

Lifetime measurements of strongly deformed rotational bands in ^{133}Pm

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We have measured lifetimes and deduced deformation parameters for rotational bands in ^{133}Pm by the Doppler-shift attenuation method. A strongly coupled band based on the configuration with a hole in the $g_{9/2}$ orbital has deformation parameter $\beta_2=0.40$ (5), which is comparable to or larger than typical superdeformed bands in the $A\sim 130$ region. We observe this band in ^{133}Pm down to its $I=K=9/2$ bandhead. Calculations with a configuration-dependent shell correction to the cranked Nilsson potential can explain the existence of such low-spin superdeformed structures in the $A\sim 130$ region. These shapes, which also occur in $^{129,131}\text{Pr}$, can be observed experimentally because of relatively low-lying shell gaps for $\beta_2=0.4$ near $Z=58$, $N=72$. No high-spin intruder orbitals ($\nu i_{13/2}$) are occupied (over the spin range observed), however the strongly deformation-driving properties of a hole in the extruder $\pi g_{9/2}$ orbital appear to be an essential ingredient in lowering the energy of the superdeformed shape. [S0556-2813(96)02809-9]

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I. INTRODUCTION

There is presently a great deal of activity in the γ -ray spectroscopy of nuclei at high angular momentum. In part, this has been stimulated by the interest in superdeformed nuclei, but more generally the field is concerned with the structure of nuclei and how that structure responds to angular momentum. In this work, we focus interest on rotational bands at low excitation and angular momentum that have deformations as large as those of superdeformed bands in their mass region.

Superdeformed nuclei are generally considered to belong to the mass regions $A\sim 130$, 150, 190, and 240 as compiled for example by Firestone and Singh [1]. We might also consider the $A\sim 140$ nuclei as separate from the $A\sim 150$ region [2]. More recently, Baktash *et al.* [3] have discovered a mass region for superdeformation near $A\sim 80$.

Until recently the main ingredients for producing superdeformation were considered to be (1) large (and complementary) shell gaps in the proton and neutron single-particle energies at the appropriate deformation and (2) the occupation of so-called "intruder" orbitals. These orbitals arise from the next higher shell and intrude into the valence space because they are strongly down sloping with increasing quadrupole deformation and rotational frequency. The significance of intruder orbitals in determining the deformation has recently been called into question by the observation of

superdeformed bands in ^{129}Pr and ^{131}Pr where no intruder orbitals are occupied [4,5]. Furthermore, our recent lifetime measurements for the superdeformed bands of ^{129}Ce [6], ^{131}Ce , and ^{132}Ce [7] ($Q_0=6.1$, 6.4, and 7.1 e b), respectively, suggest that the polarizing effect of neutrons in the $i_{13/2}$ orbitals is small in the Ce isotopes.

Our motivation in studying ^{133}Pm was to examine the spectroscopy, and to measure lifetimes for the $\pi g_{9/2}^{-1}$ configuration, which the earlier work in $^{129,131}\text{Pr}$ suggested could be superdeformed.

II. EXPERIMENT

The Tandem accelerator of the TASCC facility at AECL's Chalk River Laboratories provided a beam of ^{40}Ca ions at 176 MeV. The beam (typically 4 pna) was directed onto a target comprising a ruthenium foil of 400 $\mu\text{g cm}^{-2}$ enriched to 98% in ^{96}Ru , backed with a gold foil of 12.5 mg cm^{-2} . The gold foil was thick enough to stop recoils from fusion reactions. Gamma-ray spectroscopy was performed with the 8π spectrometer which comprises 20 HPGe detectors with BGO anti-Compton shields, and a spherical shell of 71 BGO scintillation detectors. Events were processed and written to tape on a trigger exceeding K hits on the BGO ball (where $K\geq 9$) and M hits on the HPGe array (after suppression) where $M\geq 2$.

A variety of replay programs were used in processing the data. For the spectroscopy of ^{133}Pm , all coincident pairs recorded in the HPGe array were stored in an $E\gamma$ - $E\gamma$ coincidence matrix with conditions on the sum γ -ray energy, H , registered in the BGO ball, $12<H<25$ MeV. This range was chosen to enhance the three-particle-out channels, e.g., ^{133}Pm , at the expense of the two-particle (higher H) and

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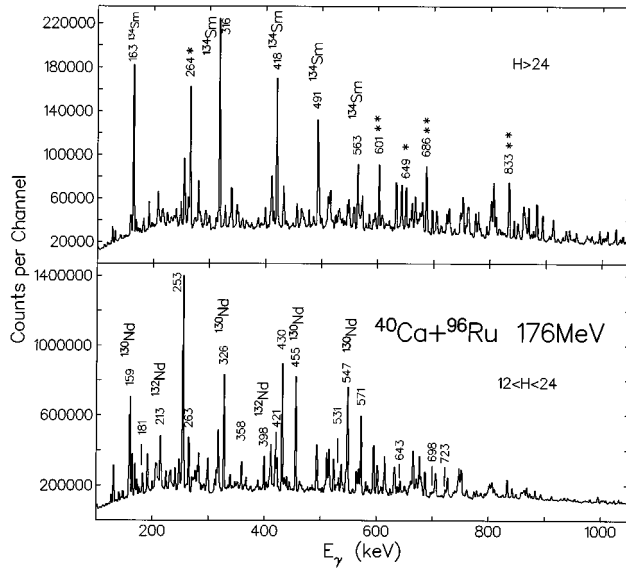


FIG. 1. Projections of the γ - γ coincidence matrix. Good separations of channels involving two (top panel), three (bottom panel), and four particles out was obtained by gating on the total energy parameter H recorded in the BGO ball. Only transitions of special interest are labeled. Transitions without a nucleus assignment are assigned to ^{133}Pm . Approximately 275 transitions were placed in the level schemes of ^{133}Pm , ^{133}Sm , ^{130}Nd , ^{132}Nd , and ^{134}Sm . Transitions marked with * and ** are members of long cascades with irregular spacings that are assigned to ^{99}Pd and ^{96}Ru arising from reactions with $^{63,65}\text{Cu}$ which contaminated the target during the electrodeposition process.

four-particle (lower H) channels (cf. Fig. 1). This matrix contained 154×10^6 pairs.

For the application of the Doppler-shifted attenuation method (DSAM) techniques, events were sorted into two matrices having in case 1 an event at any HPGe detector angle versus an event in the forward ring ($+37^\circ$), and in case 2, any angle versus the backward ring (-37°). The same conditions on H were applied and these matrices contained approximately 80×10^6 pairs. For applications of γ - γ directional correlation techniques (afterwards called DCO ratios) a variety of matrices were constructed, but the most useful results were obtained by considering intensity ratios between a matrix containing only $\pm 37^\circ$ pairs and a matrix containing only $\pm 79^\circ$ pairs. The same conditions on H were applied, and these matrices contained approximately 43×10^6 and 31×10^6 pairs, respectively.

III. ANALYSIS

A. Level scheme

The level scheme for ^{133}Pm has been studied most recently by Regan *et al.* [8]. The present level scheme is shown in Fig. 2 where we have used their nomenclature for labeling the bands. Our results are in general agreement as regards bands 1–4; in addition, we see transitions linking band 3 to band 1, which allow us to fix their relative excitation energies as well as that for band 4. As shown later, these linking transitions are $\Delta J=0$ and fix the spins of bands 3 and

4 to be one unit lower than assigned in [8]. We also found a new band (band 7) that decays to bands 1/2 over the spin range $15/2$ – $31/2$.

The main area of disagreement concerns how bands 5 and 6 are attached to the level scheme. Our scheme is based on γ - γ coincidence spectra of the quality illustrated in Fig. 3. We suggest that the corresponding spectrum shown in [8] (Fig. 9) contained impurity transitions in the gates which show γ_{410} and γ_{263} keV of band 2. These two γ rays are not in coincidence with bands 5 and 6 in our data (cf. Fig. 3).

The linking of bands 5 and 6 to bands 3 and 4 in our scheme indicates a much lower spin value for the bandhead than was suggested in [8], and as shown below, we propose that these bands are superdeformed and are based on configurations containing a hole in the $\pi g_{9/2}$ orbital, i.e., a $[404]_{9/2}$ Nilsson assignment. They therefore belong to the same configuration as the superdeformed bands found in ^{129}Pr [5] and ^{131}Pr [4].

B. Directional correlations (DCO ratios)

Gamma-ray transition energies, intensities, DCO ratios, and assignments are given in Table I. A DCO ratio is defined from the intensity of a given pair of coincident transitions in the two matrices corresponding to $\pm 37^\circ/\pm 37^\circ$ and $\pm 79^\circ/\pm 79^\circ$ correlations:

$$\text{DCO} = I_{\gamma\gamma}^{\text{coinc pair}(\pm 37^\circ)} / I_{\gamma\gamma}^{\text{coinc pair}(\pm 79^\circ/\pm 79^\circ)}. \quad (1)$$

The gamma-ray intensities must be corrected for detection efficiency. If the coincident pair are known to be stretched $E2$ transitions, then the DCO ratio provides a measure of the nuclear spin alignment.

