

SHAPE-COEEXISTENCE STUDIES IN THE Ni ISOTOPIC CHAIN BY USING THE SELECTIVITY OF DIFFERENT REACTION MECHANISMS*

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We report on the investigation of the shape coexistence phenomenon in the Ni isotopic chain, from $A = 62$ to $A = 66$, by using γ -ray spectroscopy techniques and different reaction mechanisms, such as sub-Coulomb barrier transfer reactions and thermal-neutron capture. Our aim is to understand, from the microscopic point of view, the appearance of nuclear deformation in Ni isotopes at low excitation energy. A series of experiments was performed at the Tandem Accelerator Laboratory in Bucharest, at ALTO IPN-Orsay and at the ILL reactor in Grenoble. Various mean-field theoretical approaches, as well as recent state-of-the-art Monte Carlo Shell Model (MCSM) calculations, predict in ^{66}Ni a deep secondary prolate minimum in the nuclear potential energy surface at spin zero, resulting in a hindered electromagnetic decay towards the spherical ground state (*i.e.*, with an E2 transition probability less than 1 W.u.). This has been confirmed in the first experiment performed in Bucharest. Less pronounced prolate minima, at higher excitation energies, are also expected in lighter neutron-rich Ni isotopes, from state-of-the-art Monte Carlo Shell Model (MCSM) calculations. Preliminary results are discussed for ^{62}Ni and ^{64}Ni , in comparison with theory predictions.

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1. Introduction

The shape of the atomic nucleus is one of its most fundamental properties: spherical shapes appear, most naturally, in the ground states of magic and near-magic nuclei, however, at higher excitation energies, states exhibiting a sizeable deformation may appear in the very same nucleus. When moving away from shell closures, states with different shapes may coexist at lower energy and low spin, thus competing with spherical configurations [1, 2]. Few examples of shape coexistence have also been reported in doubly-magic systems. By far, the most abundant shapes are quadrupole symmetric forms, including the special class represented by superdeformed configurations, which are most frequently observed at high spin and high excitation energy, together with spherical/oblate excitations, even in nuclei near-magic numbers [3–5].

The fingerprint of shape coexistence, in even–even systems, is the appearance of low-lying 0^+ excited states, with deformations different from the ground state. Examples have been found in several regions of the nuclear chart, from the “light” Si/Mg nuclei to the medium mass Ni/Zn/Ge, up to the very heavy systems of Po/Pb/Hg and Rn/Ra. Investigations of their properties have been carried out by employing high-resolution γ -ray spectroscopy techniques, conversion-electron measurements and laser spectroscopy. In the 1960s, rare examples of shape isomers were discovered in the U region: in ^{236}U and ^{238}U , E2 γ -ray decay branches from excited 0^+ states were observed to be retarded by a factor of the order of 10^7 , in competition with the dominant fission mode [6–8]. Such 0^+ states are interpreted as structures with different shapes, located in secondary, deep minima of the nuclear potential energy surface (PES), which are separated from the ground-state configuration by a high barrier in the deformation space [9]. Since the 1980s, different mean-field models have predicted the appearance of shape isomerism in different regions of the nuclear chart, although no firm indication has been found for other cases, until very recently. Among all possible candidates, neutron-rich ^{66}Ni and ^{68}Ni isotopes were considered the most promising for developing deep minima in the PES, associated with well-deformed prolate shapes, possibly giving rise to shape isomerism [10–12], *i.e.*, showing E2 transition probabilities < 1 W.u. In recent years, taking advantage of the most powerful supercomputing systems, fully microscopic approaches have been used to make predictions for the shape-coexistence phenomena. This is the case of the Monte Carlo Shell Model (MCSM) calculations performed by the Tokyo group for the neutron-rich Ni isotopes (see Fig. 1), which indicated ^{66}Ni as the best case for the appearance of shape isomerism, together with possible other cases, in the lighter $^{62,64}\text{Ni}$ isotopes, although with reduced magnitude [13]. Indeed, recent experiments performed at ISOLDE/CERN, MSU and RIKEN, pointed out the existence

of coexisting spherical, oblate and prolate shapes along the Ni isotopic chain, but no evidence for shape isomers was reported in ^{68}Ni and heavier systems [14–17].

