10TH International workshop on quantum phase transitions in nuclei and many-body systems

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Book of Abstracts

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Shape transitions triggered by the extremes of charge, isospin and angular momentum

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The detailed investigation of new physical mechanisms which allows to extend the boundaries of particle-bound nuclear landscape beyond the traditional limits and lead to exotic nuclear shapes has been performed over recent years [1-5]. The increased role of the Coulomb interaction in the hyperheavy ($Z \geq 126$) nuclei leads to the situation when toroidal shapes become more energetically favored than ellipsoidal ones: this provides a substantial increase of nuclear landscape [2,3]. Toroidal nuclei are stable with respect to breathing deformation, but their stability with respect of sausage deformations is established so far only in the $Z \sim 134, N \sim 210$ region for fat toroidal nuclei [1,2]. However, the analysis of toroidal shell structure indicates their potential stability for other combinations of protons and neutrons both for thin and fat toroidal nuclei [3]. In the cases when toroidal shapes become unstable, the ground states are represented by spherical shapes characterized by a substantial depletion of the density in the center of nucleus ("bubble" nuclei). This takes place in the ($Z \sim 138, N \sim 230$), ($Z \sim 154, N \sim 308$) and ($Z \sim 186, N \sim 406$) islands of stability of spherical hyperheavy nuclei [1,3].

Rotational excitations provide an alternative mechanism of the extension of nuclear landscape beyond the limits defined at spin zero [4,5]. Both in hyperheavy and rotating nuclei, the collective coordinates play an important role in extending nuclear landscape. In hyperheavy nuclei, they (deformations) drive the nuclear systems from ellipsoidal-like to toroidal shapes. In rotating nuclei, the increase of collective coordinate (rotational frequency) triggers the transition of nucleonic configurations from particle-unbound to particle-bound. Strong Coriolis interaction acting on high-N intruder orbitals is responsible for this transformation. This new physical mechanism has two important consequences. First, it leads to a substantial extension of the nuclear landscape beyond the spin zero proton and neutron drip lines. Second, exotic shapes such as giant proton halos in rotating proton-rich nuclei [5] and super-, hyper- and megadeformed shapes in rotating neutron-rich nuclei [4] are formed at high spin. Their formation is triggered by the occupation of high-N intruder orbitals.

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The use of Artificial Neural Networks in Nuclear Structure Studies

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Artificial intelligence, which has become widespread in all fields of science and technology in recent years, has taken its place as an alternative method in the field of nuclear physics. Machines, which are subjected to learning with the use of existing data, can make predictions on what they have

learned, and can complete the future data or the deficiencies in the data set it belongs to. From this point of view, it seems possible to carry out a nuclear physics experiment without the need for any experimental setup. For example, by using the binding energy information of about 3000 isotopes whose experimental data are available in the literature, it can be ensured that computers receive a good training on the binding energies of atomic nuclei. This training will open the door for us to correctly request information about any isotope whose experimental binding energy data is not available in the literature. Before artificial intelligence, computers could give us what we gave them. However, with artificial intelligence, we can now take more than we give. Because as we said, computers are learning now. Basically, they perform this learning with the artificial neural networks (ANN) method, which models the operation of the human brain. In this talk, how ANN is used as a nuclear physics laboratory will be discussed with examples such as the determinations of the nuclear ground and excited state energies, nuclear radius, beta decay energies of the isotopes, nuclear reaction cross-sections and single-particle energies for the nuclear structure calculations.

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∆K=1 Coriolis mixing of 1+ states of 164Dy

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The Coriolis interaction is known to induce perturbations to a Hamiltonian which is diagonal in projection quantum numbers K. Precision values for the branching ratios between the scissors mode and the 2_1^+ state of ^{164}Dy unveil such a scenario in first order. Employing a two-state mixing calculation, the K-mixing matrix element along with first information on $\Delta K = 0$ $M1$ excitation strength is obtained. While the latter is about two orders of magnitude smaller than usual collective $\Delta K = 1$ $M1$ strengths, the associated mixing matrix element is twice as large as the one obtained from the second-order effect which admixes ground and γ bands.

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Novel signatures for QPTs from mixed-symmetry states

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Mixed-symmetry states have proven their sensitivity to the shape evolution across quantum phase transitions. Especially the electromagnetic transitions between the 1^+ scissors mode and the 0_2^+ state are strongly affected by the amount of nuclear deformation. Also the elusive $E2$ properties of mixed-symmetry states can be established as novel signatures for phase-transitional behavior. First experimental information on such is discussed for the transitional nucleus ^{154}Gd and the quadrupole deformed nuclei ^{156}Gd and ^{162,164}Dy in connection with calculations in the IBM2.

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Shape coexistence in Ni isotopic chain

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One of the main unanswered questions of modern nuclear physics is whether the traditional magic numbers of protons and neutrons, such as they are known near stability, are maintained at extreme values of isospin, or whether new magic numbers emerge as a result of the unbalanced neutron-to-proton ratios.
The nuclear region around ^{78}Ni, with 28 protons and 50 neutrons, has attracted great attraction. This work aims at studying the even-even ^{70,72,74}Ni nuclei from β-delayed γ spectroscopy of the ^{70,72,74}Co progenitors to test the strength of state-of-the-art shell-model calculations in the vicinity of the doubly-magic ^{78}Ni core.
β-delayed γ spectroscopy study is providing a large amount of new information in the populated isotopic chains, resulting in the establishment of new decay schemes in the Fe chain and great extension of existing level schemes for the Ni isotopes.
In this contribution an insight on the shape coexistence and seniority conservation in exotic nuclei of the Ni isotopic chain will be given.

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Investigation of the B(E2; 0_1+ → 2_1+) value of 116Sn

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The tin isotopes, being proton-magic with a long chain of experimentally accessible nuclei, are an important testing ground for nuclear structure models.
Present data show systematic deviations between measured electric quadrupole (E2) ground-state excitation strengths depending on the used techniques.
Also, various nuclear structure models come to different predictions on the systematics of E2 strengths, particulary around ^{116}Sn. Latest Monte Carlo shell model calculations [1] predict a dip of E2 strengths around $N = 66$, which is explained by a second-order quantum phase transition from deformed shapes to the pairing phase.
Therefore, a measurement of ^{116}Sn relative to ^{112}Sn was performed for the first time using the nuclear resonance fluorescence method at S-DALINAC at TU Darmstadt.
Bremsstrahlung up to 2.2 MeV was used to populate the first excited 2^+ states of ^{112}Sn and ^{116}Sn and the photons of the subsequent de-excitation were measured by three high-purity germanium detectors.
With our relative measurement we aim to provide a test for the predicted dip of E2 strengths around ^{116}Sn, and obtain the absolute B(E2) value from a previous measurement of ^{112}Sn.

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Clustering and shape-phase transitions in nuclei and other physical systems / 74

Alpha-particle clustering in light nuclei

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In this contribution I present some recent results on alpha-particle clustering in odd-mass nuclei, in particular, on electromagnetic transitions and longitudinal and transverse form factors.

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Prolate to oblate transition within the proxy-SU(3) symmetry

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The consequences of the attractive, short-range nucleon-nucleon (NN) interaction on the wave functions of the Elliott SU(3) and the proxy-SU(3) symmetry [1,2,3] are discussed. The NN interaction favors the most symmetric spatial SU(3) irreducible representation, which corresponds to the maximal spatial overlap among the fermions. The percentage of the symmetric components out of the total in an SU(3) wave function is introduced, through which it is found, that no SU(3) irrep is more symmetric than the highest weight irrep for a certain number of valence particles in a three dimensional, isotropic, harmonic oscillator shell [4]. The consideration of the highest weight irreps in nuclei and in alkali metal clusters, leads to the prediction of a prolate to oblate shape transition beyond the mid-shell region [4], which in the heavy rare earths is found to be located around N=114, in agreement with experimental evidence. Similar predictions are obtained within the pseudo-SU(3) symmetry, when the highest weight irrep is used [5].

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Clustering and shape-phase transitions in nuclei and other physical systems / 64

Islands of shape coexistence in covariant density functional theory

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Using covariant density functional theory with the DDME2 functional and labeling single particle energy orbitals by Nilsson quantum numbers [1], a search for particle-hole (p-h) excitations connected to the appearance of shape coexistence is performed for Z=38 to 84 nuclei [2]. Islands of shape coexistence are found near the magic numbers Z=82 and Z=50, restricted in regions around the relevant neutron midshells N=104 and N=66 respectively, in accordance to the well accepted p-h interpretation of shape coexistence in these regions, which we call neutron induced shape coexistence, since the neutrons act as elevators creating holes in the proton orbitals. Similar but smaller islands of shape coexistence are found near N=90 and N=60, restricted in regions around the relevant proton midshells Z=66 and Z=39 respectively, related to p-h excitations across the 3-dimensional isotropic harmonic oscillator (3D-HO) magic numbers N=112 and N=70, which correspond to the beginning of the participation of the opposite parity orbitals 1i13/2 and 1h11/2 respectively to the onset of deformation [3].
We call this case proton induced shape coexistence, since the protons act as elevators creating holes in the neutron orbitals, thus offering a possible microscopic mechanism for the appearance of shape coexistence in these regions [3]. In the region around N=40, Z=40, an island is located on which both neutron p-h excitations and proton p-h excitations are present.

