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Evidence for the complete quadrupole-octupole coupled multiplet in ^{108}Cd

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The study of the coupling of various collective excitations is of great interest in nuclear structure physics. The crucial question is to what extent the fundamental building blocks of collective excitations can be combined. A particularly interesting problem is the coupling of the lowest quadrupole and octupole modes in nuclei. We report on first evidence for the complete quadrupole-octupole coupled quintuplet of negative parity $(2_1^+ \otimes 3_1^-)^{(J^-)}$ with $J=1$, 2, 3, 4, 5 in ^{108}Cd, the fourth full multiplet ever proposed. Excited states of ^{108}Cd were populated in β decay and with a nonselective (α,n) fusion-evaporation reaction. The analysis of $\gamma\gamma$ angular correlations served to assign spin values to excited states and to determine multipole mixing ratios of transitions. This powerful combination of experiments and methods resulted in a huge amount of new data allowing us to present a detailed discussion of the quadrupole-octupole coupled multiplet in ^{108}Cd based on excitation energies, branching ratios, and multipole mixing ratios and also present a comparison with the well studied neighbor ^{112}Cd. The energy splitting within the multiplet is calculated in the vibrational limit of the *sdf* interacting boson model using a simple Hamiltonian, which results in an analytical single-parameter description for the energies.

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I. INTRODUCTION

Multiphonon excitations in even-even nuclei have been investigated extensively during the last decade. Most knowledge exists on the coupling of isoscalar Q phonons [1,2] that successfully serves to describe low lying collective states with positive parity in the $A\approx 130$ region of triaxial deformation, e.g., Refs. [1,3,4], as well as in the more vibrational Cd-isotopes [5–7]. In the latter case it was necessary to disentangle the observed intruder structures from the multiphonon excitations. This was achieved in the work of Lehmann and co-workers by the use of an extended version of the interacting boson model [8]. Recently a new class of phonon excitations also became the object of great interest: mixed-symmetry states [9], resulting from the isovector quadrupole excitation in the valence shell and its coupling with the isoscalar quadrupole degree of freedom. The most prominent members are the fundamental one-phonon 2_{ms}^+ state, e.g., Refs. [4,10–12], and the two-phonon 1_{ms}^+ "scissors mode" [13,14] with two-phonon structure $(2_1^+ \otimes 2_{ms}^+)^{(1)}$. A strictly harmonic picture for the coupling of identical or similar phonons has to break down on account of the Pauli principle restraining the underlying single-particle configurations.

Together with the quadrupole oscillations the octupole degree of freedom emerges as necessary to describe the observed low lying collective states with negative parity. In many spectra of even-even nuclei the octupole vibration 3^- is the lowest excited state with negative parity. The topic of our publication is the lowest quadrupole-octupole coupled two-phonon multiplet of negative parity $(2_1^+ \otimes 3_1^-)^{(J)}$, $J=1,2,3,4,5$. Experimental information is mostly confined to the 1^- member of this quintuplet. The reason is that these states are easily accessible to the nuclear resonance fluorescence (NRF) technique [15]. Extensive data sets using NRF were accumulated by the Stuttgart-Köln collaboration and the Darmstadt group. For a detailed review see Refs. [15,16] and references within. The identification of the 1^- state with the dipole member of the $(2_1^+ \otimes 3_1^-)^{(J)}$ multiplet was based essentially on the excitation energy lying close to the sum energy of the first 2^+ and 3^- states. A more reliable proof was achieved in ^{142}Nd, ^{144}Nd, and ^{144}Sm [17], where the $B(E2;1^- \rightarrow 3_1^-)$ values were measured and found to be comparable in strength to the corresponding $B(E2;2_1^+ \rightarrow 0_1^+)$. But these experiments were rather difficult due to the heavily suppressed branching ratio of the $1^- \rightarrow 3_1^-$ transition. Thus the assignment of the two-phonon character of the 1^- excitation is nearly exclusively done from the argument of excitation energy. This is not really satisfying in view of the importance of this collective mode. The alternative approach is to find the *full multiplet*. Again this is a difficult task, only in three nuclei the complete multiplet could be assigned: ^{142}Ce [18], ^{144}Sa [19], and ^{112}Cd [20]. We believe that such data is, however, crucial for the understanding of these fundamental two-phonon states. One aim of our investigations was to establish data on the quadrupole-octupole coupled multiplet in ^{108}Cd.

