Quadrupole-octupole coupled states in ^{112}Cd

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The properties of negative-parity states in the 2.5 MeV region in ^{112}Cd have been investigated with the $(n,n'\gamma)$ reaction. For many of these levels, lifetimes have been measured, and $B(E1)$ and $B(E2)$ values for their decays have been determined. Several transitions exhibit enhanced $B(E2)$ values for decay to the 3_1^- octupole state, indicative of quadrupole-octupole coupled $(2^+\otimes 3^-)$ states. The $B(E1)$ values observed are typically in the range of $1–5\times 10^{-4}$ Weisskopf units (W.u.), irrespective of the final state.
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Multiphonon vibrational excitations in spherical nuclei have been known for many years, but they remain a subject of considerable interest. Much of the discussion has focused on quadrupole-phonon excitations, as they are typically easier to excite in processes where absolute $B(E2)$ values can be determined, as in Coulomb excitation, and generally occur at lower energy than other phonons, e.g., octupole excitations. Information regarding octupole-coupled phonon states is much less available than quadrupole-coupled phonon states. Often, only the octupole-phonon state is known. These excitations are typically higher in energy than the quadrupole-phonon state, and measurements to determine their decay $B(E3)$ values are more difficult. Examples of quadrupole-octupole coupled $(2^+\otimes 3^-)$ states, which form a quintuplet with $I^\pi=1^- - 5^-$, are rare. Most are 1^- states identified as having excitation energies near the sum of the energies of the quadrupole and octupole phonons, and having what has been regarded as (relatively) large $B(E1;1^-\rightarrow 0^+_{\mathrm{g.s.}})$ values [1]. However, these two criteria are not sufficient for a firm identification; only the measurement of enhanced $E2$ (or $E3$) rates to the octupole- (or quadrupole-) phonon state can provide the evidence needed. Examples of other members of the $2^+\otimes 3^-$ quintuplet are suggested in the $A\simeq 140$ mass region, where not only $B(E1)$ values are available (see, for example, Refs. [2–6]), but also $E2$ and $E3$ rates are known in a few cases [2,7–10], and only in ^{142}Ce and ^{144}Sm is the full quintuplet suggested [2,10]. In the $A\simeq 120$ mass region, 1^- members of the quintuplet have been identified in a series of Te nuclei [11,12] and ^{116,124}Sn [13] based on $B(E1)$ values. The full quintuplet in ^{112}Cd has been suggested [14–16], but based only on energies and branching ratios.

The purpose of the present work, which concentrates on the suggested $2^+\otimes 3^-$ quintuplet in ^{112}Cd, is twofold: to report enhanced $B(E2)$ values for decay to the 3^- octupole state, and to note $B(E1)$ values which appear to show little dependence on the final state. This latter point causes concern as many assignments of 1^- members of the $2^+\otimes 3^-$ quintuplet are based on $B(E1)$ values.

The experiments were conducted at the University of Kentucky Van de Graaff facility, where accelerator-produced approximately monoenergetic neutrons obtained from the ^{3}H$(p,n)^3$He reaction bombarded a scattering sample consisting of $\sim$50 g of CdO powder enriched to 98.17% in ^{112}Cd. The measurements consisted of excitation functions with neutron energies (E_n) from 1.8 to 4.2 MeV in 100 keV steps, and angular distributions with $E_n=2.5$, 3.4, and 4.2 MeV. The γ-ray spectra were recorded with HPGe detectors [with relative efficiencies of 57% or 52% and energy resolutions of 2.1 keV full width at half maximum (FWHM) at 1332 keV] located 1.1 m or 1.3 m from the sample. Time-of-flight gating was employed in order to reduce extraneous background events, and an annular BGO shield was used for Compton suppression. The energy calibrations were continuously monitored through the use of radioactive source spectra (^{24}Na, as well as other well-known activation lines) superimposed on the in-beam spectra. The efficiency and nonlinearity curves were determined using sources of ^{56}Co and ^{226}Ra placed at the target position. Shown in Fig. 1 is a portion of the spectrum obtained during the angular distribution measurement using 3.4 MeV neutrons. In addition to the singles measurements, $\gamma\gamma$ coincidence measurements [17] using collimated 4.2 MeV neutrons were performed. Three HPGe detectors were located $\sim$4 cm from the sample. Events were recorded whenever at least two detectors registered coincident events within a 100 ns window and sorted off line into a $4k\times 4k$ matrix with a more stringent requirement of events in an approximately 40 ns window surrounding the beam pulse.

