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E4-86-557

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ON OCTUPOLE ALIGNMENT IN ACTINIDES

Submitted to "Physics Letters B"

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1986

During the last years, a large amount of experimental information on the low-lying octupole vibrational states was accumulated, in particular in the actinide nuclei (see for example ref.[1]). The properties of negative parity band differ much from what could be expected on the basis of adiabatically slow rotation superimposed on the vibrational excitation. With increasing rotation the vibrational angular momentum tends to align in the direction of the rotational angular momentum, giving rise to distortions in the spectra of rotational states and to the new regularities in the transitions from the aligned states to the ground band states.

These new features of the rotational band have been understood in the framework of a phenomenological model including the pure boson (octupole)operators coupled to a rotor by the Coriolis force[2,3]. It was shown that the Coriolis interaction aligns the octupole angular momentum and makes nuclei softer with respect to the octupole deformation with increasing spin.

The conclusions of papers[2,3] must be checked within the microscopic approach taking into account the many-body structure of the phonons that may change with rotation. The convenient way to do this is provided by the model including cranking plus random phase approximation (CRPA)[4-6]. In this note we report the results of calculations of the alignment of octupole phonons in the states of the $K^{\pi}=0^{-}$ band in three nuclei $^{230,232}Th$ and ^{238}U . The calculations of this one was also reported in[7] for ^{232}Th and $^{236,238}U$. Our calculations differ in the treatment of the aligned angular momentum and in parametrization of the Hamiltonian. Some preliminary results were announced in[8]. We also calculate the branching ratio $R_{I^-}=B(E1,I^-_{okt}\to(I-1)^+_{yr})/B(E1,I^-_{okt}\to(I+1)^+_{yr})$ for the reduced probabilities of the electric dipole transitions from the one-phonon states to the ground band states.

The **Hamiltonian** describing octupole excitations in the rotating nuclei may be written

$$H = H_\Omega + H' \qquad (1a)$$

$$H_\Omega = H_{MO}(\varepsilon_2,\varepsilon_4) + \sum_\tau \Delta_\tau(\hat P_\tau^+ + \hat P_\tau) - \sum_\tau \lambda_\tau \hat N_\tau - \Omega \hat J_x \qquad (1b)$$

$$H' = -\frac{1}{2}\sum_{\tau\tau'} \varkappa_{\tau\tau'} \sum_m (-1)^m \hat Q_{3m}(\tau)\hat Q_{3-m}(\tau'), \qquad (1c)$$

where H_{MO} is the Nilsson **Hamiltonian** as defined in ref./9/, P^+ is the monopole pair operator and $\hat N$ is the particle number operator. The separable octupole-octupole interaction contains both an isoscalar and isovector components with the corresponding strength constants: $2\varkappa_0 = \varkappa_{pp} + \varkappa_{np}$ $(\varkappa_{nn} = \varkappa_{pp})$, $2\varkappa_1 = \varkappa_{pp} - \varkappa_{np}$ ($\tau = p$ (protons) or n (neutrons)). We assume that the parity is a good quantum number and restrict the calculation to the states of the $K^\pi = 0^-$ band only (negative signature states).

As the **Hamiltonian** (1c) may be divided into two parts differing in symmetry with respect to rotation by an angle π around x-axis, its RPA diagonalization separates into two independent parts/4-6/. So, the negative signature states are formed by the negative signature part of **Hamiltonian** (1)

$$H^{(-)} = H_\Omega - \frac{1}{2}\sum_{\tau\tau'} \varkappa_{\tau\tau'} \sum_{n=1}^{4} \hat F_n(\tau)\hat F_n(\tau'), \qquad (2)$$

where

$$\hat F_n = \frac{a}{\sqrt{2}}\left(\hat Q_{3m} - (-1)^n \hat Q_{3-m}\right),\quad a = \begin{cases} i, & n=1(3)\ m=1(3) \\ 1, & n=2(4)\ m=3(1) \end{cases}$$

