UCRL-JRNL-200311

LAWRENCE LIVERMORE NATIONAL LABORATORY

Vibrational and intruder structures in ^{116}Cd: a conundrum

M. Kadi, N. Warr, P.E. Garrett, J. Jolie, S.W. Yates

May 22, 2003

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

UCRL-JRNL-200311

Vibrational and intruder structures in ^{116}Cd: a conundrum

M. Kadi,[1,*] N.Warr,[1,2] P.E. Garrett,[1,3] J. Jolie,[2] and S.W. Yates[1]

[1] *University of Kentucky, Lexington, Kentucky 40506-0055*

[2] *Institute of Nuclear Physics, University of Cologne, D-50937 Cologne, Germany*

[3] *Lawrence Livermore National laboratory, Livermore, California 94551*

(Dated: May 22, 2003)

Abstract

Decay properties of multiphonon quadrupole vibrational states and intruder structures in ^{116}Cd have been examined with the (n,n$'\gamma$) reaction. Gamma-ray excitation functions, angular distributions and γ-γ coincidences have been measured. Lifetimes of many levels were determined with the Doppler-shift attenuationmethod, exposing the degree of collectivity of the intruder structure and the three-phonon states. In combination with other recent results, this new information reveals that the intruder picture is well supported in the Cd nuclei. However, a conundrum not present in the lighter cadmium nuclei emerges in ^{116}Cd; strong configuration mixing between intruder and multiphonon vibrational excitations cannot describe the observed decays of the lowest 0^+ excited states.

PACS numbers: 21.10.Re, 21.10.Tg, 25.40.Fq, 27.60+j

The stable even-even cadmium nuclei exhibit a more complex level structure than is anticipated for a simple anharmonic quadrupole vibrator and, at excitation energies near the two-phonon triplet, additional 0^+ and 2^+ levels are typically observed. These "intruder" states have been attributed to two-proton excitations across the Z = 50 shell and are interpreted as arising from 2p-4h configurations [1–3].

Understanding even the lowest-lying states in the Cd nuclei near the neutron mid-shell has presented a challenge. For instance, Fahlander *et al.* [4] interpreted the electromagnetic decay properties of ^{114}Cd quite well within the vibrational model, but comparable B(E2) values can be produced with and without mixing between the normal and intruder configurations [5], although the vibrational model without intruders cannot explain the large energy anharmonicities. Generally, however, the low-lying levels of the mid-shell Cd nuclei can be understood [1] through mixing of vibrational and intruder configurations, and recent experimental studies of ^{110}Cd [6, 7] and ^{112}Cd [8, 9] have reinforced the strong-mixing description. Jolie and Lehmann [10, 11] demonstrated that the O(5) symmetry present in both the U(5) and O(6) limits of the interacting boson model can lead to selective mixing between vibrational and intruder states, however, crucial tests of this explanation in heavier cadmium nuclei have not been performed. The primary goals of this work are to provide new detailed experimental information about the low-lying level of ^{116}Cd, in order to investigate the multiphonon quadrupole and intruder excitations, and to understand the mixing between the intruder and vibrational states in the Cd nuclei.

In (n,n$'\gamma$) experiments performed at the University of Kentucky accelerator facility [12], the level structure of ^{116}Cd has been investigated. The ^{3}H(p,n)^{3}He reaction with pulsed proton beams was used to produce essentially monoenergetic neutrons with energies up to 3.8 MeV. The scattering sample consisted of 14.54 g of CdO powder, enriched to 97.07% in ^{116}Cd. For the γ-ray angular distribution and excitation function measurements, the spectra were recorded with a BGO Compton-suppressed HPGe detector with a relative efficiency of 52% and an energy resolution (FWHM) of 2.1 keV at 1332 keV. In addition, γ-γ coincidence measurements with collimated pulsed beams of 3.8-MeV neutrons were performed. Four HPGe detectors, similar to the one described above, in a close geometrical arrangement were used [13]. Applying the methodology described by Belgya *et al.* [14], the Doppler-shift attenuation method (DSAM) was used to obtain the lifetimes of many levels, and absolute transition rates were determined.

