Low-lying $J = 1$ states in ^{106}Cd

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The atomic nucleus ^{106}Cd was studied via the β-decay of ^{106}In and using nuclear resonance fluorescence. The decay pattern of five $J = 1$ states and precise lifetimes of three spin 1 states have been deduced. By combining both data sets a candidate for the quadrupole-octupole coupled 1^- state was identified at 2825 keV. Only this state shows the decay pattern comparable with the known quadrupole-octupole coupled 1^- states in the other even-even stable cadmium isotopes $^{108-116}$Cd. For the description of this collective state a good agreement with predictions of the Q-phonon approach using a fermionic configurational space and microscopic calculations on the basis of the random phase approximation was found.

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I. INTRODUCTION

The $Z = 50$ region is very favorable for nuclear structure studies due to the large abundance of stable isotopes, so that a quasi-"complete study" of a long chain is feasible. Therefore, the cadmium isotopes are situated in a very interesting region of the nuclear chart. These nuclei have been intensively studied in the last decades and have revealed a wealth of information on multiphonon states [1–12] and their interaction with intruding states, leading to shape coexistence of spherical normal and deformed 2p-2h intruder states [13–16]. Furthermore, the nature of negative parity states, especially the inhomogenous phonon coupling of the octupole vibration to the quadrupole vibration leading to quadrupole-octupole coupled (QOC) states $(2^+ \otimes 3^-)^{J^\pi}$ with $J^\pi = 1^-, 2^-, 3^-, 4^-, 5^-$, was studied in most even-even cadmium isotopes [4,5,17–21]. During the last decades the 1^- member of the quintuplet has been studied with the spin-selective nuclear resonance fluorescence (NRF) technique [22,23]. The low momentum transfer in photon scattering favors dipole excitations (both $M1$ and $E1$) and to a lesser extent electric quadrupole excitations ($E2$). In our previous investigations, we were able to identify this 1^- two phonon excitation in ^{108,110,112,114,116}Cd [24–27] by analyzing absolute transition rates and parities [27] of dipole excited states. One common feature of the 1^- QOC state is its energy, which lies close to the sum energy of the 2^+_1 and 3^-_1 states [28]. Another property is the relatively large $E1$ strength, which is with about 10^{-3} W.u. [milli Weisskopf units], three orders of magnitudes smaller than the giant dipole resonance (GDR), but on the other hand three orders of magnitudes larger than other observed low-lying $E1$ strength. The smooth mass dependence of the $E1$ strength and of the excitation energy suggest the collective nature of this two-phonon excitation, which is formed by the harmonic coupling of the quadrupole and octupole phonon.

The aim of the present study is to identify the 1^- member of this multiplet in ^{106}Cd and to extend the $E1$ strength systematics to the lightest stable even-even cadmium isotope. So far four spin 1 states in ^{106}Cd were known from inelastic neutron scattering (INS) experiments [29,30] and from β-decay experiments [31,32], but no information on lifetimes and thus transition strengths was available. These states at 2825, 2918, 3120 (3119 in this work), and 3222 keV are close to the sum energy $E_{2^+_1} + E_{3^-_1} = 3011$ keV. In order to determine the absolute decay probabilities the ^{106}Cd(γ, γ') reaction was used at the 4.3 MV DYNAMITRON facility at the University of Stuttgart using continuous bremsstrahlung to measure integrated photon scattering cross sections. To extract the full decay pattern of these $J = 1$ states and measure indirectly the parities of the spin 1 states through multipole mixing ratios, we performed a $\gamma\gamma$-angular-correlation experiment after β-decay of ^{106}In. We used the ^{106}Cd(p, n) reaction to produce ^{106}In. This reaction favors the population of the low-spin $(2)^+$ isomer in ^{106}In which decays to ^{106}Cd with a half-life of 5.2 min. The high Q-value of 6.52 MeV of this β-decay and the low-spin then guaranteed the population of a large number of low-spin states in ^{106}Cd.

II. EXPERIMENTS AND RESULTS ON ^{106}CD

A. β-decay

The β-decay experiment was performed at the FN TANDEM of the University of Cologne with the HORUS CUBE spectrometer [33]. It was equipped with four bismuth germanate (BGO) shielded high-purity Germanium detectors (HPGe) with a relative efficiency of 55% each, five 30% efficient unshielded HPGe detectors and the Cologne EUROBALL Cluster detector. The detectors are placed about 12 cm from the target position. The absolute photopeak efficiency of the HORUS CUBE spectrometer in this configuration was about 1.8%. In addition, the Cologne β-slider was used.

