New, shape-related nuclear phenomena

K 128947
Final report

Atomic nucleus is a special quantum many body system which, in a good approximation, has geometrical shape. This shape is plastic and it is affected by the nuclear excitation. Thus, there is a complicated interaction between excitation, intrinsic state and the nuclear shape, which leads to interesting phenomena. The reported project aimed at studying several recently observed or predicted such phenomena especially in two main categories. One is studying two recently predicted phenomena related to the triaxially deformed shape of the nucleus, the multiple chiral bands and the wobbling motion, or tilted precession. The other is studying the role of deformation in the evolution of the shell structure.

Multiple chiral bands have been reported previously in a few nuclei with a considerable contribution of our group. In the reported project we planned to study if this phenomenon is as frequent as the nuclear chirality itself. The wobbling motion has previously been observed only in one normal-deformed nucleus. Our aim was to explore if it exists in other nuclei, with other configuration. The study of shell closures is one of the main topics of the contemporary nuclear structure research, to which topic our group made a considerable contribution previously. We planned studying the shape changes, shape coexistence as well as the effect of nuclear deformation on the properties of single-particle states near the shell closures.

These studies could only be performed in international collaborations using special, large gamma- and charged-particle detector arrays. For this reason, the COVID-19 pandemic affected considerably the details of our planned research. Due to the restrictions related to the pandemic, some planned experiments have been canceled, and possibilities to propose new experiments have also been cut. In these cases, we modified our plan, and studied other shape-related phenomena which could be reached experimentally, or for which data were available from previous experiments. The pandemic also caused the prolongation of the project by 18 months.

In spite of the pandemic, the research project has been successful. We have achieved important results on the shape related nuclear phenomena, which we published in 51 papers in high-rank journals of the field (EPJ A, Phys. Rev. C, Phys. Lett. B, Phys. Rev. Lett., Nature).
The details of these results are briefly summarized in the followings.

1) *Results related with triaxially deformed or other deformation shapes in rotational bands:*
a) *Chirality:*
- A new pair of positive-parity chiral doublet bands have been identified in ^{135}Nd which together with the previously reported negative-parity chiral doublet bands constitute a third case of multiple chiral doublet bands in the A ~ 130 mass region [1].
- We have found that in ^{131}Ba the chiral bands with opposite parity are directly connected by many E1 transitions, without involving an intermediary non-chiral

configuration. This is the first observation of multiple chiral bands in the presence of enhanced octupole correlations and pseudospin symmetry [2].

- We have also observed chiral doublet bands in ^{137}Nd. With this observation the series of Nd nuclei showing multiple chiral bands became the most extended sequence of odd–even and even-even nuclei presenting multiple chiral bands in the chart of nuclides [3].
- Two new rotational bands have been identified in ^{119}Cs, which is the first observation of candidate chiral bands built on a configuration with three protons [4].

b) *Wobbling or tilted precession:*

- We have found experimental evidence for the anticipated transverse wobbling in ^{105}Pd. This observation provides the first evidence for transverse wobbling bands based on a one-neutron configuration, and is also the first observation of wobbling motion in the A $\sim$ 100 mass region [5].
- We have observed two new rotational bands in the triaxially deformed ^{135}Nd, for which bands the excitation mode corresponds to the tilted precession of the nucleus [6].
- We have shown experimentally the transverse wobbling nature of the two high-spin bands in ^{136}Nd built on the two-quasiparticle configuration $\pi h^2_{11/2}$ [7]. They were predicted by the triaxial projected shell model as good candidates of transverse wobbling bands.
- The electromagnetic character of the DI=1 transitions connecting the 1- to 0-phonon and the 2- to 1-phonon wobbling bands in ^{135}Pr has been re-investigated using combined angular correlation and linear polarization measurements, and found not compatible with the proposed wobbling nature [8].

c) *Results on other shape related phenomena in rotational bands:*

- In the A~90 mass region we observed “delayed” rotational alignment in the deformed N=Z ^{88}Ru nucleus, which shows the presence of strong isoscalar neutron-proton pair correlations [9], while in the semi-magic ^{95}Rh nucleus a simple one-neutron cross-shell excitation has been observed [10].
- In the A~120 mass region we have identified and interpreted ten new bands in ^{118}Cs [11], while in ^{119}Cs also many new bands have been observed and interpreted [12], and the first evidence has been found for prolate-oblate shape coexistence close to the ground state in this region [13]. In ^{119}Ba and ^{120}Ba we also identified new rotational bands and measured half lifes for one of the band heads [14,15]. The ^{123}Xe nucleus was also studied and several new bands have been identified. Some of them show shape transition [16], while others involve two-proton excitation across the Z=50 as well as excitation of neutrons across the N=82 shell gaps resulting in a large deformation [17].
- In the A~130 mass region a rich and complete level scheme has been observed for ^{130}Ba [18], while strongly coupled bands, associated with the ν[404]7/2+ configuration, was identified in ^{131}Ba and ^{133}Ce [19]. This is the first evidence for this configuration in the N=75 isotones. We have observed three new highly-deformed (HD) bands in ^{136}Nd [20], and found the collective rotation of the ^{137}Nd nucleus in its oblate deformed shape [21].
- In the A~150 mass region we have studied different nuclear shape related

phenomena in nuclei with 88 – 92 neutron numbers in the Dy region. The systematics of the experimental results and the theoretical interpretations have been published in [22,23,24].