To determine the lifetimes of levels, the Doppler shift attenuation method (DSAM) was used. The energy of a γ ray emitted by a recoiling nucleus is given by

$$E_\gamma(\theta_\gamma)=E_0[1+\beta F(\tau)\cos\theta_\gamma], \qquad (1)$$

where $E_\gamma(\theta_\gamma)$ is the observed γ-ray energy at an angle θ_γ

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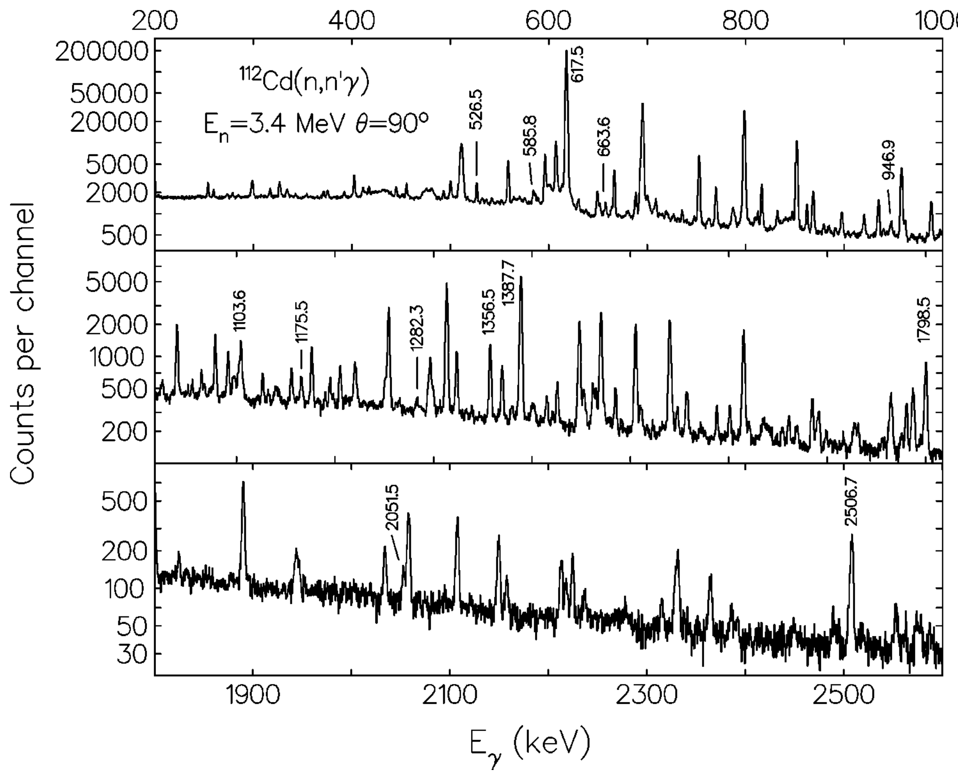

FIG. 1. Portion of the spectrum obtained with an incident neutron beam energy of 3.4 MeV. Some of the transitions from the $2^+\otimes 3^-$ states are labeled with their energies.

with respect to the recoil direction (taken to be the direction of the incident neutron), E_0 is the unshifted γ-ray energy, and $\beta = v/c$, with v the recoil velocity in the center of mass system, given by

$$\beta = 0.04635\frac{A_n}{A_n + A_A}\sqrt{\frac{E_n}{A_n}}, \qquad (2)$$

where A is the mass in amu, and E_n the neutron bombarding energy in MeV. The slope resulting from a linear least-squares fit of the γ-ray energy as a function of $\cos\theta$ yields the $\beta F(\tau)$ value, from which the attenuation factor $F(\tau)$ can be obtained since β is known from Eq. (2). The lifetime of the state can be determined (see Ref. [18] for details) by a comparison with the $F(\tau)$ value calculated using the Winterbon formalism [19] with the stopping powers of Lindhard *et al.* [20]. Since the maximum excitation energy of the nucleus is limited by the neutron beam energy, problems associated with feeding from higher-lying level can generally be avoided. Shown in Fig. 2 are the Doppler shift plots for the most intense transitions from the levels of interest.