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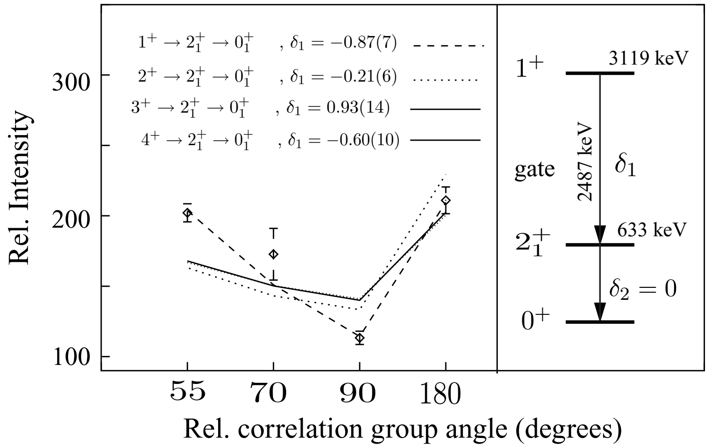

FIG. 1. Right: The decay pattern of the 3119 keV $\to 2_1^+ \to 0_1^+$ is shown. The angular correlation analysis was done by gating on the 2487 keV transition and determine the intensity of the 633 keV transition in all four groups, using the known multipole mixing ratio $\delta_2 = 0$ of the $2_1^+ \to 0_1^+$ transition. Left: The corresponding angular correlation analysis. Four correlation plots of four different $J = 1, 2, 3, 4 \to 2_1^+ \to 0_1^+$ hypothesis are compared with the efficiency-corrected $\gamma\gamma$-coincidence intensities of the (2487,632)-keV cascade in the four angular correlation groups. While the assumptions of $J = 2, 3, 4$ fail to describe the data points (the spin $J = 3$ and $J = 4$ hypothesis are nearly indistinguishable), the assumption of $J = 1$ reproduces the measured values with a multipole mixing ratio of $\delta_1 = -0.87(7)$ nicely.

The β-slider [33,34] allows the activation of the target about 1 m behind the spectrometer, the automatic and controlled transport of the target into the spectrometer and the off-beam measurement of $\gamma\gamma$ angular correlations after β-decay inside the spectrometer. The advantages of this method are the protection of the HPGe detectors against neutron damage and an increase in the target activation as a higher beam current can be used for irradiation. The ^{106}Cd(p, n) reaction was induced with a 11 MeV proton beam and a beam intensity of 8 nA. A 1 mg/cm^2 cadmium target enriched in the isotope ^{106}Cd to 90.08%, was irradiated. The first activation took about 18 min. After this initial activation, the β-slider moved from the activation position to the target position in a 6 min cycle during the whole beamtime of 5 d. Spins, multipole mixing ratios, and branching ratios were determined with the $\gamma\gamma$ angular correlation method [35]. In this measurement the geometry of the HORUS CUBE spectrometer results in four angular correlation groups defined by the relative angles of 55°, 70°, 90°, and 180° between the occupied detector positions. As an example Fig. 1 shows the $\gamma\gamma$-angular correlation plot for the 2487 keV transition of the known spin 1 state in coincidence with the $2_1^+ \to 0_1^+$ transition. For this transition a multipole mixing ratio of $\delta = -0.87(7)$ was determined. This nonzero multipole mixing ratio forbids negative parity for the dipole excitation at 3119 keV. The measured energies E_γ, γ-ray intensities I_γ, and multipole mixing ratios δ of the decays of excited states at the energy E_{Level} are listed in Table I, together with the deduced spins and parities J^π (see Sec. II C).

B. Nuclear resonance fluorescence (NRF)

The NRF experiment was performed at the 4.3 MV DYNAMITRON accelerator at the University of Stuttgart. The accelerator delivered a monochromatic electron beam with an energy of 3.1 MeV for this experiment. The electrons were stopped in a water-cooled gold radiator target and produced a continuous bremsstrahlung spectrum with photon energies up to $E_\gamma = 3.1$ MeV. A lead collimator with a length of 1 m and a bore diameter of 1 cm defined the axis of the photon beam. The target, which consisted of 2.169 g CdO with an enrichment of 80.04% in ^{106}Cd and 1.198 g ^{27}Al, was positioned in an evacuated beam pipe and surrounded by three HPGe detectors with a relative efficiency of 100% each at 90°, 127° (BGO shielded), and 150° relative to the beam axis (for technical details see [22]). The well-known photon scattering cross sections [37] of the low-lying states of ^{27}Al were used for the photon flux calibration, which allows for the determination of the absolute cross sections for the NRF reaction on ^{106}Cd. The measurement took about 100 h.

The positioning of the HPGe detectors under 90°, 127°, and 150° relative to the beam axis enables the determination of spins from angular distributions of decays to the ground state. The angular distribution ratio $W(90°)/W(127°)$ makes it possible to distinguish between states with $J = 1$ and $J = 2$ (Fig. 2).