For the experimental investigation of ^{108}Cd we used a powerful combination of two γ-spectroscopic methods. Excited states were populated following the β decay of ^{108}In and also in the fusion-evaporation reaction ^{105}Pd(α,n) ^{108}Cd. To our knowledge this was the first experiment using the nonselective (α,n) reaction near the Coulomb barrier for the study of ^{108}Cd.

II. EXPERIMENTS

Previous knowledge of ^{108}Cd was gained from the application of β-decay techniques [21,22], investigations using a

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$(p,2n)$ reaction [23] and heavy ion induced high spin measurements [24]. Our experiments were performed at the FN TANDEM accelerator facility of the University of Cologne.

In the first measurement excited states of ^{108}Cd were populated in the fusion-evaporation reaction ^{105}Pd(α,n) ^{108}Cd at 13.75-MeV beam energy. The γ spectra were observed by means of the OSIRIS cube spectrometer, which was equipped with six anti-Compton high purity germanium detectors (30–60% relative efficiency) positioned at the faces of the cubic target chamber. Three unshielded detectors at corners of the cube offered important additional angles for the $\gamma\gamma$ angular correlation analysis.

The OSIRIS cube spectrometer with its special geometry is an excellent tool for the analysis of angular correlations of γ radiation emitted from oriented states. Polar coordinates with the beam serving as z axis are used to describe the angular correlations: θ_1 and θ_2 are the polar angles of the two detected γ rays, $\Phi=\Phi_1-\Phi_2$ denotes the difference in azimuthal angles. For our setup one obtains eight different combinations $\vec{\Omega}_i=(\Theta_1,\Theta_2,\Phi)$, eight correlation groups, respectively. We briefly discuss the determination of spins and multipole mixing ratios by angular correlations from oriented states. Consider the coincidence of two successive γ transitions, connecting three levels with spins I_i, I, and I_f:

$$I_i \overset{\gamma_1}{\rightarrow} I \overset{\gamma_2}{\rightarrow} I_f .$$

The fusion-evaporation reaction orients the spin of the initial level, I_i, with respect to the beam axis. This orientation can be described by a Gaussian distribution of the magnetic substates with mean value $\langle m\rangle=0$ and variance σ^2 [25]. In order to determine an unknown spin I_i or the multipole mixing ratio we compared the eight efficiency corrected experimental correlation intensities $W^j_{exp}(E_1,E_2;\vec{\Omega}_j)$ with theoretical values $W_{theo}(I_i,\delta_1,I,\delta_2,I_f,\sigma;\vec{\Omega}_j)$. In Fig. 1 examples for the spin determination are displayed.

Our calculations follow the conventions of Krane, Steffen, and Wheeler [26]. All formulas and expressions used are given in this reference. For $\Delta J=0{,}1$ and same parity for the inital and final state electric quadrupole $(E2)$ and magnetic dipole radiation $(M1)$ compete. The square of the multipole mixing ratio equals $\delta^2=I_\gamma(E2)/I_\gamma(M1)$ and in the decay pattern of nuclei usually a broad spectrum of values for δ is observed. In the important case of parity changing decays with $\Delta J=0{,}1$ one finds for the square of the mixing ratio: $\delta^2=I_\gamma(M2)/I_\gamma(E1)=0$ due to the dominance of $E1$ over $M2$ radiation.

The previously described setup together with an additional unshielded detector at the fourth corner of the cube served to study excited states of ^{108}Cd following the β decay of the 7^+ ground state and a 2^+ low spin isomer in ^{108}In. The radioactive ^{108}In was produced in the reaction ^{108}Cd (p,n) ^{108}In at a beam energy of 13.5 MeV. We applied a cyclic procedure of activation with the beam on target for 1 s followed by 1 s of measuring $\gamma\gamma$ coincidences and γ-singles off-beam. This technique resulted in very clean spectra with low background.

