Письма в ЭЧАЯ. 2015. Т. 12, № 6(197). С. 1173–1181

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ТЕОРИЯ

DELTA $I = 1$ STAGGERING EFFECT FOR NEGATIVE-PARITY ROTATIONAL BANDS WITH $K = 1/2$ IN W/Os/Pt ODD-MASS NUCLEI

M. M. Taha [1]

Mathematics and Theoretical Physics Department, Nuclear Research Center,
Atomic Energy Authority, Cairo

The anomalous negative-parity bands of odd-mass nuclei W/Os/Pt for $N = 103$ isotones are studied within the framework of particle rotor model (PRM). The phenomenon of $\Delta I = 1$ staggering, or signature splitting in energies, occurs as one plots the gamma transitional energy over spin (EGOS) versus spin for the $1/2$-[521] band originating from $N = 5$ single-particle orbital. The rotational band with $K = 1/2$ separates into two signature partners. The levels with $I = 1/2, 5/2, 9/2, \ldots$ are displaced relative to the levels with $I = 3/2, 7/2, 11/2, \ldots$ The deviations of the level energies from the rigid rotor values are described by Coriolis coupling.

В работе исследуются полосы аномальной отрицательной четности ядер с нечетными массовыми числами W/Os/Pt для изотонов $N = 103$ в модели ротора. Явление колебания $\Delta I = 1$, или расщепления по энергиям, видно из диаграммы, на которой энергия гамма-перехода на спин изображена в зависимости от спина для полосы $1/2$-[521], соответствующей одночастичной орбитали $N = 5$. Вращательная полоса с $K = 1/2$ разделяется на два уровня-партнера. Уровни с $I = 1/2, 5/2, 9/2, \ldots$ смещаются относительно уровней с $I = 3/2, 7/2, 11/2, \ldots$ Отклонения уровней энергии от устойчивых значений для ротора описываются кориолисовым спариванием.

PACS: 21.60.-n; 21.60.Ev; 23.20.Lv

INTRODUCTION

A theoretical description for odd-mass nuclei is more complicated than for even–even nuclei because of the sensitivity of odd-mass systems to single-particle states. Due to different occupations of single-particle orbitals, the observed low-lying bands reflect more directly the single-particle structure.

In recent years the study of nuclear structure has focused on the phenomenon of staggering effects both experimentally and theoretically. Several staggering effects are known in nuclear spectroscopy:

i. The $\Delta I = 2$ staggering effect seen in superdeformed rotational bands (SDRBs) [1–6]. In such staggering the levels with angular momentum $I_n = I + 4n - 4$ are displaced relative

[1] E-mail: mahmoudmt@hotmail.com

to the levels with angular momentum $I_n = I + 4n - 2$ $(n = 1, 2, 3, \ldots)$; i.e., the level with angular momentum I is displaced relative to its neighbors with angular momentum $I \pm 2$.

ii. The $\Delta I = 1$ staggering in signature partners odd-mass superdeformed (SD) nuclei [7–9]. A large amplitude staggering pattern is found in most of the signature partner pairs.

iii. The $\Delta I = 1$ staggering effect seen in octupole bands of even nuclei [10–13]. In such staggering, the levels with odd I and negative-parity $I_n^\pi = (2n-1)^-$ are displaced relative to the levels with even I and positive-parity $I_n^\pi = (2n-2)^+$.

iv. The $\Delta I = 1$ staggering effect seen in rotational γ-bands of even nuclei [14, 15]. In such staggering, the levels with odd angular momentum $I_n = 2n + 1$ are slightly displaced relative to the levels with angular momentum $I_n = 2n$. In staggering effects (iii) and (iv) each level with angular momentum I is displaced relative to its neighbors with angular momentum $I \pm 1$.

v. The $\Delta I = 1$ energy signature splitting for large K values (K is the projection of angular momentum I on the symmetry axis) of positive-parity neutron $i_{13/2}$ rotational bands in odd-mass nuclei [16].