The photon scattering cross sections $I_{s,f}$ to the final state are used to calculate the partial widths Γ_f via

$$I_{s,f} = \left(\frac{\pi\hbar c}{E_\gamma}\right)^2 \frac{2J+1}{2J_0+1} \frac{\Gamma_0\Gamma_f}{\Gamma}. \quad (1)$$

Here, J_0 is the ground state spin, and $\Gamma = \sum_{f=0}^{N} \Gamma_f$ the sum of the partial decay widths Γ_f to the final states. From these

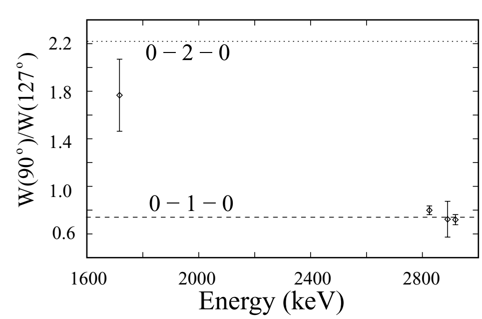

FIG. 2. Angular distribution ratios of the resonantly scattered photons in NRF. A comparison of the experimental intensity ratios $W(90°)/W(127°)$ for the $J^\pi \to 0_1^+$ transitions with the expected values for the $0 \to 1 \to 0$ (dashed line) and $0 \to 2 \to 0$ (dotted line) cascades are shown. Dipole and quadrupole transitions can clearly be distinguished. The data point at 1716 keV stems from the ground state transition of the 2_2^+ state.

TABLE I. Results for the ^{106}Cd$(p,n)^{106}$In $\rightarrow$ ^{106}Cd reaction for the states of interest. Listed are the level energies E_{Level}, spins and parities of the inital states J_i^π, γ-ray energies E_γ, energies of the final states E_f, spins and parities J_f^π of the final states, γ-ray intensities I_γ and multipole mixing ratios δ.

E_{Level} (keV)	J_i^π $\hbar$	E_γ (keV)	E_f (keV)	J_f^π $\hbar$	I_γ %	δ
1716.5(2)	2^+	1716.5(2)	0.0	0^+	100(10)	$E2$
		1083.8(1)	632.5(1)	2^+	94(10)	−1.53(14)[a]
2824.5(2)	1	2824.5(2)	0.0	0^+	100	
2889.5(3)	1	2889.5(2)	0.0	0^+	31(10)	
		2256.8(3)	632.5(1)	2^+	100(10)	
2917.6(2)	$1^{(+)}$	2917.6(2)	0.0	0^+	100(10)	$(M1)$
		2284.8(2)	632.5(1)	2^+	22(8)	0.045(46)
		1201.0(1)[b]	1716.5(2)	2^+	5(2)	0.17(11)
		1122.4(2)[b]	1794.9(1)	0^+	4(2)	$(M1)$
3118.9(2)	1^+	3118.8(1)	0.0	0^+	96(10)	$M1$
		2486.6(1)	632.5(1)	2^+	100(10)	−0.87(7)
		1402.6(2)[c]	1716.5(2)	2^+	7(1)	
		1324.0(2)[b]	1794.9(1)	0^+	3(1)	$M1$
		748.5(1)[b]	2370.3(2)	2^+	15(2)	
		557.8(2)[b]	2561.3(2)	0^+	4(1)	$M1$
		553.0(2)[b]	2566.0(1)	2^+	12(2)	
3222.3(3)	1	3222.3(3)	0.0	0^+	100(10)	
		2590.5(3)[b]	632.5(1)	2^+	16(2)	
		1427.2(2)[b]	1794.9(1)	0^+	7(2)	

[a]In excellent agreement with the known multipole mixing ratio $\delta = -1.44(11)$ [36].
[b]Marks transitions observed in the β-decay experiment the first time.
[c]Previously assigned as a decay from a state at 3118.8 keV with spin and parity $J^\pi = 2^+, 3^+, 4^+$.

cross sections the branching ratios

$$\frac{\Gamma_f}{\Gamma_0} = \frac{I_{s,f}}{I_{s,0}} \tag{2}$$

can be determined. The total decay width can be deduced from these cross sections and the branching ratios Γ_f/Γ_0 to all final states,

$$\Gamma = \frac{2J_0+1}{2J+1}\left(\frac{E_\gamma}{\pi\hbar c}\right)^2\left(1+\sum_{f>0}\frac{\Gamma_f}{\Gamma_0}\right)^2 I_{s,0}, \tag{3}$$

and provides a model-independent lifetime determination

$$\tau = \frac{\hbar}{\Gamma}. \tag{4}$$

Unfortunately, the observation of transitions to states that are higher in energy than the first excited 2^+ state is unlikely, because of the increasing nonresonant background towards lower energy in NRF experiments. This may cause an overestimation of the lifetimes in NRF experiments and, therefore, an upper limit for the lifetimes is obtained, when no other experimental information is available. In Fig. 3 the relevant part of the photon scattering spectrum measured with the 127 degree HPGe detector is shown.

