Coriolis attenuation in the $A \simeq 130-150$ region

M. Saha, A. Goswami, S. Bhattacharya, and S. Sen
Saha Institute of Nuclear Physics, Calcutta 700 009, India
(Received 23 April 1990)

The particle-rotor model has been applied to calculate the band structure in a number of highly neutron deficient odd-A rare-earth nuclei in the $A \simeq 130$–150 region. Several transitional nuclei are also included in the study. The only adjustable parameter, used in the calculation, is the Coriolis attenuation coefficient. However, it is seen that the observed band structures in these nuclei can be reproduced practically without any *ad hoc* reduction of the Coriolis matrix elements. The systematics of the Coriolis attenuation in the neutron-deficient, transitional, and well-deformed rare-earth nuclei are discussed in the light of the present work and several theoretical studies, made earlier. The importance of the pairing interaction in the Coriolis attenuation study is emphasized.

I. INTRODUCTION

In recent years, both the cranked-shell-model (CSM) and the particle-rotor-model (PRM) formalisms have been extensively used to study many interesting features of high spin states of weakly as well as strongly deformed nuclei. It has been pointed out by several workers[1,2] that near the band crossing, where the rotational frequency undergoes a rapid fluctuation, the PRM offers a much better description of the underlying physical process. However, this model suffers from an inadequacy; i.e., the calculated Coriolis matrix elements have to be attenuated to a certain extent (in some cases even up to 50% of the theoretical value), in order to reproduce the experimental energy spectra. This phenomenon, commonly known as Coriolis attenuation problem, has prompted many theoretical investigations[3-10] over the last decade. However, these investigations have failed so far to give very satisfactory explanation of this peculiar feature of the model. Recently, we have studied,[11] in detail, the Coriolis attenuation problem in a large number of well deformed rare-earth nuclei. It is observed that in these nuclei there is a definite correlation between the Coriolis attenuation coefficients needed to reproduce experimental spectra and the values of the pairing gap used in the calculation. In essence, it is found that instead of attenuating the Coriolis interaction strength by an *ad hoc* factor ranging from 0.55 to 0.95, one can get similar (in some cases even better) agreement with experimental data by reducing the pairing gap from its "normal value" by a more or less uniform factor ($\simeq 0.35$). In our opinion, this observation may be related to two different aspects of the model. It may simply express the inherent shortcomings of the model. On the other hand, this may be related to the internal consistency of the model. It has been pointed out by several authors[4,5] that, in the PRM, contrary to earlier belief, the recoil energy term arising from the conservation of the total angular momentum plays a significant role. In that case, one may ask how far it is justified to deduce the "pairing gap" from the experimental odd-even mass difference, without considering the effect of this recoil energy on the ground-state binding energy of the odd-mass system. In either case, it would be interesting to extend this study in other regions.

Recently, a number of experiments has been done[12-27] to identify band structures in highly neutron deficient rare-earth nuclei in the mass region $A \simeq 130-140$. Band structures in several Sm, Eu, and Tb nuclei situated in the $N=88$ transitional region have also been known[28-30] for some time. These data offer a very good opportunity to extend the systematics of the Coriolis attenuation coefficients in the transitional and highly neutron deficient rare-earth nuclei in the mass region $A \simeq 130-150$. With this in view, the band structures in several odd-proton and odd-neutron nuclei, ^{131}La, $^{131-135}$Pr, ^{139}Pm, $^{139-143,151}$Eu, ^{141,143,153}Tb and ^{135}Nd, ^{135,137,149}Sm, ^{139}Gd, respectively, are calculated in a version of the PRM, and compared with available experimental data in the present work.

II. MODEL

In order to study the Coriolis attenuation problem, a calculation should be made free from all other adjustable parameters. Some of the parameters needed in the PRM calculations, e.g., Nilsson single-particle parameters μ, k, deformation parameter β_2, pairing gap, etc., could easily be fixed for each individual isotope. However, except in a very well-deformed region, the excitation energy spectra of the underlying core are very difficult to simulate through any simple energy-angular momentum relationship. One way to circumvent this problem is to use a variable moment-of-inertia (VMI) formalism.[31] However, inclusion of this formalism not only introduces two additional parameters,[32,33] but it (in its simple version) also fails to describe the band structure above backbending. Therefore, we have used a version[10] of the PRM in which the experimental core energies can be fed directly as input parameters.

A. Formalism

The Hamiltonian of the odd-A system can be written as

$$H = H^0_{qp} + c\mathbf{R}\cdot\mathbf{j} + E_c(R) \ . \quad (1)$$

The first term is the Hamiltonian of a single quasiparticle and is given by

$$H^0_{qp} = \sum_K E_K a^\dagger_K a_K \ , \quad (2)$$

with

$$E_K = (\varepsilon_K - \lambda)^2 + \Delta^2 \ , \quad (3)$$

where ε_K is the energy of a single particle moving in a standard axially symmetric Nilsson potential. The pairing gap and the Fermi level are represented by Δ and λ, respectively.

The last term, $E_c(R)$, represents the collective part of the Hamiltonian, whereas the middle term, originally introduced by Neergård,[4] describes the rotational dependence of the interaction between the core and the quasiparticle. The coefficient c is defined[4] in terms of the core moment of inertia corresponding to the lowest 2^+ state in the rotational band and another parameter α,

$$c = (1-\alpha)/\mathcal{J}_2 = (1-\alpha)E_c(R=2)/3\hbar^2 \ . \quad (4)$$

The significance of the parameter α can easily be seen if the core is assumed to have constant moment of inertia. Remembering that

$$\mathbf{R} = \mathbf{I} - \mathbf{j} \quad (5)$$

(where $\mathbf{I}$ is the total angular momentum of the nucleus and $\mathbf{j}$ is that of the quasiparticle),

$$\begin{aligned} H &= H^0_{qp} + c\mathbf{R}\cdot\mathbf{j} + E_c(R) \\ &= H^0_{qp} + \frac{(1-\alpha)}{\mathcal{J}_2}(\mathbf{I}-\mathbf{j})\cdot\mathbf{j} + \frac{(\mathbf{I}-\mathbf{j})^2}{2\mathcal{J}_2} \\ &= H^0_{qp} + \frac{I^2_\perp}{2\mathcal{J}_2} + (2\alpha-1)\frac{j^2_\perp}{2\mathcal{J}_2} - \alpha\frac{I_\perp j_\perp}{\mathcal{J}_2} \ . \end{aligned} \quad (6)$$

