

INVESTIGATION OF THE STRUCTURES OF $^{110,112,116}\text{Cd}$
USING β DECAY*

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There is an ongoing debate regarding the structure of the Cd isotopes, with the traditional interpretation of multiphonon vibrational states confronted with a recent suggestion that they possess multiple shape coexistence. In order to settle this debate, detailed studies are being pursued that include Coulomb excitation with multiple reaction partners and high-statistics β -decay measurements to provide high-precision spectroscopic data. We report results from very recent β -decay studies performed with the GRIFFIN γ -ray spectrometer on $^{110,112,116}\text{Cd}$ that confirm some of the previous γ -ray placements, bring others into question, and observe new transitions from states assigned to low-lying bands.

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1. Introduction

The Cd isotopes, especially $^{110,112}\text{Cd}$, have a long history dating as far back as 1955 [1] of being cited as examples of nuclei that possess spherical vibrational structures. This interpretation was pursued through the advent of the Interacting Boson Model (IBM) in the 1970s with ^{110}Cd used as an early example for the U(5) symmetry (see, *e.g.*, [2]). In the 1980s and early 1990s, the main question was not *Are nuclei with excitation energy ratios $E(4_1^+)/E(2_1^+) \approx 2.0$ vibrational?*, but rather *How high in excitation energy do multiphonon vibrational states persist?* Work on ^{118}Cd [3, 4], for example, emphasised the nearly perfect harmonic energy spectrum and studies [5–7] of $^{110,112}\text{Cd}$ suggested the existence of states with up to six vibrational phonons. The characterisation of the Cd isotopes as the best examples of nuclei having a vibrational, or U(5), structure culminated in a survey performed by Kern *et al.* [8] that highlighted, in particular, $^{110,112}\text{Cd}$.

It has been known for nearly 50 years that shape coexisting “intruder” bands are present in the Cd isotopes following the first observation [9] of a rotational band in ^{110}Cd via γ -ray spectroscopy following ^{110}In β^+ /EC decay. The 0^+ band head was shown to have a significant pairing-excitation mode through its strong population in the $^{108}\text{Pd}(^3\text{He}, n)$ two-proton-transfer reaction [10], providing strong evidence for the role of $2p$ – $2h$ excitations across the $Z = 50$ closed shell. Soon thereafter, the natures of the excited 0_2^+ and 0_3^+ states in $^{112,114}\text{Cd}$ were investigated by Julin *et al.* [11] via electron spectroscopy. Small $\rho^2(0_3^+ \rightarrow 0_2^+)$ values were used to conclude that the mixing between the 0_2^+ and 0_3^+ states must be weak or the differences in their β_2 deformations small. Heyde *et al.* [12] developed a model for $^{112,114}\text{Cd}$, using both the particle–core coupling model and the IBM that reproduced the data for the low-lying states rather well. However, in order to reproduce the decays of the 0_2^+ and 0_3^+ levels, the mixing of the intruder and multiphonon states was taken to be strong, thus contradicting the conclusions of Julin *et al.* [11]. Fahlander *et al.* [13] deemed the strong-mixing scenario

in ^{114}Cd as unlikely based on results of their Coulomb excitation study and concluded that the best agreement with the data is reached if a highly anharmonic multiphonon structure is assumed. The detailed spectroscopic studies of $^{110,112}\text{Cd}$ performed by Kern *et al.* [5], Délèze *et al.* [6, 7], and Drissi *et al.* [14] used an interpretation based on the strong-mixing scenario, whereas the systematic investigations of the Cd isotopes by Kumpulainen *et al.* [15, 16] came to the opposite conclusion regarding the mixing strength.

