, such as, multiple backbends, dramatic shape changes and band termination. However, it has taken several decades before we were able to observe structures beyond band termination. A spectacular return to collectivity has been found to take place extending discrete gamma-ray spectroscopy into the so-called ``ultrahigh-spin regime`` (I = 50-70). These latter sequences, observed initially in ^{157,158}Er, are interpreted as being associated with a particularly stable and energetically favored strongly deformed triaxial shape minimum. These data have generated a good deal of theoretical discussion. New results on similar evolutionary trends in other neighboring nuclei will be discussed. The latter are beginning to reveal a fascinating spectroscopy in this new exotic shape and spin regime.

First Coulomb Excitation Measurement with SPIDER and GALILEO at LNL

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The nuclear shape is one of the most significant probe to study the structure of atomic nuclei. The deformation of a nucleus is due to an interplay of microscopic and macroscopic mechanism, as shell effects and collective excitations (vibration and rotation). The measurement of E2 transition strengths and quadrupole moments represents an important benchmark for testing models developed to understand the complicate quantum many-body nuclear problem. The development of new facilities for the acceleration of radioactive beams represents a vast and very active field of research in physics, since it offers the possibility to extend our investigation of nuclear structure to exotic nuclei far from the stability valley. In a near future the SPES facility will provide the first exotic beams at the National Laboratories in Legnaro. At the same time the AGATA array will be likely installed at LNL. 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. To this aim the gamma spectroscopy group in Florence has developed and assembled a new particle detector to be used at LNL, both for stable and radioactive beams. It consists of up to 8 sector shaped silicon detectors (aperture angle about 45 degrees) arranged in a pie shape. Each sector is segmented into eight independent annular strips on the front surface. This Silicon PIe DEtectoR (SPIDER) will provide a clean trigger to an array of germanium detectors (like GALILEO or AGATA) allowing the development of the Coulomb excitation technique at LNL.

The first commissioning experiment at LNL with SPIDER coupled with the GALILEO gamma ray spectrometer will be soon performed and hopefully will be followed by a Coulomb excitation experimental campaign with the stable beams at present available at the laboratories. In this talk details about the detector and the preliminary results of the commissioning experiment with GALILEO and a stable ^{66}Zn beam will be shown.

Experimental Study of the Excited Bands in ^{160}Yb: Theoretical Context of Exotic Shape-Coexistence

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Study of tetrahedral nuclear deformation has been a matter of extreme interest in nuclear structure research for the recent years. There is no experimental evidence, so far, supporting the existence of tetrahedrally deformed nuclei throughout the nuclear landscape. The N=90 nuclei around Gd and Yb, having both proton and neutron no. close to the tetrahedral 'magic' numbers (Z=64/70 and N=90) are considered to be the most suitable candidates [1-5] for the said experimental research as they are easy to populate with reasonable cross section using stable beams. Set of negative parity bands decaying to the quadrupole deformed yrast band by the emission of E3/E1 transitions forms the possible experimental signature of such structure. The absolute transitions probabilities or their ratios, measured by using high efficiency arrays, may disclose the underlying signature for the associated structure of these negative parity bands.

In the present work, the spectroscopy of ^{160}Yb has been revisited in order to study the low and moderate spin structure of the nucleus by using conventional gamma ray spectroscopic technique with Indian National Gamma Array (INGA) comprised of twenty Compton suppressed Clover detectors. The nucleus has been populated by using the fusion evaporation reaction ^{148}Sm(^{16}O,4n)^{160}Yb at E_{beam}= 90 MeV from the 14UD Pelletron beam at Tata Institute of Fundamental Research (TIFR), Mumbai, India. Level structure has been developed from the γ-γ and γ-γ-γ coincidences, the relative intensity, DCO, R(j) and IPDCO measurements. The level structure obtained in the present work, differs considerably from the existing literature [6,7]. The increased efficiency and selectivity of the INGA array has been a key factor in establishing a modified level scheme compared to the recent work on 160Yb [8]. The rotational parameters for the negative parity bands and the B(E2)/B(E1) ratios have revealed important information regarding the signature of the different λ = 3 deformation and their co-existence in these non-yrast sequences of the N = 90 Yb nucleus. The details on the experiment, data analysis and the interpretation of the structure of the negative parity level sequences of ^{160}Yb nucleus will be discussed.

