Using Coulomb excitation to study the low-lying structure of ^{104}Pd AGATA + SPIDER

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I. SCIENTIFIC MOTIVATION

The low-lying structure of nuclei between spherical (closed-shell) and deformed (open-shell) regions is traditionally interpreted in terms of rotations of a rigid rotor coupled to collective vibrations [1]. In recent years, extensive effort has been focused on studying the properties of the lowest-lying excited 0^+ states in nuclei with Z$\sim$50, which led to a new interpretation of their nature based on shape mixing and shape coexistence phenomena [2]. The Cd isotopes ($Z = 48$) located close to the $Z = 50$ major shell closure have been considered for many years as textbook examples of U(5) symmetry in the framework of the Interacting Boson Model based on patterns of excitation energies and γ-decay branching ratios. However, in a systematic study of stable even-mass Cd isotopes, it was concluded that some of these nuclei are poorly described by collective vibrational models [3]. This view left open the question of whether the neighbouring Pd isotopes ($Z = 46$) exhibit near-harmonic quadrupole vibrational behaviour as excitation energy patterns suggest. Detailed analyses from our group in the framework of the Interacting Boson Approximation (IBA-2) (see, *e.g.*, Ref. [4]) provided a good description of these nuclei as pertaining to a region of transition from the U(5) limit (vibrational) to the O(6) limit (γ-soft). In a recent work aimed at investigating the low-lying level structure of ^{106}Pd via conversion-electron spectroscopy, we proposed the coexistence of different shapes: a triaxial ground state and an oblate first excited 0^+ state. A Coulomb-excitation experiment was performed at Legnaro National Laboratories (LNL) last year with the AGATA+SPIDER setup to confirm this hypothesis. The importance of shape coexistence for the interpretation of the structure of $Z \sim 50$ nuclei has been underlined by a systematic study of the even-even Mo, Ru, Pd, Cd, and Te isotopes [5]. Significant and consistent deviations from the harmonic-vibrator predictions have been shown in every case: in particular, the $B(E2)$ values in the Pd isotopes have a trend much closer to that expected for a rigid rotor rather than a spherical-harmonic vibrator.

Experimental data on the electromagnetic structure of ^{104}Pd are surprisingly scarce if compared to the experimental information available for the neighbouring heavier even–even Pd isotopes [6]. Lifetimes have been studied only for the members of the ground state band, while Coulomb-excitation measurements have been performed using light beams of oxygen and sulfur leading to the population of a limited number of low-lying levels [7, 8]. The reduced transition probabilities for the decay of the 2^+_1, 2^+_2, 0^+_2, 4^+_1, 4^+_2 and 3^-_1 states have been deduced in Ref. [7], but no deformation parameters of any 0^+ states have been extracted. The quadrupole moment of the 2^+_1 level has been measured using the reorientation precession technique [9]. No other spectroscopic quadrupole moments have been previously extracted.

The structure of ^{104}Pd has been investigated by our group at LNL, via spectroscopy of internal conversion electrons [10, 11]. The K-internal conversion coefficients α_K of some transitions have been measured. The ratio X_{ifj} of the electric monopole B(E0; $0^+_i \rightarrow 0^+_f$) to the electric quadrupole B(E2; $0^+_i \rightarrow 2^+_f$) reduced transition probabilities and the electric monopole transition strengths $\rho^2(E0)$ between low-lying 2^+ and 0^+ states have been deduced.

The low-energy Coulomb-excitation experiment we are proposing will allow for the extraction of important new information on the electromagnetic structure of ^{104}Pd, including spectroscopic quadrupole moments of excited states and deformation parameters (β and γ). Using these new results in combination with those obtained via internal conversion electron spectroscopy will make it possible to shed light on the low-lying structure of ^{104}Pd.

II. PROPOSED EXPERIMENT

This proposal aims to clarify the structure of ^{104}Pd by studying the low-lying level deformation via Coulomb excitation using 12 triple clusters (ATCs) of the AGATA array coupled to the SPIDER array covering scattering angles from 124° to 161° with respect to the beam direction. A 1-pnA ^{58}Ni beam will be focused on a 1-mg/cm^2 thick ^{104}Pd target at an energy of 175 MeV, chosen to satisfy the "safe" energy criterion [12]. A large number of excited states will be populated in the proposed experiment, as suggested by our GOSIA [13] calculations summarised in Table I.

TABLE I: Number of γ-particle coincidences in ^{104}Pd calculated using the GOSIA code for the AGATA (12 ATCs) + SPIDER experimental setup and a ^{58}Ni beam of 1 pnA intensity. The AGATA efficiency was taken from Ref. [14] for the close-up configuration and scaled to the number of detectors assumed in the proposal. The matrix elements have been calculated on the basis of the reduced transition probabilities reported in Ref. [15]. Positive signs have been adopted. The matrix elements for the transitions from the 0^+_3 and 2^+_3 levels have been obtained on the basis of lower lifetime limits and known branching ratios. For the $0^+_3 \to 2^+_2$ transition, a conservative $B(E2; 0^+_3 \to 2^+_2) = 10$ W.u. value has been used, compatible with the upper limit (< 380 W.u.).