$$\hat Q_{3m}(\tau) = \sum_{k=1}^{N_\tau} r_k^3\, Y_{3m}(\theta_\tau^k) \qquad (3)$$

and m is the magnetic quantum number (the x-axis is the quantization axis). Then, representing **Hamiltonian** (2) in the rotating frame by bosons/4,5/, we obtain

$$H^{(-)} = \frac{1}{2}\sum_{\tau\mu} E_\mu(\tau)\, b_\mu^+(\tau) b_\mu(\tau) - \frac{1}{2}\sum_{\tau\tau'}\varkappa_{\tau\tau'}\sum_n F_n(\tau)F_n(\tau') \qquad (4)$$

Index μ denotes summation over the two-quasiparticle states: ik(positive signature+) and $i\bar k$(negative signature-),

$E_\mu = E_{ik}$ or $E_{i\bar k}$ ($E_{ik} = E_i + E_k$, $E_{i(k)}$ is the quasiparticle energy obtained from solving the Hartree-Bogolubov equations in the cranking model/4-6/). $F_n(\tau)$ is linear boson part of the corresponding operator:

$$F_{1,3} = i\sum_\mu F_\mu^{1,3}(b_\mu^+ - b_\mu)\ ;\quad F_{2,4} = \sum_\mu F_\mu^{2,4}(b_\mu^+ + b_\mu), \qquad (5)$$

where $b_\mu^+ (b_\mu)$ is two-quasiparticle boson and F_μ^n is a quasiparticle matrix element. Solving the RPA equations of motion for the negative signature phonons

$$[X_{\lambda-}, H^{(-)}] = i\omega_{\lambda-} P_{\lambda-}\ ;\ [P_{\lambda-}, H^{(-)}] = -i\omega_{\lambda-} X_{\lambda-}\ ;\ [X_{\lambda'}, P_\lambda] = i\delta_{\lambda\lambda'} \qquad (6)$$

with operators $X_{\lambda-}$ and $P_{\lambda-}$

$$X_{\lambda-} = \sum_{\tau\mu} X_\mu^\tau (b_\mu^+(\tau) + b_\mu(\tau))\ ;\ P_{\lambda-} = i\sum_{\tau\mu} P_\mu^\tau (b_\mu^+(\tau) - b_\mu(\tau)) \qquad (7)$$

one obtains a homogeneous system of equations with the condition of solvability in the form of a secular equation for the eigenvalues $\omega_{\lambda-}$

$$\det |\varkappa_{\tau\tau'} S_{k\ell}(\tau) - \delta_{\tau\tau'}\delta_{k\ell}| = 0, \qquad (8)$$

where det | | is the eighth order determinant,

$$S_{k\ell} = 4\sum_\mu \frac{F_\mu^k F_\mu^\ell E_\mu}{E_\mu^2 - \omega_-^2}\ \ (k-\ell = \text{even})\ ;\qquad S_{k\ell} = 4\omega_- \sum_\mu \frac{F_\mu^k F_\mu^\ell}{E_\mu^2 - \omega_-^2}\ \ (k-\ell = \text{odd}) \qquad (9)$$

A solution of secular equation (8) allows us to define the corresponding negative signature phonon operator

$$\mathcal{O}_{\lambda-}^+ = \frac{1}{\sqrt{2}}(X_{\lambda-} - iP_{\lambda-}) = \frac{1}{\sqrt{2}}\sum_{\tau\mu}(X+P)_\mu^\tau b_\mu^+(\tau) + (X-P)_\mu^\tau b_\mu(\tau). \qquad (10)$$

