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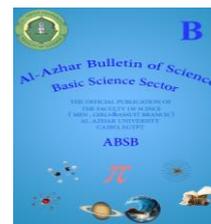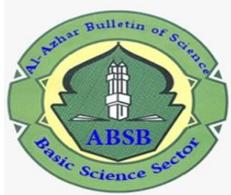
THE BEHAVIOR OF MOMENTS OF INERTIA AND ENERGY STAGGERING IN SUPERDEFORMED NUCLEI.

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ABSTRACT

Three pairs of signature partners' transition energies of Thallium (Tℓ) odd mass superdeformed (SD) nuclei's (A ~ 191-195), were fitted with the experimental one using the Bohr-Mottelson four-parameter collective rotational model. We chose the Bohr-Mottelson four-parameter rotational energy formula because it has been reported that it has excellent compatibility with the γ-ray transition energies. The four model parameters were extracted using a suitable search program. Harris's method was used to calculate the superdeformed rotational bands' (SDRBs) bandhead spins. The values of the adopted parameters, which were obtained using a simulated fitting search software, were used to measure the rotational frequency, dynamic $J^{(2)}$, and kinematic $J^{(1)}$ moments of inertia to the transition energies. When compared to the experimental values, there is a great deal of agreement $J^{(2)}$ and $J^{(1)}$ have been studied as a function of increasing rotational frequency. The suggested staggering function was used to investigate the ΔI= 1 energy staggering in Tℓ odd mass SD nuclei.

Keywords: Moments of Inertia; Energy Staggering; Signature Partners; SD Bands

1. Introduction

The first discovery of superdeformation (SD) at high angular momenta in the A~190 mass region was found in the ^{191}Hg nucleus [1], and more than 90 SD bands have since been discovered in this mass region in various nuclei [2]. At high spins, superdeformed rotational bands (SDRBs) are now regarded as one of the most significant principles in nuclear structure. Many nuclei's total energy surfaces should be stable minima in this area, according to mean-field calculations. The magnitude of the quadrupole deformation parameter = 0.5, is due to the existence of wide shell gaps at neutron number N=112 and proton number Z=80 or Z=82. Stretched E2 transitions are normally observed to dominate the decay sequences in SD bands. Several unexpected features were observed in SDRB's. The multiple SD bands in a given nucleus give us information about the orbitals involved at large deformation [3],

which may be quite different from those in normally deformed nuclei. New phenomena in this direction were generated by the observation of identical superdeformed bands (IB's) [4-7]. The γ-ray transition energies of these SD bands with distinct mass numbers are all within 1-2 KeV of each other, implying that their rotational frequencies and dynamic moments of inertia are identical. This fascinating phenomenon of IB's is very rare in nuclear physics and of great interest and recently it is observed in normally deformed nuclei [8]. Many efforts were built to understand the definition and origins of the IB's phenomena by means of conventional investigation within the framework of the semi-phenomenological Strutinski method in connection with a rotating Nilsson or Woods-Saxon potential [9] or the pseudo-spin scheme [10]. In addition, theoretical activities were done to understand the IB's phenomenon [11-16].

The spin assignments for SDRB's represent a difficult and unsolved problem, this is because determining the de-excitation of SD bands into established yrast states is complicated. Several suitable methods for assigning spins based on observed γ-ray transition energies have been proposed. [14, 16-21].

In SD band γ-ray transition energies, the "ΔI= 4 bifurcation" can be described as two sequences of states with spins differing by 4ℏ from level to level and a minor energy difference between them[22-24]. The ΔI= 2 stumbling phenomena have been clarified as a 90° rotation around the rotational axis C_4 symmetry or the appearance of hexadecapole Y_{44} deformation in the nuclear shape [25]. The ΔI = 2 stumbling effect has been studied in a variety of forms [26]. ΔI = 2 staggering has recently been found in the field bands of normally deformed (ND) nuclei, including Thorium nuclei [27].

The ΔI = 1 stagger found in signature partner pairs [16, 28-31] is another form of energy stagger found in SD odd-A nuclei. The bandhead moments of inertia of each pair are almost equal, and the bulk of these signature partners have a significant amplitude. The ΔI=1 staggering phenomenon is studied between the energies of states in the ground and octupole bands in normally deformed nuclei [27].

The key goal of this paper is to use the Harris two-term formula to assign spins to our chosen SD bands. To measure the transition energies, rotational frequencies, and kinematic and dynamic moments of inertia, we use the Bohr-Mottelson four-term model. To look at and study the unusual ΔI = 1 energy staggered in signature partner pairs of our SD odd-A nuclei.

