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Quadrupole-octupole coupled states in ^{114}Cd

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The properties of negative-parity states in ^{114}Cd have been studied with the $(n,n'\gamma)$ reaction. γ-ray angular distributions and excitation functions have been used to characterize the decays of these excited levels, and level lifetimes have been obtained with the Doppler-shift attenuation method. A set of five closely spaced, negative-parity states has been identified as the complete quadrupole-octupole quintuplet. These excited states and the observed transitions from these levels are compared to calculations performed in the framework of the *spdf* interacting boson model.

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I. INTRODUCTION

Multiphonon excitations in vibrational nuclei have long been of interest; however, most studies have concentrated on the isoscalar quadrupole phonon excitations, as these states are much easier to excite and identify [1,2]. The states of interest in this work, a quintuplet of levels arising from the coupling of quadrupole and octupole modes, have been observed in only a few vibrational nuclei [3–10].

Coupling of the one-phonon quadrupole and octupole oscillations $(2_1^+ \otimes 3_1^-)$ produces five negative-parity states, which should lie around the energy given by the sum of the single-phonon energies $[E(2_1^+)+E(3_1^-)]$. A simple characteristic depopulation pattern from this quintuplet to the single-phonon states is expected. Transitions to the one-phonon octupole state (3_1^-) arise from the destruction of a quadrupole phonon and, hence, the associated $E2$ strength is expected to be comparable to that of the $2_1^+ \rightarrow 0_1^+$ transition. Similarly, transitions from these states to the one-phonon quadrupole state (2_1^+) involve the destruction of an octupole phonon, and the associated $E3$ transition strength should be similar to the $B(E3)$ strength of the $3_1^- \rightarrow 0_1^+$ transition. However, since $E1$ transitions are much faster, these $E3$ transitions are rarely observed. Frequently, the 1^- member of this quintuplet has been assigned based on its systematic behavior in chains of isotopes; i.e., its excitation energy and $B(E1)$ values [11]. These properties alone do not assure the two-phonon character of this state. In some cases the 1^- state is assigned as a member of the quintuplet because it lies close to another member of the quintuplet and follows a systematic behavior [3–6]. The systematics of 1^- states in many even-even spherical nuclei have been investigated in Ref. [12].

In the present work, the low-lying negative-parity states in ^{114}Cd have been examined. For some time, ^{114}Cd has been a subject of interest because of its coexisting intruder structure, along with its quadrupole vibrational behavior [13–23]. The low-lying positive-parity states below 2 MeV are well explained as members of either an intruder configuration or multiphonon quadrupole excitations. Very recently, the one-phonon mixed-symmetry state was also identified in this nucleus [24].

Complete quadrupole-octupole coupled quintuplets have been suggested in ^{112}Cd and ^{108}Cd [5,6], although only in the former case are transition rate data available. The 2_1^+(558 keV) and 3_1^- (1958 keV) states are well established as the one-phonon quadrupole and octupole states in ^{114}Cd [16,25,26], and several low-lying negative-parity states have been reported [27]. Geiger *et al.* explored the low-lying dipole excitations in the ^{113,114}Cd isotopes and indicated the 1^- level at 2456 keV in ^{114}Cd as the lowest-spin $2^+ \otimes 3^-$ state [28]; however, the complete quadrupole-octupole quintuplet in this nucleus has yet to be identified. Therefore, we have examined the low-lying, negative-parity states in ^{114}Cd for evidence of quadrupole-octupole character.

II. EXPERIMENTS

Low-lying states of ^{114}Cd have been studied with the $(n,n'\gamma)$ reaction at the University of Kentucky 7 MV accelerator facility. Nearly monoenergetic neutrons produced from the ^{3}H$(p,n)^3$He reaction were scattered from 47.8 g of 98.55% enriched ^{114}Cd metal. The γ rays emitted in this reaction were recorded with a Compton-suppressed HPGe detector with a relative efficiency of 55%. An annular bismuth-germanate (BGO) shield was used for Compton suppression. The HPGe and BGO detectors were at a distance of 115 cm from the scattering sample and were further shielded by boron-loaded polyethylene, copper, and tungsten. Time-of-flight gating was implemented to suppress background radiation and to improve the quality of the spectra. The neutron flux was monitored by a BF$_3$ proportional counter and a fast liquid scintillator (NE218). Energy and efficiency calibrations of the HPGe detector were performed with a ^{226}Ra radioactive source. Additional descriptions of the experimental setup may be found elsewhere [29,30].

