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Low-lying Collective States in ^{120}Cd populated by β-decay of ^{120}Ag: Breakdown of the Anharmonic Vibrator Model at the Three-Phonon Level

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We have reinvestigated the beta decay of ^{120}Ag to levels in ^{120}Cd. Significant deviations in the decays of low-lying states from that expected from a U(5) nucleus have been observed. The results from this paper which include the 0_2^+ and 3_1^+ states (which have now been correctly identified), and previous work on lighter Cd isotopes strongly suggest that the anharmonic vibrator description of the even-even Cd isotopes is inadequate. Analysis of the decay patterns and half-life information led to the determination that there are three beta-decaying isomers in ^{120}Ag, with J$^\pi$ assignments of (0^-, 1^-), $4(^+)$, and $7(^-)$. In addition, we have identified four candidates of the quadrupole-octupole quintuplet. These states are J$^\pi$ = (5^-) at 2489.5 keV, (4^-) at 2208.4 keV, (2^-) or (3^-) at 2318.4 keV, and (1^-) or (2^-) at 2448.7 keV. All show strong transitions to the previously known 3^- octupole state at 1898.9 keV. The overall level scheme of ^{120}Cd has been significantly expanded.

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I. INTRODUCTION

Up until recently, the neutron-rich even-even Cd isotopes $^{110-114}$Cd are often cited as textbook examples [1, 2] of vibrational nuclei and the best examples of U(5) symmetry. Nuclei that are close to the limits of U(5) symmetry are expected to exhibit harmonically spaced multi-phonon states with vanishing static quadrupole moments; this includes a $0^+(N = 0)$ ground state, a $2^+(N = 1)$ one-phonon state at $E(N = 1)$, and a $0^+, 2^+, 4^+(N = 2)$ two-phonon multiplet at $E(N = 2) = 2 * E(N = 1)$. These N-phonon states should decay preferentially by one phonon (see Fig.3 of Ref. [3]). This simple picture is complicated in the cadmium isotopes, in part, by non-zero quadrupole moments and low-lying intruder states (caused by the elevation of two protons across the $Z = 50$ shell gap). The intruder states in ^{110,112}Cd have been shown to be strongly populated in the (^{3}He,n) reaction [4]. Therefore, these intruder states must be accounted for in any detailed vibration-like calculation, which is possible within the IBM-2 framework [5, 6].

Discrepancies in the decays of the two-phonon states from that expected by vibrator-like models have often been attributed to mixing with the intruder states, which are at similar energies near neutron mid-shell (i.e., ^{114}Cd). It is well established that as one moves away from the neutron mid-shell the energy of the intruder states rise in energy, forming a parabolic shape. Therefore, any potential mixing with the two-phonon levels should be reduced away from midshell. However, the intruder levels approach the three-phonon levels away from midshell near ^{120}Cd. A systematic study of these nuclei is therefore needed to fully understand what is happening in the neutron-rich Cd nuclei. With this as our motivation, we have remeasured the low-energy states in ^{120}Cd via the beta decay of ^{120}Ag. Details of the decay, candidate intruders, and branching ratios for the two- and three-phonon levels are presented.

Previous studies have observed candidates for the three-phonon states in ^{110}Cd [8] ^{112}Cd [9], ^{114}Cd [10], ^{116}Cd [11] and ^{118}Cd [12]. However, this simple picture was shown to be at odds with the experimental data for the cases of ^{110,112,114}Cd by Garrett *et al.* [6, 13] who demonstrated that the previously proposed 0^+ and 2^+ candidates for the three-phonon quintuplet are not in agreement with IBM-2 calculations. In the case of ^{116}Cd, the situation is even less clear. Kadi *et al* [7] showed that there are major disagreements with IBM-2 calculations for the decay of the lowest 0^+ states (two-phonon and intruder state). At the three-phonon level, the previously assigned 2^+ and 0^+ states described as three-phonon states do not decay as would be expected from a multi-phonon state. The 1951.4-keV (2^+) level decays primarily to the two-phonon 0^+ state, while decays to the two-phonon 2^+ (1213.1 keV) and 4^+ states (1219.5 keV) were not observed in the data [14]. The only decay observed from the (0^+) member is an E2 transition to the one-phonon 513.5-keV (2^+) state. As such, the assignment of these two levels as three-phonon states is inconsistent with the data (see figures 22 and 23 from Ref [14]).

The disagreements with calculations are unlikely due to experiments simply missing the transitions, as the nuclei ^{110,112,114,116}Cd have all been studied by a variety of methods with very high statistics. This discrepancy in the decay of the suggested three phonon 0^+ and 2^+

states with the U(5) description is a consistent feature in all the well-studied even-even neutron-rich Cd nuclei. Figure 1 shows the decays of the 0^+ and 2^+ members of the reported three-phonon quintuplet for ^{112}Cd [9], ^{114}Cd [10], ^{116}Cd [14], and ^{118}Cd [15]. None of these nuclei decay as expected in the IBM-2 framework. For instance, note that the three-phonon 2^+ candidates do not show strong preference for decay to the two-phonon members. An alternate explanation for the levels in the Cd isotopes proposed by Garrett and Wood [3] is that they arise from quasi-rotational bands built on a series of 0^+ states independent of the N-phonon levels.

The beta decay of ^{120}Ag was first reported by Fogelberg *et al*, [16]. In this work, six γ-rays from five levels in ^{120}Cd were measured from the decay of two isomers of ^{120}Ag. The measured ground state and isomer half-lives were 1.17(5) s and 0.32(4) s and assigned J^π values of 3^+ and 6^- respectively. Two unpublished studies were later done [17, 18] that greatly increased the number of states in ^{120}Cd to 15 and 19 and γ-transitions to 18 and 49 respectively.

Most recently Wang *et al*, [15] increased this to 62 γ-rays depopulating 26 levels fed by the two previously reported isomers. Four of these levels 1899.0 keV (3^+), 1920.5 keV (2^+), 1997.9 keV (4^+), and 2032.8 keV (6^+), were assigned as three-phonon states in this work. Of these levels, the 6^+ and 4^+ decay as expected for a multiphonon state, but the 2^+ and 3^+ states do not. No candidates for a three-phonon 0^+ state were reported in that work.

In Ref. [15], two 0^+ levels in ^{120}Cd at 1388.6 and 1744.5 keV are reported to be directly fed by the beta decay of a 3^+ isomer of ^{120}Ag with log *ft*'s of 7.2 and 7.4 respectively. These decays, however, would be second forbidden unique beta decays, and as such would be expected to have a much larger log ft value. (An example of this type of decay is ^{22}Na (3^+) $\rightarrow$ ^{22}Ne (0^+) with a log *ft* of 14.91^{2u} [19]). The explanation for this discrepancy must be that these levels are not fed directly but instead are fed from higher energy states in ^{120}Cd or there is a third undiscovered isomer present in ^{120}Ag, perhaps similar to the structure of ^{116}Ag [20].

II. EXPERIMENTAL METHOD

Silver-120 was produced via the proton-induced fission of ^{238}U at the Holifield Radioactive Ion Beam Facility (HRIBF). Forty MeV protons with an intensity of 25nA were used to bombard a $^{238}UC_x$ target [21] installed at the On-Line Test Facility (OLTF). The proton induced fission products were then mass-separated by the OLTF and deposited on a moving tape collector (MTC). The collected samples were subsequently moved to the counting position located at the center of the CARDS array (Clover Array for Radioactive Decay Spectroscopy), which consisted of three segmented-clover Ge detectors, and a Si conversion-electron spectrometer [22]. The clover detectors were mounted in a close geometry surrounding the tape forming three sides of a square ≈10 cm per side. The conversion-electron spectrometer BESCA (Bellows Electron Spectrometer for the CARDS Array) consists of a 5-mm thick 500-mm^2 liquid nitrogen cooled SiLi detector. The BESCA detector was placed ≈2 cm from the moving tape. Mechanical problems resulted in the BESCA detector only being used in the first 1/3 portion of the "tape move take-away" mode of the experiment (see below).

To calibrate the efficiency of the Ge detectors, standard sources of ^{241}Am, ^{133}Ba, and ^{152}Eu were used. In this work, the BESCA detector had an efficiency for conversion electrons of ≈1.5%, while the clovers had a summed efficiency of ≈2.5% for 1 MeV gamma rays. The relative error in efficiency in the energy range of these isotopes was determined to be 6%. For γ-rays above 1.4 MeV, the extrapolated efficiencies were assigned the following errors: 6% for $E \leq 1.8$ MeV, 10% for 1.8 MeV $<E \leq 2.5$ MeV, 15% for 2.5 MeV $<$ E $\leq$3.0 MeV, and 20% for E $>$3.0 MeV. More details on the experimental setup may be found in Refs. [20, 22].

The data acquisition system utilized in this work was a digital spectroscopy system based on DGF-4C modules (produced by X-ray Instrumentation Associates) [23]. There were two sets of data recorded. The first set of data in "tape move take-away" mode where the beam is collected in the center of the detector array, and the tape is moved every three seconds to remove longer-lived contaminants and daughter products. This setting was the bulk of the run with a total of ≈75 hours of data recorded. In the second set of data (of ≈ 5 hours), the beam was collected ≈ 30 cm in front of the Ge-detectors and then moved into the center of the array. The tape was moved every three seconds with a tape transport times of 800 ms. This setting was used primarily to measure half-lives (and as further check that weak peaks did not belong to the contaminent ^{120}In) and resulted in a very reduced rate of $^{120}Ag^{m3}$. The $\gamma-\gamma$ and conversion electron-γ coincidences were used to construct the decay schemes in ^{120}Cd after the β-decay. A 100 ns (4 channel) coincidence time gate was used to produce prompt $\gamma-\gamma$ matrices. A time-delayed matrix gated with the same time width was used to subtract the random background from the prompt $\gamma-\gamma$ and γ-e matrices.

The data resulting from this experiment contains isobaric contaminants from $^{120}In^{m1,m2,gs}$ which are produced in ^{238}U fission at a level ten times higher than ^{120}Ag. However, the short tape cycle compared to the half-lives of the In isomers (47s, 46s, 3s respectively) greatly favors the decays of Ag. This results in an intensity ratio of the 1171-keV $2_1^+ \rightarrow 0^+$ γ-ray in ^{120}Sn to the 506-keV $2_1^+ \rightarrow 0^+$ γ-ray in ^{120}Cd of ≈1.5 in the efficiency corrected singles gamma spectrum. Cadmium-120 is also produced, but decays only to beta decaying states in the In daughter (*i.e.* no γ-rays are associated with this decay) [24]. The other members of the isobaric chain (Pd, Rh) are refractory metals, which have a very

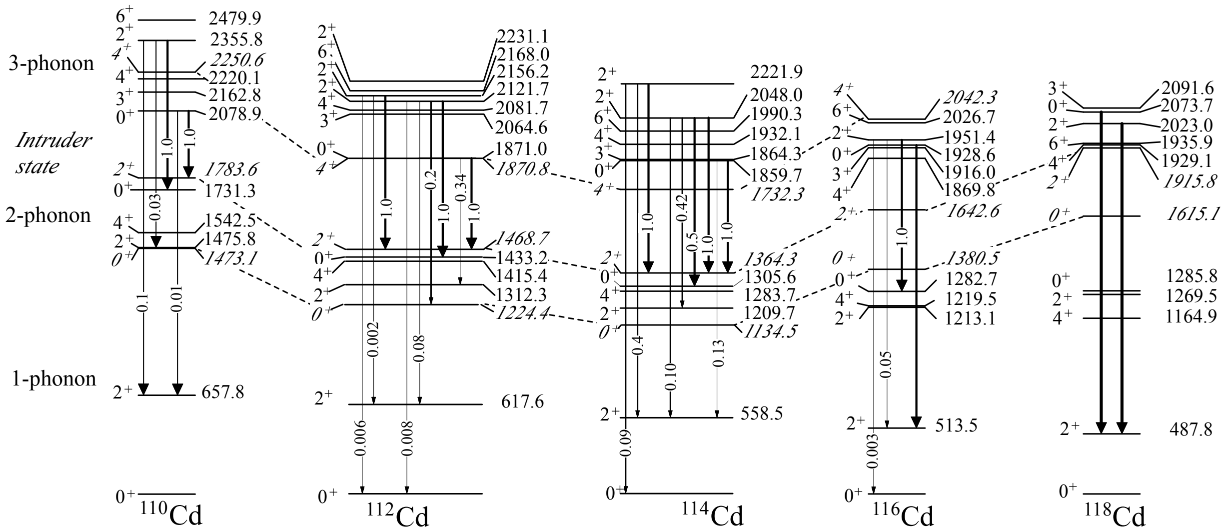

FIG. 1: Comparison of the decays of the 0^+ and 2^+ members of the candidate three-phonon levels and intruder states in ^{112,114,116,118}Cd. Multiple candidate 2^+ states are shown in ^{112,114}Cd. Level energies and γ-ray energies (keV), and their relative B(E2) values de-exciting the 0^+ and 2^+ states are shown. The intruder states are in italics for clarity. Note that the three-phonon 2^+ candidates do not show strong preference for decay to the two-phonon members, as would be expected.

low efficiency for release from the ion source, and are not observed. There is also no evidence of contamination from surrounding masses in this work (*i.e.*, no known γ-rays from any A = 119 or 121 isotopes are present in the data).

