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SHAPE COEXISTENCE AND SHAPE ISOMERISM IN THE Ni ISOTOPIC CHAIN*

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A systematic investigation of the shape coexistence phenomenon in the Ni isotopic chain, from $A = 62$ to $A = 66$, is being performed by using gamma-ray spectroscopy and employing sub-Coulomb barrier transfer reactions. The aim is to shed light on the microscopic origin of nuclear deformation along the Ni isotopic chain. The experiments were performed at the Tandem Accelerator Laboratory in Bucharest and IPN-Orsay, following the first observation of a shape-isomer-like structure at spin zero in ^{66}Ni. The study has been inspired by various mean-field theoretical approaches as well as by the state-of-the-art Monte Carlo Shell Model (MCSM) calculations, all pointing to ^{66}Ni as the lightest nucleus with a pronounced secondary prolate minimum in the nuclear potential energy surface, at spin zero, although other examples of shape isomerism in this mass region are not excluded. Preliminary results are discussed for ^{64}Ni, in comparison with MCSM predictions, together with perspectives for similar searches in ^{62}Ni.

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1. Introduction

One of the most fundamental properties of the atomic nucleus is the shape. While spherical shapes naturally appear in the vicinities of magic nuclei, different shapes are competing, and often coexist in the very same

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nucleus, at low excitation energy and low spins, when moving away from shell closures [1, 2]. Quadrupole symmetric forms are by far the most abundant, and a special class is represented by superdeformed states which are experimentally observed next to spherical/oblate excitations at high spin and high energy, even in nuclei near magic numbers [3–5].

The most striking fingerprints of shape coexistence, in even–even systems, are low-lying 0^+ excited states, characterized by deformations different from the ground state — they have been discovered in different regions of the nuclear chart (*e.g.*, in the "light" Si/Mg and Ni/Zn/Ge, all the way to the much heavier Po/Pb/Hg and Rn/Ra systems), by employing γ ray, conversion-electron measurements and laser spectroscopy.

In the U region, a rare example of shape isomers was discovered back in the 60s: in ^{236}U and ^{238}U, E2 γ branches from excited 0^+ states were observed with retardation of the order of 10^7, competing with the dominant fission mode [6–8]. They have been interpreted as structures with different shapes, residing in secondary minima of the nuclear potential energy surface (PES), and being separated by a high barrier in the deformation space [9]. Since the 80s, mean-field models have predicted the existence of shape isomerism in several regions of the nuclear chart, however, up to very recently, no additional indication was found in lighter systems. Among the best candidates, neutron-rich Ni isotopes were included, pointing, in particular, to ^{66}Ni and ^{68}Ni [10–12].

In recent years, shape coexistence in neutron-rich Ni isotopes has been also predicted by fully microscopic approaches, taking advantage of the most powerful supercomputing systems. This is the case of the Monte Carlo Shell Model (MCSM) calculations of the Tokyo group, which indicated ^{66}Ni as the best case for the existence of shape isomerism, together with possible other cases, with reduced magnitude, in the lighter ^{62,64}Ni isotopes [13]. Coexistence of spherical, oblate and prolate shapes along the Ni isotopic chain was indeed confirmed by recent experiments performed at ISOLDE/CERN, MSU and RIKEN, but no evidence for shape isomers was reported in ^{68}Ni and heavier systems [14–16].

In this contribution, we report on the research program, undertaken by our collaboration, to investigate in details, with different probes, the microscopic structure of neutron-rich Ni isotopes, from mass $A = 62$ to $A = 66$. We will first recall the experimental observation of a shape-isomer-like structure in ^{66}Ni, obtained in the first experiment performed in July 2016 at the Tandem Laboratory of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), in Bucharest [17]. This discovery shows that shape isomerism remarkably appears in significantly lighter systems than the actinides, as correctly predicted by theory. A series of measurements on the Ni chain followed, and is currently ongoing, in Bucharest, IPN-Orsay and ILL (Grenoble), aiming at a profound understanding of the microscopic origin of nuclear deformation, including shape isomerism, in close comparison with MCSM predictions. Preliminary results on ^{64}Ni, presented here, support the occurrence of a possible shape-isomer-like phenomenon also in this nucleus, although at higher excitation energy and with reduced magnitude. This is in line with MCSM predictions, which further point to ^{62}Ni as the isotope marking the onset of shape coexistence in the neutron-rich Ni chain.

