Quadrupole-octupole coupled states in ^{112}Cd populated in the ^{111}Cd($\vec{d}$, p) reaction

D. S. Jamieson, P. E. Garrett,* V. Bildstein, G. A. Demand, P. Finlay,† K. L. Green, K. G. Leach,‡ A. A. Phillips, C. S. Sumithrarachchi,§ and C. E. Svensson
Department of Physics, University of Guelph, Guelph, Ontario, Canada N1G2W1

S. Triambak
Department of Physics, University of Guelph, Guelph, Ontario, Canada N1G2W1;
Department of Physics, University of the Western Cape, P/B X17, Bellville ZA-7535, South Africa;
and iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa

G. C. Ball
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3, Canada

T. Faestermann
Physik Department, Technische Universität München, D-85748 Garching, Germany

R. Hertenberger and H.-F. Wirth
Fakulat für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
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States in ^{112}Cd have been studied with the ^{111}Cd($\vec{d}$, p)^{112}Cd reaction using 22 MeV polarized deuterons. The protons from the reaction were momentum analyzed with a Q3D magnetic spectrograph, and spectra have been recorded with a position-sensitive detector located on the focal plane. Angular distributions of cross sections and analyzing powers have been constructed for the low-lying negative-parity states observed, including the 3^-, 4^-, and 5^- members of the previously assigned quadrupole-octupole quintuplet. The 5^- member at 2373-keV possess the second largest spectroscopic strength observed, and is reassigned as having the $s_{\frac{1}{2}} \otimes h_{\frac{11}{2}}$ two-quasineutron configuration as the dominate component of its wave function.

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I. MOTIVATION

The midshell Cd isotopes have long been cited as prime examples of spherical vibrational motion, (see, e.g., Kern *et al.* [1]), with multiphonon states claimed in, for example, Refs. [2–8], but recent work has questioned this interpretation [9–11]. To date, the discussion of the validity of near-harmonic spherical vibrational motion has focused primarily on the properties of the positive-parity states and the departure of their electromagnetic decay transition rates from expectations. A complication, however, has been the presence of the intruder excitations, and their possible mixing with the phonon states [3–5,12–14]. Detailed spectroscopy of ^{110}Cd [10], achieved with high-statistics β decay and the $(n,n'\gamma)$ reaction, suggested that the mixing was weak due to the near lack of enhanced transitions between configurations. As a result, the strong-mixing scenario [14], proposed in the early 1980s when the data were sparse, was rejected and the suggestion was made that the nonintruder states in ^{110}Cd revealed the pattern of a γ-soft rotor [10].

In the discussion to date, however, very little attention has been paid to the heterogeneous multiphonon states, namely the quadrupole-octupole-coupled (QOC) states. The full quintuplet expected for the two-phonon QOC states has been assigned in ^{108}Cd [15], ^{112}Cd [16,17], ^{114}Cd [18], and ^{116}Cd [11], and in ^{112,114}Cd this has been supported by determinations of the absolute $B(E2)$ values that indicate considerable enhancement for decay to the 3^-_1 state—the one-phonon octupole state. Shown in Fig. 1 are the QOC states assigned [17] for ^{112}Cd. Also shown are the absolute $B(E2; \mathrm{QOC} \rightarrow 3^-_1)$ values, where known [17]. The 5^- and 6^- states at 2570 keV and 2818 keV, respectively, are also included as they are important in the discussion to follow.

The initial assignments for the QOC states in ^{112}Cd by Drissi *et al.* [16] were done on the basis of energy; the expected energy centroid of the QOC states is found by the energy sum $E(2^+_1) + E(3^-_1) = 2623$ keV. All of the suggested QOC states are below this energy, except the 2669-keV 2^- state. Two 5^- states at 2372 keV and 2570 keV decay to the 3^-_1 level, and thus prior to lifetime measurements, either could be considered as viable candidates for the 5^- member of the QOC state. However, once lifetime measurements became available [17], the observed enhancement for the decay of the 5^-_1 state to the 3^-_1 level, with an upper limit for the $B(E2)$ value for the decay of the 2570-keV state, strongly favored the selection of the 5^-_1

*pgarrett@physics.uoguelph.ca
†Present address: Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001, Leuven, Belgium.
‡Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T2A3 Canada.
§Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321.

