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

Proposal for the AGATA + SPIDER (+DANTE) setup

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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, 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]).

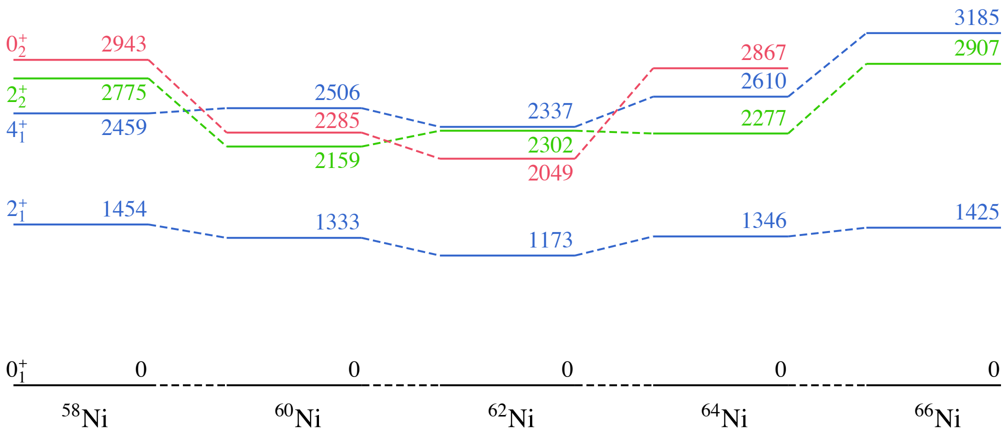

FIG. 1: Energy systematics of the 0_1^+, 2_1^+, 4_1^+, 2_2^+ and 0_2^+ states in $^{58-66}$Ni. The values are reported in keV.

Based on the excitation energies of the low-lying states in the $^{58-66}$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 may 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. 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 [9–14] and the Beyond-Mean-Field approach [15, 16]. Interestingly, as reported in Ref. [9], the total probability of the closed-core configuration in the ground-state wave function of ^{56}Ni is only $60-70\%$, it decreases in $^{58-62}$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, 19]. 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. [15], 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}Ni, where the minimum is found for oblate deformation.

The Beyond-Mean-Field calculations (SCCM method and the same D1S Gogny interaction employed in Ref. [15]), Monte Carlo Shell Model calculations (full pf shell, 0g9/2 and 1d5/2