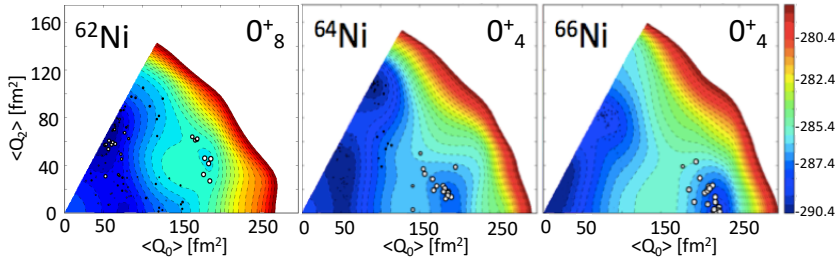


Fig. 1. Potential Energy Surface (PES) of ^{62}Ni (left), ^{64}Ni (center) and ^{66}Ni (right) nuclei, as a function of quadrupole moments Q_0 and Q_2 [13]. Circles on the PES represent shapes of the MCSM basis vectors that have important contributions to the wave functions. The plots correspond to the 0_8^+ state in ^{62}Ni and to the 0_4^+ states in ^{64}Ni and ^{66}Ni , respectively.

Starting from 2016, a research program is being carried out by our collaboration to investigate, with different probes, the microscopic structure of neutron-rich Ni isotopes, from mass $A = 62$ to $A = 66$. In this contribution, we start reporting the experimental observation of a “shape-isomer-like” structure in ^{66}Ni , obtained in the first experiment of the campaign performed at the Tandem Laboratory of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), in Bucharest [18]. This observation supports the predictions that shape isomerism can also appear in systems much lighter than the actinides. A series of measurements then followed in Bucharest, ALTO IPN-Orsay and ILL, guided by predictions from the Monte Carlo Shell Model. Preliminary results on ^{64}Ni point to the occurrence of a complex scenario of excitations based on different shapes, as in ^{66}Ni , although at higher excitation energy, while ^{62}Ni seems to be confirmed as the isotope marking the onset of shape coexistence in the neutron-rich Ni chain.

2. Experimental investigation

A detailed spectroscopic investigation of neutron-rich Ni nuclei, from $A = 62$ to $A = 66$, is being carried out by our collaboration employing different reactions, *e.g.*, sub-Coulomb barrier transfer reactions with heavy-ion stable beams and neutron-capture reactions with intense thermal-neutron beams. The focus is on comparative studies of the population of specific states by the different reaction mechanisms. In particular, proton- and neutron-transfer reactions with ^{11}B and ^{18}O heavy ions are found to selectively populate

specific excited states, thus suggesting a sensitivity to the state wave function composition. Lifetime measurements are also performed employing both plunger and Doppler Shift attenuation method techniques.

2.1. The ^{66}Ni case

The first studied case was the ^{66}Ni nucleus, which 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 [18], thus severely hindering the fusion–evaporation channel. The experimental setup consisted of the ROSPHERE HPGe array [19] equipped with 14 Ge detectors and 11 $\text{LaBr}_3(\text{Ce})$ scintillators. In the first part of the experiment, a very clean spectrum of ^{66}Ni was obtained, using a thick target, showing the population of already known states up to ≈ 4.1 MeV excitation energy, as previously observed in Ref. [20]. In the second part, the lifetime measurement of all three 0^+ excited states, located at 2443-, 2671- and 2974-keV excitation energies, was performed with a plunger setup, yielding $B(\text{E}2)$ transition 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 — an independent measurement of Olaizola *et al.* [21] reported a similar value in the case of 0_3^+ .

