

Emergence of collectivity near magic nuclei: Coulomb excitation of ^{62}Ni

(v-Ball2 + DSSSD)

I. SCIENTIFIC MOTIVATION

The nickel isotopic chain ($Z = 28$) is so far the only example in the entire Segré chart where three doubly-magic nuclei have been experimentally observed [1–4]. In addition, in this isotopic chain, the ^{68}Ni nucleus is located at the neutron sub-shell closure $N = 40$ [5]. A simple structure could be expected for these doubly- or semi-magic nuclei, due to their limited number of valence nucleons and a predicted overall spherical shape. However, recent experimental results have revealed intriguing and/or unexpected features that challenge the state-of-the-art nuclear-structure models (see, *e.g.*, Refs. [5–7]).

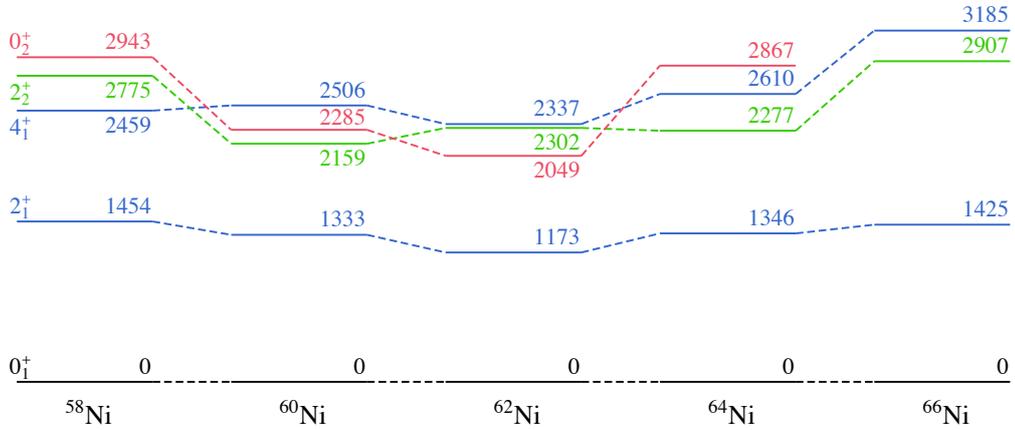


FIG. 1: Energy systematics of the 0_1^+ , 2_1^+ , 4_1^+ , 2_2^+ and 0_2^+ states in $^{58-66}\text{Ni}$. The values are reported in keV.

Based on the excitation energies of the low-lying states in the $^{58-66}\text{Ni}$ isotopes, one may identify a two-phonon multiplet $J^\pi = 0^+, 2^+, 4^+$ at roughly twice the energy of the first excited 2^+ state (see Fig. 1). A vibrational interpretation could be, therefore, drawn for these nuclei. However, this paradigm of nuclear collectivity has been recently questioned in other regions of the chart of the nuclides [8], claiming that observables such as $B(E2)$ and Q_s values are needed to make conclusions for any candidate vibrator [9]. From what it is known, it seems clear though how the stable Ni isotopes can be vibrators only as a first approximation (if they are at all), and more complex models are required to describe their structure in detail. In this context, advanced theoretical models have been applied in these isotopes, such as the Shell Model [10–15] and the Beyond-Mean-Field approach [16, 17]. Interestingly, as reported in Ref. [10], the total probability of the closed-core configuration in the ground-state wave function of ^{56}Ni is only 60–70%, it decreases in $^{58-62}\text{Ni}$, and increases again for larger neutron numbers. Excitations across shell gaps are clearly important in the radioactive, neutron-rich Ni isotopes, where shape coexistence and shape isomerism have been established [6, 18]. Still, their role in the vicinity of ^{56}Ni has yet to be explored. Also, it is worth noticing that in the Beyond-Mean-Field calculations reported in Ref. [16], the Ni isotopes from $A = 56$ up to $A = 78$ are obtained spherical within the static mean field approximation using the D1S Gogny interaction, with the exception of $^{62,64}\text{Ni}$, where the minimum is found for oblate deformation.