γ-ray yields were obtained at neutron energies (E_n) from 1.9 to 3.8 MeV in 0.1-MeV steps. Figure 1 shows a typical spectrum of the γ rays obtained at an angle of 90° with 3.0-MeV neutrons. In the angular distribution measurements with $E_n = 2.5$ and 3.0 MeV, spectra were recorded at 11 different angles from 40° to 150°. In these angular distribution measurements, the energy calibration of the HPGe detector

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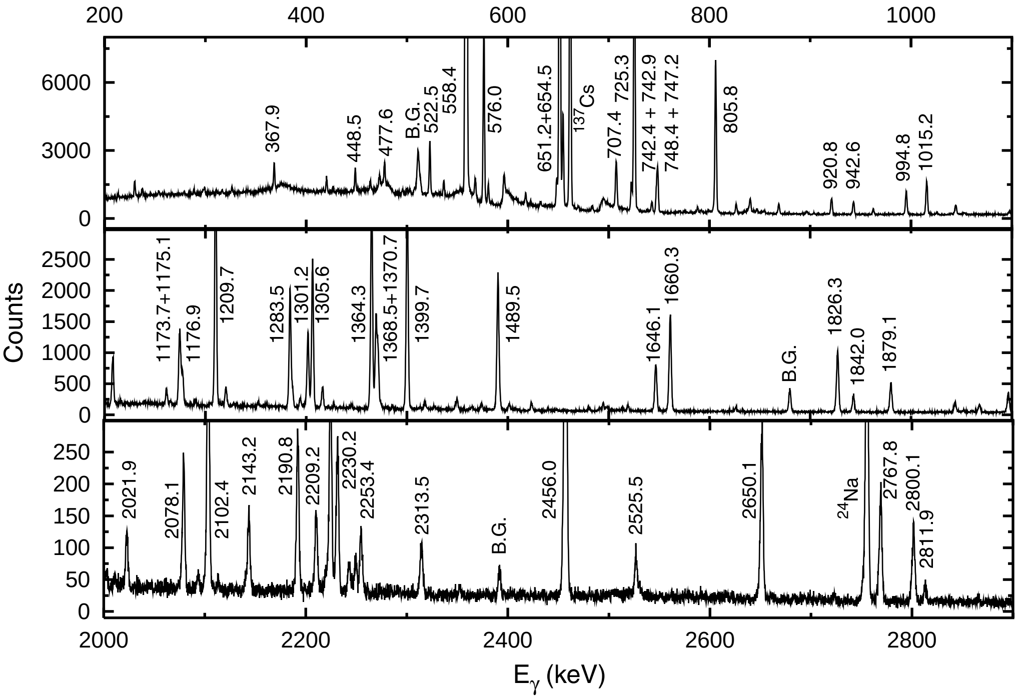

FIG. 1. γ-ray spectrum obtained in the ^{114}Cd$(n,n'\gamma)$ reaction at a neutron energy of 3.0 MeV and at a detection angle of 90°. Peaks labeled with energies in keV are from ^{114}Cd.

was continuously monitored with the 661.6-, 1368.6-, and 2754.0-keV γ rays from ^{137}Cs and ^{24}Na radioactive sources.

The angular distributions of the γ rays were fitted to even-order Legendre polynomial expansions and compared to theoretical predictions calculated with the code CINDY [31] for the spin assignments to the levels. Parity assignments for the levels were adopted from the recent evaluation [27]. The multipole mixing ratios of the potential candidates for quadrupole-octupole states are summarized in Table I.

Lifetimes of many excited states have been extracted from the angular distribution data by considering the Doppler shifts of the γ rays as a function of angle. The energy centroid of the γ-ray peak, $E_\gamma(\theta)$, at an emission angle θ relative to the incident neutrons can be described as [32]

$$E_\gamma(\theta)=E_0\left(1+F(\tau)\frac{v_{\text{c.m.}}}{c}\cos\theta\right), \tag{1}$$

where E_0 is the unshifted γ-ray energy, $F(\tau)$ is the Doppler-shift attenuation factor, $v_{\text{c.m.}}$ is the velocity of the recoiling nucleus in the center-of-mass frame, and c is the speed of light. The observed energies of γ rays from the 3_1^- level and from selected candidates for $2_1^+\otimes 3_1^-$ states are shown in Fig. 2 as a function of emission angle. The lines indicate the linear least squares fits to the experimental data from which the $F(\tau)$ values have been determined. Lifetimes can be obtained by a comparison of the experimental $F(\tau)$ values of Fig. 2 with those calculated following the Winterbon formalism [33,34]. The level lifetimes obtained for the 3_1^- level, as well as for possible quadrupole-octupole coupled states, are summarized in Table I. The uncertainties provided for the values of $F(\tau)$ are statistical values. An additional 10% due to the uncertainty in the stopping power is considered in the value of τ. The lifetime of the 1^- level was previously measured with the γ-ray induced Doppler-broadening (GRID) technique [16] as being in the range from 10 to 200 fs and by high-resolution nuclear resonance fluorescence (NRF) [28] as 66 ± 6 fs. Our result, $\tau=56\pm6$ fs, is in good agreement with both of those measurements. Casten *et al.* [16] also reported the lifetime of the 3_1^- level, measured with the GRID technique, as from 330 to 880 fs. Our more precise result, $\tau=860^{+210}_{-140}$ fs, also agrees well with their measurement. The lifetimes of the 5^- and 4^- states were too long to be determined by the Doppler shift attenuation method following inelastic neutron scattering; hence, we have obtained only lower limits for the lifetimes of these levels. To the best of our knowledge, the lifetimes for 2384.8- and 2580.3-keV levels were previously unknown and are reported here for the first time.