2) *Results related with shape changes, shape coexistence and the effect of nuclear deformation on the properties of single-particle states near the shell closures:*
a) We studied the evolution of single-particle states near the shell closures at N=50 and N=32,34.
- *Structure of nuclei in the vicinity of the doubly magic ^{78}Ni:*
We have determined large B(E2) values for ^{73,74,75}Ni, which indicate an increasing contribution of proton excitations across the Z = 28 shell closure when approaching ^{78}Ni [25]. Prompt and isomer excited states for ^{78}Cu, ^{75}Cu, ^{75}Ni and high-spin states in ^{81}Ga have been identified at RIBF, RIKEN and at GANIL using the AGATA detector array. The proposed single particle, core-coupling, and intruder states have provided further insight into the evolution of the proton single-particle orbitals and the proton-neutron interaction as a function of neutron number [26,27,28,29,30]. We have explored the medium-spin band structure of the neutron-rich nuclei ^{87}Br and ^{89}Br using the EXILL Ge detector array. The observations revealed enhanced collectivity of the $\pi g_{9/2}$ band in both bromine isotopes [31,32].
- *Structure of nuclei around the new shell closures at N=32 and N=34:*
We have investigated states of very neutron-rich Ca, K and Ar nuclei. We have determined the strength of the N=32 neutron shell closure in ^{52}Ca measuring cross sections to bound final states in ^{51}Ca and the momentum distributions. The results showed that the N=32 shell closure as strong as N=28 and N=34 ones in other Ca isotopes, and that the large radius of the $p_{3/2}$ orbital in neutron-rich Ca isotopes is responsible for the unexpected linear increase of the charge radius with the neutron number [33]. Valence proton removals in ^{55}Sc populated predominantly the ground state of ^{54}Ca, which is attributed to pairing effects [34]. The observed low-lying level structures in ^{56}Ca and ^{58}Ca precluded the possibility for a doubly magic ^{60}Ca [35]. The experimental results obtained for ^{51}K and ^{53}K have been interpreted as a restoration of a sizeable Z = 16 sub-shell gap beyond N = 30, showing the suppression of proton-induced collectivity in the region [36]. Excited states established in ^{55}K, ^{55}Ca, and ^{57}Ca suggest a transition in the calcium chain from single-particle dominated states at N=35 to collective excitations at N=37 [37]. Below Z=20 we have investigated the excited states in the N = 32 isotope ^{50}Ar and ^{51}Ar [38,39]. The population of the bound and unbound states in ^{51}Ar indicates individual-particle and collective states coexistence in this nucleus.

b) We have mapped the shape changes approaching the island of deformations at N=20, N=40, and the structure of light nuclei.
- *Structure of nuclei around the island of inversion at N=20:*
We have observed ^{28}O and ^{27}O lying beyond the neutron drip line through proton-induced nucleon knockout reactions. Although ^{28}O is expected in the shell-model picture to be a doubly magic nucleus with Z=8 and N=20, the measured single-proton removal cross-section comparing with theory was found to be consistent with it not having a closed neutron shell character. This result suggests that the island of inversion at neutron number N=20 extends beyond ^{28,29}F into the oxygen isotopes

[40]. We have identified bound and unbound excited states with intruder configurations in ^{28}Ne and ^{29}Ne revealing a breakdown of the N=20 shell gap in the neon isotopes at the transition into the corresponding island of inversion [41]. The characteristics of the identified unbound states of ^{29}Ne confirm the increased splitting of the fp-shell intruder states in contrast to lighter neon isotopes [42]. The excited states with normal and intruder configurations of ^{34}Si lying at the border of the N=20 island of deformation have been identified in beta-decay measurements [43].

- *Structure of nuclei around the island of inversion at N=40:*

The low-lying level structure of nuclei ^{59}V, ^{61}V and ^{63}V was investigated via nucleon knockout reaction and inelastic proton scattering. While the large deformation parameters measured in ^{63}V placed this nucleus on the N=40 island of inversion, ^{61}V could not be unambiguously assigned to this deformation region due to the role of the hexadecapole deformation [44,45]. Energies of the excited states obtained in ^{62}Ti indicate a deformed ground state surmising that the N=40 island of inversion extends down to Z=20, disfavoring a possible doubly magic character of the elusive ^{60}Ca [46].

- *Existence of four-neutron system:*

Using missing mass spectroscopy we have proved the existence of the tetraneutron, a nucleus including only neutrons. According to this, not only the gravitational but also the strong interaction is able to keep pure neutron matter together [47].

c) We have observed shape coexistence in the neutron-deficient ^{66}Se, ^{87}Tc and shape change in Cd isotopes.

Excited states in ^{87}Tc have been studied by the AGATA+NEDA+DIAMANT detector array. The observed new band has been interpreted to be built on a spherical configuration, which is different from the oblate yrast rotational band [48]. We have established new excited states in ^{66}Se, a nucleus near the proton drip line. Comparison to theoretical calculations has suggested shape coexistence in this selenium isotope [49]. Lifetimes of low-lying states were measured in the even-mass $^{102–108}$Cd isotopes. The deduced transition strengths showed that there is a fundamental structural difference between the ground-state bands in the Z=48 and Z=50 isotopes revealing a rotational character of the Cd nuclei with prolate-deformed ground states [50].

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