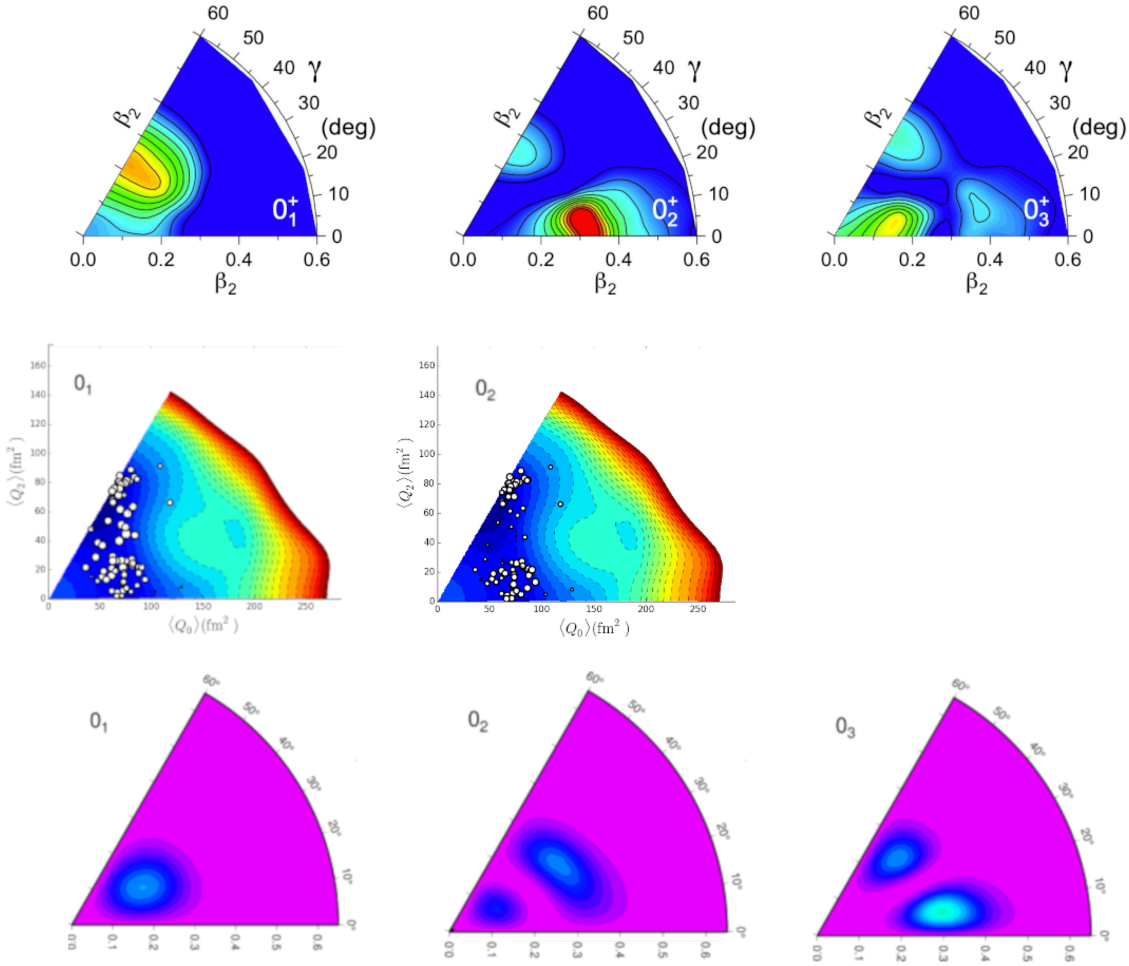

FIG. 2: Collective wave functions of the first three 0^+ states in ^{62}Ni obtained with SCCM-Gogny-D1S triaxial calculations (top), MCSM calculations (middle) and GBH model calculations (bottom).

orbits for both protons and neutrons, no truncation within this space, with the Hamiltonian based on the A3DA Hamiltonian) [17] and General Bohr Hamiltonian (with UNEDF1 interaction) [18] were performed for ^{62}Ni to investigate the structure of its excited 0^+ states. Figure 2 shows the collective wave functions of the first three 0^+ states in ^{62}Ni. In BMF and MCSM calculations, a picture of a multiple shape coexistence emerges, with a triaxial/oblate ground state, a prolate 0_2^+ state, and another prolate but less deformed 0_3^+ state. The GBH calculations, on the other hand, indicate more vibrational character than suggested by the other predictions. The models are not in agreement with each other, thus only the experimental determination of the nuclear shape of these three 0^+ states will allow us to disentangle among such contrasting predictions.

From the calculated collective wave function of the ground state, a substantial softness in γ is foreseen in all predictions. This non-axial character of the ^{62}Ni ground state is in agreement with recent collinear laser spectroscopy results from ISOLDE-CERN [20]. 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.

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 ($\gamma \approx 30°$). 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 [21], as well as optical spectroscopy [22], seem to indicate spherical shapes with minor variations between the isotopes. Nevertheless, these

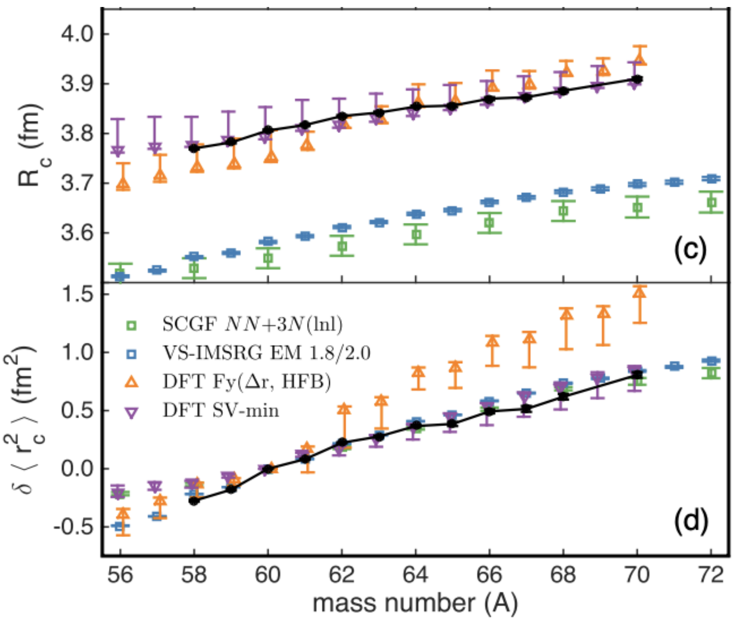

FIG. 3: Nuclear charge radii R_c and differential mean-square charge radii $\delta\langle r_c^2\rangle$ of Ni isotopes with respect to ^{60}Ni as a reference. The experimental data are shown in black and are compared to theoretical results. See Ref. [20] for additional details, from which the figure is adopted.