Starting in the mid-1990s, a series of studies of the Cd isotopes was conducted at the University of Kentucky accelerator facility using the $(n, n'\gamma)$ reaction. The neutron inelastic scattering reaction at energies of a few MeV is mainly compound nucleus in nature, and thus all levels below the neutron bombarding energy are populated in a statistical manner. Typically, the angular momentum imparted in the reaction leads to levels with spin $I \leq 6\hbar$ having sufficient cross section to be observable. This enables the development of comprehensive level schemes, and further, level lifetimes can be determined via the Doppler-shift attenuation method (DSAM) [17]. The initial studies of $^{110,112}\text{Cd}$ [18–22] were interpreted within the configuration mixing (CM) model of the IBM (or IBM2), however, this approach failed when applied to ^{116}Cd [23]. A thorough examination [24] of available data highlighted the *systematic* deviation of $B(E2)$ values from the expectations of both the simple harmonic vibrational model as well as the more sophisticated IBM2-CM calculations. In Ref. [25], it was suggested that the even–even $^{110-116}\text{Cd}$ isotopes were deformed and the low-lying states could be arranged in rotational bands.

A program of γ -ray spectroscopy following β decay in order to probe the low-spin states at high excitation energy in $^{110,112}\text{Cd}$ was initiated using the 8π spectrometer [26, 27] at the TRIUMF-ISAC facility. An early result [28] for ^{110}Cd combining the data from the ^{110}In β^+/EC -decay and lifetimes from the $(n, n'\gamma)$ reaction demonstrated that the mixing of the intruder states and the normal “vibrational” states was indeed weak. Continued analysis of the data revealed additional transitions that, despite the very small branching ratios, were collective in nature. With the aid of beyond-mean-field calculations, the assigned bands were suggested to be based on multiple deformed shapes [29, 30]. This interpretation was expanded to include ^{106}Cd by Siciliano *et al.* [31], and it has been suggested to span much of the Cd isotopic chain [32]. Figure 1 displays the spectroscopic data for the low-lying 0^+ states from ^{106}Cd through ^{118}Cd . In $^{106-114}\text{Cd}$, the $0_3^+ \rightarrow 2_2^+$ transition has a large $B(E2)$ value. In ^{116}Cd , it is the 0_2^+ state that has a strongly favoured decay to the 2_2^+ state. In ^{118}Cd , the 0_2^+ state is a mere 16 keV above the 2_2^+ state and thus the full decay characteristics cannot be ascertained at present. The 0_2^+ state has been assigned as the head of the shape-coexisting intruder band in $^{106-114}\text{Cd}$ with enhanced $B(E2; 0_2^+ \rightarrow 2_1^+)$ values, with the

0_3^+ state in ^{116}Cd displaying this behaviour. Based on these systematics, if the shapes of the 0_2^+ and 0_3^+ states can be firmly established in some of the isotopes, they can confidently be extended to the other states with the same characteristics spanning the isotopic chain.