Three $J = 1$ states were observed between 2.8 and 3.0 MeV in the present NRF experiment (Fig. 2). The measured integrated elastic photon cross sections $I_{s,0}$, the branching ratios $\frac{\Gamma_1}{\Gamma_0}$, spins and parities J^π and the energies E_{Level} of these states are given in Table II.

C. Results of both experiments

In this section the observed levels are discussed and Table III provides the combined experimental information for those levels observed in both experiments. As mentioned above, four $J = 1$ states close to the sum energy $E_{2_1^+} + E_{3_1^-} = 3011$ keV are known at 2825, 2918, 3120, and 3222 keV [29–32]. The spins of these states were confirmed and their

TABLE II. Results for the ^{106}Cd(γ,γ') reaction. Given are the excitation energy E_{Level}, the spin J^π, the branching ratio Γ_1/Γ_0 for the decay to the first excited 2_1^+ state at 633 keV, and the integrated photon scattering cross section $I_{s,0}$.

E_{Level}	J^π	Γ_1/Γ_0	$I_{s,0}$
1716.5(3)	2^+	0.92(45)[a]	2.8(3)[b]
2824.5(2)	1	<0.08	32.8(12)[c]
2889.7(2)	1	2.2(3)	3.4(3)[c]
2917.7(2)	1	0.21(2)	24.9(10)[c]

[a]Only detected in the 150° detector.
[b]Corrected for the feeding from the $J = 1$ state at 2918 keV.
[c]Marks integrated cross sections observed for the first time.

TABLE III. Decay properties of the measured states observed in NRF and after β decay. If no δ or parity could determined, pure $E1$, $M1$, and $E2$ transition strengths are given. The lifetime marked with an asterisk * is in excellent agreement with the known lifetime of $\tau = 450(70)$fs [36].

E_{Level} (keV)	J_i^π $\hbar$	E_γ (keV)	E_f (keV)	J_f^π $\hbar$	I_γ %	δ	τ (fs)	$B(E1)\downarrow$ $10^{-3}e^2\text{fm}^2$	$B(M1)\downarrow$ μ_N^2	$B(E2)\downarrow$ $e^2\text{fm}^4$
1716.5(2)	2^+	1716.5(2)	0.0	0^+	100(10)	$E2$	410(70)*			69^{+23}_{-16}
		1083.8(1)	632.5(1)	2^+	94(10)	−1.53(14)			$0.016^{+0.006}_{0.004}$	450^{+170}_{-120}
2824.5(2)	1	2824.5(2)	0.0	0^+	100	$E1$	29.0(11)	0.96(4)		
2889.5(2)	1	2889.5(2)	0.0	0^+	44(5)[a]	$E1$	25(5)	$0.32^{+0.12}_{-0.08}$		
						$M1$			$0.029^{+0.011}_{-0.008}$	
		2256.8(3)	632.5(1)	2^+	100(5)	$M1$			$0.14^{+0.04}_{-0.03}$	
						$E2$				390^{+120}_{-80}
						$E1$		$1.5^{+0.5}_{-0.3}$		
2917.6(2)	$1^{(+)}$	2917.6(2)	0.0	0^+	100(2)[a]	$M1$	21.2(16)		$0.083^{+0.009}_{-0.007}$	
		2284.9(2)	632.5(1)	2^+	21(2)[a]	0.045(46)			$0.036^{+0.007}_{-0.006}$	$0.20^{+0.04}_{-0.03}$
		1201.0(1)	1716.5(2)	2^+	5(2)	0.17(11)			$0.06^{+0.04}_{-0.03}$	16^{+10}_{-9}
		1122.4(2)	1794.9(1)	0^+	4(2)	$M1$			0.06(4)	
						$E2$				700^{+510}_{-440}

[a]Weighted average of both experiments.

