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ON THE STRENGTH OF CORIOLIS COUPLING IN ACTINIDE NUCLEI*

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Coriolis Coupling V_{cor} plays an important role in deformed nuclei.[1)] V_{cor} is proportional to $\frac{h^2}{J}[j\,(j+1) - \Omega\,(\Omega+1)]^{1/2}$ and therefore is particularly significant in the nuclei with large j and low Ω Nilsson levels close to Fermi surface: $n(i_{13/2})$ in A=150-170 rare-earth nuclei and $p(i_{13/2})$ and $n(j_{15/2})$ in $A \geq 224$ actinide nuclei. Because of larger j ($n(j_{15/2})$ versus $n(i_{13/2})$) and smaller deformations ($\beta \approx 0.22$ versus β 0.28) it was reasonable to expect that in actinide nuclei "Coriolis" effects are stronger than in the rare earth nuclei. Recently[2,3,)] it was realized that the strength of observed "Coriolis" effects depends not only on the genuine Coriolis Coupling but also on the interplay between Coriolis and pairing forces which leads to an interference between the wave functions of two mixing rotational bands. As a consequence the effective interaction V_{eff} of both bands is an oscillating function of the degree of shell filling (or chemical potential λF) . It was shown[4,5,)]that in the rare earth nuclei this interference strongly influenced conclusions about the trends in the Coriolis coupling strength and explained many of the observed band-mixing features (the sharpness of back banding curves, details of the blocking effect etc.).

This success spurred similar conclusions about "Coriolis" effects in actinide nuclei.[5-9]

From theoretical analysis it was concluded that in the majority of actinide nuclei the effective interaction V_{eff}, is strong and therefore the Coriolis band-mixing have to be very strong.[5-7,9)]

In this paper we would like to demonstrate that contrary to these predictions experimental data suggest that Coriolis band mixing in studied actinide nuclei is relatively weak and possibly significantly weaker than in rare earth nuclei. Earlier indications on this may be found in the analysis of Bohr and Mottelson[1)] where it was shown that Coriolis band mixing in the

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lower spin part of 7/2-[743]-band of ^{235}U is almost twice weaker than that expected from Nilsson Model.

Let us consider the effect of Coriolis mixing. The basic adiabatic formula for $E_{rot}(I)$ in the simplest K=0 rotational band is

$$E_{rot}(I) = \frac{h^2}{2J} I (I + 1) \qquad (1)$$

Coriolis coupling may affect this formula in two ways:

a. If it is weak enough it may change the effective moment of inertia J, but leave untouched the character of the spin-dependence I(I + 1).

b. If it is strong enough it may alter not only J, but also the character of spin-dependence and make (1) invalid.

The first effect is typical for relatively weak Coriolis coupling $\frac{h^2}{2J} \langle I, K + 1|j+ |I, K\rangle \ll \Delta E_{K,K+1}(I)$ and therefore may be treated in terms of perturbation theory. In this case E_{rot} (I) may be described by the formula:[1]

$$E_{rot} (I,K) = \sum_{n=1} An [I(I + 1)]^n + (-1)^{I+K} \frac{(I+K)!}{(I-K)!} \sum_{m=0} Am [I(I+1)]^m \qquad (2)$$

If the experimental values of $E_{rot}(I)$ for a given band obey this formula we may think that the Coriolis mixing in this band is weak.

When there is strong Coriolis mixing $(\frac{h^2}{2J} (\langle I,K + 1|j_+|I,K\rangle \gg \Delta E_{K,K+1}(I))$ perturbation theory can't be used and therefore (1) and (2) are not valid; strong Coriolis mixing may be treated in two different ways: a) by numerical matrix diagonalization of the Coriolis interaction, b) in terms of alignment model. According to[10] in the two-band mixing approximation diagonalization of V_{cor} results in a simple analytical formula for $E_{rot}(I)$ in the lower band:

$$E^{(L)}_{rot}(I) = Eo + \frac{h^2}{2J} I (I + 1) - \left[\frac{\left(E_K - E_{K+1}\right)^2}{4} + 4 \left(\frac{h^2}{2J}\right)^2 \langle K+1|j_+|K\rangle^2 [I(I+1)-K(K+1)]\right]^{1/2} \qquad (3)$$