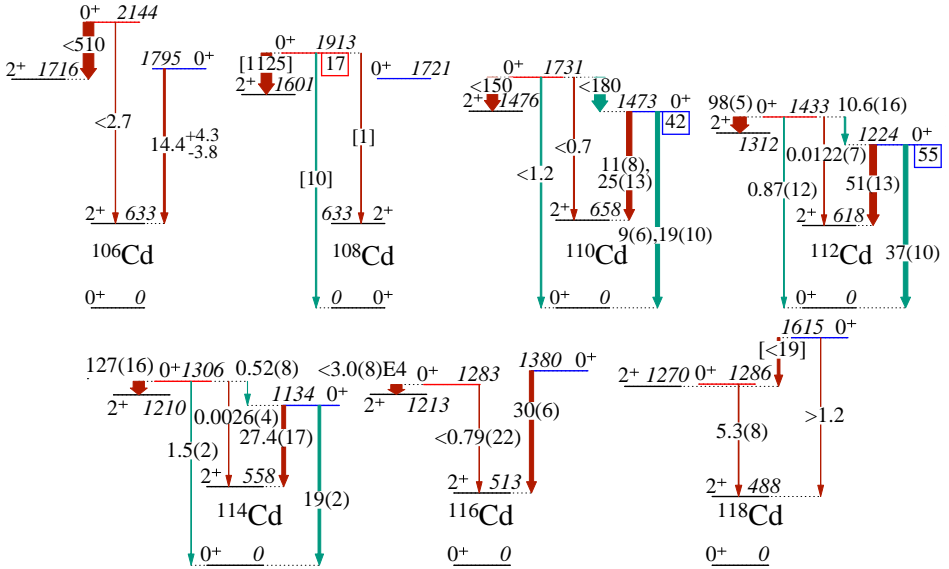


Fig. 1. (Colour on-line) Properties of the low-lying 0^+ states observed in the mid-neutron-shell Cd isotopes. The widths of the arrows are proportional to the $B(E2)$ values (rust colour/black) and $10^3 \times \rho^2(E0)$ (green/grey). The transitions are labelled with the absolute $B(E2)$ values in W.u. with uncertainties in parentheses, or relative $B(E2)$ values in square brackets. The $E0$ transitions are labelled with their $10^3 \times \rho^2(E0)$ values, or the $X(E0/E2)$ value for the 0_3^+ state in ^{108}Cd relative to the $E2$ to the 2_1^+ level. The numbers inside boxes attached to the levels are the ratios of the $(^3\text{He}, n)$ transfer cross sections to those of the ground state. Data are taken from the National Nuclear Data Center database [33] and Refs. [10, 13, 23, 29, 30, 34–37]. Figure adapted from Ref. [32] including recent data [34, 37].

Parallel to these developments, a partial-dynamical symmetry approach has been developed that successfully reconciled the discrepancies of the experimental data on $B(E2)$ values with the multiphonon vibrational interpretation [38, 39]. It was thus argued that the vibrational interpretation should not be abandoned. In order to distinguish between the interpretations and test the multiple-shape-coexistence hypothesis, a program of Coulomb-excitation experiments with the aim of extracting the shapes through the use of the invariant quantities $\langle Q^2 \rangle$ and $\langle Q^3 \cos 3\delta \rangle$ has been initiated. Results from the first study of ^{110}Cd performed at the Heavy Ion Laboratory

in Warsaw using beams of ^{14}N and ^{32}S [40, 41] led to the conclusion that the ground state has a triaxial shape [37, 40], while the 0_2^+ state has a very similar β_2 deformation but its axiality parameter γ remains unknown. Further Coulomb-excitation measurements on ^{110}Cd have been conducted at Legnaro Nuclear Laboratory (LNL) and at Argonne National Laboratory (ANL) with the aim of determining the shapes of the higher-lying 0^+ states [41, 42]. A campaign of Coulomb excitation measurements on ^{112}Cd has also been undertaken with experiments at the Maier–Leibnitz Laboratory and at LNL with ^{12}C and ^{60}Ni beams, respectively. Additionally, a Coulomb excitation experiment using a ^{116}Cd beam on a ^{208}Pb target was completed at ANL, and further measurements using lighter-mass binary partners are planned. Complementary to these studies, in order to improve the spectroscopic information on the Cd isotopes, a series of β -decay experiments was conducted at the TRIUMF-ISAC radioactive beam facility. In the present work, we concentrate on selected results on $^{110,112,116}\text{Cd}$.

2. β -decay spectroscopy at TRIUMF-ISAC

The radioactive isotopes under investigation were produced via spallation reactions involving 480 MeV proton beams from the main TRIUMF cyclotron to bombard thick UC_x targets. For the study of ^{110}Cd , the Re-surface ion source was used in conjunction with the TRIUMF laser ion source (TRILIS) [43]. For the studies of $^{112,116}\text{Ag}$ decay, the ion-guide laser ion source (IG-LIS) [44] was used that can be operated in two modes: suppression mode, where a voltage is applied to a repeller electrode to suppress the surface ions from the target with the neutral ions laser ionized, and transmission mode with the repeller electrode off. Both modes were employed in the present work depending on the isotope of interest. The GRIFFIN spectrometer consisted of 15 clover-type HPGe detectors [45] equipped with BGO Compton-suppression shields and was configured in the full-suppression mode [46]. The array was complemented by the PACES array of 5 Si(Li) detectors for conversion electron measurements, and a fast plastic scintillator and 8 LaBr₃ detectors for fast-lifetime measurements [46]. The beams were deposited onto a tape located at the center of the array and following the measurement, the tape was moved such that the spot with the residual activity was transported to a location exterior to the array behind a thick Pb shielding wall. The durations of the beam-on and measurement times were controlled by the data acquisition system [47] and adapted to the half-lives of the radioactive species delivered to GRIFFIN.