decay patterns were completed. While the data of the previous INS- [29,30] and the β-decay [31,32] experiment locate the $J = 1$ states at 3119.7 and 3120.3 keV, respectively, this spin 1 state was found at 3118.9 keV in our experiments. We observed no hint for an excited state at 3118.8 keV with spin and parity $J^\pi = 2^+, 3^+, 4^+$ identified in the above-mentioned INS-experiment. The measurement of multipole mixing ratios allows the indirect determination of the parity. The nonzero multipole mixing ratio $\delta = -0.87(7)$ of the transition at 2487 keV from the spin 1 state at 3119 keV counts as evidence for positive parity for this state, because a $M2/E1$ mixed transition with a strong $M2$ admixture is unlikely, while the multipole mixing ratio $\delta = 0.17(11)$ of the 1201 keV transition from the $J = 1$ state at 2918 keV suggests positive parity, but cannot exclude negative parity within two σ. Therefore, we can only tentatively assign positive parity $J^\pi = 1^{(+)}$. In addition, the strong population of the $(2)^+$ isomer in ^{106}In which decays to ^{106}Cd, strongly supports positive parity (allowed β-decay), also for the spin 1 state at 3222 keV (Fig. 4), whereas the weak population of the $J = 1$ states at 2825 keV and 2890 keV gives a hint for negative parity (first-forbidden β-decay). The state at 2890 keV, previously assigned a spin $J^\pi = (2, 3^+)$ [29–32], is clearly identified as a spin 1 state in the NRF experiment. The branching ratio of the level at 2890 keV to the 2_1^+ state and the ground state was determined by gating on a populating transition of 2047 keV from a level at 4936 keV in the β-decay experiment. The branching ratio $\Gamma_1/\Gamma_0 = 3.2(11)$ agrees with the NRF result of $\Gamma_1/\Gamma_0 = 2.2(3)$ within the errors. When determining the relative intensities from the singles spectra of the β-decay experiment, one gets a branching ratio of $\Gamma_1/\Gamma_0 = 17.9(32)$. This huge discrepancy indicates a doublet either at γ-ray transition energy of 2890 keV or at 2257 keV or even at both energies as shown in Fig. 5.

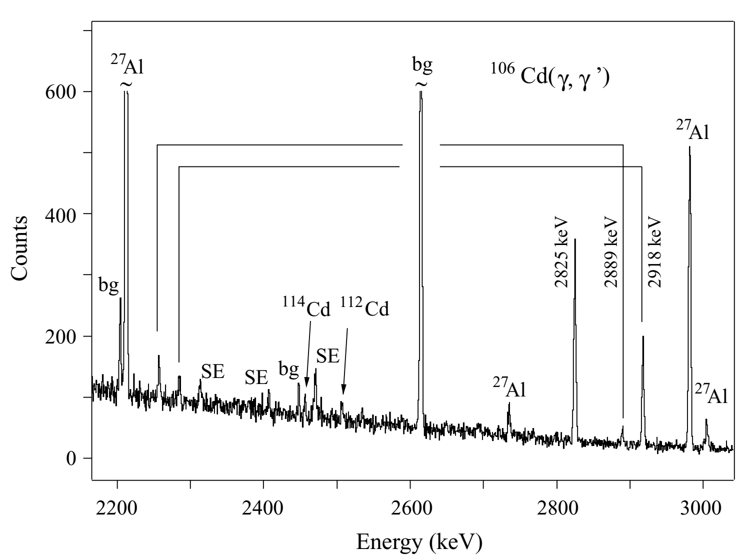

FIG. 3. Part of the photon scattering spectrum off ^{106}Cd. Ground-state transitions in ^{106}Cd are marked with an energy label, corresponding decays to the 2_1^+ state are marked with brackets. Other γ-ray peaks stem from the calibration standard ^{27}Al, background radiation (bg), impurities of the target (mainly ^{112,114}Cd) and single-escape peaks (SE).

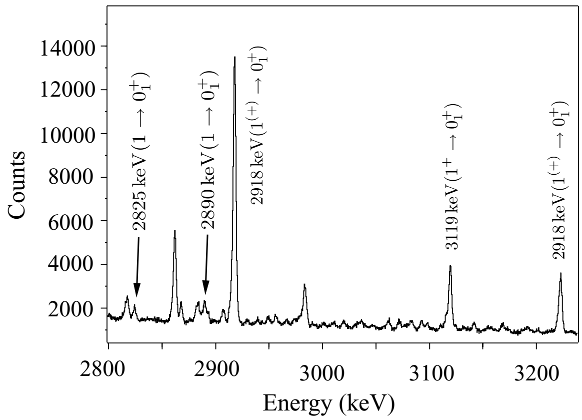

FIG. 4. Part of the singles spectrum for one detector in the β-decay experiment is shown. The $J = 1$ states at 2918 keV, 3119 keV, and 3222 keV are strongly populated. This favors a positive parity assignment for these spin 1 states. The weak population of the 2825 keV spin 1 states supports the assignment of negative parity. The states of interest are labeled with their energy.

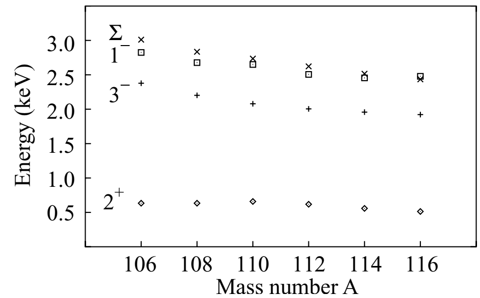

FIG. 6. Energy-systematics of $E1$ two-phonon excitations in even-even Cd isotopes. Energies of the $2_1^+, 3_1^-, 1_1^-$ states and the sum Σ of the 2_1^+ and 3_1^- energies are plotted.