III. EXPERIMENTAL RESULTS

Transitions were placed in the decay scheme from information obtained via $\gamma - \gamma$ coincidences. All possible $\gamma - \gamma$ spectra were measured to determine this. The relative intensities of the γ-transitions de-exciting a given level were determined wherever possible both by coincidences with γ-transitions feeding the given level and by gating from below. It should be noted that we were not able to determine J_i^π from $\gamma - \gamma$ angular correlations in this data set due to the small number of detectors and their close proximity. The assignment of the parent isomer feeding a given state was based on the decay curve from the "collect and move" data, the grow-in curve from the "take-away" data and the decay pattern (i.e. the states fed by transitions from the state). The measurement of the half-life of the isomers in ^{120}Ag was done by measuring the apparent half-life of each γ-ray with time equal zero defined as when the tape moved the sample in front of the detectors. The measured half-life ($T_{1/2}^{tot}$) is a combination of the β-decay $T_{1/2}^{\beta}$ and the γ-ray decay $T_{1/2}^{\gamma}$, where it was assumed $T_{1/2}^{\gamma} << T_{1/2}^{\beta}$.

A. Position of the 0_2^+ and 0_3^+ states in ^{120}Cd

Previous reports [15, 16] on the decay of ^{120}Ag have reported two 0^+ levels at 1388.9 (de-excited by a 883-keV transition) and 1744.9 keV (de-excited by a 1239-keV transition) being directly fed by beta decay with no observed gamma transitions feeding these states. This is consistent with the pattern observed in ^{116,118}Ag [14, 15] where the two corresponding levels are only fed very weakly from above. In this work, we confirm the placement of a level at 1744.4 keV which has no observed gamma feeding from above, and only decays via a 1238.8-keV gamma transition to the 505.6-keV 2^+ state (see Fig. 2). This is consistent with the assignment of a J^π of 0^+. As there is no observed feeding from above, the total apparent beta feeding (from all isomers of ^{120}Ag) to this state is 0.56(4)%. In this work there were not enough statistics in the conversion-electron detector to observe E0 transitions in this or any other $0^+ \to 0^+$ transitions.

The coincidence spectrum obtained by gating on the 883-keV transition, however does not agree with that expected from Refs. [15, 16] (see Fig. 3). In this spectrum, lines are clearly seen at 505.6, 697.6, 817.1, 829.8, 847.0, and 1323.8 keV as well as 1171.4 and 1294.8 keV from the decay of ^{120}In. Gating on the 817.7-keV γ-ray gives a peak of energy 883.2(3) keV and gating on the 829.8-keV transition gives an energy of 883.0(3). We therefore conclude that the previously reported 0^+ two-phonon 1388.9-keV level is incorrect. We propose that the 883-keV line is a multiplet where twogammas (with energies ≈883 keV) feed the 1322.9 and 2032.9-keV levels. The transition at 847.0 keV is assigned to the decay of ^{120}Ag, but is not placed in the decay scheme. In addition

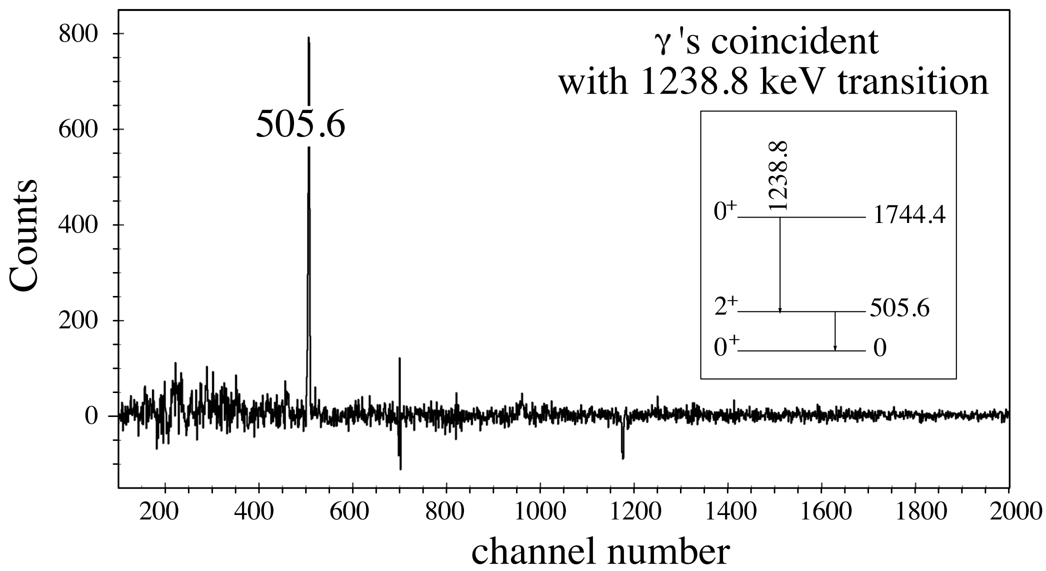

FIG. 2: The γ-ray spectrum coincident with 1238.8-keV transition. This spectrum supports the assignment of the 1238.8-keV γ as de-exciting the 1744.4-keV level.

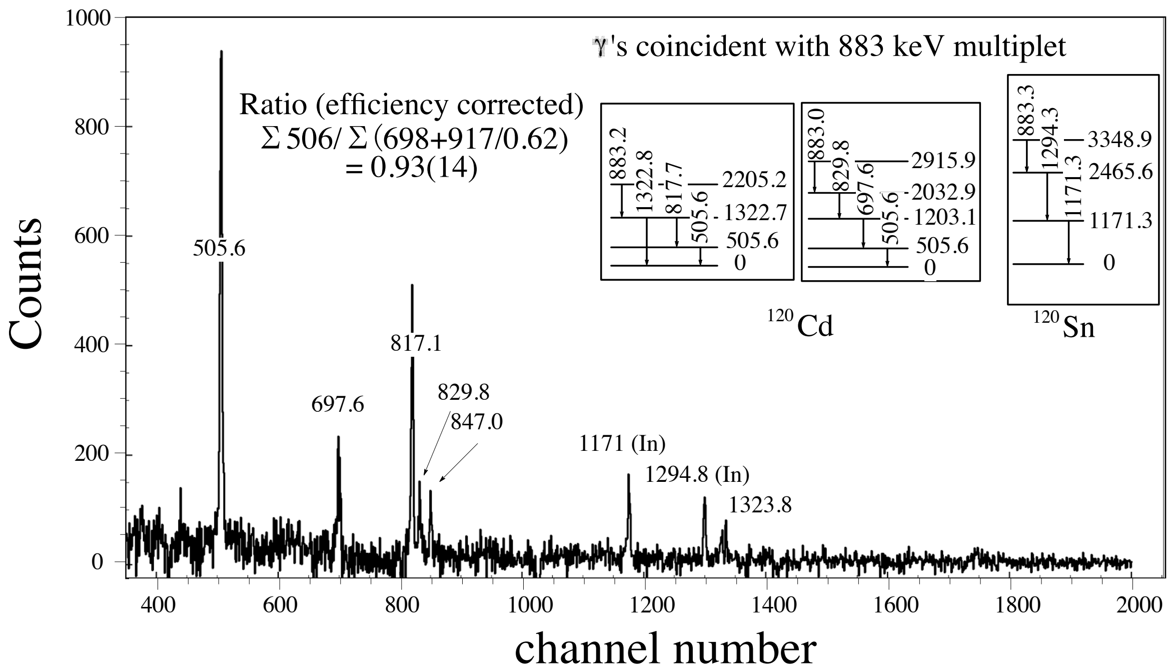

FIG. 3: Gamma-rays coincident with the 883-keV multiplet. This spectrum supports the assignment of two γ-rays with energies of 883.2 and 883.0 keV de-exciting levels at 2205.9 and 2915.9 keV, respectively (illustrated in the inset). In addition a previously unplaced gamma resulting from the β-decay of ^{120}In is observed. Previous reports [15, 16] had one 883-keV γ-ray de-exciting a level at 1388.6 keV.

there is a previously unreported γ-ray feeding the 2465.6-keV level in ^{120}Sn (from the β-decay of ^{120}In). This is graphically illustrated in the inset of Fig. 3. The ratio of the efficiency corrected counts in this spectrum for the 506-keV γ-ray compared to the sum of the 698-keV plus the 917-keV γ-rays (corrected for the 62% branching ratio) is 0.93(14).

In this data we observe a 630.4-keV γ-ray transition that is only in coincidence with the 505.6-keV γ-ray. The spectrum obtained via gating on this gamma-ray transition is shown in Fig. 4. We propose that this γ-ray de-excites a 1136.0-keV state. No evidence for a 1136.0-keV

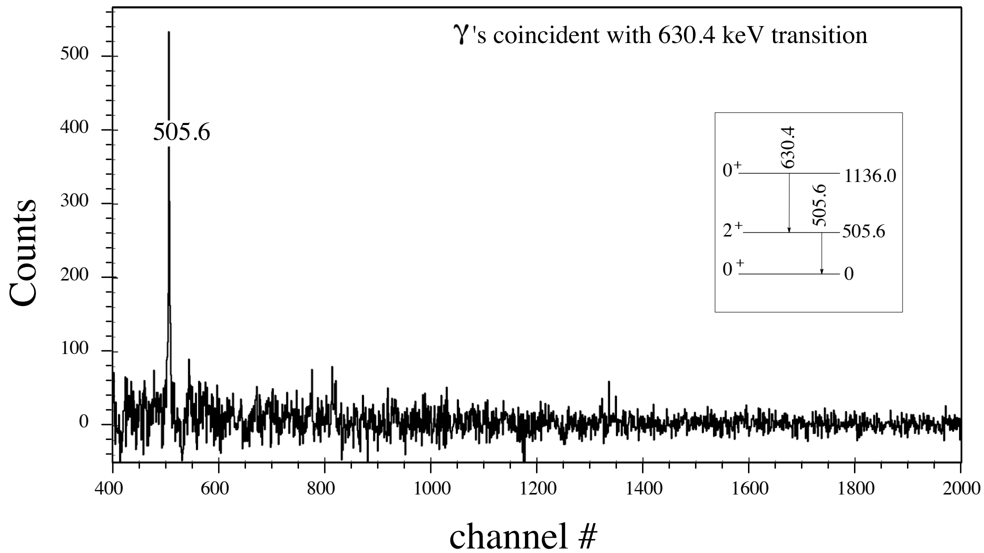

FIG. 4: Gamma-rays coincident with the 630.4-keV transition. Only the 505.6-keV $2_1^+ \rightarrow 0^+$ transition is observed to be in coincidence, supporting the assignment of the 630.4-keV γ-ray as de-exciting a level at 1136.0 keV (see inset)

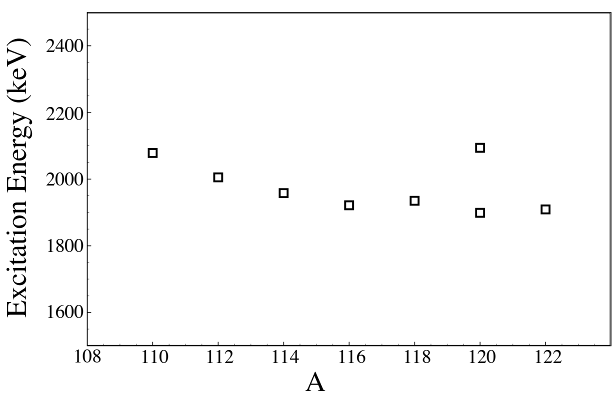

FIG. 5: Energy systematics of the 3^- octupole vibration state in ^{110}Cd [28],^{112}Cd [29], ^{114}Cd [31], ^{116}Cd [30], ^{118}Cd [27], ^{120}Cd (this work), and ^{122}Cd [32]. Of the two candidates in ^{120}Cd, the level at 1898.9 keV clearly fits the systematics better than the 2093.9 keV level.

γ-ray was observed in this data which would correspond to a decay from this state to the ground state, which is consistent with an assignment of 0^+ to this level. The energy systematics of lighter even-even Cd isotopes also supports the assignment of this level as 0^+. The apparent beta feeding to this state (from all isomers of ^{120}Ag) is 0.08(2)%. No other gamma rays with energy < 1200 keV are observed to be in coincidence with the 505.6-keV transition alone.