Here $I_\perp$ and $j_\perp$ denote the components perpendicular to the symmetry axis. So, for a constant moment of inertia, α is identical to the usual Coriolis attenuation factor. Moreover, it can be seen from expressions (4) and (6) that introduction of the $c\mathbf{R}\cdot\mathbf{j}$ term in the Hamiltonian effectively reduces the recoil energy if there is attenuation of the Coriolis matrix element. In the limit of very small attenuation ($\alpha \simeq 1$), this interaction term loses its significance.

The basis states are usually taken in the form

$$|IMK\rangle = \left[\frac{2I+1}{8\pi^2}\right]^{1/2} \times [D^I_{MK}\chi_K + (-)^{I-1/2}D^I_{M,-K}\chi_{-K}]/\sqrt{2} \ . \quad (7)$$

Here χ_K represent the Nilsson single-particle states which can be expanded into eigenstates of j^2,

$$\chi_K = \sum_j C^j_K |jK\rangle \ . \quad (8)$$

However, we have to transform the basis into a representation with sharp R and j to calculate the R-dependent terms in the Hamiltonian. The necessary transformation is given by

$$\langle (njR)IM|IMK\rangle = C^j_K(-)^{j-K}\begin{bmatrix} j & I & R \\ K & -K & 0 \end{bmatrix}[1+(-)^R]/\sqrt{2} \ . \quad (9)$$

In this representation, the matrix elements of arbitrary functions $f(j)$ and $f(R)$ are given by

$$\langle K|f(j)|K'\rangle_{qp} = (u_K u_{K'} + v_K v_{K'})\langle K|f(j_{sp})|K'\rangle_{sp} \ , \quad (10a)$$

and

$$\langle IMK|f(R)|I'M'K'\rangle = \delta_{II'}2(-)^{K-K'}\sum_{R,j} f(R)C^j_K C^j_{K'}\begin{bmatrix} j & I & R \\ K & -K & 0 \end{bmatrix} \times \begin{bmatrix} j' & I' & R \\ K' & -K' & 0 \end{bmatrix}(u_K u_{K'} + v_K v_{K'}) \ . \quad (10b)$$

In the above expressions, the u_K and v_K are the usual Bogoliubov transformation coefficients.

When the moment of inertia of the core ($\mathcal{J}_R$) changes with increasing spin R, the expression (6) for the Hamiltonian of the system, is obviously modified. The contribution to the Coriolis force is then

$$-\frac{I_\perp j_\perp}{\mathcal{J}_R} + \frac{1-\alpha}{\mathcal{J}_2}I_\perp j_\perp = -\alpha_{\text{eff}}\frac{I_\perp j_\perp}{\mathcal{J}_R} \ , \quad (11)$$

where

$$\alpha_{\text{eff}} = 1 - \frac{\mathcal{J}_R}{\mathcal{J}_2}(1-\alpha) \ . \quad (12)$$

This shows that, in the present formalism, the Coriolis attenuation factor will, in general, be a function of the angular momentum (I) of the excited state.

B. Parameter choice

The single-particle Nilsson parameters μ, k, in each individual nucleus have been deduced from Nilsson's prescription.[34] The deformation parameter (β_2) for the odd nucleus is chosen from the systematics of the experimentally deduced β_2 values[35] in the neighboring even isotopes. The pairing gap is deduced from the experimental odd-even mass difference,[36] where available; otherwise it is calculated from an expression $\Delta = 12/A^{1/2}$ MeV. The core energies are taken as averages of the excitation energies of the yrast or of the ground-state bands (this case will be discussed in more detail in the subsequent sections) of the neighboring ($A \pm 1$) even isotopes. The only adjustable parameter used in the calculation is the Coriolis attenuation coefficient α. The parameter values used in the calculation are listed in Table I.

TABLE I. Parameter values used in the calculation.

Isotope	Nilsson Parameter μ	k	β_2	Pairing Gap (MeV)	Attenuation coefficient Negative parity states	Positive parity states
^{131}La	0.578	0.066	0.230	1.05	0.98	0.95
^{131}Pr	0.578	0.066	0.260	1.05	1.00	
^{133}Pr	0.578	0.066	0.240	0.90	0.98	0.98
^{135}Pr	0.578	0.066	0.180	0.83	0.98	0.85
^{139}Pm	0.583	0.066	0.150	1.00	0.99	
^{139}Eu	0.583	0.066	0.230	1.00	0.98	
^{141}Eu	0.584	0.066	0.230	1.01	0.97	
^{143}Eu	0.586	0.066	0.150	1.00	0.99	
^{151}Eu	0.591	0.065	0.140	1.23	0.97	
^{153}Tb	0.592	0.065	0.140	1.22	0.95	
^{135}Nd	0.457	0.064	0.200	1.03	0.97	
^{135}Sm	0.457	0.064	0.280	1.03		0.65
^{137}Sm	0.455	0.064	0.230	1.03		0.93
^{149}Sm	0.440	0.064	0.140	1.00		0.98
^{139}Gd	0.452	0.064	0.210	1.02	0.97	