2.1. ^{110}In β^+ /EC-decay study of ^{110}Cd

For the production of ^{110}Ag and ^{110}In , a $15\ \mu\text{A}$ proton beam bombarded a UC_x target and the resulting yield of the $T_{1/2} = 24.6\ \text{s}$ ^{110}Ag ground state was $1.3 \times 10^6\ \text{s}^{-1}$, whereas those for the $T_{1/2} = 4.9\ \text{h}$ ^{110}In ground state and the $T_{1/2} = 69\ \text{min.}$ isomer were $1.4 \times 10^7\ \text{s}^{-1}$ and $2 \times 10^6\ \text{s}^{-1}$, respectively. During the experiment, two tape cycles were employed. A cycle with 25 s beam implantation followed by 30 s of decay was used to focus on the ^{110}Ag decay. In the present work, we concentrate on data from a longer cycle that involved building a source for 10–15 min. and counting for 8–10 h aimed at the measurement of the ^{110}In decay.

The sorting of the ^{110}In -decay data resulted in a time-random-background subtracted and symmetrised γ - γ matrix containing 12.9×10^9 events. Shown in Fig. 2 is the γ -ray spectrum in coincidence with the $1630\ \text{keV}$ $2_4^+ \rightarrow 2_1^+$ γ -ray transition in ^{110}Cd together with a partial level scheme. The present spectrum can be compared with Fig. 3 presented in Ref. [30]. While there was little doubt regarding the placement of the $418\ \text{keV}$ transition as the $4_5^+ \rightarrow 2_4^+$ transition in Refs. [29, 30], the increased level of statistics in the

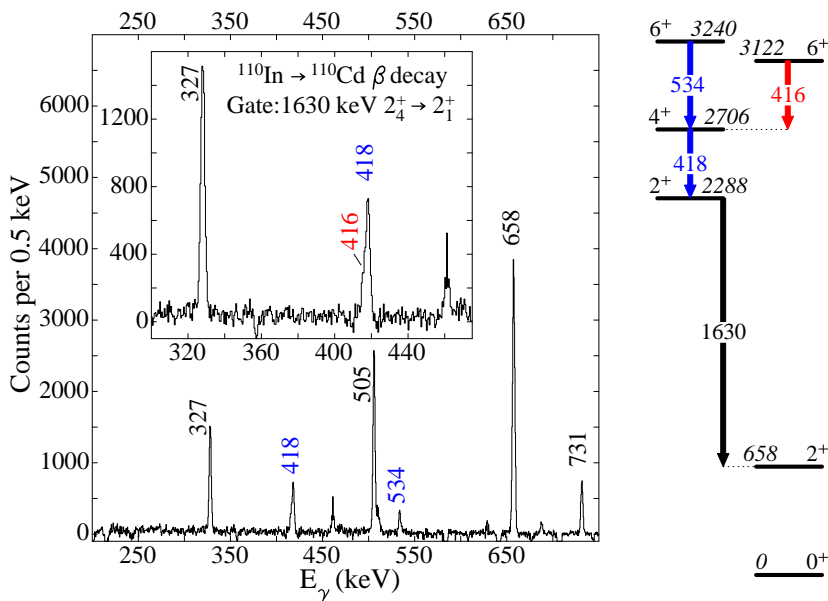


Fig. 2. (Colour on-line) Portion of the γ -ray spectrum observed in coincidence with the $1630\ \text{keV}$ $2_4^+ \rightarrow 2_1^+$ γ -ray transition (left) together with a partial level scheme (right) of ^{110}Cd . The placements of the $418\ \text{keV}$ and $534\ \text{keV}$ γ rays, which are labelled in blue, are confirmed as shown in the partial level scheme. The increased statistics of the present measurement reveals the existence of a new $416\ \text{keV}$ γ ray, labelled red in the inset, placed as feeding the $2706\ \text{keV}$ level.