According to MCSM predictions, the retardation of the E2 decay from the 0_3^+ state arises from cancellation effects in the E2 matrix elements, while the third excited 0_4^+ state is characterized by a hindered E2 decay towards the first excited 2_1^+ state, as a consequence of a sizable barrier, in the potential energy surface (PES), between the secondary prolate minimum and the spherical ground state minimum [9]. The appearance of the deep prolate (local) minimum arises from a sizable promotion of neutrons into the $g_{9/2}$ orbital, which causes a reduction of the proton spin-orbit splitting, thus favoring protons promotion across the $Z = 28$ shell gap. Such a phenomenon has been called “Type II shell evolution” [13].

The result discussed above makes ^{66}Ni a unique example of nuclear system, apart from the very heavy actinides, in which an E2 transition hindered supposedly by a shape change is observed as in the case of shape isomers. The support for this interpretation comes from the MCSM calculations which describe well the ^{66}Ni structure, and predict a retardation of the discussed transition connecting prolate and spherical PES minima.

2.2. Shape coexistence in ^{62}Ni and ^{64}Ni

Monte Carlo Shell Model calculations predict a scenario of coexisting shapes also in ^{62}Ni and ^{64}Ni , as shown in Fig. 1. In such systems, a possible appearance of “shape-isomer-like” structures is also expected, similarly to the case of ^{66}Ni , although at higher excitation energy. In the case of ^{64}Ni , the first three excited 0^+ states are calculated to be oblate, spherical and prolate,

respectively, as observed in ^{66}Ni , and additional two 0^+ states of spherical nature are predicted below 4.7 MeV. In ^{62}Ni , up to 9 excited 0^+ states are expected by MCSM below 6 MeV, all being of spherical nature, apart from 0_6^+ and 0_8^+ , which should be characterized by oblate and triaxial shapes, respectively. According to calculations, ^{62}Ni should mark the appearance of coexisting deformations in the Ni isotopes, in the neutron-rich side of the nuclear chart.

The above predictions have encouraged our collaboration to perform a detailed investigation of 0^+ excitations in ^{62}Ni and ^{64}Ni , by employing two-neutron and one-proton transfer reactions, at sub-Coulomb barrier energy, and thermal-neutron capture reactions. The transfer reaction experiments focusing on ^{62}Ni and ^{64}Ni were performed at IFIN-HH and ALTO IPN-Orsay, with the ROSPHERE [19] and Nu-Ball array, respectively. Nu-Ball was made of 24 Compton-suppressed HPGe Clover detectors, 10 Compton-suppressed HPGe coaxial detectors and 20 LaBr₃ scintillator detectors, for lifetime measurements by fast-timing techniques. The thermal-neutron capture experiments were performed at the ILL reactor, using the FIPPS ar-

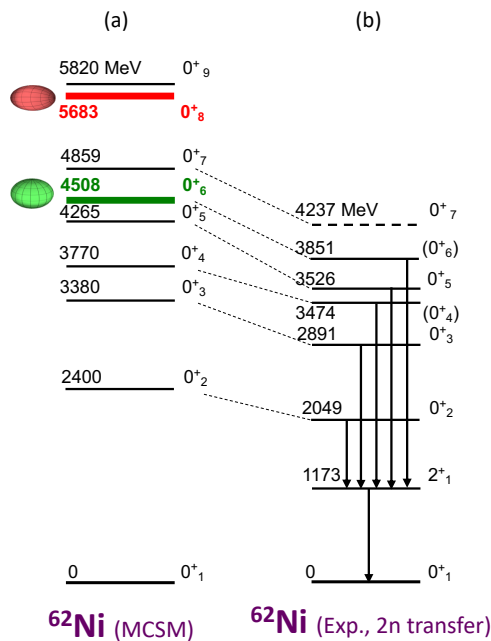


Fig. 2. (Colour on-line) Panel (a): Monte Carlo Shell Model (MCSM) calculations for ^{62}Ni , showing the expected 0^+ states below 6 MeV. Cartoons for prolate and oblate nuclear shapes are given in thick grey/red and thick black/green, respectively. Panel (b): Partial decay scheme of ^{62}Ni , focusing on the decay of the 0^+ states, as measured in the two-neutron transfer experiment performed with the Nu-Ball array at ALTO IPN-Orsay.