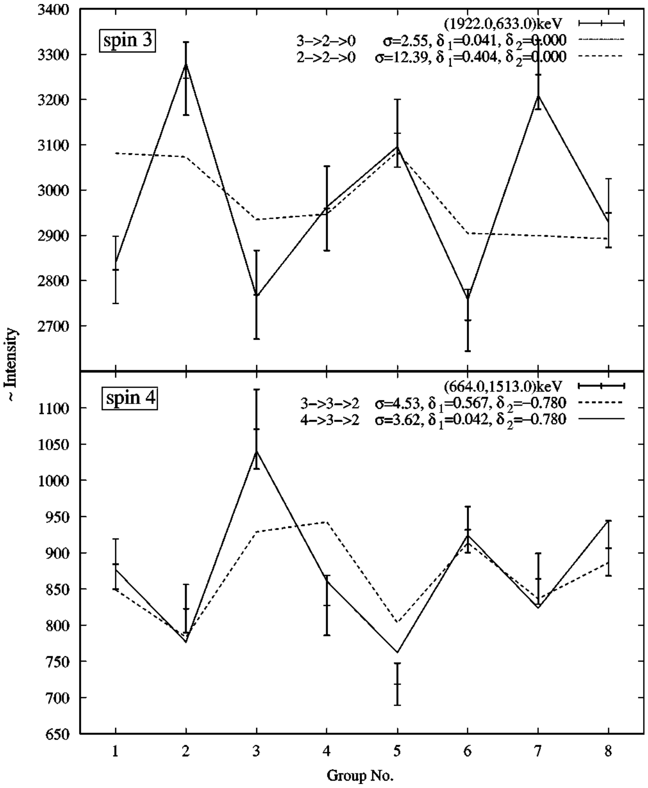

FIG. 1. Examples of the spin determination using $\gamma\gamma$ angular correlations of oriented states. Given are the correlation patterns of the 2555 keV $\rightarrow 2^+_1 \rightarrow 0^+_1$ and the 2810 keV $\rightarrow 3^+_1 \rightarrow 2^+_1$ coincidence cascades. We compare the efficiency corrected coincidence intensities determined for the eight correlation groups with the calculated results for possible spin hypotheses. In the first case (top) a spin of 3 could be assigned. For the state at 2810 keV (bottom) spin assumption 4 showed a reasonably good agreement. In both cases the respective competing spin hypotheses widely disagree within the errors.

The cubic geometry provided detector pair combinations with relative angles of 90° and 180°. The unshielded detectors at the four corners of the cube contributed important additional angles of 54.7° and 70.5°. For this setup the practical procedure of a typical $\gamma\gamma$ angular correlation analysis following the β decay is described in detail in Ref. [27] and again follows the theory and sign conventions of Ref. [26]. The technique proved its special usefulness already in the analyses of the nuclei ^{132}Ce [3] and ^{134}Ce [28] also populated in β decay.

III. THE $(2^+_1\otimes 3^-_1)$ MULTIPLET

In this publication we propose the complete quadrupole-octupole coupled $(2^+_1\otimes 3^-_1)$ quintuplet of negative parity in ^{108}Cd. The energies of the 2^+_1 and 3^-_1 states are 633 keV and 2202 keV, respectively. In a naive harmonic coupling scheme one would expect the multiplet at the sum energy: $E(2^+_1)+E(3^-_1)=2835$ keV. In the following we briefly discuss the candidates for the $J=1^-$, 2^-, 3^-, 4^-, 5^- excitations. For the 5^- state fragmentation has to be considered.