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Search for the Possibility of Existence of Isomeric State in ^{150}Pm

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Nuclear isomers are excited metastable states of nuclei, which experience a hindrance in their decays which have been the focus of attention since early days, and were first foreseen by Soddy in 1917 [1]. Several isomeric states have been predicted and observed in nuclei with N≥89 and 61≤Z≤77 [2,3]. In almost half of the known cases, the excited isomers in odd-odd nuclei have a half life greater than the lower lying ground state, the decay of which is highly forbidden to the ground state. Isomers with $t_{1/2}$~sec to hrs cannot be detected in an in-beam spectroscopy for which the decay measurement is very crucial. Following the half-lives of γ-rays of daughter nucleus is one of the possible routes for the identification of such isomeric states. In the present work, the main objective is to search or the existence of a long-lived isomeric state in ^{150}Pm by following the β delayed halflives for the γ-rays of its daughter ^{150}Sm and studying their coincidence relationships. ^{150}Pm was produced by the reaction ^{150}Nd(p, n)^{150}Pm [4] using 8.0 MeV proton beam from K=130 cyclotron at VECC, INDIA which then, following β-decay, produces the excited states of ^{150}Sm. It has been observed that the half lives measured for most of the observed γ-rays show value ~ 2.68 h corresponding to the ground state of ^{150}Pm whereas there are two other groups of γ rays that follow the half life ~ 3.8 h & ~ 2 h respectively. The γ-γ coincidences studied for all of the transitions showing the half lives of ~2 h and ~3.8 h confirms their presence in the level scheme of ^{150}Sm indicating the presence of isomeric states for the first time in the N = 89 Pm nucleus.

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Recent Highlights and Future Projects at RIBF

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In this talk, I would like to give an overview of resent results and future projects for the nuclear structure study at RIBF.
Special emphasis would be given to selected recent highlights obtained via in-beam gamma spectroscopy and decay-spectroscopy with DALI2 and EURICA, respectively, in terms of shell evolution in exotic nuclei. Concerning the future projects, next detector systems and programs with energy-degraded radioactive isotope beams have been discussed at RIBF. In addition, a facility upgrade plan of RIBF would be introduced.

Isospin Symmetry and its Breaking in Atomic Nuclei

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The concept of isospin symmetry was already introduced in the thirties by Heisenberg and Wigner to account for the charge (proton-neutron) symmetry of nuclear forces. Since then, it has been commonly used in theoretical modeling of atomic nuclei in spite of its explicit breaking by the Coulomb interaction and, to a lesser extent, the charge-dependent components of the strong force. The aim of this presentation is to overview selected aspects of isospin physics in $N \sim Z$ nuclei in terms of recently developed multi-reference density functional theory (MR-DFT) involving isospin and angular momentum projections and subsequent configuration interaction (CI) calculations [1].
This no-core formalism allows for quantum-mechanically rigorous calculation of isospin impurities to the nuclear wave functions resulting from rather subtle interplay between the long-range Coulomb force polarizing the entire nucleus and the short-range strong force. The impurities are prerequisites for further calculation of the isospin-symmetry-breaking corrections to the superallowed $0^+ \rightarrow 0^+$ Fermi beta decays which are used for testing the electroweak sector of the Standard Model of elementary particles.
I will also present the first ever application of the MR-DFT rooted no-core CI approach to study Gamow-Teller transitions [2]. This fundamental process, more specifically the physical mechanism behind quenching (or renormalization), q, of the axial coupling constant $g_A^{(\mathrm{eff})} = qg_A$ with respect to its free neutron decay value $g_A \approx -1.2701(25)$, constitutes, in my opinion, one of the biggest puzzles of the contemporary nuclear structure theory. I will demonstrate that our model accounts well for the Gamow-Teller matrix elements in $N \sim Z$ nuclei including mirror transitions.
The strong interaction is predominantly charge independent but there exists firm experimental evidence from two-body scattering data that it also contains small charge-dependent components. At many-body level, the most prominent manifestation of the charge-dependent terms comes from mirror displacement energies (MDEs) which cannot be reproduced using the isospin-invariant strong force.
In the last part of my talk, I shall comment on a recent extension of a conventional single-reference Skyrme DFT that includes the proton-neutron mixing in particle-hole channel and zero-range class II and class III forces breaking, respectively, charge independence (CIB) and charge symmetry (CSB). I shall demonstrate that these extensions allow to account not only for MDEs but also for much more subtle effect of the triplet displacement energies (TDEs) which is a measure of the binding-energy curvature within the isospin triplet [3]. I will also discuss a connection between our CSB and CIB forces and *ab initio* charge-dependent forces by comparing the coefficients of isobaric mass formula in light nuclei where *ab initio* results are available.