In this paper, we would like to focus on another staggering phenomenon, the $\Delta I = 1$ staggering for negative-parity rotational bands with $K = 1/2$. In odd-mass nuclei, rotational bands with $K = 1/2$ separate into a pair of signature partners; i.e., the levels with $I = 3/2, 7/2, 9/2, \ldots$ (with signature $\alpha = -1/2$) are displaced relative to the levels with $I = 1/2, 5/2, 9/2, \ldots$ (with signature $\alpha = 1/2$) and energies are shifted in opposite directions.

The paper is organized as follows. Following this introduction, the outline of the proposed particle rotor model (PRM) is described in Sec. 1. Section 2 is devoted to discussion and study of the aligned angular momentum and Routhians. Numerical calculations and discussion are presented in Sec. 3 for ^{177}W, ^{179}Os and ^{181}Pt. Conclusion and remarks are given in the final section.

1. MATHEMATICAL MODELS

The origin of the signature splitting in rotational band can be understood in the particle rotor model (PRM). The basic philosophy of the PRM is to consider the nucleus as a core with a few valence particles strongly coupled to this axially symmetric core. This is a well-known model [17]. For the sake of completeness, we give in the following the most relevant formulas. The total Hamiltonian is written as particle plus rotational parts:

$$H = H_p + H_{\mathrm{rot}}. \tag{1}$$

Here H_p is the single-particle shell model Hamiltonian with energy eigenvalue ϵ_K, transferred into quasiparticle energies according to

$$E_{\mathrm{sp}} = [(e_{K,\nu} - \lambda)^2 + \Delta^2]^{1/2} - \Delta, \tag{2}$$

where $e_{K,\nu}$ are the energies of the Nilsson orbitals nearest to the Fermi surface λ, obtained by using the Nilsson potential at $\omega = 0$. The Δ is the pairing gap parameter. The rotational Hamiltonian of the whole system reads

$$H_{\mathrm{rot}} = \sum_{i=1}^{3} \frac{L_i^2}{2J_i}. \tag{3}$$

The quantity J is the moment of inertia of the core, while L is the core angular momentum $L_i = I_i - j_i$, with I and j being total and intrinsic angular momentum, respectively, with I_3 and j_3 being their projections on the symmetry axis and represented by the same quantum number K. Equation (3) can be explicitly rewritten as

$$H_{\text{rot}} = \frac{1}{2J}(I^2 - I_3^2) + \frac{1}{2J}(j^2 - j_3^2) - \frac{1}{2J}(I^+ j^- + I^- j^+), \tag{4}$$

with $I^\pm = I_1 \pm iI_2$ and $j^\pm = j_1 \pm ij_2$.

As basis states for PRM, we use the standard coupling eigenfunctions:

$$|IM\rangle = \sum_{K'} C_{K'} |IMK\rangle \tag{5}$$

with

$$|IMK\rangle = \sqrt{\frac{2I+1}{16\pi^2}} \left[D^I_{MK}(\Omega)\psi_K + (-1)^{I+K} D^I_{M,-K}\psi_{-K} \right], \tag{6}$$

where $D^I_{MK}(\Omega)$ stands for the irreducible representation of the rotational group, Ω is the Euler orientation of the rotor and ψ_{-K} is the time reversal state of the particle state ψ_K which represents the solution of the intrinsic particle Hamiltonian. With the Coriolis coupling (third term in Eq. (4)) taken into account by the first-order perturbation theory, the energy spectrum $K = 1/2$ band is

$$\begin{aligned} E(I) = E_{\text{sp}} + \frac{\hbar^2}{2J} j(j+1) + \frac{\hbar^2}{2J}[I(I+1) - 2K^2] + \frac{\hbar^2}{2J} a(-1)^{I+1/2}(I+1/2)\delta_{K,1/2} = \\ = E^{(0)}_K + A[I(I+1) + a(-1)^{I+1/2}(I+1/2)\delta_{K,1/2}], \end{aligned} \tag{7}$$

with the inertial parameter $A = \hbar^2/2J$, $E^{(0)}_K$ is the intrinsic band head energy and a is the decoupling parameter, it depends on the j components which contribute to the particle state $\psi_{1/2}$.