ray [22], consisting of 8 HPGe Clovers, arranged in annular geometry at every 45° around the target. Figure 2 (b) shows preliminary results for the gamma decay from the first five excited 0^+ states of ^{62}Ni , *i.e.*, 0_2^+ to 0_6^+ (the spin assignment of the proposed 0_4^+ is being confirmed by angular correlation studies) in comparison with MCSM predictions Fig. 2 (a). It is interesting to note that one of the 0^+ states predicted by the MCSM to exhibit a deformed nature may be the band head of the positive-parity rotational band recently identified by Albers *et al.* [23] in a high spin experiment performed using GAMMASPHERE and the FMA. If this scenario is experimentally confirmed, the connection between deformation, developing at high spins and the occurrence of coexisting shapes, at spin 0, would be established for the first time. The analysis is ongoing.

In the case of ^{64}Ni , the decays from the second and third excited 0^+ states, located at 2867 and 3026 keV, are clearly observed in both the thermal-neutron capture and the $2n$ -transfer reaction $^{62}\text{Ni}(^{18}\text{O}, ^{16}\text{O})^{64}\text{Ni}$ at $E_b = 39$ MeV, as shown in panels (a) and (b) of Fig. 3, respectively. A much

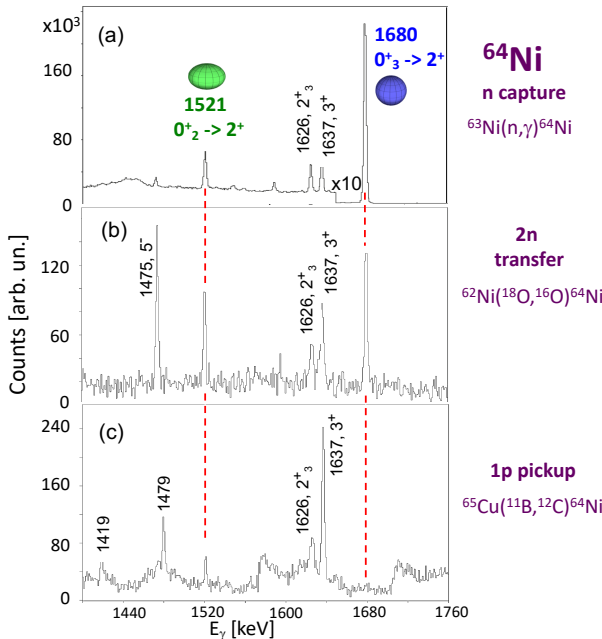


Fig. 3. (Colour on-line) Gamma-ray energy spectra of ^{64}Ni , gated by the $2_1^+ \rightarrow 0_1^+$ decay, as obtained in neutron capture (panel (a)) and two-neutron and one-proton transfer reactions at the sub-Coulomb barrier energy (panel (b) and (c), respectively). The 1521- and 1680-keV γ -rays, depopulating the 0_2^+ and 0_3^+ states, are marked by dashed black/red lines. They correspond to oblate and spherical configurations, according to MCSM predictions.

reduced population of 0_2^+ and 0_3^+ states are instead obtained in the proton pick-up reaction $^{65}\text{Cu}(^{11}\text{B}, ^{12}\text{C})^{64}\text{Ni}$ at $E_b = 26$ MeV, as shown in panel (c), pointing to a strong selectivity of the reaction mechanisms, which may be used to infer the wave-function composition of the specific states. Work is currently ongoing to compare the relative population of 0^+ excitations, observed in the $2n$ and $1p$ transfer reactions, with relative cross sections from DWBA calculations, including nuclear structure information provided by the MCSM [24].