III. COMPARISON WITH THEORY

The 1^- QOC states in ^{108,110,112,114,116}Cd are well known [24–27]. A common feature of these states in the even-even cadmium isotopes are (i) the single branch to the ground state and (ii) the vicinity to the sum energy of the first excited 2_1^+ and 3_1^- state. Only the two states at 2825 keV and 2890 keV are weakly populated in the β-decay and, therefore, are candidates for states with negative parity. Finally, only the state at 2825 keV in ^{106}Cd shows a single branch to the ground state and lies close to the sum energy of 3011 keV. But another spin 1 states at 2890 keV is also in the energy range with a transition strength of $B(E1)\downarrow = 0.32^{+0.12}_{-0.08}$ $e$fm (assuming negative parity) and thus we cannot exclude that the QOC state in ^{106}Cd is fragmented. In the following, we give arguments that the $J = 1$ state at 2825 keV with a transition strength of $B(E1)\downarrow = 0.96(4)$ $e$fm represents the main fragment for the QOC 1^- state.

The energy systematics are shown in Fig. 6. As expected, the state at 2825 keV is observed slightly below the sum energy of the single quadrupole and octupole excitations. This reflects a rather harmonic coupling. From the systematics an increasing, but small, deviation from the sum energy is found, which increases below ^{110}Cd leading to the largest lowering for ^{106}Cd. Figure 7 shows the experimental $|\langle 0_1^+|M(E1)|1_1^-\rangle|$ systematics for the Cd isotopes illustrating a slight increase of the strength with lower neutron numbers.

Recently Jolos *et al.* [38] calculated $E1$ matrix elements for the $0_1^+ \rightarrow 1_1^-$ transition using a Q-phonon approach for the description of the low-lying collective states and the random phase approximation (RPA) for the ground state wave function. They studied the known QOC states in the Nd, Sm, Ba, Ce, Sn, and Cd isotopes and found that the data are better described when the dipole two-quasiparticle contributions to the 1_1^- state are small, but not negligible. This they call the inclusion of renormalized two-quasiparticle contributions. The same trend is found for ^{106}Cd as shown in Fig. 7, which compares the data with the calculated matrix elements [39] including two-quasiparticle contributions ($|\langle 0_1^+|M(E1)|1_1^-\rangle| = 0.139e$ fm) and excluding two-quasiparticle contributions ($|\langle 0_1^+|M(E1)|1_1^-\rangle| = 0.025e$ fm). The systematics shows that the largest deviations of both calculations are obtained for the two lightest Cd isotopes. However, the systematic trend is well described when the renormalization procedure proposed by Jolos *et al.* [38] is used. As shown by the solid line in Fig. 7 a good agreement between the experimental values and theory, including all renormalized two-quasiparticle contributions, is

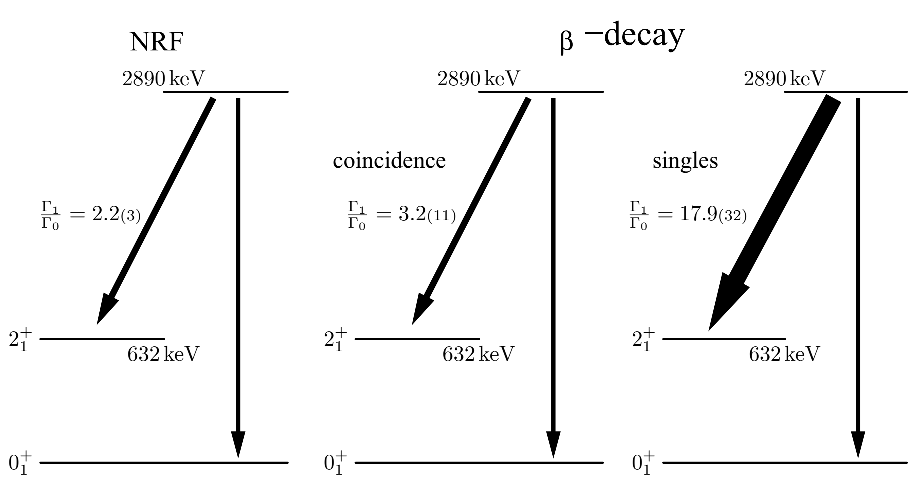

FIG. 5. The discrepancy of the two branching ratios Γ_1/Γ_2 measured for the γ transitions at 2257 keV and 2890 keV is shown. The coincidence data of the branching ratio $\Gamma_1/\Gamma_0 = 3.2(11)$ of the β-decay experiment and the NRF branching ratio $\Gamma_1/\Gamma_0 = 2.2(3)$ agrees within the errors, while the branching ratio $\Gamma_1/\Gamma_0 = 17.9(32)$ determined from the singles spectra in the β-decay experiment is in disagreement.