B. The 3_1^+ and 3_1^- states in ^{120}Cd

In the current work, a grouping of nine states (1898.9, 1920.6, 1998.0, 2032.9, 2093.9, 2128.8, 2149.3 (new), 2205.9 (new), and 2208.4 keV) between 1800 and 2300 keV were observed in the energy region where one would expect three-phonon states to be present. Of these, this work supports the J$^\pi$ assignments from previous work for the 1920.6 (2^+) [15], 1998.0 (4^+) [15], 2032.9 (6^+) [25], and 2128.8 (5^-) [26]. In Ref. [15], a level at 1899.0(2) was tentatively assigned as 3^+ "based on systematics from ^{116}Cd and ^{118}Cd". This assignment was in disagreement with an earlier assignment to a state at 1920(25) keV as the lowest 3^- octupole vibration state measured via the ^{114}Sn(d, ^{6}Li) ^{120}Cd reaction [27]. In our data both the 1898.9 and 2093.9-keV levels decay in a manner consistent with a J=3 assignment. The systematics of the 3^- octupole phonon states in Cd from A = 110 to 122 are shown in Fig. 5. This clearly shows that the 1898.9-keV level is the better candidate for the 3^- state. In addition, the state at 1898.9 keV decays strongly to the 2_2^+ and 4_1^+ states and weakly to the 2_1^+ state, while a 695.8-keV $3_1 \rightarrow 4_1^+$ transition is not observed in our data. In Fig. 6 where a gamma spectrum coincident on the 590.6-keV transition (which feeds the 1898.9 keV state) is shown. In this figure, the gamma transitions of 576.1 keV (feeding the 2_2^+ state) and 1393.4 keV (feeding the 2_1^+ state) are clearly present, while the expected 695.8-keV transition (feeding the 4_1^+ state) is clearly absent. This is similar to the decay pattern observed in ^{116}Cd [14] for the lowest 3^- state. We therefore assign the 1898.9-keV level as the 3^- octupole vibrational state.

The state at 2093.9 keV was assigned 2^+ in Ref [12] based on a reported transition to the 0^+ ground state. In

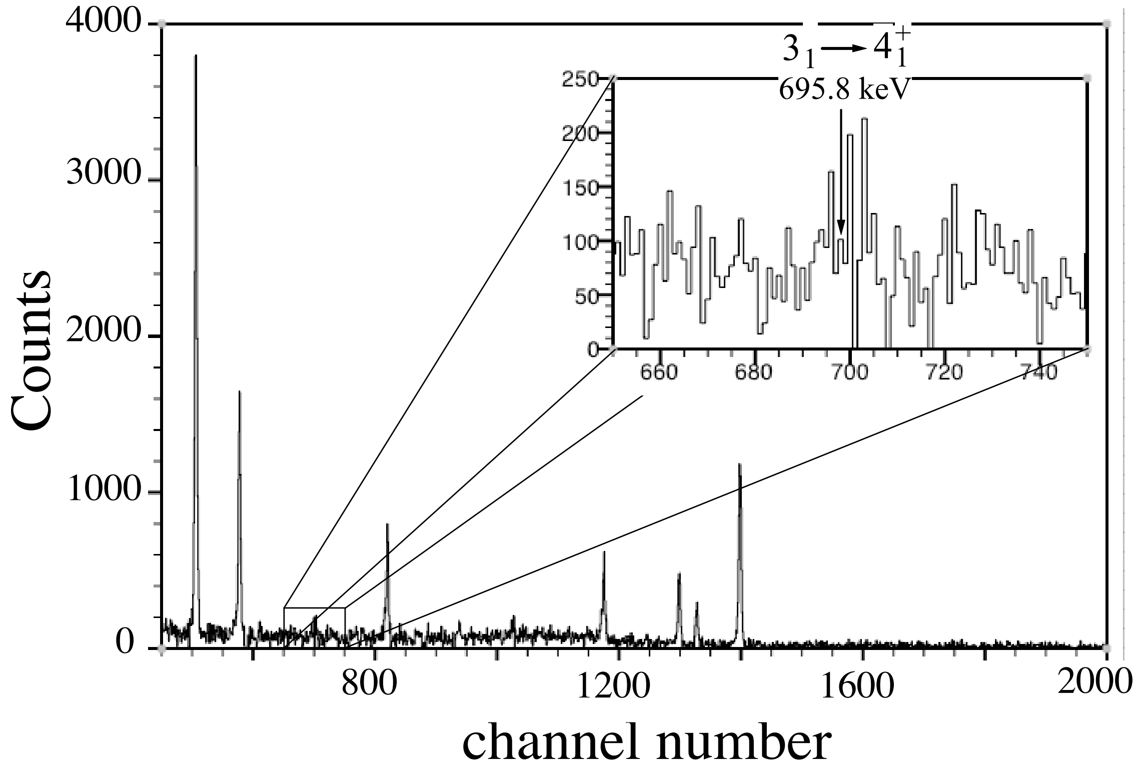

FIG. 6: Coincidence with the 590.6 keV transition that feeds the 1898.9 keV state. The $3_1 \rightarrow 4_1^+$ transition at 695.8 keV is clearly absent (see inset).

our data, this state feeds the levels at 505.6 (2^+), 1203.1 (4^+), and 1322.7 keV (2^+). No evidence for a 2093.9 keV γ-ray was observed either in singles or coincidence spectra. If this state was 2^+, one would expect to observe an E2 to the 0^+ ground state, while a higher multiplicity would not observe this decay. We therefore assign a J^π of (3^+) to this state based on the above and systematics of the lighter Cd isotopes. It should be noted however, that an assignment of 4^+ is also possible.

C. The nature of the 2_3^+ and 2_4^+ states in ^{120}Cd

In the energy region between 1900 and 2300 keV there are two states that we assign as 2^+ states. A previously known (2^+) state at 1920.6 keV and a newly discovered state at 2205.9 keV. The new state at 2205.9 keV decays to the 1327.7 keV 2_2^+, the 505.6 keV 2_1^+, and the 0_1^+ ground state, suggesting the most likely J^π as 2^+. Neither of these states decay in a manner consistent with the systematics of the lighter Cd "three-phonon states".

Figure 7a shows the systematics of the known 0^+, 2^+, and 4^+ intruder states in the even-even Cd nuclei from $^{108-120}$Cd [14, 15, 33–37], along with the 1920.6 and 2205.9 keV states in ^{120}Cd from this work. The decay patterns and relative B(E2)s of the 2^+ intruder states of these nuclei are shown as well as the $\delta E_{2^+\rightarrow 0^+}$ between the 2^+ and 0^+ intruder states. The 2^+ states were originally established as intruder states by their enhanced B(E2) values to the 0^+ intruder bandhead. The $2^+_{i.s.} \rightarrow 0^+_{i.s.}$ transitions have not been observed in ^{116,118,120}Cd due to the small branching ratio (Ref. [14] gives an upper limit for ^{116}Cd). In both the decay pattern and δE, the state at 2205.9 keV fits in much better with systematics of the known 2^+ intruder states. We therefore assign this level as the 2^+ intruder state and the 1920.6-keV (2^+) state as the candidate two-phonon state. For comparison, the candidate N-phonon 2^+ states and 2^+ intruder states in the even-even ^{108,110,112,114,116,118,120}Cd isotopes are shown in Fig. 7b.

The (2^+) state at 1920.6 keV is only observed to decay to the one-phonon 2^+ state, which agrees with Ref. [15]. A 2^+ member of the three-phonon quintuplet would be expected to strongly decay to all three two-phonon states (4^+, 2^+, 0^+) and weakly to the 2^+ one-phonon state. This is shown in Fig. 8, where the spectrum coincident with a 1580.0-keV transition that feeds the 1920.5-keV state is shown. In this spectrum, the expected 531.7-keV $2_3^+ \rightarrow 0_2^+$, 597.9-keV $2_3^+ \rightarrow 2_2^+$ and 717.5-keV $2_3^+ \rightarrow 4_1^+$ transitions are all clearly absent, while the 1415.0-keV $2_3^+ \rightarrow 2_1^+$ is dominant in the spectrum. This decay pattern is inconsistent with a three-phonon structure.

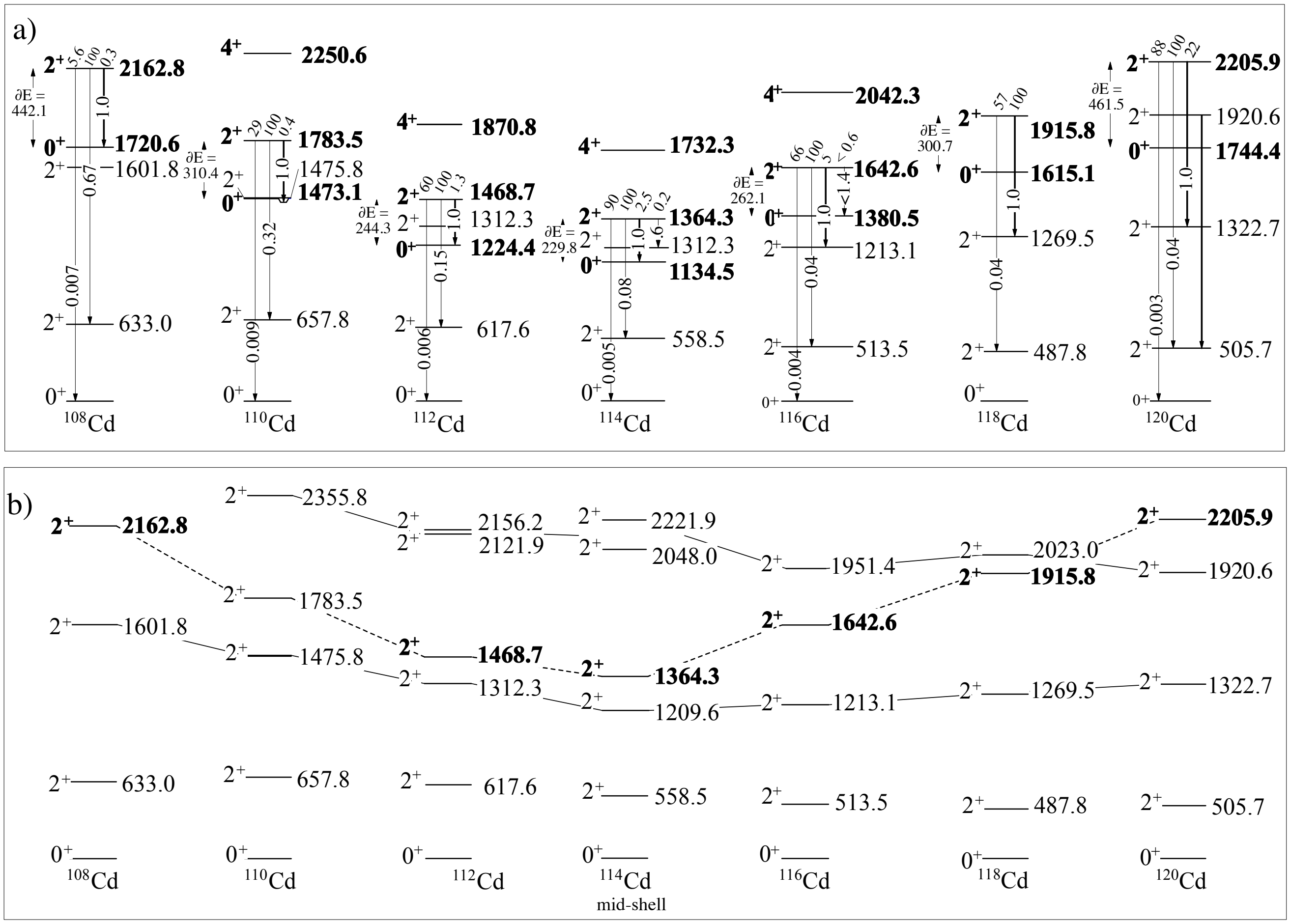

FIG. 7: Part a). The systematics of the known 0^+, 2^+, and 4^+ intruder states in the even-even Cd nuclei from $^{108-120}$Cd compared to the 1920.6 and 2205.9 keV states in ^{120}Cd. Relative B(E2)s of the 2^+ intruder states of these nuclei are shown. In both the decay pattern and energy systematics the state at 2205.9 keV fits in much better with systematics of the known 2^+ intruder states. part b). The systematics of candidate 2^+, three-phonon states and 2^+ intruder states in the even-even Cd nuclei from $^{108-120}$Cd. Note that there are multiple 2^+ three-phonon candidates in the ^{112,114}Cd isotopes.

