β decay of ^{116}Ag^{m} and the vibrational structure of ^{116}Cd

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The structure of near neutron midshell ^{116}Cd has been investigated via β decay of ^{116}Ag^{m} by β-γ and γ-γ coincidence spectroscopy. The ^{116}Ag^{m} activity was produced by symmetric fission of natural uranium induced by 25 MeV protons. The ion guide technique has been employed to produce online mass separated sources. The decay scheme of ^{116}Ag^{m} has been considerably extended by adding 19 new excited states of ^{116}Cd. The newly identified ^{116}Cd state at 1869.7 keV, along with other four levels near 2 MeV, are interpreted as forming the complete three-phonon quintuplet. The vibrational structure of ^{116}Cd is discussed in the context of an anharmonic vibrator.

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I. INTRODUCTION

Cadmium isotopes with proton number near $Z=50$ shell closure are traditionally considered as good examples of nearly spherical, vibrational nuclei that can be described by quadrupole vibrators in the collective model [1], as well as the U(5) dynamical symmetry in the interacting boson model (IBM) [2]. In the early paper of Arima and Iachello [3], ^{110}Cd was taken as an example of the U(5) limit (anharmonic quadrupole vibrator). However, observations of additional 0^{+} and 2^{+} states (see a recent review in Ref. [4]) in nuclei near the neutron midshell, i.e., ^{112,114}Cd, at the energies of the two-phonon triplet, have disturbed this simple spherical vibrator picture, and brought up the wide investigations of the role of proton intruder configurations [5–8]. Recently, Kern *et al.* [9] analyzed the energy spectra of a set of 26 nuclei presenting a vibrational structure by using a simple U(5) prescription in the IBM-1 framework. As a conclusion, even-even $^{108-114}$Cd and ^{118}Cd are selected to be among the best U(5) candidates. These five nuclei have been extensively studied by various reactions. Considering the studies of the three-phonon multiplet only, a systematics is building up for Cd isotopes. The three-phonon states in ^{110}Cd have been recently studied with the $(n,n'\gamma)$ reaction [10]. For ^{112}Cd, a comprehensive investigation by ^{110}Pd(α, $2n\gamma$) reaction spectroscopy has been published in Ref. [11]. The complete three-phonon quintuplet has been observed in ^{114}Cd, by means of Coulomb excitation [12] and by lifetime measurements with the γ-ray-induced Doppler technique [13]. It has also been identified in ^{118}Cd via β decay of ^{118}Ag [14]. Yet, information on ^{116}Cd is lacking in order to fill in the gap of the three-phonon multiplet systematics.

Compared with lighter Cd nuclei mentioned above, the level structure of the stable isotope ^{116}Cd is only partially known due to the lack of available reactions with stable beams to effectively excite high-spin levels. Nevertheless, very interesting features have been revealed by numerous investigations. Prompt γ-ray spectroscopy with spontaneous fission sources identified tentatively the yrast levels up to a 12^{+} state [15]. In-beam γ-ray studies from quasielastic and deep-inelastic heavy-ion collisions led to the identification of new yrast states as well as an intruder band on top of the second excited 0^{+} state [16]. Very recently, a negative parity band based on a two-quasiparticle state was observed with the fusion-fission reaction [17]. Results on investigations via the inelastic scattering of protons [18], as well as via the ^{114}Cd$(t,p)^{116}$Cd two-nucleon transfer reaction [19], have also been reported. In addition, a recent $(n,n'\gamma)$ reaction experiment allowed the observation of a large number of γ transitions [20]. Moreover, lifetimes of several low-lying levels in ^{116}Cd, ^{118}Cd, and ^{120}Cd were measured [21]. In the early β-decay studies of ^{116}Ag, two β-decaying states ^{116}Ag^{g} and ^{116}Ag^{m} with half-lives of 2.7 min and 10.4 s, respectively, were reported [22]. Later, more data were obtained with neutron-induced fission and fast chemical separation technique [23]. In a more recent work by Fogelberg *et al.* [24], $Q_{\beta}=6241\pm50$ keV and a more accurate half-life of 8.2 ± 0.2 s have been determined for ^{116}Ag^{m}. Prior to the present work, the decay scheme of ^{116}Ag^{m} included ten excited levels and 17 γ transitions [25]. In this paper, we report on new data on this decay. In particular, evidence for a set of five closely spaced levels in ^{116}Cd that are indicative of the complete three-phonon quintuplet is presented. In addition, the role of the fast $\nu 1g_{7/2}\rightarrow\pi 1g_{9/2}$ Gamow-Teller (GT) transition is discussed in connection with the log ft value of 4.9 for the 2958.8 keV two-quasiparticle state.