III. RESULTS

The band structure ("decoupled" or "normal") based on the intruder orbitals ($h_{11/2}$ or $i_{13/2}$ as the case may be) in the odd-proton isotopes $^{131}_{57}$La, $^{131-135}_{59}$Pr, $^{139}_{61}$Pm, $^{139-143,151}_{63}$Eu, $^{141,143,153}_{65}$Tb, and odd-neutron isotopes $^{135}_{60}$Nd, $^{135,137,149}_{62}$Sm, and $^{139}_{64}$Gd have been calculated in the present work. Bands based on the normal parity orbitals in the $N=4$ shell are also calculated in a few cases. Some of the results are shown in Figs. 1–6. The comparison between the calculated and experimental spectra are presented through a series of ω-I_x plots where $I_x=[I(I+1)-K^2]^{1/2}$ and $\omega(I_x)=dE/dI_x$. The rotational frequency is calculated using the expression

$$\omega(I_x)=\frac{E(I)-E(I-2)}{I_x(I)-I_x(I-2)}$$

and K is taken to be the value of I for the band head. Before discussing the individual isotopic series, a general comment may be made on the basis of the present calculation. An interesting feature, brought out through these calculations, is the fact that in all these isotopes (except in ^{135}Sm), the experimental band structure could be reproduced practically with full strength of the theoretical Coriolis interaction matrix elements. A comparison of the present findings with the results obtained in earlier calculations[10,11] in the rare-earth region shows that as the neutron number approaches the $N=82$ closed shell, the need for attenuation of the Coriolis matrix elements diminishes. Prompted by the observation made in our earlier work[11] about the strong dependence of the attenuation coefficient on the value of pairing gap, we repeated the calculation in several isotopes with different values of the pairing gap parameter Δ. However, it is found that even for a significant change in the pairing gap, no appreciable change in the calculated spectrum is observed.

A. Odd-proton nuclei

1. ^{131}La

In this isotope, the negative parity favored band members based on the $\pi h_{11/2}$ orbital are known[12,13] up to $I^\pi=55/2^-$. Positive parity states based primarily on the $\pi g_{7/2}$ orbital have also been identified up to $I^\pi=31/2^+$. In ^{131}La, and $^{131-133}$Pr isotopes, although the neighboring cores show strong backbend near $I\simeq 12-14$, the

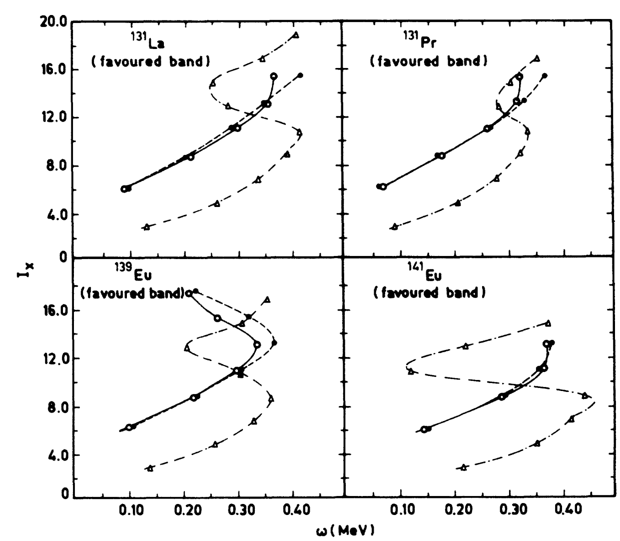

FIG. 1. Rotation-aligned angular momentum I_x vs the angular frequency ω for ^{131}La, ^{131}Pr, ^{139}Eu, and ^{141}Eu. For each nucleus, the experimental (solid circles connected by dashed line) and theoretical (open circles connected by solid line) $I_x(\omega)$ curves are shown for the favored band, based on the $\pi h_{11/2}$ orbital. The $I_x(\omega)$ curves for the corresponding experimental core spectra (triangles connected by broken line) are also shown for comparison. Parameter values are given in Table I.

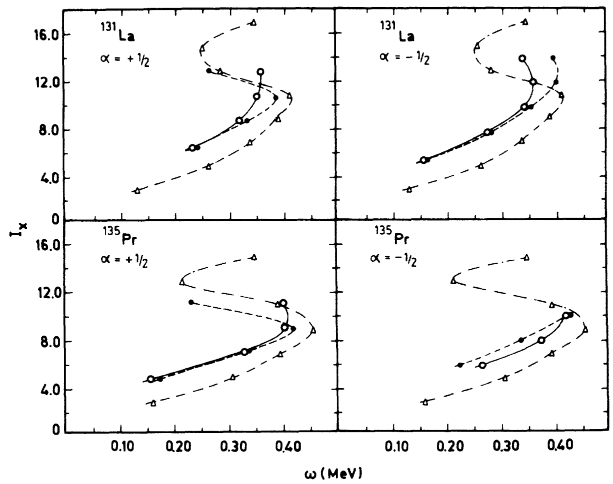

FIG. 2. Rotation-aligned angular momentum I_x vs the angular frequency ω for ^{131}La and ^{135}Pr. For each nucleus, the experimental (solid circles connected by dashed line) and theoretical (open circles connected by solid line) $I_x(\omega)$ curves are shown for two opposite signature ($\alpha = \pm\frac{1}{2}$) positive-parity bands based on the $N=4$ Nilsson orbitals. See also caption in Fig. 1.