We developed new Beyond-Mean-Field calculations for ^{62}Ni to investigate the structure of its excited 0^+ states. The calculations have been performed using the SCCM method and the same D1S Gogny interaction employed in Ref. [16]. Figure 2 shows the collective wave functions of

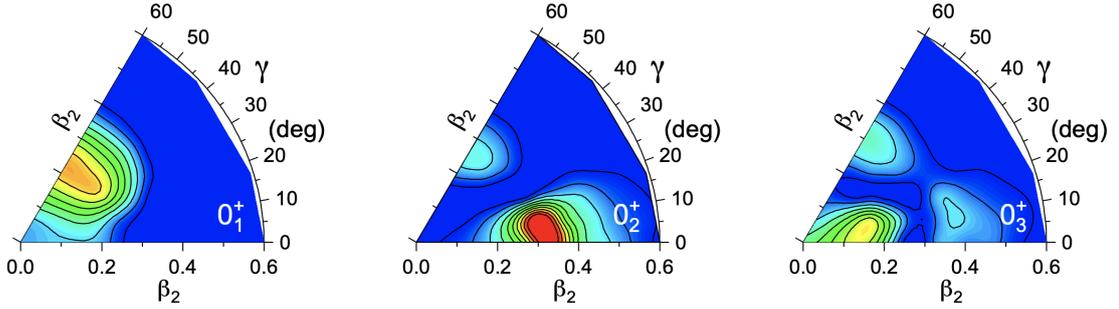


FIG. 2: Collective wave functions of the first three 0^+ states in ^{62}Ni obtained with SCCM-Gogny-D1S triaxial calculations.

the first three 0^+ states in ^{62}Ni . A picture of multiple shape coexistence is clearly visible from the results, with an oblate ground state (as predicted in Ref. [16]), a prolate 0_2^+ state with $\beta \approx 0.3$, and another prolate but less deformed 0_3^+ state with $\beta \approx 0.15$. From the calculated collective wave function of the ground state, it is also visible a substantial softness in γ . This non-axial character of the ^{62}Ni ground state is in agreement with recent collinear laser spectroscopy results from ISOLDE-CERN [19]. Indeed, as the authors report, the discrepancy between their measured mean square radii and the density functional theory predictions (see Fig. 3) might be due to a certain softness for all the measured Ni isotopes.

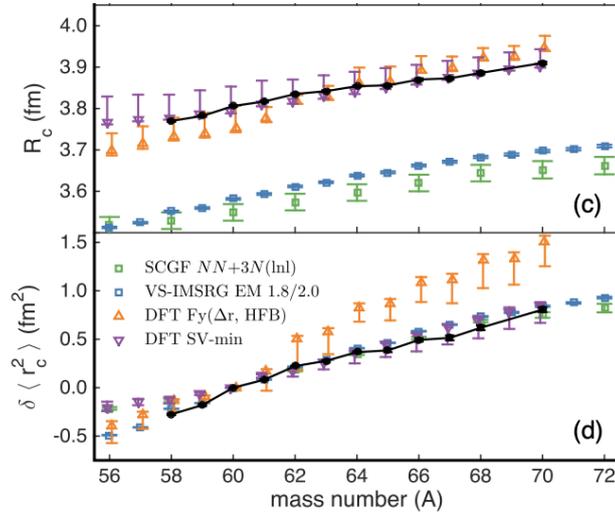


FIG. 3: Nuclear charge radii R_c and differential mean-square charge radii $\delta \langle r_c^2 \rangle$ of Ni isotopes with respect to ^{60}Ni as a reference. The experimental data are shown in black and are compared to theoretical results. See Ref. [19] for additional details, from which the figure is adopted.