present study reveals the existence of a 416 keV γ ray assigned as shown in Fig. 2. The consequence is that the previous branching ratio of the 418 keV transition, reported in Ref. [30] as 0.0059(5), is reduced to the preliminary value of 0.0046(2) leading to $B(\text{E}2; 4_5^+ \rightarrow 2_4^+) = 43(11)$ W.u.

2.2. ^{112}Ag β -decay study of ^{112}Cd

For the study of ^{112}Ag decay, a 5 μA of proton beam current was delivered to the UC_x target and the IG-LIS source was operated in transmission mode. The beam intensities were $2 \times 10^7 \text{ s}^{-1}$ of the $T_{1/2} = 3.15 \text{ h}$ ^{112}Ag ground state, and $1 \times 10^6 \text{ s}^{-1}$ and $3 \times 10^6 \text{ s}^{-1}$ of $T_{1/2} = 14.9 \text{ min}$. ^{112}In ground and $T_{1/2} = 20.7 \text{ min}$. isomeric states, respectively. Taking advantage of the large differences in half-lives, we implanted the beam for approximately 45 minutes to 1 hour, and measured the decay for up to 12 hours after irradiation. The initial sorting of the data, reported here, selected runs starting from 2 hours following the beam implantation greatly reducing the amount of In decay in the sorted spectra. Since the $^{112}\text{In} \rightarrow ^{112}\text{Sn}$ Q_{β^-} value is only 665 keV, the presence of any residual In activity does not significantly increase the background in our data. A time-random-background subtracted and symmetrised γ - γ matrix contained a total of 9×10^8 events, approximately an order of magnitude increase in statistics *vs.* the previous 8π data set reported in Refs. [29, 30].

In Refs. [29, 30], the 0_4^+ band was assigned based on the observation of very weak signals involving the 285 keV $2_5^+ \rightarrow 0_4^+$ γ ray observed in coincidence with the 1254 keV $0_4^+ \rightarrow 2_1^+$ γ ray, and the 555 keV $4_6^+ \rightarrow 2_5^+$ γ ray observed in coincidence with the 1539 keV $2_5^+ \rightarrow 2_1^+$ γ ray (see Figs. 11, 12 in Ref. [30]). Figure 3 shows a portion of the γ -ray spectrum observed in coincidence with the 1254 keV γ -ray decay of the 0_4^+ state. The enhanced statistics of the present measurement results in a clear coincidence signal for the 285 keV γ ray confirming its placement as the $2_5^+ \rightarrow 0_4^+$ transition. Our preliminary branching ratio is $9.7(6) \times 10^{-4}$ in agreement with the earlier result [30] of $7.9(33) \times 10^{-4}$ but considerably more precise. However, we find no evidence for the existence of the 555 keV γ ray as feeding the 2_5^+ level, as shown by the lack of the peak in the coincidence spectrum in Fig. 4. The feature to the right of the 555 keV region of the spectrum may provide the clue to the origin of the spurious signal in the previous measurement [30] as resulting from a Compton artifact. The lack of an observed transition thus calls into question the assignment of the 4_6^+ level as a member of the 0_4^+ band.

2.3. ^{116}Ag β -decay of ^{116}Cd

For the study of ^{116}Ag decay, a 10 μA proton beam was used to bombard the UC_x target and the IG-LIS source was used in suppression mode in