III. DISCUSSION

Ideally, in the case of harmonic coupling, the $2_1^+\otimes 3_1^-$ coupled states are expected near the sum energy $E(2_1^+)+E(3_1^-)=2516.5$ keV. Therefore, we have examined all negative-parity levels in the 2 to 3 MeV range to identify candidates for the $2^+\otimes 3^-$ quintuplet in ^{114}Cd. The $B(E2)$ of the transition from the 2_1^+ state to the ground state is known to be 31.1 ± 1.9 W.u. [27], so $E2$ transitions of similar strength should be anticipated from states of the quadrupole-octupole quintuplet to the 3_1^- state. Table I gives the properties of the strongest candidates for members of this quintuplet. The picture that emerges appears quite similar to that

TABLE I. Properties of low-lying negative-parity states in ^{114}Cd. Uncertainties in the energies are ~0.1 keV.

E_{lev} (keV)	J_i^π	$F(\tau)$	τ (fs)	E_γ (keV)	$E_f(J_f^\pi)$ (keV)	δ	B.R.	$B(E1)$ (W.u.)	$B(E2)$ (W.u.)
558.5 [a]	2^+		14700(900)	558.5	$0.0(0^+)$	1.0	1.0		31.1 ± 1.9
1958.0 [b]	3^-	0.05 ± 0.01	$860\ ^{+210}_{-140}$	748.4	$1209.7(2^+)$	$-0.01^{+0.03}_{-0.04}$	0.213 ± 0.003	$2.5^{+0.5}_{-0.5}\times10^{-4}$	
				1399.7	$558.5(2^+)$	$+0.07^{+0.02}_{-0.02}$	0.787 ± 0.003	$1.4^{+0.3}_{-0.3}\times10^{-4}$	
2298.9 [c]	5^-	0.00 ± 0.02	>1500	340.8	$1958.0(3^-)$	<7.9	0.038 ± 0.005		<116
				1015.2	$1283.7(4^+)$	$-0.01^{+0.01}_{-0.02}$	0.962 ± 0.005	$<2.2\times10^{-4}$	
2384.8 [c]	3^-	0.05 ± 0.01	800^{+230}_{-150}	426.5	$1958.0(3^-)$	$+1.2^{+0.3}_{-0.3}$	0.072 ± 0.002		92^{+47}_{-41}
						$+0.09^{+0.15}_{-0.12}$	0.072 ± 0.002		$1.3^{+9.5}_{-1.3}$
				1175.1	$1209.7(2^+)$	$0.01^{+0.1}_{-0.1}$	0.197 ± 0.009	$0.6^{+0.2}_{-0.2}\times10^{-4}$	
				1826.3	$558.5(2^+)$	$+0.01^{+0.01}_{-0.02}$	0.731 ± 0.009	$0.6^{+0.2}_{-0.1}\times10^{-4}$	
2456.0 [c]	1^-	0.44 ± 0.01	$56\ ^{+6.0}_{-6.0}$	2456.0	$0.0\ (0^+)$	$E1$	1.0	$5.0^{+0.3}_{-0.3}\times10^{-4}$	
2460.7 [c]	4^-	<0.04	>980	256.2	$2204.6(3^+)$	$+0.07^{+0.12}_{-0.12}$	0.041 ± 0.003	$<10.3\times10^{-4}$	
				502.6	$1958.0(3^-)$	$+2.5^{+0.6}_{-0.5}$	0.077 ± 0.003		<53
						$+0.58^{+0.15}_{-0.11}$	0.077 ± 0.003		<15
				596.3	$1864.3(3^+)$	$-0.02^{+0.01}_{-0.06}$	0.383 ± 0.019	$<7.7\times10^{-4}$	
				728.6	$1732.2(4^+)$	$-0.09^{+0.14}_{-0.12}$	0.083 ± 0.003	$<0.9\times10^{-4}$	
				1176.9	$1283.7(4^+)$	$-0.02^{+0.07}_{-0.06}$	0.415 ± 0.008	$<1.1\times10^{-4}$	
2580.3 [c]	2^-	0.06 ± 0.01	$610\ ^{+130}_{-90}$	532.3	$2048.0(2^+)$	$0.07^{+0.27}_{-0.18}$	0.049 ± 0.003	$2.2^{+0.6}_{-0.7}\times10^{-4}$	
				622.3	$1958.0(3^-)$	$+1.2^{+1.3}_{-0.6}$	0.041 ± 0.003		$10.5^{+8.6}_{-6.7}$
				1370.7	$1209.7(2^+)$	$+0.01^{+0.03}_{-0.03}$	0.781 ± 0.003	$2.1^{+0.4}_{-0.4}\times10^{-4}$	
				2021.9	$558.5(2^+)$	$+0.12^{+0.07}_{-0.06}$	0.129 ± 0.003	$0.11^{+0.02}_{-0.02}\times10^{-4}$	

[a] Lifetime taken from Ref. [27].