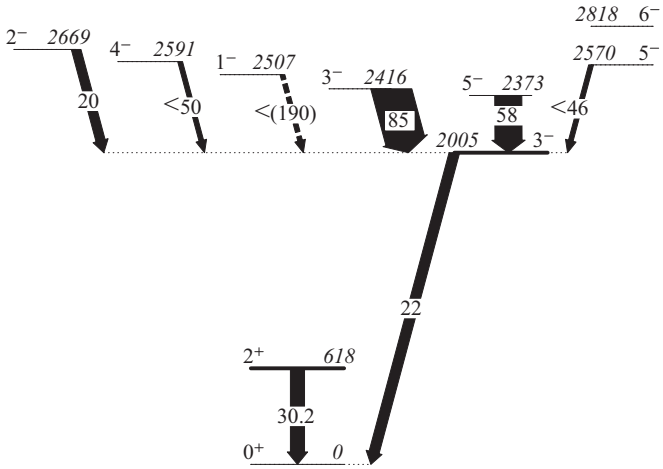

FIG. 1. Partial level scheme of ^{112}Cd displaying the one phonon quadrupole and octupole states, with their $B(E2)$ and $B(E3)$ transition strengths, and other low-lying negative-parity states with known $B(E2)$ values (or limits) for decay to the 3_1^- state. Values reported are in W.u. Solid arrows refer to observed transitions, dashed arrows to unobserved.

level as the QOC member. A reasonable reproduction using $spdf$-IBM-1 calculations of the energies and $B(E2)$ values for the QOC states was achieved in Ref. [17].

As part of a wider program to investigate the nature of the collectivity in the Cd isotopes, complementary spectroscopic probes have been used. In the present work, results of a single-neutron-transfer reaction to populate states in ^{112}Cd are reported that directly refute the earlier assignment [17] of the 2373-keV 5^- state as a member of the QOC set of states, and emphasize that mis-assignment of structure can occur even when (normally) firm indicators such as $B(E2)$ values are known.

II. EXPERIMENT

High resolution spectroscopic data of the ^{111}Cd$(\vec{d},p)^{112}$Cd single-neutron-transfer reaction were collected at the Maier-Leibnitz Laboratorium of the Ludwig-Maximilians Universität and the Technische Universität München. An MP tandem Van de Graaff accelerator was used to accelerate deuterons from a Stern-Gerlach polarized ion source [19] to 22 MeV with $P = (80 \pm 4)\%$ polarization achieved. The deuterons impinged on a ^{111}Cd target with a thickness of $159 \pm 6 \mu$g cm^{-2} determined by comparing the elastic scattering cross section at 15° with the results of distorted wave Born approximation calculations, described below. Outgoing protons were momentum analyzed using the Q3D magnetic spectrograph and detected with a cathode-strip focal plane detector [20]. Proton spectra were collected at ten angles between 10° and 60°. Elastic scattering data from the polarized deuterons on the ^{111}Cd target were also collected at 20 angles between 15° and 115°.

The spectra were energy calibrated using a cubic polynomial to account for the curvature of the Q3D focal plane. Energies of known levels in ^{112}Cd from a previous $(n,n'\gamma)$ experiment [21] were used for the calibration. The energy resolution ranged from 6 to 7 keV full width at half-maximum (FWHM). From the high-resolution data, 129 peaks attributed to levels in ^{112}Cd were identified. Figure 2 displays a portion of the spectrum associated with levels between 2 MeV and 3 MeV. The program FITPIC, that provides a model for a very flexible peak shape [22], was used to fit the observed peaks in the spectra and extract the numbers of counts in each peak which were used to construct angular distributions of the differential cross section via

$$\frac{d\sigma}{d\Omega} = \frac{N}{d\Omega N_t N_b \epsilon LT}, \tag{1}$$

where N is the number of counts, $d\Omega$ is the solid angle of the spectrograph, N_t is the areal density of the number of target atoms, N_b is the number of beam particles impinging on the target, and ϵ and LT are the detection efficiency and live time of the data acquisition system, respectively. Analyzing powers A_y were also measured using the polarized data via

$$A_y = \frac{2}{3P}\frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}, \tag{2}$$

where $\sigma_\uparrow$ and $\sigma_\downarrow$ are the cross sections measured for the spin-up and spin-down beam polarizations.