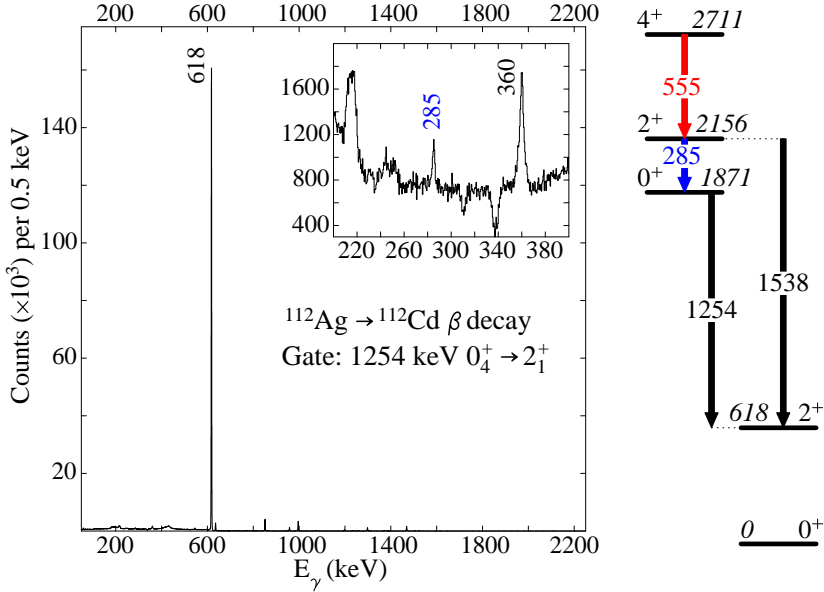


Fig. 3. (Colour on-line) Portion of the γ -ray spectrum observed in coincidence with the 1254 keV $0_4^+ \rightarrow 2_1^+$ γ -ray transition (left) together with a partial level scheme (right) for ^{112}Cd . The placement of the 285 keV γ ray, which is labelled in blue, is confirmed as the $2_5^+ \rightarrow 0_4^+$ transition.

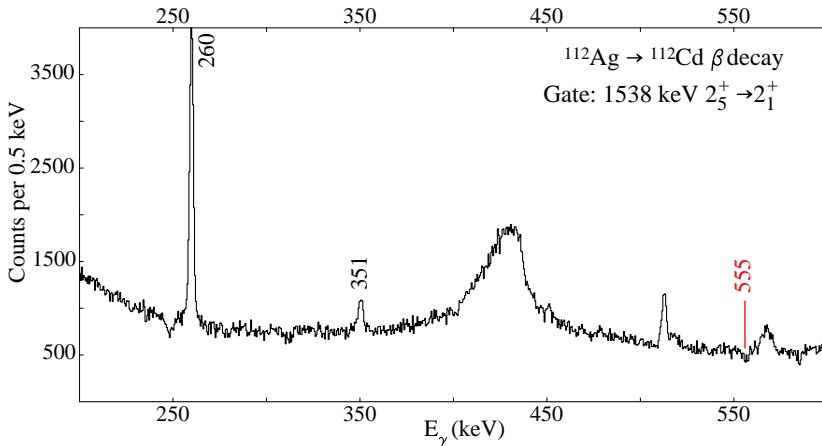


Fig. 4. (Colour on-line) Portion of the γ -ray spectrum observed in coincidence with the 1538 keV $2_5^+ \rightarrow 2_1^+$ γ -ray transition in ^{112}Cd . The red line indicates the position of the expected 555 keV γ ray assigned in Refs. [29, 30] as the $4_6^+ \rightarrow 2_5^+$ in-band transition. No evidence for its existence is found in the current data set.

order to reduce the intensity of ^{116}In . The yield measurements made in transmission mode with the $5\ \mu\text{A}$ proton current were $2 \times 10^7\ \text{s}^{-1}$ and $1 \times 10^6\ \text{s}^{-1}$ of ^{116}Ag in the $T_{1/2} = 3.8\ \text{min.}$ ground state and $T_{1/2} = 20\ \text{s}$ and $9.8\ \text{s}$ isomeric states combined. The ^{116}In yield was measured to be $1 \times 10^7\ \text{s}^{-1}$. In the suppression mode, with a $10\ \mu\text{A}$ proton beam, the corresponding yields were measured to be 5×10^5 and $5 \times 10^4\ \text{s}^{-1}$ for the ^{116}Ag ground state and isomers, respectively, and $1 \times 10^5\ \text{s}^{-1}$ of ^{116}In . The Ag-to-In ratio improved by a factor of 2.5 which was far less than expected, however the IG-LIS source has rarely been used for such high-mass beams and its operation in this regime has not been fully characterized.