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Eigenstate metamorphosis in the Bose Hubbard model

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We will discuss the metamorphosis of the spectrum and of the eigenstates of the Bose-Hubbard Hamiltonian at the transition from integrability to (quantum) chaos,
addressing universal as well as distinctive properties in the chaotic domain.
We will further contrast the spectral information with dynamical features directly accessible in cold atom experiments, with special attention to signatures of the system's many-particle character.

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Wobbling and chiral bands with non-axial quasiparticle alignments

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The variation of spectral characteristics of the wobbling and chiral partner bands and the associated dynamics inferred by non-axial quasiparticle alignments with arbitrary tilting [1] is investigated within a semiclassical approach to the particle-rotor Hamiltonian [2,3]. The results for the alignment of the valence h11/2 nucleons are investigated as a function of total angular momentum and the angles of their tilting with respect to the principal axes of the triaxial core. It will be shown that the nucleus undergoes a transition through a variety of distinct dynamical phases which arise in specific ranges of tilting angles and total angular momentum. Few examples are provided as experimental realizations of the discussed dynamics.

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Shape coexistence and mixing within the Bohr model

Authors: Alaaeddine Lahbas[1]; Andreea Ioana Budaca[2]; Azdine Ben Mennana[1]; Petrica Buganu Mustafa Oulne[1]; Radi Benjedi[1]; Radu Budaca[2]; Younes EL Bassem[1]

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The Bohr Hamiltonian [1,2] with a sextic potential, having two minima, a spherical and a deformed one separated by a barrier, was diagonalized in a basis of Bessel functions of the first kind [3]. The model, depending on the height of the potential barrier (Panels 1-4 of Figure 1 from [4]), can describe the well-known critical points from spherical vibrator to prolate / γ-unstable rotor if the barrier is very small / absent, a shape evolution as a function of the total angular momentum, respectively the shape coexistence and mixing phenomena once the barrier is gradually raised. Some preliminary applications of the model for 76Kr [4], 72,74,76Se [5], 96,98,100Mo [6], 74Ge, 74Kr [7] and 80Ge [8] revealed promising perspectives for future applications of the model to other nuclei known to manifest these phenomena.

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Studies of Pear-Shaped Nuclei

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For certain combinations of protons and neutrons it is expected that the shape of atomic nuclei can undergo octupole deformation, which would give rise to reflection asymmetry or a "pear shape". In this talk I will review the experimental evidence for octupole instability in medium-mass and heavy nuclei, including the results of recent experiments carried out at CERN using REX-ISOLDE [1] and HIE-ISOLDE [2,3,4]. The behaviour of the rotational levels and the E3 matrix elements suggests that only a few radium isotopes have stable pear shapes, although there remain some challenges for theory to reproduce the observed trend of the values of the E1 and E3 transition moments with neutron number. I will also discuss the future prospects for this field.

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Excited-state quantum phase transitions / 80

Introduction to the physics of ESQPTs

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The talk will overview some recent contributions to the ESQPT field. The main attention will be focused on the recent generalization of the ESQPT concept to systems with continuous spectra, particularly to the one-dimensional tunneling problem [1,2].

References:

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Pairwise kissing of excited states in a squeezed Kerr-oscillator

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Recent advances in the control of superconducting circuits opened new possibilities for the investigation of fundamental quantum phenomena. In this work, we demonstrate the transition into the "Schrödinger-cat regime" of a Kerr-oscillator as it is progressively dressed by squeezed microwave light.
We discover that the lifetime of the degenerate ground states in our experiment increases in steps as a function of the squeezing amplitude. This is a clear signature of pairwise degeneracy (level kissing) in the spectrum of the static effective Hamiltonian describing the system, which we also independently measure. Finally, we measure a lifetime of 1.1ms along one axis of a cat-qubit Bloch sphere, while retaining quantum nondemolition readout fidelities of 99.54% and quantum control. Our experiments provide important tools for analog Hamiltonian engineering and hardware-efficient quantum computation.

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The nature of seniority symmetry breaking in the semi magic nucleus 94Ru

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For any fermionic system, seniority, ν, is defined as the number of particles not in pairs coupled to angular momentum J=0. It is a conserved quantum number for a system with n identical particles, each with angular momentum j, interacting through a pairing force [1]. Nuclei such as 9444Ru50 with valence particles situated in the upper half of the N/Z=28-50 major shell are influenced by the relative isolation of the g9/2 subshell. The j=9/2 system has received particular recent interest with respect to the exotic partial conservation of seniority [2].

Direct lifetime measurements via γ- γ coincidences using a FAst Timing Detector Array (FATIMA) [3] has been applied to determine the half-lives of low-lying states in the semimagic 94Ru nucleus. The experiment was carried out as the first of a series of commissioning "FAIR-0" experiments with the DESPEC experimental setup at the Facility for Antiproton and Ion Research (FAIR) [4]. Excited states in 94Ru were populated primarily via the β-delayed proton emission of 95Pd nuclei, produced in the projectile fragmentation of a 850 MeV/nucleon 124Xe beam impinging on a 4 g/cm2 9Be target. While the deduced E2 strength for the 2+ ⟶ 0+ transition in the yrast cascade well follow the expected behavior for conserved seniority symmetry, the intermediate 4+ ⟶ 2+ transition
exhibits a drastic enhancement of transition strength in comparison with pure-seniority model predictions as well as standard shell model predictions in the fpg proton hole space with respect to doubly-magic 100Sn. The anomalous behavior is ascribed to a subtle interference between the wave function of the lowest seniority ν=2, Iπ = 4+ state and that of a close-lying ν =4 state that exhibits partial dynamic symmetry. In addition, the observed strongly prohibitive 6+ ⟶ 4+ transition can be attributed to the same mechanism but with a destructive interference. It is noted that such effects may provide stringent tests of the nucleon-nucleon interactions employed in state-of-the-art theoretical model calculations.

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Analogs of QPTs and ESQPTs in a dissipative spin model

Co-authors: Alvaro Rubio-García ; Angel L. Corps ; Armando Relaño ; Francisco Pérez-Bernal ; José Enrique García-Ramos ; Rafael Molina

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We will present a model of a quantum collective spin weakly coupled to a spin-polarized Markovian environment which displays extremely exotic spectral properties [1]. As a function of the environment magnetization the spectrum is divided in to two regions by a divergence in the density of Liouvillian eigenvalues. This Liouvillian spectral phase transition is the analog of the ESQPTs in closed quantum systems. One of the spectral phases has the unique characteristic of being made up exclusively of second order exceptional points in the thermodynamic limit, while the other shows a normal non-degenerate spectrum. In the limit of no bath polarization, this criticality is transferred into the steady state implying a dissipative quantum phase transition, the analog of a QPT in closed systems. Moreover, at the critical point the steady state behaves as a boundary time crystal.

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José Enrique García-Ramos, and Jorge Dukelsky. Exceptional Spectral Phase in a Dissipative Collective Spin Model. arXiv:2202.09337.

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Investigation of shape coexistence and -softness in the neutron rich A≈100 region using lifetime measurements

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The A≈100 region is an interesting region of the nuclear chart with the occurrence of different nuclear structure phenomena. For example, the well known sudden onset of collectivity in the neutron-rich Sr and Zr isotopes [1, 2], the multiple shape coexistence in the neutron-rich stable Cd isotopes [3, 4] or the evidences for -softness in the Mo, Ru and Pd isotopes. Lifetimes of excited states in 102 Mo and 104,106 Ru were measured using the (18 O, 16 O) two neutron transfer reaction in combination with the Plunger device at the Cologne FN Tandem accelerator [5–7]. In this reaction, a low amount of momentum and energy is transferred, making it a powerful tool for the investigation of nuclear structures dominating at low energies. This allows a detailed analysis of the shape coexistence phenomena in the Mo isotopes occurring at the transition from = 58 to = 60 [6] and the nuclear structure related to the -deformation in neutron-rich Mo and Ru isotopes [6, 7]. The results were compared to different nuclear structure models like the interacting boson model (IBM), the Jean-Wilets -soft model and the Davydov-Filippov rigid triaxial rotor model depending on the case.

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Lifetime measurements and shape coexistence in 97Sr

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Delayed γ rays from neutron rich A=97 fission fragments were measured using the Lohengrin spectrometer at the reactor of the Institut Laue-Langevin in Grenoble [1]. Several lifetimes of excited states in 97 Sr were measured using the fast-timing technique [2]. The rapid change in ground-state deformation between the spherical 96 Sr (N=58) and the deformed 98 Sr (N=60) is well known [3, 4]. Therefore, it is of particular interest to study the shape-coexisting structures at the spherical-deformed border (N=59). With the extracted transition probabilities, the type of excitation of some states could be studied and assigned [5].

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Clustering and shape-phase transitions in nuclei and other physical systems / 84

Alpha-clusters configurations in 12C and 16O and alpha-transfer

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Results obtained in the last few years by the Theoretical Nuclear Physics group in Padova on alpha-cluster models and on nuclear correlations in halo nuclei will be reviewed in this seminar. The algebraic cluster model assumes triangular and tetrahedral configurations of alpha particles for carbon-12 and oxygen-16 respectively. The spectroscopic description of the low-lying states achieved in this model, that is a consequence of the requirement of discrete symmetries, is extremely good. We have made a number of calculations of reactions form factors that have been applied to alpha-transfer reactions obtaining a good agreement with available data, thus corroborating the main hypotheses of the model. We have also speculated about smoking-gun nuclear fluorescence experiment that might shed light on the exact arrangements of alphas in 12C.