Angular distributions of differential cross sections and analyzing powers were calculated for levels observed in the transfer reaction and for the elastic scattering data. The code FRESCO [23] was used to perform adiabatic distorted-wave approximation (ADWA) calculations with standard global optical model potentials (OMP) for protons and neutrons. The proton optical potential from Ref. [24] was chosen for the analysis on the basis that it provided the best reproduction of elastic scattering data for protons on ^{112}Cd from the EXFOR database, measured in Ref. [25]. Distorted-wave Born approximation (DWBA) calculations were also performed using FRESCO and standard global deuteron potentials, the details of those calculations and choice of OMP's are discussed in [26]. The ADWA calculations were compared with the experimental angular distributions in order to identify the dominant orbital and total angular momentum of the transfer for each observed level, and to extract spectroscopic strengths.

Spectroscopic strengths S_{jl} were extracted by scaling the ADWA calculations to the experimental angular distributions according to

$$\left.\frac{d\sigma}{d\Omega}\right|_{\rm EXP} = \sum_{\ell j} \frac{2J_i+1}{2J_f+1} S_{\ell j} \left.\frac{d\sigma_{\ell j}}{d\Omega}\right|_{\rm ADWA}, \tag{3}$$

where the ADWA differential cross section on the right is calculated using FRESCO, and the factor involving the spins of the initial and final nucleus ensures that the spectroscopic strength does not depend on these quantities. Comparisons between multiple global optical potentials, and comparisons with standard DWBA calculations indicated an overall systematic uncertainty of about 30% on all reported spectroscopic strengths [26,27].

III. RESULTS

The ^{111}Cd target ground state has the odd neutron in the $s_{\frac{1}{2}}$ orbital, and thus to first order all final states populated in ^{112}Cd have the configuration $s_{\frac{1}{2}} \otimes j_{tr}$. The only negative-parity

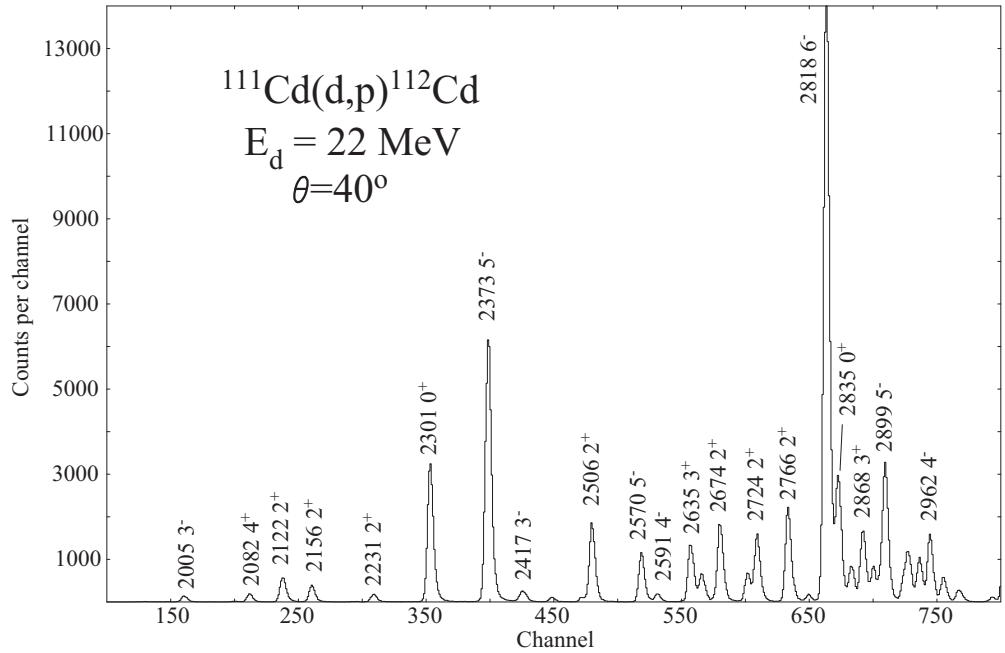

FIG. 2. Partial spectrum of protons, recorded at 40°, obtained by summing spectra for the ↑ and ↓ beam polarizations, from the ^{111}Cd$(\vec{d},p)$ reaction with a 22 MeV deuteron beam. Only the excitation energy region from 1950 keV to 3000 keV is displayed, with selected peaks are labeled with their energies in keV and I^π values. The 5^- level at 2373 keV and the 6^- level at 2818 keV have the largest spectroscopic strengths of any peak in the observed spectrum.