In this work, calculated DCO ratios take an initial state of high spin with a particular degree of spin alignment parametrized by a Gaussian distribution of m substates centered at $m=0$, and the standard deviation, σ , is expressed as a dimensionless factor, σ/J . This initial state is assumed to decay by unobserved stretched transitions to the state of interest, which defines σ/J (in the calculation) for subsequent states.

DCO ratios were calculated for all common γ_1 - γ_2 correlations as a function of σ/J , J , and the mixing ratio $\delta=E2/M1$ where applicable. These calculations are specific to our geometry $\theta_1=\pm 37^\circ$, $\theta_2=\pm 79^\circ$ and results are averaged over the azimuthal variables appropriate to the instrument.

The spin alignment given by the DCO ratios (cf. Table I) for strong pairs of transitions both of which have stretched $E2$ character ($\text{DCO}=1.99 \pm 0.06$) corresponds with $\sigma/J=0.23 \pm 0.03$ at $J=17$.

A powerful method to extract $E2/M1$ mixing ratios (δ) for transitions between signature-degenerate bands is to choose neighboring $J \rightarrow (J-1)$ transitions as the coincident γ - γ pair in a DCO ratio. In general, such a DCO ratio cannot be interpreted since two unknown mixing parameters δ_1 and δ_2 enter into it. However, in signature-degenerate bands, the mixing ratio must change very slowly with spin, except at a sharp alignment gain. We have exploited this property by evaluating DCO ratios for $J \rightarrow (J-1) \rightarrow (J-2)$ γ - γ pairs where δ is in common.

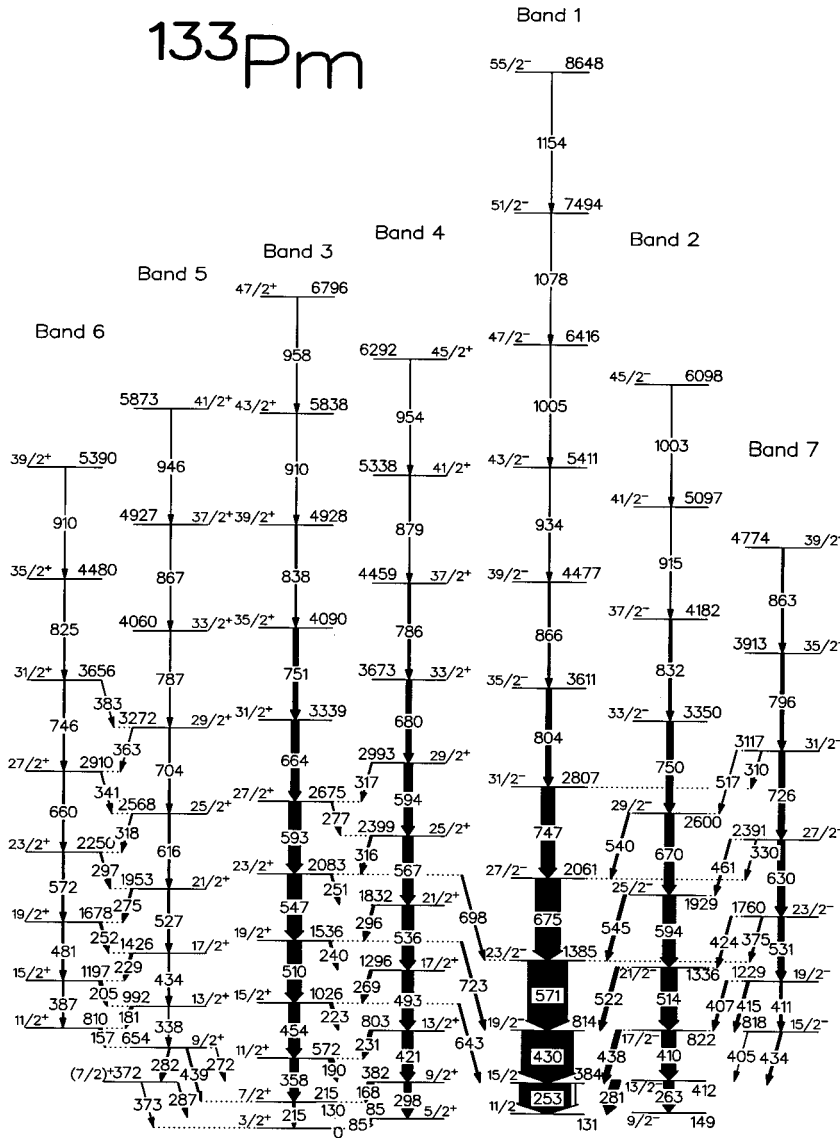


FIG. 2. Level scheme for ^{133}Pm from this work. Note that the lowest state shown need not be the ground state, since this experiment was not sensitive to isomeric decays.

C. Spin assignments

Band 3: The three transitions linking band 3 to band 1 must change parity since the parities of these bands are established [8]. Furthermore, we may assume that any $M2$ mixing would be extremely weak, since these transitions compete with collective $E2$'s in band 3. Therefore, the DCO values shown in Table I are compatible only with $J \rightarrow J$ assignments (DCO=1.93 for $\delta=0$) and not with $J \rightarrow J \pm 1$ (DCO=1.13 for $\delta=0$).

Band 7: Band 7 decays to band 1 and band 2 over a spin range $15/2-31/2$ and with any plausible choice for the spins, it follows that either the set of transitions to band 1 or the set to band 2 must have $J \rightarrow J \pm 1$ assignments. Table I shows that both these sets have DCO ratios near the value DCO=2, and therefore, the set with $J \rightarrow J \pm 1$ assignment must have strongly mixed $E2/M1$ character which implies negative parity for band 7. The DCO ratios do not allow us to distinguish which sequence has $J \rightarrow J \pm 1$ and we chose the most plausible assignment.

Band 5/6: The observed branching and DCO ratios restrict the bandhead (654 keV) to spin $5/2$, $7/2$, or $9/2$. Our assignment of $9/2$ is based on the fact that the bands are signature-

degenerate partners of a high- K , one-quasiparticle orbital for which the only candidate acceptable to theory is the $\pi g_{9/2}$. As shown later, analysis of $B(E2)$ ratios in these bands shows that the K value is $9/2$, and the measured $B(M1)/B(E2)$ ratios are consistent only with $\pi g_{9/2}$.

The state at 372 keV is most probably $7/2^+$.

D. Analysis of $B(M1)$ and $B(E2)$ values between signature-partner bands

Table II shows results for the branching ratios, and $E2/M1$ mixing ratios (δ) measured for transitions between the signature-partner bands $3/4$, $5/6$, and $1/2$. For the case of bands $3/4$ we have compared results for the mixing ratio derived from DCO values involving mixed- $E2$, with those derived from mixed-mixed sequences. The agreement is seen to be good, with the mixed-mixed analysis giving a more precise value. This is because the gradient of the function DCO versus δ in the mixed-mixed case is approximately double that in the conventional analysis (mixed $E2$). For band $5/6$, the advantage of this method is even greater since the $E2$ transitions are very weak.

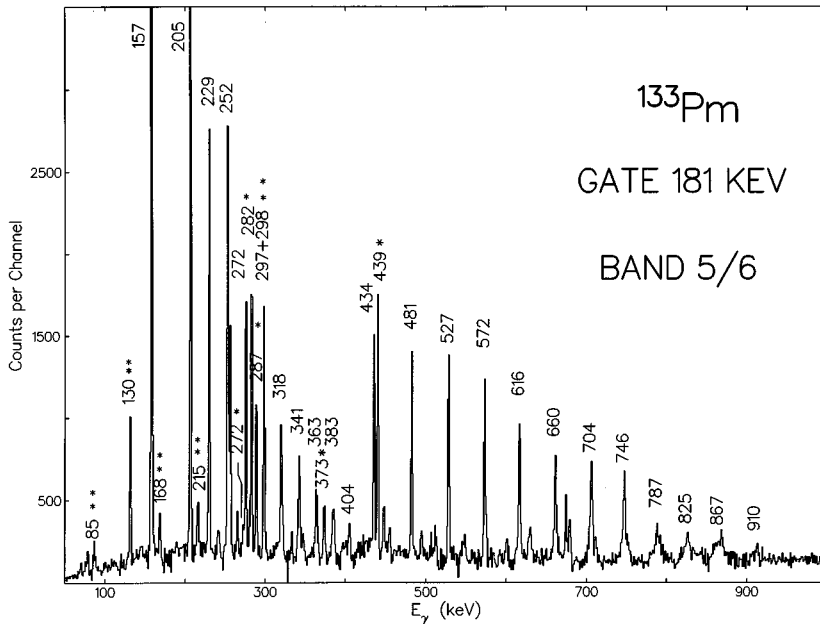


FIG. 3. Coincidence spectrum with γ 181 keV (labeled in Fig. 1) showing the strongly coupled superdeformed band in ^{133}Pm and its linking transitions (*) to the normal states (**). Note that the vertical scale cutoffs the peaks at 157 and 205 keV.

From the branching ratios and mixing ratios we have evaluated the ratios $B(M1; J \rightarrow J-1)/B(E2; J \rightarrow J-2)$ and $B(E2; J \rightarrow J-1)/B(E2; J \rightarrow J-2)$ shown in Table II and in Figs. 4 and 5. The $B(E2)$ ratios are very sensitive measures of the K value for the band. Clearly in Fig. 5, bands 5/6 have $K=9/2$ and bands 3/4 have $K=3/2$ character.