Novel aspects and signatures of QPTs in nuclei / 76

Alternative prolate to oblate QPT scheme in odd systems, preliminary results

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I will illustrate an exactly solvable algebraic Hamiltonian for odd systems, that spans the prolate-to-oblate region. The underlying $SU^{BF}(3) \otimes U_s^F(2)$ dynamical symmetry, allows to maintain the axial symmetry throughout, thanks to the mixing of quadratic and cubic Casimir operators of $SU^{BF}(3)$. A fermionic basis with j = {1/2, 3/2, 5/2} is coupled to the boson part and diagonalized finding a rich

variety of behaviours: the various orbitals do not display the same shape, some are prolate while others are oblate, and they make the transition following different paths.

Symmetries and quantum phase transitions in nuclei / 77

Phase transitions, scale invariance and criticality in self organized systems

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Symmetry methods have been of crucial importance to physics. Group theory and conservation laws have become a fundamental language, all the way from quantum mechanical phenomena to general relativity. However, these ideas have had less impact in the biological domain. In this talk I present a view of self organized biological systems as characterized by and evolving towards critical points, in the language of phase transitions in physical systems. Self similar (or scale invariant) behavior seems to signal homeostatic dynamical equilibrium in living organisms.

Symmetries and quantum phase transitions in nuclei / 27

A quantum simulation of the Agassi model

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

Empirical aspects of quantum phase transitions in nuclei / 32

Nuclei with multiple shape coexistence

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It is now well understood that shape coexistence appears in many regions throughout the nuclear chart. Until very recently, there were only a few candidates suggested for nuclei possessing multiple, i.e., more than two, distinct shapes. Within the past several years, however, this has changed dramatically with detailed spectroscopy revealing structures not previously observed, and results interpreted with shell model or beyond-mean-field calculations. Examples of these candidates, from the light-mass Mg-Si region to the Au-Pg region will be highlighted for discussion.

Transitional nuclei and shape coexistence / 29

Intertwined quantum phase transitions in the Zr isotopes

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In this talk I will discuss our latest work on the Zr isotopes with A =92−110, which have one of the most intricate evolutions of structure in the nuclear chart.
We explain their structural evolution using the notion of intertwined quantum phase transitions (IQPTs), for which a QPT involving a crossing of two configurations (Type II QPT) is accompanied by a shape evolution of each configuration with its own separate QPT (Type I QPT). We demonstrate the relevance of IQPTs to the zirconium isotopes by employing a calculation using the interacting boson model with configuration mixing (IBM-CM). Such a symmetry-based framework enables us to examine a large range of experimental data such as energy levels, two neutron separation energies, $E2$ and $E0$ transition rates, isotope shifts and magnetic moments. We consequently find the occurrence of Type II QPT between the normal and intruder configurations. Alongside the Type II QPT, we find that the Type I QPT takes place within the intruder configuration, which changes from weakly deformed to prolate deformed and finally to γ-unstable, associated with the U(5), SU(3) and SO(6) dynamical symmetry limits of the IBM, respectively. In such a situation, both Types I and II have a critical-point near $A \approx 100$.

Symmetries of interacting boson and/or fermion systems / 31

Intertwined quantum phase transitions in odd-mass Nb isotopes

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The spectrum of odd-mass medium and heavy nuclei involving multiple shell model configurations have rarely been calculated by theoretical models thus far due to their demanding computational aspect or, for some models, the lack of an adequate framework. The evolution of structure of such odd-mass nuclei with varying number of nucleons is hence difficult to investigate. In this talk I will present the novel extension of the interacting boson-fermion model with configuration mixing (IBFM-CM), which we developed to address this gap of knowledge. The IBFM-CM is employed to calculate the evolution of structure of the odd-mass Nb isotopes ($Z = 41$) with A =93−105. Using this calculation we identify a quantum phase transition between the normal and intruder configurations (Type II QPT), which cross near neutron number 60. This serves as a first example of crossing configurations in odd-mass nuclei. Alongside the Type II QPT, we also identify the shape evolution (Type I QPT) within the intruder configuration, changing from spherical-like to deformed-like. The occurrence of both types of QPTs in the Nb isotopes points towards the manifestation of intertwined quantum phase transition (IQPT), for which a QPT involving a crossing of two configurations (Type II) is accompanied by a QPT involving a shape evolution of each configuration separately (Type I), similarly to the case of the adjacent even-even Zr isotopes ($Z = 40$).

Symmetries of interacting boson and/or fermion systems / 19

Isovector-E2 strength of the scissors mode of 152Sm

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The nucleus ^{152}Sm is well known to be located at the $N = 90$ quantum shape-phase transition (QSPT) boundary. Since the scissors mode (SM) is a collective, isovector excitation, its decay characteristics depend on the proton-neutron residual interactions and are sensitive to the QSPT. The SM is known for its large $M1$-excitation strength, however, data on isovector $E2$ properties are sparse [1]. The SM of ^{152}Sm was investigated in a nuclear resonance fluorescence experiment performed at the High-Intensity γ-Ray Source with a quasi-monoenergetic, polarized photon beam with an energy of 2.99(5) MeV. Emitted photons were detected by four high-purity germanium detectors positioned at angles sensitive to the multipolarities of the decay radiation of 1^π states. The isovector $E2$ transition of the SM of ^{152}Sm to the first 2^+ state has been deduced from the $E2/M1$ multipole mixing ratio of the $1^+_{\rm sc} \to 2^+_1$ transition and its previously known transition rate. Experimental results are compared to predictions of the interacting boson model 2, yielding local values for proton and neutron effective quadrupole boson charges [2].
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Novel aspects and signatures of QPTs in nuclei / 49

Lipkin model on a quantum computer

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Quantum computers show great promise, but as yet are still limited to toy problems. Here I discuss the quantum computation of that classic toy model of nuclear structure, the Lipkin model, and what we can learn about the near and far future of quantum computing.

Symmetries and quantum phase transitions in nuclei / 3

Unmixing symmetries

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While we often use group symmetries in nuclear structure, they are seldom perfect and are often mixed. After demonstrating an efficient way to decompose a wave function into group irreps, I show how one can adapt the similarity renormalization group to 'unmix' symmetries.

Density functional and beyond-mean-field approaches to QPTs in nuclei / 68

Shape transitions and low level structure in the Hg region within the relativistic density functional theory

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Quantum phase shape transitions and shape coexistence are one of the most active areas of theoretical and experimental research in nuclei [1]. Especially the region of neutron deficient Hg isotopes is a well known case, with recent experiments revisiting the area [2-5] and making it a suitable testing ground for theoretical models. Our approach is based on the relativistic density functional theory and its point coupling variants [6,7]. At the first level, constrained relativistic mean field calculations of even-even Hg and neighbouring nuclei such as Pt and Pb, provide the potential energy surfaces which reveal shape transitions along the isotopes as well as possible coexisting shapes as additional equilibrium points. At the next level, the constrained calculations are used as input for the construction of a five dimensional collective Hamiltonian (5DCH) [8], which introduces the vibrational and rotational collective dynamics neglected at the mean field level. This allows the detailed investigation of the low level structure of the collective spectra of Hg isotopes. In particular, energy ratios of levels of the same band and ratios of B(E2) transitions, that are used as signature of shape coexistence, are compared with experimental data and with calculations of other theoretical models.

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Symmetries of interacting boson and/or fermion systems / 47

New aspects of the low-energy structure of 211At

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Lifetimes of low-energy states in ^{211}At have been measured using the recoil-distance Doppler shift, Doppler-shift attenuation, and fast-timing methods at the University of Cologne. The obtained reduced transition probabilities have been compared to two shell-model calculations, a large-scale shell-model calculation using the Kuo-Herling residual interaction and a calculation using a single-j approximation for protons in the $0h_{9/2}$ orbital. The newly obtained reduced transition probabilities

are described very well by a single-j calculation. This, together with the fact that the energy spectrum of ^{211}At is also well described, indicates that seniority can be regarded as a good quantum number in ^{211}At. While the single-j calculation can only describe states with a dominant $0h^3_{9/2}$ configuration, the presence of other low-lying proton orbitals, like $1f_{7/2}$ and $0i_{13/2}$, requires a multi-j calculation. The multi-j calculation using the Kuo-Herling interaction gives a satisfactory description of the nuclei in the region but significantly overestimates some of the ground-state transition probabilities, for example, the $B(E2; 13/2^-_1 \rightarrow 9/2^-_1)$ value in ^{211}At. This discrepancy has been attributed to the presence of higher-order particle-hole excitations in the wave function of the ground state, which are not accounted for by the Kuo-Herling interaction. The effects of those excitations on the transition rates, however, are weaker in ^{211}At than they are in ^{210}Po. On the other hand, a strong underestimation of the $E2$ strengths involving the $7/2^-_1$ state is also observed, where one proton occupies the $0f_{7/2}$ orbital. Therefore, a phenomenological modification to the $< 0h_{9/2}, 0h_{9/2}|\hat{V}|0h_{9/2}, 1f_{7/2} >_{J=2}$ two-body matrix element has been introduced which leads to a considerably better description of the structure of ^{210}Po and ^{211}At. However, the origin of this effect needs to be further investigated.