The inverse transformation

$$b_\mu^+ = \sum_\lambda \{\mathcal{O}_\lambda^+ [b_\mu, \mathcal{O}_\lambda^+] + \mathcal{O}_\lambda [\mathcal{O}_\lambda, b_\mu]\} \qquad (11)$$

represents the completeness condition for the phonon and boson states. Let us define the energy of the state α of some rotational band in the rotating frame

$$R_\alpha(\Omega) = E_\alpha(\Omega) - \Omega\, I_x^\alpha(\Omega), \tag{12}$$

where the average rotational frequency Ω is obtained from the measured transition energies by the recipe given in ref. [10] and $I_x^\alpha = \sqrt{(I_\alpha + \frac{1}{2})^2 - K_\alpha^2}$. The difference $\omega_\alpha(\Omega) = R_\alpha(\Omega) - R_{yr}(\Omega)$ ($R_{yr}(\Omega)$ being the same quantity defined for the yrast line) is the experimental excitation energy of the intrinsic degree of freedom responsible for the formation of the state α relative to the yrast line in the rotating frame

$$\omega_\alpha(\Omega) = E_\alpha(\Omega) - E_{yr}(\Omega) - \Omega\, i_\alpha(\Omega) \tag{13}$$

Here

$$i_\alpha(\Omega) = I_x^\alpha(\Omega) - I_x^{yr}(\Omega) \tag{14}$$

is the corresponding experimental aligned vibrational angular momentum [11] .

We shall compare the quantity $\omega_\alpha(\Omega)$ with the solution $\omega_{\lambda-}$ of the secular equation (8) for given values of the rotational frequency Ω . In conformity with eq. (14) the theoretical aligned vibrational angular momentum in the one-phonon state of the $K^\pi = 0^-$ band is

$$i(\Omega) = \langle \mathcal{D}_{0^-} | \hat{\mathcal{J}}_x | \mathcal{D}_{0^-} \rangle - \langle yr | \hat{\mathcal{J}}_x | yr \rangle \tag{15}$$

at given value of Ω .

Boson representation of the $\hat{\mathcal{J}}_x$ component of the angular momentum has the form

$$\hat{\mathcal{J}}_x = \langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle + \mathcal{J}_x(1) + \mathcal{J}_x(2). \tag{16}$$

Here $\langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle$ is the expectation value of the operator $\hat{\mathcal{J}}_x$ in the cranking solution $|\Omega\rangle$ that is the vacuum state for quasiparticles and for b_μ bosons ($\alpha_i |\Omega\rangle = b_\mu |\Omega\rangle = 0$). The linear part of the operator $\hat{\mathcal{J}}_x$ is defined by positive signature bosons and moreover $\mathcal{J}_x(1)|0\rangle_\phi = 0$ ($|0\rangle_\phi$ is the phonon vacuum). Therefore, $\mathcal{J}_x(1)$ does not give a contribution to the expectation value in the one-phonon negative signature state. The second order term of the boson expansion of the operator $\hat{\mathcal{J}}_x$

$$\mathcal{J}_x(2) = \sum_{ijm} \left\{ \mathcal{J}_{ij}^x \left(b_{im}^+ b_{jm} + b_{i\bar{m}}^+ b_{j\bar{m}} \right) + \mathcal{J}_{\bar{i}\bar{j}}^x \left(b_{\bar{i}m}^+ b_{\bar{j}m} + b_{\bar{i}\bar{m}}^+ b_{\bar{j}\bar{m}} \right) \right\} \tag{17}$$

with the quantity $\langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle$ defines the expectation value in the one-phonon state for the given rotational frequency Ω

$$\langle \mathcal{D}_{\lambda-} | \hat{\mathcal{J}}_x | \mathcal{D}_{\lambda-} \rangle = \langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle + \langle \mathcal{D}_{\lambda-} | \mathcal{J}_x(2) | \mathcal{D}_{\lambda-} \rangle . \tag{18}$$

The expectation value of the operator $\hat{\mathcal{J}}_x$ in the yrast state as a function of Ω may be found directly from the experimental data. In fact, the parameters of the Hamiltonian H_Ω (eq.(1b)) (ε_2 , ε_4 , Δ , λ) are usually chosen so as to reproduce these experimental data within the cranking model ansatz

$$\sqrt{I(I+1)} = \langle yr | \hat{\mathcal{J}}_x | yr \rangle \equiv \langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle .$$