II. MEASUREMENTS AND RESULTS

A. Experimental setup

The measurements were carried out at the ion-guide online isotope separator (IGISOL) [26–28] of the University of Jyväskylä. Symmetric fission of natural uranium induced by 25 MeV protons was employed to produce the ^{116}Ag^{m} parent. The ion-guide technique enables the production of ion

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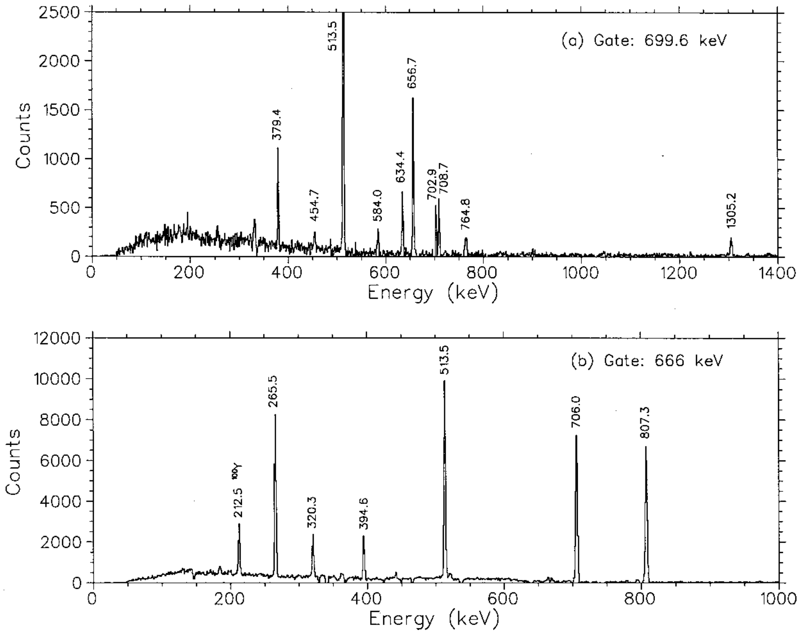

FIG. 1. γ spectra gated by the 699.6 keV and the 666 keV doublet transitions. (a) The 699.6 keV γ ray is the $2_2^+ \rightarrow 2_1^+$ transition in ^{116}Cd. The 974.4 keV γ ray included in the previous decay scheme is not confirmed in this spectrum. (b) The 265.5 keV transition is due to the 666.5 keV, the 320.3 and 394.6 keV transitions are due to the 666.4 keV, and the 807.3, 706.0, and 513.5 keV are the $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in coincidence with both. The 212.5 keV transition is from the β decay of ^{100}Y formed as monoxide ions $(A+16)$. The gate contains some amounts of the 666.0 keV transition in ^{100}Zr.

beams independently of chemical properties of their elements. The high-spin isomer of ^{116}Ag, which is not fed in the β decay of the ^{116}Pd parent, is produced directly in fission. The mass-separated beam was implanted in a movable tape placed in the center of a thin cylindrical plastic scintillator. The implantation point was viewed by four EUROGAM phase-I Ge detectors (70% relative efficiency each) placed at about 5 cm. The experimental setup enables the measurement of γ-ray singles, γ-γ coincidences, β singles, and β-γ coincidences, as well as time stamping of events defined by the period of the tape movement. The level scheme of ^{116}Cd was constructed according to the γ-γ coincidence spectra and the coincidence rates, while the relative γ intensity was extracted from the β-gated γ singles. The experimental setup and data analysis have been described in more detail in Ref. [29]. The close geometry of the detector setup introduces a modest amount of coincidence summing effects. For example, a 1219.5 keV (513.5+706.0) peak can be seen in the γ singles and in the spectrum gated by the 807.3 keV $6^+ \rightarrow 4^+$ transition. Accordingly, the area of the 1219.5 keV peak was taken as a normalization for the evaluation of coincidence summing. A first-order correction to transition intensities was thus performed for the transitions that depopulate a level in competition with a much stronger one whenever it was statistically significant.

Spectra gated by the 699.6, the 666 doublet, and the 379.4 keV γ transitions are shown in Figs. 1 and 2, respectively. Activities from $T_{1/2}=2.68$ min ^{116}Ag^g are strongly suppressed and regarded as negligible, since the collection cycle was only about 1% of the half-life. However, there are some other activities from $^{100}_{39}$Y ($T_{1/2}=0.735$ s for ^{100}Y^g and $T_{1/2}=0.94$ s for ^{100}Y^m) and its descendants, as seen in Fig. 1(b) by the presence of the 212.5 keV $2_1^+ \rightarrow 0_{g.s.}^+$ transition in $^{100}_{40}$Zr. These are due to the formation of yttrium monoxide as

