**Etude de la déformation nucléaire**

**Nom, Prénom, laboratoire**

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**Scientific Objectives:**

Theoretical description of the nuclear behavior observed through experiments reveals competing forms of the interactions acting among the nucleons in the nucleus, interactions which are non-central, non-local and depend on the energy of the interacting particles. Numerous studies confirm repeatedly the success of the nuclear mean-field theory with the simplifying concept of free nucleons moving in a common effective-potential well, which simulates certain features of a `mesoscopic’ body. Today it is known that numerous mechanisms exist related to specific orbitals or to various forms of collective behavior typical of such a mesoscopic system. The notion of the mean-field potential implies the notion of the nuclear deformation introducing the concept of geometrical symmetries, related selection rules and hindrance properties, collective rotations and shape vibrations. As a natural consequence, the combined effects of rotation, pairing and nuclear symmetries conspire creating various forms of competitive evolution as function of increasing angular momentum and excitation or temperature. One of the promising paths towards geometrical symmetry exploration involves the concept of tetrahedral and octahedral (the so-called high-rank) symmetries and deformations presented below.

**Moderate spins and high-rank nuclear deformation**

The studies of new exotic nuclear symmetries include the search for tetrahedral and octahedral symmetries and their underlying nuclear deformations. It follows in particular that tetrahedral symmetry generates a non-axial octupole deformation of the nucleus. Some of the intriguing new phenomena predicted to accompany tetrahedral symmetry are 4-fold degeneracies of certain nucleonic orbitals (rather than the usual 2-fold spin-up/spin-down Kramers degeneracy) or 16-fold degeneracies of the particle-hole exited states and 32-fold degeneracies of the 2-particle 2-hole excited states, etc. New classes of isomeric configurations producing possibly new waiting-point nuclei important for the astrophysical modelling of the stellar processes or detection of new exotic nuclei could also be expected.

**High spin states in the normal (as opposed to super-) deformed nuclei**

At moderate and increasing nuclear deformations, several topics, such as the nuclear pairing phase-transition or the structure beyond the termination of rotational bands open fundamental questions about changes in nuclear behavior with varying spin.

Phase transitions are among the most fascinating collective phenomena, which engage significant subsets of nucleons in the system. They lead “all of the sudden to changing” from one phase to another, e.g. from the nuclear superfluid phase, in which the nuclear moment of inertia is about 50% of the rigid body value, to the “normal” phase, in which the moment of inertia takes the corresponding rigid body value. This transition may be induced by increasing collective rotation or, alternatively, the nuclear temperature. What are the mechanisms which initiate these transitions? Why aligning one pair in a nucleus can lead to the partial or complete disappearance of nuclear super-fluidity? Despite the success of theoretical approaches based on the nuclear mean-field theory, the deep understanding of the mechanisms engaged such as coupling with collective oscillations or the symmetry change and shape transitions - remains challenging.

At high spins, the shape instabilities or deformation softness may give rise to a dramatic shape and structure evolution with increasing spin manifested as disappearance of the nuclear rotational collectivity known as band termination. When this happens, the single-nucleon angular momenta contributing to the high total-spins of the nucleus can be considered precessing along a symmetry axis.

The nuclear motion at angular momenta in the vicinity of the critical spins of Jacobi transitions involves dramatic shape instabilities. Indeed, the shape can oscillate between strongly oblate and prolate ranges with elongations exceeding those observed for super-deformation, while the excitation energy changes only by a few hundreds of keV. Such dramatic shape variations at almost no energy cost are accompanied by virtually dozens of individual nucleonic level crossings what corresponds to equally dramatic intrinsic structure rearrangements. Given the fact that various orbitals, which participate in these level crossings, have significantly different nodal structures (spatial distributions of the nucleons) and the fact that all of them are accompanied by virtually negligible energy changes brings us to a concept of a new state of matter and/or phase transitions, similar to those intensively studied in condensed-matter physics.

**Nuclear structure at extreme shape deformation**

The phenomenon of nuclear super-deformation (SD), from the quantum nuclear-structure theory view point, is a manifestation of the so-called pseudo-SU(3) symmetry. Based on this concept, SD bands were predicted in many mass regions before their experimental discovery and established later on showing the presence and/or absence of this mechanism in various mass regions in full correspondence with the theoretical predictions.

Hyper-deformed (HD) structures are also predicted, but have not yet been found experimentally due to the lack of resolving power of the previous-generation -ray spectrometers. Such studies can bring information about specific single-nucleonic shell configurations and their impact on stabilisation of nuclear matter on the way to fission. As known today, the population of the very elongated nuclear shapes is strongly related to the presence of the nuclear Jacobi shape transitions at high temperature in the compound nucleus involving the so-called Coriolis splitting of the giant dipole resonance (GDR).

Several theoretical developments based mainly on various applications of the nuclear mean-field theory, are employed to predict and describe the existence, feeding and decay modes of these structures at extremely high-spin. Such efforts should be favored with the goal of deepening the understanding of the nuclear structure changes and evolution in the whole Segre chart and including the very high-spin limits at varying temperature.