The 2^+ quadrupole and 3^- octupole phonon states in ^{112}Cd have been assigned previously at 617 keV and 2005 keV, with $B(E2)$ and $B(E3)$ values for transitions to the ground state of 30 and 28 Weisskopf units (W.u.) [21,15], respectively. Therefore, one would expect that the $2^+\otimes 3^-$ states are located at approximately 2.6 MeV. Indeed, as pointed out by Drissi *et al.* [16], a quintuplet of negative-parity states at approximately this energy exists. In order to make a firm assignment, the absolute $B(E2)$ values for the decay into the octupole phonon state must be determined, and the magnitude of these should be on the same order as the $B(E2;2_1^+\rightarrow 0_1^+)$ value. Transition rates for the decays of these levels, except for the 1^- state [22], have been lacking, however.

The results of the experiments are listed in Table I, and the level scheme is presented in Fig. 3. (Some transitions previously assigned to the 1^- state at 2506.7 keV are found to belong to a close-lying level at 2506.5 keV. Further details will be published separately [23].) As can be seen, lifetimes were determined for the lowest 3^- (3_1^-) state, as well as the 1_1^-, 2_1^-, 3_2^-, and 5_1^- states. [The uncertainties listed include only the statistical uncertainties; there may be, in addition, a systematic uncertainty as large as 10–15% due to the calculation of the theoretical $F(\tau)$ value.] Only the 4_1^- level has a lifetime too long to be determined with the DSAM technique following inelastic neutron scattering. The results for the 5_1^-, 3_2^-, and 2_1^- levels indicate that, although the uncertainties are large, these states have enhanced $E2$ transition rates to the octupole state at 2005 keV. The magnitudes of these $B(E2)$ values are consistent with the expectation that they should be similar in magnitude to the $2_1^+\rightarrow 0_{\text{g.s.}}^+$ $B(E2)$ value of 30 W.u. Even though no lifetime could be determined for the 4_1^- level, the fact that it has a branch to the 3_1^- level is also consistent with a $2^+\otimes 3^-$ interpretation. The $1_1^-\rightarrow 3_1^-$ branch has not been observed in this nucleus, and an upper limit of $I_{\text{rel}}<0.016$ using the data of Drissi *et al.* [16] can be assumed. This places an upper limit on the $B(E2;1_1^-\rightarrow 3_1^-)$ value of 190 W.u. It has to be noted that the results in Table I present one of the most complete data sets, equal to that for ^{144}Sm, for $2^+\otimes 3^-$ states; in ^{142}Ce enhanced $B(E2)$ values have been measured for only two states, and in ^{144}Nd the 2^- member of the quintuplet is still ''missing'' [7].

