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Helvetica Physica Acta, Vol. 60 (1987) 456–463

0018–0238/87/030456–08$1.50 + 0.20/0

Mixing of the ground band and two-particle four-hole intruder band in ^{110}Cd*

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(5. IX. 1986)

Abstract. The intruder four-hole two-particle levels in ^{110}Cd have been studied both experimentally and theoretically. Using both beta decay and in-beam Compton suppression spectroscopy, evidence has been obtained for the "intruder" band extending to high-spin ($J^{\pi} = 8^{+}$) states. These data are compared with IBM-2 calculations in order to investigate the extent of mixing between the ground-state and the 2p-4h intruder band. The observed excitation energies and the reduced B(E2) transition probabilities are used to demonstrate the large degree of mixing and the obfuscation of the simple character of both intruder and vibrational structure. Essential deviations from the standard quadrupole vibrational characteristics are conspicuous.

The even-even Cd nuclei have long been considered as typical examples of nuclei exhibiting a spectrum dominated by anharmonic quadrupole vibrational degrees of freedom. Evidence has been accumulating [1–6] through the combined

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* Work supported in part by the Swiss National Science Foundation, SIN, NATO Grant no. RG 0565/82/D1 and USDOE under contract No. W-7405-ENG-48.

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use of different experimental techniques, that besides the vibrational two-phonon triplet ($J^\pi = 0^+$, 2^+, 4^+), extra low-lying $J^\pi = 0^+$, 2^+ levels are present, especially in those even-even Cd nuclei whose neutron number is near its midshell value $N = 66$. Two-proton transfer reaction studies (^{3}He, n) have provided evidence [3] that the extra $J^\pi = 0^+$, 2^+ levels result mainly from proton 2p-4h excitations across the $Z = 50$ closed shell.

Studies have been carried out recently to determine the structure of the additional $J^\pi = 0^+$ and 2^+ states in ^{112,114}Cd. New experimental results have been obtained and compared with mixing calculations in the framework of the Interacting Boson model (IBM-2) [5–8]. A major problem has been the lack of experimental evidence for the higher band members of the intruder 2p-4h states in the even-even Cd nuclei, i.e. a $J^\pi = 0^+$, 2^+, 4^+, 6^+, 8^+, 10^+, . . . band such as has been observed in the $^{112-118}$Sn isotopes [9–12]. In the present study, we have used Compton suppression techniques to identify members of the 'intruder' band in ^{110}Cd, extending up to spin $J^\pi = 8^+$. We compare our data with IBM-2 calculations to investigate the mixing of the intruder and ground-state band in ^{110}Cd.

As shown in Fig. 1, we can identify coexisting ground-state band (gsb) and intruder-band (I–b) members up to $J^\pi = 12^+$ and 8^+, respectively. These data are the result of both Compton suppression [13] and standard in-beam studies, using the ^{108}Pd(α, 2nγ) reaction at SIN [14], combined with detailed beta decay studies using Compton suppression, coincidence and singles spectroscopy at Lawrence Livermore National Laboratory (LLNL). For the excitation function, α-particle energies of 20.6, 23.9, 27.1 and 30.8 MeV have been used. The coincidence experiment was performed at 24.9 MeV. Preliminary results on the decay work have been previously listed [15]. The details of the experimental facilities used as well as the decay scheme (in-beam and beta-decay) assignments will be presented in forthcoming studies [14].

The theoretical spectrum and E2 decay properties have been calculated in the framework of the neutron-proton Interacting Boson model (IBM-2), which allows for 2p-4h excitations. As the method is presented in detail elsewhere [5–8, 16] we give in Table I only the IBM-2 parameters used in the present calculation. The $N_\pi = 1$ parameters are in line with earlier Cd calculations [5–7]. The $N_\pi = 3$ parameters we use were obtained by interpolating between the $N_\pi = 3$ parameters used in calculations for the $^{106}_{44}$Ru$_{62}$ and $^{118}_{56}$Ba$_{62}$ nuclei [17, 18], with identical neutron number. The parameters α and β which determine the mixing Hamiltonian (see caption to Table I) are chosen equal to values used previously in the ^{112,114}Cd nuclei. The quantity Δ, which denotes the unperturbed energy for the $N_\pi = 3$ proton boson configurations with respect to the $N_\pi = 1$ boson configurations, is equal to the value for the ^{112,114}Cd nuclei i.e., we use $\Delta = 5.0$ MeV. From Fig. 1, two important features can be recognized:

(i) the combined data [14, 15] identify probably *all* collective states below an excitation energy of 2.8 MeV with an almost one-to-one correspondence between the observed and calculated levels. In a few cases the proper

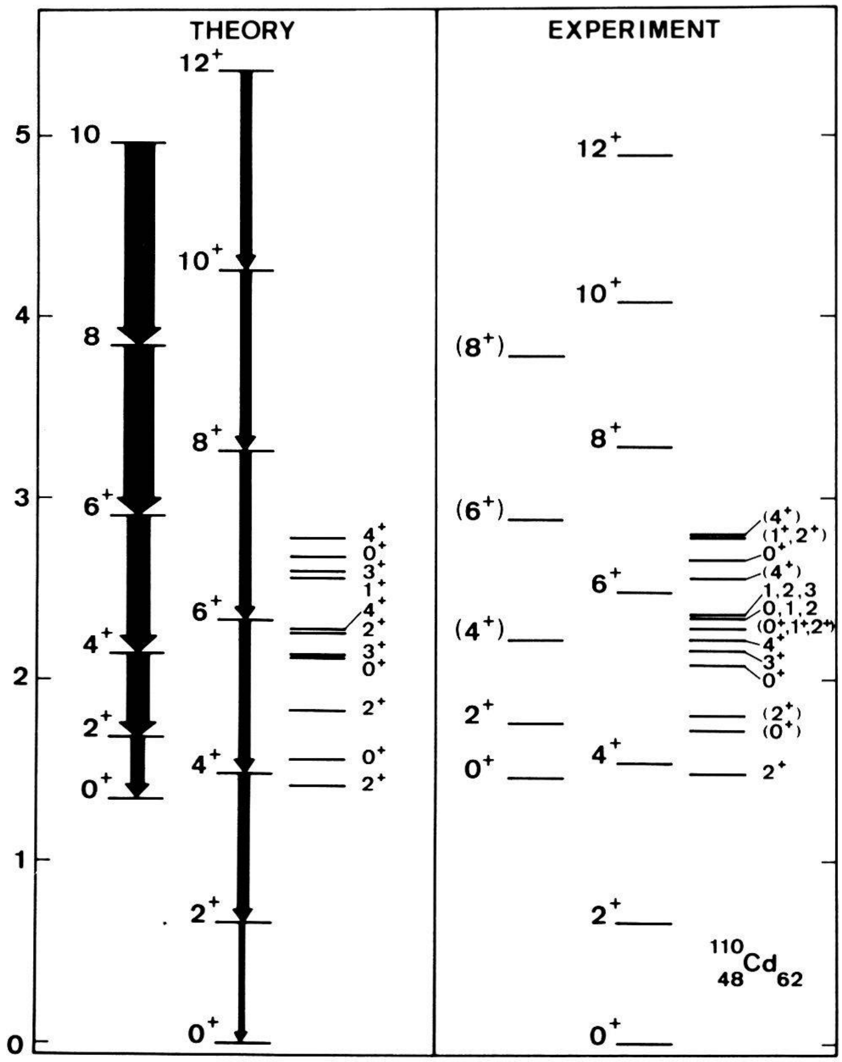

Figure 1
Positive parity levels identified in ^{110}Cd, using in-beam and β-decay Compton suppression and standard spectroscopy techniques, compared to IBM-2 configuration mixing calculations. For clarity the ground-state (center) and intruder bands (left) are staggered from the other collective states (right). The latter have been reported up to $E_x = 2.8$ MeV. Above this value the level density, appearance of broken-pair levels and uncertain spin-parity assignments do not permit one to establish a clear correspondence between calculated and experimental levels.

Table I
Parameters for the proton-neutron IBM calculations in ^{110}Cd, ^{106}Ru and ^{118}Ba. All parameters are in MeV, except for χ_ν and χ_π (dimensionless). In ^{110}Cd, the parameters for the configuration mixing between $N_\pi = 1$ and $N_\pi = 3$, $H_{\text{mix}} = \alpha\,[s_\pi^+ s_\pi^+ + \text{h.c.}]^{(0)} + \beta[d_\pi^+ d_\pi^+ + \text{h.c.}]^{(0)} + \Delta$, are $\alpha = \beta = 0.08$ MeV and $\Delta = 5.0$ MeV

	$\varepsilon_\pi = \varepsilon_\nu$	κ	χ_ν	χ_π	$C_{0,\nu}$	$C_{2,\nu}$	ξ_2
^{106}Ru($N_\pi = 3$)	0.65	−0.15	−1.0	0.4	−0.1	−0.15	0
^{118}Ba($N_\pi = 3$)	0.85	−0.14	−0.8	−0.9	−0.2	−0.15	0
^{110}Cd($N_\pi = 1$)	0.92	−0.15	−1.0	−0.2	−0.1	−0.15	0.06
($N_\pi = 3$)	0.75	−0.258	−1.0	0.0	−0.1	−0.15	0

identification is not yet secured and further work will be needed to confirm the spin and parity properties of some reported levels.