2. Experimental investigation

In July 2016, our collaboration performed the first experiment of the present research program. The aim was a detailed spectroscopic investigation of neutron-rich nuclei, from ^{62}Ni to ^{66}Ni, in order to shed light on the origin of the shape coexistence/shape isomerism phenomenon and its evolution, along the Ni chain. Special emphasis was given to lifetime measurements, as well as comparative studies of the population of specific states by different reaction mechanisms (in particular, proton and neutron transfer reactions with heavy ions), which are found to be very sensitive to the composition of the state wave function.

2.1. The ^{66}Ni case

The ^{66}Ni nucleus was populated at IFIN-HH, in Bucharest, by the two-neutron transfer reaction induced by an ^{18}O beam on a ^{64}Ni target, at the sub-Coulomb barrier energy of 39 MeV [17]. This condition severely hinders the fusion–evaporation channel, which is otherwise highly favored above the Coulomb barrier. The ROSPHERE HPGe array [18], consisting of 14 Ge detectors and 11 $LaBr_3$(Ce) scintillators, was employed to measure the γ decay from excited states in ^{66}Ni. The experiment lasted more than 40 days with a steady beam current of about 30 pnA. At first, a 5 mg/cm^2 thick target of ^{64}Ni was used, in order to obtain a very clean spectrum of ^{66}Ni, by gating on the $2^+ \rightarrow 0^+$ ground state transition, with energy of 1425 keV. In the spectrum, all observed transitions belong to ^{66}Ni and depopulate known states with excitation energy below ≈ 4.1 MeV, as reported by Broda *et al.* in [19]. After a closer inspection, several transitions clearly showed tails, pointing to emission in flight, during the slowing down process of ^{66}Ni inside the target. Half-live values, in the range of 1 to 2 ps, were then obtained by performing a lineshape analysis with the Doppler Shift Attenuation Method (DSAM) [20, 21]. A total of six transitions were analyzed in this way: the 490, 1546, 1760, 1804, 2189 and 2262 keV lines depopulating the 7^-, 3^+, 4^+, 2^+, 4^+ and 3^- states at 4089, 2971, 3185, 3229, 3614 and 3687 keV, respectively. All cases resulted in $B(\mathrm{E/M}\lambda)$ values determination in fair agreement with MCSM predictions (for the 3^- state at 3687 keV, no predictions are available) [22], thus giving very strong support to the predictive power of the model which was also found to reproduce very well the beta-decay properties of ^{66}Co into ^{66}Ni [23]. As examples, figure 1 (a) and (b) show the line-shape analysis of the 1804 and 1760 keV transitions, depopulating the 2^+ and 4^+ states at 3229 and 3185 keV.

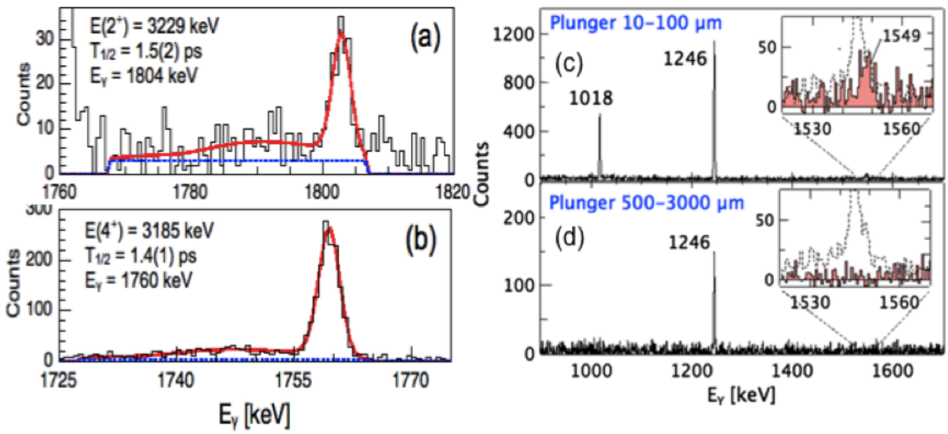

Fig. 1. (Colour on-line) Panels (a) and (b): Line shape analysis with the Doppler Shift Attenuation Method (DSAM) for the 1804 and 1760 keV transitions, depopulating the 2^+ and 4^+ states of ^{66}Ni at 3229 and 3185 keV, respectively. Only backward detectors of the ROSPHERE array are used. Solid (red) lines are the best fits of the data (with background given by the dotted (blue) lines). Panels (c) and (d): Portions of γ spectra, in coincidence with the $2^+ \rightarrow 0^+$ 1425 keV ground state transition, obtained with the plunger setup, summing over the short (c) and long (d) distances. The inset is a zoom around the 1546 keV transition, with dashed histograms giving the corresponding thick target spectrum, for comparison purposes [17, 22].