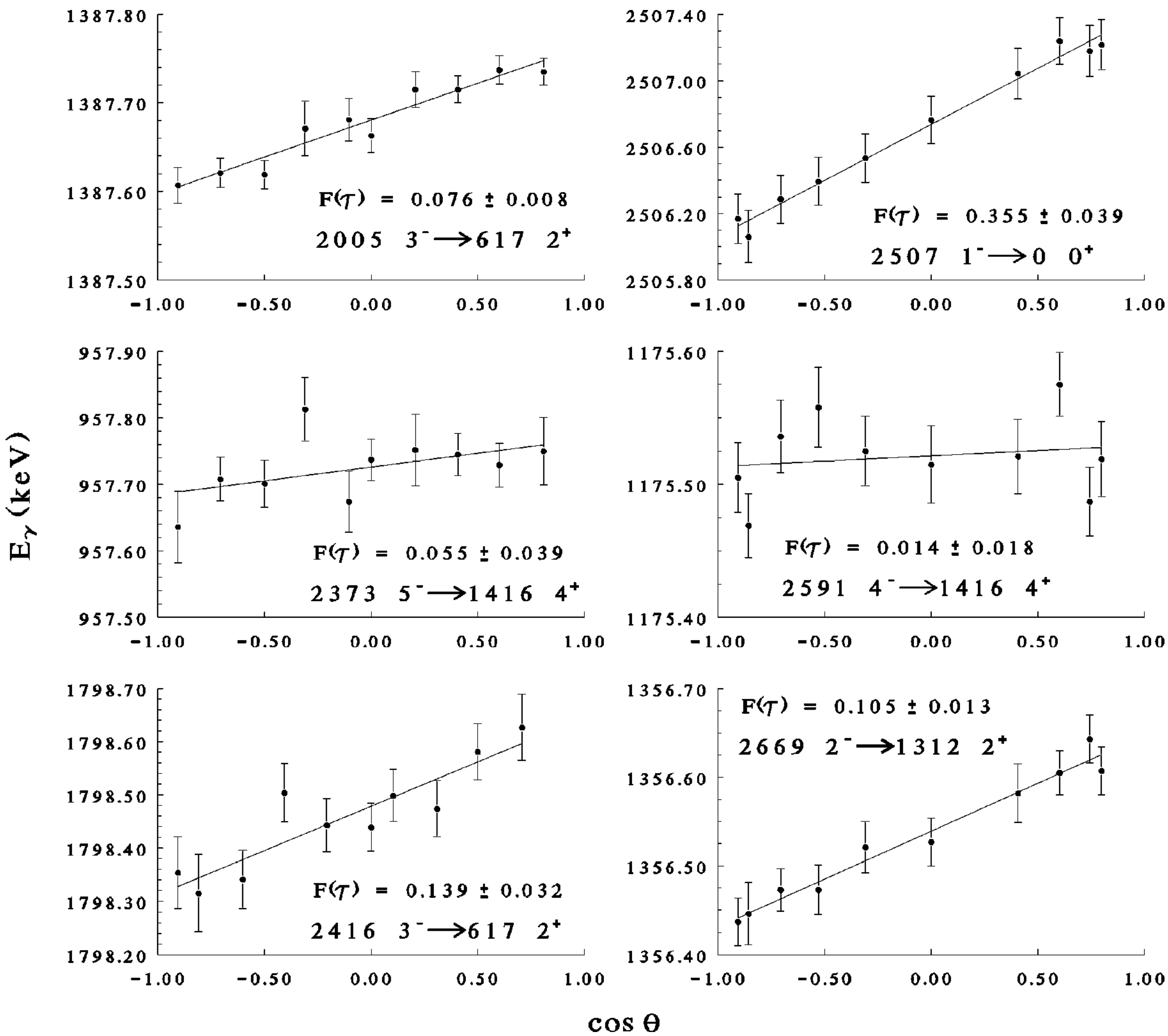

FIG. 2. Plots of γ-ray energy versus $\cos\theta$ for transitions decaying from the lowest 3^- state and from the suggested $2^+\otimes 3^-$ states.

It can also be seen from Table I that the observed $B(E1)$ values are generally on the order of $1-5\times 10^{-4}$ W.u., a value that typically evokes comments to the effect that these are ''enhanced'' $B(E1)$ values. What must be noted, however, is that these values are essentially *independent of the nature of the final state*. Similar values are obtained for decay to intruder [two-particle–four-hole (2p-4h) proton excitations] levels, such as the 2_3^+ level [15,24–27], and to the normal phonon states [15,16,24–28]. If it is assumed that the $E1$ strengths are correlated with the $E3$ strengths, one would expect to observe $B(E1)$ values to the normal vibrational states larger than those to the intruder states. Since this is not the case, there are two obvious possibilities: (1) the $E3$ strengths to the intruder levels are the same magnitude as those to the normal states or (2) there may not be a strong correlation between the $E1$ and $E3$ strengths. The first scenario is regarded as being unlikely. The second implies that the observation of a ''strong'' dipole transition may not necessarily signal the population of a $2^+\otimes 3^-$ two-phonon state. Many of the 1^- members of the $2^+\otimes 3^-$ quintuplet are assigned based on the observation of a strong dipole transition in (γ,γ') measurements, such as in ^{114}Cd where a $B(E1;1^-\rightarrow 0^+_{\text{g.s.}})=4.3\times 10^{-4}$ W.u. was determined [29]. Indeed, based on an NRF study [22] of ^{112}Cd, Drissi *et al.* [16] had assigned the 1_1^- level as a two-phonon state because of an ''enhanced'' $B(E1;1^-\rightarrow 0^+_{\text{g.s.}})$ value, enhanced when compared to the average $B(E1)$ value of $\sim 5\times 10^{-5}$ W.u. from the Endt compilation [30], but not when compared to the other $E1$ rates determined in this work, nor to those determined in the $N=82$ region [31].

