Understanding collectivity and shape transitions in Zn isotopes across N=40 by measuring γ-ray decays and lifetimes of low-lying off-yrast states in ^{72}Zn$_{42}$

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I. ABSTRACT

We propose to study the low-lying off-yrast structures in ^{72}Zn, with the aim of identifying spherical or deformed configurations feeding the ground-state band and investigate the evolution of collectivity and nuclear shapes in Zn isotopes across N=40. This will be achieved by measuring the unknown γ-ray decay from the 0_3^+ state, the lifetime of the 2_2^+ state and other possible γ-ray branchings in the decay from it. ^{72}Zn will be populated by the two-neutron transfer reaction ^{70}Zn(^{18}O,^{16}O), at energies below the Coulomb barrier (E$_{\text{beam}}$ = 40 MeV), using a thick ^{70}Zn target (5 mg/cm^2). The γ-ray decay will be measured by the 15 HPGe detectors of the ROSPHERE array, while the expected short lifetime of the 2_2^+ state will be extracted by using the Doppler Shift Attenuation Method. If possible, information on the expected longer lifetime of the 0_2^+ state will be investigated by fast timing measurements, performed with the 10 LaBr$_3$(Ce) detectors of the ROSPHERE setup.

II. SCIENTIFIC MOTIVATION

The neutron-rich region around N=40 has attracted much attention since the discovery of a double shell closure and triple shape coexistence in ^{68}Ni [1, 2]. However, many experiments have shown that this neutron subshell gap is rather weak and that deformed structures become yrast as protons are removed. This is the case, for example, of some of the neutron-rich Cr, Mn, Fe and Co isotopes, the structure of which is dominated by deformed configurations and collective excitations involving the shape-driving $\nu g_{9/2}$ orbital [3–13]. Coexistence and transitions between spherical and deformed structures in this mass region can now be understood in the context of the so-called *Type-II* shell evolution, as a consequence of the action of the monopole component of the proton-neutron tensor force between the $\pi f_{5/2,7/2}$ and the $\nu g_{9/2}$ orbitals [14–16]. The role of this interaction in connection with the emergence of collectivity and the evolution of nuclear shapes above ^{68}Ni is much less clear. As an example, the low-lying structures of the N=40 ^{70}Zn and ^{72}Ge isotones exhibit properties characteristic of spherical vibrators [17] and triaxial-deformed systems [18], respectively, suggesting a substantial contribution of protons in defining their intrinsic structure.

In this regard, Zn isotopes have been the subject of many experimental campaigns, yet the discrepancies between data and the results of calculations with various models are still puzzling. Recently, new experimental results on ^{71}Zn enabled to outline the role of neutron-neutron and proton-neutron correlations in this nucleus, the interplay of which is responsible for the occurrence of a spherical ground state and two oblate structures built on the $9/2^+$ state. At the same time, the absence of sequences associated with strong prolate deformation and large collectivity was interpreted as being due to blocking effects caused by the presence of protons above the Z=28 shell gap [19]. This is also confirmed by recent collinear laser spectroscopic results in odd-A Zn isotopes, which suggest an onset of collectivity only for $N \geq 43$ [20].

More controversial is the structure of even-even Zn nuclei, in which different experimental results indicate that the maximum of collectivity is expected in ^{72}Zn. This is suggested by the measured B(E2; $2^+ \rightarrow 0^+$) values [21–24], which are however contradicted by the constant decrease in energy of the 2^+_1 states across N=40. On top of this, the available experimental data on the B(E2; $4^+ \rightarrow 2^+$) values [22–25] disagree with each other and the B(E2; $4^+ \rightarrow 2^+$)/B(E2; $2^+ \rightarrow 0^+$) ratios point to non-collective contributions to these excitations. Moreover, theoretical calculations fail, to a large extent, to reproduce the experimental data and different theoretical frameworks were shown to predict divergent results. Fig. 1 presents the systematic of experimental and theoretical B(E2; $2^+ \rightarrow 0^+$) (a) and of B(E2; $4^+ \rightarrow 2^+$) (b) values for even-even Zn isotopes between N=38-44. Experimental data come from Coulomb excitation experiments (Coulex) as well as from lifetime measurements using the Recoil Distance Doppler Shift method (RDDS) (see [21–25] and references therein). Theoretical predictions come from shell model calculations, using two different effective interactions (JUN45 and LNPS), and Hartree-Fock-Bogoliubov calculations (HFB) [26–28].

In this context, further experimental data on even-even Zn isotopes are strongly needed to firmly establish the structure of these nuclei and to validate theoretical models in this mass region. While the majority of the experiments performed thus far were devoted to the study of yrast bands only, we propose to investigate 0^+ and 2^+ off-yrast states in ^{72}Zn, with the aim of identifying spherical or deformed configurations feeding the ground-state band, providing information on the degree of collectivity and the presence of shape transitions across N=40. It is important to note that similar studies in Ni isotopes have recently proved the existence of shape isomers in medium-mass nuclei, such as in the case of ^{66}Ni [29].