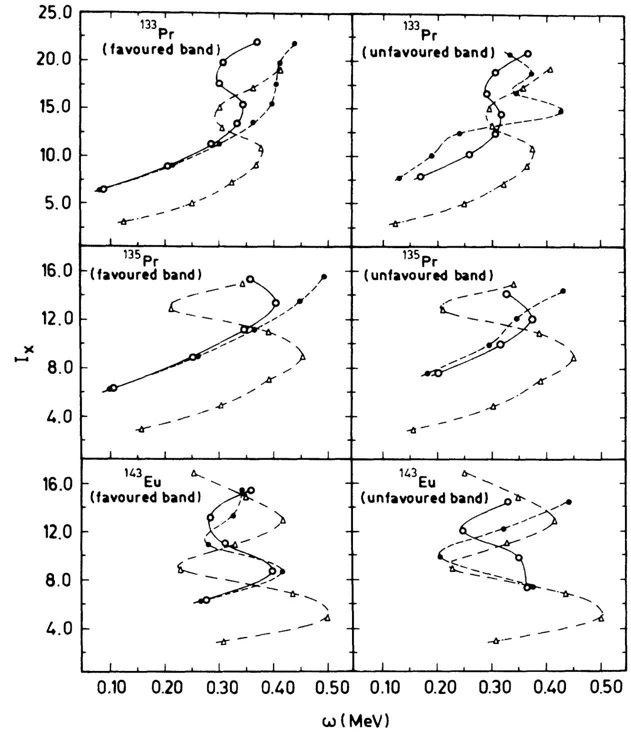

FIG. 3. Rotation-aligned angular momentum I_x vs the angular frequency ω for ^{133}Pr, ^{135}Pr, and ^{143}Eu. For each nucleus, the experimental and theoretical $I_x(\omega)$ curves are shown for the favored and unfavored bands based on the $\pi h_{11/2}$ orbital. See also the caption in Fig. 1.

alignment is blocked by the single proton.[12–15] In order to reproduce correctly this observed feature, the excitation energies of the ground-state band members of the core above backbend (in which these aligned states are unoccupied) rather than those of the yrast band should be used. However, the ground band above backbend are not known in these even isotopes. So the calculations of the yrast spectra in these isotopes are meaningful only up to the backbending frequency of the neighboring even core. The negative parity yrast states are reproduced correctly (Fig. 1) with very small attenuation ($\alpha=0.98$). In the positive parity spectrum, though the agreement is good in the low-spin region (Fig. 2) with the attenuation coefficient $\alpha=0.93$, the higher-spin states seem to require more attenuation. The core energies[37] are taken as those of ^{132}Ce since core states in ^{130}Ba are known only up to $I^{\pi}=8^{+}$.

2. *$^{131-135}$Pr*

Experimental data on band structures in several neutron deficient odd-A Pr isotopes are available.[14–18] In ^{131}Pr, although the yrast states based on the $\pi h_{11/2}$ orbital are known[14] up to $I^{\pi}=47/2^{-}$, the comparison is made (Fig. 1) only up to $I^{\pi}=31/2^{-}$ for reasons discussed earlier. Similarly, in ^{133,135}Pr, the favored band members up to $I^{\pi}=27/2^{-}$ are considered for comparison between the calculated and experimental curves[15–17] (Fig. 3). The core energies are taken as averages of those observed in neighboring even Ce and Nd cores.[37–40] The trends of the experimental curves for the negative-parity favored bands in these isotopes are reproduced more or less correctly up to spin value $I^{\pi}=27/2^{-}$, with negligibly small attenuation coefficient. However, the observed signature splitting in ^{133}Pr is not reproduced correctly. The situation is much better in ^{135}Pr. Low-spin members of the positive parity band of both signatures based on the $d_{5/2}$ and $g_{7/2}$ orbitals could also be reproduced in ^{133}Pr and ^{135}Pr with attenuation coefficients $\alpha=0.98$ and 0.85, respectively (Fig. 2). In our earlier study,[33] we used a version of VMI formalism to simulate the observed change in the moment of inertia with increasing spin in the calculation of the band structures in ^{133,135}Pr. It was found that the positive parity band in ^{135}Pr could only be reproduced with a very large attenuation factor $\simeq 0.4$. Results of the present work in ^{133,135}Pr show that a proper description of the core spectrum is essential in the study of the attenuation problem in these nuclei.

3. *^{139}Pm*

Negative parity yrast states for ^{139}Pm based on the $\pi h_{11/2}$ orbital have recently been measured[19] up to spin $I^{\pi}=43/2^{-}$ (favored band) and $I^{\pi}=33/2^{-}$ (unfavored band). Present calculation reproduces more or less correctly the backbending frequency and the slope of the $\omega - I_x$ curve deduced from the experimental data for the favored band (Fig. 4). The backbending frequency for the unfavored band is also correctly reproduced. However, the agreement between the experimentally observed and the calculated signature splitting in the low-spin region is not so good. For the favored band, the energy of the calculated $35/2^{-}$ state is somewhat lower than the observed $35/2^{-}$ state at 4645 keV. However, there is a high-spin state at 4196 keV in the experimental spectrum which is

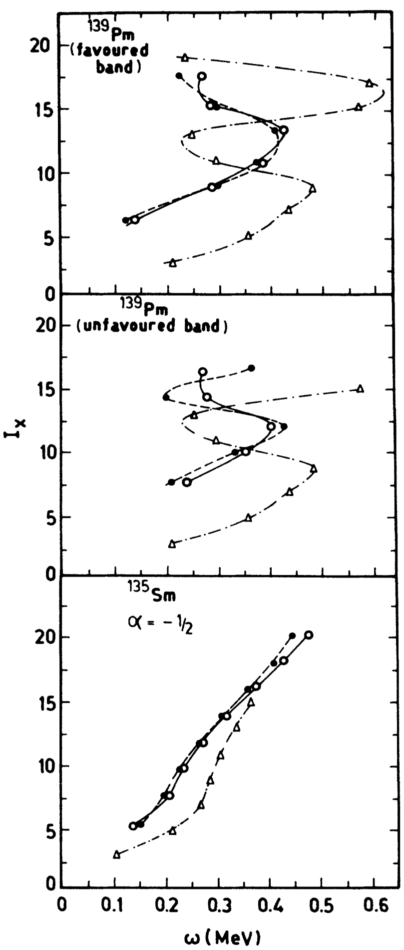

FIG. 4. Rotation-aligned angular momentum I_x vs the angular frequency ω for the favored and unfavored bands in ^{139}Pm based on the $\pi h_{11/2}$ orbital and the positive-parity, negative-signature ($\alpha=-\frac{1}{2}$) band in ^{135}Sm based on the $N=4$ Nilsson orbitals is shown. See also the caption in Fig. 1.

energetically close to the calculated $35/2^-$ state at 4276 keV. If this state is identified with the calculated one, then the agreement with the observed slope of the curve for the favored band above the backbending region becomes much better. The core energies are taken as the average of the yrast excitation energies[41,42] in ^{138}Nd and ^{140}Sm. Hardly any attenuation ($\alpha=0.99$) is needed to reproduce the experimental spectrum.