The $B(M1)/B(E2)$ ratios for signature-degenerate bands with no spin alignment are sensitive measures of the configuration through the g factor, g_K , and the K value. Spin alignment is a complicating factor, but it can be taken into account with the geometric model of Donau and Frauendorf [9]: we have for a three-quasiparticle state

$$B(M1; J \rightarrow J-1) = \frac{3}{8\pi} \frac{K^2}{J^2} \{ (g_K - g_R) [(J^2 - K^2)^{1/2} - i] - (g^{(2)} - g_R) i^{(2)} \}^2 \mu_N, \quad (2)$$

where g_R is the g factor for collective rotation and i is the aligned spin of the one-quasiparticle orbit that contributes both its signatures to the band. The two-quasiparticle component has alignment $i^{(2)}$ and g factor $g^{(2)}$.

Assuming $g_R = Z/A = 0.46$, and our measured Q_0 values (see Sec. III E), we compare the measured $B(M1)/B(E2)$ ratios with those calculated from Eq. (2) with $g_K(\pi g_{9/2}) = 1.27$, $g_K(\pi h_{11/2}) = 1.17$, $g_K(\pi d_{5/2}) = 1.38$, and $g_K(\pi g_{7/2}) = 0.72$, which are standard values for the region originally suggested by Lonroth *et al.* [10]. The one-quasiparticle alignments were taken from experiment: $i=0, 1, \text{ and } 4$ for bands 5/6, 3/4, and 1/2, respectively. Bands 3/4 and 1/2 experience an alignment gain, $i^{(2)}$, which was taken from experiment and assumed to arise from the $\pi(h_{11/2})^2$ configuration.

The results are shown in Fig. 4. We find good agreement with the $(g_{9/2}, K=9/2)$ assignment for bands 5/6. For bands 3/4, the best agreement is obtained for a $\pi d_{5/2}, K=3/2$ configuration, however with the experimental aligned spin included as in Eq. (2), the calculation is about a factor of 2 too small. Nevertheless, the only other plausible assignment, $\pi g_{7/2}, K=5/2$ is ruled out by the experimental determination of the K value $=3/2$ (see Fig. 5) and by the calculated $B(M1)/B(E2)$ ratios for a $\pi g_{7/2}, K=5/2$ configuration, which are an order of magnitude smaller than the observed

values for bands 3/4. This is readily understood from the Schmidt rules which give a much larger magnetic moment for $\pi d_{5/2}$ than for $\pi g_{7/2}$.

The transitions from band 2 to band 1 have very small $B(M1)$ values as seen in Fig. 4. This is consistent with the geometric model and indicates a near cancellation of the term $(J^2 - K^2)^{1/2}$ with the aligned spin term, i , at low spin in Eq. (2). The sign of the mixing ratio, δ , was measured to be positive (cf. Table II) therefore, the term $(J^2 - K^2)^{1/2} > i$ for $J \geq 13/2$. A rise in the experimental $B(M1)$ with spin is expected from Eq. (2), but the detailed shape is not reproduced in Fig. 4.

E. DSAM analysis

We have made a DSAM analysis of bands 1–6 in ^{133}Pm . Because bands 5 and 6 are strongly coupled, and show nearly degenerate signature partners with strong connecting dipole transitions, they had to be analyzed as a pair. Bands 1–4 could be analyzed as individual bands; although they have significant branching at low spin, this becomes negligible for spins above $31/2$ where the DSAM analysis was performed. Typical spectra are shown in Figs. 6 and 7. The DSAM code used as input the electronic stopping powers in tabular form and we took scaled [11] Northcliffe and Schilling values [12]. The nuclear stopping was treated according to the for-

TABLE I. Gamma-ray transitions assigned to ^{133}Pm . Values in column *A* refer to averages over adjacent gating transitions known to be $\Delta J=2$, *E2*. Values in column *B* refer to averages over adjacent $\Delta J=1$ mixed *M1/E2* transitions and are meaningful only for transitions between signature-partner bands, cf. text.

Band(s)	$E\gamma$ (keV)	$I\gamma$	DCO ratio ^a		$J_i^\pi \rightarrow J_f^\pi$	
			<i>A</i>	<i>B</i>		
1	252.8	140(3)	2.02(4)		$15/2^- \rightarrow 11/2^-$	
	430.0	137(6)	1.99(5)		$19/2^- \rightarrow 15/2^-$	
	571.4	104(5)	2.01(10)		$23/2^- \rightarrow 19/2^-$	
	675.4	66(3)			$27/2^- \rightarrow 23/2^-$	
	746.5	39(3)			$31/2^- \rightarrow 27/2^-$	
	803.8	26(2)			$35/2^- \rightarrow 31/2^-$	
	865.7(3)	21(2)			$39/2^- \rightarrow 35/2^-$	
	934.3(5)	10(1)			$43/2^- \rightarrow 39/2^-$	
	1005(1)	9(1)			$47/2^- \rightarrow 43/2^-$	
	1078(1)	5(1)			$51/2^- \rightarrow 47/2^-$	
	1154(2)	3.7(6)			$55/2^- \rightarrow 51/2^-$	
2	262.9	25(1)	1.92(15)		$13/2^- \rightarrow 9/2^-$	
	410.1	36(2)	2.08(17)		$17/2^- \rightarrow 13/2^-$	
	513.9	41(3)	1.93(15)		$21/2^- \rightarrow 17/2^-$	
	593.8	34(3)	2.09(20)		$25/2^- \rightarrow 21/2^-$	
	670.5	25(3)			$29/2^- \rightarrow 25/2^-$	
	749.8(2)	23(2)			$33/2^- \rightarrow 29/2^-$	
	832.3(3)	16(2)			$37/2^- \rightarrow 33/2^-$	
	915(1)	12(2)			$41/2^- \rightarrow 37/2^-$	
	1003(1)	8(2)			$45/2^- \rightarrow 41/2^-$	
1/2	281.1	23(1)	2.49(8)		$13/2^- \rightarrow 11/2^-$	
	438.3	13(1)	2.36(10)		$17/2^- \rightarrow 15/2^-$	
	522.2	9.5(6)	2.38(15)		$21/2^- \rightarrow 19/2^-$	
	544.6	7.8(6)	1.7(2)		$25/2^- \rightarrow 23/2^-$	
	539.7	5(1)	1.9(2)		$29/2^- \rightarrow 27/2^-$	
3	214.7	5.8(6)			$7/2^+ \rightarrow 3/2^+$	
	357.7	21.3(9)	1.99(9)		$11/2^+ \rightarrow 7/2^+$	
	453.8	29(1)	1.98(10)		$15/2^+ \rightarrow 11/2^+$	
	509.7	36.7(15)	1.92(15)		$19/2^+ \rightarrow 15/2^+$	
	546.7	37.7(15)			$23/2^+ \rightarrow 19/2^+$	
	592.9	31.6(20)			$27/2^+ \rightarrow 23/2^+$	
	663.8(2)	22(1)			$31/2^+ \rightarrow 27/2^+$	
	751.0(3)	19(2)			$35/2^+ \rightarrow 31/2^+$	
	838(1)	15(2)			$39/2^+ \rightarrow 35/2^+$	
	910(1)	10(2)			$43/2^+ \rightarrow 39/2^+$	
	958(1)	9(3)			$47/2^+ \rightarrow 43/2^+$	
	4	297.9	17(8)	1.93(13)		$9/2^+ \rightarrow 5/2^+$
		420.8	27.2(12)	1.98(15)		$13/2^+ \rightarrow 9/2^+$
492.5		29.2(15)	2.01(10)		$17/2^+ \rightarrow 13/2^+$	
535.9		29.4(15)			$21/2^+ \rightarrow 17/2^+$	
566.8		26.7(15)			$25/2^+ \rightarrow 21/2^+$	
594.5		22(2)			$29/2^+ \rightarrow 25/2^+$	
680.2(2)		13.5(7)			$33/2^+ \rightarrow 29/2^+$	
786.1(3)		12(1)			$37/2^+ \rightarrow 33/2^+$	
879(1)		8.9(1.8)			$41/2^+ \rightarrow 37/2^+$	
954(1)		5.7(1.5)			$45/2^+ \rightarrow 41/2^+$	
3/4	84.6	~2			$5/2^+ \rightarrow 3/2^+$	
	129.8	14.6(15)	1.45(5)	1.00(4)	$7/2^+ \rightarrow 5/2^+$	
	167.5	13.0(6)	1.49(7)	1.07(4)	$9/2^+ \rightarrow 7/2^+$	
	189.7	11.2(6)	1.43(11)	1.09(6)	$11/2^+ \rightarrow 9/2^+$	
	230.7	8.9(5)	1.46(9)	1.06(8)	$13/2^+ \rightarrow 11/2^+$	
	222.8	6.9(3)	1.35(9)	1.00(8)	$15/2^+ \rightarrow 13/2^+$	

TABLE I. (*Continued*).