In the second part of the experiment, the lifetime of all three excited 0^+ states was measured using a plunger setup: the same reaction was used and a 5 mg/cm^2 thick Ta stopper was placed at 12 distances (between 10 and 3000 μm) from a 1 mg/cm^2 target. The population pattern of the 1018, 1246 and 1549 keV lines, depopulating the 0^+_2, 0^+_3 and 0^+_4 states at 2443, 2671 and 2974 keV excitation energies, respectively, is shown in Fig. 1 for short (panel (c)) and long (panel (d)) distances. The analysis of the plunger data yielded the half-live values of $T_{1/2} = 7.6(8)$, 134(9) and 20(7) ps, corresponding to B(E2) decay probabilities of 4.3 ± 0.5, 0.09 ± 0.01, and 0.21 ± 0.07 W.u., for the 0^+_2, 0^+_3 and 0^+_4 states, respectively. We note that in the case of 0^+_3, an independent measurement of Olaizola *et al.* [24] reported a similar value. By performing a more detailed analysis of the excited 0^+ states wave function composition given by MCSM predictions, the retardation of the E2 decay from the 0_3^+ state was found to arise from cancellation effects among E2 matrix elements. On the contrary, in the case of the third excited 0_4^+ state at 2974 keV, the hindrance could be interpreted as arising from the existence of a sizable potential barrier, in the potential energy surface (PES), between the secondary prolate minimum and the spherical ground state minimum [17]. In this case, the appearance of a deep prolate (local) minimum is caused by a sizable promotion of neutrons into the $g_{9/2}$ orbital, which leads to the reduced separation between the proton $f_{7/2}$, $p_{3/2}$ and $f_{5/2}$ orbitals (the proton $f_{7/2}$ state rises, while the $f_{5/2}$ orbital lowers in energy), thus favoring the promotion of protons across the $Z = 28$ shell gap (the so-called Type II shell evolution [13]).

The above result makes the ^{66}Ni nucleus a unique example of a nuclear system, apart from the actinides, in which a “shape-isomer-like” structure exists, as correctly predicted by theory.

2.2. Shape coexistence in ^{64}Ni

A scenario similar to the case of ^{66}Ni, discussed in Sec. 2.1, although occurring at higher excitation energy and with possibly reduced magnitude, is predicted by the MCSM calculations also for ^{64}Ni. Here again, the first three excited 0^+ states are calculated to have oblate, spherical and prolate shapes, respectively, and the third excited 0^+ state lies in the secondary minimum of the PES which is separated from the spherical minimum by a sizeable potential barrier, as shown in Fig. 2. Circles on the PES of ^{64}Ni and ^{66}Ni represent prolate shapes in the MCSM basis vectors, corresponding to 0_4^+ states.

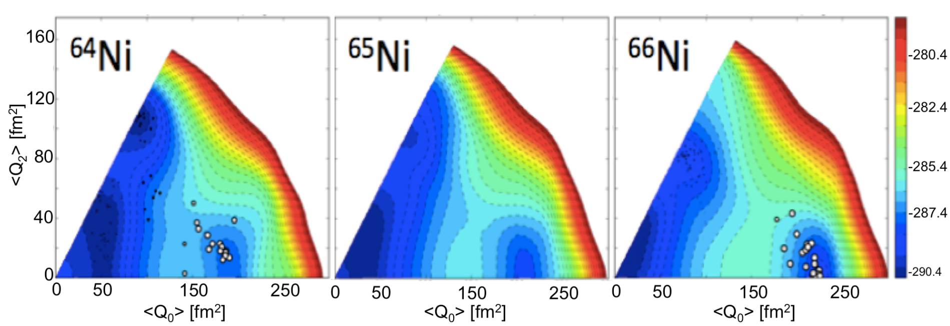

Fig. 2. Potential Energy Surface (PES) of ^{64}Ni (left), ^{65}Ni (center) and ^{66}Ni (right), as a function of the prolate and oblate quadrupole moments Q_0 and Q_2 [17, 25]. Circles on the PES represent prolate shapes in the MCSM basis vectors, corresponding to 0_4^+ states in ^{64}Ni and ^{66}Ni.