Level	Energy [keV]	Transition	E$_\gamma$ [keV]	Counts/8 hours
2^+_1	556	$2^+_1 \to 0^+_1$	556	7×10^6
4^+_1	1324	$4^+_1 \to 2^+_1$	768	4.7×10^5
2^+_2	1342	$2^+_2 \to 2^+_1$	786	4×10^4
		$2^+_2 \to 0^+_1$	1342	3.8×10^4
0^+_2	1334	$0^+_2 \to 2^+_1$	778	5.8×10^4
0^+_3	1793	$0^+_3 \to 2^+_1$	1237	1.1×10^5
		$0^+_3 \to 2^+_2$	451	874
2^+_3	1794	$2^+_3 \to 0^+_1$	1794	163
		$2^+_3 \to 2^+_1$	1238	1×10^4
		$2^+_3 \to 0^+_2$	460	157
4^+_2	2082	$4^+_2 \to 2^+_2$	740	2.9×10^3
		$4^+_2 \to 4^+_1$	758	1×10^3
		$4^+_2 \to 2^+_1$	1526	2.5×10^3
6^+_1	2250	$6^+_1 \to 4^+_1$	926	21
3^-_1	2194	$3^-_1 \to 0^+_1$	2194	2.3×10^3

The transitions from the 2^+_3 and 0^+_3 states were not reported in the most recent Coulomb-excitation measurement summarized in Ref. [8]. Only upper limits of the reduced transition probabilities $B(E2; 0_3^+ \to 2_1^+)$, $B(E2; 2_3^+ \to 2_1^+)$ and $B(E2; 2_3^+ \to 0_1^+)$ were obtained in the study of Luontama et al. [7], as it was not possible to establish whether the intensity of the observed 1238 keV line originates from the $2_3^+ \to 2_1^+$ transition or the $0_3^+ \to 2_1^+$ one, or their sum. In the proposed experiment, we expect to observe the $2_3^+ \to 0_1^+$ γ–ray transition and thus we will be able to extract not only the corresponding $B(E2; 2_3^+ \to 0_1^+)$ value but also the remaining transition strengths governing the decay of the 2_3^+ state using known branching ratios [10]. The extraction of the $\langle 2_3^+||E2||0_2^+\rangle$ matrix element will be crucial for the calculation of the $\langle Q^3 \cos 3\delta\rangle$ invariant for the 0_2^+ state. We are confident in observing the $2_3^+ \to 0_2^+$ transition both based on the calculations reported in Table I and from our previous Coulomb-excitation measurement carried out with the same setup for the ^{106}Pd isotope. Figure 1 shows the Doppler-corrected AGATA+SPIDER coincidence spectrum, where the transition at ~430 keV is clearly visible. The analysis of this experiment is still ongoing.

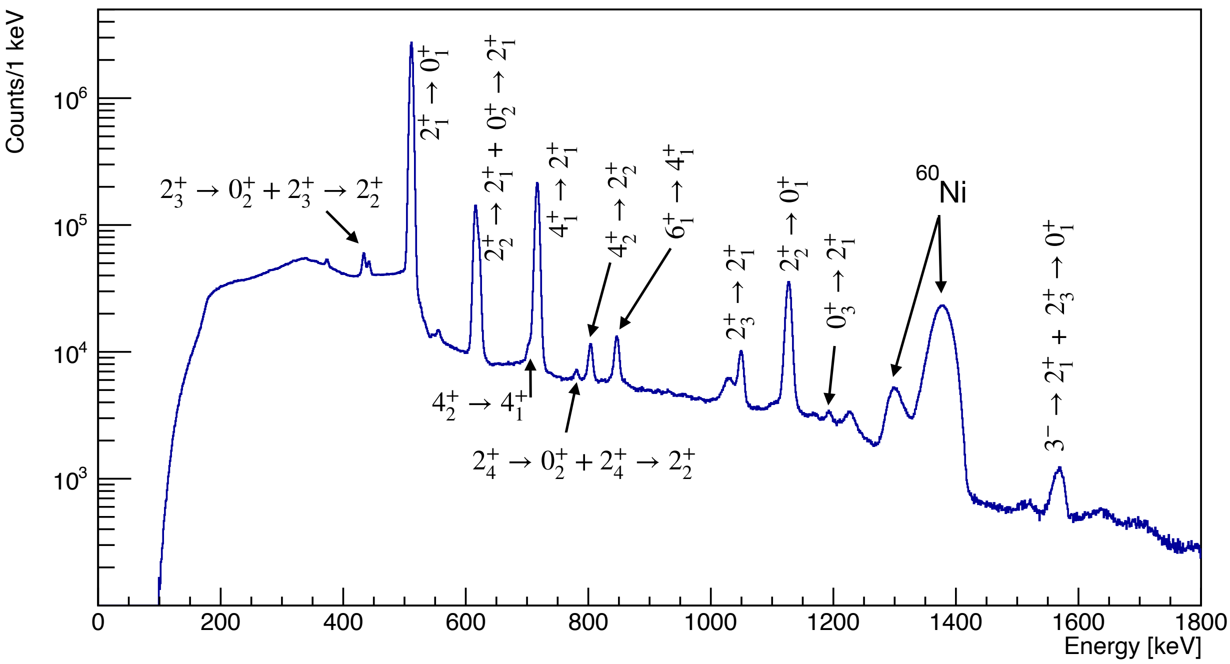

FIG. 1: Total γ-ray spectrum resulting from Coulomb excitation of ^{106}Pd measured in coincidence with scattered beam particles detected with the SPIDER array.