2. Spin Assignment and Moments of Inertia.

Because of the challenges in calculating the de-excitation of SD bands into established yrast states, spins in SD nuclei are not determined experimentally. Several related procedures for assigning spins to SD states were proposed [16-21]. The most familiar method is to use Harris expansion [32]. The energy of the rotational states of deformed nuclei can be expressed as

powers of angular frequency ω using the two-term Harris formula:

$$E = \frac{1}{2}\alpha\omega^2 + \frac{3}{4}\beta\omega^4 \qquad (1)$$

with the cranking inertial parameters α and β. The corresponding expression for the dynamic moment of inertia $J^{(2)}$ is given by;

$$J^{(2)} = \frac{1}{\omega}\frac{dE}{d\omega} = \alpha + 3\beta\omega^2 \qquad (2)$$

The parameters α and β are obtained by fitting of $J^{(2)}$ versus ω^2. Integrating equation (2) concerning ω leads to an expression for the intermediate nuclear spin,

$$\hbar\hat{I} = \int J^{(2)} \, d\omega = \alpha\omega + \beta\omega^3 \quad (3)$$

where the constant of integration is taken to be halffor odd-A nuclei.

The corresponding expression for the kinematic momentof inertia $J^{(1)}$is given by;

$$\frac{J^{(1)}}{\hbar^2} = \frac{\hat{I}}{\hbar\omega} = \alpha + \beta\omega^2 \qquad (4)$$

The two moments of inertia are related as follows;

$$J^{(2)} = J^{(1)} + \omega\frac{dJ^{(1)}}{d\omega} \qquad (5)$$

The only spectroscopic quantity observed in the SD bands is the level transition energies(γ-ray). To compare the structure of these SD bands, the level transition energies are usually converted into rotational frequency and the dynamic moment of inertia $J^{(2)}$ as follows:

$$\hbar\omega(I) = \frac{1}{4}\big[E_\gamma(I+2) + E_\gamma(I)\big](\text{MeV}) \quad (6)$$

$$\frac{J^{(2)}}{\hbar^2} = \frac{4}{\Delta E_\gamma}(\hbar^2\text{MeV}^{-1}) \quad (7)$$

where ΔE_γ is the difference in level transition energies for two consecutive γ-ray transitions in the cascade,

$$\Delta E_\gamma = E_\gamma(I+2) - E_\gamma(I) \qquad (8)$$

The following relation can be used to apply the kinematic moment of inertia for the rotational band to the transition energies $E_\gamma(I)$:

$$J^{(1)} = \frac{2I-1}{E_\gamma(I)} \qquad (9)$$

We can see that the dynamic moment of inertia is determined by the calculated γ-ray transition energies rather than the spin I proposition, while the kinematic moment of inertia $J^{(1)}$ is determined by the spin I proposition.

3. Outline of the Model.

The rotational energy spectrum deviates from the $I(I + 1)$ rule and one can express the rotational energies under the adiabatic approximation of an axially symmetric nucleus as an expansion in the power of $I(I + 1)$, considered by Bohr-Mottelson [33];

$$E(I) = A\hat{I}^2 + B\hat{I}^4 + C\hat{I}^6 + D\hat{I}^8 \qquad (10)$$

with $\hat{I}^2 = I(I + 1)$

The corresponding rotational frequency ħω, for the expression E, the kinematic and dynamic moments of inertia are:

$$\hbar\omega = \frac{dE(\hat{I})}{d\hat{I}} = 2A\hat{I} + 4B\hat{I}^3 + 6C\hat{I}^5 + 8D\hat{I}^7 \quad (11)$$

$$\frac{J^{(1)}}{\hbar^2} = \left[\frac{1}{\hat{I}}\frac{dE(\hat{I})}{d\hat{I}}\right]^{-1}$$
$$= \left(\frac{1}{2}\right)\frac{1}{[A + 2B\hat{I}^2 + 3C\hat{I}^4 + 4D\hat{I}^6]}$$

$$(12)$$

$$\frac{J^{(2)}}{\hbar^2} = \left[\frac{d^2E(\hat{I})}{d\hat{I}^2}\right]^{-1} =$$

$$\frac{1}{2A}\left[1 + \frac{6B}{A}\hat{I}^2 + \frac{15C}{A}\hat{I}^4 + \frac{28D}{A}\hat{I}^6\right]^{-1}$$

$$(13)$$

For a pair of signature partner I, I+2, I+4 … and I-1, I+1, I+3 … yields,

$$E_{\gamma 1}(I) = E(I) - E(I - 1) \qquad (14)$$

4. Parameterization of ΔI= 1 staggering in SD signature partners.

We will suggest a staggering function $\Delta^2 E_\gamma(I)$ to demonstrate the ΔI = 1 staggering in signature partner pairs of odd-A SD nuclei (I).