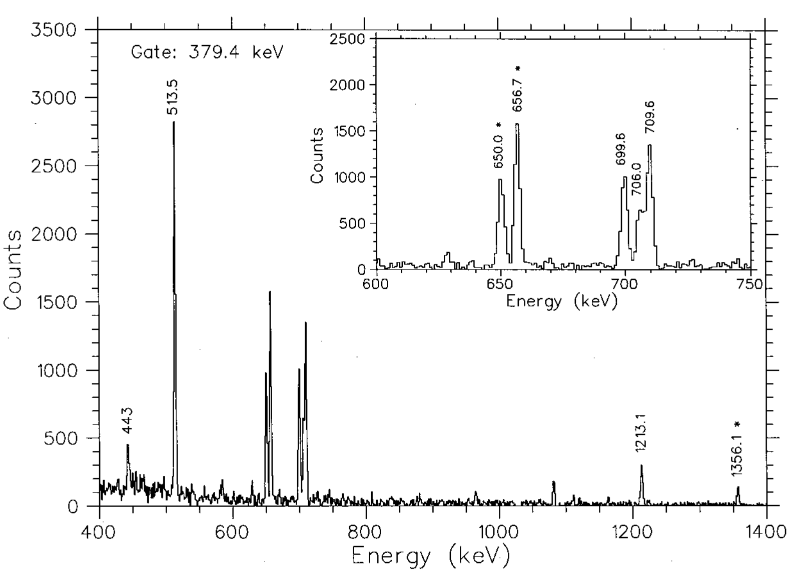

FIG. 2. γ spectrum gated by the 379.4 keV transition. A new level at 1869.7 keV is established by transitions marked with an asterisk. The peak at 443 keV is the superposition of the 442.0 and 444.0 keV transitions.

singly charged ions from oxygen impurity in the helium gas. These molecular contaminants, although contributing to the background, are also very useful for internal energy and relative efficiency calibrations.

B. Decay scheme

Transitions assigned to $^{116}Ag^{m}$ decay are listed in Table I. The ^{116}Cd levels fed in this decay are listed in Table II. The decay scheme is shown in two parts as Figs. 3 and 4. The previous decay scheme [25] is mostly confirmed with the exception of the 2187.8 keV level. This level was based on a 974.4 keV γ ray in coincidence with the 699.6 keV transition. However, we do not confirm the 974.4 keV γ ray in the spectrum gated by the 699.6 keV transition, Fig. 1(a). In addition, γ rays with energies of 102.7 and 1038.6 keV are not confirmed either.

Our observations of the 650.0, 656.7, and 1356.1 keV γ rays, as shown in the spectrum gated by the 379.4 keV transition in Fig. 2, support a new ^{116}Cd level at 1869.7 keV. The 656.7 keV γ transition was previously observed in Ref. [20]. To place this fairly intense γ transition, the authors introduced a 2037.1 keV level [20]. The new data do not show evidence for this level. According to the $E2$ multipolarity of the 656.7 keV γ ray [20] to the 1213.1 keV 2_2^+ state, and feedings by the 379.4 and 634.4 keV transitions from the 2249.1 and 2504.1 keV 5^- levels [17,25,30], the new level at 1869.7 keV is assigned as $I^\pi = 4^+$. For the two transitions depopulating the 2249.1 keV 5^- level, the intensity ratio of $I_\gamma(379)/I_\gamma(1030)$ is 0.057, which is very close to the $(379.4/1029.7)^3$ ratio of 0.050 defined by the single-particle units.

Above the 2292.3 keV 5^- state, 18 new energy levels of ^{116}Cd are reported for the first time. Some of them are strongly populated in this decay. For example, the low log ft values to the 3013.8, 3088.1, and 3213.5 keV levels indicate allowed β transitions. According to the selection rule, and their γ transitions to the (7^-) state at 2693.2 keV, the former two levels could be 6^+ states. The probable spin for the 3213.5 keV state is 4^+, according to the log ft value of 5.5 and the γ transition to the 2_1^+ state. There are two γ transitions of 666.5 and 666.4 keV in the decay scheme, depopulating the 2958.8 and 2693.2 keV levels, respectively. The former transition was included in the previous decay scheme [25], and the latter was reported in Refs. [17,30]. The coincidence relationships between the 320.3, 394.6, and 666 keV transitions, as shown in Fig. 1(b), ensure the present placement and allow the calculation of respective transition intensities. Moreover, the 522.4 keV γ ray is observed in coincidence with two transitions of 664.3 and 442.0 keV, which indicates the existence of a level at 2691.1 keV with the same decay pattern as the 2693.5 keV state. Figure 5 shows the spectra gated by the 522.4 and 320.3 keV transitions, in which the energy shift of the relevant transitions is clearly visible. About one-third of $^{116}Ag^{m}$ decays to the 2958.8 keV state in ^{116}Cd. The low log ft value of 4.9 indicates a fast $\nu 1g_{7/2} \rightarrow \pi 1g_{9/2}$ Gamow-Teller (GT) transition, which will be discussed later in the paper. The nonzero branchings to the 2^+ and 3^+ levels in ^{116}Cd are not consistent with the

TABLE I. List of γ rays from the decay of $^{116}Ag^{m}$. 100 γ intensity units correspond to a β feeding of 90.6%.