[b] Properties determined from the $E_n=2.5$-MeV data.

[c] Properties determined from the $E_n=3.0$-MeV data.

observed for ^{112}Cd [5]. Fast $E2$ transitions to the 3_1^- level have been observed from the 2_1^- and 3_2^- states, confirming their quadrupole-octupole character. While $E2$ transition rates are not available for the long-lived 4_1^- and 5_1^- levels, both display significant branches to the 3_1^- state. Figure 3 shows the comparison of the excitation energies of the quadrupole-octupole coupled states for different Cd isotopes. The solid lines indicate the energies of the $2^+\otimes3^-$ states. Similar spin states in different isotopes are connected by dotted lines. The dashed lines are at the sum energy of the 2_1^+ and 3_1^- levels. The complete quintuplet has been suggested for ^{108}Cd [6] and ^{112}Cd [5] isotopes; however, less is known about these states in ^{110}Cd and ^{116}Cd. For ^{110}Cd, a 5^- state was found to exhibit quadrupole-octupole character in the inelastic neutron scattering study of Corminboeuf *et al.* [1]. Later, the 1^- state of the quintuplet was found [35]. A strong $E2$ transition to the 3_1^- state has led to an assignment of the 2340-keV 4^- state in ^{116}Cd as a member of the quadrupole-octupole quintuplet [40]. The 1^- state of the quintuplet was assigned [35] in a study of ^{116}Cd by the NRF method. As expected, the excitation energies of these states decrease with increasing neutron number, indicating an increase in collectivity. In the following subsections, the potential of each candidate for the quadrupole-octupole quintuplet in ^{114}Cd is discussed in greater detail.

A. 1^- state

The 2456-keV level has been suggested previously as the 1^- member of the $2^+\otimes3^-$ quintuplet [28,35]. The angular distribution of the 2456-keV ground-state transition from this level is consistent only with dipole behavior, making the spin-1 assignment firm. Mheemeed *et al.* [13] reported a very weak 1091.6-keV transition (branching ratio 0.015) from this level to the 1364.3-keV level following thermal neutron capture. The branching ratio of this $E1$ transition has been measured as 0.005 in the present study. However, the threshold for this transition has been found to be ~3.0(1) MeV in the excitation function measurement, indicating that the 1091.6-keV γ ray cannot come from the 2456-keV level. Kohstall *et al.* [35] compared the dipole excitations of the Cd isotopes from NRF studies and confirmed the systematic

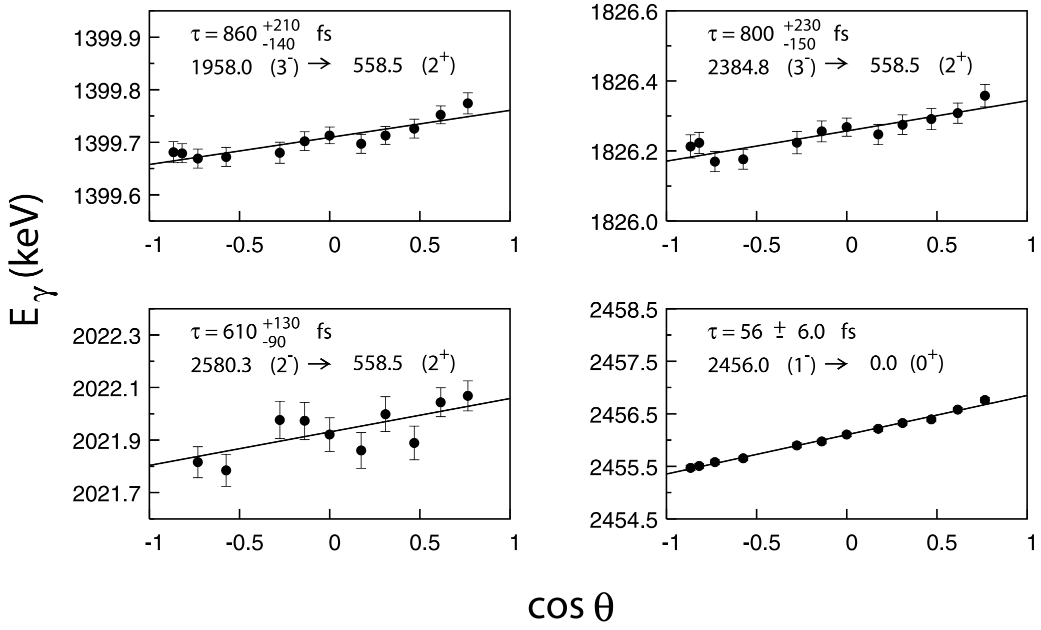

FIG. 2. γ-ray energies as a function of cos θ for the indicated transitions. The lines are linear fits to the data from which the $F(\tau)$ values have been extracted.