4. $^{139-143,151}Eu$

Negative parity[19–23] yrast bands based on the $\pi h_{11/2}$ orbital have recently been measured in the neutron-deficient ^{139,141,143}Eu isotopes. Same for the well-known transitional nucleus ^{151}Eu has been measured earlier.[28] The core energies are taken as the average of the yrast excitation energies in the neighboring even Sm and Gd isotopes.[23,37,41–45] In ^{139}Eu, only the favored band members are known[19] up to $I^\pi=35/2^-$. The present calculation reproduces correctly the backbending frequency as well as the slope of the $\omega-I_x$ curve in ^{139,141}Eu (Fig. 1). The calculated energies of the states above backbend are somewhat lower than the corresponding experimental values. It seems that, for these states, the Coriolis matrix elements need larger attenuation value than that used in the present calculation ($\alpha=0.98$). In ^{143}Eu, the favored and unfavored band members are known[22,23] up to $I^\pi=31/2^-$ and $29/2^-$, respectively. The calculation reproduces beautifully the observed $\omega-I_x$ curve for the favored band (Fig. 3). However, the signature splitting observed in the experimental spectrum is not reproduced correctly giving rise to a much sharper backbend in the calculated unfavored band. Practically, no attenuation ($\alpha=0.99$) is needed to reproduce the experimental spectra. In ^{141}Eu and ^{151}Eu the favored band members are known[21,28] up to $I^\pi=27/2^-$. The agreement between the experimental and the theoretical curves (calculated in both cases with $\alpha=0.97$) is excellent (Figs. 1 and 5). In ^{141}Eu, no member of the unfavored band is known, whereas in ^{151}Eu, they are know only up to $I^\pi=17/2^-$. In this low-spin region, the calculated signature splitting is found to be somewhat stronger than that observed experimentally.

5. $^{141,143,153}Tb$

Information on a few negative-parity yrast states ($I^\pi=11/2^-$, $15/2^-$, $19/2^-$, and $23/2^-$) in ^{141,143}Tb based on the $\pi h_{11/2}$ orbital has recently become available.[20] The yrast band up to $I^\pi=31/2^-$ was measured[29] earlier in the transitional nuclei ^{153}Tb. The core energies are taken from the averages of the yrast states[20,45,46] in neighboring even Gd and Dy nuclei. Since in ^{141,143}Tb only a few negative parity states are known, the calculated and the experimental energy spectra are not shown. It is seen that the agreement is very good for the favored band members in all the Tb nuclei considered in the present work. The signature splitting observed in ^{153}Tb is also reproduced quite accurately up to the spin value $27/2^-$ (Fig. 5). The attenuation coefficient ($\alpha\simeq0.95-0.99$) is rather small in these nuclei.

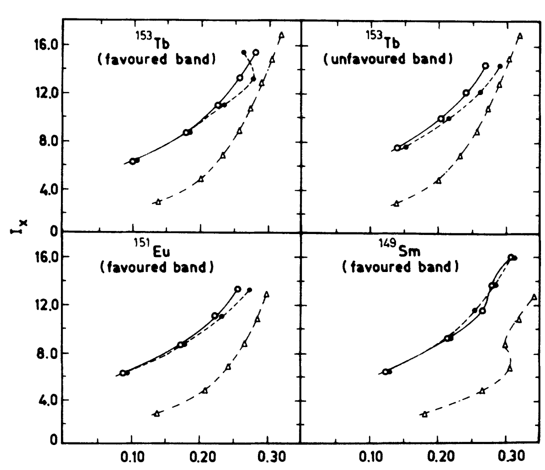

FIG. 5. Rotation-aligned angular momentum I_x vs the angular frequency ω for the favored bands in ^{153}Tb, ^{151}Eu, and ^{149}Sm, based on the $\pi h_{11/2}$ and $\nu i_{13/2}$ orbitals, respectively, is shown. In ^{153}Tb the unfavored band is also shown. See also the caption in Fig. 1.

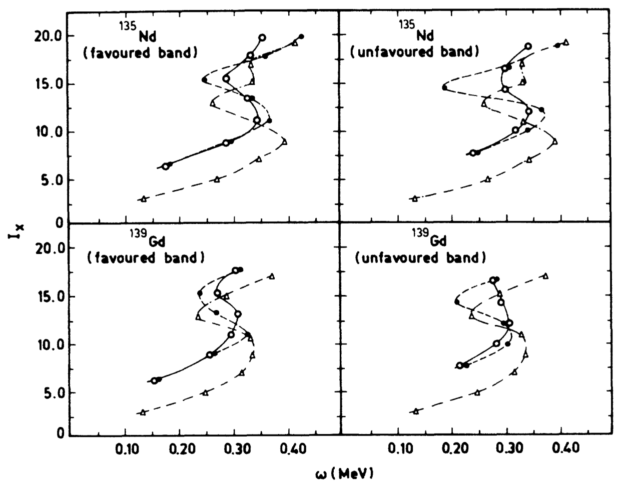

FIG. 6. Rotation-aligned angular momentum I_x vs the angular frequency ω for the favored and unfavored bands based on $\nu h_{11/2}$ orbital in ^{135}Nd and ^{139}Gd is shown. See also the caption in Fig. 1.

