High-spin states in ^{109}Cd

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Levels of ^{109}Cd populated by ^{108}Pd$(\alpha, 3n\gamma)^{109}$Cd have been studied by measuring γ-ray excitation functions, direct γ spectra, γ-γ coincidences, and γ-ray angular distributions and by performing lifetime measurements. An intense γ-ray cascade has been observed, built on the $\frac{11}{2}^-$ intrinsic state and involving states of spin $\frac{11}{2}^-$, $\frac{15}{2}^-$, $\frac{19}{2}^-$, $\frac{23}{2}^-$, and $(\frac{27}{2}^-)$. A decay level scheme is proposed including states up to 4502 keV.

[NUCLEAR REACTION ^{108}Pd$(\alpha, 3n\gamma)$, E=36.7–45.8 MeV; enriched ^{108}Pd target; measured $\sigma(E)$, γ-γ coin, $\sigma(\theta)\gamma$, $T_{1/2}$, deduced decay scheme, J, π.]

I. INTRODUCTION

The anomalous behavior of the ground-state rotational bands (g.s.b.) in rare-earth nuclei has stimulated considerable interest in understanding the structure of high spin yrast states observed by (HI, $xn\gamma$) reactions. It is interesting to look for similar states in odd-A nuclei, especially in soft ones. Recently in odd-Pd and -Hg isotopes,[1,2] $\Delta I = 2$ γ-ray cascades have been observed with energy spacings quite comparable to the g.s.b. of the e-e cores. They may be explained by the Coriolis coupling model of Stephens.[3] One condition for observing such "decoupled bands" is the existence of high-j unique parity orbitals. The presence in many Cd isotopes of neutron states $h_{11/2}$ suggests looking for quasirotational bands in odd-Cd isotopes and looking first in the ^{109}Cd nucleus, already investigated from ^{109}In decay.[4]

This paper reports on our ^{109}Cd experiments and results. We have performed in-beam γ-ray experiments using the reaction ^{108}Pd$(\alpha, 3n)^{109}$Cd. The experiments include excitation functions, singles spectra, γ-γ coincidences, γ-ray angular distributions, and lifetime measurements. At the same time, the ^{107}Cd isotope has been investigated by Hagemann *et al.*[5]

II. EXPERIMENTAL

The experimental setup used at the Grenoble variable energy cyclotron has been described in earlier publications.[6] In the present experiment, metallic Pd targets enriched in ^{108}Pd up to 94.7%, approximately 15 mg/cm^2 thick, and deposited on a 14 mg/cm^2 polyethylene backing have been used.

A. Excitation functions and singles γ-ray spectra

The γ-ray spectra of the reaction ^{108}Pd + α have been measured at 36.7, 42, and 45.8 MeV α-particle energies. Two sets of singles spectra were taken with two coaxial Ge(Li) detectors of 63 and 67 cm^3, one set with each detector. Energies and intensities of γ rays have been determined using the program SAMPO.[7] In order to have the maximum γ-ray yield for the reaction ^{108}Pd$(\alpha, 3n)^{109}$Cd, we fixed the energy of the α projectile at 42 MeV, as shown in Fig. 1. Table I gives the energies and intensities of the γ transitions assigned to ^{109}Cd.

B. γ-γ coincidences

Two coaxial Ge(Li) detectors were used in the horizontal plane at $\theta = 45°$ and 135° from the beam axis. The target foil was positioned at 45° with respect to the beam axis in order to eliminate effects due to absorption. γ-γ coincidences have been stored event by event on a magnetic tape connected to the PDP-9 computer. The time window was about 10 nsec wide and the size of the matrix was 1024 × 1024 channels. We continuously viewed 11 gated spectra during the measurement. We have stored more than 1.4×10^6 events. Figure 2 shows the γ-ray spectrum in coincidence with the 522 γ-ray line.

C. Measurement of the 463.3 keV level lifetime

In order to establish that the cascade 522-835.7-1040.0-1159 keV is built on the 463.3 keV $\frac{11}{2}^-$ state, we have measured the lifetime of this $\frac{11}{2}^-$ state by studying the time correlation between 522 and 259.8 keV γ rays. This has been done using a transistorized digital time correlator. This apparatus working in real time gives the time correlation function between input signals X and Y.[8] The γ rays were detected by NaI scintillators coupled to 2106 photomultipliers. Using Ortec discriminators, we selected 260 keV γ rays on the X input and 522 keV γ rays on the Y input. The cross correlation between X and Y displayed on a two channel analyzer is shown in Fig. 3. We used a time display of 500 nsec/channel.