The high efficiency of the setup used in the proposed experiment will also allow us to investigate the structures built on the 0_3^+ state. In this regard, a possible candidate for the 2^+ band member is the 2125 keV level, which is reported to decay only to the 0_3^+ state in Ref. [16]. Furthermore, the use of γ-γ-particle coincidences will offer the possibility to study, in a more detailed way with respect to Ref. [11], the decay of the 0_4^+ state.

Information on the octupole collectivity in the ^{104}Pd isotope may be obtained via the observation of the decay of the 3_1^- state at 2194 keV, identified in Ref. [10]. No information on the B(E2, $3_1^- \to 2_1^+$) value is available in the literature, whereas a value for the B(E3;$3_1^- \to 0_1^+$) is reported in Ref. [7].

In summary, the goal of the present experiment is to probe the low-lying structure of ^{104}Pd, in particular regarding possible vibrational or deformed intruder states. We will build on the previous available measurements, whose results will be included in our data analysis. Particularly, the low-energy Coulomb excitation measurement from Ref. [7] and our recent conversion electron experiment needed to constrain the $E0$ components. A set of matrix elements will be obtained, allowing for the application of the quadrupole sum rules to probe in a model-independent way the structure of the isotope of interest. Specifically, our main goals are:

- First determination of the $\langle Q^2 \rangle$ and the $\langle Q^3 \cos 3\delta \rangle$ invariants for the 0_1^+ and 0_2^+ states.
- First determination of the spectroscopic quadrupole moment of the 2_2^+ state.
- Search for $E2$ transitions from 2^+ states on top of the 0_3^+ state and, in case of their existence, the first determination of the $\langle Q^2 \rangle$ invariant for the 0_3^+ state.
- Study of the decay of the 0_4^+ state.

III. BEAM TIME REQUEST

Our beam time request is based on the estimated γ–particle coincidences presented in Table I, particularly on the transitions related to the excited 0^+ states. Within 5 days we will achieve enough statistics and precision to determine the $\langle Q^3 \cos 3\delta \rangle$ invariant for the 0_2^+ state. Also, we will accumulate ∼1000 counts (corresponding to ∼5% statistical uncertainty) in the $2_3^+ \to 0_1^+$ transition. This is needed to study the 2_3^+ state since the stronger $2_3^+ \to 2_1^+$ transition is overlapping with the $0_3^+ \to 2_1^+$ transition. In summary, we ask for:

- Beam: ^{58}Ni, 1 pnA, 175 MeV, continuous.
- Target: ^{104}Pd, 1 mg/cm^2, self-supporting.
- Setup: AGATA+SPIDER.
- Duration: 5 days.

[1] A. Bohr and B. Mottleson, Nuclear Structure **Vol. II** (1975).
[2] K. Heyde and J. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[3] P. E. Garrett and J. L. Wood, J. Phys. G **37**, 064028 (2010).
[4] A. Giannatiempo, A. Nannini, and P. Sona, Phys. Rev. C **58**, 3316 (1998).
[5] P. E. Garrett, M. Zielińska, and E. Clément, Prog. Part. Nucl. Phys. **124**, 103931 (2022).
[6] L. Svensson et al., Nucl. Phys. A **584**, 547 (1995).
[7] M. Luontama et al., Z. Phys. A **324**, 317 (1986).
[8] S. Dutta, P. Napiorkowski, et al., Acta Physica Polonica B **47**, 917 (2016).
[9] C. Fahlander, L. Hasselgren, and J. E. Thun, Nucl. Inst. Meth. **146**, 329 (1977).
[10] M. E. Bellizzi, A. Giannatiempo, A. Nannini, A. Perego, and P. Sona, Phys. Rev. C **63**, 064313 (2001).
[11] N. Marchini et al., Phys. Rev. C **105**, 054304 (2022).
[12] D. Cline, Annu. Rev. Nucl. Part. Sci. **36**, 683 (1986).

[13] T. Czosnyka et al., Bull. Am. Phys. Soc. **28**, 745 (1983).
[14] *AGATA pre-PAC meeting technical information, available at*, `https://agenda.infn.it/event/34322/attachments/101184/140913/Technical-prePAC-final.pdf`.
[15] *National Nuclear Data Center, Brookhaven National Laboratory, available at*, `https://www.nndc.bnl.gov`.
[16] D. L. Dittmer and W. W. Daehnick, Phys. Rev. **187**, 1553 (1969).