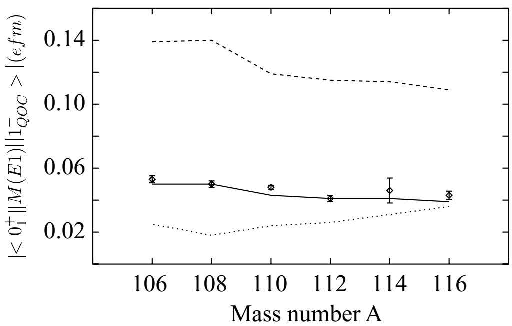

FIG. 7. Absolute values of the reduced matrix elements for the $E1$ transitions in the even-even Cd isotopes calculated with the inclusion of all contributions (dashed line), with the renormalization procedure proposed by Jolos *et al.* [38] (solid line), without inclusion of the contribution coming from two-quasiparticle admixture (dotted line), and experimental data (error bars).

obtained. Nevertheless, the inclusion of all quasiparticle contributions without renormalization leads to an overprediction (dashed line) of the absolute values, as can also be seen in Fig. 7.

IV. CONCLUSION

Low-lying dipole $J = 1$ states in the lightest stable cadmium isotope were studied. A candidate for the QOC 1^- state in ^{106}Cd was identified using β-decay and nuclear resonance fluorescence. Although the parity of this state could not be measured directly, the typical single transition to the ground state, as it was found in the other stable even-even Cd isotopes, the $E1$ strength, the energy of the state and the weak population in β-decay support a negative parity for this state. The results were compared to predictions using a Q-phonon scheme approach with a microscopic description of the phonons. Although the absolute values of the calculated matrix elements show large deviations, the values after a proper renormalization are in excellent agreement with the data. This shows that the two quasiparticle contributions to the quadrupole-octupole 1^- states have to be taken into account.

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[1] A. Aprahamian, D. S. Brenner, R. F. Casten, R. L. Gill, A. Piotrowski, and K. Heyde, Phys. Lett. **B140**, 22 (1984).

[2] A. Aprahamian, D. S. Brenner, R. F. Casten, R. L. Gill, and A. Piotrowski, Phys. Rev. Lett. **59**, 535 (1987).

[3] C. Fahlander, A. Bäcklin, L. Hasselgren, A. Kavka, V. Mittal, L. E. Svensson, B. Varnestig, D. Cline, B. Kotlinski, H. Grein, E. Grosse, R. Kulessa, C. Michel, W. Spreng, H. J. Wollersheim, and J. Stachel, Nucl. Phys. **A485**, 327 (1988).

[4] M. Délèze, S. Drissi, J. Kern, P. A. Tercier, J. P. Vorlet, J. Rikovska, T. Otsuka, S. Judge, and A. Williams, Nucl. Phys. **A551**, 269 (1993).

[5] A. Gade, J. Jolie, and P. von Brentano, Phys. Rev. C **65**, 041305(R) (2002).

[6] M. Kadi, N. Warr, P. E. Garrett, J. Jolie, and S. W. Yates, Phys. Rev. C **68**, 031306(R) (2003).

[7] R. F. Casten, J. Jolie, H. G. Börner, D. S. Brenner, N. V. Zamfir, W.-T. Chou, and A. Aprahamian, Phys. Lett. **B297**, 19 (1992).

[8] F. Corminboeuf, T. B. Brown, L. Genilloud, C. D. Hannant, J. Jolie, J. Kern, N. Warr, and S. W. Yates, Phys. Rev. Lett. **84**, 4060 (2000).

[9] F. Corminboeuf, T. B. Brown, L. Genilloud, C. D. Hannant, J. Jolie, J. Kern, N. Warr, and S. W. Yates, Phys. Rev. C **63**, 014305 (2001).

[10] H. Lehmann, P. E. Garrett, J. Jolie, C. A. McGrath, Minfang Yeh, and S. W. Yates, Phys. Lett. **B387**, 259 (1996).

[11] A. Gade, A. Fitzler, C. Fransen, J. Jolie, S. Kasemann, H. Klein, A. Linnemann, V. Werner, and P. von Brentano, Phys. Rev. C **66**, 034311 (2002).

[12] P. E. Garrett, H. Lehmann, J. Jolie, C. A. McGrath, Minfang Yeh, W. Younes, and S. W. Yates, Phys. Rev. C **64**, 024316 (2001).

[13] K. Heyde, P. Van Isacker, M. Waroquier, G. Wenes, and M. Sambataro, Phys. Rev. C **25**, 3160 (1982).