This correlation shows that 259.8 keV γ rays are delayed by $\tau = (15.6 \pm 1.0)$ μsec with respect to the last γ ray of the cascade 522.2 keV. The lifetime of the $\frac{11}{2}^-$ level established by this method is in very good agreement with published values.[9]

D. Angular distributions

1. Measurements

The angular distribution experiments have been performed with two Ge(Li) detectors and with a third one placed at a fixed angle to check the beam monitoring. The target plane was located at a 60° angle with respect to the beam direction to minimize the effect due to γ-ray attenuation in the target. In order to avoid systematic errors, the first detector was placed at 30°, 45°, 60°, and 90° forward angles whereas the second one was positioned at 90°, 60°, 45°, and 30° backward angles. The target-detector distances were 10 cm for the forward detector and 11 cm for the backward one. We took the geometrical attenuation factor values Q_2 and Q_4 given in the tables of Ref. 10.

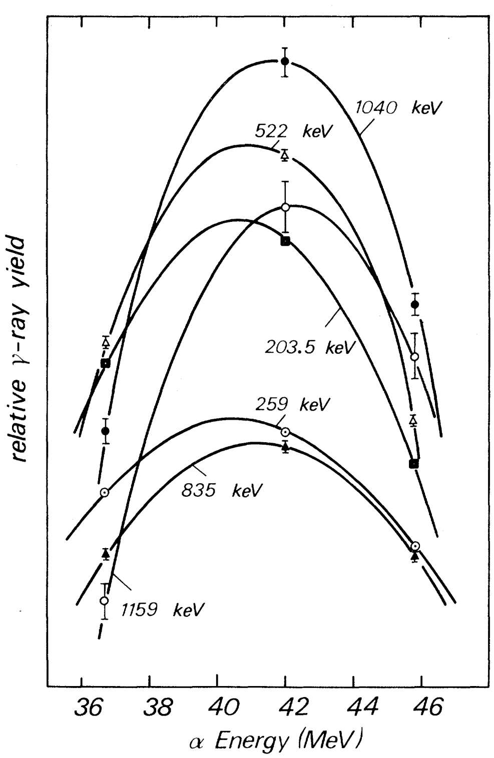

FIG. 1. Excitation functions of some intense γ rays observed following the ^{108}Pd$(\alpha, 3n)^{109}$Cd reaction.

TABLE I. γ rays observed in the reaction ^{108}Pd + α (E_α = 42 MeV) and assigned to ^{109}Cd. (The weakest lines $I_\gamma / I_{203} < 10^{-2}$ have been omitted.)

E_γ (keV)	ΔE_γ (keV)	I_γ	ΔI_γ
184.5	0.3	22	4
191.8	0.3	23	8
197.6	0.5	30	15
203.5	0.2	1000	
214.4	0.2	19	4
259.8	0.2	800	80
273.3	0.3	14	3
287.6	0.4	9	2
290.6	0.4	12	3
311.8	0.2	13	2
324.1	0.3	24	5
415.2	0.2	30	5
426.6	0.4	10	2
433.9	0.2	91	10
440.4	0.3	28	5
465.2	0.3	20	10 [a]
481.4	0.3	18	3
522.2	0.2	610	61
556.2	0.4	21	5
571.0	0.5	12	5
613.9	0.3	20	4
619.1	0.3	25	5
623.8	0.3	21	4
662.3	0.3	24	6
703.9	0.5	13	3
707.3	0.5	24	4
717.7	0.4	22	3
721.8	0.4	31	4
755.4	0.4	10	2
778.7	0.5	10	2
786.7	0.4	15	3
822.3	0.5	11	2
835.7	0.3	431	45
862.9	0.3	32	5
962.5	0.4	39	6
1014.4	0.4	25	5
1040.4	0.4	116	15
1044.8	0.5	46	9
1075.1	0.4	18	3
1120.3	0.4	22	4
1158.9	0.4	19	4
1180.2	0.3	30	5
1220.8	0.5	14	3
1237.2	0.3	109	10

[a] 466 KeV of ^{110}Cd subtracted.