TABLE I. Experimental results for the proposed quadrupole-octupole coupled multiplet in ^{108}Cd. We give spin, transition energy E_γ, spin of the final state, multipole mixing ratio δ, and branching ratios. All branching ratios were determined using a coincidence spectrum obtained by gating on a feeding transition. With this method we were able to fit all relevant peak areas of a decay pattern in one spectrum with only one underlying coincidence condition (see also Fig. 2). Transitions observed for the first time are marked by underlined E_γ. The results for the decay branches are compared to ^{112}Cd [20]. The decay pattern for both isotopes is very similar, deviations occur for the $2^{(-)}$ state and for the 5^- fragments (see text). In the lower part of the table all states below 3 MeV with unclear parity assignments are listed. Both states were populated in β decay supporting the assumption of positive parity but the final exclusion of negative parity failed. The pairing gap is of the order of 2.3 MeV, so the level density increases strongly above this energy. But looking at the Nilsson scheme one notes that the negative parity states will lie considerably higher because they have to involve the $h_{11/2}$ orbit. From the Nilsson scheme we estimate their energy to be around 3 MeV.

E (keV)	J_i^π ($\hbar$)	E_γ (keV)	J_f^π ($\hbar$)	δ	^{108}Cd Branching (%)	^{112}Cd Branching (%)
2555.1	$3_2^{(-)}$	$\underline{353.1}$	3_1^-		12(3)	13
		$\underline{392.5}$	2_3^+		<0.6	9
		$\underline{409.1}$	3_1^+		3(2)	
		$\underline{953.3}$	2_2^+	0.07(8)	33(4)	47
		1922.1	2_1^+	0.041(38)	100(10)	100
2601.5	5_1^-	$\underline{399.4}$	3_1^-	$E2$	1.6(2)	1
		1056.6	4_1^+	$-0.012(19)$	100(8)	100
2678.0	1_1^-	2678.0	0_1^+		100	100
2707.0	5_2^-	$\underline{105.5}$	5_1^-		2.0(2)	100
		$\underline{467.7}$	4_2^+		1.2(2)	
		$\underline{504.9}$	3_1^-		1.5(5)	20
		1198.5	4_1^+	$-0.006(21)$	100(10)	80
2810.2	4_1^-	$\underline{608.1}$	3_1^-		18(2)	23
		$\underline{664.4}$	3_1^+	0.04(3)	40(3)	
		1301.8	4_1^+		100(8)	100
2820.2	$2_1^{(-)}$	$\underline{618.0}$	3_1^-		<6	5
		$\underline{1218.3}$	2_2^+	0.2(2)	26(4)	100
		2187.2	2_1^+		100(10)	6
$\underline{2790.8}$	2^+, 3, 4^+	$\underline{551.4}$	4_2^+		9(2)	
		$\underline{1189.0}$	2_2^+		44(4)	
		$\underline{1282.3}$	4_1^+		100(8)	
$\underline{2998.1}$	1^-,2	$\underline{315.3}$	$1^{(+)}$		100(8)	
		$\underline{320.1}$	1^-		44(4)	
		$\underline{796.1}$	3_1^-		19(3)	
		$\underline{835.3}$	2_3^+		24(3)	

A. 2555.1 keV

The state at 2555 keV was assigned as $J=3(2^+)$ [29,30]. In the angular correlation analysis of the (α,n) measurement, we were able to exclude spin $2\hbar$ (Fig 1, top panel). The multipole mixing ratios for the decays to the first and second 2^+ states were zero within the errors (Table I) and therefore compatible with the assumption of negative parity. We were able to identify four new transitions depopulating this level. In Fig. 2 parts of a coincidence spectrum are shown. This spectrum contains all events coincident to a feeding transition of the discussed state and demonstrates the quality of our data. The 1922-keV transition and the newly observed 953-keV decay are marked. In the β decay this state was only very weakly populated supporting a negative parity assignment. As a conclusion we assume spin and parity to be $3^{(-)}$ for this state.