Transitional nuclei and shape coexistence / 55

Tests of collectivity in 98Zr by absolute transition rates

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Lifetimes of low-spin excited states in ^{98}Zr were measured using the recoil-distance Doppler-shift technique and the Doppler-shift attenuation method. The nucleus of interest was populated in a ^{96}Zr(^{18}O,^{16}O)^{98}Zr two-neutron transfer reaction at the Cologne FN Tandem accelerator giving access to the low-sping structure of the nucleus. Lifetimes of six excited states, of which four unknown, were measured. The deduced $B(E2)$ values were compared with Monte-Carlo shell model and interacting boson model with configuration mixing calculations. Both approaches reproduce well most of the data but leave challenging questions regarding the structure of some low-lying states. Most notable is the low collectivity of the $B(E2; 2^+_1 \rightarrow 0^+_2)$ which is not predicted by both models.

Clustering and shape-phase transitions in nuclei and other physical systems / 58

Quantum Fidelity Susceptibility as a tool to characterize shape transitions in molecular bending spectra

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Molecular bending spectra can be broadly categorized into three physical cases, depending on the molecular equilibrium configuration: linear, bent, and nonrigid. We have studied the three cases in detail with an extended Hamiltonian (including up to four-body interactions) of the 2D limit of the Vibron Model (2DVM), and analyzed shape transitions such as bent to linear transition [1], and isomerization reaction between HCN and HNC isomers [2]. These Hamiltonians depend on different parameters according to the interactions taken into account to reproduce experimental data.

We purpose a method which allows to define a unique control parameter to drive the system from one dynamical symmetry to the other one [3]. This method has been proved to be useful in the

study of precursors of excited states quantum phase transitions in the 2DVM [3,4] and in the Lipkin-Meshkov-Glick model [5].

Fixed the method, we need a physical quantity to study the dynamical structure of eigenstates. To solve this issue, authors have extended the usage of quantum fidelity susceptibility from the ground state to excited states domain. This quantity allows us not only to determine in an elegant and basis-independent way the linear or bent character of any excited state [3], but also to determine the transition state in isomerization reactions [4].

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Clustering and shape-phase transitions in nuclei and other physical systems / 34

γ-decay Behavior of the Giant Dipole Resonances of 154Sm and 140Ce

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The giant dipole resonance (GDR) is one of the most fundamental nuclear excitations and dominates the dipole response of all nuclei. Its evolution from a single-humped structure to a double-humped structure is considered as one of the most direct signatures of collectivity and nuclear deformation. Yet, its γ-decay behavior, despite being a key property, is still mostly unknown.
Recently, novel data on the γ-decay of the GDR of the well-deformed nuclide ^{154}Sm and the spherical nuclide ^{140}Ce were obtained through photonuclear experiments at the HIγS facility. Individual regions of the GDR were selectively excited by HIγS' intense, linearly-polarized and quasi-monochromatic γ-ray beam. This enabled an excitation-energy resolved determination of the GDR's γ-decay behavior. For ^{154}Sm in particular, the obtained data allow for a first experimental test of the commonly accepted K-quantum-number assignments to the double-humped GDR observed in deformed nuclei.
This work was supported by the State of Hesse under the grant Nuclear Photonics within the LOEWE program and within the Research Cluster ELEMENTS and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under award numbers 97ER41041 and DE-FG02-97ER41033.

Symmetries of interacting boson and/or fermion systems / 35

Majorana Parameters of the Interacting Boson Model of Nuclear Structure and their Implication for 0νββ-decay

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The well-known near-X(5) nucleus ^{150}Nd is the mother nucleus of a two-neutrino double beta ($2\nu\beta\beta$) decay and therefore also a candidate for neutrinoless double beta ($0\nu\beta\beta$) decay with the daughter being ^{150}Sm. $0\nu\beta\beta$-decay is a process only allowed if the neutrino were a Majorana particle and recently gained much attention with numerous experiments searching for $0\nu\beta\beta$-decays, even more so as it would furthermore allow the determination of the elusive neutrino mass from its decay rate. To extract the neutrino mass or estimate decay rates, however, a nuclear matrix element (NME) is needed, which has to be calculated through suitable nuclear structure models like the Interacting Boson Model (IBM). Those calculations are further complicated by the fact that many of the $0\nu\beta\beta$-decay candidate nuclei are located in regions of shape coexistence with the pair of ^{150}Nd and ^{150}Sm even being in the region of a shape phase transition along their respective isotopic chains. For a precise calculation of the $0\nu\beta\beta$-decay NME in the IBM in particular also a determination of the model's Majorana parameters is necessary. This can be achieved by investigating the properties of mixed symmetry states, such as the scissors mode, whose description in the IBM is dominated by the Majorana parameters. Hence, to improve $0\nu\beta\beta$-decay NME calculations new data on the decay characteristics of the scissors mode in ^{150}Nd and ^{150}Sm was recently taken in nuclear resonance fluorescence experiments performed at the High Intensity γ-ray Source, which I would like to present. The decay characteristics of the scissors mode are known to be sensitive to the nuclear deformation and were found to induce strong constraints on the three Majorana parameters of the IBM. This in turn resulted in an improved prediction of the $0\nu\beta\beta$-decay NME from an updated IBM calculation utilizing newly constrained IBM parameter sets for ^{150}Nd and ^{150}Sm [1].

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Density functional and beyond-mean-field approaches to QPTs in nuclei / 20

Nuclear charge radius predictions from DFT-based models

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The nuclear charge radii can provide information about the strong and electromagnetic forces acting inside the atomic nucleus on its constituents. While the global trend of nuclear charge radius is governed by the nuclear-matter bulk properties, its local variation is affected by the quantum mechanical nuclear-structure aspects. In recent years, tremendous progress in the experimental measurement of nuclear charge radii has been made. This has challenged current nuclear-structure models and motivated the development of new ones.

I will discuss predictions of the nuclear charge radii on various isotopic chains with DFT-based models. Recent measurements in K [1], Ag [2], Ni [3], and Pd [4] isotopic chains have shown that while these models can predict overall trends well, there are, nevertheless, some deficiencies. When comparing predictions from Fayans and Skyrme EDF models, we have found that generally Fayans EDF, although often overestimating odd-even staggering of charge radius, tends to follow more closely the experimental trend. This can be attributed to the subtle interplay between pairing correlations, nuclear deformation, and charge radius [4]. The results for potassium charge radii do not support the magic number character of $N = 32$.

With Ag isotopic chain, none of the used EDF models could reproduce the unexpectedly large charge radius of ^{96}Ag, below the $N = 50$ shell gap [2]. It is very unlikely that such kind of increase in the charge radius can be reproduced with any reasonable single-reference EDF model. A possible solution towards a more accurate description would be symmetry-restored, beyond mean-field approaches.

Lastly, I will also discuss the strikingly similar pattern of differential charge radii in even-even isotopic chains from Ca to Zn, predicted with DFT and ab-initio based models [5]. We have found that each theoretical model predicts its own, nearly element-independent sequence of differential charge radii across these isotopic chains. Experimental data, where available, supports this very same picture.

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Excited-state quantum phase transitions / 40

Theory of dynamical phase transitions driven by excited-state quantum phase transitions

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During recent years there has been a growing interest in the different kinds of phase transition that many-body quantum systems may exhibit as well as in the thermodynamic properties associated to the resulting quantum phases. Besides the well-known quantum phase transition, occurring in the ground-state of a physical system as a certain control parameter is varied, and its generalization to high-lying levels, excited-state quantum phase transitions (ESQPTs), two new forms of non-analytic behavior have been explored, especially in models with long-range and infinite-range interaction: they have been termed dynamical phase transitions (DPTs). The first kind, which we call DPT-I, is characterized by an abrupt change of a given order parameter after a quench from an initial value of a control parameter to a final value; these values are in general unrelated to the critical quench leading the system to the (ground-state) quantum phase transition. The second kind of DPT, which we call DPT-II, consists in non-analytic point in the return probability (sometimes also called Loschmidt echo or survival probability) at certain critical times after a quench from an initial state in a broken-symmetry phase where the eigenlevels are pairwise degenerate. The signatures of both kinds of DPTs sharpen as the system size of the model is increased.

In this talk I will present a theory for the two kinds of dynamical quantum phase transitions in a large class of collective many-body systems (that is, with infinite-range interaction). These two DPTs are shown to be rooted in excited-state quantum phase transitions. For quenches below the critical energy of the ESQPT, the existence of an additional conserved charge [1] identifying the corresponding broken-symmetry phase means that the dynamical order parameter of DPTs-I can take on a non-zero value, while it becomes zero for quenches leading the initial state above the ESQPT. This same conserved charge forbids the appearance of non-analyticities in the return probability after a quench ending in the broken-symmetry phase demarcated by the ESQPT, meaning that DPTs-II are forbidden in this phase. The long-time averages of order parameters associated with DPTs-I are described by a generalization of the standard microcanonical ensemble, and we provide an analytical proof for the absence of DPTs-II within the symmetry-broken phase. Our results are exemplified by means of the fully-connected transverse-field Ising model, which is mathematically equivalent to a simple version of the Lipkin-Meshkov-Glick model, as this model shows all four kinds of phase transitions (QPT, ESQPT, DPT-I and DPT-II). These are the main findings reported in [2,3].