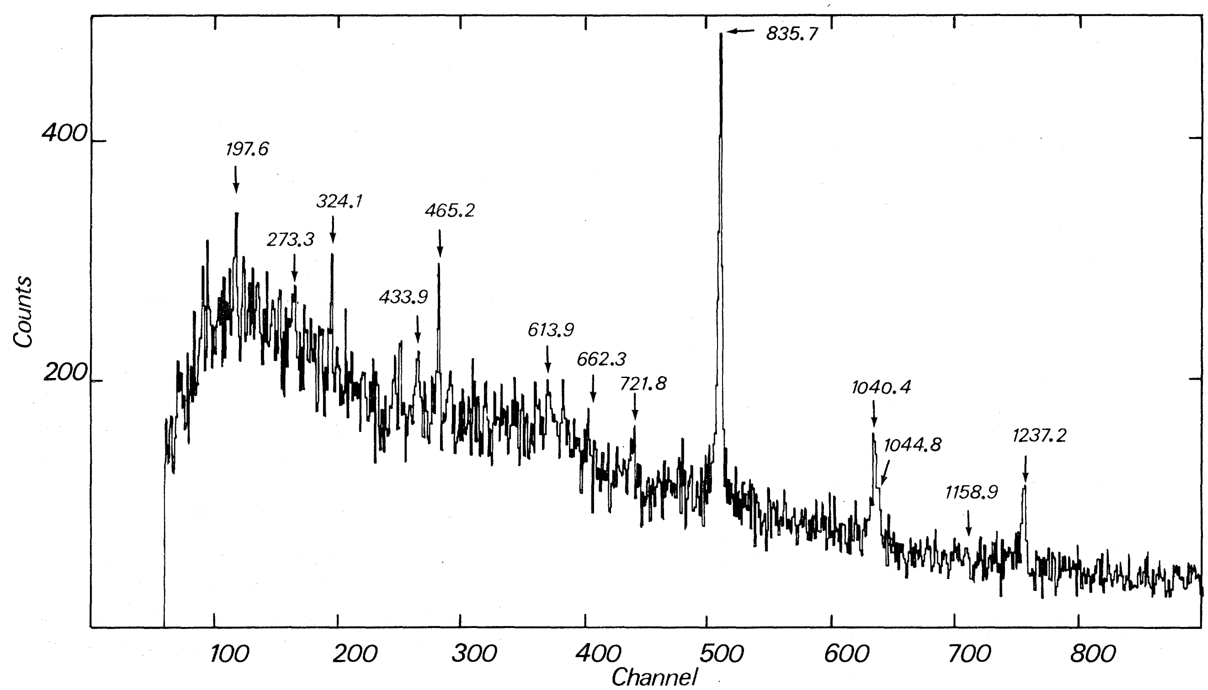

FIG. 2. Coincident γ-ray spectrum gated by the 522 γ-ray line.

To normalize the angular distribution data we used the peak area of the 259.8 keV γ ray, the distribution of which must be isotropic because of relaxation processes occurring during the long-lived (15.6 ± 1.0) μsec 463.3 keV $\frac{11}{2}^-$ level.[11] This point has been checked by measuring the current with a Faraday "cup" and the 259.8 keV peak area in the third detector. As the reaction used did not give rise to long-lived radioactivities, the beam centering could not be checked directly. To prevent an eventual decentering effect, the normalization has been performed on each detector separately.

2. *Results*

According to Ref. 12, the angular distribution of a γ ray emitted from a partially aligned nucleus has the form:

$$W(\theta) = 1 + A_2 Q_2 P_2(\cos\theta) + A_4 Q_4 P_4(\cos\theta),$$

where Q_K are the solid-angle correction factors and P_K the Legendre polynomials. The coefficient A_K is the product of a γ distribution coefficient $A_K(\gamma)$ and an orientation parameter $B_K(I)$ that describes the orientation of the nuclear state I. In Table II, the experimental corrected coefficients concerning the $\frac{11}{2}^-$ cascade are reported and compared with the maximum values corresponding to the ideal case of complete alignment (tabulated in Ref. 12). In Table III are summarized the results for the other γ rays. Figure 4 shows the least-squares fits of angular distributions for some γ-ray transitions in ^{109}Cd.