From the spectrum of Eq. (7), one sees that for a positive (negative) decoupling parameter, the levels with odd (even) values of $I+1/2$ $(I = 1/2, 5/2, 9/2, \ldots)$, $(I = 3/2, 7/2, 11/2, \ldots)$ are shifted downwards, thus splitting one band into two branches. The splitting amplitude and phase are respectively determined by the size and the sign of the decoupling parameter a.

The $\Delta I = 1$ transition energy $E_\gamma(I)$ can be written as

$$\begin{aligned} E_\gamma(I) = E(I) - E(I-1) = [2I(1 + a(-1)^{I+1/2}\delta_{K,1/2})]A = \\ = \left\{ \begin{array}{lll} 2I(1+a)A & \text{for} & I = 3/2, 7/2, 11/2, \ldots \\ 2I(1-a)A & \text{for} & I = 5/2, 9/2, 13/2, \ldots \end{array} \right\}. \end{aligned} \tag{8}$$

It is informative to consider Eq. (8) for limiting values of the decoupling parameter a.

1. $a = 0$ (for $K > 1/2$), the signature splitting disappears and the transition energies follow the simple rule:

$$\frac{1}{2}[E_\gamma(R+1/2) + E_\gamma(R-1/2)] = E^{\text{core}}_\gamma(R), \quad R = 2, 4, 6, \ldots \tag{9}$$

2. $a = \pm 1$, the sequences in odd-A nucleus with favored $I = 1/2, 5/2, 9/2, \ldots$ and unfavored $I = 3/2, 7/2, 11/2, \ldots$ signature are degenerate and

$$E_\gamma(I = R \pm 1/2) \simeq E_\gamma^{\text{core}}(R), \quad R = 2, 4, 6, \ldots \tag{10}$$

If the favored sequence was $I = 3/2, 7/2, 11/2, \ldots$ and the unfavored sequence $I = 1/2, 5/2, 9/2, \ldots$

$$E_\gamma(I = R \pm 1/2) = E_\gamma^{\text{core}}(R), \quad R = 1, 3, 5, \ldots \tag{11}$$

We use as a basic reference parameter the gamma transitional energy over spin (EGOS$^{(\text{ref})}$):

$$\text{EGOS}^{(\text{ref})} = \frac{E_\gamma(I)}{I} = 2(1 \pm a)A = \text{const.} \tag{12}$$

The amplitude of the oscillation of the EGOS is then $4Aa$ and the average value is simply $2A$. In order to see fine variations in the transition energies $E_\gamma(I)$, we introduce the staggering parameter

$$\text{EGOS} = \text{EGOS}^{(\text{exp})} - \text{EGOS}^{(\text{ref})}, \tag{13}$$

where EGOS$^{(\text{exp})}$ are obtained from experimental data.

2. ALIGNED ANGULAR MOMENTUM AND ROUTHIANS

In this section we shall give an introduction to the quasiparticle energies in rotating frame discussed in [18]. This approach was very successful to interpret the irregularity in the transition energies at high-spin states. In cranked shell model (CSM) [18], the total angular momentum projected onto the rotation axis I_x is derived from the spin I and the $\Delta I = 2$ transition energy, using

$$I_x(I_m) = \sqrt{(I_m + 1/2)^2 - K^2}, \tag{14}$$

where I_m is the mean angular momentum $(I - 1)$. The rotational frequency is

$$\hbar\omega_m = \frac{E(I_m + 1) - E(I_m - 1)}{I_x(I_m + 1) - I_x(I_m - 1)}. \tag{15}$$

The intrinsic contribution to the aligned angular momentum i is obtained by subtraction of the collective contribution I^{ref}, so that

$$i(\omega) = I_x(\omega) - I^{\text{ref}}(\omega), \tag{16}$$

$I^{\text{ref}}(\omega)$ is derived from the formula

$$I^{\text{ref}} = J_0\omega + J_1\omega^2, \tag{17}$$

where J_0 and J_1 are the moment-of-inertia parameters.