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Nuclear Structure Studies near Shell Closure Using Prompt-Delayed Coincidence Technique

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Recent years have seen tremendous progress in the field of nuclear structure studies. The advent of RIBs and advanced detectors have revolutionized the field by providing access to more and more neutron rich nuclei and enabling the study of rare events, respectively. At the same time, the advanced high-speed digital data acquisition systems (DDAQs) have changed the way of conventional methods of gamma-ray spectroscopy by providing high count rate handling capability and better gain stability. One of the advantages of using DDAQ is that the time stamped data can be sorted offline at one's own convenience using different coincidence time windows, thereby enabling spectroscopic studies across isomeric states over a wide range of half-life.

This work presents results from spectroscopy experiments performed using the Indian National Gamma Array \cite{palit,Tan09} at TIFR, where, the technique of prompt-delayed coincidence has been used to search for states above isomeric levels. With this technique spectroscopy across isomeric states with lifetime ranging from hundreds of nanosecond to few microsecond have been made possible. The technique has been successfully used in ^{88}Zr \cite{saha} and ^{132}Te \cite{biswas}.

In addition to results from these nuclei, a detailed overview of spectroscopic study in 66cu will be presented, where this technique has been used recently to search for levels above the known 6^{-} ($T_{1/2}$ = 600 ns) isomer \cite{singh}.

Chiral Basis for Particle-Rotor Model for Odd-Odd Triaxial Nuclei

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In the last decade nuclear chirality resulting from an orthogonal coupling of angular momentum vectors in triaxial nuclei has been a subject of numerous experimental and theoretical studies. Three perpendicular angular momenta can form two systems of the opposite handedness, the right-handed and the left-handed system; the time-reversal operator, which reverses orientation of each of the components, relates these two systems. In the simplest case of odd-odd nuclei, two mutually orthogonal angular momenta are provided by the high-spin valence proton and neutron which are of particle and hole character. The third angular momentum component is provided by the collective core rotation and aligns along the axis of the largest moment of inertia; this is the intermediate axis for irrotational flow-like moments of inertia for a triaxial body. This simple picture leads to prediction of distinct observables manifesting chirality in rotational structures, most notably to the doubling of states.

It needs to be noted, though, that one of the common feature of current model calculations is that the chiral geometry of angular momentum coupling is extracted from expectation values of orientation operators, rather than being a starting point in construction of a model. In that sense, chirality has been perceived as an approximate symmetry attained only in a limited range of angular momentum. However, using the particle-hole-coupling model for triaxial odd-odd nuclei it is possible to construct a basis which contains right-handed, left-handed and planar states of angular momentum coupling. If this basis is used, the chirality is explicit rather than extracted feature as in any other models with non-chiral basis. The time-reversal symmetry which relates the basis states of opposite handedness can be used to reduce the dimension of matrices for diagonalization of the model Hamiltonian, proving usefulness of this approach. Moreover, the final model eigenstate wave functions show a concentration of amplitudes among relatively small number ~1 of components as comparing to the full model space. In that sense, the ``chiral'' basis provides a useful tool to examine model predictions providing direct insight into the structure of doublet states. The model, the basis, numerical results, and comparison to the data will be presented and discussed.