(ii) the gsb and I-b members are well reproduced in the IBM-2 mixing calculations. Due to mixing between levels in the two bands, E2 transitions connecting the gsb and I-b result.

The mixing between the regular quadrupole gsb and the I-b results in the modification of the E2 deexcitation patterns in an important way. In Fig. 2(a), we show the unperturbed part, including the two-quadrupole phonon triplet ($J^\pi = 0_3^+$, 2_2^+, 4_1^+) and the lowest $J^\pi = 0_2^+$, 2_3^+, 4_2^+ levels of the I-band. If the mixing Hamiltonian is neglected, the B(E2) values follow the standard quadrupole vibrational intensity rules and the I-band cannot decay by allowed E2 transitions (dashed arrows indicate forbidden E2 transitions). When we include the configuration mixing Hamiltonian (see caption to Table I), the wave functions mix in an important way (see Table II). Thereby the B(E2) values are *modified in a major way* [see Fig. 2(b)]. The band structure is modified such that the original $J^\pi = 0_2^+$ I-band head decays in a regular way to the $J_f^\pi = 2_1^+$ level. Also the $J^\pi = 0_3^+$ two-quadrupole phonon level deexcitation to the $J^\pi = 2_1^+$ one-quadrupole phonon E2 transition is almost completely quenched. Such interference effects, which have also been observed [4–8] in the E2 decay properties of the quintuplet of

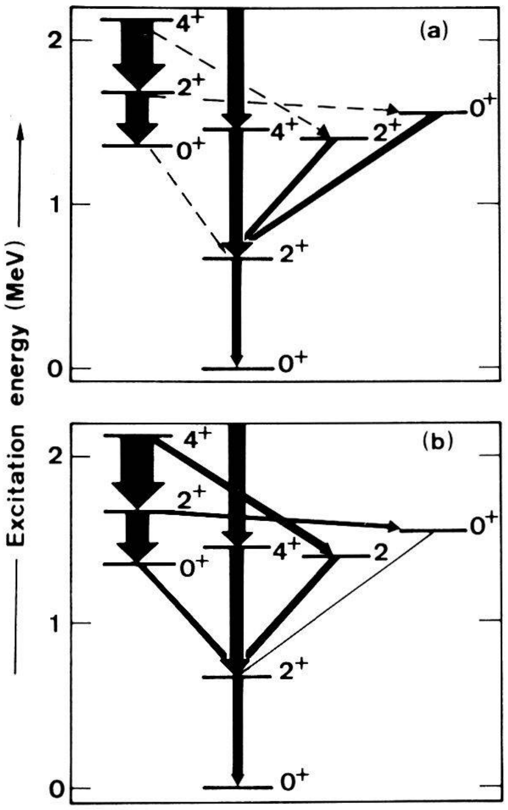

Figure 2
The two-phonon quadrupole triplet and lowest $J^\pi = 0^+$, 2^+, 4^+ intruder states for ^{110}Cd (a) with the standard B(E2) values (drawn proportional to the reduced transition probability) for non-interacting states. Forbidden transition are indicated by dashed lines. In part (b) modified B(E2) transition probabilities for the lowest levels in ^{110}Cd are presented. Again the thickness of the arrows is proportional to the reduced transition probabilities.

levels in ^{112,114}Cd, are important in accounting for the detailed description of these levels. Moreover, the present calculations show the need to be cautious in ascribing a particular configuration to nuclear levels. For example, experimental results corresponding to the pattern shown in Fig. 2(b) could, at first sight, be analyzed as if the $J_i^\pi = 0_2^+$, 4_1^+, 2_2^+ levels would correspond to the regular quadrupole two-phonon triplet. This property is understood by examination of the wave function amplitudes in Table II. They show that the mixing is so strong that the identity of the gsb and I–bands is lost, that their distinction has no physical meaning anymore. However, for the clarity of the discussion, we use the following notation: $2_g^+ = 2_1^+$, $4_g^+ = 4_1^+$, $6_g^+ = 6_1^+$, $0_I^+ = 0_2^+$, $2_I^+ = 2_3^+$, $6_I^+ = 6_2^+$. The 4_I^+ is the second theoretical 4_2^+ level, which corresponds to the third experimental one. The 8_I^+ is the 2nd theoretically expected level, which appears as the 3rd experimental one, a presumably broken-pair level appearing at 3440 keV.