With the strengthening of Coriolis coupling $\left(\frac{E_{K,K+1}^2}{\langle K+1|j+|K\rangle^2} \longrightarrow 0\right)$ for higher states with I>>K we come to the formula (without spin independent terms)

$$E^{(L)}_{rot} (I) \approx \frac{h^2}{2J} I (I+1) - 4 \left(\frac{h^2}{2J}\right)^2 \langle K+1|j_+|K+\rangle^2 I = AI(I+1)-BI \qquad (4)$$

It means that strong Coriolis mixing affects the perturbation theory description of $E_{rot}(I)$ in simple way: it adds to (1) and (2) a linear spin term:

$$E_{rot}(I) = {}_{n=1}A_n[I(I+1)]^n - BI \qquad (5)$$

The same result follows from alignment model. According to this model[11) strong Coriolis coupling tend to decouple intrinsic moment from axis of deformation and align it along the axis of rotation. For aligned rotational states total spin I include not only rotational moment R, but also aligned intrinsic moment $i_\alpha = j$ and $I = R+i_\alpha$

In the first approximation:

$$E_{rot}(I) = \frac{h^2}{2J} R\ (R+1) = \frac{h^2}{2J} (I-i_\alpha)\ (I-i_\alpha+1)$$

$$= \frac{h^2}{2J} I\ (I+1) - \frac{h^2}{J} i_\alpha\ I + \text{const} = AI\ (I+1) - BI \qquad (6)$$

with $B = 2A\ i_\alpha$ and $i_\alpha = \frac{B}{2A}$.

From comparison (4) and (6) it follows that i_α is proportional to the strength of Coriolis coupling ($i_\alpha \sim \langle K+1|j_+|K\rangle$) . Thus experimental determination of the aligned moment $_\alpha$ becomes very important. Until now the "experimental" values of i_α were extracted from comparison of the experimental function $I(\omega)$ (with $2h\omega = E\gamma(I\text{->}I-2)$ for a given aligned band with a similar function for the non aligned reference band.[12)

$$i_\alpha(\omega) = I_{exp}(\omega) - I_{ref}(\omega) \qquad (7)$$

As a reference band GRB[12) and later on the VMI band with low-spin GRB parameters was used.[5-7,9) However this i_α includes characteristics not only of considered aligned band, but also of GRB[13) and therefore is not a real aligned moment.

We propose to find the value of i_α without a reference band by extracting from the experimental function $E_{rot}(I)$ the linear term proportional to i_α . (See (5) and (6)). This can be done by two methods. The first is the direct fitting of experimental curves $E_\gamma(I\longrightarrow I-2) = f(I)$ for aligned band with many known levels with formula(5). We may also find the linear term of $E_{rot}(I)$ by extrapolating the experimental curve $I(E_\gamma(I\longrightarrow I-2))$ in the direction of decreasing $\omega\text{->}0$ (or $E_\gamma\text{->}0$).

It is easy to show that for any rotational band with $K \neq 1/_2$ with weak Coriolis mixing, where the level energies may be described by (1) or (2), the interception of the curve $I(E_\gamma\ (I \rightarrow I-2))$ with axis I occurs at $I_{cr}(E\gamma=0) = +1/_2$.[10,14] If the formula for $E_{rot}(I)$ includes the linear term (this is typical for all strongly mixed aligned bands) then $I_{cr} = i_\alpha + 1/2$ and the aligned moment i_α may be immediately determined as $i_\alpha = I_{cr} - 1/2$[14]. This method is particularly useful for the bands with K<7/2 where extrapolation of $I(E_\gamma)$ to the point $I_{cr}\ (E_\gamma=0)$ is relatively short and therefore more reliable.

First we applied both of these methods to the analysis of $E_{rot}(I)$ in actinide octupole bands. It was expected that the Coriolis mixing of the K=0-,1-, 2- and 3- bands is so strong that it may produce alignment of the octupole phonon moment L=3 along the axis of rotation.

