PHYSICAL REVIEW C VOLUME 51, NUMBER 1 JANUARY 1995

# Study of low-spin states in $^{122}$Cd

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(Received 2 August 1994)

The structure of $^{122}$Cd was studied through the decay of $^{122}$Ag by $\gamma$-$\gamma$ concidences, $\gamma$-ray angular correlations, and $\beta$-$\gamma$-$\gamma$ fast electronic scintillation timing (FEST) measurements. The phonon and intruder structure of the $0^+$ states is discussed. The energy systematics of the low-lying levels in the Cd isotopes exhibits two distinct patterns, one minimizing at midshell, one somewhat later.

PACS number(s): 21.10.−k, 23.20.Js, 21.60.−n, 27.60.+j

## I. INTRODUCTION

The cadmium nuclei, with proton number near the magic number 50, present interesting aspects of nuclear structure, namely, the coexistence and mixing of vibrational with intruder rotational degrees of freedom which arise from the promotion of a proton pair across the $Z = 50$ shell gap [1], as well as evidence for intact multiphonon excitations, possibly including up to four-phonon states [2]. Despite numerous studies (see, e.g., Refs. [2–4]), the interplay of phonon and intruder degrees of freedom is still not completely understood and important ambiguities are unresolved. The excitation energy of the intruder configuration depends on the size of the shell gap in comparison to the strength of the integrated residual neutron-proton interaction, and it depends directly on the number of active neutrons. The Cd isotopes offer an opportunity to study a nearly complete systematic picture of the evolution of an intruder configuration across a neutron shell. Moreover, because of the expected parabolic intruder systematics across the shell, establishment of intruder configurations far from midshell can also shed light on those in the midshell region.

## II. MEASUREMENTS AND RESULTS

The present work is part of the systematic study [5–7] of the neutron-rich Cd isotopes from the decay of Ag nuclei produced at the fission product mass separator TRISTAN [8] at the High Flux Beam Reactor, Brookhaven National Laboratory. The measurements included $\gamma$-ray singles, $\gamma$-$\gamma$ coincidence, $\gamma$-$\gamma$ angular correlation, and $\beta$-$\gamma$-$\gamma$ coincidence spectroscopy. The $\gamma$-ray spectra of $^{122}$Ag decay were measured by collecting the $A = 122$ beam from TRISTAN on a movable aluminized-Mylar tape while simultaneously counting for 3 s. Subsequently the tape was moved to minimize $\gamma$ activity from other isobars. This procedure was repeated over the length of each run. Neutron-rich even-$A$ Ag nuclei typically exhibit isomerism which leads to population of a wide range of spins in the daughter nucleus. This seems to be the case of $^{122}$Ag in which two beta decaying states are known, with $T_{1/2}$ of 1.5 s and 0.48 s, respectively, although definitive spin assignments have not been made. Our experiments do not discriminate between these two beta decays.

We performed $\gamma$-$\gamma$ coincidence experiments using four Ge $\gamma$-ray detectors and all the pairwise combinations of these to determine the coincident relationships among $^{122}$Cd $\gamma$ rays and to establish new excited levels in $^{122}$Cd, in addition to the six previously known excited states [9,10]. The resulting level scheme, which includes only levels established by the coincidence data, is shown in Fig. 1. The relative $\gamma$-ray intensities obtained from the singles spectra are also given.

We also carried out $\gamma$-$\gamma$ angular correlation measurements. The experiment was performed with four Ge detectors positioned to provide six different pair correlation angles. The only cascades which show significant anisotropy are $1704 \rightarrow 569 \rightarrow 0$ keV and $1992 \rightarrow 569 \rightarrow 0$ keV where the data are consistent with a $0^+ \rightarrow 2^+ \rightarrow 0^+$ spin sequence in both cases, as shown in Fig. 2. Consequently, we assigned spin $0^+$ to these levels at $E = 1704.5$ and 1991.9 keV.