which corresponds to the difference between the average transitions I→I-2 and I+1→I-1 in one band and the transition I+2→I in the other band;

$$\Delta^2 E_\gamma(I) = \frac{1}{2}\left[E_{\gamma 2}(I + 2) + E_{\gamma 2}(I)\right]$$
$$- E_{\gamma 2}(I + 1)$$

$$= \frac{1}{2}\left[E_{\gamma 2}(I + 2) - 2E_{\gamma 2}(I + 1) + E_{\gamma 2}(I)\right]$$

$$(15)$$

5. Results and discussion

Spin assignments to SD bands were established by fitting experimental values of dynamical moments of inertia $J^{(2)}$ as a function of rotational frequency with Harris parametrization.

After extracting spins of the levels, the Bohr-Mottelson parameters can be adjusted in order to get the measured transformation energies and obtain the smallest root mean square deviation $E_\gamma^{cal}(I)$ from the measured $E_\gamma^{exp}(I)$ using;

$$\chi = \sqrt{\frac{1}{N}\sum_i \left(\frac{E_\gamma^{exp}(I_i) - E_\gamma^{cal}(I_i)}{\delta E_\gamma^{exp}(I_i)}\right)^2}$$

The number of data points entering the fitting procedure is N, and the experimental errors in $E_\gamma(I)$ are $\delta E_\gamma^{exp}(I)$. Table (1) shows, the adopted Harris parameters (α, β), the estimated bandhead spin (I_0), the Bohr-Mottelson model parameter (A, B, C, D), and the root mean square deviation(χ).

Fig. 1 presents the variation of $J^{(1)}$ and $J^{(2)}$ against ħω for all bands of the studied signature partners and comparison to that of the experimental ones. A smooth rise in $J^{(1)}$ and $J^{(2)}$ with increasing ħω is shown as seen in most SD bands of A Σ 190 region of superdeformation which is due to the gradual alignment of a pair of $j_{15/2}$ (N=7) neutrons and a pair of $i_{13/2}$ (N=6) protons [34-36]. The dynamic moment of inertia $J^{(2)}$ is significantly larger than the kinematic moment of inertia $J^{(1)}$ for all values of the rotational frequency ħω.

The major finding of this study is the discovery of an I= 1 energy staggering effect in the tested signature partners: ^{191}Tℓ(SD1, SD2), ^{193}Tℓ(SD1, SD2), and ^{195}Tℓ(SD1, SD2) in odd-A Tℓ nuclei. We investigate this effect by calculating the staggering function $\Delta^2 E_\gamma(I)$ equations (15).