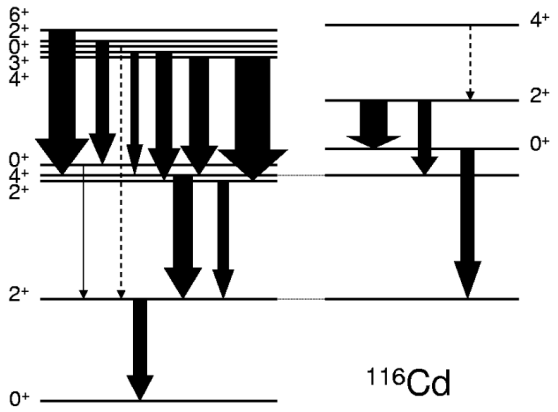

FIG. 1: Partial level scheme of ^{116}Cd. On the left are the suggested two- and three-phonon states. On the right are the intruder states proposed by Juutinen *et al.*[3]. The widths of the arrows are proportional to the measured B(E2) values. The dashed transitions were observed in this study; however, their transition rates could not be determined. The data from which this figure was constructed are contained in Table I.

A nearly harmonic three-phonon quintuplet, the first identified in this region, was suggested in ^{118}Cd [15] from energy and γ-ray branching ratio considerations. In ^{112}Cd [8, 9, 16], members of the quintuplet were suggested based on $E2$ transition rates. Strong mixing between the 0_2^+ and 0_3^+ states was also considered in order to explain the observed structures. Recently, a (n,n$'\gamma$) study of ^{110}Cd permitted a straightforward interpretation of the three-phonon states, where mixing with the intruder band again provided a successful description [6, 7]. While ambiguities may exist for certain decays in these nuclei, usually those of the lower-spin states, the phonon picture with extensive mixing between the phonon, intruder, and mixed-symmetry components can be used to interpret these multiplets.

At first glance, the level structure of ^{116}Cd looks similar to most of the other stable Cd nuclei, with an evident two-phonon triplet. The limited lifetime information [17] supports the assignment of the 2_2^+ and 4_1^+ states to this triplet; however, the character of the low-lying 0^+ states is less straightforward. Additional 0^+ and 2^+ levels, interpreted [2, 3] as the lowest members of the intruder stucture, are observed near this triplet at energies somewhat greater than twice the energy of the first excited 2^+ state in ^{116}Cd.

With the identification of the 4^+ member in this nucleus [18, 19], the three-phonon

TABLE I: Measured properties of selected levels in ^{116}Cd.

E_{level} (keV)	τ (ps)	J_i^π	J_f^π	E_γ (keV)	I_γ	δ	B(E2) (W.u.)	B(M1) (μ_N^2)
513.490(15)[a]	20.3(7)[a]	2_1^+	0_1^+	513.50(5)[a]	1		33.5(11)	
1212.99(2)	2.7(4)[a]	2_2^+	0_1^+	1213.00(3)	0.345(11)		g1.18(16)	
			2_1^+	699.50(2)	0.655(11)	$-1.55^{+0.55}_{-1.10}$	25^{+7}_{-8}	$0.012^{+0.008}_{-0.007}$
1219.43(2)	2.5(6)[a]	4_1^+	2_1^+	705.94(2)	1		55(11)	
1282.58(2)	94(6)[a]	0_2^+	2_1^+	769.08(2)	1		0.96(6)	
1380.37(5)	1.66(33)[a]	0_3^+	2_1^+	866.88(6)	1		30(5)	
1642.56(3)	$0.72^{+0.20}_{-0.13}$	2_3^+	0_1^+	1642.56(4)	0.419(13)		1.18(26)	
			2_1^+	1129.02(2)	0.569(17)	1.14(23)	5.9(16)	0.014(4)
			4_1^+	423.14(7)	0.012(2)		30(8)	
1869.46(3)	$0.34^{+0.24}_{-0.10}$	4_2^+	2_1^+	1356.00(4)	0.19(8)		3.0(17)	
			2_2^+	656.48(2)	0.39(16)		230(130)	
			4_1^+	650.02(2)	0.42(16)	$-1.16^{+0.19}_{-0.32}$	150(90)	0.109(67)
1915.83(3)	$0.70^{+0.24}_{-0.15}$	3_1^+	2_1^+	1402.34(4)	0.502(25)	-2.05(26)	2.6(7)	0.0028(10)
			2_2^+	702.84(2)	0.365(18)	$-2.13^{+0.32}_{-0.39}$	61^{+17}_{-16}	0.015(6)
						-0.2(7)		
			4_1^+	696.40(3)	0.133(11)	$-1.3^{+0.9}_{-0.5}$	18(10)	0.012(10)
						$-0.6^{+0.2}_{-1.2}$		
1928.44(3)		0_4^+	2_1^+	1414.95(2)	1			
1951.39(3)	$0.81^{+0.32}_{-0.18}$	2_4^+	0_1^+	1951.40(5)	0.125(6)		0.13(4)	
			2_1^+	1437.88(2)	0.738(22)	$-0.72^{+0.10}_{-0.14}$	1.23(44)	0.0115(35)
			0_2^+	668.81(3)	0.137(4)		31(9)	
2027.01(12)	$0.64^{+0.45}_{-0.19}$	6_1^+	4_1^+	807.58(12)	1		110(46)	
2041.88(4)		4_3^+	2_1^+	1528.43(3)	0.615(19)			
			4_1^+	822.46(2)	0.173(9)	1.66(23)		
			2_3^+	399.27(4)	0.212(10)			