For the data presented in the present work, we employed a measurement cycle that consisted of approximately 20 min. of beam deposit followed by 8 min. decay. With this cycling, the majority of the data collected was for the ^{116}Ag $J^\pi = (0^-)$ decay. The initial sorting of the data resulted in a time-random-background subtracted and symmetrised γ - γ matrix containing 9.9×10^9 events. The ^{116}In decay Q_{EC} value of 3.28 MeV limited the population to only a few states in ^{116}Sn with well-characterized decays that generally do not interfere with the γ -ray lines from ^{116}Cd .

As outlined in the introduction, there is an interchange of character of the 0_2^+ and 0_3^+ states occurring at ^{116}Cd compared to the lighter Cd isotopes. A key element identifying the 0_3^+ as the shape-coexisting intruder band was the placement of a 262 keV transition from the 2_3^+ state feeding the 0_3^+ level, which, using the results from Ref. [23], has a $B(\text{E}2; 2_3^+ \rightarrow 0_3^+) = 86_{-30}^{+24}$ W.u. The 262 keV γ ray was observed in one experiment only — the inelastic-scattering reaction using heavy ions performed by Juutiinen *et al.* [48], where a branching ratio of 0.33(7)% was determined [23, 48]. Figure 5 shows portions of the γ -ray spectra observed in coincidence with the 769 keV $0_2^+ \rightarrow 2_1^+$ and 866 keV $0_3^+ \rightarrow 2_1^+$ γ rays. The 866 keV coincidence spectrum confirms the existence of the 262 keV transition, and also reveals the existence of a 571 keV transition from the 2_4^+ level. The preliminary branching ratio of the 262 keV transition is 0.56(2)% resulting in $B(\text{E}2; 2_3^+ \rightarrow 0_3^+) = 150(30)$ W.u. using the lifetime from Ref. [23]. Examining the coincidence spectrum of the 769 keV transition, the 669 keV γ ray is clearly observed and its placement as the $2_4^+ \rightarrow 0_2^+$ transition confirmed, but also a new 360 keV γ ray is observed that is placed as the $2_3^+ \rightarrow 0_2^+$ transition. This latter transition has a branching ratio of $5.4(3) \times 10^{-4}$ yielding $B(\text{E}2; 2_3^+ \rightarrow 0_2^+) = 3.0(7)$ W.u. Thus, the band structure presented in Fig. 6 remains consistent with that originally proposed [23, 48]. Also shown in Fig. 6 are the placements of several new γ -ray transitions from the low-lying 2^+ states.