Detail Studies of Holstein-Primakoff Boson Representation Applied to the Particle-Rotor Model

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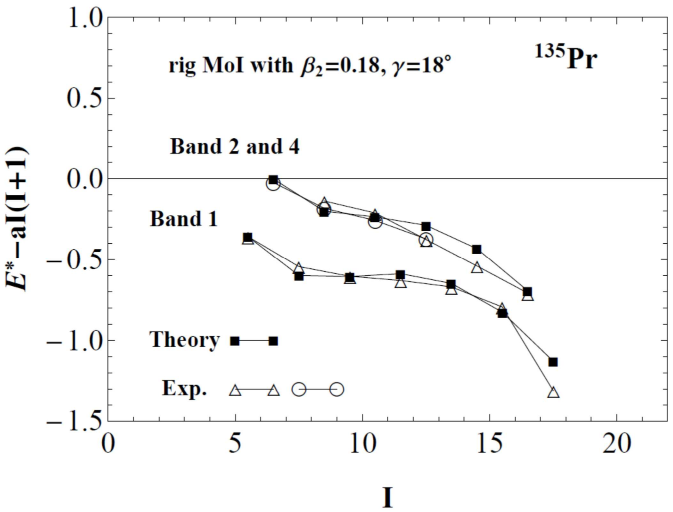
An extensive application of Holstein-Primakoff boson expansion to both single-particle angular momentum $\vec{j}$ with positive commutation relations and total angular momentum $\vec{I}$ with negative commutation relations provides an algebraic solution, which gives a good approximation to the exact results for the particle-rotor model with one high-j nucleon coupled to a triaxially deformed core [1]. Two kinds of quantum numbers (n_α, n_β) classify the rotational bands characteristic of the particle-rotor model, where n_α is related with the wobbling motion of the rotor, and the other n_β to the precession motion of $\vec{j}$. The stability condition deduced from this procedure shows there is no transverse wobbling in the particle-rotor model even with the hydrodynamical (hyd) moments of inertia (MoI) indicating no stable rotation around the middle MoI.
Recently, the wobbling modes are found in the yrast band near the ground state before the first backbending in ^{135}Pr [2,3]. Because the pairing effect is essential for these bands which are before the gapless superconductor, we apply the rigid-body (rig) MoI which can include the Coriolis antipairing effect with 2 parameters [4]. The results are compared with the experimental data of Band 1, Band 2 and 4 [3] in the figure. The agreement with the experimental data is not only in the energy level scheme, but also in $B(E2)_{\text{out}}/B(E2)_{\text{in}}$, $B(M1)_{\text{out}}/B(E2)_{\text{in}}$ and the mixing ratio of δ.



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Pushing High-Spin Calculation to the Extreme: Application of the Pfaffian Algorithm in Angular Momentum Projection

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Performing shell model calculations for heavy, deformed nuclei has been a challenging problem in nuclear physics. The projected shell model (PSM) idea [1] makes it possible to bridge two traditional nuclear physics methods: the deformed mean-field and the traditional shell model. By using the angular-momentum-projection technique, in which one starts with (in principle, any) deformed single-particle states to construct a shell model basis, one can demonstrate the simplicity and efficiency of this method for the description of heavy, deformed nuclei.

The original version of the PSM [1] assumes restricted types of quasi-particle configurations in its model space, which severely limits the application for high-spin states and/or high-excitations. The problem lies in the fact that in applying the generalized Wick's theorem to calculate rotational matrix elements, the number of the terms becomes so large that it is very difficult to write down expressions explicitly for more than 4-qp states. Recently, the Pfaffian formulae have been proposed [2] to calculate the rotated matrix element. The proposal was largely inspired by the initial introduction of Pfaffian by Robledo [3]. The configuration space of the PSM has been expanded to include up to 10-qp states for both positive and negative parities [4,5]. This development enables us to study some interesting high-spin phenomena. As the first applications of the Pfaffian algorithm in spectroscopy calculation, we take ^{166}Hf [4] as an example and show that 6-qp states become the main configuration in the yrast band beyond spin I~34, which explains the observed third back-bending in moment of inertia. Multi-qp high-K isomers in ^{176}Hf with different configurations are investigated as another example. We also discuss other potential applications for the structure calculation with the chaotic motion and in nuclear astrophysics when states are highly excited.