[a]From Ref. [22]

quintuplet is complete. In this study, new lifetime data, along with many newly observed transitions and levels, provide the grounds on which firm assignments of these vibrational excitations can be made. Figure 1 and Table I illustrate the decay properties of the suggested three-phonon states. The 3^+, 4^+, and 6^+ members of the three-phonon quintuplet decay to the states of the two-phonon triplet by enhanced $E2$ transitions, consistent with the predictions of the vibrational model; however, identification of the lower-spin members is more ambiguous. The decay pattern of the 2_4^+ state, as well as the enhanced 424-keV transition from the 2_3^+ state to the 4_1^+ level indicates mixing between the intruder and 3-

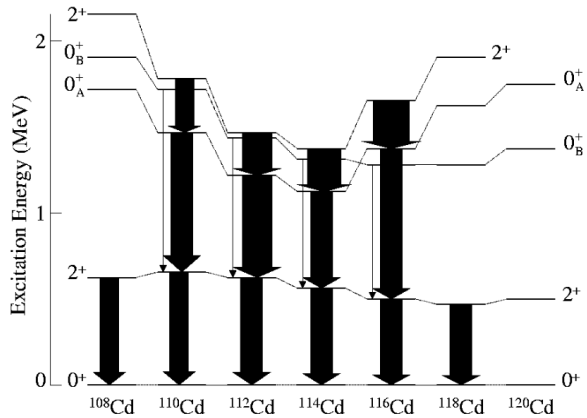

FIG. 2: Systematics of the intruder configurations in the even-mass Cd nuclei, as adopted from Refs. [2] and [3]. The $E2$ transition strengths, as obtained from the literature and Table II, are indicated by the widths of the arrows.

phonon 2^+ states. Moreover, the lone observed branch from the 0_4^+ state to the first excited state sheds doubts on a vibrational assignment. Similar ambiguities were reported for the low-spin members of the three-phonon states in other Cd isotopes, e.g., ^{112}Cd [9] and ^{114}Cd [5]. Decays to the phonon states from the 4^+ and 6^+ members of the intruder band are also indicative of configuration mixing[3].

In Fig. 2, low-lying 0^+ and 2^+ levels of the even-even $^{108-120}$Cd isotopes are presented. For clarity, the 2^+ members of the two-phonon triplet are omitted. The notation for the 0^+ states used by Kumpulainen *et al.* [2] and Juutinen *et al.* [3] is retained. The systematics of intruder levels reveal the expected V-shaped behavior in excitation energy, where the energies decrease to a minimum in the neutron mid-shell nucleus ^{114}Cd [2, 3]. Recent measurements have led to the determination of absolute transition rates for several of the crucial transitions, and B($E2$) values, where known, are indicated. *The large B($E2$) values for the $2_3^+ \rightarrow 0_A^+$ transitions are conspicuous and lend strong support to the identification of the initial and final states as members of a strongly collective structure.*

From the B($E2$) values shown in Fig. 2 the collective character of the intruder bands, which had previously been based primarily on energy and branching arguments [2], is evident. The intruder state explanation for the additional 0^+ and 2^+ states found systematically near the two-phonon states in the Cd nuclei is clearly supported. Also evident from this figure is

the change in character of the two lowest excited 0^+ states in crossing the neutron mid-shell from ^{114}Cd to ^{116}Cd.

