PROBING LOW-ENERGY STATES IN ^{110}Cd USING COULOMB EXCITATION*

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A campaign of Coulomb-excitation experiments to study the electromagnetic structure of ^{110}Cd was performed using beams of ^{14}N, ^{32}S, and ^{60}Ni. The use of various reaction partners enables disentangling the contributions of individual electromagnetic matrix elements involved in the excitation process, yielding, among others, a precise determination of the lifetime of the 2^+_2 state in ^{110}Cd.

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1. Introduction

For several decades, stable even-mass Cd isotopes have been considered to be textbook examples of multiphonon spherical vibrators [1] based on the excitation energy pattern of their low-lying states. However, in the isotopes near the neutron mid-shell, "additional" 0^+ and 2^+ states were found in the vicinity of the presumed two-phonon states that were initially unexplained [2]. A study of the β decay of ^{110}In established a rotational-like band built on the 0^+_2 level in ^{110}Cd, indicating the presence of deformed intruder states [3]. The γ-ray transition B(E2) values were explained by invoking strong mixing between the intruder and vibrational states [4], but detailed γ-ray spectroscopy of stable even–even Cd isotopes (summarized in Refs. [5–7]) revealed consistent and systematic discrepancies between a number of the determined B(E2) values and the model predictions. These discrepancies were perhaps the most clearly delineated in ^{110}Cd, for which a number of transition intensities determined in the β decay of ^{110}In [6] were in severe disagreement with the predictions. Subsequent investigation of ^{110}Cd and ^{112}Cd using the symmetry-conserving configuration-mixing (SCCM) method [8, 9] and the General Bohr Hamiltonian (GBH) approach [10] suggested the presence of multiple-shape coexistence in these isotopes. On the other hand, it has been demonstrated that the spherical-vibrational-model picture for even-mass $^{110-116}$Cd isotopes can be preserved using the concept of a partial dynamical symmetry in the U(5) Hamiltonian [11, 12].

To establish the shapes of low-lying 0^+ states in even–even Cd nuclei, complete sets of transitional and diagonal E2 matrix elements, including their relative signs, are needed. This key experimental information can be obtained using the low-energy Coulomb-excitation technique [13].

2. Experiments with ^{32}S and ^{14}N beams (EAGLE at HIL)

Coulomb-excitation cross sections depend on the projectile scattering angle, its energy, and the atomic (Z) and mass (A) numbers of the collision partners. They are also sensitive to various E2 matrix elements, and this sensitivity changes as a function of the strength of the electromagnetic field created by the collision partner [10]. For this reason, a variety of beams and experimental setups have been used in our campaign of systematic Coulomb-excitation measurements of ^{110}Cd.

This multi-faceted experimental program started with measurements performed at the Heavy Ion Laboratory (HIL), University of Warsaw, using beams of ^{14}N (35 MeV) and ^{32}S (91 MeV) [14]. The γ rays emitted from the excited states of ^{110}Cd were detected by the EAGLE γ-ray spectrometer [15] in coincidence with back-scattered beam ions registered by a set of PIN-diode detectors [16] placed in a compact scattering chamber. In the experiment with the ^{14}N beam, transitions deexciting the 2^+_1, 4^+_1, 2^+_2, 0^+_2, and 3^-_1 states in ^{110}Cd were observed. The same transitions were present in the spectrum obtained in the experiment with the ^{32}S beam, but in this case also the $0^+_3 \rightarrow 2^+_1$ transition was at the observational limit. The total Doppler-corrected γ-ray spectrum from the measurement with the ^{14}N beam is presented in Fig. 1.