To evaluate the effect of alignment for pure $K = 1/2$ band and for large I $(I \gg K)$, Eq. (14) becomes

$$I_x(I_m) \simeq (I + 1/2) \simeq I \simeq (I - 1/2), \tag{18}$$

which yields

$$I_x(I_m + 1) - I_x(I_m - 1) = 2. \tag{19}$$

We obtain a good approximation of the rotational frequency

$$\hbar\omega = \frac{E(I) - E(I-2)}{2} = \frac{1}{2}A[(4I-2) + 2a(-1)^{I+1/2}] = 2A\left[\left(I - \frac{1}{2}\right) \pm \frac{a}{2}\right]. \tag{20}$$

Therefore,

$$\left(I - \frac{1}{2}\right) = \frac{\hbar\omega}{2A} \pm \frac{a}{2} = I_x(\omega), \tag{21}$$

which yields

$$i(\omega) = \frac{\hbar\omega}{2A} \pm \frac{a}{2} - I^{\mathrm{ref}}(\omega). \tag{22}$$

Then, the decoupling parameter a is the difference between the aligned angular momentum of the two signatures:

$$a = i(\omega, \alpha = +1/2) - i(\omega, \alpha = -1/2). \tag{23}$$

The Routhians $e(\omega)$ represent the intrinsic excitation energy in the rotating frame. Relative to a reference rotor configuration, it can be calculated by the relation

$$e(\omega) = \left[\frac{1}{2}(E(I_m + 1) + E(I_m - 1)) - \hbar\omega(I_m)I_x(I_m)\right] - E^{\mathrm{ref}}(\omega). \tag{24}$$

The term $\omega(I_m)I_x$ represents the total rotational energy including the Coriolis and the centrifugal force effects, and the energy $E(I)$ is approximated by the average between the neighboring values for $I \pm 1$. The energy reference may be obtained by integrate equation (22) with respect to ω:

$$E^{\mathrm{ref}}(\omega) = -\hbar \int d\omega I^{\mathrm{ref}}(\omega) = -\frac{1}{2}J_0\omega^2 - \frac{1}{4}J_1\omega^4 + \frac{\hbar^2}{8J_0}, \tag{25}$$

where the last term represents the integrating constant.

3. RESULTS AND DISCUSSION

Signature is a quantum number specifically appearing in a deformed intrinsic system. It is related to the invariance of a system with quadruple deformation under a rotation of 180° around a principal axis. For an odd-mass nucleus, depending on the total spin, the signature quantum number can take the different values. It is convenient to assign $\alpha_I = (1/2)(-1)^{I-1/2}$ as a signature quantum number for a state of spin I of an odd-mass nucleus. A rotational band with a sequence of levels differing in spin by $1\hbar$ is now divided into two branches, each consisting of levels differing in spin by $2\hbar$ and classified by the signature quantum number $\alpha_I = \pm 1/2$, respectively. For some bands, one observes experimentally an energy splitting for the two branches. The energetically favored branch is formed by those spin I states that satisfy $I - j =$ even, where j is the total angular momentum of the corresponding single-particle state.