B. Odd-neutron nuclei

1. ^{135}*Nd*

In this neutron-deficient Nd nucleus, yrast states based on the $\nu h_{11/2}$ orbital are known[24] up to $I^{\pi}=47/2^{-}$. The core energies[37,38] are taken as averages of those in ^{134}Nd and ^{136}Nd up to $J^{\pi}=14^{+}$. Above this spin value, core energies observed[38] in ^{134}Nd are used. Although the backbending frequencies for the favored and unfavored bands are reproduced more or less correctly (Fig. 6), the observed backbending in both the cases is much sharper than the calculated ones. So the agreement is not good for the states above backbend. The attenuation coefficient used in the calculation is very small ($\alpha=0.97$). However, in view of the rapid decrease of collectivity of the yrast states with increasing spin[47] in ^{134}Nd, the strong alignment observed in the experimental spectrum is not surprising. Since the calculation is carried out with ground-state deformation for all the spin states, the increase in Coriolis interaction strength due to decrease in β_2 could not be accounted for in the theoretical spectrum.

2. ^{135,137,149}*Sm*

The yrast bands in ^{135,137}Sm have been studied[25,26] very recently. Existence of a band based on the $i_{13/2}$ neutron orbital in the $A=130$ region has been identified[25] for the first time in ^{135}Sm. A band with large deformation has been identified[26] in ^{137}Sm. The positive-parity yrast states in ^{135}Sm based on the $g_{7/2}$ orbital show an interesting feature. The states having negative signature ($\alpha=-\frac{1}{2}$) do not show any backbend even up to $I^{\pi}=39/2^{+}$, whereas the positive signature ($\alpha=+\frac{1}{2}$) states based on a $\nu i_{13/2}$ orbital become yrast near $I^{\pi}\simeq 29/2^{+}$, thus showing a backbend near $\omega=0.25$ MeV. Moreover, of all the isotopes studied in the present work, this isotope shows largest ground-state deformation ($\beta_2 \simeq 0.28$). The deformation is deduced from the average of the ground-state deformations of the neighboring even ^{134,136}Sm isotopes.[47] The present calculation reproduces very closely the negative signature states in ^{135}Sm (Fig. 4). The other signature states are also reproduced below the backbending frequency. However, a much larger value of attenuation coefficient is needed to reproduce the experimental curves ($\alpha=0.65$). This is in conformity with the earlier observation[10,11] that the need for attenuation increases with increasing deformation. The negative-parity states based on the $\nu h_{11/2}$ orbital in ^{137}Sm are also reproduced correctly, with $\alpha=0.93$. The core excitation energies in the low-spin region change drastically as one goes from ^{134}Sm to ^{138}Sm. In ^{137}Sm, it is found that better agreement with the experimental spectrum is achieved if the core energies of ^{138}Sm, rather than the average of those in ^{136}Sm and ^{138}Sm are used.

Positive-parity yrast states up to $I^{\pi}=33/2^{+}$ based on the $\nu i_{13/2}$ orbital have been measured earlier in the ^{149}Sm nucleus.[30] The nucleus is situated near the $N=88$ transitional region. The present calculation gives a very good agreement for the favored band members (Fig. 5). However, the calculated signature splitting in the high-spin region is less than that observed experimentally, making the agreement worse for the unfavored band. Hardly any attenuation ($\alpha \simeq 0.98$) is needed in this isotope. The core energies are taken at the average of those[37,44] in ^{148}Sm and ^{150}Sm.

3. ^{139}*Gd*

Negative-parity yrast states based on the $\nu h_{11/2}$ orbital have been measured recently[19,27] up to $I^{\pi}=33/2^{-}$ and $35/2^{-}$ for the favored and unfavored bands, respectively. The core states are taken from the data on the yrast band[43] in ^{140}Gd. Only two yrast states are known[20,40] in ^{138}Gd, so the averaging is not done. Although the backbending frequencies in the favored and unfavored bands are reproduced correctly (Fig. 6), the backbending features are much sharper in the experimental spectrum similar to that observed in ^{135}Nd.

IV. DISCUSSION

Present study shows that except in ^{135}Sm the experimental features of the yrast bands in a number of odd nuclei in the $A \simeq 130-150$ region can be reproduced within the formalism of PRM, practically without any attenuation of the Coriolis interaction strengths. However, in several cases, signature splitting is not reproduced very accurately. The isotopes in this mass region are predicted[48] to be soft with respect to the shape asymmetry parameter γ. The signature splitting sensitively depends upon the value of γ. Since the calculations are done for $\gamma=0$, this disagreement in some cases is not surprising. In order to see the sensitivity of the calculated results on the choice of different parameters, the following studies are also made.

In several nuclei, the calculations have been repeated with several values of the pairing gap parameter Δ, ranging from the value deduced from $\Delta=12/A^{1/2}$ MeV to about one-third its value. The calculated results are seen to depend very weakly on the choice of this parameter. This is in contrast to our earlier observation in the rare-earth region.[11] The calculations have been repeated in several nuclei with about 10–15 % change in the deformation parameter. The results do not show any significant effect on our main observation that a negligibly small attenuation is needed in these nuclei to reproduce the experimental band structures. The signature splitting in the calculated spectra is found to be quite sensitive to the choice of the Fermi level. In fact, reproduction of the experimental signature splitting as closely as possible has been the main criterion for making final choice of the Fermi level. Since present calculations mainly involve bands based on high spin intruder levels, the results are not expected to be sensitive to the choice of the Nilsson single-particle parameters μ and k. Calculation of the positive parity band energies based on the $N=4$ Nilsson orbitals in ^{131}La has been repeated with the μ, k values prescribed recently by Zhang *et al.*[49] in this mass region. The results are almost identical with those obtained by using μ, k given by Nilsson.[34] In the present formalism a term describing the rotation dependence of the interaction between core and particle has been incorporated. However, this term has practically no effect on the results of the calculation for $\alpha \simeq 1.0$.