A lifetime measurement was also performed using the fast electronic scintillation timing (FEST) technique that was developed at TRISTAN [11]. This approach employs a $\beta$-$\gamma$-$\gamma$ triple coincidence. The timing information is obtained from $\beta$-$\gamma$ coincidences between a thin NE111A plastic and a small $BaF_2$ scintillator. The additional $\gamma$ coincidence obtained with a Ge detector is used to select the decay branch of interest. The lifetime is extracted from a centroid-shift analysis of the $\beta$-$\gamma$ time-to-amplitude converter (TAC) peak. The lifetime of the 569.5-keV level was determined from the *difference* between the centroid shift gated by the deexciting $\gamma$ ray of 569.5 keV and the centroid shift gated by the feeding $\gamma$ transition of 759.7 keV (Fig. 3). This difference procedure obviates the need to know the details of the $\beta$ feeding or the lifetimes of intermediate states. The $BaF_2$ gates were set on the peaks themselves and on the Compton continuum. The shape of the two curves is sim-

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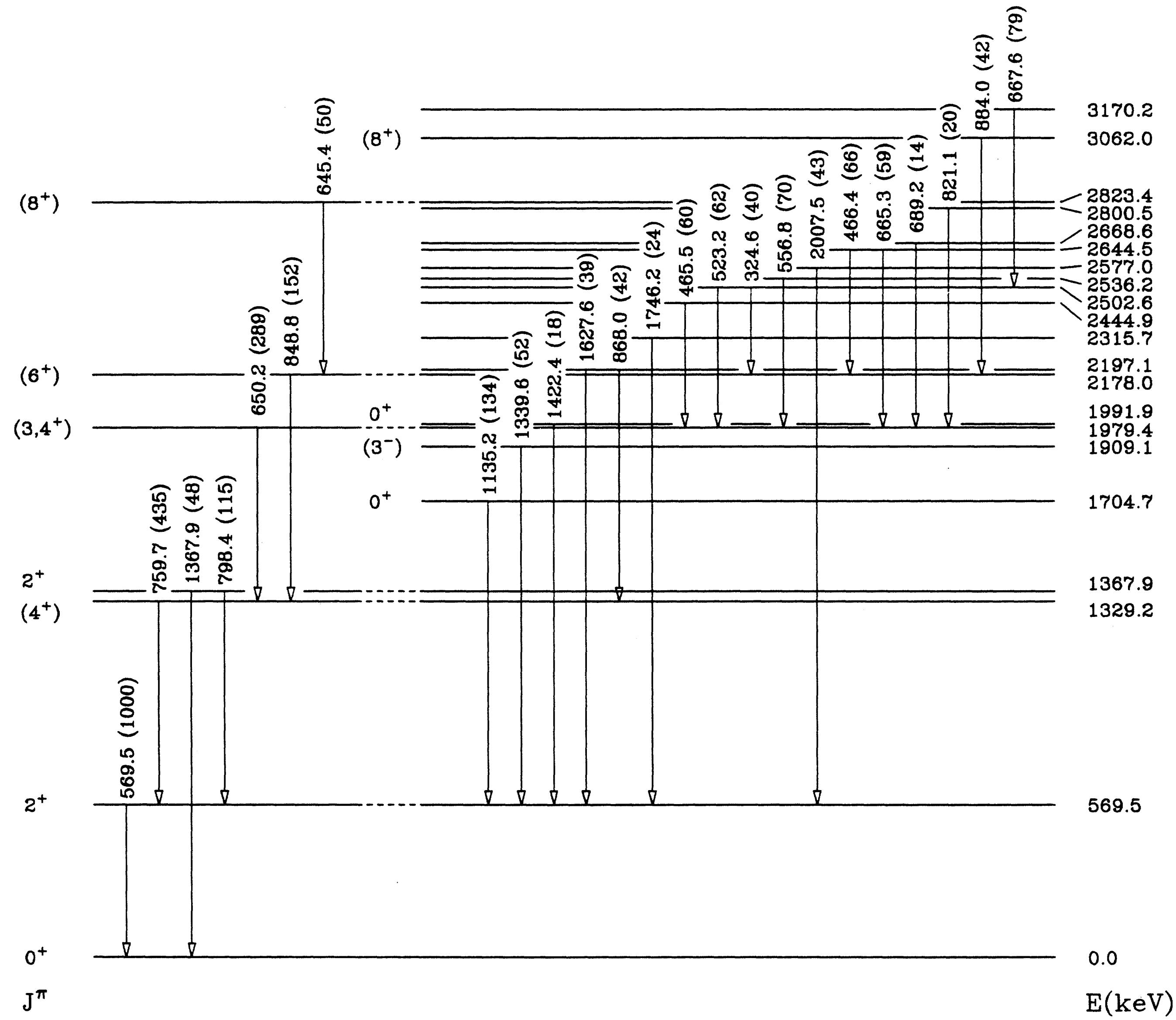