In Table III, the experimental branching ratios of the $J^\pi = 2_g^+$, 2_2^+, 4_g^+, 2_I^+, 4_I^+, 6_I^+ and 8_I^+ levels are compared with our theoretical values. The theoretical value for the $4_I^+ \rightarrow 2_2^+$ branching ratio (21. vs 2.3 experimental) is too large. This results from too large admixtures in both the 4_I^+ $(0.52\,|\,2\rangle)$ and in the 2_2^+ $(-0.23\,|\,\bar{1}\rangle)$ states, compared to the completely unmixed situation (see also Fig. 2). This is probably due to a somewhat too small unperturbed energy difference between the lowest 4^+ intruder state ($N_\pi = 3$ system) and the second 4^+ level in the $N_\pi = 1$ system. Another striking difference is the relatively stronger experimental interband $8_I^+ \rightarrow 6_g^+$ E2 transition with respect to the intraband $8_I^+ \rightarrow 6_I^+$

Table II
Wave functions for the lowest $J^\pi = 0^+$, 2^+, 4^+ levels in ^{110}Cd using IBM-2 mixing calculations. The notation $|1\rangle$, $|2\rangle, \ldots$ and $|\bar{1}\rangle$, $|\bar{2}\rangle, \ldots$ stand for the lowest four $N_\pi = 1$ and $N_\pi = 3$ boson eigenstates, respectively

$$|0_1^+\rangle = 0.99\,|1\rangle$$
$$|0_2^+\rangle = 0.66\,|2\rangle + 0.75\,|\bar{1}\rangle$$
$$|0_3^+\rangle = -0.75\,|2\rangle + 0.66\,|\bar{1}\rangle$$

$$|2_1^+\rangle = 0.99\,|1\rangle - 0.11\,|\bar{1}\rangle$$
$$|2_2^+\rangle = 0.97\,|2\rangle - 0.23\,|\bar{1}\rangle$$
$$|2_3^+\rangle = -0.23\,|2\rangle - 0.26\,|3\rangle + 0.13\,|4\rangle - 0.92\,|\bar{1}\rangle$$

$$|4_1^+\rangle = 0.98\,|1\rangle - 0.18\,|\bar{1}\rangle$$
$$|4_2^+\rangle = -0.15\,|1\rangle + 0.52\,|2\rangle - 0.84\,|\bar{1}\rangle$$
$$|4_3^+\rangle = 0.85\,|2\rangle + 0.51\,|\bar{1}\rangle$$

$$|6_1^+\rangle = 0.97\,|1\rangle - 0.24\,|\bar{1}\rangle$$
$$|6_2^+\rangle = -0.24\,|1\rangle + 0.26\,|2\rangle - 0.94\,|\bar{1}\rangle$$

$$|8_1^+\rangle = 0.97\,|1\rangle + 0.25\,|\bar{1}\rangle$$
$$|8_2^+\rangle = -0.25\,|1\rangle + 0.22\,|2\rangle + 0.94\,|\bar{1}\rangle$$

$$|10_1^+\rangle = 0.98\,|1\rangle - 0.20\,|\bar{1}\rangle$$
$$|10_2^+\rangle = -0.19\,|1\rangle + 0.35\,|2\rangle - 0.92\,|\bar{1}\rangle$$

$$|12_1^+\rangle = 0.99\,|1\rangle - 0.12\,|\bar{1}\rangle$$
$$|12_2^+\rangle = 0.99\,|2\rangle + 0.15\,|\bar{1}\rangle$$
$$|12_3^+\rangle = -0.12\,|1\rangle + 0.15\,|2\rangle - 0.98\,|\bar{1}\rangle$$

Table III
Comparison between IBM-2 mixed configuration and experimental B(E2) values