Table 1. **The rotational model parameters for 1/2-[521] bands in the isotones ^{177}W, ^{179}Os and ^{181}Pt**

Parameter	^{177}W	^{179}Os	^{181}Pt
ϵ_2	0.2579	0.2572	0.2587
$\hbar\omega_0$, MeV	7.3022	7.2749	7.2481
G, MeV	0.1016	0.1005	0.0994
$E^{(0)}$, keV	0.561	1.2000	0.7490
A, keV	14.783	15.790	14.695
a	0.7880	0.8260	0.8010
J_0, $\hbar^2\,\mathrm{MeV}^{-1}$	35.0	24.8	28.7
J_1, $\hbar^4\,\mathrm{MeV}^{-3}$	70.0	91.1	163.8

Our $K^\pi = 1/2^-$ band has been assigned as a $1/2$-[521] configuration based on the systematics of the Nilsson level ordering in neighboring nuclei. The assignment is confirmed by a large signature splitting of the level energies, attributed to the decoupling term which is necessary to reproduce energy spectrum of $K = 1/2$ bands. The adopted optimized model parameters for $1/2$-[521] bands in our selected nuclei are listed in Table 1.

The negative-parity band $1/2$-[521] in $N = 103$ isotones ^{177}W, ^{179}Os and ^{181}Pt exhibits significant signature splitting. This signature splitting is illustrated in Table 2 and Fig. 1, in terms of the staggering parameters EGOS(I) as a function of spin I. That is, the regular structure in the one-quasi-neutron ν $1/2$-[521] negative-parity band is attributed to the decoupling effect [19], which is usually seen in rotational bands with a high-j and low-K state (e.g., $K = 1/2$) as the main configuration. In our particle rotor model the decoupled band is explained in terms of the rotation alignment by the strong Coriolis force of the particle angular momentum j with that of the rotor L. This happens in the case when the odd particle occupies an isolated high-j single-particle orbital with small projection orbits. As a result, the nucleonic angular momentum j is aligned along the axis of rotation of the nucleus and the particle motion is effectively decoupled from the rotational motion of the core. Further, there are states with approximately anti-aligned.

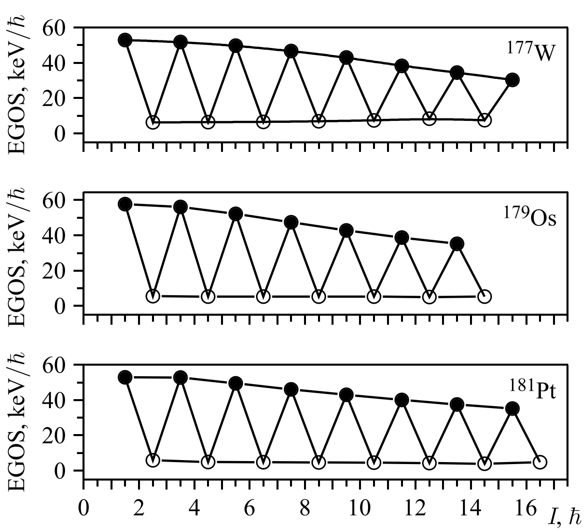

Fig. 1. Energy staggering plots of gamma transitional energy over spin (EGOS) versus the spin I for the 1/2-[521] neutron bands in ^{177}W, ^{179}Os and ^{181}Pt isotones. The open and filled circles represent the $\alpha = +1/2$ and $\alpha = -1/2$ signatures, respectively

Table 2. **Staggering parameters EGOS plotted against the spin I within the 1/2-[521] rotational bands in the isotones ^{177}W, ^{179}Os and ^{181}Pt**

I	EGOS, keV/$\hbar$		
	^{177}W	^{179}Os	^{181}Pt
3/2	52.866	57.666	52.933
5/2	6.240	5.480	5.840
7/2	51.857	56.085	52.742
9/2	6.333	5.266	4.933
11/2	49.709	52.200	49.490
13/2	6.523	5.230	4.769
15/2	46.733	47.426	46.120
17/2	6.835	5.270	4.670
19/2	43.021	42.800	42.978
21/2	7.304	5.219	4.523
23/2	38.234	38.721	40.052
25/2	8.352	5.032	4.280
27/2	34.459	35.162	37.474
29/2	7.517	5.206	3.862
31/2	30.258		35.225
33/2			4.812