Therefore, it is reasonable to take

$$i(\Omega) = \langle \mathcal{D}_{\lambda-} | \hat{\mathcal{J}}_x | \mathcal{D}_{\lambda-} \rangle - \langle \Omega | \hat{\mathcal{J}}_x | \Omega \rangle . \tag{19}$$

Then, using eqs. (11),(17),(18) we obtain

$$\begin{aligned} i(\Omega) = 2 \sum_{ijm} \Big\{ & \mathcal{J}_{ij}^x \left[(X+P)_{im} (X+P)_{jm} + 2 (X-P)_{im} (X-P)_{jm} \right] + \\ & + \mathcal{J}_{\bar{i}\bar{j}}^x \left[(X+P)_{\bar{i}\bar{m}} (X+P)_{\bar{j}\bar{m}} + 2 (X-P)_{\bar{i}\bar{m}} (X-P)_{\bar{j}\bar{m}} \right] \Big\} \end{aligned} \tag{20}$$

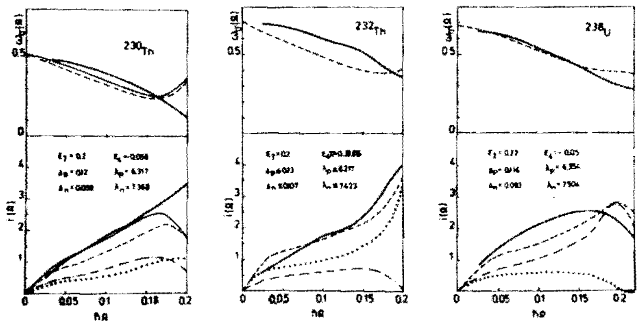
the theoretical aligned vibrational angular momentum that will be compared with the quantity $i(\Omega)$ from eq.(14).

Another experimental quantity is the branching ratio R_{I^-}. Using the results from [4,12] in the framework of the model, we have

$$R_{I^-} = \frac{\left| \sqrt{I} \sum_{\tau\mu} e_\tau P_\mu^\tau \mathcal{M}_\mu^{(-)}(\tau) + \sqrt{I+1} \sum_{\tau\mu} e_\tau X_\mu^\tau \mathcal{M}_\mu^{(+)}(\tau) \right|^2}{\left| \sqrt{I+1} \sum_{\tau\mu} e_\tau P_\mu^\tau \mathcal{M}_\mu^{(-)}(\tau) - \sqrt{I} \sum_{\tau\mu} e_\tau X_\mu^\tau \mathcal{M}_\mu^{(+)}(\tau) \right|^2} . \tag{21}$$

where $\mathcal{M}^{(-)} = \frac{1}{\sqrt{2}} (\hat{Q}_{11} - \hat{Q}_{1-1})$, $\mathcal{M}^{(+)} = \frac{i}{\sqrt{2}} (\hat{Q}_{11} + \hat{Q}_{1-1})$, $\hat{Q}_{1m}(\tau) = \sum_{k=1}^{N_\tau} z_k Y_{1m}(\theta_\tau^k)$ are the components of the dipole operator, $e_p = Ne/A,\ e_h = -Ze/A$ are the standard effective dipole charges, $I = I_{o\kappa t}^{-}$.

In our calculation the spherical oscillator shells N = 4, 5,6 for protons and N = 5,6,7 for neutrons were taken into account. The parameters of deformation (ε_2, ε_4), gap (Δ) and chemical potential (λ) taken from /13,14/ are kept constant. This approximation provides an excellent description of some properties of the yrast levels in the **entire** deformed actinide region /13-15/. The isoscalar strength constant $\varkappa_0$ was fixed to reproduce the $I^{\pi} = 1^{-}_{1}$ level of $K^{\pi} = 0^{-}$ band*). According to the estimate of ref. /18/ $\varkappa_1/\varkappa_0$ = -3.6. The variation of this ratio gives an average value of $\varkappa_1/\varkappa_0$ = -3, that permits one to reproduce simultaneously an alignment pattern and the branching ratio R_{I^-} in three nuclei. The results of calculation for ω_0- are not so critical to the choice of the ratio value but the quantitative description of the aligned octupole angular momentum becomes worse for $\varkappa_1/\varkappa_0$ = -3 (see fig.1a).