The spectroscopic quadrupole moment Q_s is an observable of the nucleus closely related to its shape and can be determined for low-lying states in low-energy Coulomb excitation. Overall, considering the available data, the spectroscopic quadrupole moments of the first 2^+ states along the Ni isotopic chain are compatible with either spherical ground states, or deformed, but characterized by maximum triaxiality ($\gamma \approx 30^\circ$). The ground-state properties of the stable Ni isotopes heavier than the doubly-magic ^{56}Ni have been studied with other complementary spectroscopic probes as well. Detailed muonic X-ray measurements [20], as well as optical spectroscopy [21], seem to indicate spherical shapes with minor variations between the isotopes. Nevertheless, these techniques are not sensitive to the axial asymmetry in the nuclear shape and, therefore, the definite degree of

deformation and the triaxiality of these isotopes have never been directly probed. In the case of ^{62}Ni , the $Q_s(2_1^+)$ was published about 50 years ago [22] as a compilation of results obtained in Refs. [23–25]. While these measurements represented pioneering achievements with the available technology at that time, unfortunately, the precision on the extracted value $Q_s(2_1^+) = +0.05(12)$ eb is not sufficient to establish a spherical or deformed shape.

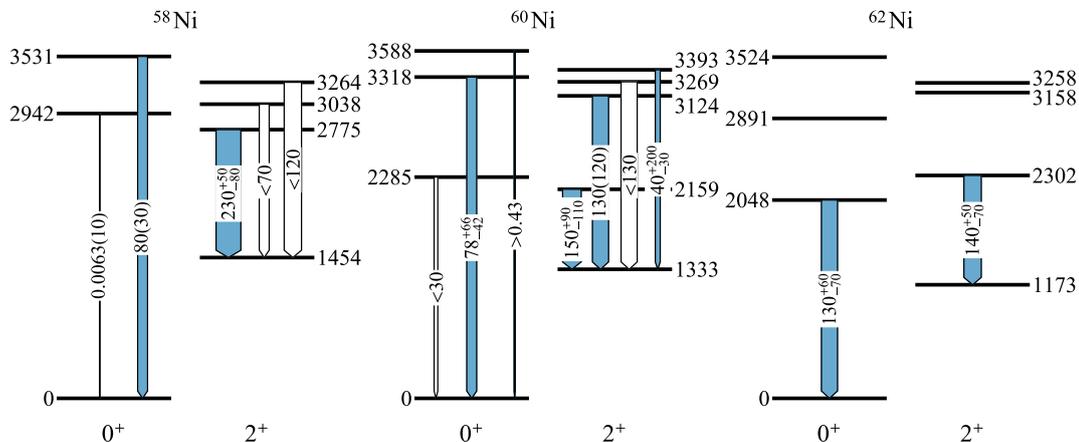


FIG. 4: Experimental $\rho^2 \cdot 10^3$ values in $^{58,60,62}\text{Ni}$. Unfilled transitions indicate upper limits. Level energies are shown in keV. Figure taken from Ref. [26].

Moving to higher-lying states, for the excited 2_2^+ state the monopole strength $\rho^2(E0; 2_2^+ \rightarrow 2_1^+)$ has been measured in $^{58,60,62}\text{Ni}$ [7], obtaining some of the largest values in medium and heavy nuclei reported to date (see Fig. 4). Since in a spherical vibrator the $E0$ transitions are forbidden if the change in phonon number is one, this state cannot be the two-phonon 2^+ state. Also, a microscopic approach for calculating $E0$ transition strengths, recently proposed in Ref. [27], fails at reproducing the large observed $\rho^2(E0; 2_2^+ \rightarrow 2_1^+)$ values, resulting in a puzzling situation. Since $E0$ transition strengths can originate from a large difference in mean-square charge radii and/or by a significant amount of mixing between the two involved states, the next step to investigate the nature of the 2_2^+ state is to measure the $Q_s(2_2^+)$, which combined with $Q_s(2_1^+)$ and $\rho^2(E0; 2_2^+ \rightarrow 2_1^+)$ will enable for the extraction of the mixing between the 2_1^+ and 2_2^+ states.