Band(s)	$E\gamma$ (keV)	$I\gamma$	DCO ratio ^a		$J_i^\pi \rightarrow J_f^\pi$	
			A	B		
5	269.4	6.8(4)	1.38(10)	0.93(10)	$17/2^+ \rightarrow 15/2^+$	
	240.0	4.9(3)	1.38(10)	0.92(10)	$19/2^+ \rightarrow 17/2^+$	
	295.6	5.6(3)	1.35(12)		$21/2^+ \rightarrow 19/2^+$	
	250.8	3.6(2)			$23/2^+ \rightarrow 21/2^+$	
	315.8(3)	4.7(4)			$25/2^+ \rightarrow 23/2^+$	
	277.4(3)	2.3(2)			$27/2^+ \rightarrow 25/2^+$	
	317.3(5)	2.4(3)			$29/2^+ \rightarrow 27/2^+$	
	338.4(3)	1.51(15)			$13/2^+ \rightarrow 9/2^+$	
	434.5(2)	3.45(25)			$17/2^+ \rightarrow 13/2^+$	
	526.8(2)	4.35(30)			$21/2^+ \rightarrow 17/2^+$	
	615.5(2)	4.0(3)			$25/2^+ \rightarrow 21/2^+$	
	704.3(4)	4.2(4)			$29/2^+ \rightarrow 25/2^+$	
	787.7(2)	3.0(6)			$33/2^+ \rightarrow 29/2^+$	
	866.7(3)	3.5(7)			$37/2^+ \rightarrow 33/2^+$	
	946(1)	2.2(5)			$41/2^+ \rightarrow 37/2^+$	
6	386.8(2)	2.27(20)			$15/2^+ \rightarrow 11/2^+$	
	481.0(2)	3.84(25)			$19/2^+ \rightarrow 15/2^+$	
	572.0(2)	4.0(3)			$23/2^+ \rightarrow 19/2^+$	
	660.0(2)	3.5(4)			$27/2^+ \rightarrow 23/2^+$	
	746.1(2)	3.7(6)			$31/2^+ \rightarrow 27/2^+$	
	824.7(3)	3.0(6)			$35/2^+ \rightarrow 31/2^+$	
	910(1)	2.0(5)			$39/2^+ \rightarrow 35/2^+$	
	5/6	156.5	5.4(3)		1.21(12)	$11/2^+ \rightarrow 9/2^+$
181.2		6.0(3)		1.28(12)	$13/2^+ \rightarrow 11/2^+$	
205.3		6.8(3)		1.21(12)	$15/2^+ \rightarrow 13/2^+$	
228.8		5.3(3)		1.25(12)	$17/2^+ \rightarrow 15/2^+$	
251.8		4.5(3)			$19/2^+ \rightarrow 17/2^+$	
274.6		4.0(3)		1.23(15)	$21/2^+ \rightarrow 19/2^+$	
297.1		3.0(4)			$23/2^+ \rightarrow 21/2^+$	
318.4		2.2(5)			$25/2^+ \rightarrow 23/2^+$	
341.4		1.9(4)			$27/2^+ \rightarrow 25/2^+$	
362.6(2)		1.4(3)			$29/2^+ \rightarrow 27/2^+$	
383.7(4)		1.6(4)			$31/2^+ \rightarrow 29/2^+$	
404(1)		1.0(4)			$33/2^+ \rightarrow 31/2^+$	
From Band 5		271.6(10)	0.9(1)			$9/2^+ \rightarrow 9/2^+$
		439.1(2)	3.7(3)	1.27(25)		$9/2^+ \rightarrow 7/2^+$
	281.6(2)	3.3(3)	1.30.(35)		$9/2^+ \rightarrow (7/2)^+$	
	287.4(2)	2.1(1)	1.22(15)		$(7/2)^+ \rightarrow 5/2^+$	
	372.6(7)	1.2(6)			$(7/2)^+ \rightarrow 3/2^+$	
3/1	643(1)	4.3(4)	1.9(2)		$15/2^+ \rightarrow 15/2^-$	
	723(1)	5.3(4)	1.7(2)		$19/2^+ \rightarrow 19/2^-$	
	698(1)	3.7(4)	1.8(2)		$23/2^+ \rightarrow (23/2)^-$	
7	411.0(3)	5.6(5)			$(19/2) \rightarrow (15/2)^-$	
	531.4	14.9(7)			$(23/2)^- \rightarrow (19/2)^-$	
	630.3	19.2(9)			$(27/2)^- \rightarrow (23/2)^-$	
	725.9(3)	16.2(16)			$(31/2)^- \rightarrow (27/2)^-$	
	796(1)	8(3)			$(35/2)^- \rightarrow (31/2)^-$	
	862(1)	~ 4			$(39/2)^- \rightarrow (35/2)^-$	
7/1	433.9	5.4(7)	2.05(15)		$(15/2)^- \rightarrow 15/2^-$	
	415.0	5.9(6)	1.95(25)		$(19/2)^- \rightarrow 19/2^-$	
	374.9	3.8(3)	2.10(15)		$(23/2)^- \rightarrow 23/2^-$	
	329.9	2.1(3)			$(27/2)^- \rightarrow 27/2^-$	
	309.5	2.2(3)			$(31/2)^- \rightarrow 31/2^-$	

TABLE I. (Continued).

Band(s)	$E\gamma$ (keV)	$I\gamma$	DCO ratio ^a		$J_i^\pi \rightarrow J_f^\pi$
			A	B	
7/2	405.1(4)	3.0(3)			(15/2) ⁻ → 13/2 ⁻
	406.6(3)	5.4(4)	1.9(2)		(19/2) ⁻ → 17/2 ⁻
	424.1(3)	4.3(3)	1.8(3)		(23/2) ⁻ → 21/2 ⁻
	461.1(2)	3.8(4)			(27/2) ⁻ → 25/2 ⁻
	516.6(3)	1.6(3)			(31/2) ⁻ → 29/2 ⁻

^aDCO ratios are $I\gamma\gamma(\pm 37^\circ, \pm 37^\circ)/I\gamma\gamma(\pm 79^\circ, \pm 79^\circ)$.

mulas of Lindhard *et al.* [13] as parametrized by Winterbon [14]. Corrections for multiple scattering were introduced according to the prescription of Blaugrund [15]. The code analyzed peak centroids or full line shapes for either a single band or for signature-partner bands, in which case branching ratios were entered as input. The time history for feeding the band was simulated by adding extra transitions at the top of the cascade, and by introducing sidefeeding at each stage of the cascade. The sidefeeding was parametrized as a rotational band with an intrinsic quadrupole moment, $Q_0(\text{SF})$, and moment of inertia, of $I^{(1)}(\text{SF})$; the sidefeeding intensities were taken from experiment.

Centroid shifts extracted from the data and normalized to the maximum possible shifts (F values) are shown in Fig. 8. The simplest analysis is to assume that the lifetimes in the band are given by a rotational model, and that the time history of sidefeeding is the same as that for feeding down the band. We have

$$T(E2) = 1.225 \times 10^{13} E_\gamma^5 B(E2) \text{ sec}^{-1}, \quad (3)$$

$$B(E2; J_1 \rightarrow J_f) = 5/16 \pi Q_0^2 \langle J_1 K 20 | J_f K \rangle^2 e^2 \text{ b}^2, \quad (4)$$

where E_γ is in MeV, and the $B(E2)$ in units of $e^2 \text{ b}^2$. We can

TABLE II. Summary of $E2/M1$ mixing ratios, δ , $M1$, and $E2$ reduced matrix elements.

		δ				
	Initial spin I	γ -ray transition (keV)	$B(M1)/B(E2) \times [1 + \delta^2]$	A mixed- $E2$	B mixed-mixed	$B(E2; J \rightarrow J-1)/B(E2; J \rightarrow J-2)$
Band 3/4	7/2	130	0.36(4)	0.188(25)	0.150(16)	$0.68_{0.12}^{0.16}$
	9/2	168	0.263(14)	0.212(35)	0.178(16)	$0.42_{0.08}^{0.08}$
	11/2	190	0.31(2)	0.18(6)	0.195(24)	$0.46_{0.11}^{0.11}$
	13/2	231	0.244(14)	0.19(5)	0.175(30)	$0.20_{0.07}^{0.07}$
	15/2	223	0.281(16)	0.13(5)	0.15(3)	$0.18_{0.07}^{0.07}$
	17/2	269	0.243(16)	0.15(6)	0.12(4)	$0.07_{0.05}^{0.06}$
	19/2	240	0.23(2)	0.15(6)	0.12(4)	$0.08_{0.05}^{0.06}$
	21/2	296	0.226(15)	0.13(6)		
	23/2	251	0.209(13)			
	25/2	316	0.23(2)			
	27/2	277	0.18(2)			
	29/2	318	0.18(2)			
Band 5/6	11/2	157			0.23(3)	
	13/2	181	2.05(25)		0.25(3)	$5.3_{1.1}^{1.3}$
	15/2	205	2.1(2)		0.23(3)	3.5(9)
	17/2	229	1.31(12)		0.24(3)	2.0(5)
	19/2	252	1.31(12)			
	21/2	274	1.26(13)		0.23(5)	1.2(5)
	23/2	297	1.18(18)			
	25/2	318	1.06(25)			
	27/2	341	1.2(3)			
Band 2/1	13/2	281	0.036(2)	~1		
	17/2	438	0.035(3)	~1		
	21/2	522	0.033(3)	~1		
	25/2	545	0.07(1)			
	29/2	540	0.120(15)			