Since ^{112}Cd has been studied extensively with the interacting boson model (IBM), it is a logical model to use in an attempt to reproduce the properties of the $2^+\otimes 3^-$ states. The *spdf*-IBM calculations employing the codes of Kusnezov [32] were similar to those of Refs. [22,26]. Briefly, the low-lying positive-parity normal and intruder configurations were described in the U(5) and O(6) limit, respectively, and to describe the negative-parity states, *p* and *f* bosons are used and coupled to the normal and intruder levels. The total Hamiltonian becomes

$$\hat{H}_\rho=\hat{H}^\rho_{sd}+\epsilon_p\hat{n}_p+\epsilon_f\hat{n}_f+2\kappa\hat{Q}^{(2)}_{sd}\cdot\hat{Q}^{(2)}_{pf}+\kappa'\hat{L}^{(1)}_{sd}\cdot\hat{L}^{(1)}_{pf}, \tag{3}$$

where $\rho=n,i$ designates the normal or intruder configuration, respectively, and

$$\hat{Q}^{(2)}_{sd}=[s^\dagger\tilde{d}+d^\dagger s]^{(2)}-\frac{\sqrt{7}}{2}[d^\dagger\tilde{d}]^{(2)}, \tag{4}$$

TABLE I. Properties of negative-parity states in ^{112}Cd. I_{rel} is the relative γ intensity for decay from each level. Uncertainties on the entries are statistical only, and do not include systematic uncertainties. The $spdf$-IBM calculations include intruder configurations and a one-body $E1$ operator, while the sdf-IBM predictions include only normal phonon states and a two-body $E1$ operator.

Experiment							$spdf$-IBM			sdf-IBM	
E_{ex} (keV)	E_γ (keV)	Placement	τ (fs)	I_{rel}	$B(E1)$ [W.u.]	$B(E2)$ [W.u.]	E_{ex} (keV)	$B(E1)$ [W.u.]	$B(E2)$ [W.u.]	E_{ex} (keV)	$B(E1)$ [W.u.]
2005.2	1387.7	$3^-_1\to 2^+_1$	380(65)	0.811(5)	$3.35(57)\times 10^{-4}$		1943	7.1×10^{-4}		1876	1.5×10^{-3}
	692.8	$3^-_1\to 2^+_2$		0.180(5)	$6.0(10)\times 10^{-4}$			6.7×10^{-5}			2.3×10^{-4}
	536.3	$3^-_1\to 2^+_3$		0.009(1)	$6.5(13)\times 10^{-5}$			3.8×10^{-7}			5.0×10^{-6}
		$3^-_1\to 4^+_1$		a				6.3×10^{-5}			3.3×10^{-5}
2373.3	957.7	$5^-_1\to 4^+_1$	590^{+880}_{-230}	0.980(2) [b]	$7.9^{+5.0}_{-4.7}\times 10^{-4}$		2424	1.3×10^{-3}		2374	3.5×10^{-3}
	367.9	$5^-_1\to 3^-_1$		0.009(2) [b]		58^{+39}_{-37}			33		
	291.5	$5^-_1\to 4^+_3$		0.011(2) [b]	$3(2)\times 10^{-4}$			1.0×10^{-4}			3.5×10^{-4}
2416.0	1798.5	$3^-_2\to 2^+_1$	220(50)	0.591(10)	$1.94(44)\times 10^{-4}$		2632	1.2×10^{-6}		2618	2.6×10^{-4}
	1103.6	$3^-_2\to 2^+_2$		0.278(8)	$3.9(9)\times 10^{-4}$			2.3×10^{-4}			2.0×10^{-3}
		$3^-_2\to 4^+_1$		a				1.1×10^{-4}			3.6×10^{-5}
	946.9	$3^-_2\to 2^+_3$		0.056(7)	$1.3(3)\times 10^{-4}$			1.1×10^{-3}			1.7×10^{-4}
	410.9 [c]	$3^-_2\to 3^-_1$		0.076(10) [d]		85^{+110}_{-66}			3.6		
2506.7	2506.7	$1^-_1\to 0^+_1$	64(12)	0.854(5)	$3.6(7)\times 10^{-4}$		2522	3.9×10^{-4}		2585	3.7×10^{-4}
		$1^-_1\to 2^+_1$		a				1.3×10^{-3}			7.9×10^{-7}
	1282.3	$1^-_1\to 0^+_2$		0.047(4)	$1.46(31)\times 10^{-4}$			6.5×10^{-4}			1.5×10^{-3}
		$1^-_1\to 2^+_2$		a				2.7×10^{-4}			2.6×10^{-4}
	1073.3	$1^-_1\to 0^+_3$		0.041(4)	$2.2(5)\times 10^{-4}$			8.7×10^{-4}			1.5×10^{-3}
	1037.8	$1^-_1\to 2^+_3$		0.058(6) [e]	$3.4(7)\times 10^{-4}$			7.0×10^{-4}			7.0×10^{-5}
		$1^-_1\to 3^-_1$		<0.015 [f]		<190			63		
2591.0	1175.5	$4^-_1\to 4^+_1$	>1000	0.548(6)	$<1\times 10^{-4}$		2634	2.2×10^{-4}		2492	5.7×10^{-4}
	720.4	$4^-_1\to 4^+_2$		0.064(4)	$<8\times 10^{-5}$			6.7×10^{-9}			1.0×10^{-6}
	585.8 [g]	$4^-_1\to 3^-_1$		0.126(4)		<50			18		
	526.5	$4^-_1\to 4^+_3$		0.263(6)	$<8\times 10^{-4}$			1.1×10^{-7}			8.0×10^{-6}
2668.9	2051.5	$2^-_1\to 2^+_1$	310(45)	0.144(6)	$2.26(34)\times 10^{-5}$		2778	5.2×10^{-6}		2693	5.1×10^{-5}
	1356.5	$2^-_1\to 2^+_2$		0.804(6)	$4.4(6)\times 10^{-4}$			4.1×10^{-4}			1.4×10^{-3}
	663.6 [h]	$2^-_1\to 3^-_1$		0.052(2)		20^{+12}_{-11}			19		