a) b) c)

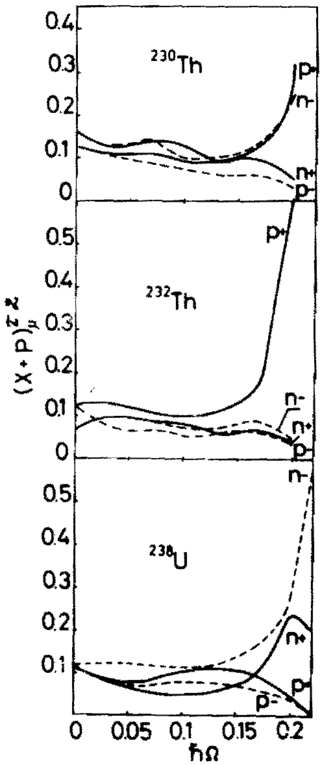
F i g. 1. The excitation energy of the vibrational states of the $K^{\pi} = 0^{-}$ band ω_0-(MeV) and the aligned octupole angular momentum $i(\Omega)$ at different rotational frequency $\hbar\Omega$ (MeV). The solid line corresponds to the experimental values calculated with eqs.(13),(14); the thin line, to theoretical calculation for $\varkappa_1/\varkappa_0 = 0$; and the dashed line, to the case $\varkappa_1/\varkappa_0 = -3$. Proton and neutron contributions are given respectively by the points and point-dashed lines. The parameters (Δ, λ) are given in $\hbar\omega_0$ units. The experimental data are taken from ref.[19] for ^{230}Th, ref.[3] for ^{232}Th and ref.[20] for ^{238}U.

*)The strength constant may be obtained from the condition for restoration of translational symmetry of the Hamiltonian (2). But in the last case early RPA calculation in this region of nuclei without rotation have shown little change of the value $\varkappa_0$ (only ~ 4%) and the energy of the states of $K^{\pi} = 0^{-}$ band practically do not change[16]. Moreover, $\varkappa_0$ depends very little on the rotation at low spins[17].

In spite of the very schematic residual interaction in our model we still observe a good qualitative agreement of $\omega_{0^-}(\Omega)$ and $i(\Omega)$ with experimental data up to 0.17 MeV. The worse agreement in the case ^{230}Th may be due to the Coriolis antipairing effect that descreases the gap at large rotational frequency /18/. Another source of the discrepancy is the possible change in the deformation of the mean field.

It is easy to understand the structure of octupole alignment from the point of view of the behaviour of the maximal two-quasiparticle components of the phonon (see fig.2). Their weight is defined from the normalization condition of the phonons

$$[\mathcal{D}_\lambda, \mathcal{D}_\lambda^+] = 1 \Rightarrow \sum_{\tau\mu} (X+P)^{\tau\,2}_{\mu} - (X-P)^{\tau\,2}_{\mu} = 1 \qquad (22)$$



at each value of the rotational frequency changing with step 0.05 $\hbar\omega_0$ in the region from 0 to 0.2 MeV.

In ^{232}Th up to the value $\hbar\Omega \leqslant$ 0.15 MeV the aligned octupole angular momentum forms due to the collective octupole vibrations (see fig. 1b and 2). This is because the weight of the maximal component is lower than 15%. The octupole phonon blocks the two-quasiparticle alignment. At $\hbar\Omega >$ 0.15 MeV the proton component ($p+$), the structure of which is defined by the octupole interaction of the quasiprotons from $h_{11/2}$-shell with the quasiprotons from $i_{13/2}$- shell carrying large aligned quasiparticle angular momentum, begins to dominate in the alignment.