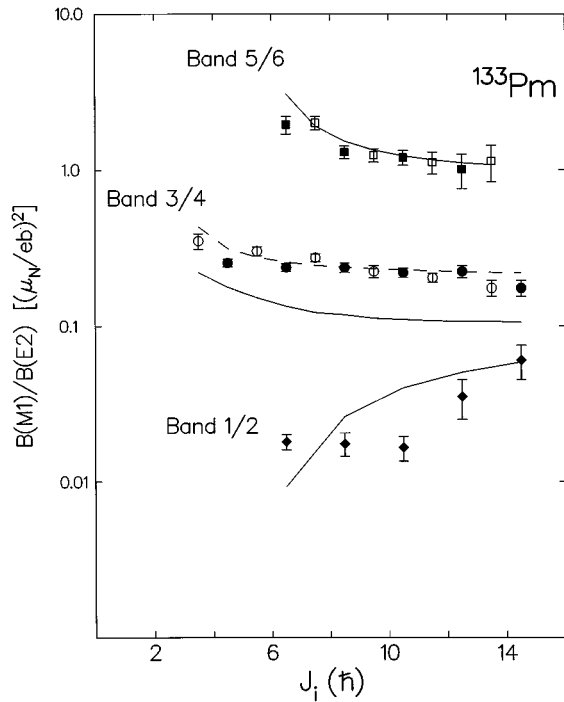


FIG. 4. Measured and calculated $B(M1)/B(E2)$ ratios for transitions between signature partner bands in ^{133}Pm . The solid line for band 5/6 and the dashed line for band 3/4 were calculated with no spin alignment. The solid lines for bands 3/4 and 1/2 use the experimental spin alignment with the Donau-Frauendorf formalism (cf. text).

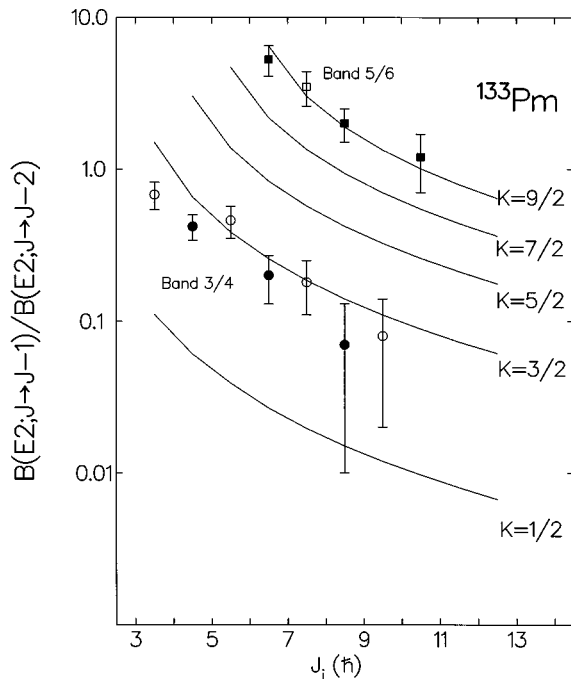


FIG. 5. Calculated (solid line) and measured ratios of $B(E2)$, values between signature partner bands. In a rigid rotor model these are given as the ratio of the appropriate Clebsh-Gordon coefficients (solid lines) which have a strong dependence on the K quantum number.

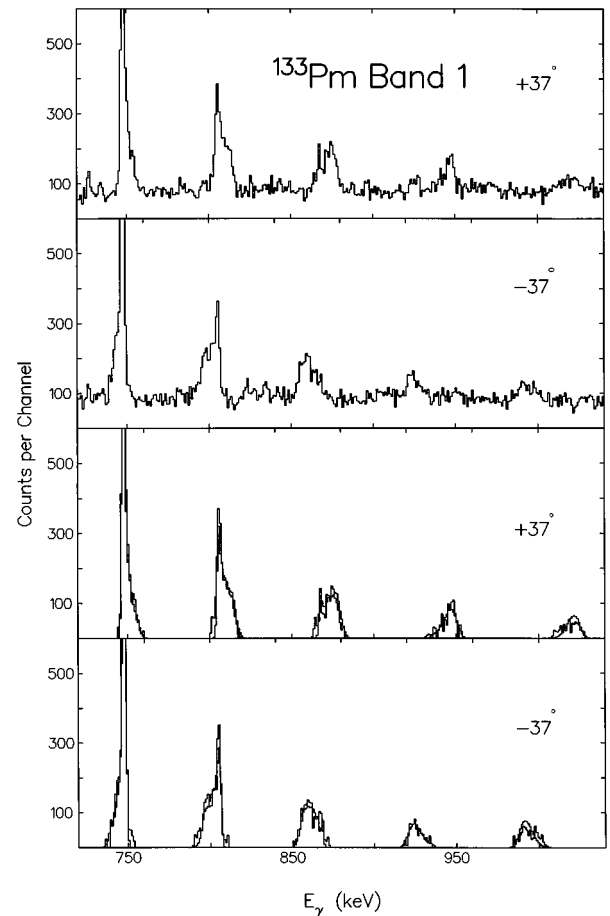


FIG. 6. Top panels: spectra in coincidence with γ_{675} keV in band 1, selected on all angles and projected for detectors in the $+37^\circ$ and -37° rings. Bottom panels: Background subtracted Doppler-broadened line shapes derived from the spectra shown in the top panels and compared with a line-shape calculation (cf. text). The fit shown corresponds with $Q_0=5.0$ e b ($J \geq 43/2^-$ $E\gamma \geq 934$ keV); $Q_0=5.2$ e b ($J=39/2^-$ $E\gamma=866$ keV); $Q_0=5.6$ e b ($J=35/2^-$ $E\gamma=804$ keV); and $Q_0=5.8$ e b ($J=31/2^-$ $E\gamma=747$ keV).

then fit the F curve with only one free parameter, namely Q_0 . At the next level of sophistication one can assume that the sidefeeding has a systematic character and can be parametrized with $Q_0(\text{SF})$. There are then two free parameters to fit the F curve. In the case of large side feeding intensity, there will be a large covariance between the parameters Q_0 and $Q_0(\text{SF})$ which limits the accuracy on Q_0 . To some degree, this uncertainty can be reduced by appealing to the line shapes which have a sensitivity to $Q_0(\text{SF})$ beyond that expressed in the centroids. It was not straightforward to assign uncertainties in the analysis. We have considered fits allowing Q_0 to vary with spin. Although there is some indication that Q_0 increases with decreasing spin, these effects are not outside the uncertainties. The adopted values and uncertainties quoted in Table III represent averages of different analyses with an uncertainty large enough to encompass the spread of the results.

Band 1: The processed spectra were from a single gate set on γ 675 keV (Fig. 6). The F curve is shown in Fig. 8. Because the sidefeeding was very strong, there was a large covariance between $Q_0(\text{band})$ and $Q_0(\text{SF})$, resulting in a flat

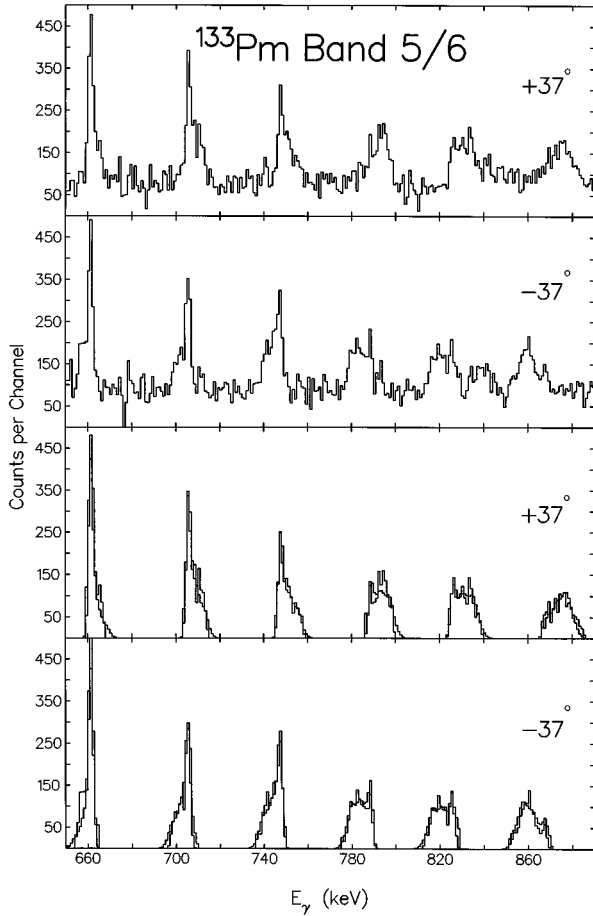


FIG. 7. Top panels: Spectra in coincidence with low-spin transitions in band 5/6 selected on all angles and projected for detectors in the $+37^\circ$ and -37° rings. Bottom panel: background-subtracted Doppler broadened line shapes from the spectra shown in the top panels compared with a line-shape calculation (cf. text). The fits shown correspond to $Q_0=7.35 e b$ for $J>29/2$, $E\gamma>704$ keV and $Q_0=8.3 e b$ for $J\leq 29/2$, $E\gamma\leq 704$ keV.

minimum of χ^2 extending from approximately $Q_0(\text{band})=5$, $Q_0(\text{SF})=5$ to $Q_0(\text{band})=7.5$, $Q_0(\text{SF})=2$. The line-shape analysis ruled out the extremes of slow and fast sidefeeding discussed below and agrees best for a sidefeeding history identical to that coming down the band. Results are summarized in Table III.