E_γ (keV)	I_γ	E_i	E_f	I_i^π	I_f^π
255.0 (1)	6.6 (4)	2504.1	2249.1	(5_3^-)	5_1^-
265.5 (1)	5.8 (4)	2292.3	2026.8	5_2^-	6^+
320.3 (1)	1.8 (1)	3013.8	2693.2		(7^-)
327.3 (2)	0.2 (1)	2249.1	1921.8	5_1^-	3^-
379.4 (1)	2.4 (2)	2249.1	1869.7	5_1^-	4_2^+
394.6 (2)	2.0 (2)	3088.1	2693.2		(7^-)
399.4 (2)	0.2 (1)	2041.9	1642.5	4_3^+	2_3^+
424.5 (1)	1.2 (1)	2340.4	1916.0		3^+
442.0 (1)	4.2 (6)	2691.1	2249.1		5_1^-
444.0 (2)	0.8 (2)	2693.2	2249.1	(7^-)	5_1^-
449.8 (2)	1.7 (4)	2698.9	2249.1		5_1^-
454.7 (2)	1.5 (2)	2958.8	2504.1		(5_3^-)
509.7 (2)	0.3 (1)	3013.8	2504.1		(5_3^-)
513.5 (1)	100.0	513.5	0.0	2_1^+	0_1^+
522.4 (2)	2.4 (2)	3213.5	2691.1		
580.5 (2)	1.0 (1)	2829.6	2249.1	(6^-)	5_1^-
584.0 (1)	2.8 (2)	3088.1	2504.1		(5_3^-)
628.2 (1)	2.6 (3)	2877.3	2249.1		5_1^-
634.4 (1)	3.0 (4)	2504.1	1869.7	(5_3^-)	4_2^+
650.0 (2)	2.2 (3)	1869.7	1219.5	4_2^+	4_1^+
656.7 (1)	4.1 (3)	1869.7	1213.1	4_2^+	2_2^+
664.3 (1)	4.0 (5)	2691.1	2026.8		6^+
666.4 (1)	3.2 (4)	2693.2	2026.8	(7^-)	6^+
666.5 (1)	5.8 (6)	2958.8	2292.3		5_2^-
673.4 (1)	2.0 (1)	3013.8	2340.4		
699.6 (1)	7.0 (5)	1213.1	513.5	2_2^+	2_1^+
702.9 (3)	1.6 (3)	1916.0	1213.1	3^+	2_2^+
706.0 (1)	79.7 (52)	1219.5	513.5	4_1^+	2_1^+
708.7 (3)	2.5 (4)	1921.8	1213.1	3^-	2_2^+
709.6 (1)	23.2 (18)	2958.8	2249.1		5_1^-
764.8 (1)	1.7 (1)	3013.8	2249.1		5_1^-
769.1 (3)	0.2 (1)	1282.6	513.5	0_2^+	2_1^+
807.3 (1)	21.3 (14)	2026.8	1219.5	6^+	4_1^+
839.1 (1)	1.4 (1)	3088.1	2249.1		5_1^-
866.8 (3)	0.2 (1)	1380.3	513.5	0_3^+	2_1^+
900.3 (2)	0.4 (1)	2822.2	1921.8		3^-
932.0 (1)	4.6 (3)	2958.8	2026.8		6^+
964.4 (2)	2.1 (2)	3213.5	2249.1		5_1^-
987.0 (2)	0.8 (1)	3013.8	2026.8		6^+
1029.7 (2)	42.1 (28)	2249.1	1219.5	5_1^-	4_1^+
1045.9 (2)	1.1 (2)	3550.0	2504.1		(5_3^-)
1061.2 (2)	0.7 (1)	3088.1	2026.8		6^+
1083.5 (2)	0.6 (1)	2303.0	1219.5		4_1^+
1111.2 (2)	1.8 (1)	3360.3	2249.1		5_1^-
1120.8 (2)	2.3 (2)	2340.4	1219.5		4_1^+
1129.0 (3)	0.4 (1)	1642.5	513.5	2_3^+	2_1^+
1157.7 (3)	0.4 (1)	2377.2	1219.5		4_1^+
1186.6 (3)	0.4 (1)	3213.5	2026.8		6^+
1213.1 (2)	3.7 (3)	1213.1	0.0	2_2^+	0_1^+
1285.0 (3)	0.5 (1)	2504.1	1219.5	(5_3^-)	4_1^+
1305.2 (3)	1.1 (2)	2518.3	1213.1		2_2^+

TABLE I. (*Continued*).

E_γ (keV)	I_γ	E_i	E_f	I_i^π	I_f^π
1333.4 (3)	0.3 (1)	3360.3	2026.8		6^+
1356.1 (3)	0.8 (1)	1869.7	513.5	4_2^+	2_1^+
1402.5 (3)	1.7 (1)	1916.0	513.5	3^+	2_1^+
1408.3 (3)	1.7 (1)	1921.8	513.5	3^-	2_1^+
1414.9 (4)	0.2 (1)	1928.4	513.5	0_4^+	2_1^+
1437.9 (4)	0.5 (1)	1951.4	513.5	2_4^+	2_1^+
1459.6 (5)	0.5 (1)	3486.4	2026.8		6^+
1528.4 (4)	0.9 (1)	2041.9	513.5	4_3^+	2_1^+
1602.9 (4)	1.3 (1)	2822.2	1219.5		4_1^+
1646.3 (5)	0.8 (2)	2865.8	1219.5		4_1^+
1735.6 (5)	0.7 (1)	2249.1	513.5	5_1^-	2_1^+
2008.0 (6)	0.7 (1)	3227.5	1219.5		4_1^+
2072.8 (6)	0.8 (1)	3292.5	1219.5		4_1^+
2079.6 (6)	1.8 (2)	3292.5	1213.1		2_2^+
2083.0 (6)	0.7 (1)	3302.5	1219.5		4_1^+
2133.8 (6)	1.0 (1)	3353.3	1219.5		4_1^+
2205.6 (7)	0.7 (1)	2719.1	513.5		2_1^+
2307.0 (7)	0.9 (1)	2820.5	513.5		2_1^+
2328.2 (7)	0.4 (1)	2841.7	513.5		2_1^+
2699.9 (5)	0.9 (2)	3213.5	513.5		2_1^+
2837.6 (8)	1.2 (2)	3351.1	513.5		2_1^+

spin parity of 5^+ for $^{116}Ag^m$, which suggests that some intensity to balance the feedings to these states might have not been observed.