In some odd-proton nuclei, e.g., ^{131}La, ^{131,133,135}Pr it is found that the negative parity bands do not show any strong alignment as observed in the neighboring even nuclei, i.e., alignment is blocked by the single proton. One possible way to include this blocking mechanism in the PRM is to use the ground state band in which these aligned states are also unoccupied, instead of the yrast band, as the core beyond the backbend. However, for these nuclei, this could not be done due to lack of necessary experimental data. It is interesting to note that in the neighboring odd-proton and odd-neutron nuclei, ^{139}Pm, ^{135}Nd, and ^{139}Gd, this blocking mechanism is not present, and the experimental backbending frequency is reproduced in the calculation. However, in ^{135}Nd and ^{139}Gd, the observed backbending feature is much sharper than that obtained in the calculated spectra. Recent experimental investigations have revealed a significant change in collectivity with increasing spin in the yrast bands of several nuclei in this mass region.[47] In ^{134}Nd, the deformation (β_2) parameter changes from 0.20 to 0.10 as the spin of the excited states increases from 2 to 8. Therefore Coriolis interaction experienced by the odd neutron in the neighboring odd-A nucleus ^{135}Nd should also increase considerably with increasing spin (due to bunching of Nilsson single-particle levels at small deformation), resulting in strong alignment. Since the theoretical calculation of the yrast band is done for a fixed β_2 value (corresponding to ground-state deformation), the strong alignment observed in the experimental spectrum cannot be properly reproduced. On the other hand, if the collectivity increases significantly with increasing spin of the yrast states in even nuclei, one may observe blocking of alignment in the neighboring odd nuclei. More experimental investigations on the change of collectivity with increasing spin of the yrast bands of even Ce, Nd, Sm, Gd nuclei in this mass region will be of considerable help in understanding the difference in behavior of the rotational alignment observed in neighboring even and odd nuclei.

The present work shows that the PRM works reasonably well even in those regions, where excitation spectra of the nuclei bear little resemblance to those expected in a good rotor. Moreover, a comparison of the results obtained in the present work and earlier investigations[10,11] shows that the need for attenuation arises only when one goes to a region of large deformation, i.e., a region where the PRM has the strongest validity. A close scrutiny of the role played by the pairing interaction in the PRM formalism may be of some help in understanding this anomaly.

In the PRM, the pairing interaction comes into picture in two different ways: (a) indirectly through the coupling strength $1/2\mathcal{J}$, i.e., the value of the moment of inertia, and (b) directly through the quasiparticle formalism. It is well known that the moment of inertia of a nucleus depends sensitively on the strength of the pairing interaction. The stronger the pairing interaction, smaller will be the value of the moment of inertia leading to stronger Coriolis interaction. On the other hand, explicit use of the quasiparticle formalism produces bunching of the single-particle states near Fermi level which effectively leads to stronger Coriolis effect. So, it seems that the effect of the pairing interaction on the strength of the Coriolis interaction is somewhat overestimated. In a well-deformed nucleus, the wide spacings between the Nilsson orbitals arising from a high spin intruder state are significantly reduced through the use of quasiparticle formalism. On the other hand, in a weakly deformed system, since these orbitals are not well separated, introduction of pairing does not significantly alter their relative spacings. So when the PRM is applied to a weakly deformed system, the pairing interaction comes into play mainly through the coupling strength $1/2\mathcal{J}$, whereas in a well-deformed system it acts in both ways. Moreover, if one considers the internal consistency of the model, there is no *a priori* justification for estimation of a pairing gap from experimental odd-even mass difference, completely ignoring the effect of the recoil term on the binding energy of the odd mass system.

V. CONCLUSION

The Coriolis attenuation problem has engaged the attention of a large number of workers for a long time. However, it is not yet well understood at all why this attenuation is necessary. Moreover, it is found that the need for attenuation is greatest where it is least expected. On the basis of the present as well as our earlier study[11] in the well-deformed region, it appears that the problem is intimately related to the way the pairing interaction is treated within the PRM formalism. More detailed investigations along this line may help in understanding this well-known problem of Coriolis attenuation.