Bands 3/4: The spectra processed were sums of coincidence gates set on $E\gamma=168, 421, 536$, and 567 keV for band 4 and gates set on $E\gamma=130, 358$, and 510 keV for band 3. The data were similar to band 1 and are not shown. The sidefeeding was less severe than for band 1, and definitive results could be obtained by allowing $Q_0(\text{band})$ and $Q_0(\text{SF})$ to vary freely.

Bands 5/6: The F curve (Fig. 8) was generated from spectra obtained with a single gate on $\gamma 181$ keV; for higher statistical accuracy at the expense of bringing in contaminating transitions, the line shapes, Fig. 7, were analyzed from a sum of gates set on low spin transitions. There was relatively little sidefeeding into these bands, but there was a problem in defining the feeding history at high spins, since the fastest observed transitions had $F\approx 0.5$ (of Fig. 7). In this case we simulated the history at high spin by extending the level scheme by four rotational cascades in each signature above

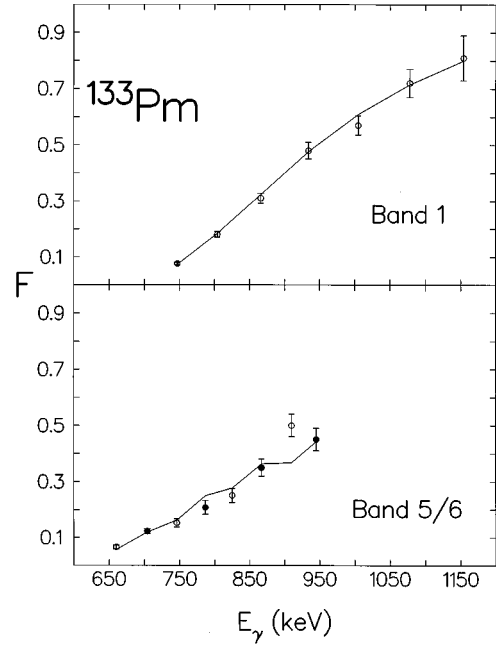


FIG. 8. Experimental and fitted values of the ratio $F=(\text{observed centroid shift}/\text{maximum shift})$ for rotational bands in ^{133}Pm . The fits shown for band 1 corresponds to $Q_0=5.0 e b$ ($J\geq 43/2^-$, $E\gamma\leq 934$ keV), $Q_0=5.2 e b$ ($J=39/2^-$, $E\gamma=866$ keV), and $Q_0=5.6$ ($J\leq 35/2^-$, $E\gamma\leq 804$ keV). The figure shown for band 5/6 corresponds with $Q_0=7.35 e b$. The staggering in the fitted value is an artifact of including a finite number of precursor transitions (cf. text) so that the two signatures do not see exactly the same delay in the feeding process.

the highest spins observed. The branching ratios between signatures were extrapolated with the parameters shown in Fig. 4. The Q_0 for these extrapolated cascades was allowed to vary freely with $Q_0(\text{band})$. The sidefeeding was assumed to have the same history as that feeding down the bands. Line-shape analysis is shown in Fig. 7. The fit to the transitions at 704 and 660 keV is improved by increasing the Q_0 band as indicated in Fig. 7.

IV. COMPARISON WITH THEORY AND DISCUSSION

The measured deformation of bands 5/6 ($\beta_2=0.40$) is comparable to that of the most superdeformed rotational band in the region [7] (namely ^{132}Ce which has $\beta_2=0.39$). In Fig. 9(a) we compare dynamical moments of inertia for some known superdeformed bands in nuclei with $72\leq N\leq 74$. The signature-partner bands shown in ^{133}Pr were assigned by Wilson *et al.* [16] to the high-spin configuration with a pro-

TABLE III. Summary of measured Q_0 values and derived deformation parameters.

Band	Measured Q_0 ($e b$)	Deformation parameter	
		β_2	ϵ
1	5.2(5)	0.29(3) ^a	0.25(3)
3/4	5.4(6)	0.29(3)	0.255(30)
5/6	7.4(10)	0.40(5)	0.33(4)

^aPrevious result: $\beta_2=0.333(14)$ [23].

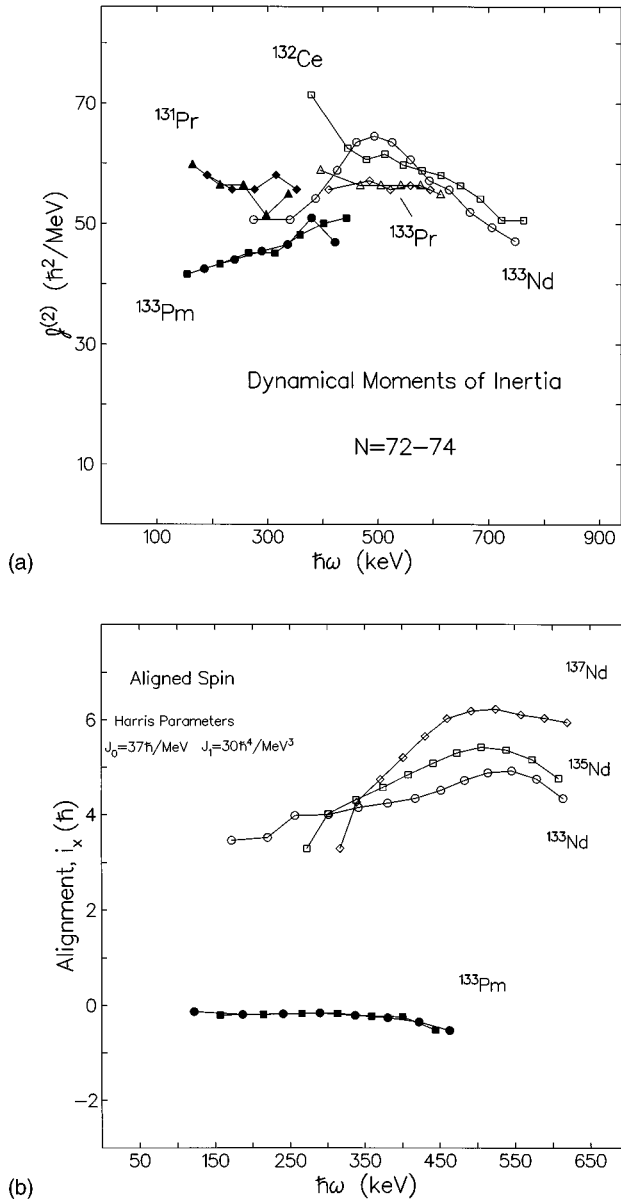


FIG. 9. (a) Typical dynamical moments of inertia $I^{(2)}$ for bands believed to have superdeformed character in the $A \sim 130$ region. To keep the figure as clear as possible, not all band members are shown in all nuclei. (b) Aligned spins in $^{133,135,137}\text{Nd}$ yrast superdeformed bands relative to the superdeformed bands (5/6) in ^{133}Pm . These Nd isotopes were chosen because they are the only high-spin superdeformed bands in the $A \sim 130$ region with firm spin assignments.

ton hole in the $g_{9/2}$ orbital. The comparison in Fig. 9 suggests to us that typical high-spin superdeformed bands, i.e., ^{132}Ce , ^{133}Pr , and ^{133}Nd differ from the low-spin bands, i.e., ^{131}Pr and ^{133}Pm in that they contain additional aligned components presumably $\pi h_{11/2}$, $\nu h_{11/2}$, and/or $\nu i_{13/2}$. These contribute to the dynamical moment of inertia, but do not change the deformation very much. To see this more explicitly we have compared the aligned spin in the yrast superdeformed bands of $^{133,135,137}\text{Nd}$ referenced to the superdeformed bands in ^{133}Pm in Fig. 9(b). These Nd isotopes are the only high-spin superdeformed bands in the $A \sim 130$ region for which firm spin assignments are known [17]. The analysis demonstrates

that there is a relatively constant (with rotational frequency) alignment gain of approximately $5h$ between the high-spin superdeformed bands and the ^{133}Pm bands. In our interpretation there will be high-spin superdeformed bands in ^{131}Pr and ^{133}Pm with aligned particles coupled to $\pi g_{9/2}^{-1}$: conversely, we would expect that the pure $\pi g_{9/2}^{-1}$ structure should occur at low excitation in ^{133}Pr . We note that there need be no strong or even measurable decay path between the $\pi g_{9/2}^{-1}$ and $\pi g_{9/2}^{-1} \otimes (\text{aligned particle})$ structures: this follows because these bands lie well above yrast, and therefore at the critical frequency for dealignment, the decay path will mainly go to the yrast line, rather than following through a backbending pattern.