D. Isomers of ^{120}Ag

If there are only two isomers of ^{120}Ag with J$^\pi$'s of 3^+ and 6^-, a 0^+ state would have to be fed via a second-forbidden unique beta transition. If that were so (with a reasonable log*ft* value of 13) one would expect only a few counts in the γ-singles peak, which would not be observable. If however, the level were being directly fed by a new previously unreported isomer with J$^\pi$ = 0 or 1, it would be consistent with what was observed in our data.

The conversion-electron spectrum in Fig. 9 clearly shows the previously reported [16] K- and L-conversion electrons from the 203(1)-keV transition of an isomer to the ground state, and the known 197.7 keV transition in ^{120}Sn [38]. In this work, better statistics allow us to refine the value as 203.2(2) keV. A comparison of the rates of K to L conversion electrons from a given transition allows one to determine the multipolarity of the transition. For the 203.2-keV transition, the K/L ratio is 3.31(27) which compares well with the calculated value [39] of 3.33 for a 203.2-keV E3 transition. The corresponding 203.1(3)-keV gamma-ray was used to refine the calibration efficiency for the BESCA detector by setting the efficiency-corrected ratio to that expected from a pure E2 transition.

Different isomers in ^{120}Ag would be expected to have similar (same order of magnitude) but different half-lives. In order to determine these half-lives via the γ-rays, it is best to use levels that seem only to be directly fed with no gamma feeding from above, otherwise the half-life measurement may be a combination of different isomers. The apparent half-lives of the 1329.7, 1238.8 and 203.2 keV γ-rays are shown in Fig. 10. The $T_{1/2}$ of the previously-known high-spin isomer was determined to be 440(50) ms from the 203-keV γ-ray transition. This transition was used for the half-life because it can't have any feeding from above. The apparent half-life of the 1238.8

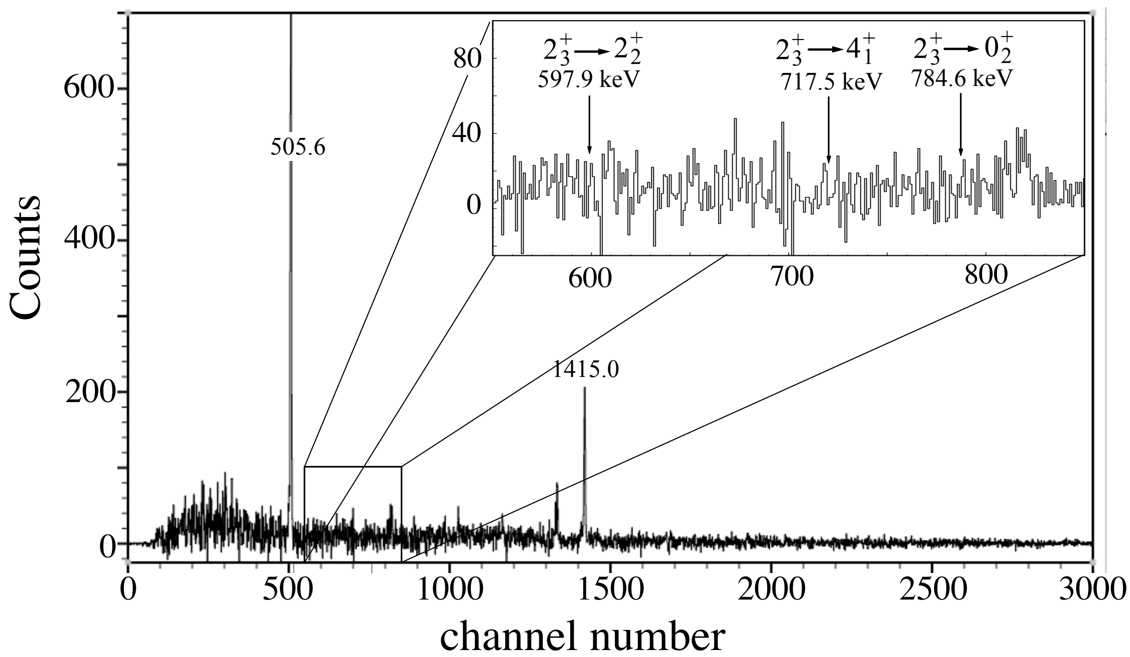

FIG. 8: The spectrum coincident with a 1580.0-keV transition that feeds the 1920.5-keV state is shown. A 2^+ member of the three-phonon quintiplet (2_3^+) would be expected to strongly decay to all three two-phonon states (4_1^+, 2_2^+, 0_2^+) and weakly to the 2^+ one-phonon state. The spectrum above is the $\gamma - \gamma$ coincidence with the 1580.0-keV transition that feeds the 1920.6-keV (2_3^+) two-phonon state. The expected 597.9 and 715.7, and 784.6-keV transitions are clearly absent (see inset).

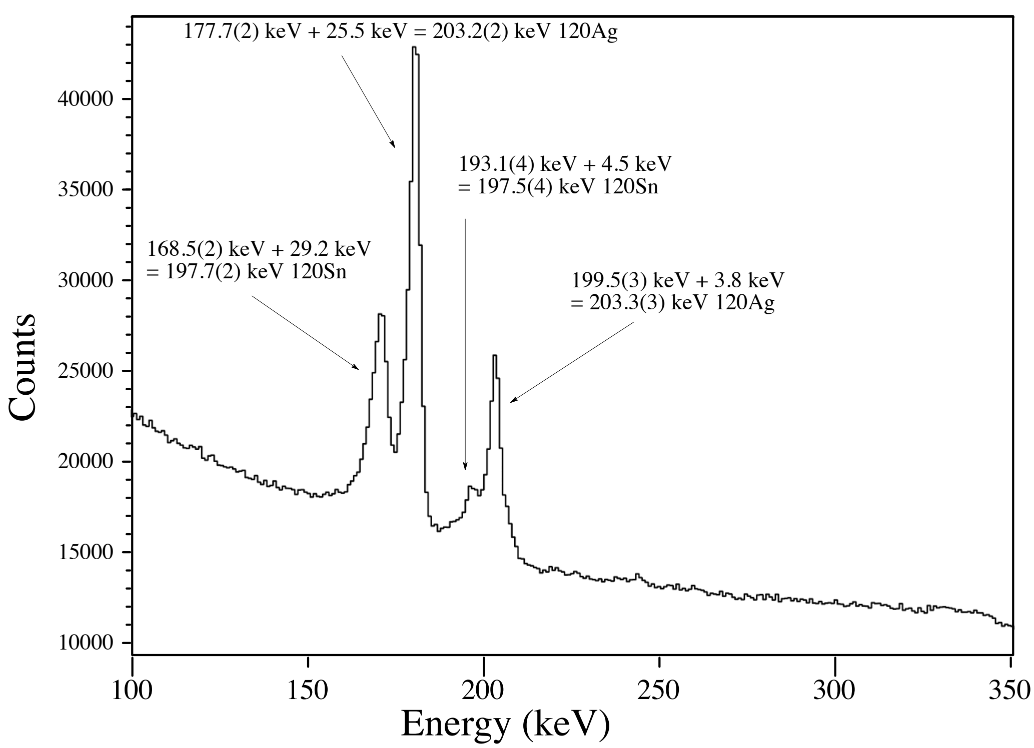

FIG. 9: Portion of the energy spectrum of conversion electrons recorded by the BESCA detector in this work. The conversion-electron lines are attributed to the known isomeric transitions in ^{120}Ag at 203.2 keV [16] and to the isomeric transition of 197.7 keV depopulating the 2481.6-keV level in ^{120}Sn [38], respectively.

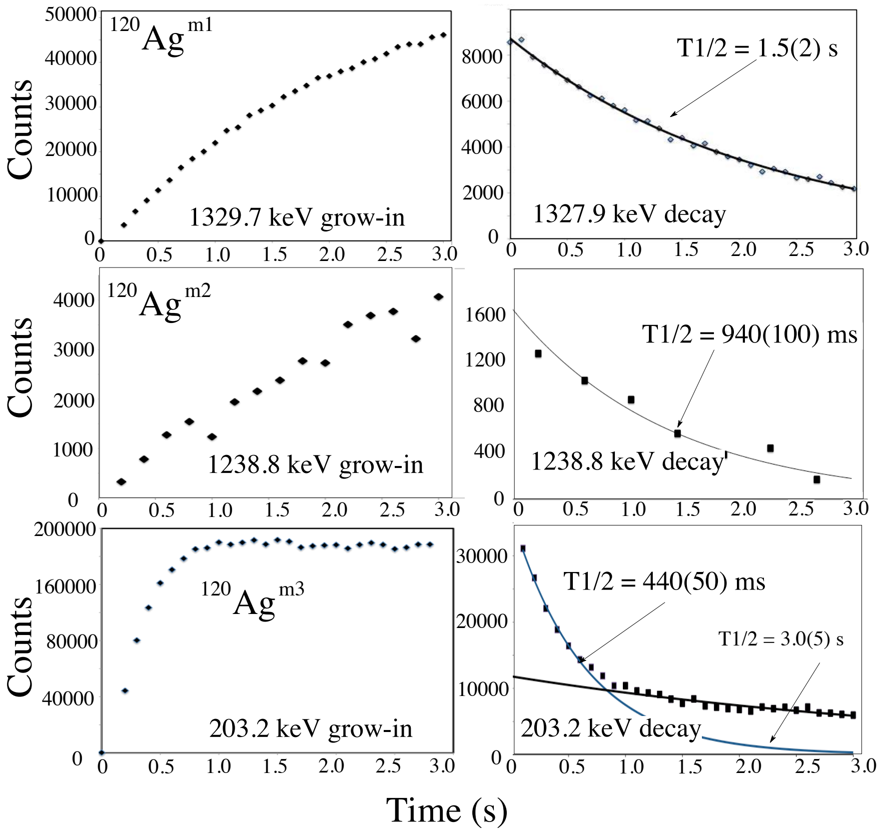

FIG. 10: Grow-in and decay curves for the 203.1, 1238.8, and 1329.7-keV γ-ray transitions arising from the β-decay of three isomers of ^{120}Ag.

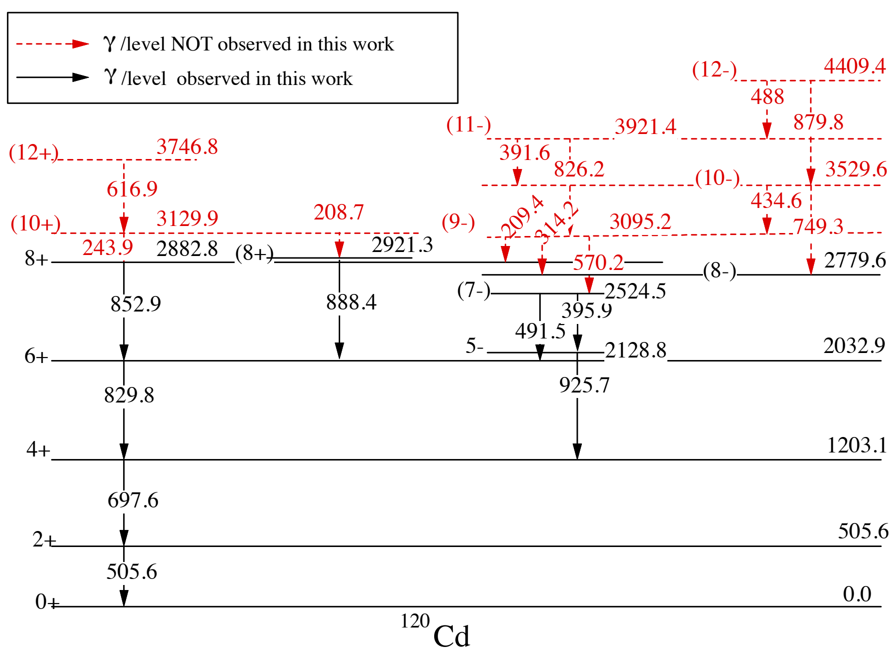

FIG. 11: (color online) Levels fed via ^{252}Cf spontaneous fission decay [40] up to J =12. The gammas de-exciting these levels observed in the beta-decay of ^{120}Ag in this work are shown as solid black lines, and those which are not observed are shown as dashed red lines. This evidence supports the conclusion that the states observed in the decay of ^{120}Ag have spins of 7 or less. All energies are given in keV.