According to MCSM calculations, the wave function of the prolate 0^+ excitation in ^{64}Ni is found to involve promotion of about 2 protons and 2 neutrons across the $Z = 28$ and $N = 40$ shell gaps, respectively. In contrast, the oblate and spherical excited 0^+ states are not associated with significant proton excitations. It is then natural to expect that a transfer reaction involving protons might be particularly efficient in populating the prolate 0^+ state in ^{64}Ni. As discussed earlier, the same reasoning holds for the shape-isomer-like 0^+_4 state in ^{66}Ni, however, in this case, no proton-transfer reaction is possible using a stable beam and target combination.

Based on the above observations, our collaboration searched for a prolate deformed 0^+ state in ^{64}Ni by carrying out in 2018 (March and July), at IFIN-HH, measurements which employed the two-neutron transfer reaction ^{62}Ni(^{18}O, ^{16}O)^{64}Ni at $Eb = 39$ MeV and the one-proton transfer reaction ^{65}Cu(^{11}B, ^{12}C)^{64}Ni at $Eb = 26$ MeV. In both cases, the beam energies were chosen to stay just below the Coulomb barrier in order to hinder the fusion–evaporation mechanism, as was successfully done in the ^{66}Ni case [17]. A different selectivity in the population of excited states in ^{64}Ni was clearly observed when comparing the spectra from the two reactions. While the transitions of 1521 and 1680 keV, deexciting the 0^+_2 and 0^+_3 states at 2867 and 3026 keV, respectively, are strong in the 2-neutron transfer data, they are almost absent in the reaction involving proton transfer (only the 1521 keV γ ray is weakly seen). This is very much in line with the predictions of MCSM calculations, as discussed above.

Further, inspection of the spectrum obtained for the ^{11}B+^{65}Cu reaction revealed two gamma transitions at 2138 and 2502 keV, which were not observed with the $2n$ transfer reaction. They would depopulate states at 3484 and 3848 keV, respectively. However, after performing a careful analysis of the 2502 keV line, it was found that such a line must originate from a state with spin > 2, thus leaving the level at 3484 keV as the only candidate for the 0^+_4 excitation. It is noted that, in ^{64}Ni, a level at 3480(10) keV energy (with no spin assignment) was identified in the (t,^{4}He) proton pick-up reaction [26], while it was not seen in the (t, p) reaction study [27]. Moreover, it is found that 2138 keV gamma line does not show traces of a "tail" which indicates that the lifetime of the 3484 keV level is longer than the stopping time of the ^{64}Ni product in the target.

Experiments aimed at a detailed characterization of the level at 3484 keV in ^{64}Ni are ongoing. A possible confirmation of the 0^+ spin-parity assignment to this state would represent a strong experimental validation of the MCSM calculations, which, in fact, predict a strong proton component in the wave function of the 0^+_4 prolate state, leading to its preferential population in a proton transfer reaction.

Figure 3 displays the partial level schemes of ^{64}Ni, ^{66}Ni, ^{68}Ni and ^{70}Ni, focusing on the decay of the 0^+ states, as follows from the most recent experimental investigation [28]. Comparison with MCSM calculations is also given for the prolate deformed shapes, clearly showing the good reproduction of the evolution of the excitation energy spectrum of these deformed structures along the Ni isotopic chain. The top panel gives the systematics of the $B(\mathrm{E2};\, 0^+_{\mathrm{prolate}} \to 2^+_1)$ values, experimental and from MCSM calculations, for the even Ni nuclei with $62 \leq A \leq 70$. A minimum value seems to be reached for ^{66}Ni, in agreement with the observation of the shape-isomer-like structure in this nucleus. In the left part of the figure, MCSM calculations are shown also for ^{62}Ni. According to these calculations, ^{62}Ni is the first in the Ni neutron-rich chain to exhibit a coexistence of spherical and deformed configurations, manifested by the appearance of a multitude of 0^+ states (nine below 6 MeV, as shown in Fig. 3) with different deformations.