FIG. 1. The level scheme for $^{122}$Cd. The left side is from Refs. [9,10] and the right side are new levels from the present work. All relative $\gamma$-ray intensities, shown in parentheses, are from our direct singles spectra (uncertainties $\sim$ 3%).

ilar due to the similar energy of the observed transitions. The corrections related to the background subtraction for $BaF_2$ gates are negligible because the $BaF_2$ spectra, gated by Cd transitions in the Ge detector, do not contain other $\gamma$ peaks with significant intensities. The lifetime obtained for the 569.5-keV level is $\tau = 15 \pm 7$ ps giving a transition probability $B(E2; 2_1^+ \rightarrow 0_1^+) = 0.091 \pm 0.042$ $e^2\,b^2 = 26 \pm 12$ W.u.

## III. DISCUSSION

We now discuss the properties of $^{122}$Cd in the context of the other Cd isotopes.

Figure 4(a) shows the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for the Cd isotopes against neutron number for $N \geq 58$. The present lifetime measurement for $^{122}$Cd is consistent with the evidence for a decreasing trend in these $B(E2)$ values past $N = 70$ and for the existence of a maximum extending along a plateau from midshell to $N = 70$ on the neutron-rich side. We will see below other evidence that collectivity in Cd maximizes past midshell. It has been shown in Refs. [13,14] that an analytic expression for the $B(E2)$ value in the symmetry limits of the interacting boson approximation (IBA) model can be used to extract proton and neutron boson effective charges. Specifically, for U(5), we have [13]

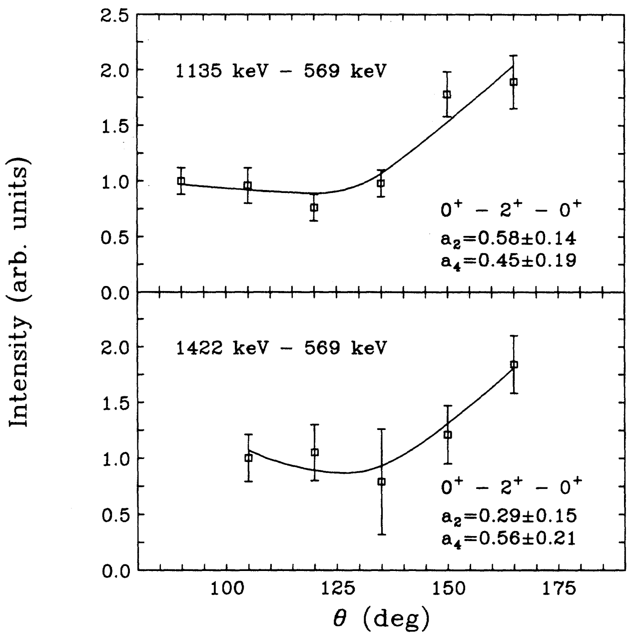


FIG. 2. The angular correlation data, corrected for finite solid angle, for the 1705 $\rightarrow$ 569 $\rightarrow$ 0 keV and 1992 $\rightarrow$ 569 $\rightarrow$ 0 keV cascades. The solid line represents an angular correlation of a $0^+ \rightarrow 2^+ \rightarrow 0^+$ spin sequence. The fitted $a_2$ and $a_4$ parameters are given.

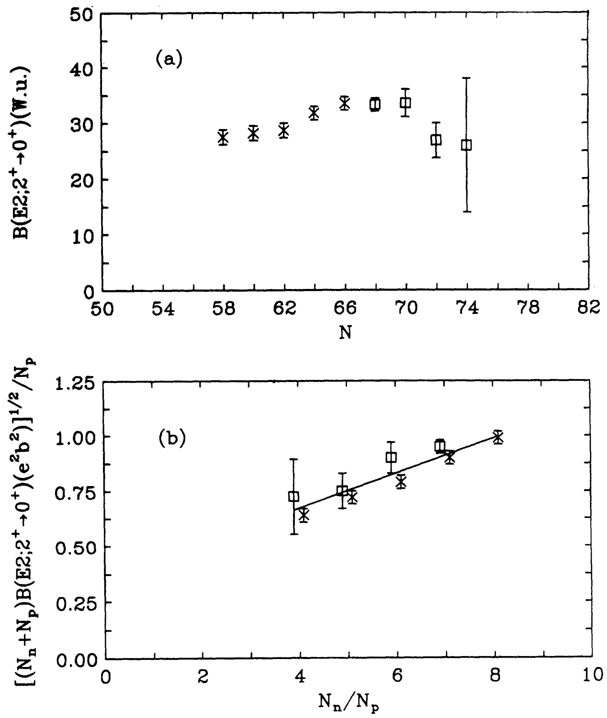


FIG. 4. The $B(E2;2_1^+ \rightarrow 0_1^+)$ values for Cd isotopes plotted against (a) neutron number $N$ and (b) $N_n/N_p$. The straight continuous line in (b) is a bilinear fit of the form of Eq. (2). The values for the second half of the neutron shell are represented by open squares. The data are from Refs. [7,12] and the present work.