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 [23, 24]. While these measurements represented pioneering achievements with the available technology at that time, unfortunately, the precision on the extracted values, $Q_s(2_1^+) = -0.08(17)$ eb and $Q_s(2_1^+) = +0.08(12)$ eb, respectively, are not sufficient to establish a spherical or deformed shape.

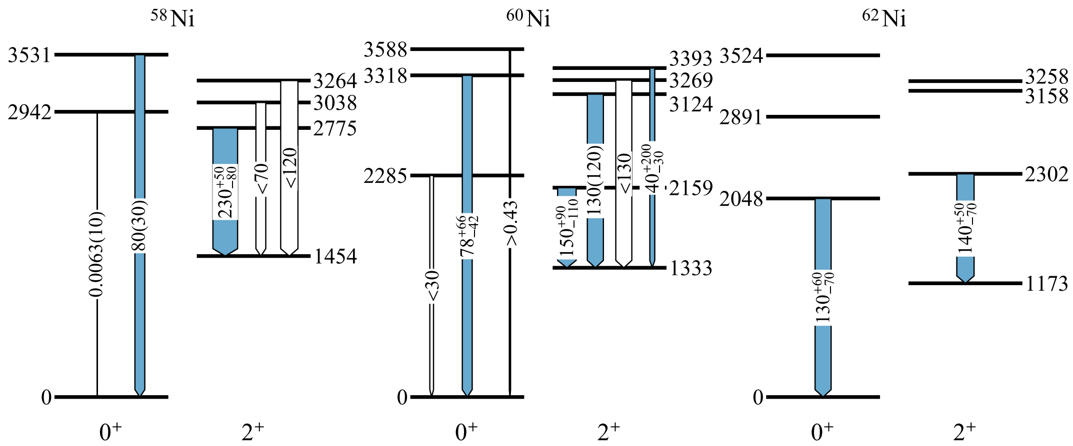

FIG. 4: Experimental $\rho^2 \cdot 10^3$ values in ^{58,60,62}Ni. Unfilled transitions indicate upper limits. Level energies are shown in keV. Figure taken from Ref. [26].

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}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. Such a result seems to support the shape coexistence scenario, in place of the vibrational description. Thus, the shape and structure of the low-lying states appear to be much more complex than what to expect for semi-magic nuclei. 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. Recently, the large $\rho^2(E0; 2_2^+ \rightarrow 2_1^+)$ value was also measured in ^{74}Se [28], supporting the findings in the Ni isotopic chain.

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 $\rho^2(E0;2_2^+ \to 2_1^+)$ 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, 19], with inversions in the energy of the states appearing at different neutron numbers [29]. The $E0$ strengths in stable Ni isotopes were reported in Ref. [30] and, more recently, in Ref. [7, 26]. An exceptionally small value was found for the $\rho^2(E0;0_2^+ \to 0_1^+)$ in ^{58}Ni (as expected in a vibrational picture), while a large $\rho^2(E0;0_2^+ \to 0_1^+)$ was reported for ^{62}Ni (see Fig. 4). This behavior 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). In the case of ^{62}Ni, instead, the properties of the 0_2^+ state remain unknown. Although the $B(E2;0_2^+ \to 2_1^+) = 100(55)$ W.u. is measured [30], the large uncertainty avoids a conclusive extraction of the $\rho^2(E0;0_2^+ \to 0_1^+)$, currently known with 55% uncertainty. A more recent measurement done by Chakraborty et al., [31] indicates a much lower value of 42^{+23}_{-20} W.u., however, the value is still known with weak precision and the problem of the collectivity of this transition needs to be resolved.

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. [33], is that it is the band-head of a strongly deformed band 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 using the Quadupole Sum Rules method [32].