An intruder band built on the 1380-keV 0^+ level of ^{116}Cd has been identifyed by Juutinen *et al.* [3]. The 266-keV γ ray originating from the 1642-keV 2^+ level is not observed in our work, but this is not surprising considering the small branching ratio, 0.33 ± 0.07 % [21], and low energy of this transition. The branching of the 2042-keV 4^+ level to the 2^+ intruder state compared to the transition to the 4^+ two-phonon state indicates that this state has retained its intruder character. Calculations (see discussion below) indicate, however, that in any configuration mixing scenario the first excited 0^+ state, not the second as in ^{116}Cd, should contain the collective two-phonon strength.

As these collective intruder structures involve proton 2p-4h configurations, their behaviors might be expected to mimic those of the ground-state bands of their Ba and Ru isotones having 6 valence protons and 6 valence holes, respectively. Table II provides a summary of the B($E2$) values of interest. In the case of the Cd intruder bands and their corresponding Ru isotones, the striking agreement solidifies the identification of the 0^+ states as intruder structures and evinces an interesting conundrum. Why does the intruder 0^+ state systematically decay strongly to the one-phonon state, even when it is not the lowest 0^+ excitation? This exchange in character has been noted previously [2, 3], but the description of the lowest 0^+ states in ^{116}Cd remains ambiguous. Because of the strong mixing of the 0^+ intruder and phonon excitations that appear to be typical of the near mid-shell Cd nuclei, it can be argued that assignments of the character of these excitations may not be meaningful. It is surprising, however, that the 0^+_A and 0^+_B states iin ^{116}Cd exhibit the same de-excitation and feeding patterns as in the lighter Cd isotopes (see Fig. 2).

Since the stable cadmium nuclei are considered to be explained well by the interacting boson approximation (IBM), it is useful to compare the experimental results with the predictions of the IBM in which the intruder configurations and their effects on the phonon states are also taken into account, unlike the pure vibrational model. To understand the structure of ^{116}Cd, we have performed standard IBM-2 mixing calculations. In the absence of previous calculations for ^{116}Cd, the parameter set obtained by Délèze *et al.* [8] for the lighter Cd isotopes was extrapolated, starting from their values for ^{114}Cd. The major difference in the parameter sets concerns the mixing strengths, $\alpha = \beta = 0.06$, which are weaker than in the lighter Cd isotopes. This weaker mixing is required to reproduce the small energy difference

TABLE II: B(E2) values in "six valence proton" configurations.

Neutron	Cd Intuder	Ru	Ba
Number	B(E2;$2_3^+ \rightarrow 0_A^+$)	B(E2;$2_1^+ \rightarrow 0_1^+$)	B(E2;$2_1^+ \rightarrow 0_1^+$)
62	23^{+27}_{-18}	–	–
64	56±17	58±5	–
66	61±8	70±5	154±14
68	86^{+24}_{-30}	74±7	116±6
70	–	–	98±16

between the excited 0^+ states. While a good description of the excitation energies is generally obtained, the spin sequence of the three-phonon states is incorrectly reproduced. The experimental and theoretical B($E2$) values for the higher-spin states are in good agreement; however, as will be illustrated here, those for the excited 0^+states are problematic. To study the decay of the excited 0^+ states in detail, we have varied the parameter Δ, which gives the relative excitation energy between the normal and intruder configurations, around the best value and have discovered that the increase of the B($E2$) to the first excited 2^+ state is correlated with a decrease of the feeding transition from the third 2^+ state to the excited 0^+ state. This effect is illustrated in Fig. 3. Note also that an inversion of the assignments of the second and third 0^+ states would improve the description of the feeding and de-exciting B($E2$) values.

It is tempting to speculate about the problems in reproducing the data in ^{116}Cd. From the systematics of the Cd isotopes (Fig. 2), the 0_A^+ state seems to cross the 0_B^+ state without changing its characteristic decay and feeding patterns. This observation could be an indication that, besides the effects understood in the U(5)-O(6) model of shape coexistence [10], another symmetry is present. This additional symmetry freezes the wave functions in a way which reproduces the results understood well for the lighter Cd isotopes (O(5) effects) such that they are conserved in ^{116}Cd. Such a symmetry would have to yield an $E2$ selection rule which forbids the $0_B^+ \rightarrow 2_{1ph}^+$ transition and, as a good guess, also the generally unobserved $2_{3ph}^+ \rightarrow 0_A^+$ transition. Because of the non-conservation of boson numbers in the U(5)-O(6) model, such a symmetry should most likely involve non-compact Lie groups.