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Stability for the Wobbling Motion in the Triaxially Deformed Odd-A Nucleus

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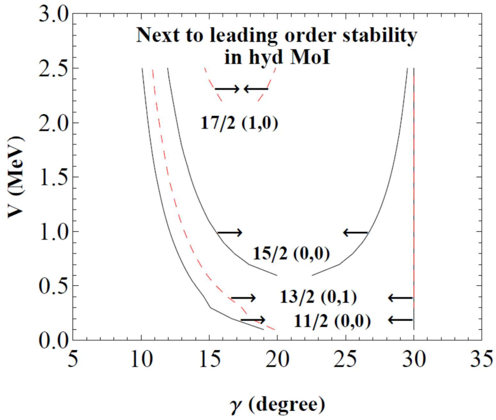
Recent discovery of a pair of negative parity wobbling bands in ^{135}Pr [1,2] has stimulated theoretical discussion on their physical nature. Transverse wobbling around the axis with the medium moment of inertia (MoI) [3] was proposed to describe these bands. The transverse wobbling mode never exists in the pure rotor, while there may be such a possibility for the particle-rotor model with hydrodynamical (hyd) MoI. By introducing two kinds of Holstein-Primakoff bosons for the total angular momentum $\vec{I}$ and the singleparticle angular momentum $\vec{j}$, we identify the nature of each band in terms of a set of two quantum numbers (n_α, n_β), i.e., the wobbling of $\vec{I}$ and the precession of $\vec{j}$, respectively [4].

In the figure, we show boundary lines of the stability region for each I together with (n_α, n_β). The level I =13/2 with (0,1) is characterized by the precession of $\vec{j}$, and the wobbling level I =17/2 with (1,0) is realized only in the circumstance, where $\vec{j}$ is pinned along the shortest nuclear axis by abnormally strong single-particle potential V. We cannot find any stable physical solution for common values of γ and V. There is no transverse wobbling in the odd mass nucleus with hyd MoI.

We adopt rigid-body (rig) MoI for ^{135}Pr, and got quite good fit to the experimental data. The formalism with rig MoI is free from the stability problem. Moreover, the rig MoI can take into account Coriolis antipairing effect described by Hartree-Fock-Bogoliubov theory [5].



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Isoscalar Pairing and Pairs in Nuclei

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The question whether isoscalar pairing between neutrons and protons gives rise to correlation effects similar to those observed for the isovector pairing between identical nucleons remains unanswered. Some schematic properties of "ideal" isoscalar-pair condensates are pointed out. Isoscalar-pairing correlations can be probed with deuteron transfer reactions, which are the subject of an experimental programme at GANIL. It is shown that simple predictions based on the assumption of a pair vibrational behaviour can assist in the interpretation of such experiments. A different but related question is whether the low-energy structure of N~Z nuclei can be interpreted in terms of spin-aligned isoscalar pairs. This hypothesis can be tested, for example by measuring magnetic and quadrupole moments of isomeric levels in odd-odd N=Z nuclei, such as for instance ^{94}Ag or ^{90}Rh, which is one of the aims of the S3 project in preparation at GANIL.

High-Spin Spectroscopy with AGATA after Multinucleon Transfer

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Multinucleon transfer reactions (MNT) are a competitive tool to populate exotic neutron-rich nuclei. Excited reaction products have been measured (i) in transfer products of ^{136}Xe+^{238}U and ^{136}Xe+^{208}Pb MNT reactions and (ii) as a fission product after the ^{136}Xe+^{238}U reaction employing the high-resolution Advanced Gamma Tracking Array (AGATA) coupled to the mass spectrometer PRISMA at LNL (INFN, Italy). Furthermore, the ^{136}Xe+^{198}Pt MNT reaction was studied with the γ-ray spectrometer GAMMASPHERE in combination with the gas detector array CHICO at LBNL. Mass yields of the ^{136}Xe+^{238}U reaction have been extracted and compared with calculations based on the GRAZING model for MNT reactions. Population yields for nuclei in the actinide region were obtained and compared to x-ray yields measured by AGATA. An extension of the ground-state rotational band in ^{240}U was achieved and evidence for an extended first negative-parity band in ^{240}U is found. The results were compared to recent mean-field and DFT calculations. Several high-spin states on top of long-lived isomers in the N~82 nuclei ^{134}Xe, ^{135}Xe, and ^{137}Ba were discovered and placed based on γγ-coincidence relationships and information on the γ-ray angular distributions as well as excitation energies from the total kinetic energy loss and fission fragments. Latest shell model calculations employing different effective interactions reproduce the experimental findings and support the new spin and parity assignments.