[a] Transition not observed.
[b] Relative γ intensities from Ref. [16].
[c] A δ value of $-0.36^{+0.18}_{-0.23}$ was determined for this transition, which results in $B(M1)=0.25^{+0.07}_{-0.08}\ \mu_N^2$.
[d] Branching ratio with respect to 1798.5 keV transition from Ref. [21].
[e] Branching ratio with respect to 2506.7 keV transition from Ref. [16].
[f] Upper limit established from the data of Ref. [16] assuming a transition with $I_\gamma>1$ (in units used in Ref. [16]) could have been observed.
[g] A δ value of $0.48^{+0.012}_{-0.010}$ was determined for this transition, which results in $B(M1)<0.03\mu_N^2$.
[h] A δ value of $1.2^{+1.9}_{-0.7}$ was determined for this transition, which results in $B(M1)=0.013^{+0.012}_{-0.010}\mu_N^2$.

$$\hat{Q}^{(2)}_{pf}=\frac{3\sqrt{7}}{5}[p^\dagger\tilde{f}+f^\dagger\tilde{p}]^{(2)}-\frac{9\sqrt{3}}{10}[p^\dagger\tilde{p}]^{(2)}-\frac{3\sqrt{42}}{10}[f^\dagger\tilde{f}]^{(2)}, \tag{5}$$

$$\hat{L}^{(1)}_{sd}=\sqrt{10}[d^\dagger\tilde{d}]^{(1)}, \tag{6}$$

$$\hat{L}^{(1)}_{pf}=\sqrt{2}[p^\dagger\tilde{p}]^{(1)}+2\sqrt{7}[f^\dagger\tilde{f}]^{(1)}. \tag{7}$$

The normal and intruder configurations were mixed with an interaction of the form [33]

$$\hat{H}_{\mathrm{mix}}=\alpha[s^\dagger s^\dagger+ss]^{(0)}+\beta[d^\dagger d^\dagger+\tilde{d}\tilde{d}]^{(0)}. \tag{8}$$

The same parameter values for the normal, intruder, and mixing Hamiltonians as in Refs. [22,26], where further details regarding their choice can be found, were used in the present calculations.

For the *p*- and *f*-boson parts of the Hamiltonian the same parameters as used in Ref. [22] were adopted and are $\epsilon_f=2.0$, $\epsilon_p=2.85$, $\kappa_n=-0.02$, and $\kappa_n'=-0.025$ (all in MeV). For the intruder configuration, κ_i and κ_i' were adjusted to -0.029 and -0.03 MeV, respectively. These parameters were chosen in an attempt to describe the 3^-_1 level, the $2^+\otimes 3^-$ states, and also levels observed in a recent (γ,γ') study [22]. The results of this calculation are shown in Table I. As noted by Drissi *et al.* [16], it is difficult to reproduce the energies of all members of the two-phonon quintuplet.