III. DISCUSSION

A. Three-phonon multiplet in ^{116}Cd

A partial level scheme of ^{116}Cd is shown in Fig. 6 up to 2249.1 keV. In Ref. [16], the systematics of intruder bands from ^{106}Cd up to ^{122}Cd, thus including ^{114}Cd at the neutron midshell, was proposed. In ^{116}Cd, the intruder band was reported up to the 6^+ level. The 1380.3 keV 0_3^+, 1642.5 keV 2_3^+, and the 2041.9 4_3^+ states thus belong to the intruder band. In addition, the octupole vibrational 3^- bandhead at 1921.8 keV has been well determined previously [31,32]. At energies near 2.0 MeV, the other four states at 1916.0, 1928.4, 1951.4, and 2026.8 keV have spins of 3^+, 0^+, 2^+, and 6^+, respectively. With the newly identified 1869.7 keV 4^+ level, these five states are very closely spaced and form the candidates of the complete three-phonon quintuplet which we will discuss.

According to the quadrupole vibration model [1], the ‘‘pure’’ vibrator would present the equally spaced multiphonon excited states between which one-phonon jump transitions are allowed as electric quadrupole transitions. The observed energy splitting can be accounted for by introducing anharmonic terms [33]. However, as was pointed out in Ref. [9], most nuclei regarded as vibrational exhibit a ratio $R_{4/2}=E(4_1^+)/E(2_1^+)$ actually larger than 2, typically $\sim$2.3. This is also the case of ^{116}Cd with a ratio $R_{4/2}=2.37$, which is very close to those of ^{114}Cd and ^{118}Cd, 2.30 and 2.39, respectively. The energy spread between the upper and the lower members of the two-phonon triplet in ^{116}Cd of 69.5 keV is clearly smaller than those of ^{114}Cd (95.5 keV) and ^{118}Cd (120.9 keV). Furthermore, the $B(E2;2_2^+\to2_1^+)/B(E2;2_2^+\to0_1^+)$ ratio for the 1213.1 keV 2_2^+ level is 20. The corresponding ratio for ^{118}Cd is 17 [14], while a value of $\approx$30 is indicative for a ‘‘good vibrator.’’ Therefore,

TABLE II. Levels in ^{116}Cd populated in the decay of $^{116}Ag^m$. log *ft* values are calculated with $Q_\beta=6.241$ MeV and $T_{1/2}=8.2$ s [24]. The typical error for log *ft* is 0.1.

Energy (keV)	β feeding (%)	log *ft*	I^π
0.0			0^+
513.5 (1)			2^+
1213.1 (1)			2^+
1219.5 (1)	4.6 (53)	6.6	4^+
1282.6 (3)			0^+
1380.3 (3)			0^+
1642.5 (3)			2^+
1869.7 (1)	1.5 (6)	6.8	4^+
1916.0 (2)	2.0 (4)	6.6	3^+
1921.8 (2)	3.3 (5)	6.4	3^-
1928.4 (4)			0^+
1951.4 (4)	0.4 (1)	7.3	2^+
2026.8 (2)	0.9 (15)	6.9	6^+
2041.9 (3)	1.0 (1)	6.9	4^+
2249.1 (1)			5^-
2292.3 (2)			5^-
2303.0 (2)	0.5 (1)	7.0	
2340.4 (2)	1.4 (2)	6.6	
2377.2 (3)	0.4 (1)	7.2	
2504.1 (1)	4.0 (7)	6.1	(5^-)
2518.3 (3)	1.0 (2)	6.6	
2691.1 (1)	5.2 (8)	5.8	
2693.2 (2)			(7^-)
2698.9 (2)	1.5 (4)	6.4	
2719.1 (7)	0.6 (1)	6.7	
2820.5 (7)	0.8 (1)	6.6	
2822.2 (3)	1.5 (2)	6.3	
2829.6 (2)	0.9 (1)	6.5	(6^-)
2841.7 (7)	0.3 (1)	7.0	
2865.8 (5)	0.7 (2)	6.6	
2877.3 (2)	2.4 (4)	6.1	
2958.8 (1)	31.8 (33)	4.9	
3013.8 (1)	6.0 (6)	5.6	(6^+)
3088.1 (1)	6.2 (7)	5.5	(6^+)
3213.5 (1)	5.3 (6)	5.5	(4^+)
3227.5 (6)	0.6 (1)	6.5	
3292.5 (4)	2.4 (3)	5.8	
3302.5 (6)	0.6 (1)	6.4	
3351.1 (8)	1.1 (1)	6.1	
3353.3 (6)	0.9 (1)	6.2	
3360.3 (2)	1.9 (2)	5.9	
3486.4 (5)	0.4 (1)	6.4	
3550.0 (2)	1.0 (2)	6.0	