To understand the reasons for the coexisting deformations at low spin in ^{133}Pm we have performed calculations within the configuration-dependent shell correction approach using the cranked Nilsson potential [18]. The (K, μ) parameter set from [18] was used in the present calculations for the parametrization of the Nilsson potential. These calculations suggest that the superdeformed band has the configuration $\pi(g_{9/2})^{-1}5^6 \otimes \nu(h_{9/2}, f_{7/2})^25^8$, where 5^6 denotes the high- j particle configuration $(h_{11/2})^6$. It should be noted that the labeling is only approximate and that the full Nilsson Hamiltonian was diagonalized in the calculations. Compared to the normal deformed configuration, the superdeformed core has two neutrons in $[541]_{1/2}$ (originating in the $h_{9/2}, f_{7/2}$ subshells); two protons in $[532]_{5/2}$ (originating in the $h_{11/2}$ subshell); and a proton hole in $[404]_{9/2}$ (originating in the $g_{9/2}$ subshell). These shell gaps are readily seen in the single-particle energies of a Woods-Saxon or modified oscillator potential (for example, [4]); the normal core for $Z=60$, $N=72$ is centered near $\beta_2 \sim 0.25-0.30$ whereas the “excited” $Z=60$, $N=72$ core is centered near $\beta_2 \sim 0.4-0.45$. In our calculations, the energy needed to excite to the higher core [with $\pi(g_{9/2})^{-1}$] is only 640 keV.

The predicted configurations relative to an arbitrary rigid rotor reference are shown in Figs. 10 and 11. The lowest configuration $\pi5^4\nu5^8$ is predicted to have the odd proton in $(d_{5/2}/g_{7/2})$ in agreement with experiment. The calculated deformation is $\varepsilon_2=0.261$, $\varepsilon_4=0.021$, $\gamma \sim 0^\circ$ for the states with $I=3^+/2$ and $I=5^+/2$ (bandheads of bands 3 and 4). Assuming a uniform charge distribution and that the matter distribution coincides with the potential distribution, we can estimate the charge quadrupole moment Q_0 from the expression [19].

$$Q_0 = \frac{4}{5} Z r_0^2 A^{2/3} \left[\varepsilon_2 \left(1 + \frac{1}{2} \varepsilon_2 \right) + \frac{25}{33} \varepsilon_4^2 - \varepsilon_2 \varepsilon_4 \right] \frac{\cos(\gamma + 30^\circ)}{\cos(30^\circ)}. \quad (5)$$

Assuming $r_0=1.2$ fm, this gives $Q_0=5.3 e b$ for states with $I=3^+/2$ and $I=5^+/2$, which is in good agreement with the experimental value (cf. Table III). The superdeformed bandhead $[g_{9/2}]^{-1}$ is predicted to lie ~ 640 keV above yrast and has a calculated deformation $\varepsilon_2=0.363$, $\varepsilon_4=0.036$, $\gamma=0^\circ$ at $I=9/2$ corresponding to $Q_0=7.57 e b$. In the experiment, the bandhead lies 272 keV above yrast and $Q_0=7.4 \pm 1.0 e b$ (of Table III).

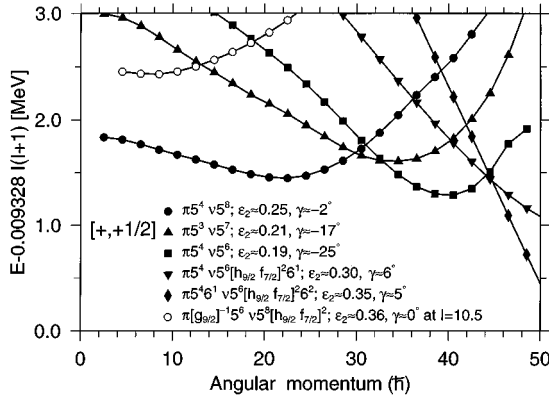


FIG. 10. Calculated low-lying configurations of positive parity and signature $\alpha=+1/2$ in ^{133}Pm relative to a rigid rotor reference. The configurations are labeled by the number of particles in the high- j orbitals of the $N=5$ ($h_{11/2}$) and $N=6$ ($i_{13/2}$) shells and by the number of particles in the $h_{9/2}/f_{7/2}$ subshells as well as the number of holes in the $g_{9/2}$ subshell. The deformations given for specific configurations correspond to spins where they are yrast. The normal-deformed yrast configuration is $\pi 5^4 v 5^8$ or $\pi d_{5/2}$ (bands 3/4 in the experiment). The superdeformed configuration is $\pi [g_{9/2}]^{-1} 5^6 v 5^8 [h_{9/2} f_{7/2}]^2$ (bands 5/6 in the experiment).

The calculation reproduces the near signature degeneracy of the superdeformed ($g_{9/2}$) $^{-1}$ and the $d_{5/2}$ configurations as shown in Figs. 11 and 12. With increasing spin, the excitation energy of the superdeformed band relative to the $d_{5/2}$ band increases both in the experiment and in the theory (see Figs. 11 and 12). However, the calculations overestimate the excitation energy of the superdeformed band. For example, at $I=41/2$, $E_{\text{SD}} - E_{d_{5/2}} = 1.367$ MeV in the calculation versus 0.535 MeV in the experiment.

In these calculations, the structure of the typical high-spin superdeformed band in ^{133}Pm is predicted to be $\pi 5^4 6^1 v 5^6 [h_{9/2} f_{7/2}]^2 6^2$ for positive signature (cf. Fig. 10), and $\pi 5^4 v 5^6 [h_{9/2} f_{7/2}]^2 6^2$ for negative signature (cf. Fig. 11). Relative to the low-spin strongly coupled superdeformed band, these bands contain two neutrons in the intruder $i_{13/2}$ ($N=6$) orbital and either zero or one proton in the intruder $i_{13/2}$ ($N=6$) orbital. They are predicted to become yrast at

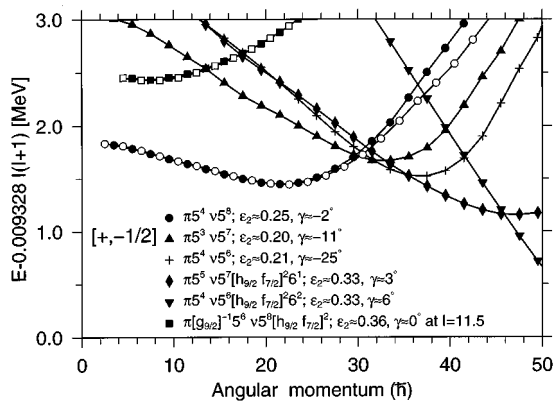


FIG. 11. Same as for Fig. 10 but for signature $\alpha=-1/2$. Open symbols are used for two configurations of signature $\alpha=+1/2$ in order to show that the calculations predict the observed signature degeneracy.

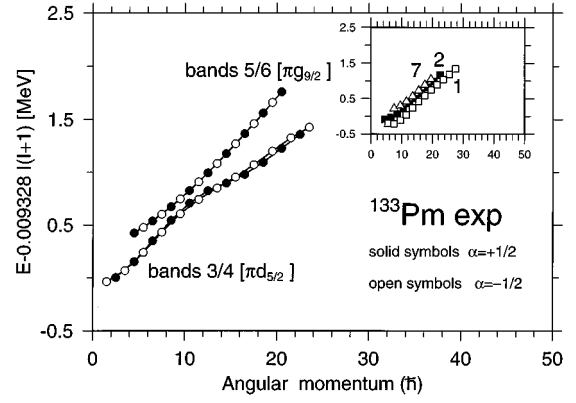


FIG. 12. Same as for Fig. 10 but for experimental rotational bands in ^{133}Pm . The $(E - E_{\text{RLD}})$ curves for negative parity bands 1/2 and 7 are given in upper right corner scaled by 33% relative to main figure which means that the slopes of these curves are unchanged.

around spin $45\hbar$. However, despite the intruder content, their deformation is predicted to be smaller than that for the low-spin superdeformed band (cf. Figs. 10 and 11 and Table IV). This is partly due to the fact that the bands are considered at different spin values; namely for the fixed configurations considered here, there is a general tendency that the deformation decreases with spin, as can be seen in Table IV. One should also note that the shape polarization from $g_{9/2}$ holes appears comparable or even larger than from high- j $vi_{13/2}$ particles. In the present experiment we would not expect to see high-spin superdeformed bands since first the angular momentum input, $I_{\text{max}} \sim 44\hbar$, is close to the predicted yrast crossing spin, and second, the backed target would have introduced Doppler smearing.

It is worth examining whether the observed band crossings are consistent with the measured deformations. From the experimental Routhians shown in Fig. 13, the $\pi(h_{11/2})^2$ crossing occurs in bands 3/4 at $\hbar\omega=0.27$ MeV, whereas in a cranked-shell model (CSM) with standard parameters, at $\beta_2=0.29$ (as measured), the crossing frequency is predicted to be $\hbar\omega=0.30$ MeV: the observed crossing frequency corresponds with $\beta_2=0.275$. (Figures illustrating these remarks may be found in [8].)

The first pair of protons to align from $\pi(h_{11/2})^2$, the AB crossing in CSM terms, is blocked in bands 1/2 and the second $\pi(h_{11/2})^2$ pair (BC) are predicted to cross at $\hbar\omega=0.46$ MeV, for the measured deformation $\beta_2=0.29$, versus an observed crossing frequency at $\hbar\omega=0.39$ MeV (Fig. 13). Conversely, the observed crossing frequency corresponds with $\beta_2=0.25$.