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Novel aspects and signatures of QPTs in nuclei / 44

Shape phase transitions and shape coexistence through two-neutron transfer

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Two-neutron transfer reactions are sensitive to Quantum shape phase transitions along isotopic chains through two-neutron intensities, as calculated for example in the framework of the Interacting Boson Model [1-3]. Alternatively, the ground state of an isotope can also change along the isotopic chain, for example from spherical to deformed, due to shape coexistence.

In this contribution we will discuss the possibility of distinguishing these two cases through two-neutron transfer reactions [4,5]. We will take as example two isotopic chains: Samarium and Zirconium, as respective examples of shape phase transition [1] and shape coexistence [6].

Two-neutron transfer cross sections are calculated in second-order DWBA from two-neutron intensities obtained in the IBM model [1,7] for the Samarium and from two-neutron amplitudes calculated in Monte Carlo Shell Model framework from T. Togashi and collaborators [6] for the Zirconium. A good agreement with available experimental data is found in both cases [8,9]. More importantly, qualitative differences are found in the cross sections along both isotopic chains, allowing us to use two-neutron transfer as a probe to distinguish among the two scenarios.

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Symmetries and quantum phase transitions in nuclei / 67

Nuclear radius, neutron skin and the mirror energy differences

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Differences between excitation energies of analogue states in mirror nuclei depend on the variations of the nuclear radius as a function of the spin. These mirror energy differences (MED) can be reproduced by shell model calculations where the evolution of the radius can be accounted for through the occupation of low-l orbits, that present larger radius than the large-l ones in a main shall. Recent data on MED put in evidence the reduction of the low-l orbital radius when they are not fractionally occupied.
Due to the isovector monopole polarizability, proton and neutron radii tend to equalize but still a neutron skin develops. It will be shown that data on MED for sd shell nuclei can be used to estimate the skin of each excited state. Interestingly, the skin is correlated with the difference of occupation number of neutrons and protons in the $s_{1/2}$ orbit.

Symmetries and quantum phase transitions in nuclei / 23

What EDFs can tell us on PDSs in nuclei

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In a partial dynamical symmetry (PDS), the stringent conditions imposed by an exact dynamical symmetry are relaxed, so that solvability and/or good quantum numbers are retained by only a subset of states. Detailed studies have shown that PDSs account quite well for a wealth of spectroscopic data in various nuclei. In all these phenomenological studies, an Hamiltonian with a prescribed PDS is introduced, its parameters are determined from a fit to the spectra, and the PDS predictions (which are often parameter-free) are compared with the available empirical energies and transition rates. In the present contribution, we show that the PDS notion is robust and founded on microscopic grounds [1]. We use self-consistent mean-field methods in combination with the interacting boson model (IBM) of nuclei, to establish a linkage between universal energy density functionals (EDFs) and PDSs. An application to ^{168}Er shows that IBM Hamiltonians derived microscopically from known non-relativistic and relativistic EDFs in this region, conform with SU(3)-PDS.

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Density functional and beyond-mean-field approaches to QPTs in nuclei / 36

Microscopic description of octupole deformations and collective excitations in even - even Xe and Ba isotopes

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In this talk, some of the recent results of the microscopic description of octupole collective excitations in the nuclei near N=56 and N=88 are presented. By performing the axially symmetric self-consistent mean field (SCMF) calculations with the DD-PC1 energy density functional, octupole deformations of the ground state shapes of even-even Ba and Xe isotopes are analysed. The excitation energies and transition strengths are calculated by using the quadrupole-octupole collective Hamiltonian (QOCH) model. The calculated excitation energy spectrum is mostly in good agreement with experimental data. Octupole-deformed ground states are found in Ba and Xe isotopes with neutron numbers

around N=56 and N=88.
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Symmetries and quantum phase transitions in nuclei / 26

Exact analytical treatment of nuclear shape phase transitions in terms of the sextic oscillator

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The sextic oscillator V(r) = Ar^2 + Br^4 +Cr^6 + D/r^2 offers a flexible shape that can be used in the Bohr Hamiltonian to model transition between spherical and deformed shape phases in the r=beta variable. The general form of the sextic oscillator is not solvable, however, the A, B and C coefficients can be parametrized in terms of two independent parameters (a, b) such that the problem reduces to a quasi-exactly (QES) form. This means that the lowest few energy eigenvalues and the wave functions can be determined in closed form, and the B(E2) values can also be calculated analytically [1,2]. The model has been applied to describe the transition between the spherical and gamma-unstable shape phases [1,2] for even-even nuclei near the Z=50 shell closure, and it has been shown that the two phases are separated by a parabola in the (a,b) phase space. Later the model has been generalised to discuss further types of phase transitions too (see e.g. [3]). Here we report on the extension of the model that allows the treatment of 22 energy levels instead of the original 10, while all the calculations remain analytically solvable [4]. The model is applied to the Ru, Pd, Pt and Os isotope chains, and the trajectory obtained in the (a,b) phase space is analysed for each chain.

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Transitional nuclei and shape coexistence / 85

Experimental fingerprints of shape coexistence

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Shape coexistence can be studied via a variety of experimental probes. The first indication of nuclear deformation can be obtained from the level energies, or alternatively from the electromagnetic transition strengths. In this context, the use of systematics is typically far more reliable than focusing on individual states in a specific nucleus, and it should ideally be followed by measurements of other quantities that are sensitive to the nuclear shape. For example, direct information on the charge distribution in the nucleus can be obtained from
the measurements of spectroscopic quadrupole moments using laser spectroscopy for longlived states and low-energy Coulomb excitation for the short-lived ones. However, shape coexistence is often accompanied by mixing of the wave functions corresponding to different microscopic configurations, which may influence those simple observables. Therefore, a more sophisticated approach is beneficial, involving determination of complete sets of electromagnetic transition rates between low-lying excited states, and static quadrupole moments. Those can be further analysed in terms of quadrupole invariants resulting from the Kumar–Cline sum rules yielding model-independent information on shape parameters of individual states. Alternatively, measurements of E0 transition strengths bring invaluable complementary data on configuration mixing, and microscopic compo-

nents of the wave
functions can be deduced from nucleon-transfer cross sections.

I will briefly present the observables that are used to investigate shape coexistence, illustrating the discussion with recent examples showing the importance of complementary measurements when making conclusions about the structure of states.

Empirical aspects of quantum phase transitions in nuclei / 42

Evolution of nuclear structure in and around semi-magic nuclei

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Abstract
Nuclei with either protons or neutrons at closed-shell magic configuration, have only one type of active nucleons and are called semi-magic nuclei. Presence of like-nucleons in such semi-magic nuclei result in the simplicity out of complex nucleonic structure. This can be understood in terms of the symmetries of pairing Hamiltonian and seniority/ generalized seniority quantum number(s). Due to certain seniority and generalized seniority selection rules, seniority isomers exist in these nuclei where isomers refer to the excited states having longer life-times than the normal excited states [1]. For example, Sn (Z = 50) isotopes, the longest known semi-magic isotopic chain, present an interesting ground to understand the origin of seniority isomers including their decay probabilities and moments [2, 3]. But what will happen if we move to two-proton holes configuration in Cd (Z = 48) isotopes to the two-proton particles configuration in Te (Z = 52) isotopes [4]? Will the generalized seniority symmetries hold on going from Cd to Sn to Te isotopes for the seniority isomers and low-lying excitations such as the first 2+ and 3− states [5]? These questions will primarily be focused in the presentation.
Acknowledgements
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Novel aspects and signatures of QPTs in nuclei / 8

The microscopic origin of the Interacting Boson Model

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A new microscopic interpretation of the s and d bosons of the Interacting Boson Model shall be suggested. The s and d bosons will be symmetric pairs of harmonic oscillator quanta deriving from the occupancy of the valence Shell Model orbitals by the valence nucleons. It will be discussed that if such is the case, then the SU(3) limit of the Interacting Boson Model coincides the Elliott SU(3) symmetry.

Transitional nuclei and shape coexistence / 30

Shape coexistence in Strontium isotopes

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SHAPE COEXISTENCE IN STRONTIUM ISOTOPES

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

The aim of this contribution is the study of the nuclear structure of 92-102 even-even isotopes using the description of excitation energies, B(E2) transition rates, nuclear radii and two neutron separation energies using the framework of the Interacting Boson Model with configuration mixing.

For the whole chain of isotopes analyzed, good agreement between theoretical and experimental values of excitation energies, transition rates, separation energies, radii and isotope shift has been found. Furthermore, the wave functions, together with the obtention of mean field energy surfaces and the value of nuclear deformation have been analyzed.

This study will clarify the presence of low-lying intruder states in even-even Sr isotopes and the way it connects with the onset of deformations. Lightest Sr isotopes considered present a spherical structure while heaviest one are clearly deformed. The onset of deformation at N = 60 is motivated by the crossing of the regular and intruder configuration, furthermore, both families of states present an increase of deformation with the neutron number.