TABLE I: List of γ-rays resulting from the beta decay of $^{120}Ag^{m1,m2}$. Gamma intensities are based on a) singles, or b) coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J^π_i	J^π_f
114.5(4)	0.020(4)%^{b}	2208.4	2093.9	(4^-)	(3^+)
131.1(3)	0.27(17)%^{b}	2128.8	1998.0	(5^-)	(4^+)
147.1(5)	0.09(7)%^{b}	2489.5	2342.6	(5^-)	5^-
195.0(4)	0.009(2)%^{b}	2093.9	1898.9	(3^+)	3^-
213.8(2)	0.30(7)%^{b}	2342.6	2128.8	5^-	(5^-)
309.6(2)	0.30(2)%^{b}	2208.4	1898.9	(4^-)	3^-
360.6(2)	0.5(1)%^{b}	2489.5	2128.8	(5^-)	5^-
419.4(4)	0.05(1)%^{b}	2318.4	1898.9	$(2^-, 3^-)$	3^-
441.4(3)	0.053(5)%^{a}	2362.0	1920.6		(2^+)
453.3(3)	0.05(1)%^{b}	2942.8	2489.5		(5^-)
456.7(4)	0.0011(6)%^{b}	2489.5	2032.9	(5^-)	6^+
469.9(3)	0.10(2)%^{b}	2563.6	2093.9		(3^+)
505.6(1)	40(1)%^{a}	505.6	0.0	2^+	0^+
549.8(2)	0.14(2)%^{b}	2448.7	1898.9	$(1^-,2^-)$	3^-
555.1(3)	0.11(2)%^{b}	2763.4	2208.4		(4^-)
576.1(2)	0.97(5)%^{a}	1898.9	1322.7	3^-	2^+
590.6(2)	0.39(6)%^{b}	2489.5	1898.9	(5^-)	3^-
612.5(5)	0.04(2)%^{b}	3420.6	2808.1		2^+
630.4(3)	0.04(1)%^{b}	1136.0	505.6	(0^+)	2^+
664.1(3)	0.09(2)%^{b}	3423.5	2759.4		
669.4(4)	0.11(4)%^{b}	2763.4	2093.9		(3^+)
675.3(2)	0.73(6)%^{b}	1998.0	1322.7	(4^+)	2^+
697.6(1)	13.6(4)%^{b}	1203.1	505.6	4^+	2^+
724.2(4)	0.06(1)%^{b}	3613.6	2889.4		
771.1(2)	1.3(1)%^{b}	2093.9	1322.7	(3^+)	2^+
774.6(4)	0.02(1)%^{b}	3664.0	2889.4		
789.5(2)	0.15(1)%^{b}	3548.9	2759.4		
794.9(2)	0.56(4)%^{b}	1998.0	1203.1		(4^+)
795.8(3)	0.06(2)%^{b}	2889.4	2093.9		(3^+)
817.1(1)	4.5(2)%^{a}	1322.7	505.6	2^+	2^+
860.1(4)	0.018(6)%^{b}	3423.5	2563.6		
883.2(2)	0.19(2)%^{b}	2205.9	1322.7		(2^+)
886.8(4)	0.13(2)%^{b}	3833.6	2946.7		
890.5(2)	0.86(5)%^{b}	2093.9	1203.1	(3^+)	4^+
925.7(1)	1.4(1)%^{a}	2128.8	1203.1		4^+
946.1(3)	0.07(1)%^{b}	2149.3	1203.1		4^+
985.4(3)	0.21(1)%^{a}	3548.9	2563.6		
995.5(2)	0.12(1)%^{b}	2318.4	1322.7	$(2^-, 3^-)$	2^+
1005.2(3)	0.50(4)%^{b}	2208.4	1203.1	(4^-)	4^+
1039.2(2)	0.10(1)%^{b}	2362.0	1322.7		2^+
1047.1(3)	0.13(1)%^{b}	2946.0	1898.9		3^-
1051.0(3)	0.03(1)%^{b}	3500.2	2448.7		$(1^-,2^-)$
1060.2(3)	0.06(1)%^{b}	3423.5	2362.0		
1064.4(4)	0.16(4)%^{b}	3062.4	1998.0		(4^+)
1101.2(3)	0.04(1)%^{b}	3549.9	2448.7		$(1^-,2^-)$
1139.4(2)	0.14(3)%^{b}	2342.6	1203.1	5^-	4^+
1158.9(2)	0.84(6)%^{b}	2362.0	1203.1		4^+

TABLE II: (table 1 continued) List of γ-rays resulting from the beta decay of $^{120}Ag^{m1,m2}$. Gamma intensities are based on a) singles or b) coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J^π_i	J^π_f
1187.0(3)	0.04(1)%^{b}	3548.9	2362.0		
1224.4(3)	0.14(4)%^{b}	3944.6	2720.1		
1238.8(3)	0.28(2)%^{b}	1744.4	505.6	0^+	2^+
1245.3(4)	0.009(3)%^{b}	4353.1	3107.8		
1286.5(2)	0.35(5)%^{b}	2489.5	1203.1	(5^-)	4^+
1294.6(2)	0.05(1)%^{a}	3500.2	2205.9		(2^+)
1322.8(2)	2.7(2)%^{a}	1322.7	0.0		0^+
1329.7(2)	2.4(2)%^{a}	3423.5	2093.9		(3^+)
1351.1(5)	0.06(4)%^{b}	3500.2	2149.3		
1360.3(2)	0.31(2)%^{b}	2563.6	1203.1		4^+
1381.0(4)	0.06(1)%^{b}	3944.6	2563.6		
1385.4(5)	0.03(1)%^{b}	3949.0	2563.6		0^+
1393.4(2)	1.7(1)%^{bb}	1898.9	505.6	3^-	2^+
1406.6(2)	0.46(4)%^{b}	3500.2	2093.9		(3^+)
1415.0(2)	0.75(6)%^{b}	1920.6	505.6	(2^+)	2^+
1426.0(5)	0.05(1)%^{b}	3423.5	1998.0		(4^+)
1451.7(3)	0.09(1)%^{b}	3545.6	2093.9		(3^+)
1455.1(4)	0.46(4)%^{b}	3548.9	2093.9		(3^+)
1465.5(3)	0.15(2)%^{b}	3559.0	2093.9		(3^+)
1492.3(2)	0.37(3)%^{b}	1998.0	505.6	(4^+)	2^+
1502.8(3)	0.10(2)%^{b}	3423.5	1920.6		(2^+)
1516.9(2)	0.32(2)%^{b}	2720.1	1203.1		4^+
1524.9(2)	0.86(6)%^{b}	3423.5	1898.9		3^-
1551.0(4)	0.36(5)%^{b}	3548.9	1998.0		(4^+)
1556.6(2)	0.10(1)%^{b}	2759.4	1203.1		4^+
1580.0(3)	0.21(3)%^{b}	3500.2	1920.6		(2^+)
1588.4(1)	1.8(1)%^{b}	2093.9	505.6	(3^+)	2^+
1623.8(3)	0.14(3)%^{b}	2946.7	1322.7		2^+
1629.4(4)	0.07(1)%^{b}	3549.9	1920.6		(2^+)
1636.2(2)	0.06(2)%^{a}	4356.3	2720.1		
1664.6(3)	0.09(2)%^{b}	3758.5	2093.9	(3^+)	
1686.2(2)	0.31(3)%^{b}	2889.4	1203.1		4^+
1700.3(3)	0.22(3)%^{b}	2205.9	505.6	(2^+)	2^+
1714.7(3)	0.06(1)%^{b}	3613.6	1898.9		3^-
1717.2(2)	0.11(1)%^{b}	3039.9	1322.7		2^+
1739.7(3)	0.06(1)%^{b}	3833.6	2093.9		(3^+)
1743.8(3)	0.24(2)%^{b}	2946.7	1203.1		4^+
1802.7(3)	0.05(1)%^{b}	2308.3	505.6		2^+
1812.9(2)	0.16(2)%^{b}	2318.4	505.6	$(2^-, 3^-)$	2^+
1835.2(2)	0.11(1)%^{b}	3157.9	1322.7		2^+
1835.7(3)	0.07(1)%^{b}	3929.5	2093.9		(3^+)
1858.4(3)	0.05(1)%^{b}	3757.3	1898.9		3^-
1882.6(3)	0.09(2)%^{b}	3085.7	1203.1		4^+
1894.0(3)	0.16(3)%^{b}	2399.5	505.6		2^+
1902.2(4)	0.05(1)%^{b}	3105.4	1203.1		4^+
1907.6(5)	0.07(1)%^{b}	3107.8	1203.1		4^+
1946.6(3)	0.28(3)%^{b}	3944.6	1998.0		(4^+)

TABLE III: (table 2 continued) List of γ-rays resulting from the beta decay of $^{120}Ag^{m1,m2}$. Gamma intensities are based on a) singles, or b) coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J_i^π	J_f^π
1959.7(2)	0.14(2)%^{b}	3162.8	1203.1		4^+
1973.3(2)	0.08(1)%^{b}	4067.2	2093.9		(3^+)
2000.8(4)	0.03(1)%^{b}	3204.2	1203.1		4^+
2024.0(4)	0.14(2)%^{b}	3944.6	1920.6		(2^+)
2048.8(4)	0.08(4)%^{b}	4198.1	2149.3		
2058.1(2)	0.27(3)%^{b}	2563.6	505.6		2^+
2078.4(3)	0.08(1)%^{b}	3281.5	1203.1		4^+
2100.6(2)	0.26(3)%^{b}	3423.5	1322.7		2^+
2125.0(2)	0.36(4)%^{b}	3328.3	1203.1		4^+
2132.6(3)	0.06(1)%^{b}	2638.2	505.6		2^+
2153.6(2)	0.22(3)%^{b}	3356.7	1203.1		4^+
2177.1(2)	0.43(5)%^{b}	3500.2	1322.7		2^+
2205.9(4)	0.02(1)%^{a}	2205.9	0.0	(2^+)	0^+
2212.4(2)	0.07(1)%^{b}	3535.1	1322.7		2^+
2214.5(5)	0.05(2)%^{b}	2720.1	505.6		2^+
2219.7(3)	0.22(3)%^{b}	3542.4	1322.7		2^+
2219.9(2)	0.22(3)%^{b}	3423.5	1203.1		4^+
2226.7(4)	0.05(1)%^{b}	3548.9	1322.7		2^+
2253.8(2)	0.19(2)%^{b}	2759.4	505.6		2^+
2274.1(2)	0.16(2)%^{b}	3477.4	1203.1		4^+
2296.3(4)	0.74(8)%^{b}	3500.2	1203.1		4^+
2302.6(2)	0.12(2)%^{b}	2808.1	505.6		2^+
2311.0(5)	0.03(2)%^{b}	2816.6	505.6		2^+
2317.1(4)	0.05(1)%^{b}	2822.6	505.6		2^+
2329.7(4)	0.015(5)%^{b}	2835.3	505.6		2^+
2345.8(2)	2.6(3)%^{b}	3548.9	1203.1		4^+
2402.6(3)	0.08(1)%^{b}	3605.8	1203.1		4^+
2407.8(3)	0.04(1)%^{b}	3730.5	1322.7		2^+
2433.5(4)	0.03(1)%^{b}	4354.0	1920.6		(2^+)
2441.1(3)	0.18(3)%^{b}	2946.7	505.6		2^+
2458.4(3)	0.08(1)%^{b}	3661.5	1203.1		4^+
2475.3(4)	0.07(2)%^{b}	2980.9	505.6		2^+
2482.5(2)	0.27(4)%^{b}	2988.0	505.6		2^+
2509.3(3)	0.08(1)%^{b}	3831.9	1322.7		2^+
2518.8(3)	0.09(2)%^{b}	3721.9	1203.1		4^+
2532.3(2)	0.21(3)%^{b}	3037.8	505.6		2^+
2553.1(3)	0.04(1)%^{b}	3756.2	1203.1		4^+
2579.9(5)	0.02(1)%^{b}	3085.7	505.6		2^+
2595.3(6)	0.03(2)%^{b}	3107.8	505.6		2^+
2599.8(5)	0.016(7)%^{b}	3105.4	505.6		2^+
2621.8(2)	0.10(2)%^{b}	3944.6	1322.7		2^+
2628.7(2)	0.17(3)%^{b}	3831.9	1203.1		4^+
2638.5(4)	0.04(1)%^{a}	2638.2	0.0		0^+
2656.9(5)	0.010(6)%^{b}	3162.8	505.6		2^+
2662.1(3)	0.05(1)%^{b}	3865.4	1203.1		4^+
2699.0(6)	0.02(1)%^{b}	3204.2	505.6		2^+
2701.9(3)	0.04(1)%^{b}	3207.5	505.6		2^+