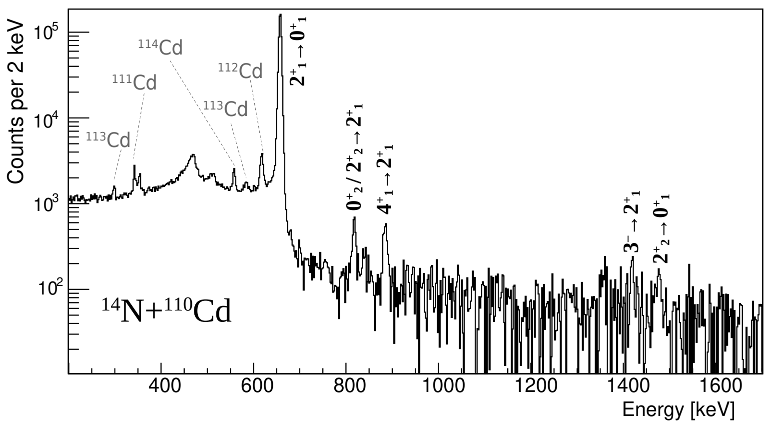

Fig. 1. Doppler-corrected γ-ray spectrum of ^{110}Cd from the Coulomb-excitation experiment performed at HIL using a 35 MeV ^{14}N beam. The γ rays originating from ^{110}Cd are marked in black. Transitions resulting from Coulomb excitation of target isotopic impurities ($^{111-114}$Cd) are labelled accordingly.

From the measured γ-ray intensities combined with known spectroscopic data [6, 17], a set of electromagnetic matrix elements was extracted [14] using the GOSIA code [18]. With the use of light projectiles (*e.g.*, ^{14}N), multi-step excitations are suppressed and the single-step Coulomb-excitation process dominates. Consequently, the number of electromagnetic matrix elements required to describe the population of the observed excited states is strongly limited, increasing sensitivity to B(E2) values involving states that can be reached from the ground state in a single-step excitation process. This was particularly important for the extraction of the B(E2) values for the decay of the 2_2^+ state. Indeed, a notable result of this analysis was a precise determination of the lifetime of the 2_2^+ state, $\tau = 1.40(-8;+6)$ ps. Previously, the $\tau(2_2^+)$ lifetime has been measured using the Doppler-shift attenuation method (DSAM) [6, 19, 20] and electron scattering [21]. The uncertainties of literature values range from 22% to 37%. The currently obtained $\tau(2_2^+)$ value agrees within 1σ with all but one of the previous results, but has a considerably higher precision, as presented in Fig. 2. Accurate information on the properties of the 2_2^+ state — assigned as the γ bandhead in Ref. [6] — is important in order to distinguish between the existing interpretations of its character, *i.e.* to establish if it results from a multi-phonon excitation or a non-axial rotation. Within the harmonic vibrational model, the absolute $B(\mathrm{E2})$ values for the decay of two-phonon states (0^+, 2^+, 4^+) to the one-phonon level (2_1^+) are twice as large as the $B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ value, while transitions changing the phonon number by more than one are prohibited. The $B(\mathrm{E2}; 2_2^+ \to 2_1^+)/B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ and $B(\mathrm{E2}; 2_2^+ \to 0_1^+)/B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ ratios equal 1.00(6) and 0.035(2) [14], respectively, obtained from the present analysis, contradict the vibrational interpretation.

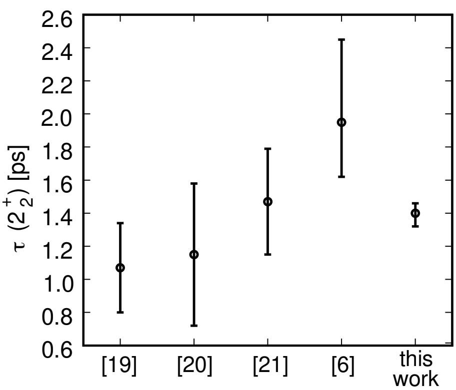

Fig. 2. The $\tau(2_2^+)$ lifetime obtained from the present data compared with the literature values resulting from DSAM measurements [6, 19, 20] and electron scattering [21].

3. Experiment with a ^{60}Ni beam (AGATA at LNL)

The next important step was possible thanks to the availability at the Legnaro National Laboratories (LNL) of the new-generation γ-ray spectrometer AGATA [22, 23]. This powerful device was used for a multi-step Coulomb-excitation experiment performed with a ^{60}Ni beam with an energy of 187 MeV, delivered by the Tandem accelerator. AGATA was composed of 11 germanium triple-cluster detectors and worked in coincidence with the segmented silicon detector array SPIDER [24]. SPIDER was used to detect back-scattered beam ions at laboratory angles ranging from 128° to 160° (θ_{CM} = 154°–171°), enhancing the probability of multi-step Coulomb excitation. A 0.93(6) mg/cm^2 thick ^{110}Cd target, isotopically enriched to 97%, was used. The target thickness was measured using the Rutherford Backscattering Spectrometry (RBS) method [25] at the LABEC INFN laboratory in Florence, Italy.