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Coexistence of Nuclear Shapes: Self-Consistent Mean-Field and Beyond

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A quantitative analysis of the evolution of nuclear shapes and shape phase transitions, including regions of short-lived nuclei that are becoming accessible in experiments at radioactive-beam facilities, necessitate accurate modeling of the underlying nucleonic dynamics. Important theoretical advances have recently been made in studies of complex shapes and the corresponding excitation spectra and electromagnetic decay patterns, especially in the 'beyond mean-field' framework based on nuclear density functionals. Interesting applications include studies of shape evolution and coexistence in N = 28 isotones, the structure of lowest $0^{(+)}$ excitations in deformed N approximate to 90 rare-earth nuclei, and quadrupole and octupole shape transitions in thorium isotopes.

High-K Isomers in Exotic Nuclei

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Recent experimental results from RIKEN using ^{238}U projectile fission [1,2] highlight to role played by high-K isomers in the exploration of the structure of neutron-rich deformed nuclei, including their influence on the r-process abundance peak at A≈160. However, the understanding of K isomer half-lives is rudimentary, and it remains a challenge to quantify the influence of the different K-mixing mechanisms [3,4]. In the present work, recent data that shed new light on K mixing are examined, and the implications for high-K isomers in super-heavy nuclei are discussed.

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Pre-Scission Shapes of Fissioning Nuclei

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One of the most important observables in fission is fragment mass distribution. It provides information about the structure of fissioning nucleus and fission barrier. Basically two types of fission can be observed: symmetric, where the most probable is fission into two identical fragments and asymmetric with mass of the heavier fragment A ∼ 140.

It has been shown that fragment mass asymmetry can be deduced from the shape of the fissioning nucleus before scission [1-4]. The structure of the fragments can be found in the mass distribution of a nucleus on fission path between saddle and scission. The spherical shape of the fragments that can be often seen in the molecular shape of a nucleus is manifestation of their magic structure far before separation.

Shapes of the fissioning nuclei in the pre-scission configuration will be discussed. Wide rage of isotope will be analysed, from cluster-radioactivity in the actinides [5], and neutron deficient nuclei from Hg region [2,6] to Fm isotopes [7].

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Multipole Modes of Deformed Superfluid Nuclei with the Finite Amplitude Method in Three-Dimensional Coordinate Space

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Our goal is to construct a microscopic collective model to treat large-amplitude shape fluctuation and mixing in nuclei, which appears in a mass region of around 100. For our goal, we plan to construct a five-dimensional quadrupole collective Hamiltonian as a function of deformation parameters β and γ from the so-called constrained Hartree-Fock-Bogoliubov (CHFB) for the collective potential plus local quasiparticle random phase approximation (LQRPA) for the inertia functions in the kinetic energy with self-consistent Skyrme energy density functionals. Therefore, we need to perform LQRPA calculations in three-dimensional coordinate space. However, due to the fact that QRPA calculations require large resources of computations QRPA in three-dimensional coordinate space is currently not available, and only recently, QRPA with axially symmetric nuclei has been able to be carried out.

Recently, the finite amplitude method (FAM) has been proposed in Ref.[1] and applied to wide range of nuclei by many groups [2,3,4]. Main advantages of FAM are that (1) functional derivatives of single-particle Hamiltonian and pairing field as the residual interactions are replaced with finite difference forms and (2) diagonalization of huge QRPA matrix is avoided using an iterative method. These advantages considerably reduce the computational cost for performing QRPA calculations. As a first step to construct microscopic collective Hamiltonian, we develop the code of FAM-QRPA in three-dimensional coordinate space. In this contribution, we will present recent progress of 3D FAM-QRPA and show results of multipole strength functions of representative nuclei. We will also show excitation modes of triaxial nuclei.