TABLE IV: (table 3 continued) List of γ-rays resulting from the beta decay of $^{120}Ag^{m1,m2}$. Gamma intensities are based on a) singles, or b) coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J_i^π	J_f^π
2741.5(2)	0.12(2)%^{b}	3944.6	1203.1		4^+
2775.9(4)	0.05(1)%^{b}	3281.5	505.6		2^+
2822.8(2)	0.92(2)%^{b}	3328.3	505.6		2^+
2831.9(3)	0.05(1)%^{b}	4035.0	1203.1		4^+
2851.0(4)	0.03(1)%^{b}	3356.7	505.6		2^+
2863.3(2)	0.11(2)%^{b}	4066.6	1203.1		4^+
2917.5(2)	0.23(4)%^{b}	3423.5	505.6		2^+
2972.3(4)	0.06(2)%^{b}	3477.4	505.6		2^+
2994.7(2)	1.3(2)%^{b}	3500.2	505.6		2^+
3032.5(2)	0.10(2)%^{b}	4355.2	1322.7		2^+
3043.4(3)	1.0(2)%^{b}	3548.9	505.6		2^+
3053.4(2)	0.6(2)%^{b}	3559.0	505.6		2^+
3082.7(4)	0.02(1)%^{b}	4286.0	1203.1		4^+
3155.9(3)	0.013(3)%^{b}	3661.5	505.6		2^+
3161.2(4)	0.008(3)%^{b}	3666.7	505.6		2^+
3194.1(5)	0.04(1)%^{b}	4516.7	1322.7		2^+
3197.0(4)	0.02(1)%^{b}	4398.7	1203.1		4^+
3216.2(5)	0.03(2)%^{b}	3721.9	505.6		2^+
3226.7(4)	0.04(1)%^{b}	3732.3	505.6		2^+
3250.6(4)	0.02(1)%^{b}	3756.2	505.6		2^+
3253.3(4)	0.04(1)%^{b}	3758.5	505.6		2^+
3270.9(4)	0.06(1)%^{b}	4593.6	1322.7		2^+
3290.9(4)	0.006(2)%^{b}	3796.5	505.6		2^+
3313.3(4)	0.03(1)%^{b}	4516.7	1203.1		4^+
3336.2(4)	0.14(4)%^{b}	3841.7	505.6		2^+
3360.0(3)	0.10(2)%^{b}	3865.4	505.6		2^+
3369.6(4)	0.02(1)%^{b}	4572.8	1203.1		4^+
3375.0(4)	0.05(1)%^{b}	3880.5	505.6		2^+
3385.8(4)	0.04(1)%^{b}	3891.3	505.6		2^+
3439.4(4)	0.07(2)%^{b}	3944.6	505.6		2^+
3464.3(2)	0.05(1)%^{b}	3969.9	505.6		2^+
3496.6(2)	0.05(1)%^{b}	4002.1	505.6		2^+
3561.1(2)	0.17(4)%^{b}	4066.6	505.6		2^+
3606.1(4)	0.017(5)%^{b}	4809.3	1203.1		4^+
3732.9(4)	0.02(1)%^{b}	4238.5	505.6		2^+
3780.5(3)	0.04(1)%^{b}	4286.0	505.6		2^+
3801.9(3)	0.03(1)%^{b}	5005.1	1203.1		4^+
3836.7(4)	0.015(4)%^{b}	5039.9	1203.1		4^+
3893.1(3)	0.023(6)%^{b}	4398.7	505.6		2^+
3930.1(3)	0.016(5)%^{b}	5133.3	1203.1		4^+
3948.9(4)	0.06(2)%^{b}	3949.0	0		0^+
4011.0(5)	0.008(3)%^{b}	4516.7	505.6		2^+

TABLE V: Levels in ^{120}Cd populated by the β-decays of ^{120}Ag^{m1,m2}. The literature values for β feeding and J$^\pi$ are taken from a) [15] and b) [18]. The levels at 2318 and 2564 keV were reported in Ref. [18], but beta feeding values were assigned.

Level (keV)	β %	β %(lit.)	T$_{1/2}$ (s)	J$^\pi$	J$^\pi$(lit.)
0.0				0+	0+
505.6(1)	24(2)%	13.9(53)%^{a}	1.43(3)	2^+	2^{+a}
1136.0(5)	0.09(2)%			(0^+)	2^{+a}
1203.1(1)	6.0(8)%	18.6(50)%^{a}	1.42(4)	4^+	4^{+a}
1322.7(2)	4.0(8)%	9.7(15)^a	1.47(9)	2^+	2^{+a}
1744.4(3)	0.67(5)%	0.4(1)^a	0.94(11)	0^+	0^{+a}
1898.9(2)	1.8(4)%	3.5(7)^a	1.49(9)	3^-	$(3^+)^a$
1920.6(2)	0.4(2)%	2.4(3)^a	1.6(1)	(2^+)	$(2^+)^a$
1998.0(2)	1.7(4)%	5.7(6)^a	1.4(2)	(4^+)	$(4^+)^a$
2032.9(2)	0			6^+	6^+
2093.9(2)	0.5(4)%	0.7(10)^a	1.8(2)	(3^+)	2^{+a}
2128.8(2)	0.8(3)%	18.0(42)%^{a}	1.2(2)	5^-	5^{-a}
2149.3(3)	0				
2205.9(3)	0.85(7)%		1.7(8)	(2^+)	
2208.4(3)	2(1)%		1.2(3)	(4^-)	4^{+a}
2308.3(3)	0.11(5)%				
2318.4(3)	0.81(6)%	^{b}		$(2^-, 3^-)$	
2342.6(2)	1.0(2)%	8.6(15)%^{a}		5^-	
2362.0(3)	2.0(2)%	2.4(3)^a			
2399.5(3)	0.39(6)%				
2448.7(3)	0.19(6)%	6.1(6)^a	1.9(4)	$(1^-, 2^-)$	
2489.5(3)	4.3(2)%	12.5(21)%^{a}		(5^-)	
2515.7(3)	0.06(2)%^{b}	4964.4	2449.0		
2563.6(2)	0.8(1)%	^{b}	1.8(6)		
2638.2(3)	0.15(3)%				
2720.1(2)	0.42(12)%				
2759.4(2)	0.48(8)%		1.1(5)		
2763.4(4)	0.5(1)%				
2808.1(2)	0.19(4)%				
2816.6(5)	0.08(6)%		1.1(3)		
2822.6(4)	0.12(3)%				
2835.3(4)	0.04(1)%				
2889.4(2)	0.85(7)%		1.3(5)		
2942.8(4)	0.12(9)%				
2946.0(4)	0.32(3)%				
2946.7(3)	0.5(1)%		1.1(4)		
2980.9(4)	0.16(4)%				
2988.0(2)	0.65(9)%		1.6(4)		
3037.8(2)	0.51(8)%		1.3(2)		
3039.9(3)	0.26(3)%				
3062.4(5)	0.39(8)%				
3085.7(3)	0.25(4)%				
3105.4(4)	0.17(3)%				
3107.8(5)	0.21(6)%				
3157.9(3)	0.26(3)%				
3162.8(3)	0.43(5)%		1.6(2)		
3204.2(3)	0.12(3)%				
3207.5(3)	0.09(2)%				

TABLE VI: (Table 5 continued). Levels in ^{120}Cd populated by the β-decays of ^{120}Ag^{m1,m2}. The literature values for β feeding and J$^\pi$ are taken from a) [15] and b). [18].

Level (keV)	β %	β %(lit.)	T$_{1/2}$ (s)	J$^\pi$	J$^\pi$ (lit.)
3281.5(4)	0.31(4)%				
3328.3(2)	3.1(4)%	4.0(5)^a	1.5(2)		
3356.7(3)	0.62(7)%		1.4(4)		
3420.6(5)	0.10(4)%				
3423.5(3)	4.5(4)%	10.3(10)^a	1.5(3)		
3477.4(3)	0.52(6)%		1.3(3)		
3500.2(3)	8.0(6)%	10.4(10)^a	1.5(1)		
3535.1(3)	0.17(3)%		1.6(4)		
3542.4(3)	0.54(7)%				
3545.6(4)	0.21(2)%				
3548.9(3)	11.8(8)%	11.3(11)^a	1.55(10)		
3549.9(4)	0.25(4)%				
3559.0(2)	1.7(3)%		1.6(1)		
3605.8(3)	0.20(3)%		1.3(6)		
3613.6(4)	0.29(4)%				
3661.5(3)	0.21(3)%				
3662.7(4)	0.3(2)%		1.2(5)		
3664.0(5)	0.05(2)%				
3666.7(4)	0.02(1)%				
3721.9(4)	0.29(7)%		1.0(4)		
3730.5(3)	0.10(2)%				
3732.3(4)	0.09(2)%				
3756.2(4)	0.15(3)%				
3757.3(4)	0.12(2)%		1.0(3)		
3758.5(4)	0.30(6)%				
3796.5(4)	0.014(5)%				
3831.9(2)	0.61(8)%				
3833.6(5)	0.46(5)%				

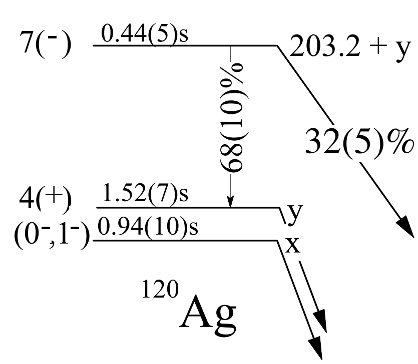

FIG. 12: The proposed partial decay scheme for ^{120}Ag. All energies are given in keV.

TABLE VII: (Table 5 continued). Levels in ^{120}Cd populated by the β-decays of ^{120}Ag^{m1,m2}. The literature values for β % are taken from a). [15] and b). [18].

Level (keV)	β %	β %(lit.)	$T_{1/2}$ (s)	J^π	J^π (lit.)
3841.7(4)	0.03(1)%				
3865.4(3)	0.34(6)%				
3880.5(4)	0.12(3)%				
3891.3(4)	0.09(4)%				
3929.5(4)	0.16(3)%				
3944.6(4)	2.2(2)%		1.4(3)		
3949.0(5)	0.21(4)%				
3969.9(2)	0.11(2)%				
4002.1(2)	0.12(3)%				
4035.0(3)	0.13(3)%				
4066.6(2)	0.66(9)%		1.5(5)		
4067.2(3)	0.18(3)%				
4198.1(5)	0.2(1)%				
4238.5(4)	0.04(1)%				
4286.0(4)	0.14(3)%				
4353.1(7)	0.02(1)%				
4354.0(4)	0.08(2)%				
4355.2(3)	0.23(5)%		1.4(3)		
4356.3(3)	0.15(6)%				
4398.7(4)	0.10(2)%				
4516.7(4)	0.18(2)%				
4572.8(4)	0.05(2)%				
4593.6(4)	0.15(3)%				
4809.3(4)	0.04(1)%				
4964.4(4)	0.12(4)%				
5005.1(3)	0.06(2)%				
5039.9(4)	0.04(1)%				
5133.3(3)	0.03(1)%				

transition was measured to be 940(100) ms. The half-life of the 1329.7 keV line (which de-excites the 3423.5-keV state)was measured as 1.5(2) s. Overall, the half-life for this isomer was determined to be 1.52(7)s based on a weighted average of the half-lives of the relatively high intensity (and well-resolved) γ-rays of energies 1329.7, 2177.1, 2994.7 and 3053.4 keV counting only those events between 1 and 3 seconds. These gamma transitions de-excite levels which decay to the 505.6-keV 2_1^+ or 1322.7-keV 2_2^+ levels in ^{120}Cd.