neutron shell-model orbital near to the Fermi surface is $h_{\frac{11}{2}}$, and thus it is expected that the strongest populated negative-parity states would have $I^\pi = 5^-$ and 6^-. All other negative-parity states, if populated, would be expected to be weak.

One-phonon states in nuclei may be represented as a coherent sum over two-quasiparticle states near the Fermi surface. As such, they may be populated in single-nucleon-transfer reactions, sometimes significantly if the particular two-quasiparticle amplitude in the wave function is large. Two-phonon states, on the other hand, involve four-quasiparticle configurations, whether they are homogeneous phonon states or heterogeneous states, and thus will not be populated in a single-nucleon-transfer reaction. While mixing of states can perturb these rules, a fact remains incontrovertible; if a state is strongly populated in a single-nucleon-transfer reaction, its main component cannot be of multiphonon origin.

All of the known negative-parity states below 2.8 MeV of excitation energy in ^{112}Cd, with the exception of the 5_2^- 2570 keV level, have been interpreted as single-octupole or coupled quadrupole-octupole excitations. The 1_1^- level at 2507 keV, and the 2_1^- level at 2669 keV were not observed in this study. (The former state is nearly degenerate with a 2^+ level that was observed in the current work.) All other negative-parity states displayed in Fig. 1 are discussed below and their properties are listed in Table I.

A. 2005-keV level

The level at 2005 keV, with $I^\pi = 3^-$ has been interpreted as the single octupole phonon level in ^{112}Cd, with a $B(E3)$ derived from Coulomb excitation of 22 ± 2 W.u. [29]. It was observed in the previous (d,p) study by Barnes, Comfort, and Bockelman [30] using 8 MeV deuterons. However, the statistics were too low in that study to assign a dominant ℓ-transfer. It was observed in the current work to be weakly populated, with the transfer clearly dominated by the $2f_{\frac{7}{2}}$ component of the wave function, as shown in Fig. 3. The spectroscopic strength extracted in the present work is $S \approx 0.01$.

B. 2373-keV level

The 2373-keV level was assigned as a member of the QOC quintuplet [16,17], and has an enhanced $B(E2)$ for decay to the 3_1^- state of 58^{+39}_{-37} W.u., on the same order as the $B(E2; 2_1^+ \rightarrow 0^+_{\text{g.s.}})$ value of 30 W.u. [31]. The 2373-keV level was observed to be dominated by $1h_{\frac{11}{2}}$ transfer, as shown in Fig. 3, with a spectroscopic strength of $S \approx 2.7$. The 2373-keV level was observed in the previous (d,p) study [30], however

TABLE I. Results from the ^{111}Cd$(\vec{d},p)^{112}$Cd reaction for the low-lying negative-parity states. Also included are the deduced $B(E2; I^\pi \rightarrow 3_1^-)$ values in W.u. from Ref. [28].

E_{ex} (keV)	I^π	ℓ	S_{jl}	$B(E2; I^\pi \rightarrow 3_1^-)$ (W.u.)
2005	3_1^-	$f_{\frac{7}{2}}$	0.0126(2)	
2373	5_1^-	$h_{\frac{11}{2}}$	2.66(3)	58^{+39}_{-37}
2417	3_2^-	$f_{\frac{7}{2}}$	0.0264(4)	85^{+110}_{-66}
2570	5_2^-	$h_{\frac{11}{2}}$	0.468(6)	<46
2591	4_1^-	$f_{\frac{7}{2}}$	0.0126(2)	<50
2818	6_1^-	$h_{\frac{11}{2}}$	6.07(7)	