III. LEVEL SCHEME

Analyzing the preceding data and results, we have built a partial decay scheme of the ^{109}Cd

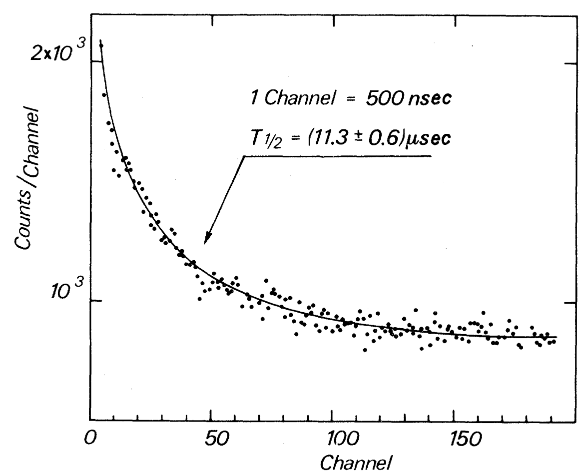

FIG. 3. Time correlation function between 522 and 260 keV γ rays measured with a digital time correlator.

TABLE II. Results of angular distribution of γ rays from the $\frac{11}{2}^-$ cascade following the reaction ^{108}Pd$(\alpha, 3n)^{109}$Cd.

E_γ (keV)	A_2	A_4	$I_i \to I_f$	A_2^{max}	A_4^{max}
1158.9	+0.18 ±0.05	−0.04 ±0.07	$\frac{27}{2} \to \frac{23}{2}$	+0.397	−0.152
1040.4	+0.26 ±0.04	−0.09 ±0.05	$\frac{23}{2} \to \frac{19}{2}$	+0.404	−0.161
835.7	+0.274 ±0.005	−0.093 ±0.008	$\frac{19}{2} \to \frac{15}{2}$	+0.414	−0.175
522.2	+0.292 ±0.003	−0.108 ±0.004	$\frac{15}{2} \to \frac{11}{2}$	+0.429	−0.198

levels, which are populated by the reaction ^{108}Pd $(\alpha, 3n)^{109}$Cd. This level scheme, shown in Fig. 5, is now discussed in detail.

We can notice that some low-energy levels already known from earlier ^{109}In decay studies[4] appear here also, fed by the reaction ^{108}Pd$(\alpha, 3n)^{109}$Cd; in particular, the 203.5 keV $\frac{7}{2}^+$, 463.3 keV $\frac{11}{2}^-$, and 822.6 keV $\frac{9}{2}^+$ states.

A. Stretched $E2$ γ-ray cascades

$\frac{11}{2}^-$ *band.* Coincidence measurements, associated with angular distribution experiments, confirm the existence of stretched $E2$ transitions with the following spin sequence: $\frac{11}{2}^-$, $\frac{15}{2}^-$, $\frac{19}{2}^-$, $\frac{23}{2}^-$, and $(\frac{27}{2}^-)$ assigned to the 463.6, 985.5, 1821.2, 2861.6, and 4020.5 keV levels. The measurement of the lifetime of the 463.3 keV state establishes unambiguously that the $\frac{11}{2}^-$ state is the "band head." As we can see from Table I, the γ rays of this band carry out the main part of the total intensity, the other rays being comparatively weak.

$\frac{7}{2}^+$ *band.* A second band seems to be built on the 203.5 keV $\frac{7}{2}^+$ state, with the spin sequence $\frac{7}{2}^+$, $(\frac{11}{2}^+)$, $(\frac{15}{2}^+)$, and $(\frac{19}{2}^+)$: the intensities of these γ rays are very weak. Concerning the 1066.4 keV state, the absence of a direct transition at 1066.4 keV led to the assignment of $\frac{11}{2}$ for its spin.

B. Other high spin states

3058.4 *keV level.* The angular distribution results implies $I=\frac{17}{2}$ or $\frac{21}{2}$ for its spin, but the existence of the 197.6 keV γ ray in coincidence with the 1040.4 keV γ ray allows only the spin value $I=\frac{21}{2}$.

3382.5 *keV level.* The spin values given by angular distribution results of the 324.1 keV γ ray are $\frac{17}{2}$, $\frac{19}{2}$, $\frac{21}{2}$, $\frac{23}{2}$, and $\frac{25}{2}$. The data concerning the level at 3938.8 keV will limit the spin values of the 3382.5 keV level to $\frac{19}{2}$ or $\frac{23}{2}$.