The transition rates are computed with the operators

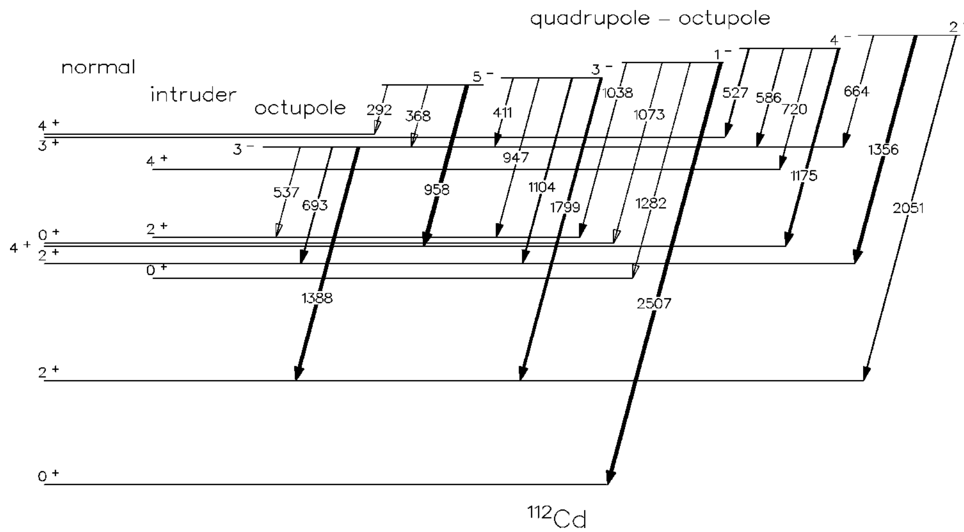

FIG. 3. Partial level scheme for ^{112}Cd. The widths of the arrows are proportional to the relative γ intensity for decay from each level. The levels under the heading ''normal'' have been labeled previously [15,16,24–28] as phonon states with a total of eight bosons, while those under the heading ''intruder'' are 2p-4h proton excitations corresponding to a total of ten bosons [15,24–27]; for some states (e.g., the 0_2^+ and 0_3^+ levels) the mixing between the intruder and normal configurations is very large. The octupole vibration corresponds to the 3^- state at 2 MeV, and the quadrupole-octupole phonon quintuplet to the remaining states around 2.5 MeV.

$$\hat{T}^{(1)}(E1)=e_1([p^\dagger\tilde{d}+d^\dagger\tilde{p}]+\chi[s^\dagger\tilde{p}+p^\dagger s]+\chi'[d^\dagger\tilde{f}+f^\dagger\tilde{d}]), \quad (9)$$

$$\hat{T}^{(2)}(E2)=e_2([s^\dagger\tilde{d}+d^\dagger s]+\chi''[d^\dagger\tilde{d}]+\hat{Q}_{pf}^{(2)}), \quad (10)$$

which are applied separately to the normal and intruding configurations. The total transition strengths are found by summing both contributions. The parameters used for e_2 in Eq. (10) were the same as those in Refs. [16,25]. For the $E1$ operator, the application of the parameter set of Drissi *et al.* [16] underestimated the $B(E1)$ values for most transitions. It was found that a better description could be obtained by adjusting e_1 from 0.011 to 0.006 $e\,\mathrm{b}^{1/2}$, χ from 0.305 to -0.14, and χ' from -0.227 to -0.45, as determined in Ref. [22]. The $B(E\lambda)$ values obtained from the present calculation are presented in Table I. As can be seen, the $E2$ rates are reproduced well, except for the $3_2^-\rightarrow 3_1^-$ transition. This is calculated to be small because the 3_2^- state is highly mixed, with the intruder component being the largest. This can be remedied by choosing the *f*-boson energy for the intruder component to be larger than 2 MeV; however, this leads to poorer agreement between the calculations and results from the (γ,γ') study [22]. There are serious discrepancies between the calculated $E1$ rates and the experimental data. Differences of an order of magnitude are common, and several $B(E1)$ values differ by two orders of magnitude. In general, one can see that the selection rules which follow from the form of the $E1$ transition operator (transitions connect states which have, for example, Δn_s or $\Delta n_d=\pm 1$ with $\Delta n_p=\mp 1$) are too restrictive. In order to reproduce the nonselectivity in the $E1$ decays, the wave functions would have to become highly mixed so that the selection rules are satisfied for all states. For example, the predicted $E1$ rates for the 1_1^- (significant mixing with the p boson) and 3_2^- states have the best agreement with the data. The result of highly mixed states, however, is that the description of the $E1$ rates improves while that for the $E2$ rates becomes unsatisfactory. This can be seen for the 3_2^- state. In the present calculations, it is a highly mixed state and is predicted to have $B(E1)$ values that are approximately equal for decay to all states (except the 2_1^+ one-phonon state). The $B(E2)$ value, however, is quite small. If the intruder *f*-boson energy is increased to 3 MeV in order to make the 3_2^- level retain more of its $2^+\otimes 3^-$ character, the $B(E2)$ value increases to 13 W.u., but the $B(E1)$ values now differ by two orders of magnitude between the $3_2^-\rightarrow 2_2^+$ and $3_2^-\rightarrow 2_3^+$ transitions, contrary to the data. Therefore, the description of the $E1$ rates remains unsatisfactory.