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Recent Results from EURICA at RIBF: Decay Spectroscopy of ^{172}Dy and ^{70}Co

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Gamma-ray spectroscopy following the β decay is an effective tool for probing low-lying yrast and nonyrast states, from which key information on nuclear structure, such as shape transitions/coexistence and single-particle orbits, can be obtained. For the study of rare isotopes, especially when the nucleus of interest lies at the boundaries of availability for spectroscopic studies, isomeric decays are likely to be a more useful means than β decays to populate excited levels. The combined β-γ and isomeric-decay measurements at RIBF, which has the capability of providing the world's strongest RI beams, are at the forefront of exploration of exotic nuclei far from stability. Research opportunities for decay spectroscopy at RIBF have been expanded in the EURICA (EUROBALL-RIKEN Cluster Array) project. The main body of EURICA consists of 12 Clustertype HPGe detectors, surrounding a highly segmented silicon stopper system named WAS3ABi. In addition to the normal EURICA setup, 18 $LaBr_3$(Ce) detectors and plastic scintillators are installed for the fast-timing measurement of γ and β rays, respectively. A wide range of unstable nuclei on the Segre chart are within the scope of the EURICA project. In this presentation, two recent topics from EURICA will be introduced. First, low-lying states of ^{172}Dy have been populated following the decay from a newly identified $K^{\pi} = 8^{-}$ isomer. While the robust nature of the K isomer and the ground-state rotational band reveals an axially-symmetric structure for this nucleus, the γ-vibrational levels have been identified at unusually low excitation energy compared to the neighboring well-deformed nuclei, indicating the significance of the microscopic effect on the non-axial collectivity in this doubly mid-shell region. Secondly, the level properties of ^{70}Co have been investigated by the β decay from ^{70}Fe and towards ^{70}Ni. The results are compared to the advanced Monte Carlo shell-model calculations, which predict strongly prolate-deformed shapes for the low-lying levels in ^{70}Co, including its ground state. It is revealed that the decay patterns in the neutron-rich A = 70 isobars from the new island of inversion to the Z = 28 closed-shell regime are governed significantly by the selectivity of nuclear shape.

Intruder Isomer and Shape Coexistence in ^{79}Zn

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Shape coexistence has been observed in different regions of the nuclear [1], and has been associated with 'intruder' particle-hole excitations across shell gaps occurring at low energy. Along the neutron-rich N = 50 shell gap, intruder states have been known for more than three decades in some N = 49 isotones [2,3]. Only recently the first evidence for shape coexistence in the region around ^{78}Ni has been provided nearly simultaneously by two experiments as well as theoretically [4-6]. In the ^{79}Zn isotope, the shape coexistence is seen in the measurement of the nuclear spins and moments of the ground and long-lived isomeric states, and more significantly, the substantial increase in charge radius of the intruder isomer, extracted from the isomer shift.

The experiment is performed at ISOLDE-CERN using the high-resolution collinear laser spectroscopy setup COLLAPS. The existence of a long-lived isomer is confirmed from the hyperfine structure measurement of ^{79}Zn, which also allowed the nuclear spins and moments of the ground and isomeric states to be determined. This confirmed the intruder configuration of the isomer, with a wave function dominated by a 2h-1p neutron excitation across the N = 50 shell gap. Furthermore, a large isomer shift is observed for ^{79m}Zn, resulting in a large root mean square charge radius with respect to its ground state, pointing to a larger deformation of the isomeric state. This result provides the evidence of shape coexistence in ^{79}Zn.

In this talk, a detailed discussion on the properties (half-life, energy, spin, magnetic moment, and isomer shift) of the isomer will be presented, along with a comparison with other N = 49 isotones and theoretical calculations.