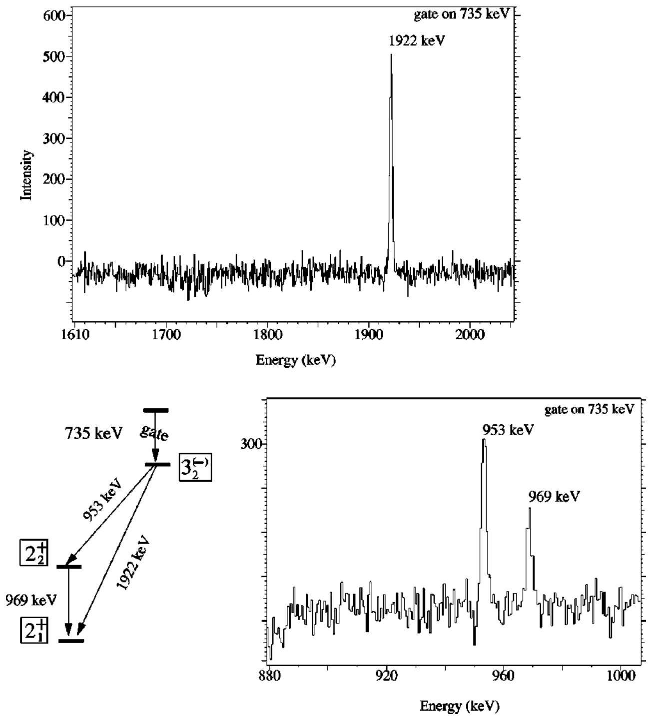

FIG. 2. Parts of a coincidence spectrum obtained from the ^{105}Pd (α,n) ^{108}Cd measurement. This spectrum contains events coincident to a 735-keV feeding transition of the 2555.1-keV 3^- candidate of the discussed multiplet. Decays depopulating this $3^{(-)}$ state are marked. The 953-keV transition to the 2_2^+ state was observed for the first time.

B. 2601.0 keV

This state was assigned as the first 5^- state [29,30]. Aside from the previously known decay to the 4_1^+ state we extended the decay pattern by the transition to the 3_1^- excitation. All multipole mixing ratios were in agreement with the expected $E1$ radiation.

C. 2678.0 keV

This state was already known as electric dipole excitation 1^- [29,30]. Neither in the (α,n) reaction nor in the β decay transitions other than the decay to the ground state could be observed.

D. 2707.0 keV

The state at 2707 keV was assigned as the second 5^- excitation [29,30]. In the (α,n) experiment we were able to establish three new decays of this level. The multipole mixing ratio for the decay to the 4_1^+ state equals zero within the errors meeting the expectations of pure $E1$ radiation (Table I). Also a transition to the first 5^- state was observed.

E. 2810.2 keV

In the literature [29] possible spin values and parity assignments for this state were 3^+, 4^-. In our angular correlation analysis a spin value $4\hbar$ is clearly favored (Fig. 1, bottom panel). The multipole mixing ratio $\delta = 0.04(3)$ for the decay to the 3_1^+ state is in agreement with the assumption of negative parity. We could extend the decay pattern of this state by two new transitions (Table I).

F. 2820.2 keV

In Ref. [29] this state is referred to as 2^- excitation while in Ref. [30] no parity assignment is given. Also for this state we established two new decays (Table I). The determination of the multipole mixing ratio for the presumed parity changing decay to the 2_1^+ state failed due to the occurrence of a doublet structure at 2187 keV. We assume spin and parity to be $2^{(-)}$ for this state.

G. 2790.8 and 2998.1 keV

These are the only states below 3 MeV for which negative parity cannot be excluded. We note that both states were populated in the β decay of the positive parity states of ^{108}In supporting rather positive than a negative parity assignment but a final proof failed.