Density functional and beyond-mean-field approaches to QPTs in nuclei / 89

Coexistence of nuclear shapes: mean-field and beyond

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The microscopic self-consistent mean-field (SCMF) framework based on an universal energy density functionals provides an accurate global description of nuclear ground states and collective excitations, from relatively light systems to superheavy nuclei, and from the valley of beta-stability to the particle drip-lines.
Based on this framework, structure models have been developed that go beyond mean-field approximation and include collective correlations related to restoration of broken symmetries and fluctuation of collective variables (generator coordinate method, collective Hamiltonian model). These models have become standard tools for nuclear structure calculations, able to describe new data from radioactive-beam facilities and provide microscopic predictions for low-energy nuclear phenomena of both fundamental and practical significance.
Recent applications of the SCMF framework for description of of shape evolution and coexistence will be presented.

Symmetries of interacting boson and/or fermion systems / 72

Evolution and coexistence of nuclear shapes in transitional regions

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The phenomena of shape phase transitions and shape coexistence are prominent aspects of nuclear structure. Experiments using radioactive-ion beams have allowed to study these phenomena in thus far unknown nuclei, and stimulate timely systematic and reliable theoretical predictions. This presentation will review recent theoretical studies on the shapes and the related collective excitations in transitional, neutron-rich nuclei within the framework of the interacting boson model that is formulated microscopically by using the mean-field methods. Topics to be discussed during the presentation include the shape phase transitions, shape coexistence, and octupole correlations in the mass A=70-100 nuclei, and the inclusion of the particle-boson coupling for the odd-even and odd-odd systems, which further points to a simultaneous description of the low-lying structures, and the single- and double-beta decay properties of the transitional nuclei in a wide mass region.

Transitional nuclei and shape coexistence / 63

Shape coexistence in the n-deficient Hg isotopes

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Two of the main observables which have emerged as model-independent probes of the shape-coexistence phenomenon are the transition strengths, in particular B(E2) and ρ^2(E0) [1]. From them, the matrix elements can be extracted, which are particularly sensitive to the wavefunctions of the states they connect and to the degree of mixing between the different nuclear shapes. Therefore, they are one of the most stringent tests of the different theoretical models used to describe nuclei.

The n-deficient Pb region (to the south-west of Z=82, N=126) is characterized by clear cases of shape coexistence, with the Hg (Z=80) isotopes being a prime example [1]. A combination of experiments has yielded a consistent picture of two distinct shapes: a nearly-spherical ground state and a more deformed (prolate) one at low energies, corresponding to 2-proton promotions across Z=82. For the transitional isotopes between the stable ^{200}Hg and the beginning of the midshell ^{190}Hg, these two shapes are still reasonably separated in energy (the relative energy of the intruder states has a parabola-shape with a minimum at ^{182}Hg), thus reducing to negligible levels the mixing between the two bands. These presented a great opportunity to benchmark the normal ground-state configuration without the perturbations experienced in the lighter isotopes, simplifying the comparison with different theoretical calculations.

A systematic study of the decay of the n-deficient $^{188-200m}$Tl into Hg was performed using the GRIFFIN spectrometer at TRIUMF-ISAC. Lifetimes, angular correlations and conversion electrons were measured and B(E2) and ρ^2(E0) values extracted. For the transitional Hg isotopes, any significant mixing was discarded between the two shapes [2]. However, when the study was extended to the lighter ^{188}Hg, some hints appeared that maybe the structure inside the mid-shell cannot be simplified to a two-level mixing [3].

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Transitional nuclei and shape coexistence / 81

Competing structures in 186Pb nucleus

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In the atomic nucleus, the interplay between single-particle motion, collectivity and pairing is seen as a rich tapestry of coexisting nuclear shapes and exotic excitations. One of the richest regions is formed by very neutron-deficient nuclei with the proton number Z close to the magic 82 and the neutron number N close to 104 midshell [1-3]. A considerable body of both theoretical and experimental evidence has been gathered for coexisting configurations possessing different shapes in this region, yet there are many open questions to be answered. In this presentation, our new experimental findings on 186Pb obtained employing simultaneous in-beam g-ray and electron spectroscopy using the SAGE spectrometer [4] will be discussed.
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Clustering and shape-phase transitions in nuclei and other physical systems / 17

Sensitivity of the γ-decay of the Pygmy Dipole Resonance to nuclear deformation

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Axial nuclear deformation results in a splitting of the isovector Giant Dipole Resonance into two parts, corresponding to oscillations along and perpendicular to the symmetry axis of the nucleus (K-splitting). A similar sensitivity is expected for the Pygmy Dipole Resonance (PDR) [1], a low-lying enhancement of E1 strength observed for heavy nuclei that is often attributed to a semi-collective oscillation of a neutron skin.

In recent years, the dipole response in the PDR energy region has been studied for several heavy nuclei using quasi-monochromatic linearly polarized photon beams [2] provided by the High Intensity γ-ray Source (HIγS). In this work, the dipole response of ^{150}Nd ($P = 4.4$) located close to the critical point X(5) was studied in nuclear resonance fluorescence experiments. The resulting average decay branches and partial photoabsorption cross sections are presented and compared to results for other deformed and non-deformed nuclei in the same mass region.

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Transitional nuclei and shape coexistence / 69

Shape evolution in neutron-rich nuclei around mass 100: lifetime measurements in Zr isotopes

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Nuclei around N=60, Z=40 show a rapid variation in the deformation of their ground state with a rather small change in the neutron number. This feature manifests a subtle interplay between different aspects of the forces in the nucleus and makes this region an ideal testing ground for various nuclear structure theories. As an example, it is established that the ground state of Zr isotopes vary from nearly spherical for N<60 to well deformed after N=60 [1–4]. However, the drastic shape transition in Zr beyond N=60 is still a challenge for the description of different theoretical models [5–11].

Lifetime measurements are an effective way to shed light on the shape evolution in this region of the Segrè chart. For this purpose, a successful experiment was performed in 2017 at GANIL by using the γ-ray tracking array AGATA [12] coupled to the magnetic spectrometer VAMOS [13]. The Orsay Universal Plunger system [14] was installed allowing lifetime measurements in the order of the picosecond with the Recoil Distance Doppler Shift technique [15]. The data set obtained from this experiment contains hundreds of isotopes and is producing many new lifetime results.

In this contribution I will present preliminary results for transition probabilities obtained for $^{98-104}$Zr isotopes by applying the Differential Decay Curve Method of analysis [15], both in single gamma and in coincidence gamma-gamma.

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Excited-state quantum phase transitions / 73

Detection of excited state quantum phase transition with a Kerr-nonlinear resonator

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Kerr nonlinear resonators have been used to study dynamical bifurcation, to squeeze quantum fluctuations, and to prepare Schroedinger cat states. They can be realized by coupling a superconducting two-level system to a microwave cavity. This is also the setup for the transmon qubit adopted by companies such as IBM, Google, and Rigetti. We show that the experimentally detected spectrum of a Kerr-nonlinear resonator signals the presence of an excited state quantum phase transition. The analysis of the classical limit of the Hamiltonian explains the origin of the quantum critical point and its consequence for the quantum dynamics, which includes the exponential growth of out-of-time ordered correlators.

Empirical aspects of quantum phase transitions in nuclei / 83

Aspects of ‚Empirical Aspects'

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The 10th edition of the International Workshop on Quantum Phase Transitions in Nuclei and Atomic Systems and other anniversaries call for some remarks on the development of this topic. I will point out crucial milestones for determining empirical aspects of quantum phase transitions and critical-point phenomena in nuclei and give an introduction to this session and to the rationale of structuring its content.

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Novel aspects and signatures of QPTs in nuclei / 24

A Novel Interpretation of the Wobbling Motion in 163Lu

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One of the fingerprints for nuclear triaxiality, i.e., wobbling motion, present in ^{163}Lu is described within a semi-classical formalism that introduces the concepts of Signature Partner Bands and Parity Partner Bands, which are amended to a Particle-Rotor Model. These two ideas help re-defining the band structure of this isotope in such a way that the experimental wobbling spectrum can be accurately reproduced with a set of equations that depend on the moments of inertia of the nucleus and the triaxiality parameter. Besides the energy spectrum, a geometrical representation of the classical energy function is realized within a phase space that characterizes the motion of the entire particle + rotor system. Moreover, a three-dimensional sketch that shows the allowed trajectories of the system (defined as intersections between the energy ellipsoid and the angular momentum sphere) is realized for several values of excitation energy and spin. The current re-interpretation of the wobbling bands for ^{163}Lu proves to be a useful approach for providing a realistic description of the wobbling phenomenon, and moreover it gives an insight into the classical geometry that arises in triaxial shapes.

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Lifetime measurements around A = 100 with pγ-concidence DSAM

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Nuclear level lifetimes, together with branching ratios and multipole-mixing ratios, give access to transitions strengths between excited states. Such information can be used to examine the nature of these states and underlying common structures and can be indicative of nuclear-structure phenomena such as shape coexistence.
A method targeting lifetimes of excited low-spin states in the order of fs up to ps is the Doppler-shift attenuation method (DSAM). It uses the continuous velocity decrease of a recoiling nucleus excited by a projectile within a stopper medium and its connection to the Doppler-shift of γ-rays emitted by this nucleus. The detection of the emitted photons in coincidence with the scattered charged projectile gives complete reaction kinematics, allowing the determination of both the recoil velocity and the excitation energy. This way, direct excitations can be selected and feeding from higher-lying excitations is excluded [1].
Such coincidence data have been measured with the SONIC@HORUS array [2] at the 10 MV FN tandem accelerator of the University of Cologne. It consists of the γ-ray detector array HORUS with 14 HPGe detectors. Mounted into the center of HORUS is SONIC, a particle detector array with 12 silicon detectors positioned in three rings under backward angles where scattered particles are detected, exploiting the higher momentum transfer under backward angles. Together, SONIC@HORUS allows to form 168 particle-γ detector combinations resulting in various different Doppler angles. Lifetimes of dozens of states can be extracted from a single experiment.
In recent years, extensive studies with the pγ-coincidence DSAM have been performed on the isotopic chains of Sn [3], Ru [1,4,5] and Te [6] at or near the Z = 50 and N = 50 and 82 shell closures, inspecting nuclei at closed shells as well as towards midshell. In this contribution, the pγ-coincidence DSA method will be presented and some results of recent experiments will be shown.