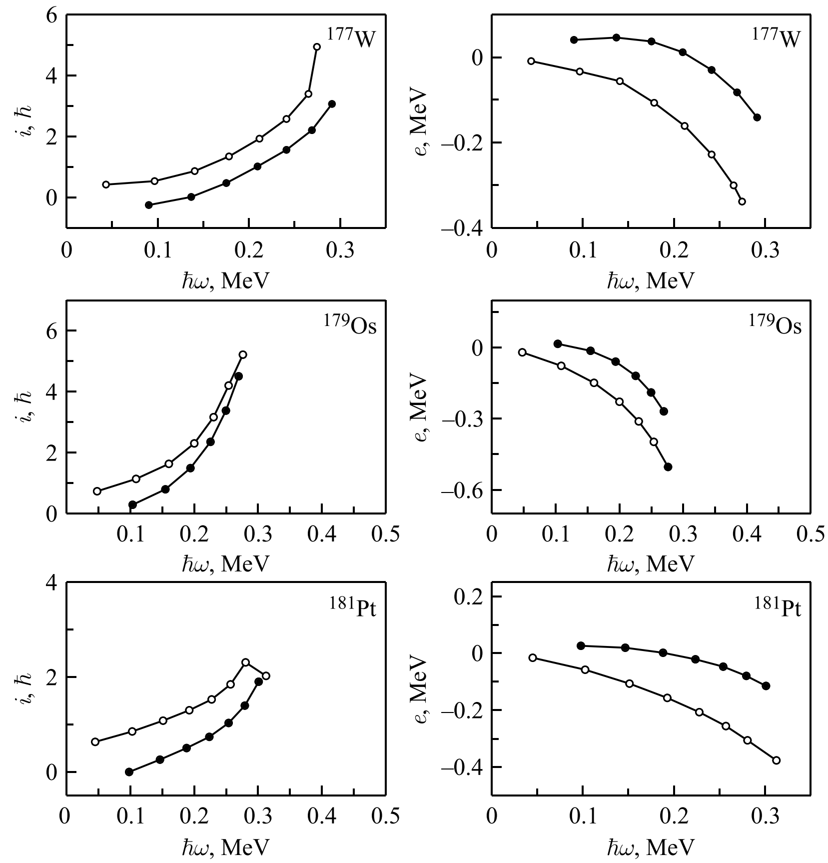

Fig. 2. Left: aligned angular momentum i as a function of rotational frequency $\hbar\omega$ for the rotational band 1/2-[521] in ^{177}W, ^{179}Os and ^{181}Pt using CSM. The Harris moment-of-inertia reference parameters are listed in Table 1. Right: Routhians e for the same bands. The open and filled circles represent the $\alpha = +1/2$ and $\alpha = -1/2$ signatures, respectively

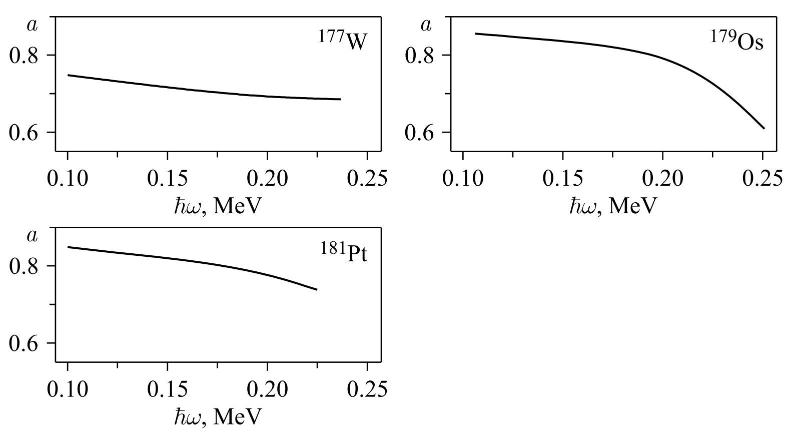

Fig. 3. The decoupling parameter in terms of the difference between alignments in the two signatures