quadrupole-octupole origin of the 1^- states in these nuclei. Therefore, we have accepted the 2456-keV level as the lowest-spin member of the $2_1^+ \otimes 3_1^-$ quintuplet.

B. 2^- state

From the energy systematics of the 2^- states belonging to the $2_1^+ \otimes 3_1^-$ quintuplet in the other Cd isotopes (Fig. 3), the 2^- state in ^{114}Cd is expected at an energy around 2.5 MeV. Only one 2^- state, at 2580.3 keV, is found in the literature [27]. A thermal neutron capture study [13] indicated a mixed $E2/M1$ transition of 622.3 keV from this level to the 3_1^- state. From our angular distribution data, we obtained a value for δ of 1.2, which gives a $B(E2)$ of 10.4 W.u. Within uncertainties, this value agrees well with the predictions of the

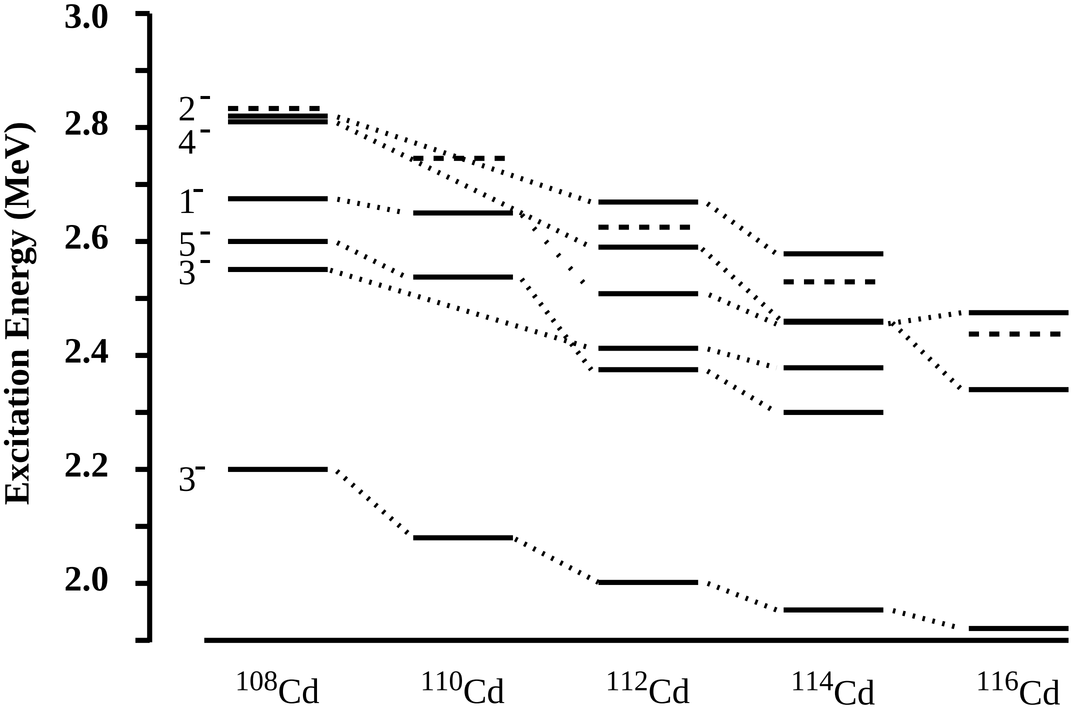

FIG. 3. Comparison of the excitation energies of the levels belonging to the $2^+ \otimes 3^-$ quintuplet for different Cd isotopes. The dashed lines are at sum of $E_{2_1^+}$ and $E_{3_1^-}$.

TABLE II. Comparison of the properties of the quadrupole-octupole coupled states suggested in ^{114}Cd with the *spdf* IBM-1 calculation.