$$M(E2;2_1^+ \rightarrow 0_1^+) \equiv \sqrt{B(E2;2_1^+ \rightarrow 0_1^+)} = \frac{1}{\sqrt{N_p + N_n}}(e_p N_p + e_n N_n), \quad (1)$$

where $N_p$ and $N_n$ are the numbers of proton and neutron bosons, respectively, and $e_p$ and $e_n$ are the corresponding boson effective charges.

Following the analysis in Ref. [14] we rewrite this as

$$\frac{\sqrt{N_p + N_n}}{N_p} M(E2;2_1^+ \rightarrow 0_1^+) = e_p + e_n \frac{N_n}{N_p}. \quad (2)$$

In Fig. 4(b) is shown the left-hand side of Eq. (2) against $N_n/N_p$. The $e_n$ and $e_p$ values are obtained as the slope and intercept, respectively. From the measured $B(E2)$ values for all the Cd isotopes we obtain $e_p = 0.35 \pm 0.06$ $e$b and $e_n = 0.08 \pm 0.01$ $e$b. In principle, values of $e_p$ and $e_n$ extracted from such an analysis depend on the structure assumed for the nuclei studied: in our case, Eqs. (1) and (2) assume a U(5) structure. However, in practice rather similar $e_p$ and $e_n$ values often result from the use of formulas corresponding to the other structures. This is the case here. Values of $e_p$ and $e_n$ have also been extracted from inelastic scattering experiments on $^{106-116}$Cd by De Leo *et al.* [15]. They obtained $e_n = 0.11$ $e$b with $e_p$ ranging from 0.13 to 0.17 $e$b. While their $e_n$ is similar to our value, $e_p$ seems quite different. However, the range of isotopes used to extract $e_p$ differs. If we redo our analysis with Eq. (2) for the same isotopes as were considered by De Leo *et al.*, we obtain $e_p = 0.26 \pm 0.05$ $e$b, which is closer to the value from Ref. [15]. This can, in fact, be seen in Fig. 4(b) if one connects only the points for each individual set of symbols. The slopes are similar but the intercepts differ. This highlights the point that application of Eq. (2) and similar expressions

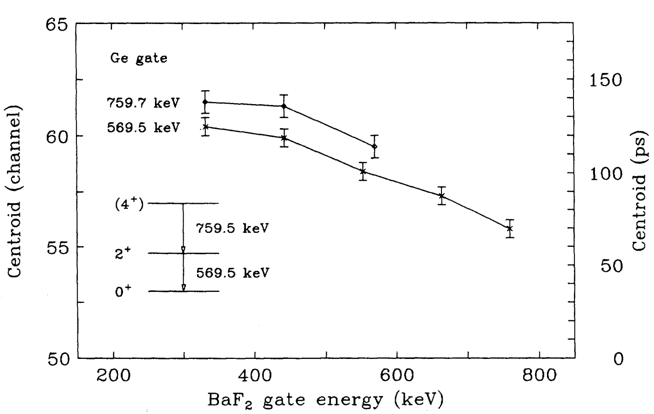


FIG. 3. The centroid positions of the $\beta$-$\gamma$ TAC peaks for different gates on the Ge detector as a function of the $BaF_2$ $\gamma$ energy gates.

for other structural regions is probably best limited to half shells only.