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Novel aspects and signatures of QPTs in nuclei / 48

Quantum simulation and quantum phase transitions of an extended Agassi model

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Quantum simulations provide a fast-developing and powerful tool to realize the analysis of various physical systems of quantum nature and should be able to outperform classical computers and solve previously intractable problems. As such, many experimental setups are being proposed to validate the feasibility of the quantum simulation of different physical models. In this work, we study an extended Agassi model, which describes a many-body system in Nuclear Physics. It is a two-level

system that includes a combination of long range monopole-monopole and short range pairing interactions. Also, it presents a very rich quantum phase diagram that gives rise to several quantum phase transitions (QPTs) of different character. Here, we introduce this model, propose an experimental setup for its quantum simulation and analyze its QPTs using machine learning tools.

Symmetries of interacting boson and/or fermion systems / 54

Structure of low-lying quadrupole states of polonium isotopes in the vicinity of 208Pb

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The nuclei with few proton and neutron particles (holes) away from doubly-magic nuclei are the simplest nuclear systems in which both nuclear collectivity and the two-fluid nature of the nuclear matter can simultaneous be manifested. The relatively small number of valence particles (holes) allows the low-lying collective states in these nuclei to be described in the shell-model framework. The comparison of shell-model results with experimental data reveals the microscopic structure of these states and allows one to identify and, eventually, adjust the two-body matrix elements of the effective shell-model interaction which give rise to the configuration mixing responsible for the observed properties of the collective states.
The nuclei in the vicinity of the doubly magic nucleus 208Pb have attracted significant interest in last several years. In the present contribution I will present the results from several lifetime measurements aimed to the properties of low-lying quadrupole states of 208, 210, 212Po. The results will be discussed in the shell-model framework with a focus on the onset of quadrupole collectivity and on the properties of low-lying quadrupole isovector excitations.

Excited-state quantum phase transitions / 39

Constant of motion identifying excited-state quantum phases and some applications to quantum optical models

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ESQPTs have an important drawback compared with quantum and thermal phase transitions: it is not easy to define two different phases, with different equilibrium properties, separated by the corresponding critical energy. In this talk, I will review our work [1], where we proposed a way to address this issue. We find an operator which is a constant of motion only in one of these two phases. This allows us to define two different phases at both sides of the ESQPT: one in which equilibrium thermodynamics depends on this new constant of motion, and another one in which this observable plays no relevant role. The main characteristic of this operator is that it acts like a discrete symmetry in the first of these phases, with just two possible eigenvalues. Hence, we propose that the trademark of this phase in many systems displaying ESQPTs, like the Dicke and Rabi models, is having two different discrete symmetries: parity and this new constant of motion. We show analytically that these two operators are noncommuting. This explains one of the typical features of this kind of ESQPTs: the transition from degenerate doublets to non-degenerate energy levels. Numerical results in the Rabi and Dicke models show that the expectation values of observables in equilibrium crucially depend on this new constant of motion in the corresponding phase. Furthermore, its mere existence implies a number of relevant consequences for example linked to chaos [2], and allowing for the generation of certain cat states [3].

References:

[1] A. L. Corps and A. Relaño, \textit{Constant of Motion Identifying Excited-State Quantum Phases},

Phys. Rev. Lett. \textbf{127}, 130602 (2021).
[2] A. L. Corps, R. A. Molina and A. Relaño, \textit{Chaos in a deformed Dicke model}, J. Phys. A: Math. Theor. \textbf{55}, 084001 (2022).
[3] A. L. Corps and A. Relaño, \textit{Energy cat states induced by a parity-breaking excited-state quantum phase transition}, Phys. Rev. A \textbf{105}, 052204 (2022).

Density functional and beyond-mean-field approaches to QPTs in nuclei / 15

Beyond-mean-field approaches for nuclear neutrinoless double beta decay

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Neutrinoless double beta decay, if it exists, would provide a crucial probe to fundamental symmetries in nature. Over the years, it has been investigated with many different methods ranging from mean-field approaches based on the quasiparticle random-phase approximation over investigations within the Interacting Boson Model and configuration mixing calculations in restricted configuration spaces. In this talk, we discuss calculations of the nuclear matrix elements for neutrinoless double beta-decay based on beyond mean-field methods in relativistic and non-relativistic density functional theories. In particular, we also present recent progress in the microscopic derivation of relativistic mean-field applications for asymmetric nuclear matter and for finite nuclei.

Density functional and beyond-mean-field approaches to QPTs in nuclei / 71

Quantum phase transitions in microscopic nuclear structure calculations

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Studying the structure of the atomic nucleus from its constituent interacting particles is a difficult task. One of the most successful methods to tackle the nuclear many-body problem from a microscopic perspective is based on the definition of non-relativistic and/or relativistic energy density functionals (EDFs). In this contribution I will summarize some quantum phase transitions that could be identified with mean-field and beyond-mean-field EDFs, in particular, those related to shape and/or pairing degrees of freedom.

Density functional and beyond-mean-field approaches to QPTs in nuclei / 78

Shape coexistence with Gogny EDF: recent results

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Gogny energy density functionals including beyond-mean field effects are the perfect theoretical tool to study the shape evolution and potential shape mixing and coexistence along isotopic/ isotonic chains. In this presentation I will discuss recent calculations within the symmetry conserving configuration mixing method (SCCM) performed in the cadmium isotopic chain, in particular, I will show the overall description of excitation energies and transition probabilities, as well as the detailed description of different collective bands in 110-112Cd isotopes.

References:

1. Lifetime Measurements in the even-even 102−108Cd Isotopes, M. Siciliano et al., Physical Review C 104, 034320 (2021).

2. Shape coexistence and multiparticle-multihole structures in 110, 112Cd, P. E. Garrett et al., Physical Review C 101, 044302 (2020).

3. Multiple Shape Coexistence in Cd 110,112, P. Garrett et al., Physical Review Letters 123, 142502 (2019).

Symmetries of interacting boson and/or fermion systems / 75

Symmetries of the IBFFM and transfer reactions between odd-odd and even-even nuclei by using IBFFM

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Symmetries of the IBFFM will be discussed and Spectroscopic Amplitudes (SA) in the Interacting Boson Fermion Fermion Model (IBFFM) are necessary for the computation of $0\nu\beta\beta$ decays but also for cross-sections of heavy-ion reactions, in particular, Double Charge Exchange reactions for the NUMEN collaboration, if one does not want to use the closure limit. We present for the first time: the formalism and operators to compute in a general case the spectroscopic amplitudes in the scheme IBFFM from an even-even to odd-odd nuclei, in a way suited to be used in reaction code, i.e., extracting the contribution of each orbital. The one-body transition densities for ^{116}Cd $\rightarrow$ ^{116}In and ^{116}In $\rightarrow$ ^{116}Sn are part of the experimental program of the NUMEN experiment, which aims to find constraints on Neutrinoless double beta decay matrix elements [1].

[1] https://arxiv.org/pdf/2101.05659 submitted to PRC

Clustering and shape-phase transitions in nuclei and other physical systems / 86

Magnetic dipole moments as a signature for α-clustering in even-even self-conjugate nuclei

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The magnetic dipole moments in even-even self-conjugate nuclei from ^{12}C to ^{44}Ti are investigated. For the latter, the measured gyromagnetic factors of excited states turn out to assume the same value of $g \approx +0.5$ within statistical errors. This peculiar feature can be interpreted on the basis of collective excitations of α-clusters. Analogously, the behaviour of the same observable is studied for all isotopes obtained by adding one or two neutrons to the considered self-conjugate nuclei. It is found that for the $N = Z + 1$ isotopes the α-cluster structure hardly contributes to the observed negative gyromagnetic factor, corroborating molecular α-cluster models. The addition of a further neutron, however, restores the original α-cluster g-factors, except for the semi-magic isotopes, in which the deviations from $g \approx +0.5$ can be associated with the relevant shell closures. Secondly, the same observable is analyzed in the framework of a macroscopic α-cluster model on a finite lattice of side length L. In particular, discretization effects induced in the magnetic dipole moments of the 2_1^+ and the 3_1^- states of ^{12}C at different values of the lattice spacing a are discussed. The context provides eventually the opportunity to probe the effectiveness of the existing approaches in reducing the artifacts introduced by a finite lattice spacing.