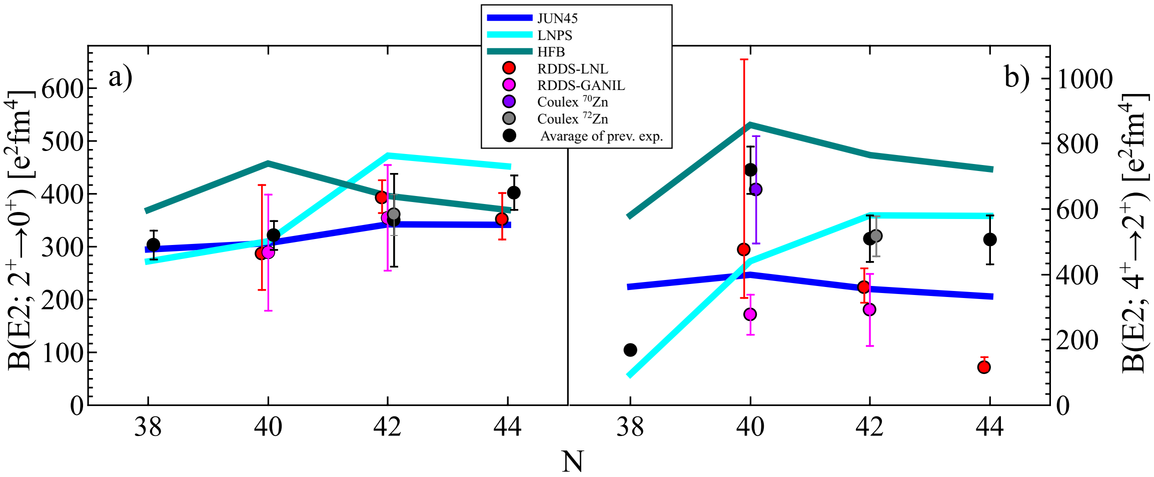

FIG. 1: Systematic of B(E2; $2^+ \to 0^+$) (a) and of B(E2; $4^+ \to 2^+$) (b) values for even-even Zn isotopes between N=38 and N=44, presenting comparisons between experimental data and theoretical predictions (see [21–28] and references therein).

III. PROPOSED EXPERIMENT

The low-lying level schemes and γ-ray decays in even-even Zn isotopes across N=40 are presented in Fig. 2, along with the know lifetimes and B(E2) values [30]. This comparison shows a decrease in energy of the 2_1^+, 2_2^+ and 4_1^+ states as a function of the neutron excess, while the energy of the 0_2^+ and 0_3^+ states displays a minimum in ^{70}Zn. Moreover, feedings of off-yrast structures from the 4_1^+ state are observed in ^{68}Zn only. Concerning the 0_2^+ state, a 100% feeding to the 2_1^+ state has been measured in all isotopes, whereas the γ-ray decay from the 2_1^+ level shows different behaviors. In ^{68}Zn the strongest γ-ray decays populate the ground state and the 0_2^+ state, with the former being the dominant one, and a small γ-ray branching to the 0_2^+ state can be also observed. In ^{70}Zn and ^{72}Zn there is no signature of the latter and the most intense γ-ray decay populates, in this case, the 2_2^+ state only. Finally, the 0_3^+ in ^{68}Zn feeds directly the 2_2^+ state, with only a small contribution to the 2_1^+ level. This is reversed in ^{70}Zn, where only a γ-ray decay to the 2_1^+ state is present. In ^{72}Zn there is a candidate for the 0_3^+ state, as measured in a ^{70}Zn(t,p) experiment [31], but no γ-ray decay was observed so far. Concerning lifetimes, the 2_2^+ states are in the range of a few ps, whereas the 0_2^+ states are in the range of a few ns. Particularly interesting is the 0_2^+ in ^{70}Zn, where the decrease in energy results in a sizable collectivity for this state (B(E2; $0_2^+ \to 2_2^+$) $\sim$ 40 W.u.). The available experimental data clearly point to a different structure for the yrast and non-yrast configurations in these isotopes, although information on lifetimes and γ-ray decays in ^{72}Zn is only partial.