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Nuclear Spins, Moments and Charge Radii of Neutron-Rich Zinc Isotopes and Isomers

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A variety of nuclear structure information has been revealed recently on the isotopes in the vicinity of ^{78}Ni both experimentally and theoretically [1,2]. However, whether or not ^{78}Ni can be considered to be a double magic nucleus still remains as a question and attracts much attention. In order to further understand the various properties of nuclei in this region, we have studied the neutron-rich Zn (Z = 30) isotopes, from N = 39 up to N = 50, via collinear laser spectroscopy at ISOLDE.
The experiment provides us with information on the ground- and isomeric state spins, magnetic and quadrupole moments, as well as the nuclear charge radii of Zn isotopes. The experimental magnetic moment can been well accounted for by large scale shell model calculations using jj44b/JUN45 effective interactions (^{56}Ni core and pfg shell) [4,5]. The calculated wave functions confirm the inversion of $p_{3/2}$, $f_{5/2}$ proton orbits, as observed in the Cu and Ga isotopic chain. However, in order to explain the measured quadrupole moments of more neutron-rich isotopes and the spin and magnetic moment of a newly discovered intruder isomer, the interactions [2,6] with an extended model space including orbits beyond N = 50 are necessary. The extracted charge radii of Zn isotopes across N = 40 and up to N = 50 gives us information on the subshell/shell closures.

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Proton and Heavier Charged Particles Emission Half-Lives within a Gamow-Like Model

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The proton emission from the ground state of mother nuclei with mass ranging 110 ≤ A ≤ 150 was measured in the early 1980s [1]. This decay mode is observed for the odd-Z emitters beyond the proton drip line. The associated half-lives range from nano to seconds. Another decay mode -cluster radioactivity - was theoretically predicted in 1980 [2] and discovered four years later [3]. This is a very rare process and corresponds to the emission of a nucleus heavier than ^{4}He, but lighter than a mass of a lighter fragment of a binary fission. The observed atomic masses of clusters are in the range 14 ≤ A ≤ 34, while the mass of a daughter nucleus is close ± 4 nucleons) to the doubly-magic ^{208}Pb isotope. One of the most important decay modes of heavy nuclei is α radioactivity. The first explanation of this process was given by Gamow in 1928 [4]. It was assumed that emission is due to the quantum mechanical tunneling of a charged α-particle through the nuclear Coulomb barrier. We made an attempt to reproduce the half-lives for the mentioned above, three types of decay within the same simple formalism, based on Gamow theory [5]. The simple formula for the half-lives is derived using the WKB theory for the penetration of the Coulomb barrier with a square well for the nuclear part. We show that using only one adjustable parameter - the radius constant - it is possible to reproduce with a good accuracy the half-lives for even-even α and cluster emitters. This simple phenomenological formalism is also extended by including the centrifugal term to describe proton emission. The adjustable parameter – the effective nuclear radius constant has the same value (1.21 fm) for all discussed decay modes. A good agreement with the experimental data is achieved.

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Fission Fragment Mass Distribution Within Microscopic Approach

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Fragment mass distribution is one of the major, measurable characteristics of fission. The shape of the observed yield allows to determine type of fission and - indirectly – to investigate structure of the mother nucleus. It has been proven, that basic properties of nascent fragments are preliminary determined by the configuration of pre-scission point [1]. We assume, that the shape of a nucleus obtained in its pre-scission point provides information about the possible fragment mass asymmetry.

Spontaneous fission is successfully described by the self-consistent microscopic models of the nuclear forces [2,3]. In this work, the potential energy surface is calculated using Hartree-Fock-Bogolubov model with density dependent functional of the Gogny type. The preferred fission paths are found by the minimization of energy integral on the surface and the pre-scission point is determined by Dubray's method [4]. Fragment mass distributions were obtained in macroscopic method proposed by Brosa [5,6]. This simple procedure allows to deduce the fission fragment mass yield from the pre-scission nuclear density distribution. The probability, that fissioning system achieves certain point along the pre-scission line, might be determined in dynamic calculations [7]. Method proposed by Brosa should then be treated as an additional effect, since each obtained in that way configuration corresponds to the specific mass yield. We discuss fragment mass distributions of ^{252}Cf isotope [8].

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