A preliminary Doppler-corrected γ-ray spectrum of ^{110}Cd, summed over all AGATA crystals and all sectors of the SPIDER charged-particle detector, is presented in Fig. 3. A partial level scheme of ^{110}Cd indicating the γ rays observed in the ^{60}Ni + ^{110}Cd experiment is shown in Fig. 4. The excitation probabilities of ^{110}Cd states with ^{14}N and ^{60}Ni beams differ significantly, with multi-step excitations enhanced in the latter case, as illustrated in Table 1. For example, the $4_1^+ \to 2_1^+$ transition intensity, normalised to that of the $2_1^+ \to 0_1^+$ transition, is 17(2) times larger in the experiment with ^{60}Ni than in that with the ^{14}N beam, while for the $2_2^+ \to 0_1^+$ transition only a 9(2)-fold increase is observed.

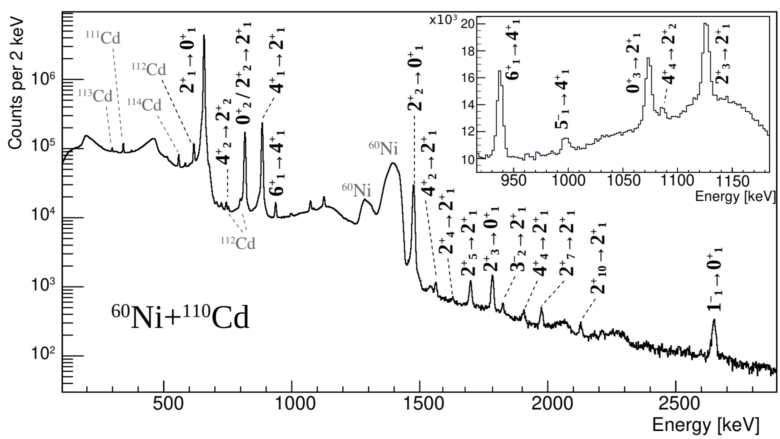

Fig. 3. Preliminary Doppler-corrected γ-ray spectrum from the Coulomb-excitation experiment of ^{110}Cd performed at the LNL using a 187-MeV ^{60}Ni beam. The γ rays originating from ^{110}Cd are labelled in black. Transitions resulting from the Coulomb excitation of target isotopic impurities ($^{111-114}$Cd) and of the ^{60}Ni projectile are also marked. Inset: Part of the same spectrum expanded around the 1073 keV $0_3^+ \to 2_1^+$ γ-ray transition.

In total, 19 excited states of both positive and negative parity were populated up to 2.8 MeV excitation energy. In addition to states up to spin-6 in the ground-state band, members of the side bands built on the 0_2^+ and 0_3^+ states were also excited (see Fig. 4). In particular, the $0_2^+ \to 2_1^+$ and $0_3^+ \to 2_1^+$ transitions are clearly visible in the experimental spectrum. From