F i g. 2. The maximal two-quasiparticle components $(X+P)^{\tau\,2}_{\mu}$ of the octupole phonon at different rotational frequency $\hbar\Omega$ (MeV).

Consequently, the quantity $i(\Omega)$ increases sharply with angular frequency. The collective nature of the octupole phonon defines the alignment in ^{238}U up to $\hbar\Omega \leq 0.18$ MeV. With increasing rotational frequency the competition between two-quasiparticle neutron components (n -) and (n +), in which the quasineutrons of the $i_{13/2}$ -shell interact by the octupole forces with quasineutrons of the $j_{15/2}$ -shell, influences the alignment behaviour. But the aligned quasiparticle angular momentum corresponding to the maximal components (n -) is small, and therefore, the full octupole alignment is dictated by more "collective" (with small weight) proton and neutron two-quasiparticle components. The octupole phonon blocks the two-quasiparticle alignment in ^{238}U.

The alignment of the octupole phonon of the negative signature influences the branching ratio R_{I^-}(see eq.(21) and the table). In ^{230}Th R_{I^-} is seen to change slightly with increasing angular momentum as there are the proton and neutron two-quasiparticle components with the same weight in the transition operator.

T a b l e The branching ratio R_{I^-}(eq.(21)) as a function of the spin of the octupole state at the $K^\pi = 0^-$ band. The experimental data are taken from ref./19/ for (a), from ref./3/ for (b) and from ref./20/ for (c).

I^π	^{230}Th exp. (a)	calc.	^{232}Th exp. (b)	calc.	^{238}U exp. (c)	calc.
1^-	0.41	0.2	0.12	0.71		1.4
3^-	0.51	0.23	~0.08	0.79	> 1	4
5^-	0.31	0.24	~0.04	0.78		7
7^-	0.33	0.242	~0.02	0.73		10
9^-	-	0.245	-	0.6		13
11^-	-	0.254	-	0.53		15

The predomination of the proton two-quasiparticle component in the octupole state of ^{232}Th leads to a decrease of the quantity R_{I^-} with increasing angular momentum. In spite of the collective nature of the aligned octupole angular momentum, the neutron two-quasiparticle component determines the branching ratio

in ^{238}U by increasing the dipole transtion probability of $I^-_{oct} \rightarrow (I-1)^+_{yr}$ compared to $I^- \rightarrow (I+1)^+_{yr}$. The qualitative correspondence of the quantity R_{I^-} to experimental data shows the importance of the isovector part of the octupole-octupole interaction in a low-spin region. However, it is necessary to investigate this question more carefully because the additional parameter $\varkappa_1$ in fact increases the collectivity of the interaction. The calculation shows that the rotation decreases the collectivity of the octupole phonon in ^{232}Th , that is conserved in ^{230}Th and ^{238}U up to $\hbar\Omega = 0.2$ MeV. Therefore, the microscopic analysis allows one to determine in which case the condition (collectivity or noncollectivity of the phonon) for stabilization of the octupole deformation of the quadrupole-deformed rotating nuclei is fulfilld.

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Received by Publishing Department
on August 14, 1986.

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Назмитдинов Р.Г., Михайлов И.Н., Бриансон Ш. E4-86-557
Об октупольном выстраивании в актинидах

В рамках микроскопической модели проанализировано выстраивание октупольного углового момента в ротационных состояниях полосы $K^{\pi}=0^{-}$. Модель качественно описывает ветвление E1-переходов из этих состояний в состояния ираст полосы.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1986

Nazmitdinov R.G., Mikhailov I.N., Briançon Sh. E4-86-557
On Octupole Alignment in Actinides

The analysis of the alignment of the octupole angular momentum in the rotational states of the $K^{\pi}=0^{-}$ band is carried out in the microscopic model. The model qualitatively describes the branching ratio for the E1-transitions from these states to the ground band states.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1986