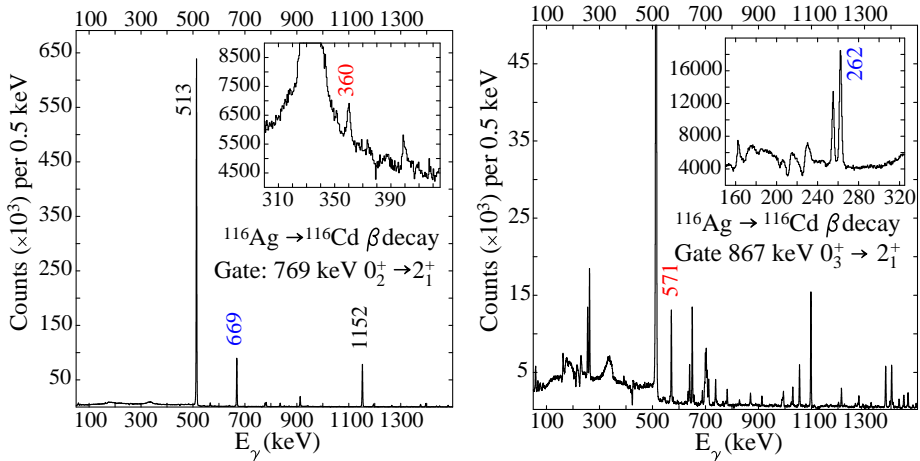


Fig. 5. (Colour on-line) Portions of the γ -ray spectra observed in coincidence with the 769 keV $0_2^+ \rightarrow 2_1^+$ (left) and the 867 keV $0_3^+ \rightarrow 2_1^+$ (right) γ -ray transitions in ^{116}Cd . The previously-observed 669 keV and 571 keV transitions from low-lying 2^+ states are labelled in blue, whereas the newly-observed 360 keV and 262 keV transitions are labelled in red. The confirmation of the 262 keV transition feeding the 0_3^+ state is especially important as it establishes the 0_3^+ state as the intruder band head, but was observed in only one previous experiment [48].

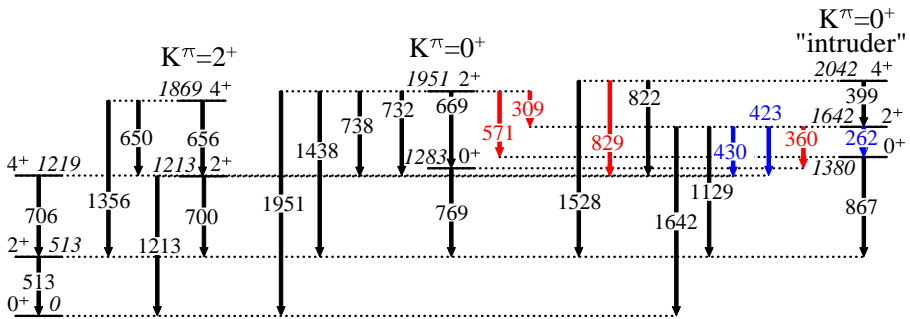


Fig. 6. (Colour on-line) Portion of the level scheme for ^{116}Cd established from the present data. The blue/gray arrows represent transitions previously observed in one experiment only, and red/light gray ones indicate newly-observed transitions based on the γ - γ coincidence analysis. The levels are arranged into band structures with $K^\pi = 0^+$ and 2^+ bands built on the 0_2^+ and 2_2^+ states, and the intruder band based on the 0_3^+ level.

3. Summary

The decay schemes of $^{110,112,116}\text{Cd}$ have been investigated using γ -ray spectroscopy following β decay. The mass-separated radioactive beams of ^{110}In , ^{112}Ag , and ^{116}Ag were produced at the TRIUMF-ISAC facility by

bombarding UC_x targets with 480 MeV protons and were delivered to the GRIFFIN spectrometer. The initial analysis focused on the high-statistics γ - γ coincidence data. In ^{110}Cd , the placements of the 418 keV and 534 keV transitions, previously assigned to levels in the second $K = 2$ band, were confirmed, but the 418 keV γ -ray peak was found to be part of an unresolved doublet. The resulting new branching ratio leads to $B(\text{E}2; 4_5^+ \rightarrow 2_4^+) = 43(11)$ W.u. In ^{112}Cd , the 285 keV γ ray assigned as the $2^+ \rightarrow 0^+$ transition of the 0_4^+ band was confirmed and its branching ratio measured with an increased precision that previously [30], leading to $B(\text{E}2; 2_5^+ \rightarrow 0_4^+) = 42(6)$ W.u. The 555 keV γ ray — the $4^+ \rightarrow 2^+$ transition in the band — was not confirmed. For ^{116}Cd , the 262 keV $2_3^+ \rightarrow 0_3^+$ transition was confirmed and the new branching ratio leads to $B(\text{E}2; 2_3^+ \rightarrow 0_3^+) = 150(30)$ W.u.

The present results confirm key placements of transitions used to assign band structures as presented in Refs. [23, 29, 30, 32, 48]. The present data do not provide conclusive evidence of multiple shape coexistence, but will be vital for the analysis of Coulomb excitation measurements aimed at the model-independent determination of the shape parameters (β, γ) .

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