It was recently suggested [16] that the low-energy structure of nearly all collective nonrotational nuclei $[R_{4/2} \equiv E(4_1^+)/E(2_1^+)$=2.05–3.15] from $Z$=38–82 can be interpreted in terms of a nearly universal anharmonic vibrator (AHV) description. In such a description the yrast levels are $n$-phonon states satisfying

$$E(J^+ = 2n) = nE(2_1^+) + \frac{n(n-1)}{2}\epsilon_4, \qquad (3)$$

where $\epsilon_4$ is the anharmonicity. Remarkably, all these nuclei lie along a compact trajectory that can be described with a *single* value of $\epsilon_4$ of $\sim$ 156 keV. Since Cd nuclei are archetypical vibrator nuclei it is interesting to apply this analysis to $^{122}$Cd. The $4_1^+$ level of $^{122}$Cd gives $\epsilon_4$=190 keV, which is close to the global value. This $\epsilon_4$ leads to a predicted $6_1^+$ energy of 2279 keV, in quite reasonable agreement with the suggested $(6^+)$ level at 2178 keV. Alternatively, we can use Eq. (3) to extract $\epsilon_4$ directly from $E(6_1^+)$, obtaining 158 keV. These anharmonicities $\epsilon_4(4_1^+)$ and $\epsilon_4(6_1^+)$ derived from $E(4_1^+)$ and $E(6_1^+)$, respectively, are consistent with the data for other Cd isotopes, suggesting that the 2178-keV level is a reasonable choice for the $6_1^+$ state, as was also suggested by Durell [10]. In Ref. [10] an $8^+$ level was assigned at 2823 keV. Arguments similar to those just above would seem to favor the 3062-keV level as the $8^+$ state of the ground band. Both $8^+$ levels are shown in Fig. 1 even though their spin and parity assignments are speculative.

In addition, we suggest a possible $3^-$ level at 1909 keV based on the 1340-keV line seen in the 569-keV coincidence gate and also on extension of the smooth energy systematics of the $3^-$ states as shown in Fig. 5.

It is interesting to use these energy systematics further, along with the decay properties of the low-lying levels, to investigate the multiphonon characteristics of $^{122}$Cd levels.

In $^{112,114}$Cd the $0_2^+$ level has $B(E2;0_2^+ \to 2_1^+)$ values of 51 and 41 W.u., respectively, while the $B(E2;0_3^+ \to 2_1^+)$ values are $\sim 10^{-2}$ W.u. [3]. In $^{116}$Cd these values interchange: $B(E2;0_3^+ \to 2_1^+)$=31 W.u. and $B(E2;0_2^+ \to 2_1^+)$=0.95 W.u. This points to an interchange of character for these two $0^+$ levels between $^{114}$Cd and $^{116}$Cd as suggested in Ref. [3]. In this view the $0_2^+$ level in $^{112,114}$Cd and the $0_3^+$ level in $^{116}$Cd are the two-phonon states. In $^{114}$Cd the $B(E2;0_3^+ \to 2_2^+)$=136 W.u. which, at face value, seems to suggest a three-phonon character. However, Délèze *et al.* [4] have also been able to reproduce this large strength (within a factor of 2) in an intruder picture as a result of suitable mixing and cancellation effects [2].

Beyond $^{116}$Cd, the situation is much less clear. The $B(E2;0_2^+ \to 2_1^+)$ values are either small or known as lower limits only. Hence, while some of these transition rates *could* be consistent with collective phonon transitions of $\sim$ 30 W.u., there is no positive evidence of this. There is also no direct suggestion of a three-phonon $0^+$ state in $^{122}$Cd, such as provided by the strong (136 W.u.) $B(E2;0_3^+ \to 2_2^+)$ value noted above for $^{114}$Cd. For exam-

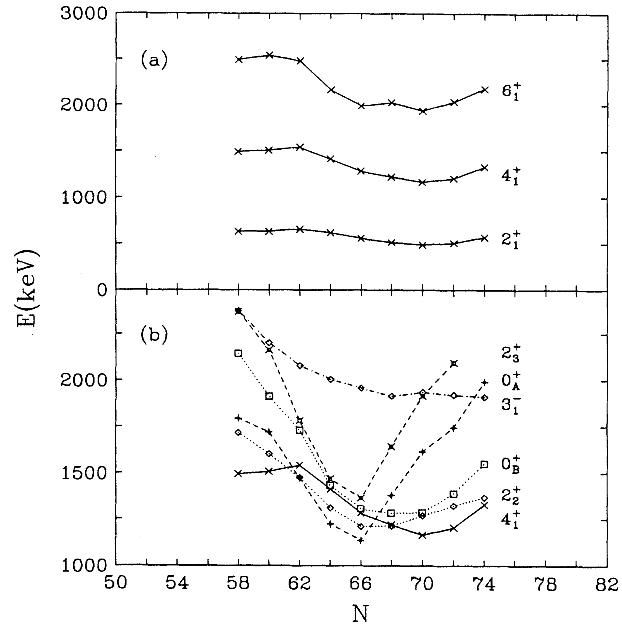


FIG. 5. Energy systematics for the Cd isotopes. The $0_{2,3}^+$ levels are connected with an interchange between $^{114,116}$Cd, as discussed in the text. The data are from Refs. [3,4,10,18] and the present work.