[14] J. Kern, A. Bruder, S. Drissi, V. A. Ionescu, and D. Kusnezov, Nucl. Phys. **A512**, 1 (1990).

[15] J. Jolie and H. Lehmann, Phys. Lett. **B342**, 19 (1995).

[16] H. Lehmann and J. Jolie, Nucl. Phys. **A588**, 19 (1995).

[17] D. Bandyopadhyay, C. C. Reynolds, S. R. Lesher, C. Fransen, N. Boukharouba, M. T. McEllistrem, and S. W. Yates, Phys. Rev. C **68**, 014324 (2003).

[18] M. Délèze, S. Drissi, J. Jolie, J. Kern, and J. P. Vorlet, Nucl. Phys. **A554**, 1 (1993).

[19] S. E. Drissi, P. A. Tercier, H. G. Börner, M. Délèze, F. Hoyler, S. Judge, J. Kern, S. J. Mannanal, G. Mouze, K. Schreckenbach, J. P. Vorlet, N. Warr, A. Williams, and C. Ythier, Nucl. Phys. **A614**, 137 (1997).

[20] P. E. Garrett, H. Lehmann, J. Jolie, C. A. McGrath, Minfang Yeh, and S. W. Yates, Phys. Rev. C **59**, 2455 (1999).

[21] A. Gade and P. von Brentano, Phys. Rev. C **66**, 014304 (2002).

[22] U. Kneissl, H. H. Pitz, and A. Zilges, Prog. Part. Nucl. Phys. **37**, 349 (1996).

[23] U. E. P. Berg and U. Kneissl, Annu. Rev. Nucl. Part. Sci. **37**, 33 (1987).

[24] A. Gade, D. Belic, P. von Brentano, C. Fransen, H. von Garrel, J. Jolie, U. Kneissl, C. Kohstall, A. Linnemann, H. H. Pitz, M. Scheck, F. Stedile, and V. Werner, Phys. Rev. C **67**, 034304 (2003).

[25] H. Lehmann, A. Nord, A. E. de Almeida Pinto, O. Beck, J. Besserer, P. von Brentano, S. Drissi, T. Eckert, R.-D. Herzberg, D. Jäger, J. Jolie, U. Kneissl, J. Margraf, H. Maser, N. Pietralla, and H. H. Pitz, Phys. Rev. C **60**, 024308 (1999).

[26] W. Geiger, Zs. Nèmeth, I. Bauske, P. von Brentano, R. D. Heil, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, N. Pietralla, H. H. Pitz, C. Wesselborg, and A. Zilges, Nucl. Phys. **A580**, 263 (1994).
[27] C. Kohstall, D. Belic, P. von Brentano, C. Fransen, A. Gade, R.-D. Herzberg, J. Jolie, U. Kneissl, A. Linnemann, A. Nord, N. Pietralla, H. H. Pitz, M. Scheck, F. Stedile, V. Werner, and S. W. Yates, Phys. Rev. C **72**, 034302 (2005).
[28] W. Andrejtscheff, C. Kohstall, P. von Brentano, C. Fransen, U. Kneissl, N. Pietralla, and H. H. Pitz, Phys. Lett. **B506**, 203 (2001).
[29] S. A. Berendakov, L. I. Govor, A. M. Demidov, and I. V. Mikhailov, INDC(CCP)299/G, 26 (1988).
[30] S. A. Berendakov, L. I. Govor, A. M. Demidov, and I. V. Mikhailov, Proceedings of the 38th Annual Conference on Nuclear Spectroscopy Structure of Atomic Nuclei, Baku (1988), p. 82.
[31] H. Huang, B. P. Pathak, and J. K. P. Lee, Can. J. Phys. **56**, 936 (1978).
[32] B. Roussière, P. Kilcher, J. Sauvage-Letessier, C. Bourgeois, R. Beraud, R. Duffait, M. Meyer, J. Genevey-Rivier, and J. Treherne, Nucl. Phys. **A419**, 61 (1984).
[33] A. Linnemann, Ph.D. thesis, University of Cologne, 2005, urn:ubn:de:hbz:38-17477.
[34] P. Knoch, Master thesis, University of Cologne, 2004.
[35] K. S. Krane, R. M. Steffen, and R. M. Wheeler, Nucl. Data Tables **11**, 351 (1973).
[36] D. De Frenne and E. Jacobs, Nucl. Data Sheets **72**, 1 (1994).
[37] N. Pietralla, I. Bauske, O. Beck, P. von Brentano, W. Geiger, R.-D. Herzberg, U. Kneissl, J. Margraf, H. Maser, H. H. Pitz, and A. Zilges, Phys. Rev. C **51**, 1021 (1995).
[38] R. V. Jolos, N. Y. Shirikova, and V. V. Voronov, Phys. Rev. C **70**, 054303 (2004).
[39] R. V. Jolos (private communication).