For a simple spherical vibrational structure of ^{62}Ni , a good candidate for the two-phonon 0^+ state is missing as well. Considering the excitation energies, two candidates are available, namely the second and third 0^+ states. In the heavier Ni isotope, however, these states have been interpreted as coming from shape-coexisting, multi-particle-hole excitations [4, 6, 18], with inversions in the energy of the states appearing at different neutron numbers [28]. The $E0$ strengths in stable Ni isotopes were reported in Ref. [29] and, more recently, in Ref. [7, 26]. An exceptionally small value was found for the $\rho^2(E0; 0_2^+ \rightarrow 0_1^+)$ in ^{58}Ni (as expected in a vibrational picture), while a large $\rho^2(E0; 0_2^+ \rightarrow 0_1^+)$ was reported for ^{62}Ni (see Fig. 4). This behaviour suggests an evolution in the shape and/or the degree of mixing of the 0_2^+ and 0_1^+ states in the stable Ni isotopes, which is also in agreement with the decrease of the 0_2^+ energy moving away from the doubly-magic ^{56}Ni (see Fig. 1). For ^{62}Ni , the properties of the 0_2^+ state remain unknown. Although the $B(E2; 0_2^+ \rightarrow 2_1^+) = 100(55)$ W.u. is measured [29], the large uncertainty avoids a conclusive extraction of the $\rho^2(E0; 0_2^+ \rightarrow 0_1^+)$, currently known with 55% uncertainty.

Finally, it is worth noticing how an inversion of the ordering of 0_2^+ and 2_2^+ states arises in ^{62}Ni , as could be seen in Fig. 1. A recent interpretation of the 0_2^+ state at 2048 keV in this isotope, proposed in Ref. [30], is that it is the band-head of a strongly deformed band (in agreement with our Beyond-Mean-Field calculations, see Fig. 2) resulting from $4p - 4h$ excitations from the ^{56}Ni core, and the 2302-keV 2_2^+ state is the first-excited band member. It is therefore of extreme importance

to extract the deformation of 0_2^+ state in ^{62}Ni , which will help understand the evolution of single-particle and collective structures along the Ni isotopic chain.

In this light, low-energy Coulomb excitation represents a unique method for probing the still poorly known structure of the stable Ni isotopes in the vicinity of ^{56}Ni . It is the only experimental technique to provide information on the spectroscopic quadrupole moments along with the transitional matrix elements, together with their relative signs, which will allow for probing the deformation of the ground and excited states in the ^{62}Ni isotope. Our collaboration already performed a low-energy Coulomb excitation of ^{58}Ni at INFN-LNL with the GALILEO+SPIDER setup, using the ^{208}Pb , ^{196}Pt and ^{116}Sn targets, in 2020 [31] (the analysis is ongoing). Furthermore, a Coulomb-excitation experiment to study the structure of ^{110}Cd with a ^{60}Ni beam was completed in October 2022 at INFN-LNL, using the AGATA+SPIDER setup, providing a rich dataset to study ^{60}Ni . That experiment will be complemented by the recently accepted proposal for the $^{60}\text{Ni}+^{208}\text{Pb}$ Coulomb excitation reaction that will be studied with the AGATA+DANTE+SPIDER setup at INFN-LNL. The rich set of experimental information from all these datasets and the new one coming from the project here proposed will enable a systematic investigation of the evolution of collectivity and shapes in the vicinity of ^{56}Ni .

II. PROPOSED EXPERIMENT

We propose to perform a dedicated low-energy Coulomb-excitation experiment to populate the ground state band and other low-lying, non-yrast states of interest in the stable ^{62}Ni nucleus. For this purpose, a 233-MeV ^{62}Ni beam provided by the TANDEM accelerator at IJC Lab will impinge on a 1.5-mg/cm^2 ^{208}Pb target.

The low collectivity of the nucleus of interest and the high energy of its low-lying states make such an experiment a challenge. In this context, the use of the powerful v-Ball2 γ -ray spectrometer is of particular interest. We propose to use this spectrometer with the Warsaw DSSD array for detecting charged particles. The v-ball2 setup consists of 24 HPGe clover detectors placed in two rings at 75.5° and 104.5° , and 10 coaxial HPGe detectors placed at 134° . All detectors are equipped with BGO shields for Compton suppression and the whole array has a total efficiency of about 4% at 1.3 MeV.

The γ rays will be measured in coincidence with the backscattered ^{62}Ni ions registered in the DSSD array, recently commissioned at IJC Lab in December 2022. This array will cover the laboratory angles from 120 – 160° .