We want to stress that aside from the 3_1^- excitation the levels discussed above are the only states with negative parity below 3 MeV. In Table I we summarize our results on the proposed candidates for the quadrupole-octupole coupled multiplet and compare the relevant branching ratios of ^{108}Cd and ^{112}Cd for which also the complete multiplet was suggested [20]. The branching ratios are very similar in both nuclei, only the decay properties of the suggested $2^{(-)}$ states show an unexpected deviation. With the knowledge of absolute $B(E2;5_i^- \rightarrow 3_1^-)$ transition strengths the first 5^- excitation in ^{112}Cd is proposed to belong to the discussed multiplet [20]. The two lowest 5^- states in ^{108}Cd are fairly close in energy ($\Delta E = 105$ keV) and are therefore expected to mix. Both 5^- states in ^{108}Cd show a very similar decay pattern, while in ^{112}Cd the first 5^- state is considered to be the main fragment contributing to the quadrupole-octupole coupled multiplet [20]. In Fig. 3 the excitation energies of the quintuplet in ^{108}Cd and ^{112}Cd are compared. Aside from the 5^- state discussed above the energy splitting within the multiplet is very similar in both isotopes.

IV. ANALYTIC DESCRIPTION OF THE ENERGY SPLITTING

In the paper on ^{112}Cd [20] the energies and absolute transition strengths are described by extended *sdf*-IBM (interacting boson model) and *spdf*-IBM calculations. With large sets of parameters a satisfying agreement could be reached while certain discrepancies still remained.

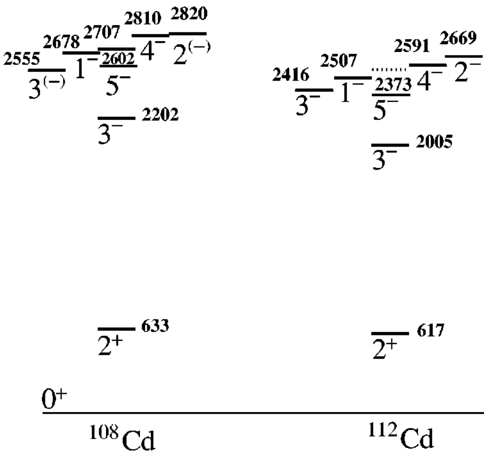

FIG. 3. Comparison of the suggested $(2_1^+ \otimes 3_1^-)^{(J)}$ quintuplet of negative parity in ^{108}Cd and ^{112}Cd. The excitation energies are very similar. In ^{108}Cd we consider both 5^- states as fragments, while in ^{112}Cd the first 5^- excitation is proposed [20]. The 5_2^- state of ^{112}Cd is drawn with dotted lines.

Due to the lacking knowledge of absolute transition strengths in ^{108}Cd we concentrate on the description of the energy splitting within the quintuplet. In a simple vibrational coupling scheme without any anharmonicities the sdf-IBM Hamiltonian is given by [9]

$$\hat{H}_0 = \epsilon_d \hat{n}_d + \epsilon_f \hat{n}_f . \tag{1}$$

$\hat{n}_d$ and $\hat{n}_f$ are boson number operators for d boson ($J=2$, $\pi=+$) and f bosons ($J=3$, $\pi=-$). The expectation value $\langle H_0 \rangle_{(2_1^+ \otimes 3_1^-)^{(J)}}$ simply results in the sum energy of 2_1^+ and 3^-:

$$\langle (2_1^+ \otimes 3_1^-)^{(J^-)} | \hat{H}_0 | (2_1^+ \otimes 3_1^-)^{(J^-)} \rangle = E(2_1^+) + E(3_1^-), \quad J = 1,2,3,4,5. \tag{2}$$

Obviously, the energies within the multiplet are totally degenerated. For the discussion in this paper we assume a pure quadrupole-quadrupole interaction to remove degeneracy:

$$\hat{H} = \epsilon_d \hat{n}_d + \epsilon_f \hat{n}_f - \kappa \hat{Q}^{sd} \hat{Q}^f . \tag{3}$$

$\hat{Q}_{sd}$ and $\hat{Q}_f$ are the quadrupole operators for each kind of bosons:

$$\hat{Q}^f = [f^\dagger \tilde{f}]^{(2)}, \tag{4}$$

$$\hat{Q}^{sd} = [d^\dagger s + s^\dagger \tilde{d}]^{(2)} . \tag{5}$$

The energies within the quadrupole-octupole coupled multiplet can then be written as function of J [31]:

$$E(J) = E(2_1^+) + E(3_1^-) - \kappa(-1)^{J+1} \begin{Bmatrix} 2 & 2 & 2 \\ 3 & J & 3 \end{Bmatrix} Q(2_1^+) Q(3_1^-), \tag{6}$$

with the spin dependence given in the $6j$ symbol and the phase factor. $Q(2_1^+)$ and $Q(3_1^-)$ are the static quadrupole