We fitted the $E_{rot}(I)$ for I=7-23 levels of K=0 octupole bands in ^{236}U[15] and ^{238}U[7] with formula (5)* and extracted the parameter of the linear terms. From (6) we deduce that for $E_{exp}\ (I)-E_{calc}(I)<0.5$ keV the value of i_α in all I=7-23 states is small. (≈ 0.5 in ^{238}U, ≈ 0.7 in ^{236}U).

In Fig. 1 we present the experimental curves $I(E_\gamma)$ for octupole bands with K=0- in some actinide even-A nuclei. In all of them the very short and reliable extrapolation led to $I_{cr} \approx +1/2$ and therefore $i_\alpha \approx 0$ (at least for I=1-9 levels).

Both methods bring us to the same conclusion: aligned moments i_α in all known K=0-,1-,2- actinide octupole bands in the levels with I<23 are very small, $\lesssim 0.6$, and therefore Coriolis band-mixing can't be strong. From Fig. 2 where we present the data for K=0- and K=0+ bands in ^{238}U, it is seen that for $E_{exp}\ (I)-E_{calc}\ (I)< 0.5$ keV the values of i_α in all I=7-23 states are small (≈ 0.5 in ^{238}U, ≈ 0.7 in ^{236}U). These values strongly negates large values of i_α traditionally derived from (7) with different reference bands-GRB (BM(1)) and VMI-band (BM(2)).

*Detailed discussion of used formula and results are presented in [14].

Our experience in rare earth nuclei suggests that n{5/2 + [642]}-($i_{13/2}$)-rotational bands are strongly mixed and therefore have significant aligned moments. This can be seen from Fig. 3 where we present I(E_γ) curve for ^{159}Dy [17] with Icr ≈ 3 and i_α ≈ 5/2 . Similar band in the actinide nuclei ^{237}Np-{p5/2 + [642]} ($i_{13/2}$) [7] has I_{cr} ≈ +1/2 and therefore i_α ≈ 0. Practical absence of alignment in the states with I<29/2 suggest that the Coriolis mixing in this band is weak, much weaker than in similar bands in rare earth nuclei $_{64}$Gd, $_{66}$Dy, $_{68}$Er. $_{70}$Yb .

Fig. 4 shows experimental curves I(E_γ) for many known ^{235}U bands[18] with different j from 15/2 (j15/2) to 5/2 (d5/2) (for main component of the wave function). Accordingly it was reasonable to expect, in these bands, a wide range of strong to weak Coriolis mixing. But Fig. 4 demonstrates that contrary to these expectations all $\Omega \neq 1/2$ observed bands reveal I_{cr} ≈ +1/2 and i_α ≈ 0.

It means that in all studied ^{235}U bands (even with large j) the Coriolis mixing is relatively weak (in agreement with earlier Bohr-Mottelson conculsions for 7/2-[745] band).

These analyses as well as similar analyses of rotational bands in other actinide nuclei demonstrate that Coriolis mixing in actinide nuclei contrary to the usual expectations is relatively weak, probably significantly weaker than in the rare-earth nuclei.

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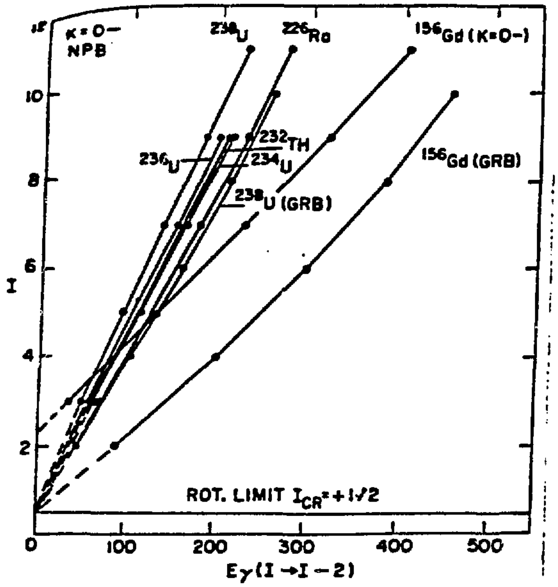

Fig. 1 The function $I(\omega)=f(E_\gamma(I\text{->}I-2))$ for octupole K=0-bands in some actinide even-even nuclei, ^{156}Gd. and ^{156}Gd K=0+ ground rotational band (GRB).