In summary, with the proposed experiment we aim to explore collectivity and shapes in ^{62}Ni , specifically:

- first high-precision measurement of $Q_s(2_1^+)$ to investigate the deformation of the ^{62}Ni ground state, particularly its triaxiality
- first measurement of $Q_s(2_2^+)$ and, combining with the recently obtained $\rho^2(E0; 2_2^+ \rightarrow 2_1^+)$ value, extraction of the mixing between the 2_1^+ and 2_2^+ states
- precise measurement of the $B(E2; 0_2^+ \rightarrow 2_1^+)$ value and, consequently, extraction of the mixing between $0_{1,2}^+$ states
- relative signs of $E2$ matrix elements for the observed $2_i^+ \rightarrow 2_j^+$ transitions and extraction of Hill-Wheeler parameters (β, γ) for the ground state and, possibly, for excited 0^+ states (for the 0_2^+ state the feeding from higher-lying 2^+ states is known and will be observed in this experiment)

III. RATE ESTIMATES AND BEAM TIME REQUEST

The number of γ -particle coincidences for the different transitions of interest was estimated by using the GOSIA code [32], assuming the experimental conditions mentioned in the previous section and a 2 pA intensity for the beam. The results of the calculations are shown in Table I.

Transition	Energy [keV]	Rate / 7 days
$6_1^+ \rightarrow 4_1^+$	1182	$1.9 \cdot 10^2$
$2_4^+ \rightarrow 0_1^+$	3518	$2.7 \cdot 10^2$
$2_4^+ \rightarrow 0_2^+$	1469	$5.7 \cdot 10^2$
$4_3^+ \rightarrow 2_1^+$	2105	$2.0 \cdot 10^3$
$4_2^+ \rightarrow 2_1^+$	2004	$8.3 \cdot 10^2$
$2_3^+ \rightarrow 2_1^+$	1984	100
$0_3^+ \rightarrow 2_1^+$	1717	$2.5 \cdot 10^2$
$4_1^+ \rightarrow 2_1^+$	1163	$1.8 \cdot 10^5$
$2_2^+ \rightarrow 0_1^+$	2301	$1.6 \cdot 10^4$
$2_2^+ \rightarrow 2_1^+$	1128	$2.3 \cdot 10^4$
$0_2^+ \rightarrow 2_1^+$	876	$1.1 \cdot 10^6$
$2_1^+ \rightarrow 0_1^+$	1173	$1.2 \cdot 10^7$

TABLE I: Estimated number of counts for 7 days of data taking in ^{62}Ni .

Transition	Energy [keV]	Rate / 7 days	
		BE2=100 Wu	BE2=42 Wu
$6_1 \rightarrow 4_1$	1182	1,9E+02	2,5E+02
$2_5 \rightarrow 0_1$	3518	2,7E+02	6,2E+01
$2_5 \rightarrow 0_2$	1469	5,7E+02	1,3E+02
$4_3 \rightarrow 2_1$	2105	2,0E+03	3,4E+03
$4_2 \rightarrow 2_1$	2004	8,3E+02	1,3E+03
$2_3 \rightarrow 2_1$	1984	8,5E+01	7,9E+01
$0_3 \rightarrow 2_1$	1717	2,5E+02	4,6E+02
$4_1 \rightarrow 2_1$	1163	1,8E+05	2,5E+05
$2_2 \rightarrow 0_1$	2301	1,6E+04	2,6E+04
$2_2 \rightarrow 2_1$	1128	2,3E+04	3,7E+04
$0_2 \rightarrow 2_1$	876	1,1E+06	3,4E+05
$2_1 \rightarrow 0_1$	1173	1,2E+07	1,0E+07

TABLE II: Estimated number of counts for 7 days of data taking in ^{62}Ni .

From the estimated yields, the expected statistics with a 7-day experiment will provide sufficient precision on the transitions necessary to achieve the experiment goals mentioned above. Particularly, in the key and relatively weak transitions, such as $2_3^+ \rightarrow 2_1^+$, $2_4^+ \rightarrow 0_2^+$ and $0_3^+ \rightarrow 2_1^+$.

In conclusion, based on the performed simulations and our previous experience with the same experimental setup, we ask for:

- beam – ^{62}Ni , 2 pA, 233 MeV (TANDEM)

- target – ^{208}Pb , 1.5 mg/cm², self-supporting
 - experimental setup – v-ball2 + DSSD
 - beam time – 7 days
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