To see the properties of the two sequences of the $1/2$-[521] bands in our selected nuclei, a plot of the aligned angular momentum i and the Routhians e as a function of rotational frequency $\hbar\omega$ is shown in Fig. 2. The reference parameters were taken from a fit to the neighbour even–even nuclei. The relative alignment rises smoothly with increasing rotational frequency $\hbar\omega$, with a sudden strong alignment in the two signature members. The alignment is about $2\hbar$. Signature splitting is observed, since a $K = 1/2$ band has a large Coriolis decoupling parameter. In ^{177}W both signatures upend at $\hbar\omega = 0.28$ MeV as a result of a crossing between two configurations. In ^{179}Os, the alignment of the $5/2, 9/2, 13/2, \ldots$ sequences displays a slight irregularity at $\hbar\omega = 0.30$ MeV. From Fig. 3, we conclude that the Coriolis force is almost constant in ^{177}W, decreasing quickly in ^{179}Os and decreasing slowly in ^{181}Pt.

CONCLUSIONS

In odd-A nuclei, the excitation energy of a rotational band depends on the signature quantum number $\alpha_I = (1/2)(-1)^{I-1/2}$ in the particle-rotor model which defines the admissible spin sequence for a band. If the last odd nucleon occupies a unique-parity high-j orbital, the rotational levels with spin $I = j +$ even integer have lower excitation energies (a favored band). On the other hand, the spins of the unfavored band is given by $I = j +$ odd integer. The excitation energies are pushed up as compared with those of the favored band. The Coriolis force splits a given $\Delta I = 1$ cascade into $\Delta I = 2$ bands, favored signature when $\alpha = 1/2$, $I = 1/2, 5/2, 9/2, \ldots$ and unfavored when $\alpha = -1/2$, $I = 3/2, 7/2, 11/2, \ldots$ Signature inversion was observed in high-spin states in odd-A nuclei and discussed in detail in [20]. It was suggested that such an inversion might be a specific fingerprint for a triaxial shape in nuclei. The signature inversion in odd–odd nuclei [21, 22] occurs at low spins in contrast to odd-A nuclei. The levels of the favored signature lie lower in energy at lower spins, but the levels lower in energy of other signature lie beyond a certain angular momentum due to higher-order Coriolis effects. The development of the aligned angular momentum with rotational frequency is determined by the rotation alignment of two neutrons occupying high spin orbital. The rotation alignments of the two sequences of different signatures of $1/2$-[521] bands in our considered ^{177}W, ^{179}Os and ^{181}Pt isotones have been examined. The $\Delta I = 1$ energy staggering is very sensitive to the Coriolis force for $K = 1/2$, since a $K = 1/2$ band has a large Coriolis decoupling parameter. In all the considered nuclei one finds a gradual increase of the aligned angular momentum with increasing rotational frequency.

REFERENCES

1. *Flibotte S. et al.* $\Delta I = 4$ Bifurcation in a Superdeformed Band: Evidence for a C_4 Symmetry // Phys. Rev. Lett. 1993. V. 71. P. 4299;
   Kanaya K. Multi-Particle Excitations in the Superdeformed ^{149}Gd Nucleus // Nucl. Phys. A. 1995. V. 584. P. 373.
2. *Hamamoto I., Mottelson B.* Superdeformed Rotational Bands in the Presence of Y_{44} Deformation // Phys. Lett. B. 1994. V. 333. P. 294.
3. *Yu-xin Liu et al.* Description of Superdeformed Nuclear States in the Interacting Boson Model // Phys. Rev. C. 1997. V. 56. P. 1370.