We propose to measure the γ-ray decay of the 0_3^+ state, the lifetime of the 2_2^+ state and other possible γ-ray branchings from it in ^{72}Zn. To accomplish this goal, ^{72}Zn will be populated by using the two-neutron transfer reaction ^{70}Zn(^{18}O,^{16}O) at energies below the Coulomb barrier (E_{beam} = 40 MeV) and using a thick ^{70}Zn target (5 mg/cm^2). The experience gained by this collaboration in previous experiments has shown the effectiveness of this reaction mechanism to populate 0^+ and 2^+ off-yrast states while inhibiting fusion reaction channels down to cross sections of the order of a few mb, hence comparable with two-nucleon transfer probabilities [29]. Moreover, the states of interest were all observed in the ^{70}Zn(t,p) experiment [31], indicating that they are likely to be observed also in this measurement, owing to the similar reaction mechanism employed. It is worth mentioning that many other states at higher energies were measured in [31], the γ-ray decay of which might feed the states under study in the current proposal.

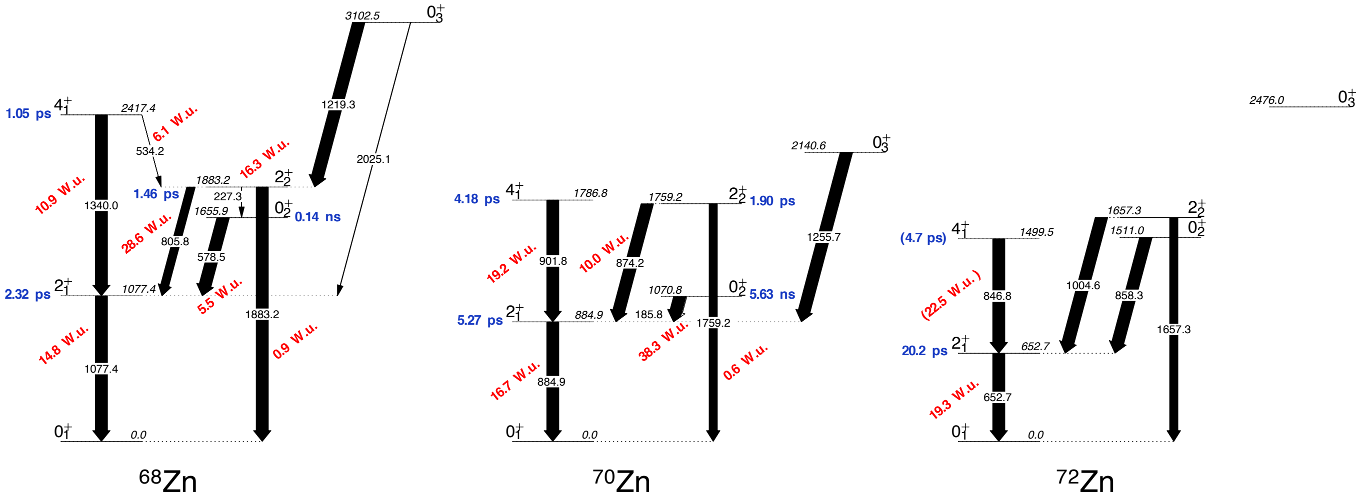

FIG. 2: Low-lying level schemes and γ-ray decays of ^{68}Zn, ^{70}Zn and ^{72}Zn. Known lifetimes and B(E2) values are also reported [30].

The γ-ray decay of ^{72}Zn will be detected by the 15 HPGe detectors of the ROSPHERE array, which will help determine possible γ-ray branchings from the 2_2^+ state to the 0_2^+ state and, in particular, the unknown γ-ray decays from the 0_3^+ state. The usage of a rather thick target will enhance the reaction rate, ensuring the collection of enough statistics to observe even small γ-ray branchings. Regarding lifetimes, we expect less than 2 ps for the 2_2^+ level, as suggested by comparisons with neighboring isotopes. Therefore, we propose to use the Doppler Shift Attenuation Method (DSAM) to measure it.

The expected longer lifetime of the 0_2^+ state would require different techniques to be measured. If new γ-rays feeding this state would be observed, the fast timing technique will be applied by using the 10 LaBr$_3$(Ce) detectors of the ROSPHERE setup. No predictions can be made for the 0_3^+ state in ^{72}Zn, as no lifetimes have been measured in adjacent nuclei for any of the observed 0_3^+ levels, nor theoretical predictions have described the features of these states so far. Nevertheless, the combination of DSAM and fast timing techniques, if any γ-ray feeding this state would be observed, will enable to establish, in the worst case, an upper and lower limit for the lifetime of the 0_3^+ state.

IV. BEAM TIME REQUEST

Assuming a conservative cross section for the two-neutron transfer channel of ~5 mb, a beam intensity of 5 pnA, the maximum sustained by the 5 mg/cm^2 Zn target, and an average efficiency for γ-ray detection of ~1% we request **7 days of beam time** (^{18}O at E_{beam} = 40 MeV) to collect sufficient γ-ray events to successfully perform γ-ray spectroscopy studies, even in the case of small γ-ray branchings, and lifetime measurements using the DSAM technique as well as fast timing techniques, when possible.

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