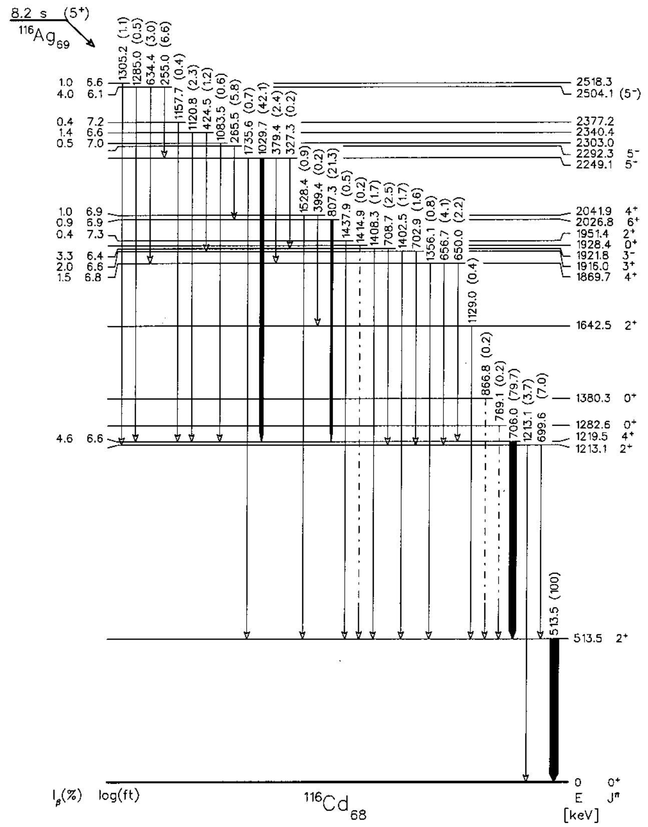

FIG. 3. Decay scheme of $^{116}Ag^{m}$ (lower part). β feedings are normalized to 94 according to the measurement of the isomeric transition in Ref. [24]. Dashed transitions are weak and only seen in the 513.5 keV gated spectrum.

the properties of two-phonon triplet in ^{116}Cd fulfill the criteria for vibrational character. Turning to the three-phonon candidates in ^{116}Cd, the relative $B(E2)$ branching ratios, as displayed on the transition arrows in Fig. 6, are the most convincing evidence supporting our interpretation. We observe strongly preferred decays to the two-phonon triplet. For example, $B(E2;4_2^+\rightarrow 2_2^+)/B(E2;4_2^+\rightarrow 2_1^+)=200$, and $B(E2;2_4^+\rightarrow 0_2^+)/B(E2;2_4^+\rightarrow 2_1^+)=45$ for the new 1869.7 keV 4_2^+ level and the 1951.4 keV 2_4^+ level, respectively. For the 1916.0 keV 3^+ state, $B(E2;3_1^+\rightarrow 2_2^+)/B(E2;3_1^+\rightarrow 2_1^+)$ is extracted to be 30 (assuming both transitions are pure $E2$). Therefore, the overall preference for the one-phonon decay to $N=2$ states is clearly shown. Moreover, for the 1869.7 keV level, $B(E2;4_2^+\rightarrow 2_2^+)/B(E2;4_2^+\rightarrow 4_1^+)=1.8$ (assuming that the 650.0 keV γ transition is pure $E2$). This ratio is predicted to be 1.1 according to the spherical quadrupole-phonon model [34], which is in reasonable agreement. Finally, we can compare the experimental spectrum with the predictions of an anharmonic vibrator [33]. The energies of the three-phonon quintuplet, deduced from the observed two-phonon anharmonicities, are listed in Table III and also displayed in Fig. 6. The agreement is only qualitative, showing that the anharmonic vibrator model Hamiltonian is not fully realistic. Considerations of configuration mixing may be necessary in order to give a good description of the experimental spectrum of ^{116}Cd.

B. β decay of $^{116}Ag^{m}$

In the β-decay studies of ^{116}Ag [22,23], spins of 2^- and 5^+ were proposed for $^{116}Ag^{g}$ and $^{116}Ag^{m}$, respectively. The