4. *Khalaf A. M., Sirag M. M.* Analysis of $\Delta I = 2$ Staggering in Nuclear Superdeformed Rotational Bands // Egypt. J. Phys. 2004. V. 85. P. 359.
5. *Khalaf A. M., Taha M. M., Kotb M.* Identical Bands and $\Delta I = 2$ Staggering in Superdeformed Nuclei in $A \sim 150$ Mass Region Using Three Parameters Rotational Model // Progr. Phys. 2012. V. 8. P. 39.
6. *Khalaf A. M., Sirag M.M., Taha M. M.* Spin Assignment and Behavior of Superdeformed Bands in $A \sim 150$ Mass Region // Turk. J. Phys. 2013. V. 37. P. 49.
7. *Wu C. S., Zhou Z. N.* $\Delta I = 1$ Staggering in Odd Superdeformed Nuclei // Phys. Rev. C. 1997. V. 56. P. 1814.
8. *Khalaf A. M., Allam M. A., Eman Saber.* Signature Partners in Odd Superdeformed Nuclei in Mass Region $A \sim 190$ // Egypt. J. Phys. 2008. V. 39. P. 41.
9. *Khalaf A. M. et al.* $\Delta I = 1$ Signature Splitting in Signature Partners of Odd Mass Superdeformed Nuclei // Progr. Phys. 2013. V. 9. P. 39.
10. *Ahmed I., Butler P. A.* Octupole Shapes in Nuclei // Ann. Rev. Nucl. Part. Sci. 1993. V. 43. P. 71.
11. *Butler P. A., Nazarewicz W.* Intrinsic Reflection Asymmetry in Atomic Nuclei // Rev. Mod. Phys. 1996. V. 68. P. 349.
12. *Bonatsos D., Daskaloyannis C.* $\Delta I = 1$ Staggering in Octupole Bands of Light Actinides: Beat Patterns // Phys. Rev. C. 2000. V. 62. P. 024301.
13. *Khalaf A. M., Altalhi F.* Staggering Phenomenon in Gamma Transitional Energies over Spin for Negative Parity States of Octupole Vibrational Nuclear Bands // Progr. Phys. 2014. V. 10, No. 2. P. 89.
14. *Bonatsos D.* Systematics of Odd–Even Staggering in γ-Bands as a Test for Phenomenological Collective Models // Phys. Lett. B. 1988. V. 200. P. 1.
15. *Singh M. et al.* Evidence of Rigid Triaxiality in Some Xenon Nuclei // Can. J. Phys. 2007. V. 85, No. 8. P. 899.
16. *Khalaf A. M. et al.* Energy Signature Splitting for Large K Values in Odd-Mass Osmium Nuclei // Arab J. Nucl. Sci. Appl. 2013. V. 46, No. 2. P. 241.
17. *Bohr A., Mottelson B. R.* Nuclear Structure. V. II. New York: Benjamin, 1975.
18. *Bengtsson R., Frouendorf S.* Quasiparticle Spectra near the Yrast Line // Nucl. Phys. A. 1979. V. 327. P. 139.
19. *Khalaf A. M.* High Spin Properties in Deformed Nuclei Using Weak Coupling Model // Ind. J. Pure Appl. Phys. 1986. V. 24. P. 469.
20. *Ikeda A., Shimano T.* Shape Fluctuation as Responsible for Signature Inversion // Phys. Rev. Lett. 1989. V. 63. P. 139.
21. *Kvasil J. et al.* Signature Inversion in Axially Deformed ^{160,162}Tm // Phys. Rev. C. 2001. V. 63. P. 061305(R).
22. *Goel A., Jain A. K.* Systematics of Signature Inversion in Doubly-Odd Nuclei and the Role of the 1/2[541] Proton Orbital // Nucl. Phys. A. 1997. V. 620. P. 265.

Received on December 7, 2014.