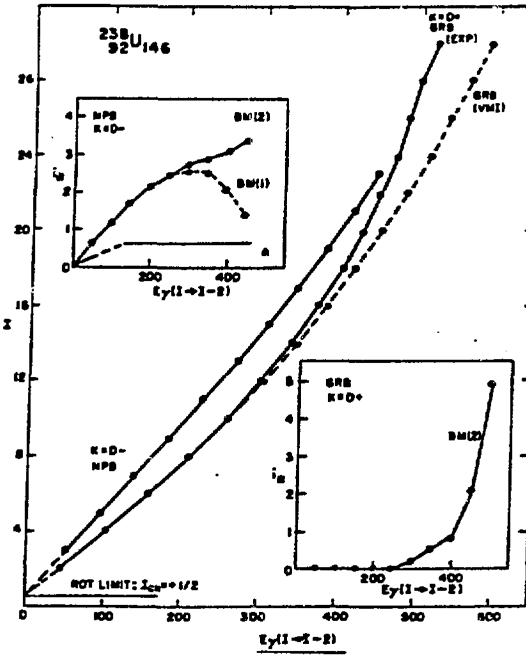

Fig. 2 The function $(I(E_\gamma(I\text{->}I-2))$ for K=0- and K=0+ bands in ^{238}U. The solid line for GRB is based on (2) with n=4 and coincide with experimental curve, the dashed line is from Variational Moment of Inerti (VMI) 2 term formula with parameter derived from E_{GRB} (exper;I<6). In inserts we present i_α from (5) with linear term (curve A), from (7) with $E_{ref}(I)=E_{GRB}$(exper) (curve BM(1)) and with $E_{ref}(I)=E_{GRB}$(VMI) (curve BM(2)).

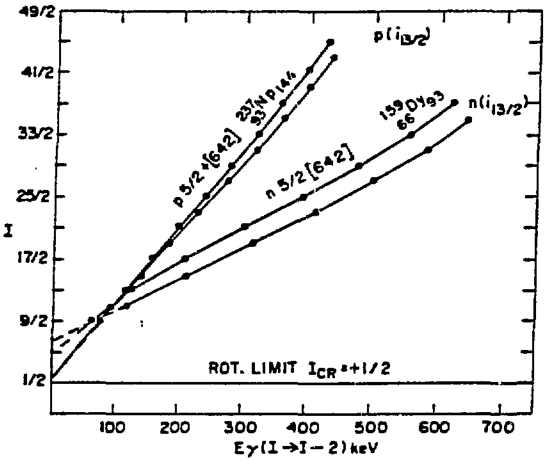

Fig. 3 The function $I(\omega)=f(E_\gamma(I\text{->}I-2))$ for 5/2+[642] sub-bands with both signatures in the rare earth $^{159}_{66}Dy_{93}$ and actinide $^{237}_{93}Np_{144}$ nuclei.

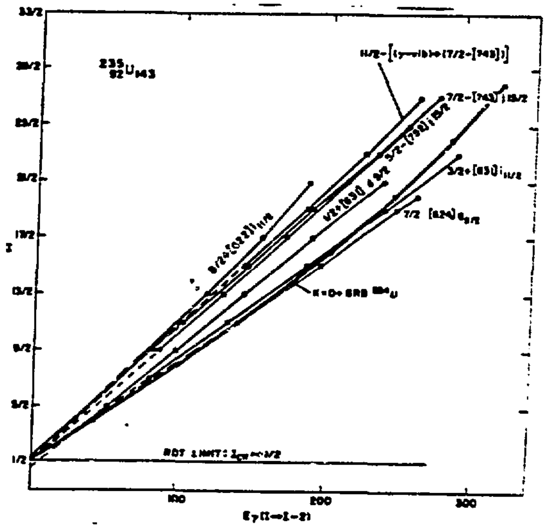

Fig. 4 Functions $I(E_\gamma(I\text{->}I-2))$ for ^{235}U rotational bands with different value of j for the major component of the wave function.