It has been argued [34–37] that the *p*-boson degree of freedom can be eliminated in IBM calculations, leading to two-body terms in the $E1$ operator. Heyde and De Coster [38] have also constructed a two-body $E1$ operator by including 1p-1h admixtures at the tail of the giant dipole resonance in the two-phonon states. Calculations using a two-body $E1$ operator with the sdf IBM have been successful in describing $B(E1;1^-\rightarrow 0_{\mathrm{g.s.}}^+)$ values in a number of nuclei [34–37]. To test the effectiveness of this approach for other members of the $2^+\otimes 3^-$ quintuplet, sdf-IBM calculations were performed using the codes PHINT and FBEM [39] with an $E1$ operator of the form

$$\hat{T}^{(1)}(E1)=e_1\Bigg[[d^\dagger\tilde{f}+\tilde{d}f^\dagger]^{(1)}+\chi_1[\hat{Q}_{sd}^{(2)}\times[s^\dagger\tilde{f}+f^\dagger s]^{(3)}]^{(1)} + \chi_1'\sum_l \sqrt{2l+1}(-1)^{l+1}\begin{pmatrix}2 & 1 & 1\\ 2 & 3 & l\end{pmatrix} \times[\hat{Q}_{sd}^{(2)}\times[d^\dagger\tilde{f}+f^\dagger\tilde{d}]^{(l)}]^{(1)}\Bigg]. \quad (11)$$

For the positive-parity states, the parameters of Cata *et al.* [40] were used. Intruder states are not included in the calculation. Parameters for the negative-parity states were determined by the energies of the 3_1^- and 1_1^- levels, and those for the $E1$ transition operator by fitting the available $E1$ rates, and were $e_1=0.019\ e\,b^{1/2}$, $\chi_1=-0.1975$, and $\chi_1'=-0.342$. The results of the calculations are presented in Table I, and it can be seen that there are still disagreements with the data, although typically within an order of magnitude. Some of this discrepancy may be due to the omission of intruder states, inclusion of which tends to increase the amount of mixing for each state, in the calculation. However, while including intruder configurations may improve the description of some levels, it is unlikely to result in a reproduction of all data, as some of the most serious discrepancies occur between states that are thought to be relatively pure phonon structures [15,16,24–28].

The failure of both the $spdf$-IBM and sdf-IBM calculations in reproducing in detail the $B(E1)$ rates should not be unexpected. While the boson picture can, for the most part, reproduce the *allowed* $E2$ transition rates, since these depend on the collective wave functions, the *forbidden* $E1$ transition rates depend on the microscopic composition of the phonons. The fermionic structure of phonon states and calculations of $B(E1)$ rates from $2^+\otimes 3^-$ states have recently been considered within the quasiparticle-phonon model by Ponomarev *et al.* [41]. For ^{120}Sn, ^{144}Sm, and ^{144}Nd the calculations were able to reproduce the observed $E1$ rates for $[2^+\otimes 3^-]_{1^-}\rightarrow 0^+_{\mathrm{g.s.}},2_1^+$ and $3_1^-\rightarrow 2_1^+$ transitions. It would be of great interest for such calculations to be applied to all possible $2^+\otimes 3^-$ decays.

In summary, the $(n,n'\gamma)$ reaction has been used to investigate candidates for the quadrupole-octupole coupled states in ^{112}Cd. Lifetimes for the 3_1^- octupole state, as well as the 1_1^-, 2_1^-, 3_2^-, and 5_1^- levels, have been determined. The $E2$ transition rates from the 2_1^-, 3_2^-, and 5_1^- levels to the 3_1^- level are enhanced, and of the magnitude expected for $2^+\otimes 3^-$ states. The $E1$ rates from these levels are typically $1-5\times 10^{-4}$ W.u., irrespective of the nature of the final state. The $spdf$-IBM calculations give good agreement with the observed $B(E2)$ values, but serious discrepancies remain for the $E1$ transitions. Consideration of a two-body $E1$ transition operator with the sdf-IBM calculation leads to some improvement, but discrepancies remain.

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