A recent study of ^{252}Cf spontaneous-fission decay [40] reported positive parity levels up to 18^+, and negative parity levels up to 13^-. All of the levels from Ref [40] with spins of 9 or higher are not observed in our data (see Fig. 11). However, we see apparent beta feeding to two known 8^+ states at 2885.8 [15] and 2921.3 keV [25], and an 8^- state at 2779.6 keV, this strongly supports an assignment of J = 7 for the highest spin beta-decaying isomer in ^{120}Ag. This is not consistent with the previous

TABLE VIII: List of γ-rays resulting from the beta decay of ^{120}Ag^{m3}. Gamma intensities are based on a)singles, or b). coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J_i^π	J_f^π
114.5(4)	0.05(1)%^{b}	2208.4	2093.9	(4^-)	(3^+)
131.1(3)	0.22(8)%^{b}	2128.8	1998.0	(5^-)	(4^+)
147.1(5)	0.05(4)%^{b}	2489.5	2342.6	(5^-)	5^-
181.7(5)	0.11(6)%^{b}	2524.5	2342.6	(7^-)	5^-
195.0(4)	0.15(2)%^{b}	2093.9	1898.9	(3^+)	3^-
196.8(4)	0.96(5)%^{b}	2686.0	2489.5	(6^+)	(5^-)
213.8(2)	1.1(3)%^{b}	2342.6	2128.8	5^-	5^-
255.1(3)	0.33(5)%^{a}	2779.6	2524.5	(8^-)	(7^-)
281.0(2)	0.22(3)%^{a}	2489.5	2208.4	(5^-)	(4^-)
309.6(2)	0.75(6)%^{b}	2208.4	1898.9	(4^-)	3^-
335.4(3)	0.62(8)%^{b}	2678.0	2342.6		5^-
360.6(2)	0.29(6)%^{b}	2489.5	2128.8	(5^-)	5^-
395.9(2)	0.9(1)%^{b}	2524.5	2128.8	(7^-)	(5^-)
413.8(2)	2.3(2)%^{b}	2542.6	2128.8		(5^-)
456.7(4)	0.0006(3)%^{b}	2489.5	2032.9	(5^-)	6^+
491.5(3)	1.1(1)%^{b}	2524.5	2032.9	(7^-)	6^+
505.6(1)	21.2(6)%^{a}	505.6	0.0	2^+	0^+
537.4(3)	0.48(5)%^{a}	2880.0	2342.6		5^-
549.8(2)	0.025(6)%^{b}	2449.0	1898.9		3^-
556.9(3)	0.9(1)%^{b}	2686.0	2128.8	(6^+)	(5^-)
569.4(3)	0.16(2)%^{b}	2602.5	2032.9		6^+
576.1(2)	1.57(9)%^{a}	1898.9	1322.7	3^-	2^+
590.6(2)	0.21(3)%^{b}	2489.5	1898.9	(5^-)	3^-
604.6(4)	0.5(2)%^{b}	2602.5	1998.0		(4^+)
617.7(2)	0.55(7)%^{b}	2746.5	2128.8		(5^-)
633.5(3)	0.20(4)%^{b}	2762.4	2128.8		(5^-)
653.2(2)	0.71(8)%^{b}	2686.0	2032.9	(6^+)	6^+
659.6(2)	1.2(1)%^{b}	2788.4	2128.8		(5^-)
675.3(2)	0.75(6)%^{b}	1998.0	1322.7	(4^+)	2^+
697.6(1)	18.3(5)%^{b}	1203.1	505.6	4^+	2^+
733.0(5)	0.03(2)%^{b}	2765.9	2032.9		6^+
747.8(4)	0.26(5)%^{b}	2876.7	2128.8		(5^-)
753.3(2)	0.73(8)%^{b}	2882.1	2128.8		(5^-)
766.6(3)	0.6(2)%^{b}	2764.6	1998.0		(4^+)
771.1(2)	0.48(3)%^{b}	2093.9	1322.7	(3^+)	2^+
794.9(2)	0.77(6)%^{b}	1998.0	1203.1	(4^+)	2^+
795.8(3)	0.9(3)%^{b}	2889.4	2093.9		(3^+)
817.1(1)	1.8(1)%^{a}	1322.7	505.6	2+	2^+
829.8(2)	7.1(5)%^{b}	2032.9	1203.1	6+	4^+
835.9(4)	0.44(14)%^{b}	2833.8	1998.0		(4^+)
852.9(3)	0.30(5)%^{b}	2885.8	2032.9	(8^+)	6^+
883.0(3)	0.10(1)%^{b}	2915.9	2032.9	(8^+)	6^+
888.4(4)	0.18(3)%^{b}	2921.3	2032.9	(8^+)	6^+
890.5(2)	0.36(2)%^{b}	2093.9	1203.1	(3^+)	4^+
925.7(1)	11.1(4)%^{a}	2128.8	1203.1		4^+
944.3(3)	0.30(5)%^{b}	3833.4	2889.4		
985.0(2)	0.45(3)%^{a}	3773.5	2788.4		

TABLE IX: (table 8 continued) List of γ-rays resulting from the beta decay of $^{120}Ag^{m3}$. Gamma intensities are based on a)singles, or b). coincidence relationships.

E_γ (keV)	I_γ (%)	E_i	E_f	J_i^π	J_f^π
1005.2(3)	1.2(1)%^{b}	2208.4	1203.1	(4$^-$)	4$^+$
1091.5(2)	0.21(2)%^{b}	3124.5	2032.9		6$^+$
1139.4(2)	0.5(1)%^{b}	2342.6	1203.1	5$^-$	4$^+$
1230.6(5)	0.27(10)%^{a}	3773.5	2542.6		
1286.5(2)	1.9(1)%^{b}	2489.5	1203.1	(5$^-$)	4$^+$
1300.8(3)	0.34(8)%^{b}	3662.7	2362.0		
1322.8(2)	1.25(7)%^{a}	1322.7	0.0		0$^+$
1393.4(2)	1.9(1)%^{b}	1898.9	505.6	3$^-$	2$^+$
1430.7(3)	0.41(2)%^{a}	3773.5	2342.6		5$^-$
1482.9(3)	0.28(5)%^{b}	2686.0	1203.1	(6$^+$)	4$^+$
1492.3(2)	0.55(4)%^{b}	1998.0	505.6	(4$^+$)	2$^+$
1560.7(2)	0.68(8)%^{b}	3689.5	2128.8		(5$^-$)
1588.4(1)	0.58(3)%^{b}	2093.9	505.6	(3$^+$)	2$^+$
1644.7(2)	2.6(3)%^{b}	3773.5	2128.8		(5$^-$)
1665.8(3)	0.24(5)%^{b}	3698.7	2032.9		6$^+$
1686.2(2)	0.48(5)%^{b}	2889.4	1203.1		4$^+$
1704.6(3)	0.41(5)%^{b}	3833.4	2128.8		(5$^-$)
1755.6(2)	1.2(1)%^{b}	2958.7	1203.1		4$^+$
1761.7(2)	0.41(5)%^{b}	3890.4	2128.8		(5$^-$)
1763.8(3)	0.20(3)%^{b}	3662.7	1898.9		3$^-$
1770.1(3)	0.31(4)%^{b}	2973.2	1203.1		4$^+$
1779.7(3)	0.28(4)%^{b}	2982.9	1203.1		4$^+$
1788.0(4)	0.04(1)%^{b}	3820.9	2032.9		6$^+$
1836.1(2)	1.1(1)%^{b}	3039.2	1203.1		4$^+$
1868.3(4)	0.21(6)%^{b}	3071.5	1203.1		4$^+$
1888.6(4)	0.29(15)%^{b}	3886.6	1998.0		(4$^+$)
2145.0(4)	0.24(7)%^{b}	3348.2	1203.1		4$^+$
2354.3(3)	1.4(2)%^{b}	3557.5	1203.1		4$^+$
2687.0(4)	0.10(3)%^{b}	3890.4	1203.1		4$^+$
3117.9(3)	0.17(4)%^{b}	4321.0	1203.1		4$^+$
3132.3(3)	0.15(3)%^{b}	4335.5	1203.1		4$^+$
3141.6(3)	0.19(4)%^{b}	4344.7	1203.1		4$^+$

[16] J^π assignments of 3$^+$ and 6$^-$.

Based on the observed beta-decay pattern, apparent beta half-lives, and systematics of neighboring nuclei, we conclude that there are three beta decaying isomers in ^{120}Ag. The relative ordering of the energies of the two "low-spin" isomers cannot be determined from the data in this work. As such, we assign the energies of x and y to the 0.9 s m1 and 1.5 s m2 isomers respectively (see Fig. 12). We assign the decay of the m3 isomer via the 203-keV transition as feeding the 1.5 s m2 isomer due to the relatively large number of counts in the 203 keV peak compared to the 1238 keV line. The energy of the m3 isomer is therefore assigned as 203.2 + y keV.

Silver-120 is predicted [41] to be moderately oblate deformed ($\beta_2 = +0.14$), and as such, the 47th proton and

TABLE X: Levels in ^{120}Cd populated by the β-decay of $^{120}Ag^{m3}$. The literature values for β feeding and J^π are taken from [15].

Level (keV)	β %	β %(lit.)	log ft	J^π	J^π (lit.)
505.6(1)				2$^+$	2$^+$
1203.1(1)				4$^+$	4$^+$
1322.7(2)				2$^+$	2$^+$
1898.9(2)				3$^-$	(3)$^+$
1998.0(2)				(4$^+$)	(4$^+$)
2032.9(2)	14(2)%	5.6(17)%	5.2(1)	6$^+$	6$^+$
2093.9(2)		1.8(2)		(3$^+$)	2$^+$
2128.8(2)		18.0(42)%		5$^-$	5$^-$
2205.9(3)				(2$^+$)	
2208.4(3)		7.3(14)%		(4$^-$)	(4)$^+$
2342.6(2)		8.6(15)%		5$^-$	
2489.5(3)		12.5(21)%		(5$^-$)	
2524.5(3)	6.6(3)%	7.8(13)%	5.4(1)	(7$^-$)	
2542.6(2)	7.3(7)%	4.5(8)%	5.4(1)		
2602.5(5)	2.3(7)%		5.8(2)		
2678.0(4)	2.2(3)%	2.2(4)%	5.8(1)		
2686.0(3)	10.4(6)%	16.7(26)%	5.2(1)	(6$^+$)	
2746.5(3)	1.9(2)%		5.9(1)		
2762.4(3)	0.7(2)%		6.3(2)		
2764.6(4)	2.3(7)%		5.8(2)		
2765.9(5)	0.12(6)%		7.1(2)		
2779.6(4)	1.2(2)%	2.6(4)%	6.1(1)	(8$^-$)	(7$^-$)
2788.4(3)		1.9(4)%			
2833.8(5)	1.6(5)%		5.9(2)		
2876.7(4)	0.9(2)%		6.2(1)		
2880.0(4)	1.7(2)%		5.9(1)		
2882.1(3)	2.6(3)%		5.7(1)		
2885.8(4)	1.1(2)%	0.5(1)%	6.1(1)	(8)$^+$	(8)$^+$
2889.4(2)					
2915.9(4)	0.37(5)%		6.5(1)		
2921.3(4)	0.65(9)%	0.8(2)%	6.3(1)	(8)$^+$	(8)$^+$
2958.7(2)	0.62(4)%		6.3(1)		
2973.2(3)	0.17(2)%		6.8(1)		
2982.9(3)	0.15(2)%		6.9(1)		
3039.2(2)	0.59(7)%		6.3(1)		
3071.5(4)	0.7(2)%		6.2(2)		
3124.5(3)	0.73(9)%		6.2(1)		
3348.2(4)	0.8(3)%		6.0(2)		
3557.5(3)	5.1(2)%		5.2(1)		
3689.5(3)	2.4(3)%		5.4(1)		
3698.7(4)	0.9(2)%		5.9(1)		
3773.5(3)	13(1))%	10.9(18)	4.7(1)		
3820.9(5)	0.16(4)%		6.7(2)		
3833.4(3)	2.5(3)%		5.4(1)		
3886.6(5)	1.0(5)%		5.7(2)		
3890.4(3)	1.8(2)%		5.5(1)		
4321.0(3)	0.6(2)%		5.8(2)		
4335.5(3)	0.5(1)%		5.8(1)		
4344.7(3)	0.7(2)%		5.7(2)		

73rd neutron would be expected to be in the $\pi g_{9/2}$ and either $\nu h_{11/2}$ or $\nu d_{3/2}$orbitals, respectively. This would indicate that both positive and negative parity states can be present at low energies. In the nuclei near $^{120}_{47}Ag_{73}$, $^{122}_{49}In_{73}$ [42], $^{116}_{47}Ag_{69}$ [20], and $^{122}_{47}Ag_{75}$ [43, 44], all have been reported to have three isomers with the highest energy isomer having negative parity. Silver-118 is reported to have only two isomers with J^{π} values of 1^- and 4^+. We therefore tentatively assign based on the systematics of lighter even-A Cd isotopes a negative parity for the high-spin isomer giving J^{π} assignments for the m1, m2 and m3 isomers as (0,1), 4(+), and 7(−) respectively. This information is summarized in Fig. 12.

Overall, this work has approximately 50 times greater statistics than previous reports [15, 18] with good agreement on the placement of most of the transitions with Ref. [15]. A total of 242 γ-ray transitions (157 of which are new) were assigned to 143 levels (112 of which are new) in ^{120}Cd from the three isomers in ^{120}Ag.

E. $^{120}Ag^{m1,m2}$ decay

In this work, the statistics for the "take away" is a factor of ≈ 12 less than for the grow-in data. The result of this is that many of the γ-rays (and their associated levels) do not have sufficient statistics to measure their half-lives with enough accuracy to determine which of the two low spin isomers is feeding that state via β-decay. Since they can't be adequately separated, the levels populated and their associated γ-rays are listed from both isomers in a single list. The observed γ-ray transitions resulting from the β-decays of the states of $^{120}Ag^{m1,m2}$ are listed in Tables 1-4. Only those γ-transitions that have been placed in the decay scheme have been listed. Tables 5-7 list the levels fed by the β-decays, with the previous values from Ref. [15] listed for comparison. In these tables the β intensities are corrected for conversion electrons with calculated α_k values [39]. Log *ft* values are not quoted in the table because this data is a mixture of two beta decaying states. The measured half-lives for the states (see section III.) are also listed. These were determined by a weighted average of all the γ-rays de-exciting that level. Only those levels with adequate statistics to produce errors on the half-lives of <50% are included. The partial decay scheme for $^{120}Ag^{m1,m2}$ from this work is shown in Figs. 1-4 of the Supplemental Material [46].