State	Transition	Expt.			IBM-1		
		E_{ex} (keV)	$B(E1)$ (W.u.)	$B(E2)$ (W.u.)	E_{ex} (keV)	$B(E1)$ (W.u.)	$B(E2)$ (W.u.)
3_1^-	$3_1^- \rightarrow 2_1^+$	1958.0	$1.4_{-0.3}^{+0.3} \times 10^{-4}$		1959	2.5×10^{-4}	
	$3_1^- \rightarrow 2_2^+$		$2.5_{-0.5}^{+0.5} \times 10^{-4}$			0.37×10^{-4}	
1_1^-	$1_1^- \rightarrow 0_1^+$	2456.0	$5.0_{-0.3}^{+0.3} \times 10^{-4}$		2453	1.2×10^{-4}	
	$1_1^- \rightarrow 2_1^+$ [a]					8.6×10^{-4}	
	$1_1^- \rightarrow 3_1^-$ [a]						60
2_1^-	$2_1^- \rightarrow 3_1^-$	2580.3		$10.5_{-6.7}^{+8.6}$	2671		14
	$2_1^- \rightarrow 2_1^+$		$0.11_{-0.02}^{+0.02} \times 10^{-4}$			0.02×10^{-4}	
	$2_1^- \rightarrow 2_2^+$		$2.1_{-0.4}^{+0.4} \times 10^{-4}$			1.2×10^{-4}	
3_2^-	$3_2^- \rightarrow 3_1^-$	2384.8		$1.3_{-1.3}^{+9.5}$	2585		4
	$3_2^- \rightarrow 2_1^+$		$0.6_{-0.1}^{+0.2} \times 10^{-4}$			0.5×10^{-6}	
	$3_2^- \rightarrow 2_2^+$		$0.6_{-0.2}^{+0.2} \times 10^{-4}$			2.3×10^{-4}	
4_1^-	$4_1^- \rightarrow 3_1^-$	2460.7		<53	2553		10
	$4_1^- \rightarrow 3_1^+$		$<7.7 \times 10^{-4}$			0.5×10^{-4}	
	$4_1^- \rightarrow 4_1^+$		$<1.1 \times 10^{-4}$			0.8×10^{-4}	
	$4_1^- \rightarrow 4_2^+$		$<0.9 \times 10^{-4}$			0.1×10^{-7}	
5_1^-	$5_1^- \rightarrow 3_1^-$	2298.9		<116	2375		28
	$5_1^- \rightarrow 4_1^+$		$<2.2 \times 10^{-4}$			5×10^{-4}	

[a] Transition not observed.

interacting boson model as shown in Table II and discussed later. Three additional transitions from this level are observed. The very small values of the multipole mixing ratios for these transitions indicate their pure or nearly pure electric dipole nature.

C. 3^- state

According to a recent compilation [27], 3^- states exist at 2384.8 and 2387.3 keV. The level at 2387.3 keV is assigned on the basis of a 1828.8-keV transition to the first excited state. This energy is close to the 1826.3-keV transition from the 2384.8-keV level to the first excited state observed in the thermal neutron capture experiment by Mheemeed *et al.* [13] and in a neutron scattering experiment by reactor-produced fast neutrons [36]. The 1826.3-keV γ ray observed in our spectra does not appear to be a doublet, thus supporting the observations of Refs. [13,36]. We have no evidence for a 3^- level at 2387.3 keV. The 2384.8-keV level is hence considered to be the 3^- member of the $2_1^+ \otimes 3_1^-$ multiplet. This assignment is also supported by the systematic trend of level energies shown in Fig. 3. Unfortunately, the 426.5-keV $E2$ transition from this level to the 3_1^- level has two values for δ with more or less equal χ-square fits, making a determination of the $B(E2)$ ambiguous. As shown later, interacting boson model calculations agree well with the $B(E2)$ value calculated with the lower value of δ. The 1175.1- and 1826.3-keV transitions from this state to the 2_2^+ and 2_1^+ levels, respectively, exhibit very small values for δ, reflecting their expected electric dipole character.

D. 4^- state

The 2460.7-keV level was assigned a spin of 3^- or 4^- in the thermal neutron capture reaction study [13]. A previous inelastic scattering measurement on ^{114}Cd with reactor fast neutrons supported the 4^- spin assignment [36] for this state. A comparatively intense $E2$ transition of 502.6 keV is observed from this level to the 3_1^- state, supporting the quadrupole-octupole assignment. The energy of this state is consistent with the energies of the 4^- states in other Cd isotopes (Fig. 3) and the identification of this state as the 4^- member of the quadrupole-octupole quintuplet. From the thermal neutron capture study [13], the 502.6-keV transition from the 2460.7-keV level to the 3_1^- state is reported to be of $E2/M1$ character. We obtained two values of δ for this transition; however, the angular distribution gives a lower χ-square fit for the higher value and $B(E2) < 53$ W.u. This result is in good agreement with our expectations from the interacting boson model calculation shown in Table II. All the other transitions from this level show the expected $E1$ characteristics, as reported in the literature [27]. The 596.3-keV transition was not resolved from the close-lying back-