Figure 4 (a) shows the experimental partial decay schemes of ^{64}Ni focusing on the decay of the first two excited 0^+ states (observed in all three reaction mechanisms here discussed). Preliminary results from plunger measurements provide lifetime values in the ps range for both 0_2^+ and 0_3^+ that result in transition rates in fair agreement with predictions from MCSM

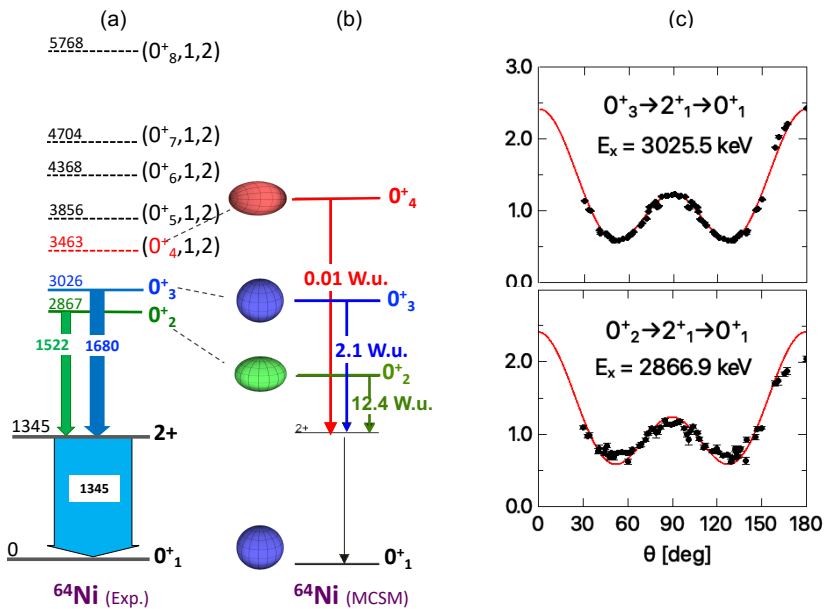


Fig. 4. Panel (a): Experimental partial decay schemes of ^{64}Ni , focusing on the decay of the first two excited 0^+ states. Additional excitations observed in the (n, γ) experiment are shown, which are consistent with a 0^+ assignment and basis of their decay pattern (a firm spin-parity assignment is being confirmed by angular correlation studies). Panel (b): Monte Carlo Shell Model (MCSM) calculations for the spherical, oblate and prolate structures. Panel (c): examples of angular correlations studies performed with the (n, γ) data on ^{64}Ni , confirming the 0^+ spin-parity assignment for the excited states at 2867 and 3026 keV. Solid grey/red lines give the expected angular correlation for a $0 \rightarrow 2 \rightarrow 0$ pair of stretched transitions.

calculations (panel (b)). In addition, tentative 0^+ excitations are given in panel (a) by dashed lines. They are directly populated in the (n, γ) experiment by primary transitions from the capture state at 9657.5 keV. The spin and parity of such states is being confirmed by angular correlation studies, which are shown in Fig. 4 (c) in the case of the already known $0_{2,3}^+ \rightarrow 2^+ \rightarrow 0_1^+$ correlations.

3. Conclusions

The recent discovery, in ^{66}Ni , of a “shape-isomer-like” structure, *i.e.*, a photon decay hindered — solely — by a nuclear shape change, has encouraged our collaboration to investigate in great detail the phenomenon of shape coexistence in the neutron-rich $A = 62, 64$ Ni isotopes in close comparison with predictions from the Monte Carlo Shell Model calculations. In all cases, the MCSM predicts the appearance of a deep prolate (secondary) minimum, ascribed to sizable excitations of neutrons into the $g_{9/2}$ orbital, which then favors promotion of protons across the $Z = 28$ shell gap. This results in the development of deformation.

Experiments have been performed in Bucharest, ALTO IPN-Orsay and ILL (Grenoble), employing different reaction mechanisms to probe the state wave function composition. Preliminary results on ^{62}Ni and ^{64}Ni point to a complex scenario of 0^+ excitations, which are currently under investigation by angular correlations studies and lifetime measurements. Preliminary results clearly show a different/strong selectivity in the population of specific states, in particular when using reactions involving transfer of neutrons or protons, thus pointing to the need of a theoretical interpretation in which both structural properties and reaction dynamics are properly taken into account.

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