3523.6 *keV level.* The result of angular distributions of the 465 keV γ ray implies the spin value $I=\frac{25}{2}$, $\frac{21}{2}$: the existence of the 497 keV γ ray deexciting the $(\frac{27}{2}^-)$ level leads to prefer the $\frac{25}{2}$ spin value.

3938.8 *keV level.* The spin values extracted from the angular distribution of the 415 keV γ ray are

TABLE III. Results of angular distribution of γ rays (except that of the $\frac{11}{2}^-$ cascade) following the reaction ^{108}Pd$(\alpha, 3n)^{109}$Cd.

E_γ (keV)	A_2	A_4	ΔI
214.4	−0.05 ±0.06	+0.08 ±0.10	±1
324.1	+0.13 ±0.03	−0.08 ±0.04	0 ±1, +2
415.2	+0.037 ±0.034	−0.02 ±0.05	(±1)
426.6	+0.25 ±0.05	−0.16 ±0.07	0 ±2
433.9	−0.27 ±0.01	−0.08 ±0.02	±1
465.2	+0.29 ±0.02	−0.13 ±0.02	0, −2
556.2	+0.35 ±0.03	−0.19 ±0.04	0, −2
662.3	−0.47 ±0.09	+0.17 ±0.14	±1
721.8	+0.37 ±0.03	−0.16 ±0.05	0, −2
862.9	+0.32 ±0.06	−0.02 ±0.08	0 ±1 ±2
1044.8	−0.06 ±0.02	−0.06 ±0.03	0, ±1
1075.1	+0.23 ±0.09	+0.30 ±0.16	0, −2
1120.3	+0.28 ±0.05	−0.19 ±0.07	0, −2
1180.2	+0.55 ±0.04	+0.22 ±0.06	±1 (with $1 \leq \delta \leq 4$)
1237.2	−0.29 ±0.02	+0.05 ±0.03	±1

$\frac{23}{2}$ or $\frac{27}{2}$. These values being accepted, the result of the angular distribution of the 556 keV γ ray led to spin values $\frac{19}{2}$ or $\frac{23}{2}$ for the 3382.5 keV level.

DISCUSSION

The deexcitations of ^{109}Cd (this paper) and ^{105}Cd (Ref. 5) nuclei following (α, xn) reactions are dominated by strong $\Delta I = 2$ bands, built on the $\frac{11}{2}^-$ states. The similarity in energy spacing in these bands and in the g.s.b. (0^+, 2^+, 4^+, 6^+ ...) of the e-e cores, indicates that they are due to the coupling of the odd-particle to the rotating core. If we extract the effective inertia moments $\mathcal{I}$ of the states in each band {according to the relation $E_{\text{band state}} - E_{\text{bandhead}} = [I(I+1)\hbar^2]/2\mathcal{I}$ with $I = 2, 4, 6$, etc.} we conclude that $\mathcal{I}$ increases smoothly with spin (Fig. 6). As in Pd nuclei,[1,13] the inertia moments are larger in $\frac{11}{2}^-$ bands than in $\frac{7}{2}^+$ ones. The $\mathcal{I}$ values deduced in Cd nuclei ($5 \leq \mathcal{I} \leq 10$ MeV^{-1}), lower than the corresponding Pd ones, indicate that the Cd nuclei are "soft" and nearly spherical ($\beta < 0.2$). We must remember that for strongly deformed nuclei, the value of $\mathcal{I}$ is about 40 MeV^{-1}. Imanishi, Fujiwara, and Nishi[14] have shown in their calcuation that for heavier Cd isotopes only a 150 keV energy difference exists between oblate and prolate minima: Their conclusion was that the Cd nuclei are soft.