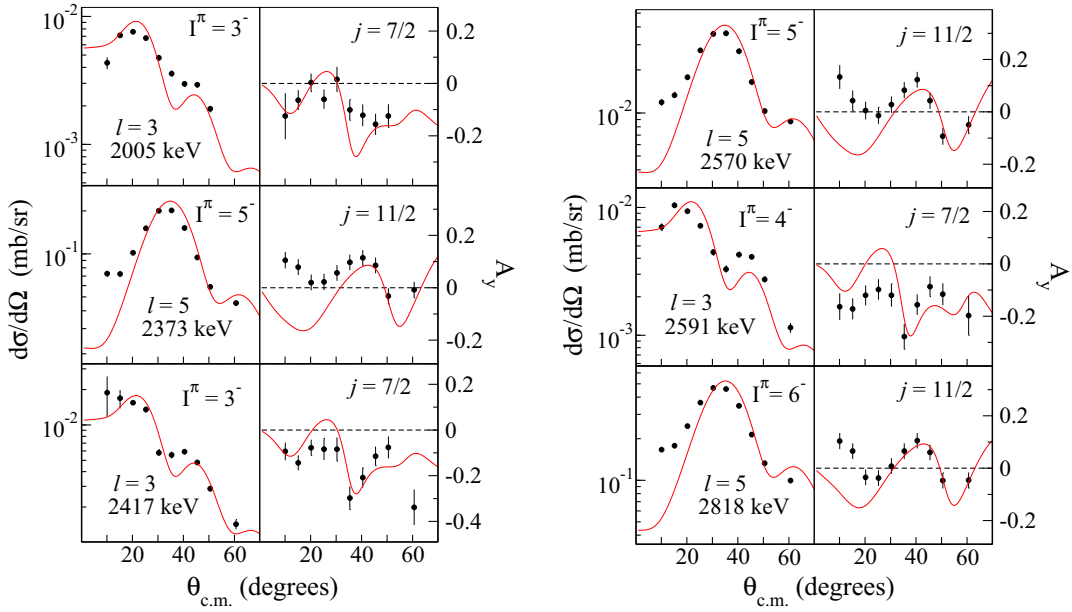

FIG. 3. (Color online) Angular distributions of differential cross sections and analyzing powers for the negative-parity states in ^{112}Cd up to ≈2.9 MeV of excitation energy. The red curves are the corresponding ADWA calculations for the dominant ℓ and j of the transfer.

their DWBA analysis did not involve contributions above $\ell = 4$, so the spin-parity was not identified and a spectroscopic strength was not extracted.

C. 2417-keV level

This level was first identified as the 3^-_2 state in ^{112}Cd by Drissi *et al.* [16] and was assigned to the QOC quintuplet on the basis of its observed transition to the 3^-_1 level. Further evidence for this assignment was provided by Garrett *et al.* [17] from the measurement of its enhanced $B(E2; 3^-_2 \rightarrow 3^-_1)$ value. In the current work this level was weakly populated via $2f_{\frac{7}{2}}$, with spectroscopic strength of ≈0.03.

D. 2570-keV level

Initially, excitation energy predictions favored this level over the 2373-keV 5^-_1 state as a candidate of the quadrupole-octupole quintuplet. However, the transition strength measurements by Drissi *et al.* [16] and by Garrett *et al.* [17] strongly favored the 5^-_1 level as the QOC member. In the present work, the 2570-keV level was observed to be populated with $1h_{\frac{11}{2}}$ transfer with a spectroscopic strength of ≈0.5.

E. 2591-keV level

Since the 2591-keV level is the only 4^- state below 3 MeV, it was the only 4^- candidate for the QOC quintuplet. A γ-ray branch to the 3^-_1 level was observed [16], but the lack of a measured lifetime (a lower limit of >1000 fs was established in Ref. [17]) yielded an upper limit of <50 W.u. In the current work, the transfer to this level is dominated by a $2f_{\frac{7}{2}}$ contribution with a spectroscopic strength of ∼0.02.