For the above-mentioned bands, this level of agreement is perhaps as good as could be expected since systematically the $\pi(h_{11/2})^2$ crossings are lower than predicted with a standard CSM in odd- Z nuclei. This is because the odd proton will partially quench the proton pairing field, making it easier to align protons. Despite the fact that the $\pi(h_{11/2})^2$ AB alignment is open, the superdeformed bands 5/6, assigned $\pi g_{9/2}^{-1}$, show no crossings up to the highest frequency observed $\hbar\omega \sim 0.46$ MeV [Fig. 9(b)]. The predicted crossing frequency is a strong function of deformation, and from the CSM results we note that the nonappearance of this crossing by $\hbar\omega \sim 0.46$ MeV implies a deformation $\beta_2 > 0.41$. This is

TABLE IV. The calculated deformations of superdeformed configurations at two different spin values.

Configuration	ϵ_2	ϵ_4	γ	ϵ_2	ϵ_4	γ
$\pi=+, \alpha=+1/2$						
		$l=10.5\hbar$			$l=46.5\hbar$	
$\pi 5^4 \nu 5^6 [h_{9/2} f_{7/2}]^2 6^1$	0.325	-0.010	1.6°	0.292	0.015	7.5°
$\pi 5^4 6^1 \nu 5^6 [h_{9/2} f_{7/2}]^2 6^2$	0.375	-0.023	1.4°	0.357	0.0	4.8°
$\pi 5^6 [g_{9/2}]^{-1} \nu 5^8 [h_{9/2} f_{7/2}]^2$	0.359	0.036	0.6°	0.317	0.014	1.0°
$\pi=+, \alpha=-1/2$						
		$l=11.5\hbar$			$l=47.5\hbar$	
$\pi 5^5 \nu 5^7 [h_{9/2} f_{7/2}]^2 6^1$	0.325	0.008	1.3°	0.316	0.026	4.6°
$\pi 5^4 \nu 5^6 [h_{9/2} f_{7/2}]^2 6^2$	0.358	-0.010	0.1°	0.328	0.017	6.0°
$\pi 5^6 [g_{9/2}]^{-1} \nu 5^8 [h_{9/2} f_{7/2}]^2$	0.361	0.036	0.2°	0.311	0.013	0.9°

consistent with our measured deformation. The $\nu(h_{11/2})^2$ has the opposite dependence on deformation to the $\pi(h_{11/2})^2$ alignment, i.e., it moves to lower frequency with increasing deformation. For the superdeformed bands 5/6 at the measured deformation ($\beta_2=0.40$) the predicted crossing frequency is $\hbar\omega=0.46$ MeV. Its nonappearance is also consistent with our measured deformation. The CSM therefore predicts that for $\beta_2=0.4$, the $\nu(h_{11/2})^2$ and $\pi(h_{11/2})^2$ alignments will occur simultaneously at $\hbar\omega\sim 0.46$ MeV. This is just the frequency where we lose sight of the band in the experiment, and it suggests that a large alignment gain and structural change are the underlying cause.

Several years ago, Leander and Möller [20] made a theoretical study of ground-state deformations at the boundary between the near-spherical light rare-earth region near $N=82$, and the then unexplored deformed region centered near $N=66$. An interesting aspect of that study was the prediction of a promontory of strong deformation for Pm isotopes which juts in towards the valley of stability. In addition, a sharp transition was obtained for Pm isotopes, where the deformation was predicted to change from $\beta_2=0.22$ at ^{136}Pm to $\beta_2=0.34$ at ^{135}Pm .

Our total Routhian surface (TRS) calculations with standard parameters [21] also give a sharp transition in Pm iso-

topes, but it occurs between ^{135}Pm ($\beta_2=0.23$) and ^{133}Pm ($\beta_2=0.31$) for $(\pi,\alpha)=(-,-1/2)$ at rotational frequency $\hbar\omega=0.05$ MeV as shown in Fig. 14. Results for other (π,α) configurations are similar. Measurements by Mullins *et al.* [22] and by Wadsworth *et al.* [23] with a recoil distance technique for ^{137}Pm ($\beta_2=0.201\pm 0.009$), ^{135}Pm

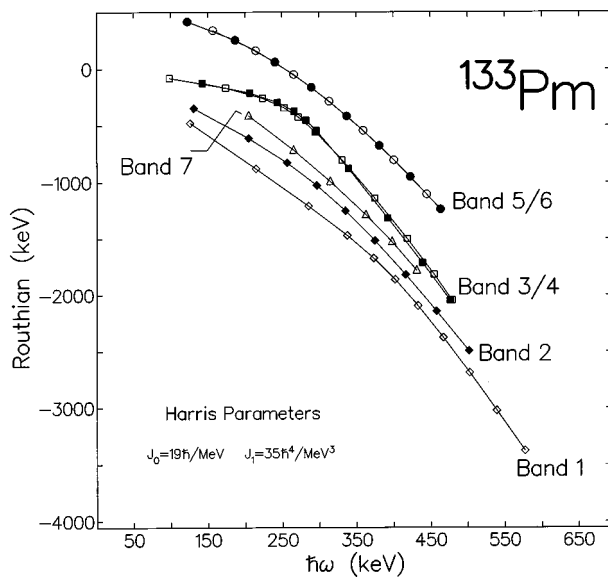
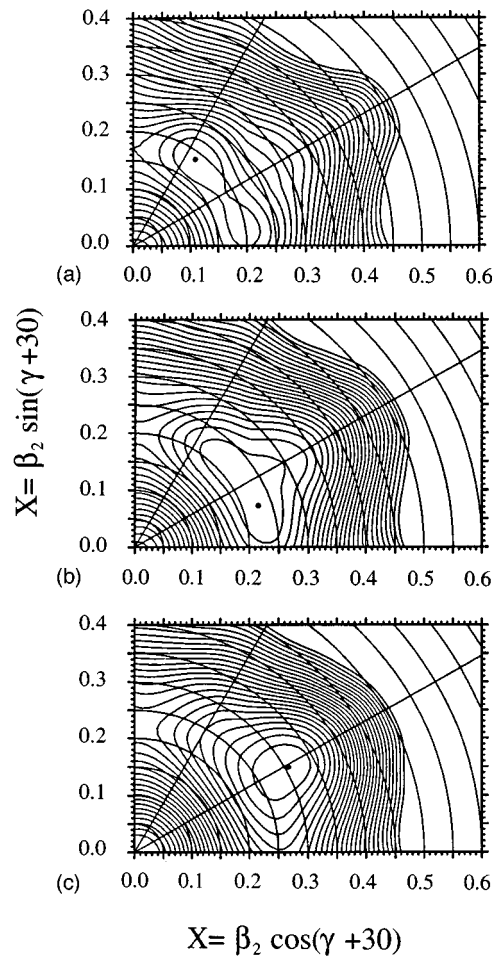
FIG. 13. Experimental Routhians for rotational bands in ^{133}Pm .

FIG. 14. Total Routhian surfaces at $\hbar\omega=0.05$ MeV for the $(\pi,\alpha)=(-,-1/2)$ proton configuration in (a) ^{137}Pm , (b) ^{135}Pm , and (c) ^{133}Pm . This configuration corresponds to the occupancy of a low- K $h_{11/2}$ orbital by the odd proton, manifest as the decoupled yrast bands that are observed in these isotopes. Note the increasing, and less γ -soft, prolate deformation as the neutron number decreases.

($\beta_2=0.226\pm 0.006$), and ^{133}Pm ($\beta_2=0.303\pm 0.013$) are in very close agreement with the TRS calculations, and in good agreement with the present ^{133}Pm measurement ($\beta_2=0.29\pm 0.3$), for bands 3/4.

V. CONCLUSIONS

We have measured lifetimes for several rotational bands in ^{133}Pm with the DSAM. The strongly coupled structure based on a hole in the Nilsson proton [404] 9/2 orbital was found to have a deformation parameter $\beta_2=0.40\pm 0.05$, which is as large as that of the most superdeformed band found in the $A=130$ region. Its systematics follow the pattern established for $^{129,131}\text{Pr}$, although the deformation in ^{133}Pm is higher. In all three cases, the band can be followed up to $\hbar\omega\sim 0.45$ MeV, and it seems plausible that we lose sight of the band at the critical frequency for alignment of $\pi h_{11/2}$ and $\nu h_{11/2}$ quasiparticles which for the ^{133}Pm case are

predicted to occur at $\hbar\omega\sim 0.45$ MeV for a deformation $\beta_2=0.40$.

Other rotational bands in ^{133}Pm were found to have substantial deformation ($\beta_2\sim 0.29$) and this is supported both by standard TRS calculations and by the configuration-dependent shell correction approach, thus confirming the long-standing prediction of Leander and Möller that the Pm isotopes would be the most accessible (i.e., closest to β stability) of nuclei in the deformed region centered near $N=Z=66$.

It will now be of interest to search for further examples of superdeformation where the nucleus exploits shell gaps of high deformation at low spin. The next candidates might involve the shell gap at $N=80$, however, preliminary calculations indicate the superdeformed bandhead rises rapidly in excitation, making it hard to populate and detect. Nevertheless, the sensitivity of the new generation of γ -ray spectrometers may be sufficient.

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