[1]M. Hasegawa, S. Tazaki, and K. Muramatsu, Phys. Lett. B **226**, 1 (1989).
[2]I. Hamamoto, in *Proceedings of the Winter College on Fundamental Nuclear Physics, Trieste, 1984,* edited by K. Dietrich, M. Di Toro, and H. J. Mang (World Scientific, Singapore, 1985), Vol. II, p. 755.
[3]A. J. Kreiner, Phys. Rev. Lett. **42**, 829 (1979).
[4]K. Neergärd, Phys. Lett. **89B**, 5 (1979).
[5]J. Rekstad and T. Engeland, Phys. Lett. **89B**, 316 (1980).
[6]A. Bohr and B. R. Mottelson, Phys. Scr. **22**, 461 (1980).
[7]J. Almberger, I. Hamamoto, and G. Leander, Phys. Scr. **22**, 331 (1981).
[8]T. Engeland, Phys. Scr. **25**, 467 (1982); A. Henriquez, T. Engeland, and J. Rekstad, Nucl. Phys. **A410**, 1 (1983); T. Engeland, in *Collective Phenomena in Atomic Nuclei,* edited by T. Engeland, J. Rekstad, and J. S. Vaagan (World Scientific, Singapore, 1984), p. 155.
[9]P. Ring and H. J. Mang, Phys. Rev. Lett. **33**, 1174 (1974).
[10]E. M. Müller and U. Mosel, J. Phys. G **10**, 1523 (1984).
[11]M. Saha, S. Bhattacharya, A. Goswami, and S. Sen, Z. Phys. A **332**, 383 (1989).
[12]L. Hildingsson, C. W. Beausang, D. B. Fossan, R. Ma, E. S. Paul, W. F. Piel, Jr., and N. Xu, Phys. Rev. C **39**, 471 (1989).
[13]E. S. Paul, C. W. Beausang, D. B. Fossan, R. Ma, W. F. Piel, Jr., N. Xu, L. Hildingsson, and G. A. Leander, Phys. Rev. Lett. **58**, 984 (1987).
[14]M. J. Godfrey, P. J. Bishop, A. Kirwan, P. J. Nolan, D. J. Thornley, D. J. Unwin, D. J. G. Love, and A. H. Nelson, J. Phys. G **13**, 1165 (1987).
[15]L. Hildingsson, C. W. Beausang, D. B. Fossan, and W. F. Piel, Jr., Phys. Rev. C **33**, 2200 (1986).
[16]M. Kortelahti, R. Julin, J. Hattula, A. Pakkanen, and M. Piiparinen, Z. Phys. A **321**, 417 (1985).
[17]T. M. Semkow *et al.*, Phys. Rev. C **34**, 523 (1986).
[18]N. Xu, C. W. Beausang, R. Ma, E. S. Paul, W. F. Piel, Jr., D. B. Fossan, and L. Hildingsson, Phys. Rev. C **39**, 1799 (1989).
[19]T. Burrows, Nucl. Data Sheets **57**, 337 (1989).
[20]L. Goettig, W. Gelletly, C. J. Lister, R. Moscrop, and B. J. Varley, Nucl. Phys. **A475**, 569 (1987).
[21]H. Guven, R. Julin, M. Lach, J. Styczen, M. Müller-Veggian, A. Kramer-Flecken, and P. Kleinheinz, Z. Phys. A **330**, 437 (1988).
[22]M. Müller-Veggian, K. Zuber, H. Guven, G. de Angelis, J. Styczen, M. Lach, G. Hebbinghaus, and P. Kleinheinz, Z. Phys. A **330**, 343 (1988).
[23]M. Lach, J. Styczen, R. Julin, M. Piiparinen, H. Beuscher, P. Kleinheinz, and J. Blomqvist, Z. Phys. A **319**, 235 (1984).
[24]E. M. Beck, F. S. Stephens, J. C. Bacelar, M. A. Deleplanque, R. M. Diamond, J. E. Draper, C. Duyar, and R. J. McDonald, Phys. Rev. Lett. **58**, 2182 (1987).
[25]S. M. Mullins, R. Wadsworth, J. M. O'Donnell, P. J. Nolan, A. J. Kirwan, P. J. Bishop, M. J. Godfrey, and D. J. G. Love, J. Phys. G **13**, L201 (1987).
[26]E. S. Paul, R. Ma, C. W. Beausang, D. B. Fossan, W. F. Piel, Jr., S. Shi, N. Xu, and J. Y. Zhang, Phys. Rev. Lett. **61**, 42 (1989).
[27]R. Ma, K. Ahn, Y. Liang, E. S. Paul, N. Xu, and D. B. Fossan, Phys. Rev. C **39**, 530 (1989).
[28]B. Singh, J. A. Szucs, and M. W. Johus, Nucl. Data Sheets **55**, 185 (1988).
[29]M. A. Lee, Nucl. Data Sheets **37**, 487 (1982).
[30]J. A. Szucs, M. W. Johus, and B. Singh, Nucl. Data Sheets **46**, 1 (1985).
[31]M. A. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. **178**, 1864 (1969).
[32]P. C. Simms, F. A. Rickey, and R. K. Popli, Nucl. Phys. **A347**, 205 (1980).
[33]S. Bhattacharya, S. Sen, and R. K. Guchhait, Phys. Rev. C **32**, 1026 (1985); A. Goswami, S. Bhattacharya, M. Saha, and S. Sen, Phys. Rev. C **37**, 370 (1988).
[34]S. G. Nilsson *et al.*, Nucl. Phys. **A131**, 1 (1969).
[35]S. Raman, C. H. Malarkey, W. T. Milner, C. W. Nester, Jr., and P. H. Stelson, At. Data Nucl. Data Tables **36**, 1 (1987).
[36]A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).
[37]M. Sakai, Internal Report of INS, University of Tokyo, 1982; M. Sakai, At. Data Nucl. Data Tables **31**, 399 (1984).
[38]I. Jenkins, P. J. Nolan, A. J. Kirwan, M. J. Godfrey, P. J. Bishop, D. J. Thornley, K. L. Ying, and R. Wadsworth, Z. Phys. A **333**, 405 (1989).
[39]R. Wadsworth, S. M. Mullins, J. R. Hughes, P. J. Nolan, A. Kirwan, P. J. Bishop, I. Jenkins, M. J. Godfrey, and D. J. Thornley, J. Phys. G **15**, L47 (1989).
[40]D. M. Todd, R. Aryaeinejad, D. J. G. Love, A. H. Nelson, P. J. Nolan, P. J. Smith, and P. J. Twin, J. Phys. G **10**, 1407 (1984).
[41]L. K. Peker, Nucl. Data Sheets **53**, 177 (1988).
[42]L. K. Peker, Nucl. Data Sheets **51**, 395 (1987).
[43]E. S. Paul, K. Ahu, D. B. Fossan, Y. Liang, R. Ma, and N. Xu, Phys. Rev. C **39**, 153 (1989).
[44]E. der Mateosian, Nucl. Data Sheets **48**, 345 (1986).
[45]L. K. Peker, Nucl. Data Sheets **58**, 93 (1989).
[46]R. G. Helmer, Nucl. Data Sheets **52**, 1 (1987).
[47]R. Wadsworth, J. M. O'Donnell, D. L. Watson, P. J. Nolan, P. J. Bishop, D. J. Thornley, A. Kirwan, and D. J. G. Love, J. Phys. G **13**, 205 (1987).
[48]Y. S. Chen, S. Frauendorf, and G. A. Leander, Phys. Rev. C **28**, 2437 (1983).
[49]J. Zhang, N. Xu, D. B. Fossan, Y. Liang, R. Ma and E. S. Paul, Phys. Rev. C **39**, 714 (1989).