F. 2818-keV level

Previous studies [5,16] have demonstrated the existence of a $I^\pi = 6^-$ level at 2818 keV. In the present work, a level dominated by a $1h_{\frac{11}{2}}$ transfer was observed at this energy with the largest spectroscopic strength in the spectrum, with a value twice that of the ground-state transfer. This level is assigned as the 6^- member of the $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ configuration. The $I^\pi = 4^+$ level observed by Garrett *et al.* [21] at 2816 keV was not observed, but would have been difficult to identify if it was weakly populated in the (d,p) reaction because of the strength of the transfer into the 6^- level.

IV. DISCUSSION

With the present data in hand, the nature of the states previously assigned to the QOC quintuplet [16,17] can be reassessed. The QOC assignments by Garrett *et al.* [17] were believed to be firm based on the observed enhanced $B(E2)$ values, and indeed this fact remains; all states assigned to the quintuplet have either observed enhanced $B(E2)$ values, or upper limits which are still consistent with the QOC assignment. In the present study, aside from the 5^-_1 level all other members of the QOC quintuplet are weakly populated, and thus there is no evidence *against* a QOC assignment.

The result from the $(n,n'\gamma)$ experiment [17] of an enhanced $B(E2; 5^-_1 \rightarrow 3^-_1)$ value of 58^{+39}_{-37} W.u. would appear, on face value, to provide strong evidence of the 5^-_1 QOC character. This QOC assignment implies that the 5^-_1 level has a four quasiparticle character, and thus should not be populated in a single-neutron transfer reaction. The present results, however, indicate that the 5^-_1 level is dominated by $1h_{\frac{11}{2}}$ transfer with a spectroscopic strength of $S \simeq 2.7$ – the second largest observed in the spectrum. This strong population is inconsistent with the multiphonon assignment, and indicates

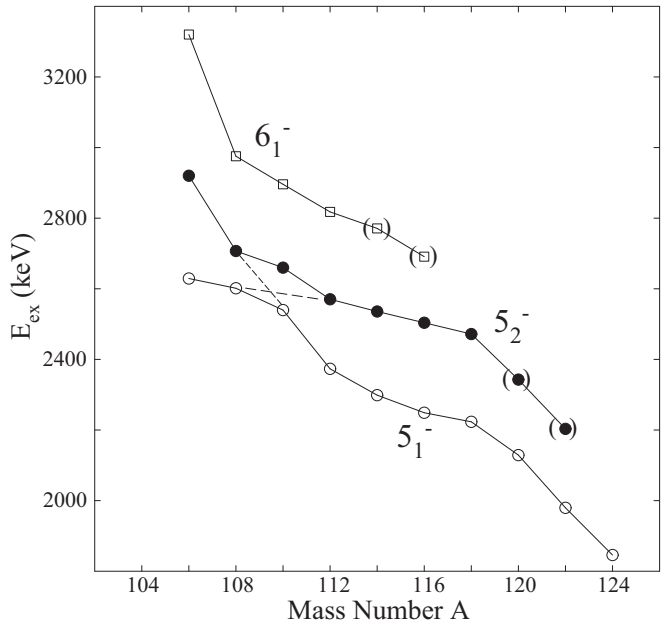

FIG. 4. Energy systematics of the 5_1^-, 5_2^- levels (left), and 6_1^- levels (right) in the Cd isotopes. The nature of the 5_1^- and 5_2^- levels is suggested to cross at ^{110}Cd.

that the 5_1^- wave function must, in fact, be dominated by an $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ two-quasineutron configuration.

Since there are two 5^- states in the region expected for the QOC states, it is natural to ask if the 5_2^- level could be the QOC member, and that mixing with the 5_1^- level is responsible for the latter's enhanced $B(E2)$ value, and the former's transfer strength of $S \simeq 0.5$. Indeed, the systematics of these 5^- states, and the 6_1^- level as shown in Fig. 4, strongly suggests that the 5^- states do mix and that a crossing occurs in the vicinity of ^{110}Cd. Using a simple two-level mixing prescription with one state being a pure QOC state and the other being a pure two-quasineutron state, and further ascribing the $E2$ matrix element to be due solely to the QOC wave function component, and the transfer strength as due solely to the $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ two-quasineutron configuration, leads to the condition that

$$\frac{S(5_1^-)}{S(5_2^-)} = \frac{B(E2; 5_2^- \to 3_1^-)}{B(E2; 5_1^- \to 3_1^-)}$$

for mixing to be responsible for the observed transfer strength and $B(E2)$ value simultaneously. Clearly

$$\frac{S(5_1^-)}{S(5_2^-)} \simeq \frac{2.7}{0.5} \neq \frac{B(E2; 5_2^- \to 3_1^-)}{B(E2; 5_1^- \to 3_1^-)} = \frac{<46}{58^{+39}_{-37}}.$$