Several attempts have been made to interpret these rotational bands built on high-j states of unique parity in odd-A nuclei. It has been shown that, because of the Coriolis force, the external particle is decoupled from the collective rotation and aligns its angular momentum to the rotation axis of the core[3]; therefore, decoupled bands arise with spin sequence j, $j+2$, $j+4$, etc. Different

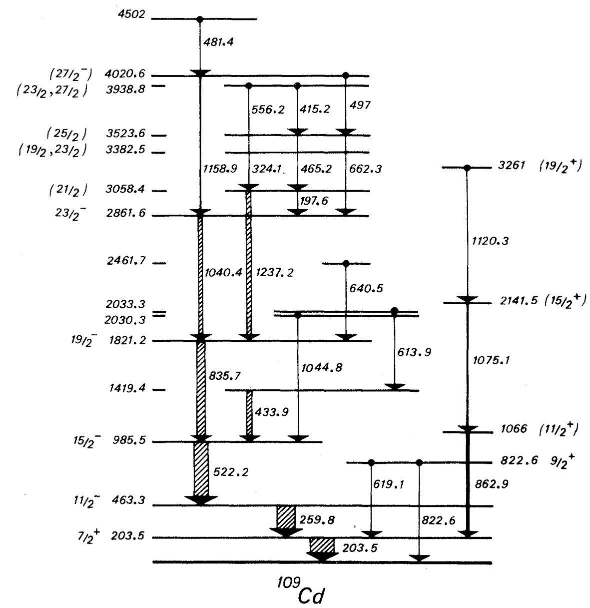

FIG. 5. Simplified level scheme of ^{109}Cd obtained from our measurements.

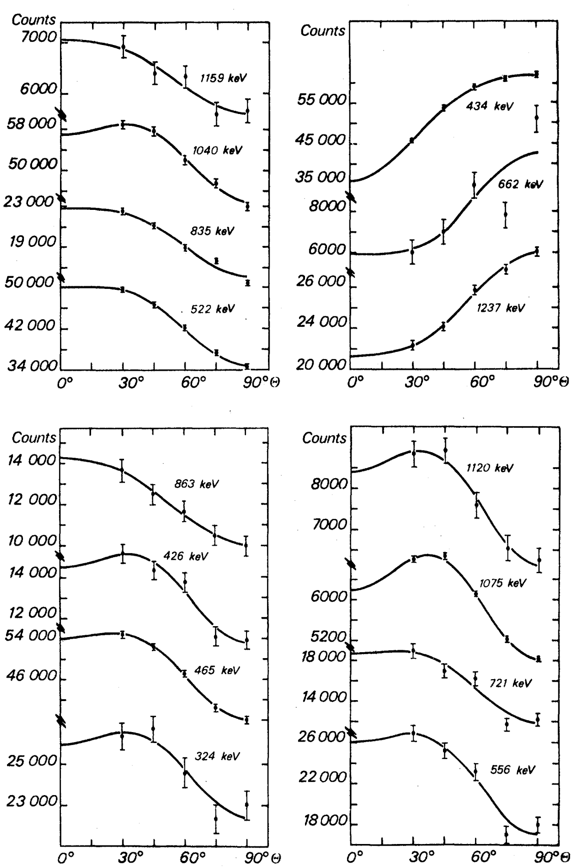

FIG. 4. Least-square fits of angular distributions for some γ-ray transitions in ^{109}Cd.

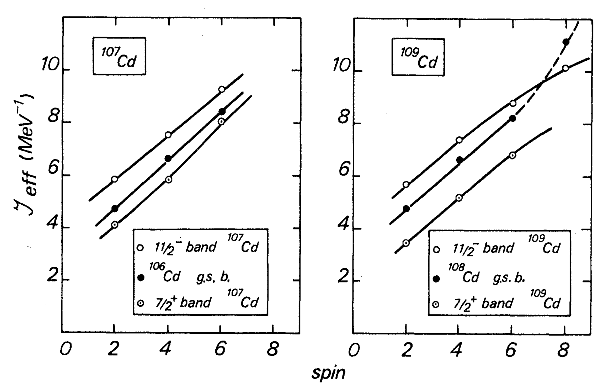

FIG. 6. Variation of the effective inertia moments versus spin in the $\frac{7}{2}^+$ and $\frac{11}{2}^-$ bands of $^{107-109}$Cd, compared to those of the g.s. band of $^{108-110}$Cd.