Empirical aspects of quantum phase transitions in nuclei / 18

M1 Transition strenght of the mixed-symmetry 2+ state of 132Te

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The one-phonon mixed-symmetry 2^+ of ^{132}Te is of high interest due to the specific structure of this nucleus, with two valence-proton particles and two valence-neutron holes with respect to the doubly-magic nucleus ^{132}Sn. In recent experiments, the second excited 2^+ state has been assigned as the one-phonon mixed-symmetry 2^+ state [1], due to the high B(M1) transition strength between this state and the 2^+_1 state, which is the proton-neutron symmetric counterpart of the mixed-symmetry state. However, the obtained value is highly uncertain and extraordinarily large with 5.4(3.5) μ_N^2, mainly due to the $50\,\%$ uncertainty in the reference value of its decay branching ratio to the 2^+_1 and 0^+_1 state [2].

By populating the 2^+_2 state in a two-neutron transfer reaction ^{130}Te(^{18}O,^{16}O)^{132}Te at IFIN-HH in Romania, it was now possible to obtain a more precise value for the B(M1) transition strength. This was achieved by determining the lifetime after performing a lineshape analysis of the deexcitation γ-rays using the Doppler-shift attenuation method.

[1] M. Danchev *et al.*, Phys. Rev. C **84** (2011) 061306(R)

[2] R. O. Hughes *et al.*, Phys. Rev. C **71** (2005) 044311

Excited-state quantum phase transitions / 79

Stabilization of quantum states at ESQPTs

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It is well known that ESQPTs can either enhance or suppress survival probability of the initial state after a quantum quench. These effects, theoretically demonstrated particularly in the Lipkin model, the Tavis-Cummings model and the Rabi model, see e.g. Refs. [1,2], represent a possible experimental test of criticality in the excited domain. We will show the common origin of both these phenomena and provide their semiclassical explanation in terms of Wigner quasiprobability distributions.

References:

[1] M. Kloc, D. Šimsa, F. Hanák, P.R. Kaprálová-Žďánská, P. Stránský, P. Cejnar, Phys. Rev. A 103, 032213 (2021).
[2] P. Stránský, P. Cejnar, R. Filip, Phys. Rev. A 104, 053722 (2021).

Novel aspects and signatures of QPTs in nuclei / 56

Probing nucleon-nucleon correlations in heavy ion transfer reactions

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The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighbouring states. The two-nucleon transfer reactions turned to be a very specific probe of this pairing.

The experimental transfer probabilities for one- and two-neutron transfer channels as a function of the distance of closest approach have been extracted for the closed shell 40Ca+96Zr, superfluid 60Ni+116Sn and heavy 118Sn+206Pb systems, from the Coulomb barrier energy to energies corresponding to large distances of closest approach. For the superfluid 60Ni+116Sn system, the experimental two-neutron transfer probabilities were reproduced by incorporating neutron-neutron correlations (D. Montanari et al., Phys. Rev. Lett. 113 (2014) 052501).
Very recently, this study has been characterized as the nuclear analogue
to the (alternating-current) Josephson effect (G. Potel, F. Barranco, E. Vigezzi, and R. A. Broglia, Phys. ReV. C 103 (2020) L021601).

The talk will focus on the main outcome of these recent studies, critically addressing the new achievements, the present problems and new challenges.

Symmetries of interacting boson and/or fermion systems / 28

Manifestation of the Berry phase in the atomic nucleus 213Pb

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I will present some of our later results on the ^{213}Pb neutron-rich nucleus [1] studied using the unique availability of a primary 1 GeV A ^{238}U beam and of the FRS-RISING setup at GSI. The products of the uranium fragmentation were separated in mass and atomic number and then implanted for isomer decay γ-ray spectroscopy. A level scheme from the decay of the $21/2^+$ isomer, based on γ intensities, γ-γ coincidences and state lifetimes was built up and the $E2$ transition probabilities from the $21/2^+$ isomer to two low-lying $17/2^+$ levels were also deduced.

This experimental data has evidenced one of the best examples of a semi-magic nucleus with a half-filled isolated single-j shell where seniority selection rules are obeyed to a very good approximation. In the most simple shell-model approach ^{213}Pb can be described as five neutrons in the $1\mathrm{g}_{9/2}$ orbital on top of the ^{208}Pb core. Large scale shell-model calculations in the full valence space beyond ^{208}Pb confirm that although the $1\mathrm{g}_{9/2}$ orbital is not isolated in energy, it is found to carry the dominant component in the wave function of the low-energy states. The experimental level scheme and the reduced transition probabilities are in good agreement with the theoretical description that predicts the existence of two $17/2^+$ levels of a very different nature: one with seniority $v = 3$, while the other with $v = 5$. The absence of mixing between the two $17/2^+$ states follows from the self-conjugate character of ^{213}Pb, where the particle-hole transformation defines an observable Berry phase that leads to the conservation of seniority for most but not all states in this nucleus.

The Berry phase [2], which is a gauge-invariant geometrical phase accumulated by the wavefunction along a closed path, is a class of observables that are not associated with any operator. It is a key feature in quantum-mechanical systems, that has far reaching consequences, and has been found

in many fields of physics since its postulation in the eighties. In the atomic self-conjugate nucleus ^{213}Pb, the quantized Berry phase is evidenced by the conservation of seniority under the particle-hole conjugation transformation. In atomic nuclei no experimental signature of the Berry phase was reported up to now.

[1] J.J. Valiente-Dob\'on et al., Physics Letters B 816, 136183 (2021).
[2] M. V. Berry, Proc. Roy. Soc. A392, 45 (1984).

Symmetries and quantum phase transitions in nuclei / 33

The symmetry structure of octupole phonons in nuclei

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Nuclei with a closed-shell configuration for neutrons and protons exhibit low-energy excitations with angular momentum J=3 and negative parity. Such excitations are associated with nuclear shapes that break reflection symmetry and, in particular, with pear-like or octupole shapes. In this talk the symmetry structure of octupole excitations is discussed and the question of their phonon-like behaviour is addressed. It is shown that with some simple assumptions concerning single-particle energies and nucleonic interactions octupole excitations obey universal symmetry properties. The results of this schematic approach are compared with those of a realistic shell-model calculation for 208Pb. An extension to odd-mass is also discussed.

Empirical aspects of quantum phase transitions in nuclei / 70

Signs of shape coexistence in mid-shell Te isotopes

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Many examples of shape coexistence are found, when one type of nucleon is at or close to a shell closure and the other type approaches midshell. This holds also for the Z=50 shell gap at the tin isotopes [1]. Shape coexistence in the region is attributed to 2p-2h intruder states in Sn, or 2p-4h states in Cd. This discovery led to a change in the perception of many nuclei especially in the Cd isotopic chain, that had been regarded as prime examples of vibrational excitations up to that point. Shape coexistence in Te isotopes has long been suspected, but experimental evidence is still scarce. The energy systematics of low lying 0_2^+, 0_2^+ and 2_3^+ states makes these states possible candidates for 4p-2h states [3], but information on E0 and E2 transition strengths is often lacking [2].
We want to present recent lifetime measurements in $^{112-120}$Te, that have been performed using the recoil-distance Doppler-shift method. The nuclei of interest were populated in fusion-evaporation reactions. The lifetime of low-lying yrast states and their absolute transition strengths could be determined in all cases with the differential decay-curve method. The resulting B(E2,$2_1^+ \rightarrow 0_1^+$) systematics confirm the collective nature of the low lying states. The $B_{4/2} = \frac{B(E2,4_1^+ \rightarrow 2_1^+)}{B(E2,2_1^+ \rightarrow 0_1^+)}$ ratio suggests that in these Te isotopes - as in the Cd isotopes - a vibrational picture is too simple.
We want to conclude with an outlook on upcoming spectroscopic and lifetime measurements in neutron-midshell Te isotopes, which comprise also the low-lying off-yrast states. This will allow to further clarify the role of shape coexistence.

References
[1] P. Garrett *et al.*, Journal of Physics G: Nuclear and Particle Physics **43(8)** 084002 (2016).
[2] P. Garrett *et al.*, Progress in Particle and Nuclear Physics **124** 103931 (2022).
[3] J. Rikovska *et al.*, Hyperfine interactions **22** 405-412 (1985).

Clustering and shape-phase transitions in nuclei and other physical systems / 4

Localization and clustering in nuclei

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Nucleon localization, and formation of clusters in nucleonic matter and finite nuclei are explored in a framework based on nuclear energy density functionals. The liquid-cluster transition is investigated and different measures of localization are discussed. The formation and evolution of alpha-clusters in excited states of light and heavy nuclei are analysed.

Empirical aspects of quantum phase transitions in nuclei / 53

Boundaries of the QPT and evolution of deformation in rare earth nuclei

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Recent work on the neutron-rich 148Ce showed that it marks the boundary of the N=90 shape-phase transitional region. However, a model analysis within the IBM shows its proximity to the QPT, however, involving the gamma-degree of freedom. This is brought into context with the evolution of trajectories in the symmetry space (Casten triangle) and the NpNn formalism, in which larger numbers of valence particles should invoke larger deformation and correspondingly evolving basic observables like E(2+) and B(E2)s. Seemingly, data on E(2+) energies in rare-earth isotopes are contradictory to this expected trend and - in view of newly emerged theoretical approaches to very deformed systems - motivate a new strain of experimental work.

Transitional nuclei and shape coexistence / 7

The Shape-Phase Transition(s) in Zr Isotopes

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An overview on the status of the QPT, or even intertwined QPT, in Zr isotopes above N=50 will be given, mainly from the experimental side, but brought into context with recent MCSM and IBM type calculations.