ple, in $^{122}$Cd, the levels at 1704.5 keV and 1991.9 keV, assigned as $0^+$ states (Fig. 1), are observed to decay only to the one-phonon $2_1^+$ state. The upper limits for the branching ratios $B(E2;0_2^+ \to 2_2^+)/B(E2;0_2^+ \to 2_1^+)$ and $B(E2;0_3^+ \to 2_2^+)/B(E2;0_3^+ \to 2_1^+)$ are $< 2$ and $< 4$, respectively. Neither of these limits is consistent with the large values expected if one of these $0^+$ levels were a three-phonon state.

Finally, the energy systematics shows an interesting dichotomy. We discussed above an interchange of $0^+$-state character in the $0_{2,3}^+$ states in $^{116}$Cd relative to the lighter isotopes. If we suppose that this interchange persists beyond $^{116}$Cd we get the smooth energy systematics shown in Fig. 5(b), where we follow Ref. [3] in labeling the $0^+$ states by $A$ and $B$. The $0_A^+$ and $2_3^+$ levels minimize at midshell and show a steep and symmetric rise around this minimum. This behavior about midshell is reminiscent of that predicted [17] for intruder states. In contrast, the yrast levels [see Fig. 5(a)], the $2_2^+$, $0_B^+$, and the $3_1^-$ states, show a more gradual drop in energy up to $^{114}$Cd, flattening out at and beyond midshell. Interestingly, the apparent implication of this that the maximum in collectivity occurs near $N$ = 70 is supported by the $B(E2;2_1^+ \to 0_1^+)$ values [Fig. 4(a)] which rise to a flat maximum for $N$ = 66–70. The present FEST result for $^{122}$Cd is consistent with the decreasing trend in this $B(E2)$ value for $^{120}$Cd although the uncertainty is large. The microscopic origin of this behavior is not understood. It could be related to an enhanced $p$-$n$ interaction in the neutron-rich Cd nuclei where lower-$j$ neutron orbits are filling. It could alternatively be related to a possible neutron subshell closure at $N \sim 58$. If this neutron number is taken to define the beginning of the larger shell ($N = 58$–82), the midshell point would be at $N \sim 70$ as suggested by the data.

One additional point concerning the yrast level energies in Cd is interesting. Taken globally, they vary very little despite the presence of both valence protons and neutrons. This behavior is similar to that of Hg, another two-proton hole nucleus, which is well known for its essentially constant $2_1^+$ energies. In contrast, elements such as Te and Po, which are two-proton particle nuclei, exhibit a more structured systematics. This dissimilarity warrants further comparison of the properties of other nuclei with a few proton holes or particles.

## IV. CONCLUSION

In conclusion, we have extended the systematics of the Cd nuclei to the very neutron-rich nucleus $^{122}$Cd. The lifetime of the $2_1^+$ level has been measured with FEST giving a $B(E2; 2_1^+ \to 0_1^+) = 26 \pm 12$ W.u. The $0_2^+$ and $0_3^+$ levels have been identified for the first time, and candidates for the $3_1^-$ and $8^+$ levels have been proposed. The issue of intruders versus multiphonon nature, at least for the $0^+$ states, remains vexing and unresolved for the Cd isotopes including $^{122}$Cd, where the fact that both the $0_2^+$ and $0_3^+$ states decay to the $2_1^+$ level suggests that both $0^+$ states may have substantial two-phonon character. The energy level systematics exhibits two distinct patterns, one for the $0_A^+$ and $2_3^+$ levels, whose parabolic behavior about midshell suggests an intruder character, and another set of levels, including the yrast states, which shows a more gradual phenomenology and suggests a maximum in collectivity past midshell.

## ACKNOWLEDGMENTS

We would like to take this opportunity to thank the entire TRISTAN operating staff over the years for their excellent and dedicated service. In particular, we are grateful to F. Paffrath, V. Manzella, D. McDonald, R. Savino, W. Hayes, and R. Wall. This work was supported by Contracts No. DE-AC02-76CH00016 and No. DE-FG02-88ER40417 with the U.S. DOE.

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