Having ruled out a mixing scenario that involves a QOC state and a two-quasiparticle state, a satisfactory explanation of both the enhanced $B(E2)$ value and large transfer strength for the 5_1^- level must be sought. The solution, in fact, has already been suggested by Délèze *et al.* [5] where the 5_1^- level was assigned as a rotational band member of the 3^- octupole band. As suggested in Ref. [10], the nonintruder states of the midshell Cd isotopes may reflect a γ-soft deformed rotor rather than spherical vibrator, a suggestion in line with the existence of a rotational band based on the 3_1^- level. The 2570-keV state was assigned by Délèze *et al.* [5] as the head of a 5^- band, with the 2416-keV 3^-, 2591-keV 4^-, and 2818-keV 6^- loosely associated with a third negative-parity band structure. The study of ^{110}Cd by Juutinen *et al.* [32] suggested that the octupole band evolved from a collective character towards an $h_{\frac{11}{2}} \otimes d_{\frac{5}{2}}$ two-quasineutron structure with increasing spin. While the microscopic components of the high-spin members of the 3^- band are not probed in the present study, the 5^- band member is dominated by the $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ configuration.

In the inelastic-scattering reactions performed by Pignanelli *et al.* [33], the $I^\pi = 5^-$ 2373-keV level was strongly populated and its angular distribution was fitted assuming a direct $E5$ excitation with $\beta_5 = 0.05$ and a two-step process with β_2 and β_3 given by the excitation to the 2_1^+ and 3_1^- states. This is consistent with the present results; the assignment of the $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ configuration has $\Delta l = 5$ and a coherent superposition of such orbitals can build $E5$ collectivity. Furthermore, the inelastic scattering reactions performed would be incapable of distinguishing a two-phonon vibrational state from a rotational excitation based on an octupole excitation.

The results of the present study reinforce the need for comprehensive spectroscopy in making assignments. Despite the measurements of the enhanced $B(E2)$ value [17], and the attractiveness of the QOC picture, the assignment of the 5^- at 2373-keV as a member of the QOC quintuplet is clearly wrong. At the time of the assignment [16,17] of the QOC states in ^{112}Cd, there were no conflicting data. The continued investigation of the Cd isotopes, initiated to address the question of how high in excitation energy the existence of multiphonon vibrational states persists, has resulted in the demise of the multiphonon picture [9] and the reinterpretation of the structure of the positive-parity nonintruder states [10]. The present study has shown the incorrectness of the assignment of the 2373-keV 5^- level as a member of the QOC quintuplet, and naturally raises the question of the validity of the QOC picture in ^{112}Cd. Thus, vibrational states for both homogeneous and heterogeneous multiphonon excitations are challenged, and in the larger context, demonstrates the dangers of relying too strictly on simple structural indicators.

V. SUMMARY

Low-lying negative-parity states in ^{112}Cd have been investigated using the ^{111}Cd$(\vec{d}, p)$ reaction with 22 MeV deuteron beams. The reaction products were analyzed with a Q3D magnetic spectrograph that achieved $\approx$ 6–7-keV resolution, and both angular distributions of the cross sections and analyzing powers were extracted. States with $I^\pi = 5^-$ and 6^- at 2373-keV and 2818-keV, respectively, possessed the largest spectroscopic strengths of any peaks in the spectrum, and were assigned as having the $3s_{\frac{1}{2}} \otimes 1h_{\frac{11}{2}}$ configuration as the dominating part of the wave function. These results convincingly demonstrate that the 5^- state is not a member of the quadrupole-octupole two-phonon quintuplet. Consideration of the present results with the available $B(E2)$ data suggest that the 5^- level is a rotational-band member based on the 3^- octupole state.

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