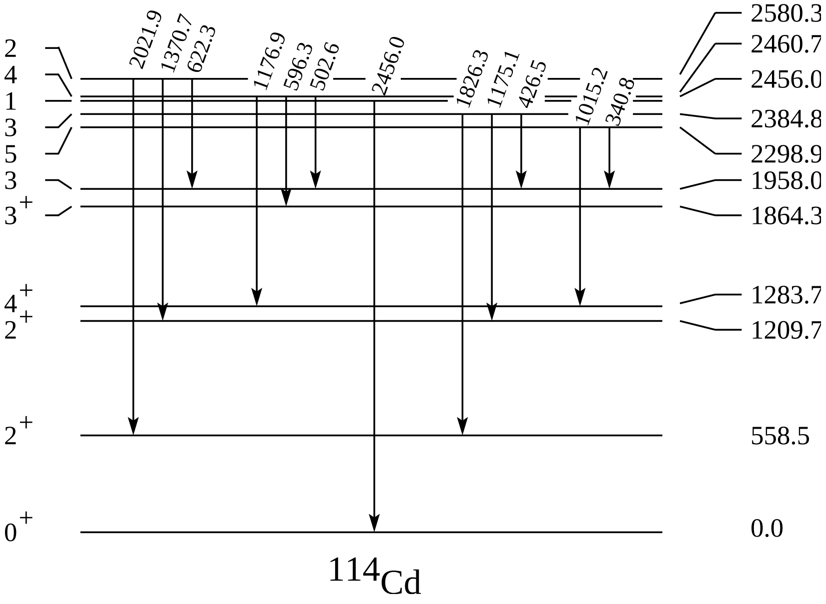

FIG. 4. Partial level scheme of quadrupole-octupole coupled states in ^{114}Cd.

ground transition of 595.8 keV from the ^{73}Ge(n,γ) and ^{74}Ge$(n,n'\gamma)$ reactions. The effect of this background line on the 596.3-keV transition is estimated from the excitation function data as ~5% at 3.0 MeV neutron energy and is included in the uncertainty of the branching ratio for this transition.

E. 5^- state

Two 5^- states are reported in ^{114}Cd [27] in the energy range of 2 to 3 MeV. The 2535.8-keV level was assigned tentatively as 5^- in an $(n,n'\gamma)$ study with reactor fast neutrons [36]. According to the recent compilation, only a transition from this level to the 2298.9-keV level is reported [27]. We have observed a new transition of 1252.0 keV from this level to the 4_1^+ state. A 577.7-keV transition from this level to the 3_1^- state is expected for this state to be a member of the $2_1^+ \otimes 3_1^-$ quintuplet, but this γ ray would be very close to the strong 576.1-keV transition from the 0_2^+ to the 2_1^+ state and is beyond the resolving power of the present measurements. We have adopted the 2298.9-keV 5^- level, which was found to be the band head of a negative-parity band in a heavy-ion reaction study [37], as the 5^- member of the multiplet. From our excitation function data, we have placed an unassigned 340.8-keV transition, which was previously observed following thermal neutron capture [13], as a decay from the 2298.9-keV level to the 3_1^- level. Unfortunately, as reported in Ref. [13], this transition is weak and forms a doublet with the closely spaced 340.3-keV γ ray from the 2204.5-keV level. This difficulty prevented us from obtaining a good value for the multipole mixing ratio and resulted in only an upper limit for δ in this case. However, the systematics shown in Fig. 3, as well as the interacting boson model calculations (Table II), support the assignment of the 2298.9-keV level as the 5^- member of the quadrupole-octupole quintuplet. An additional 1015.2-keV transition from this level to the 4_1^+ state exhibits the expected electric dipole character.

F. IBM calculation

Since the low-lying positive-parity normal and intruder states in ^{114}Cd have been studied extensively in the interacting boson model [16,18,21], it is meaningful to have similar calculations for the quadrupole-octupole coupled states. We have performed an $spdf$-IBM1 calculation using the code of Kusnezov [38]; similar calculations may be found in Refs. [21,39]. According to this model, the normal and intruder configurations are described in the U(5) and O(6) limits, respectively. The p and f bosons are coupled to normal and intruder levels to describe the negative-parity states. The total Hamiltonian is

$$H_\rho^{tot} = H_\rho^{sd} + \epsilon_p n_p + \epsilon_f n_f + 2\kappa_\rho Q_{sd}^{(2)} \cdot Q_{pf}^{(2)} + 2\kappa'_\rho L_{sd}^{(1)} \cdot L_{pf}^{(1)}, \tag{2}$$

where $\rho = n, i$ describe the normal and intruder configurations, respectively. The second and following terms give the contributions from the p and f bosons. The quadrupole operators $Q^{(2)}$ are defined as

$$Q_{sd} = [s^\dagger \times \tilde{d} + d^\dagger \times s] - \frac{\sqrt{7}}{2}[d^\dagger \times \tilde{d}], \tag{3}$$