In summary,the role of configuration mixing between intruder and multiphonon vibra-

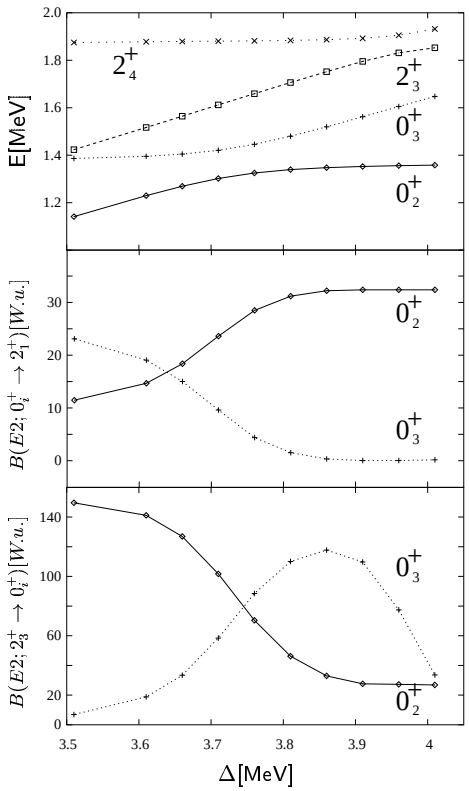

FIG. 3: Energies of the low-lying 0^+ and 2^+ states (top) and selected B(E2) values as calculated in the IBM-2 mixing model [10] as a function of Δ, the relative energy shift between the intruder and normal configurations

tional excitations has been explored for the first time in a Cd nucleus above the neutron mid-shell. The strong-mixing formalism that has worked so successfully in the lighter stable Cd cannot explain the decay properties of the lowest 0^+ excited states, and we are left with an unresolved conundrum.

We wish to acknowledge useful discussions with R. Julius, M.T. McEllistrem and J.L. Wood. This work was supported by the U.S. National Science Foundation under Grant No. PHY-9803784 and was performed in part under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

* Present address: King Abdul-Aziz University,P.O.Box 92028, Jeddah, 21413, Saudi Arabia

[1] K. Heyde *et al.*, Phys. Rev. C **25**, 3160 (1982)

[2] J. Kumpulainen *et al.*, Phys. Rev. C **45**, 640 (1992).

[3] S. Juutinen *et al.*, Phys. Lett. **B386**, 80 (1996).

[4] C. Fahlander *et al.*, Nuc. Phys. **A485**, 327 (1988).

[5] R. F. Casten *et al.*, Phys. Lett. **B297**, 19 (1992).

[6] F. Corminboeuf *et al.*, Phys. Rev. Lett. **84**, 4060 (2000).

[7] F. Corminboeuf *et al.*, Phys. Rev. C **63**, 014305 (2001).

[8] M. Délèze *et al.*, Phys. **A554**, 1 (1993).

[9] H. Lehmann *et al.*, Phys. Lett. **B387**, 259 (1996).

[10] J. Jolie and H. Lehmann, Phys. Lett. **B342**, 1 (1995).

[11] H. Lehmann and J. Jolie, Nucl. Phys. **A588** 623 (1995).

[12] P. E. Garrett, N. Warr, and S. W. Yates, J. Res. Natl. Inst. Stand. Technol. **105**, 141 (2000), and references therein.

[13] C. A. McGrath *et al.*, Nucl. Instrum. Methods Phys. Res. **A421**, 458 (1999).

[14] T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. **A607**, 43 (1996).

[15] A. Aprahamian *et al.*, Phys. Rev. Lett. **59**, 535 (1987).

[16] S. Drissi *et al.*, Nuc. Phys. **A614**, 137 (1997).

[17] H. Mach *et al.*, Phys. Rev. Lett. **63**, 143 (1989).

[18] S. W. Yates *et al.*, in Proceedings of the International Symposium on Nuclear Structure Physics, Göttingen, Germany, 2001, edited by R. Casten, J. Jolie, U. Kneissl, and P. Lieb, (World Scientific, 2001) p. 99.

[19] Y. Wang *et al.*, Phys Rev. C **64**, 054315 (2001).

[20] H. W. Fielding *et al.*, Nuc. Phys. **A281**, 389 (1977).

[21] A. Savelius, dissertation, University of Jyväskylä, 1998.

[22] J. Blachot, Nucl. Data Sheets **92**, 455 (2001)