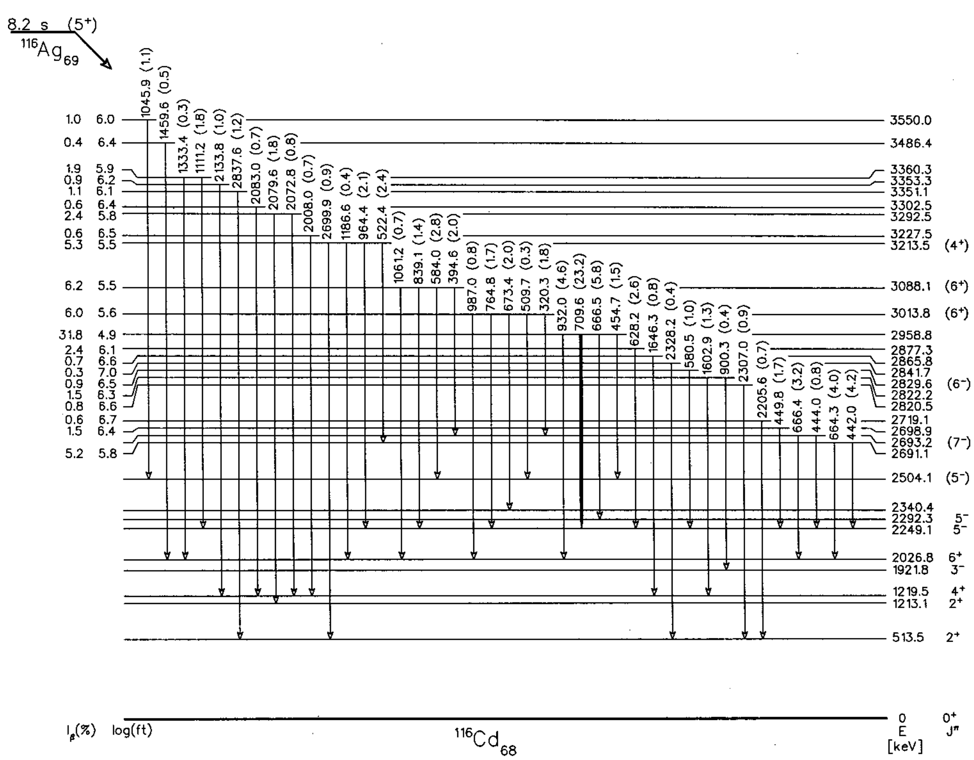

FIG. 4. Decay scheme of $^{116}Ag^{m}$ (higher part). See caption for Fig. 3.

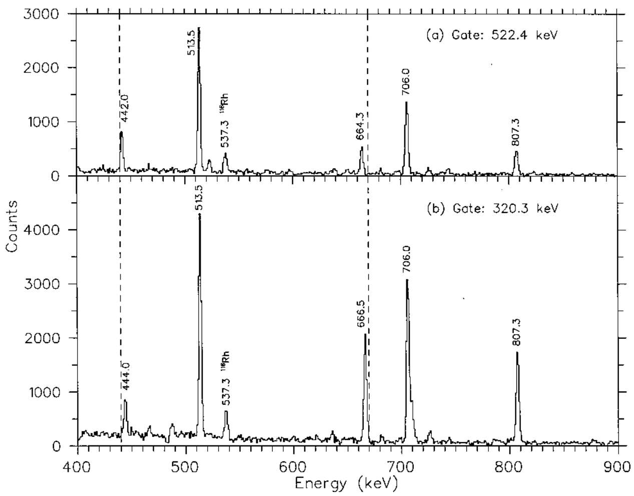

FIG. 5. γ spectra gated by the 522.4 and 320.3 keV transitions. The 537.3 and 340.5 keV transitions are present in the spectra by accidental coincidence. They are the $4^+\rightarrow2^+\rightarrow0^+$ transitions in the ground-state band of ^{116}Pd, following the β decay of ^{116}Rh. The dashed lines are drawn only for the convenience of comparison. See text for details.

transition from a 114.7 keV 1^+ level to the ground state of ^{116}Ag [35] was measured to have an $E1$ multipolarity, which in turn agrees with the 2^- assignment to ^{116}Ag^g. Fogelberg *et al.* determined the $E3$ isomeric transition from ^{116}Ag^m to be about 6% of the decay [24]. Since the ground state of odd-mass Ag isotopes from ^{107}Ag up to ^{117}Ag has the spin of $1/2^-$ [36], which is the proton $p_{1/2}$ hole state in the shell model picture, the main configuration for the proposed 2^- ground state of ^{116}Ag could involve $[\pi p_{1/2}^{-1}\nu d_{3/2}^{-1}]_{2^-}$ or $[\pi p_{1/2}^{-1}\nu d_{5/2}^{-1}]_{2^-}$, following the parabolic rule for odd-odd nuclei [37]. Another possible configuration could involve the $h_{11/2}$ neutron orbital with a $g_{9/2}$ proton or $(g_{9/2})^3_{7/2}$, but is expected to be higher in excitation energy. The main configurations for the proposed 5^+ ^{116}Ag^m could be $[\pi g_{9/2}^{-1}\nu s_{1/2}^{-1}]_{5^+}$ or $[\pi p_{1/2}^{-1}\nu h_{11/2}]_{5^+}$. In the former case, allowed β decay from the $\nu g_{7/2}$ to $\pi g_{9/2}$ spin-orbit partner will leave an odd neutron in the $g_{7/2}$ orbital, which in turn couples to the spectator neutron in the final state, resulting in the