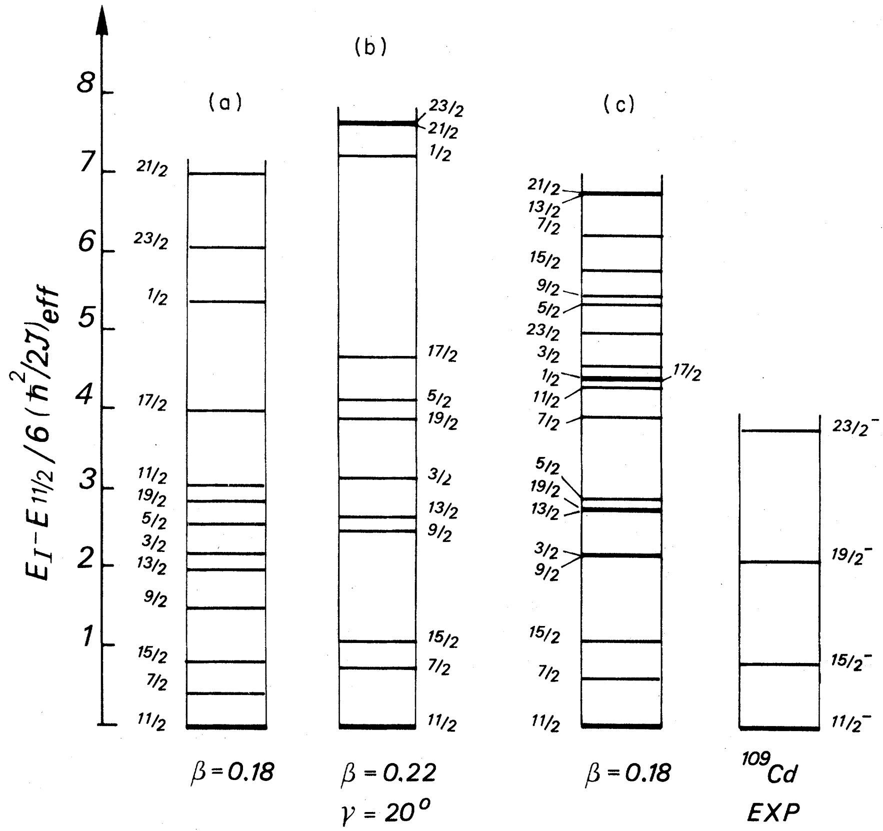

FIG. 7. Comparison between theoretical and experimental negative parity levels built on the $\frac{11}{2}^-$ intrinsic state. The calculated schemes noted (a), (b), and (c) are extracted from Refs. 3, 16, and 17, respectively.

descriptions of the *e*-*e* rotational core have been proposed: a pure rotor (R^2), a modified one ($R^2 + BR^4 + CR^6$), an asymmetric one by Stephens and co-workers,[3,15,16] and also a rotor including an inertia moment varying with the spin R by Quentin *et al.*[17] We can notice in Fig. 7 that, for a given deformation $\beta \simeq 0.18$ [value extracted from the $B(E2;\ 2 \rightarrow 0)$ of the *e*-*e* adjacent cores $^{108-110}$Cd nuclei], the sequence of spin of the various predicted level schemes is the same for the $\frac{11}{2}^-$ decoupled negative parity band states and in particular the position of $\frac{13}{2}^-$, $\frac{17}{2}^-$, and $\frac{21}{2}^-$ states.

It is also interesting to notice that if the $^{112-110}$Cd and probably ^{108}Cd[18,19] nuclei present the backbending behavior, Fig. 8 shows that this phenomena, if it exists, does not take place at the same value of (rotational value)^2 or spin in ^{109}Cd. One possible explanation is the effect of blocking of the external neutron ($\nu h_{11/2}$), the orbital of which is already involved in the g.s.b. of ^{108}Cd and responsible for the anomalous behavior of the *e*-*e* core. The same situation seems to occur in $^{127-129}$La (Ref. 20). One of the two sequences of 3058.4 keV ($\frac{21}{2}$), 3523.6 keV ($\frac{25}{2}$) states and 3382.5 keV ($\frac{19}{2}$, $\frac{23}{2}$), 3938.8 keV ($\frac{23}{2}$, $\frac{27}{2}$) states is analogous of the 5^-, 7^- states observed in $^{108-110}$Cd (Refs. 18 and 19): This similarity is also suggested by the probable $E2$ nature of the corresponding transitions. The same situation arises in Hg (Ref. 21),

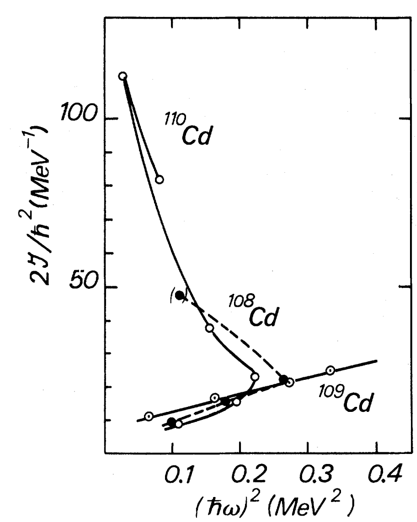

FIG. 8. Backbending plots for $^{108-109-110}$Cd isotopes.