Initial level[a]) $E_x(J_i^\pi)$	Final level[a]) $E_x(J_f^\pi)$	B(E2) Theory	Experiment[b])
$658(2_g^+)$	$0(0_g^+)$	1.0	≡1.0
$1476(2_2^+)$	$0(0_g^+)$	0.0035	0.049
	$658(2_g^+)$	1.30	1.30
$1542(4_g^+)$	$658(2_g^+)$	1.67	1.53
$1783(2_I^+)$	$1473(0_I^+)$	≡100	≡100[c])
	$1476(2_2^+)$	21	unobs.
	$658(2_g^+)$	0.06	0.047[d])
	$0(0_g^+)$	0.21	0.45
$2250(4_I^+)$	$1783(2_I^+)$	≡100	≡100
	$1542(4_g^+)$	9.0	≤149[e])
	$1476(2_2^+)$	21.0	2.3
	$658(2_g^+)$	0.03	0.19
$2877(6_I^+)$	$2250(4_I^+)$	≡100	≡100
	$1542(4_g^+)$	0.38	1.49
$3792(8_I^+)$	$2837(6_I^+)$	≡100	≡100
	$2490(6_g^+)$	1.4	11.4[f])

[a]) The assignment of levels to the gsb (J_g^π) and I-bands (J_1^π) is made for convenience (see text).
[b]) Absolute values taken from Nuclear Data Sheets, ref. 15 (where absolute rates are not measured, the interband B(E2) are normalized to a relative value of 100).
[c]) The experimental intensity is unprecise (see ref. 1).
[d]) Experimental B(E2) calculated using the mixing ratio of Kawase et al. [24].
[e]) B(E2) upper limit based on a pure E2 transition (presently unknown mixing ratio).
[f]) Possible mixing with a third band (see text).

one. This points toward a larger configuration mixing in the experimental situation as compared to the calculations. Above $E_x = 3.5$ MeV, the experimental level scheme becomes more complicated: We observe additional levels with presumably $J \geq 8$ which are expected to mix with corresponding members of the gsb and I-bands. At this excitation energy ($E_x > 3.5$ MeV), proton 1p-1h excitations across the $Z = 50$ proton closed shell become energetically possible, as was indicated by Van Poelgeest et al. [10] and Van der Werf et al. [19] in studying even-mass Sn nuclei: the lowest $J^\pi = 8^+$ level in ^{110,112}Sn is mainly a proton $1g_{9/2}^{-1}\ 1g_{7/2}$ configuration. Quasiparticle calculations [10, 20–23] in the even–even Sn isotopes ($^{110-118}$Sn) and even-even Te nuclei (^{118,120}Te) have also indicated the importance of neutron two-quasiparticle excitation with $J^\pi = 5^-, \ldots, 9^-, 10^+$ in describing levels in the region $E_x \gtrsim 2.5$ MeV. Thus, a purely collective approach in describing high-spin positive and negative parity states (IBM-2; particle-core coupling) fails to give a detailed description of the levels above an excitation energy $E_x > 2.5$ MeV.

Besides the level properties we have discussed, our joint Compton suppression studies have revealed a number of new features. Of particular importance is the complex low-energy deexcitation paths of high-energy levels. For example, we note that the 3611-keV, $J^\pi = 10^+$, yrast level possesses many deexcitation paths that were not observed in previous studies of ^{110}Cd. The exact nature of these levels, however, must await further work such as life-time determinations, using techniques such as DSAM, and transition mixing ratio measurements by the observation of angular distributions.

In conclusion, by using in-beam Compton suppression and standard techniques on the $(\alpha, 2n\gamma)$ reaction in conjunction with detailed radioactive decay studies, we have been able to place a large number of low-energy transitions that occur between levels at 2 to 5 MeV. These data provide evidence for gs and intruder 2p-4h bands with J^{π} members up to 12^+ and 8^+ respectively. The low-energy collective states as well as the intruder 2p-4h bands are found to be well explained by the IBM-2 configuration mixing calculations. However, our data suggest a higher degree of mixing near the backbending region due to the interaction of *gs*- and *I*-band members with a presumably broken pair configuration. In addition, the data show that the 10^+ yrast state of ^{110}Cd possesses multiple deexcitation paths. Rather than a sole deexcitation, as previously believed, we find the major transition strength populates a previously unknown 3440 keV level.

Acknowledgments

We wish to thank the members of the SIN cyclotron staff in Villigen, especially Drs. S. Jaccard and Th. Stammbach, for their kind cooperation. Two of us (D.K. and R.A.M.) thank SIN for financial support while staying at SIN and in Fribourg. Also, one of us (D.K.) wishes to thank the Nuclear Chemistry Division of LLNL for support. Some of the authors (J.M., M.W., P.V.I. and K.H.) are most grateful to the NFWO and I.I.K.W. for financial support.

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