Fig.2. shows the measured values versus spin I. The signature partners of all three pairs are seen to have a zigzag pattern. It's important to note that each signature partner SD band's bandhead moment of inertia is almost similar.
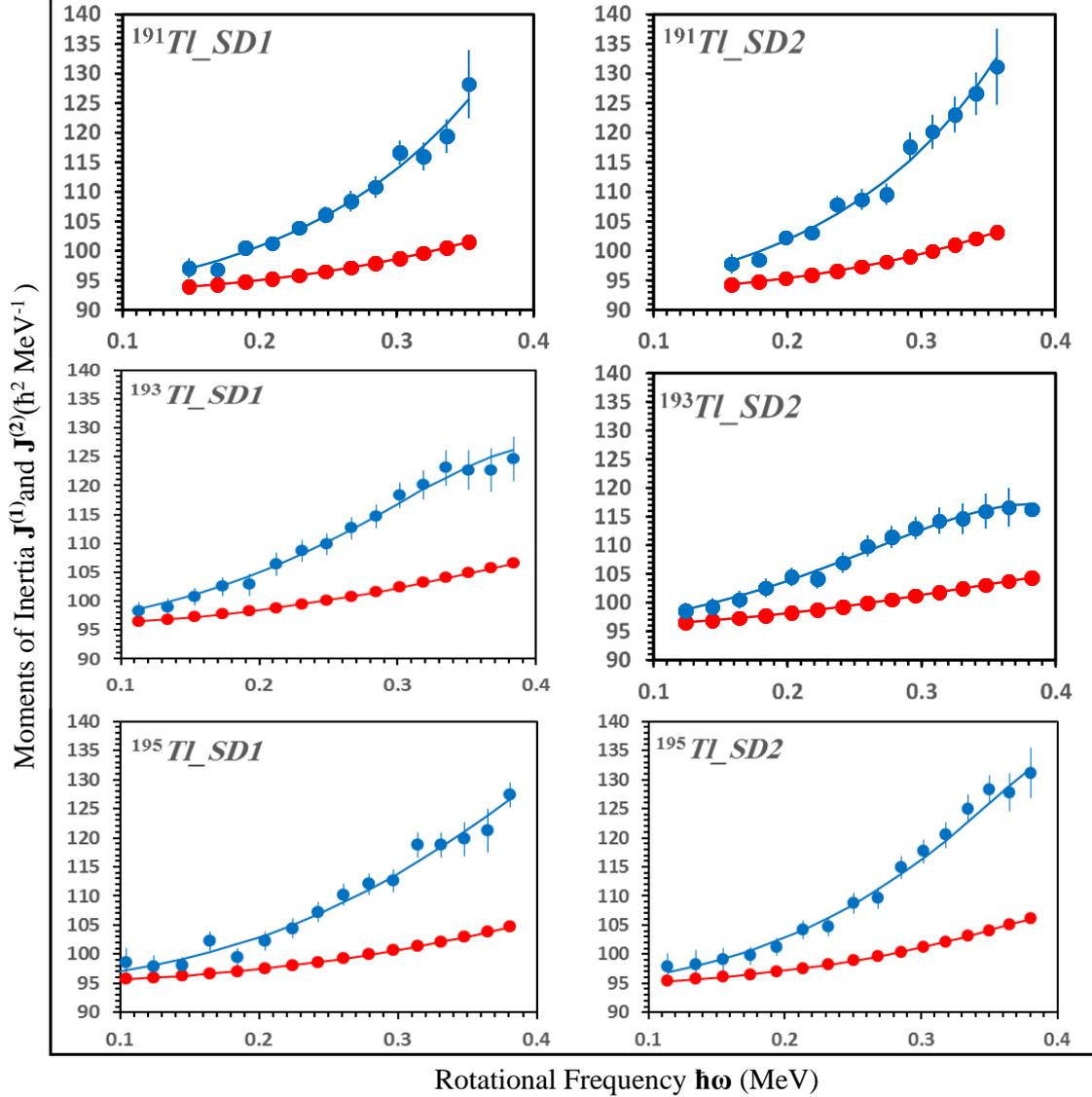

Fig. 1. The theoretical and experimental kinematic $J^{(1)}$ and dynamic $J^{(2)}$ moments of inertia for the three signature partner SD bands of Tl nuclei as a function of rotational frequency. Calculated and experimental $J^{(2)}$ are defined by solid curves and closed circles with error bars, respectively. Solid curves and closed circles denote calculated and experimental $J^{(1)}$ respectively.

Table 1: The fitting procedure yielded the measured best Harris parameters (α, β), the approximate bandhead spin (I_0), and the adopted Bohr-Mottelson parameters (A, B, C, D) for the tested signature partners in Tl odd-mass SD nuclei. For each SD band, the experimental lowest transition energy $E(I_0+2 \rightarrow I_0)$ is also given (Ref [2]).