Ba (Ref. 22), and also in Pt (Ref. 23). In a very simple picture we can deduce the $^{109-111}$Cd schemes from the $^{108-110}$Cd cores, just by adding *e-e* core $+\nu(h_{11/2})$. Complimentary experiments on lighter Cd isotopes are necessary to draw conclusions on the structure of these nuclei and are in progress in our group.

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[1]P. C. Simms, G. J. Smith, F. A. Rickey, J. A. Grau, J. R. Tesmer, and R. M. Steffen, Phys. Rev. C 9, 684 (1974).

[2]D. Proetel, D. Benson, Jr., A. Gizon, M. R. Maier, R. M. Diamond, and F. S. Stephens, Nucl. Phys. A226, 237 (1974).

[3]F. S. Stephens, in *Proceedings of the International Conference on Nuclear Physics, Munich 1973,* edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam/American Elsevier, New York, 1973), Vol. 2, p. 367.

[4]J. Rivier and R. Moret, Nucl. Phys. A149, 337 (1970).

[5]U. Hagemann, H. F. Brinckmann, W. D. Fromm, C. Heiser, and H. Rotter, Nucl. Phys. A228, 112 (1974).

[6]D. Barnéoud, C. Foin, A. Baudry, A. Gizon, and J. Valentin, Nucl. Phys. A154, 653 (1970).

[7]J. T. Routti, UCRL Report No. UCRL-19452, 1969 (unpublished).

[8]J. Danière, R. Rougny, E. Descroix, D. Charnay, R. Billerey, and H. Chevallier, Nucl. Instrum. Methods 115, 165 (1974).

[9]D. H. Bloch, D. Frosch, E. J. Jaeschke, H. Pauli, and E. Rindsdorf, *Hyperfine Interactions in Nuclei,* edited by G. Goldring and E. Kalish (Gordon and Breach, New York, 1971), p. 356.

[10]D. C. Camp and A. L. Van Lehn, Nucl. Instrum. Methods 76, 192 (1969).

[11]H. Bertschat, J. Christiansen, H. E. Mahnke, E. Recknagel. G. Schatz, R. Sielemann, and W. Witthuhn, Phys. Rev. Lett. 25, 102 (1970).

[12]T. Yamazaki, Nucl. Data A3, 1 (1967).

[13]J. A. Grau, Nucl. Phys. A229, 346 (1974).

[14]N. Imanishi, I. Fujiwara, and T. Nishi, Nucl. Phys. A205, 531 (1973).

[15]F. S. Stephens and R. S. Simon, Nucl. Phys. A183, 257 (1972).

[16]J. Meyer ter Vehn, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 32, 1383 (1974).

[17]M. A. Deleplanque, C. Gerschel, N. Perrin, and P. Quentin, Phys. Lett. 46B, 312 (1973).

[18]A. H. Lumpkin, A. W. Sunyar, K. A. Hardy, and J. K. Lee, Phys. Rev. C 9, 258 (1974).

[19]R. Geiger, P. Von Brentano, H. G. Friederichs, B. Heits, W. Schuh, K. O. Zell, H. Weigmann, and A. Berinde, Z. Phys. 271, 129 (1974).

[20]D. Ward, H. Bertschat, P. A. Butler, P. Colombani, R. M. Diamond, and F. S. Stephens (unpublished).

[21]D. Proetel, R. Diamond, and F. S. Stephens, Nucl. Phys. A231, 301 (1974).

[22]C. Flaum, D. Cline, A. W. Sunyar, and O. C. Kistner, Phys. Rev. Lett. 33, 973 (1974).

[23]M. Piiparinen, J. C. Cunnane, P. J. Daly, C. L. Dors, F. M. Bernthal, and T. L. Khoo, Phys. Rev. Lett. 34, 1110 (1975).