II. PROPOSED EXPERIMENT

In the presented project, we propose to perform a dedicated low-energy safe 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 230-MeV ^{62}Ni beam will impinge on a 2-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 AGATA γ-ray spectrometer is of particular interest. We propose to use this spectrometer with the SPIDER (+DANTE) array for detecting charged particles to detect simultaneously the beam ejectiles and the target recoils.

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 $\rho^2(E0;2_2^+ \to 2_1^+)$ 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 $2_i^+ \longrightarrow 2_j^+$ transitions and extraction of Hill-Wheeler parameters (β, γ) for the ground state and, possibly, for excited 0^+ states
- First extraction of the 0_3^+ lifetime from the measured $B(E2;0_3^+ \rightarrow 2_1^+)$ value.

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 [35], assuming the experimental level scheme (see Fig. 5) and conditions mentioned in the previous section and a 2 pnA intensity for the beam. The results of the calculations are shown in Table I.

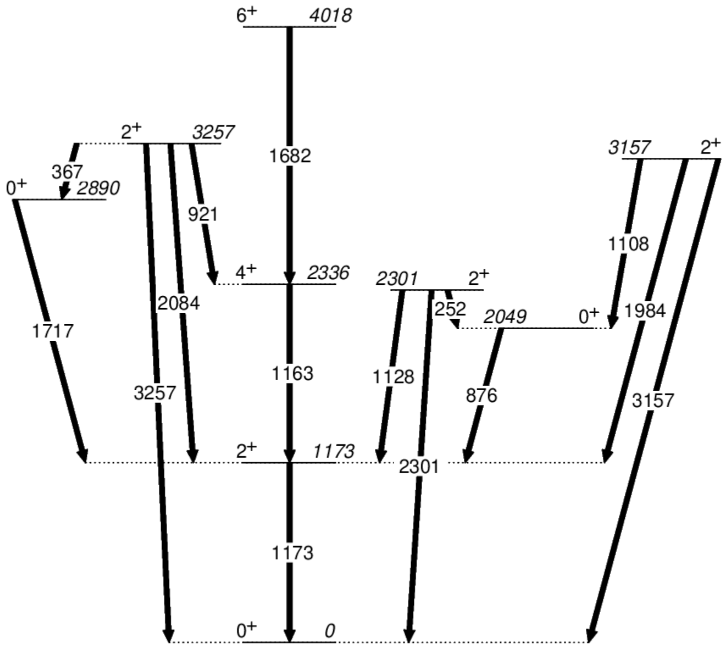

FIG. 5: ^{62}Ni level scheme.

Transition	Energy [keV]	Rate / 5 days
$2_3 \rightarrow 2_1$	1984	200
$0_3 \rightarrow 2_1$	1717	300
$4_1 \rightarrow 2_1$	1163	4 x 10^6
$2_2 \rightarrow 0_1$	2301	5 x 10^5
$2_2 \rightarrow 2_1$	1128	6 x 10^5
$0_2 \rightarrow 2_1$	876	4 x 10^4
$2_1 \rightarrow 0_1$	1173	3 x 10^8

TABLE I: Estimated number of counts for 5 days of data taking in ^{62}Ni.

From the estimated yields, the expected statistics with a 5-day experiment will provide sufficient precision on the transitions necessary to achieve the experiment goals mentioned above.

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

- beam – ^{62}Ni, 2 pnA, 230 MeV
- target – ^{208}Pb, 2 mg/cm^2, self-supporting
- experimental setup – AGATA + SPIDER (+DANTE)
- beam time – 5 days

IV. ADDITIONAL INFORMATION

Our collaboration already performed a low-energy Coulomb excitation of ^{58}Ni at INFN-LNL, Legnaro, Italy (GALILEO+SPIDER setup), using the ^{208}Pb, ^{196}Pt and ^{116}Sn targets, in 2020 [34], and of ^{60}Ni at IJC Lab, Orsay, France (Nuball2+DSSD setup), and at INFN-LNL (AGATA+SPIDER setup) using the ^{197}Au and ^{110}Cd+^{208}Pb targets, respectively (the analysis is ongoing). The rich set of experimental information from all these datasets and the new one from the proposed project will enable a systematic investigation of the evolution of collectivity and shapes in the vicinity of ^{56}Ni.

Data analysis from the present proposal on ^{62}Ni will be performed at the Heavy Ion Laboratory in Warsaw and will be led by the Master Student under the supervision of dr. K. Hadyńska-Klęk.

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