The related studies address the following questions:

* What is the impact of exotic nuclear symmetries on nuclear behavior, new hindrance mechanisms and on the stellar nucleo-synthesis processes?
* What is the relation between nuclear super-fluidity and single-particle structure?
* What are the forms of nuclear behavior and/or possible phase transitions, in particular at spins beyond the band termination?
* What is the impact of nuclear structure effects on the process of nuclear fission?
* How pseudo-SU(3) symmetry stabilizes the extremely deformed nuclear shapes from the ground-state up to the highest angular momenta?

**Experimental methods:**

Nuclear fusion can be considered as the main avenue to high-spin state feeding. It can be initiated using a large variety of intense stable beams at about 6 MeV/A and various targets. For example, moderate spins for exotic (such as tetrahedral) symmetry studies may be populated with α or C beams whereas high- and extremely high-spin states can be populated with heavier (A up to ~90) beams. The latter states may be better fed preferably in mass-symmetric reactions. Fission barriers being higher in neutron-rich nuclei, HD structures are expected to better survive fission in such nuclei and therefore very intense neutron-rich radioactive beams are the best choice to populate the HD shapes.

A new way to studying the high-rank symmetry structures is to identify them through rotational-like series of long living isomers. Those very special isomers are expected as the result of the symmetry-imposed restriction that the quadrupole and dipole moments of the high-rank symmetry states vanish. This hinders the usually strongest decay channels leading to isomeric states (see Instrumentation section).

**Experimental Facilities:**

Large intensity stable beams are delivered in LNL, Italy and GANIL, France. Intense Radioactive Ion Beams (RIBs) with the appropriate energies will be soon available in LNL with the advent of SPES but also at HIE-ISOLDE, Switzerland, FRIB, USA and RIKEN, Japan. FAIR is the perfect place for searching the long-lived isomers via mass-spectrometry measurements profiting from the high-rank symmetry electromagnetic hindrance of the otherwise strong collective transitions.

**Instrumentation:**

**Nuclear state studies at moderate spins and high-rank symmetry shapes**

A partial symmetry breaking caused, e.g., by the zero-point motion may lead to some electromagnetic signals from the very special tetrahedral configurations. They are expected to be very weak and specific analysis techniques have to be introduced, where the application of high-efficiency gamma-ray arrays such as AGATA will be particularly important in searching for these intricate signals. While at the exact tetrahedral and octahedral symmetry limits the nuclei would exhibit neither E2 nor E1 collective transitions, such exact symmetries are never physically present due to different symmetry breaking processes, not only the zero-point motion in the `quadrupole-direction’ in the deformations space but also Coriolis coupling of the high-j orbitals to the collective-rotation angular momentum vector.

Consequently, AGATA will be primordial for detecting the weak collective E2 and E1 signals originating from the configurations with partially broken symmetries. Similarly, the E3 transitions between specific states along the tetrahedral bands can be sought. Such structures are predicted in stable nuclei (for example 96Zr and 152Sm) as well as in exotic isotopes (e.g. 104Zr).

Another promising high-rank symmetry fingerprint is the presence of long-lived isomers in doubly magic tetrahedral nuclei and in the neighboring nuclei. Exploratory works will soon be conducted at the FRS Ion Catcher (GSI) with the use of mass spectrometry (MR-TOF-MS). This new work will open up the possibility for a full SUPER FRS (FAIR) program of isomeric beams studies with Ge detectors and possibly AGATA.

**High spins in the normal-deformed nuclei and at extreme deformations**

In the above mentioned physics cases, the highest -ray detection efficiency is mandatory, as provided by the most powerful 4gamma-ray spectrometer AGATA. Only in this case the necessary sensitivity can be achieved by exploiting very high-fold n coincidences. In addition, the pulse-shape analysis and tracking properties will allow obtaining the best possible energy resolution and optimizing the peak-to-background ratio, both of which are also important in maximizing the detector sensitivity.

A coupling of the AGATA array to detectors such as PARIS (for GDR detection), GRIT (for charged particle identification) and a detector of fission fragments for fission rejection (such as RFD) would enable a breakthrough in the studies of the HD-structure feeding driven by GDR and lead to the discovery and study of the extremely deformed HD bands. A 0° spectrometer to select fusion products and reject fission fragments would permit a drastic background reduction necessary for the identification of these extremely weak evaporation channels. A mass selectivity as well as atomic number sensitivity would greatly help identifying the emitting nuclei.

**Strategy:**

The goal of our project is to adapt the physics cases to the progressive construction of AGATA from 4π/3 in 2022 to 4π in 2030. High-rank symmetries as well as pairing phase transition search and studies may be started right now with the present AGATA configuration. High-spin and extremely high-spin studies may be started with the AGATA 2π configuration, which covers the stay of AGATA at LNL, using intense stable or SPES beams. Installation of AGATA in HIE-ISOLDE around 2026 would enable using the intense neutron-rich beams in the HD structure studies. The coming back of AGATA in a more complete configuration to GANIL would open new perspective for high-spin studies.