SD band	E_γ (KeV) $(I_0+2 \rightarrow I_0)$	I_0 $(\hbar)$	α $\hbar^2 MeV$	β $\hbar^4 MeV^-$	A (KeV)	B (KeV)	C (KeV)	D (KeV)	χ
^{191}Tℓ(SD1)	276.5	11.5	92.7557	59.9493	5.390	-2.024E^{-04}	6.531E^{-09}	-3.416E^{-24}	3.51E^{-2}
(SD2)	296.3	12.5	92.8177	66.9172	5.386	-2.254E^{-04}	8.309E^{-09}	-2.386E^{-24}	3.97E^{-2}
^{193}Tℓ(SD1)	206.6	08.5	95.6809	73.6030	5.225	-2.197E^{-04}	2.248E^{-08}	-3.555E^{-25}	3.86E^{-2}
(SD2)	227.3	09.5	95.6956	66.5935	5.224	-1.986E^{-04}	2.464E^{-08}	-4.388E^{-25}	3.11E^{-2}
^{195}Tℓ(SD1)	146.2	05.5	95.1275	60.6993	5.256	-1.853E^{-04}	1.236E^{-08}	-2.767E^{-25}	4.10E^{-2}
(SD2)	167.5	06.5	94.8298	76.0716	5.272	-2.351E^{-04}	1.903E^{-08}	-1.269E^{-24}	6.06E^{-2}
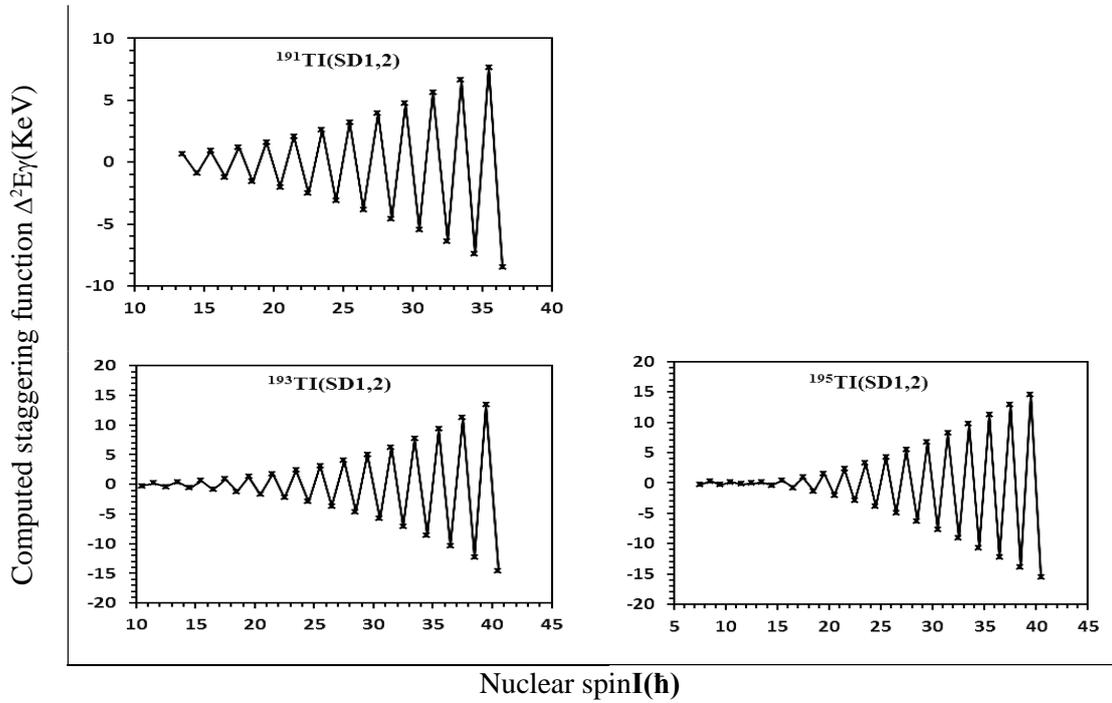
Fig. 2. For the signature partners ^{191}Tℓ(SD1, SD2), ^{193}Tℓ(SD1, SD2) and ^{195}Tℓ(SD1, SD2) in Tℓ odd-A nuclei, the computed $\Delta I=1$ staggering function as a function of nuclear spin I. $\Delta^2 E\gamma(I)$

6. Conclusions

Thallium odd-A $^{191\text{-}195}$Tℓ nuclei's SD signature partners were studied in this study. The two-parameter Harris formula was used to determine the spin of the levels. It has been reported that the Bohr-Mottelson four-parameter rotational energy formula has excellent compatibility with the γ-ray transition energies. The four model parameters were extracted using a suitable search program. The variation of $J^{(1)}$, $J^{(2)}$ with ℏω has been determined, and the rotational frequency, the moments of inertia kinematic $J^{(1)}$, and dynamic $J^{(2)}$ have been determined. The presence of ΔI=1 staggering in the studied signature partner pairs is investigated using a staggering function. Many of the signature partners tested have a zigzag pattern.

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سلوك عزوم القصور الذاتية وطاقة التعرج في الأنوية فائقة التشوه.

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الملخص العربي

استخدام نموذج بور- موتلسون الجماعي الدوراني ذو الأربعة بارامترات في توفيق الطاقات الانتقالية التجريبية مع تلك النظرية لثلاثة أزواج من شركاء الدلائل لأنوية الثاليوم فردية رقم الكتلة. تم حساب عزوم رؤوس الحزم الدورانية فائقة التشوه باستخدام صيغة هارس. استخلصت بارامترات النموذج باستخدام برنامج مضاهاة باحث للطاقات الانتقالية ومن ثم استخدمت القيم المثلى للبارامترات في حساب قيم كلا من التردد الدوراني وعزوم القصور الذاتية الكيناماتيكية والديناماتيكية والتي توافقت جيدا مع نظريتها التجريبية. تم أيضا دراسة تغير كلا من عزوم القصور الذاتية الكيناماتيكية والديناماتيكية مع تغير التردد الدوراني. وأخيرا تم فحص ظاهرة التعرج في الطاقات الانتقالية بين شركاء الدلائل عن طريق اقتراح دالة التعرج.