$$Q_{pf}^{(2)} = \frac{3\sqrt{7}}{5}[p^\dagger \times \tilde{f} + f^\dagger \times \tilde{p}]^{(2)} - \frac{9\sqrt{3}}{10}[p^\dagger \times \tilde{p}]^{(2)} - \frac{3\sqrt{42}}{10}[f^\dagger \times \tilde{f}]^{(2)}, \tag{4}$$

whereas the angular momentum operators $L^{(1)}$ are given by

$$L_{sd}^{(1)} = \sqrt{10}[d^\dagger \times \tilde{d}]^{(1)} \tag{5}$$

and

$$L_{pf}^{(1)} = \sqrt{2}[p^\dagger \times \tilde{p}]^{(1)} + 2\sqrt{7}[f^\dagger \times \tilde{f}]^{(1)}. \tag{6}$$

The normal and intruder configurations were mixed with a mixing Hamiltonian of the form

$$H_{mix}=\alpha[s^{\dagger}\times s^{\dagger}+s\times s]^{(0)}+\beta[d^{\dagger}\times d^{\dagger}+\tilde{d}\times\tilde{d}]^{(0)}. \quad (7)$$

The parameters corresponding to the U(5) Hamiltonian were obtained by fitting the low-lying phonon states. The parameters for the intruder states were obtained in the O(6) limit as reported by Lehmann *et al.* [21]. The parameters corresponding to the p and f parts of the Hamiltonian are $\epsilon_p=-2.78$, $\epsilon_f=-2.021$, $\kappa_n=-0.018$, and $\kappa_n'=-0.02$ (all in MeV) for the normal states and intruder configuration, except $\kappa_i=-0.0234$ MeV. These parameters were chosen to reproduce the energies of the 3_1^- and 1_1^- levels and are consistent with the parameter set used for ^{112}Cd [5]. Results from this calculation are shown in Table II. Good agreement with the experimental energy values for the 3_1^- and 1_1^- states is achieved, as expected, since the parameters are tuned to match these levels. Except for the 3_2^- state, the deviations from the experimental energies of the quadrupole-octupole coupled states are less than 100 keV. $E2$ and $E1$ transition rates are computed with operators of the form

$$\hat{T}^{(2)}(E2)=e2([s^{\dagger}\times\tilde{d}+d^{\dagger}\times s]+\ddot{\chi}_1[d^{\dagger}\tilde{d}]+\hat{Q}_{pf}^{(2)}), \quad (8)$$

$$\hat{T}^{(1)}(E1)=e1([p^{\dagger}\times\tilde{d}+d^{\dagger}\times\tilde{p}]+\chi_1[s^{\dagger}\times\tilde{p}+p^{\dagger}\times s] + \chi_1'[d^{\dagger}\times\tilde{f}+f^{\dagger}\times\tilde{d}]) \quad (9)$$

for both the normal and intruder configurations. The final $E2$ strengths are found as

$$\hat{T}_{Total}^{(2)}(E2)=\hat{T}_{Normal}^{(2)}(E2)+\epsilon_{rel}\hat{T}_{Intruder}^{(2)}(E2), \quad (10)$$

where, $\epsilon_{rel}=0.86$, as noted in Ref. [21]. Lehmann and Jolie [21] calculated the $E2$ transition strength between the low-lying states and obtained a consistent set of parameters for a wide range of Cd isotopes. We have used their parameters. Unfortunately, they did not provide results for $E1$ transitions. For the $E1$ transitions, we have used the same parameters as for similar calculations for ^{112}Cd [5,39]. The ϵ_{rel} parameter through which the contribution of intruder configuration is weighted with respect to the normal configuration before summing is 1.0 in this case. The results are shown in Table II. Good agreement is observed for the $E2$ and $E1$ transition rates, except for the $3_2^-\rightarrow 2_1^+$ $E1$ transition. This result differs from ^{112}Cd [5], in which little agreement with calculated $E1$ transition rates was found. No transitions have been observed from the 1_1^- state to the 2_1^+ and 3_1^- states, as expected from the calculation.

IV. SUMMARY AND CONCLUSIONS

Low-lying levels of ^{114}Cd have been studied through the inelastic scattering of fast neutrons to identify negative-parity states resulting from quadrupole-octupole coupling. Five negative-parity states in the energy range of 2 to 3 MeV are suggested as the complete $2_1^+\otimes 3_1^-$ quintuplet. The full set of five coupled states, and those to which they decay, are presented in Fig. 4. $E2$ transitions from 2^-, 3^-, 4^-, and 5^- levels to the 3_1^- state indicate the quadrupole-octupole nature of these states. Transitions from the 1^- level to the 2_1^+ and 3_1^- levels were not observed; however, this level has been assigned as the lowest-spin member of the multiplet on the basis of the systematic behavior of 1^- states in other Cd isotopes. The level energies and the transition strengths could be explained well by $spdf$ IBM-1 calculation.

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