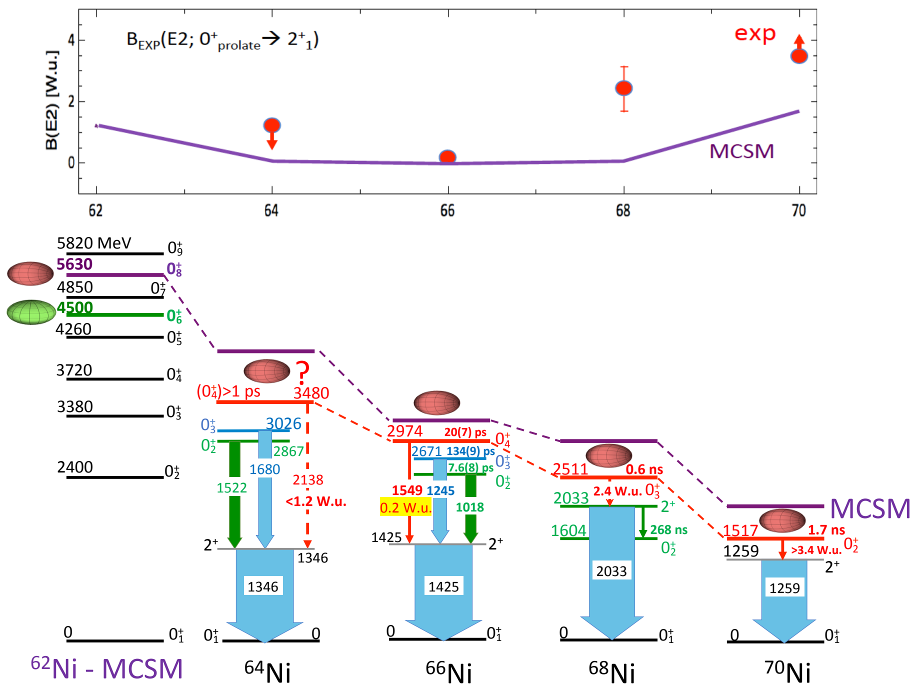

Fig. 3. (Colour on-line) Experimental partial decay schemes of ^{64}Ni, ^{66}Ni, ^{68}Ni and ^{70}Ni, focusing on the decay of the 0^+ states [28], in comparison with predictions from Monte Carlo Shell Model (MCSM) calculations for the prolate structures. On the left, MCSM calculations for ^{62}Ni, showing the expected excited 0^+ states below 6 MeV. Cartoons for prolate and oblate nuclear shapes are also given. Top panel: systematics of the $B(\mathrm{E2};\, 0^+_{\mathrm{prolate}} \to 2^+_1)$ values, experimental and from MCSM calculations, for the even Ni nuclei with $62 \leq A \leq 70$.

Here, deformed structures, of prolate and oblate nature, are predicted to lie at quite high excitation energies (*i.e.*, around 5 MeV). This nucleus is, therefore, expected to mark the appearance of coexisting deformations in the Ni isotopes in the neutron rich part of the nuclear chart. From previous measurements of ^{62}Ni [28], only six excited 0^+ states have been identified below 5.5 MeV, however, their nature has not been established. It is also interesting to note that one of the 0^+ states predicted by the MCSM to exhibit deformed nature may be the band head of the positive parity rotational band recently identified by Albers *et al.* in a high spin experiment performed with GAMMASPHERE and FMA [29].

At present, data on ^{62}Ni, collected by our collaboration in a recent experiment at IPN-Orsay with the Nu-ball array, employing the sub-Coulomb transfer reaction ^{60}Ni(^{18}O, ^{16}O)^{62}Ni, are under analysis, in order to provide further important benchmark to theory predictions.

3. Conclusions

A photon decay from a 0^+ state, hindered — solely — by a nuclear shape change, has been recently discovered by our collaboration in ^{66}Ni [17]. This is a clear-cut evidence of a shape-isomer-like structure, an extremely rare process, involving a transition between totally different microscopic configurations (prolate and spherical in this case), coexisting at similar excitation energy. Up to date, only two other examples of γ-decaying shape isomers have been found, back in the 60s, in the very heavy actinide region — these are ^{236}U and ^{238}U. According to recent large scale shell model calculations, based on Monte Carlo computational schemes, the appearance of a deep prolate (secondary) minimum in ^{66}Ni is ascribed to a sizable excitations of neutrons into the $g_{9/2}$ orbital, causing a reduced separation between the $f_{7/2}$, $p_{3/2}$ and $f_{5/2}$ orbitals, which favors promotion of protons across the $Z = 28$ shell gap and, what follows, development of deformation. Experimental campaigns are ongoing in Bucharest, IPN-Orsay and ILL (Grenoble), aiming at an extended spectroscopic investigation of neutron rich Ni isotopes, from $A = 62$ to 66. They employ different reaction mechanisms to probe the state wave function composition. Preliminary results on ^{64}Ni, in comparison with MCSM predictions, point to the existence of shape isomerism also in this nucleus, although at higher excitation energies and, very likely, with reduced magnitude. In turn, the ^{62}Ni nucleus, currently under analysis, is expected to mark the onset of the shape coexistence phenomenon in the neutron-rich Ni chain. It is quite certain that such a detailed experimental investigation, performed with a strong support from theory, will significantly contribute to our understanding of the microscopic origin of nuclear deformation, a key issue in nuclear structure physics.

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