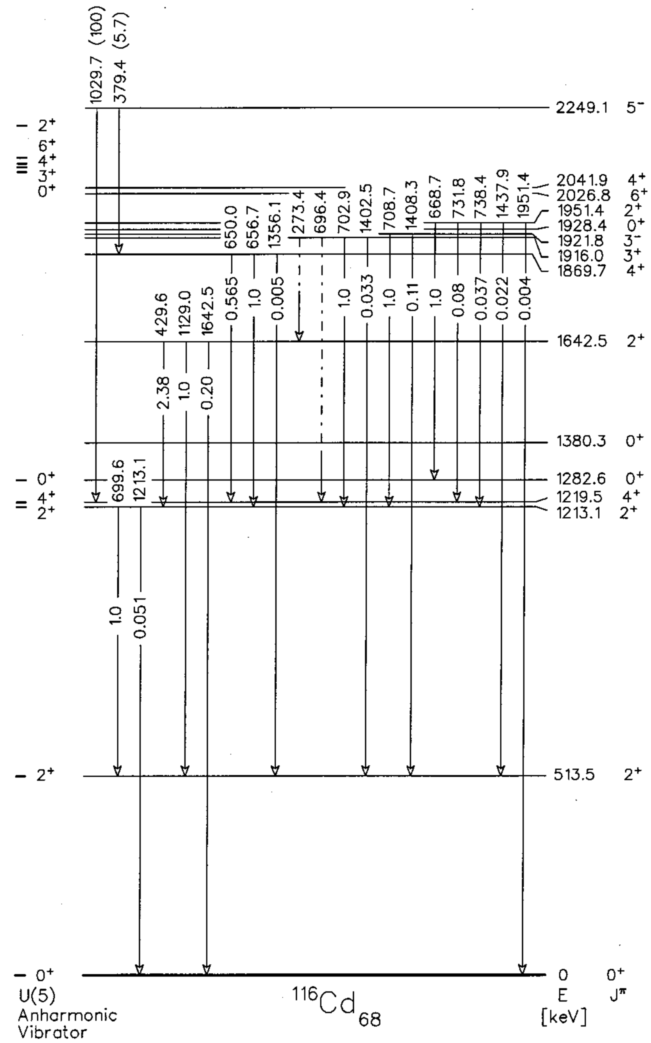

FIG. 6. Partial level scheme of ^{116}Cd. Transitions are drawn only for levels with more than one observed decay branch. Some data are taken from Ref. [20]. The relative $B(E2)$ branching ratios are indicated on the transition arrows. $B(E2)$ ratios are obtained with corrections of the mixing ratios whenever available. For the two transitions depopulating the 2249.1 keV level, relative intensities are shown in the brackets. Predictions of anharmonic vibrator (Ref. [33]) or U(5) spectrum are drawn at the left side.

TABLE III. Energies of the three-phonon quintuplet in terms of the two-phonon anharmonicities (Ref. [33]).

L^π	Formula	Energy [U(5)] (keV)	Energy (expt.) (keV)
0_4^+	$3E(2_2^+)-3E(2_1^+)$	2098.8	1928.4
3_1^+	$-3E(2_1^+)+\frac{6}{7}E(4_1^+)+\frac{15}{7}E(2_2^+)$	2104.3	1916.0
4_2^+	$-3E(2_1^+)+\frac{10}{7}E(4_1^+)+\frac{11}{7}E(2_2^+)$	2107.9	1869.7
6_1^+	$3E(4_1^+)-3E(2_1^+)$	2118.0	2026.8
2_4^+	$-3E(2_1^+)+\frac{36}{35}E(4_1^+)+\frac{4}{7}E(2_2^+)+\frac{7}{5}E(0_2^+)$	2202.7	1951.4

two-quasineutron state in ^{116}Cd, with the $[\nu g_{7/2}^{-1}\nu s_{1/2}^{-1}]_{4^+}$ configuration. In the latter case, the final state has the $[\pi g_{9/2}(\pi p_{1/2}^{-1}\nu h_{11/2})\nu g_{7/2}^{-1}]$ configuration, which turns out to be a four-quasiparticle state, but is only expected at quite high energy. Therefore, the 2958.8 keV level in ^{116}Cd, with the log *ft* value of 4.9, is most probably a two-quasineutron state. The probable spin of this level is 4^+ from the mere spin-flip transition, while the γ transitions to 5^- and 6^+ are in no contradiction with this assignment. However, these discussions have not taken the possible deformation of the nuclei into account (see a discussion in Ref. [17], for example), so it may be oversimplified.

As discussed above, the main configuration of the 2958.8 keV state in ^{116}Cd could be of two-quasineutron origin, as the result of the $\nu 1g_{7/2}\rightarrow\pi 1g_{9/2}$ Gamow-Teller (GT) transition from $^{116}Ag^{m}$. Very similar states, with log *ft* values below 5.0 and energies within the 2–3 MeV range, have been observed in neutron-rich even-even Pd nuclei systematically [29,38,39]. Capote *et al.* demonstrated that the pairing strength for the deformed neutron-rich $A\approx 100$ nuclei [40] can be determined from the two-quasineutron bandhead energies by using a quantum Monte Carlo method [41]. We hope that the method will be adapted to the case of Cd and Pd isotopes to obtain the strength of the pairing interaction, which is of essential significance in nuclear structure formation.

In conclusion, a set of five states in ^{116}Cd near 2 MeV, with the preferential one-phonon decay, suggest that they compose the complete set of the three-phonon quintuplet. For the role of the proton intruder configuration and the mixing with the collective vibration, it is necessary to perform more detailed measurements, such as lifetime measurements, or the two-proton transfer reaction for definite elucidation.

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