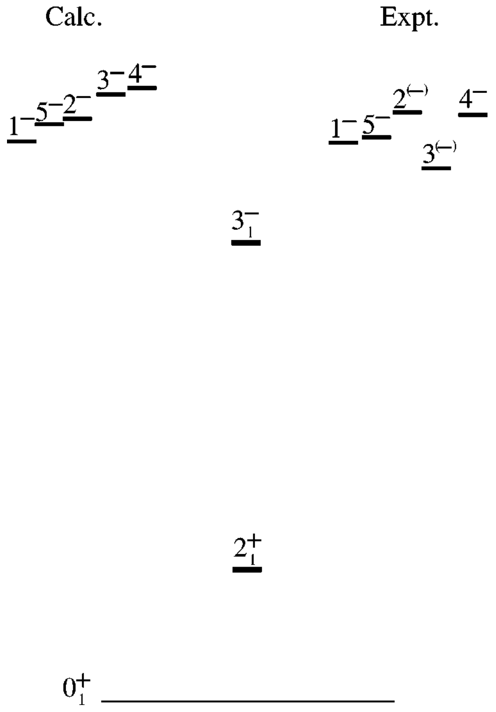

FIG. 4. The quadrupole-octupole coupled multiplet in ^{108}Cd compared to a one-parameter model calculation. We used a quadrupole-quadrupole interaction to remove the degeneracy within the multiplet. With exception of the 3^- state the agreement is remarkably good. The only parameter $\tilde{\kappa}$ was fitted to reproduce the experimental energy of the 1^- excitation that is considered to be fairly pure.

moments of the involved one-phonon states. The product of these quadrupole moments multiplied with the interaction strength κ results in a new parameter $\tilde{\kappa}$ specifying the energy splitting. One obtains in ascending order the states with $J=1^-, 5^-, 2^-, 3^-, 4^-$. We adjusted the only parameter $\tilde{\kappa}$ of this model to reproduce the excitation energy of the 1^- dipole state ($\tilde{\kappa}=1122.4$ keV). The comparison between the experimental and calculated energy splittings under the assumption of pure quadrupole-quadrupole interaction is shown in Fig. 4. We obtained a remarkably good agreement for a model with only a single parameter. The energy of the $3^{(-)}$ state differs by 350 keV from the prediction, it is the only sizeable deviation from the simple calculation, which neglects octupole-octupole and quadrupole-octupole interactions. Also possible mixing of the 3^-_1 and $3^{(-)}_2$ states is not considered in this approach and may also contribute to the deviation.

V. CONCLUSION

We assign the complete quadrupole-octupole coupled quintuplet of negative parity $(2^+_1 \otimes 3^-_1)^{(J^-)}$ in ^{108}Cd on the basis of excitation energies, decay properties, and systematics. To our knowledge this is the fourth nucleus for which the full multiplet was proposed. Excited states in ^{108}Cd were populated in the β decay of ^{108}In and using the nonselective (α,n) fusion-evaporation reaction. We observed twelve new decays for the discussed members of the multiplet, determined branching ratios, multipole mixing ratios δ, and performed important spin assignments with the method of $\gamma\gamma$ angular correlation. We compare our results to ^{112}Cd and describe the energy splitting within the multiplet using a very simple sdf-IBM Hamiltonian in the vibrational limit. The obtained analytical description of the energies results in a single-parameter formula and offers a remarkable agreement.

We stress that the determination of absolute transition strength would be desirable but does not seem to be feasible with the presently available experimental techniques. The natural abundance below 1% prevents, for example, investigations using the powerful $(n,n'\gamma)$ reaction mechanism.

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