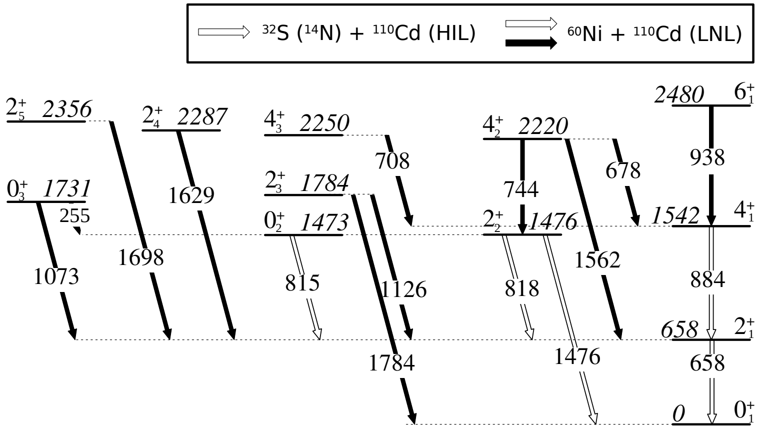

Fig. 4. Partial level scheme of ^{110}Cd presenting the γ-ray transitions observed in the ^{60}Ni + ^{110}Cd experiment with their energies given in keV. The transitions marked in black were only observed in the experiment using ^{60}Ni beam, while the transitions marked in white were observed in all three Coulomb-excitation experiments, *i.e.* with ^{14}N, ^{32}S, and ^{60}Ni beams. Only states assigned in Refs. [8, 9] to the ground-state band, the bands built on the $0^+_{2,3}$ states, and the $K = 2$ 'γ' and 'γ-intruder' bands are plotted.

Table 1. Relative intensities of γ-ray transitions in ^{110}Cd, normalized to that of the $2^+_1 \to 0^+_1$ transition, in the Coulomb-excitation measurements performed with ^{14}N and ^{60}Ni beams. Only transitions observed in both experiments are listed.

Transition	Energy	Relative intensity	
$I_{\mathrm{i}} \to I_{\mathrm{f}}$	E_γ [keV]	^{14}N + ^{110}Cd	^{60}Ni + ^{110}Cd
$2^+_1 \to 0^+_1$	658	1	1
$0^+_2 \to 2^+_1$ & $2^+_2 \to 2^+_1$	815 & 818	$3.8(4) \times 10^{-3}$	$4.2(3) \times 10^{-2}$
$4^+_1 \to 2^+_1$	844	$3.4(4) \times 10^{-3}$	$5.8(4) \times 10^{-2}$
$2^+_2 \to 0^+_1$	1476	$1.3(3) \times 10^{-3}$	$1.12(8) \times 10^{-2}$

the measured 1073 keV $0^+_3 \to 2^+_1$ γ-ray transition intensity, combined with the known $0^+_3 \to 2^+_2/0^+_3 \to 2^+_1$ γ-ray branching ratio [6], it will be possible to determine the corresponding $B(\mathrm{E2})$ values, for which only upper limits are currently known [6, 8, 9]. Moreover, the decay of a number of other states in ^{110}Cd was observed, in particular, the 2^+_2 state at 1476 keV and the 2^+_4 state at 2287 keV, which are assigned as heads of two γ-like bands [8, 9]. Several other positive-parity states were also populated, namely 2^+_7 at 2633 keV,

2^+_{10} at 2287 keV, and 4^+_4 at 2561 keV. As they have no clear band assignments, they are not presented in the level scheme in Fig. 4. Finally, decays of negative-parity 1^-, $3^-_{1,2}$, and 5^- states to ground-state band members are also present in the spectrum. The Doppler-broadened $2^+_1 \to 0^+_1$ transition in ^{60}Ni obscures the region of the spectrum between 1250 and 1450 keV, making it impossible to observe the 1420 keV $3^-_1 \to 2^+_1$ transition in ^{110}Cd. The population of the 3^-_1 state can, however, be determined from the measured intensity of the $3^-_1 \to 2^+_2$ decay and the known $3^-_1 \to 2^+_2$ / $3^-_1 \to 2^+_1$ branching ratio [17]. Moreover, the data obtained at HIL were also sensitive to the $B(\mathrm{E3}; 3^-_1 \to 0^+_1)$ value.

4. Outlook

The analysis of the data collected in the experiment with the ^{60}Ni beam is in progress. We aim to extract a rich set of electromagnetic matrix elements in ^{110}Cd, including their relative signs and spectroscopic quadrupole moments of excited states, particularly of the 2^+_3 state assigned to the 0^+_2 intruder band. This experimental information is crucial to deduce the degree of non-axial deformation (*i.e.* the γ deformation parameter) for the 0^+_2 state and to validate or refute the shape-coexistence scenario in stable cadmium isotopes at neutron mid-shell, predicted by state-of-the-art beyond-mean-field models [6, 8–10, 26].

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