F. $^{120}Ag^{m3}$ decay

In this work, 80 γ-ray transitions de-exciting 50 levels are assigned to the decay of the high-spin $^{120}Ag^{m3}$ isomer. The observed gamma-rays are listed in tables 8-9, and the levels fed via beta decay are listed in Table 10. In table 10, the β intensities are corrected for conversion electrons [39]. The $Q_{\beta-}$ value used in determining the log *ft* values was 8.2(1) MeV [26], which was determined by measuring the beta-endpoint. These log *ft* values quoted in the table should be considered as lower limits (especially in the weaker transitions) due to reasons related to the potential "pandemonium" effect [45], (*i.e.* missing transitions that feed these states and an underestimation of the Q value [47]). The partial decay scheme for $^{120}Ag^{m3}$ from this work is shown in Figs. 5-6 of the Supplemental Material [46].

IV. DISCUSSION

A. Low energy collective states of ^{120}Cd as multi-phonon states

Nuclei that are close to the limits of U(5) dynamical symmetry would be expected to have multi-phonon states that decay with a strong preference by one phonon. In Ref. [15], levels at 1899.0 (3^+), 1920.5 (2^+), 1997.9 (4^+), and 2032.8 keV (6^+) were reported to be members of the three-phonon quintiplet in ^{120}Cd. No candidates for 0^+ three-phonon state were reported in [15]. Our data confirm the existence and placement in the decay scheme of these levels (the energies are 1898.9, 1920.6, 1998.0, and 2032.9 keV from this work). However, as is detailed above, the 1898.9-keV level is the 3^- octupole phonon state. The (3^+) state at 2093.9 keV is a better candidate for a three-phonon state. Of these four states the 3^+, 4^+, and 6^+ states decay in a manner qualitatively consistent with that of a three-phonon state.

There is one candidate three-phonon 2^+ level based on the expected energy that can be assigned in our data at 1920.6 keV. A three-phonon state would be expected to show enhanced decay to two-phonon states. We observe that this level decays only to the 550.6-keV 2^+_1 level, with no observed transitions to any of the 0^+, 2^+, or 4^+ "two-phonon" levels (see figure 8). In our data for ^{120}Cd, no suitable candidates for a three-phonon 0^+ state in this energy region was observed. In all of the heavy even-even Cd nuclei discussed in this paper from 108-120, neither the 2^+ or 0^+ "three-phonon" states decay in a similar fashion that is consistent with the decay of a multi-phonon state, despite the rapidly changing energy of the intruder states.

Figure 13 shows a comparison of experimental relative B(E2)s from the decay of the ^{120}Cd states and expected but unobserved transitions. Upper limits have been set on the unobserved transitions based on γ-γ gates feeding from below. While these weak transitions may exist, the upper limits on the intensities is at least a factor of 50 less than what would be expected from the decay of a three-phonon state. This figure for ^{120}Cd shows a similar pattern as the lighter Cd isotopes, with no good candidates observed for 2^+ and 0^+ three-phonon states. In Ref.[3] Garrett and Wood described the low-lying states in the Cd isotopes as independent bands. The data presented in this work supports this idea. This is illustrated in Fig. 14 for ^{120}Cd. This interpretation is more con-

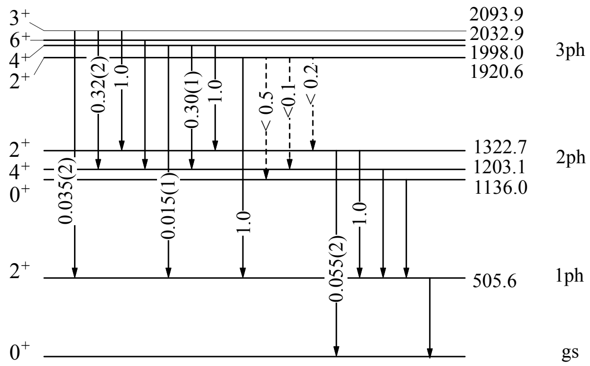

FIG. 13: Partial level scheme of 120Cd with the suggested three phonon levels [15], and their corresponding relative B(E2) values calculated with the data from the present work. The dashed lines are unobserved decays (see Fig. 8).

sistent with the experimental data especially for the 0_4^+ and 2_4^+ states, than the three-phonon picture. It should be noted that in all of the heavy even-even Cd isotopes, the 4^+ is lower in energy than the 3^+ states, which is reversed from what would be expected in a quasi-gamma band. The explanation for this may be that there are more states nearby that can mix with the 4^+ state than the 3^+, lowering the 4^+ below the 3^+ in energy. A similar situation exists in the Te isotopes [48].

B. Quadrupole-octupole coupled states

The coupling of the 1898.9-keV 3^- octupole state with the 2^+ one-phonon quadrupole state (505.6 keV) will produce five closely spaced negative parity states near the sum of the energy of these two states at 2404.5 keV with $J^\pi = 1^-, 2^-, 3^-, 4^-$ and 5^-. Transitions from these states to the 1921.7-keV 3^- state which involve the destruction of a quadrupole phonon will have enhanced B(E2) values. Candidate states for the complete quintuplet have been reported for ^{108}Cd [33], ^{112}Cd [49], ^{114}Cd [50], and ^{116}Cd [14]. In the energy region from 2100 to 2600 we observe 14 levels, of which four levels (2208.4, 2318.4, 2448.7, and 2489.5 keV) decay to the 1898.9-keV 3^- state. The levels at 2208.4, 2448.7, and 2489.5 keV and the gamma transitions that de-excite them were observed in Ref. [40], but no J^π assignments were made. The weakly populated state at 2318.4 keV is reported first in this work. In addition there are two known 5^- states at 2128.8 and 2342.6 keV [40] that are not observed to decay to the 1889.9 keV state. Both of these states were assigned as members of a band with the 2128.8 keV level as the bandhead in Ref. [40]. They conclude that the 2128.8-keV state is not a quadrupole-octupole coupled (QOC) state (in agreement with this work), but rather a mix of two quasi-proton and two quasi-neutron configurations.

Table 11 lists the candidates for QOC states in ^{120}Cd

TABLE XI: Candidates for quadrupole - octopule states in ^{116}Cd.

Level (keV)	J_i^π	E_γ (keV)	E_{final} (keV)	J_f^π	B.R. (%)
2208.4	(4^-)	114.5	2093.9	(3^+)	4(1)
		309.6	1198.9	3^-	62(6)
		1005.2	1203.1	4^+	95(5)
2318.4	$(2^-, 3^-)$	419.4	1898.9	3^-	32(8)
		995.5	1322.7	2^+	78(11)
		1812.9	505.6	2^+	100
2448.7	$(1^-,2^-)$	549.8	1898.9	3^-	100
2489.5	(5^-)	281.0(2)	2208.4	(4^-)	75(9)
		360.6(2)	2128.8	(5^-)	100
		590.6(2)	1898.9	3^-	74(9)
		1286.5(2)	1203.1	4^+	67(8)
		456.7(4)	2032.9	6^+	0.20(5)
		147.1(5)	2342.6	(5^-)	17(7)

from this work. This table shows the decay of these states, and in each case the low-energy E2 transition to the 3^- octupole phonon state is observed. Arguments for J^π assignments for these levels as are as follows:

1. *2489.5 keV: 5⁻*

This level is fed directly by a 196.8-keV γ-ray from the 2686.0-keV state (observed in Ref. [40] with J^π unassigned) and a 453.3-keV gamma from a previously unknown state at 2942.8 keV. The 2686.0-keV state also de-excites via gamma emission to the 5^- (2128.8-keV), 6^+ (2032.9-keV), and 4^+ (1203.1-keV) states making 6^+ the most likely assignment for this state. The 2489.5 keV level de-excites to states with assigned J^π of 3^-, 4^-, 4^+, 5^- and 6^+. Based on the decay pattern into and out of this state we conclude that this state is (5^-).

2. *2208.4 keV: 4⁻*

This level is fed directly by a 281.0-keV γ-ray from the 5^- 2489.5-keV state and a 555.1 keV γ-ray from a previously unknown state at 2763.4 keV. The 2763.4-keV state also de-excites via gamma emission to the (3^+) 2093.9-keV state. The 2208.4-keV QOC candidate state decays to states with J^π assignments of 3^+, 3^-, and 4^+ (see Table 10), making an assignment of (4^-) the most likely configuration.

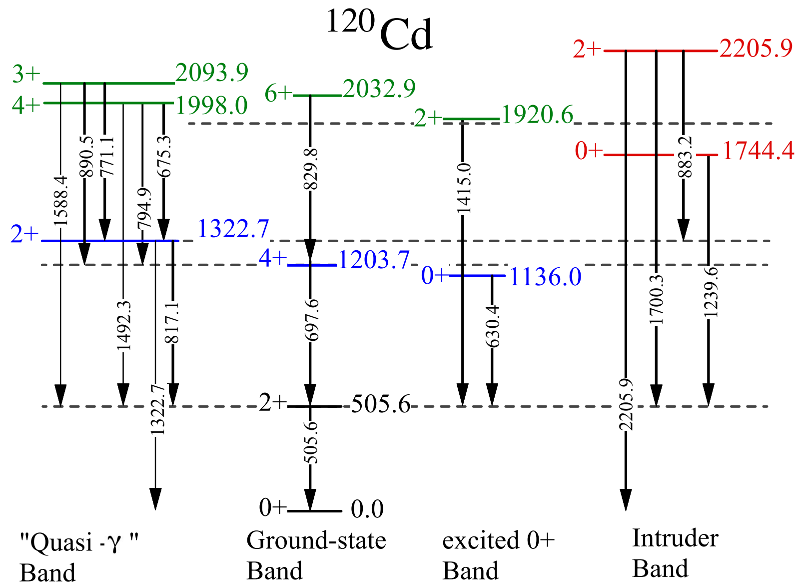

FIG. 14: (color online) Low energy levels in ^{120}Cd drawn as band structures.

3. 2318.4 keV: 2$^-$ or 3$^-$

No gammas are observed in this work to feed the state at 2318.4 keV. It decays to states with J$^\pi$ of 2$^+$ and 3$^-$. A negative parity QOC state could have either (2$^-$) or (3$^-$). We note that assignments of 4$^+$ and 3$^+$ cannot be ruled out if this state does not have a QOC configuration.

4. 2448.7 keV: 1$^-$ or 2$^-$

This level is observed to be directly fed by three levels: 1) A previously unobserved 1051.0-keV transition from a known state at 3500.2 keV [15]. This state also decays to levels with J$^\pi$ of 2$^+$, 3$^-$, 3$^+$ and 4$^+$ making an assignment of 2$^+$ or 3$^+$ most likely for the 3500.2-keV state. 2) A 1101.2-keV γ-ray de-exciting a previously unknown state at 3549.9 keV. this is not the same state as the one listed as 3549.9-keV in Ref. [15] (that level is the same as the 3548.9-keV level in this work). 3) A previously unobserved 2515.7-keV γ-ray from a state at 4964.4 keV. The 2448.7-keV QOC candidate level is only observed to decay to the 1898.9-keV 3$^-$ octupole state. Taking all this into account allows assignments of 1$^-$ or 2$^-$ for this state.

V. CONCLUSIONS

We have reinvestigated the beta decay of ^{120}Ag to levels in ^{120}Cd. Through the use of decay patterns and half-life information, we were able to determine that there are three beta-decaying isomers in ^{120}Ag, with J$^\pi$ assignments of (0$^-$, 1$^-$), 4$^{(+)}$, and 7$^{(-)}$ and half-lives of 0.94(10), 1.52(7) and 0.44(5) s respectively. We have identified four candidates of the quadrupole-octupole quintuplet. The states are (5$^-$) at 2489.5 keV, (4$^-$) at 2208.4 keV, (2$^-$) or (3$^-$) at 2318.4 keV, and (1$^-$) or (2$^-$) at 2448.7 keV. All show E2 transitions to the previously known 3$^-$ octupole state at 1898.9 keV. In addition, the 0_2^+ and 3_1^+ states have been correctly identified for the first time.

Overall, the multi-phonon vibrational approach fails to explain the low-energy structure of these Cd isotopes. The intruder states are further lifted higher in energy for ^{120}Cd than they are for the lighter even-even Cd isotopes, so there will be less mixing between intruder and multi-phonon states. The decay pattern of ^{120}Cd, however is similar to the lighter Cd isotopes despite the higher energy of the intruder states, with no good candidates for 2$^+$ and 0$^+$ three-phonon states. The work described in this paper further supports the conclusion that the anharmonic vibrator model does not adequately describes the structure of the neutron-rich Cd isotopes.

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