Al-Azhar Bulletin of Science Vol. 31, No. 2, (December) 2020, pp. 1-9

STRUCTURE AND BEHAVIOR OF SUPERDEFORMED ROTATIONAL BANDS IN THE A~190 MASS REGION USING EXPONENTIAL MODEL WITH PAIRING ATTENUATION

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ABSTRACT

The exponential model with pairing attenuation (EMPA) is extended and used to analysis the superdeformed rotational bands (SDRB's) in Thallium nuclei in the mass region A~190. The level spins are extracted by fitting the experimental dynamical moment of inertia $J^{(2)}$ to the theoretical version of Harris expansion in even powers of rotational frequency ħω. Using the assigned spins, the parameters of the extended exponential model are adjusted by using a computer simulated search program to fit the transition energies with experimental ones. The best adopted parameters are used to calculate transition energies $E_\gamma(I)$ rotational frequencies ħω, kinematic $J^{(1)}$ and dynamic $J^{(2)}$ moments of inertia .The variation of $J^{(1)}$ and $J^{(2)}$ versus ħω are examined. A staggering function depends on the concept of EGOS and finite differences are suggested to investigate and exhibit the ΔI=1 staggering effect in transition energies in the studied SDRB's. The phenomenon of identical bands in also investigated in Thallium nuclei.

Keywords: Pairing Attenuation, Staggering, Thallium nuclei

1. INTRODUCTION

Since the discovery of the first superdeformed (SD) bands in ^{152}Dy[1] and ^{191}Hg[2], a great number of superdeformed rotational bands (SDRB's) were identified in different mass regions A~190,150,130,80,60[3] which have their own characteristic features .These high spin SDRB's are associated with extremely large quadrupole deformation parameter. The difference between the SDRB's in various mass regions are manifested through the behavior of the dynamical moment of inertia. The A~190 mass region is of special interest, since in this region the SD bands were observed down to quite low spin, Most SDRB'S in A~190 region display the same smooth rise in dynamical moment of inertia with increasing rotational frequency [4]. This rise behavior was attributed in the cranked shell model calculations mainly to the successive alignment of both $J^{15}/_2$ quasi neuron and $J^{13}/_2$quasi proton pairs from high N intruder orbital under rotation in the presence of pairing correlations [5,6]. For all SDRB's the transition energies are the only quantities to be detected, there are no direct experimental method to determine spins, parities and excitation energies ,this is due to the difficulty of establishing the de excitation of SD band into ground states .Several theoretical procedures for assigning spins were proposed[7,13]. One of the unexpected feature happen in SDRB's is the existence of identical bands (IB's) [14,15],that is states in different SD bands having nearly the same γ – ray transition energies .This indicate that the rotational frequencies as well as the dynamical moment of inertia are very similar. Many authors tried to understand the IB's phenomenon [16-19]. The interesting discovery of IB's was seen also in pairs of normal deformed nuclei [20-22].

Another interesting feature related to the SDRB's is the measurement of magnetic properties. The branching ratio of M1 transition linking two signature partners SD bands were observed [23-24] and is denoted as ΔI=1 staggering. The crosstalk was originally observed in one direction, then it was established that the crosstalk goes both ways[25], The ΔI=1 staggering effect is also investigated in normal deformed nuclei between the energies of states of the ground and octupole bands[26]. Some SDRB's in mass region A~190 show an unexpected ΔI=2 staggering effects in the transition energies[27,28],This is commonly called ΔI=4 bifurcation because the states of the band splits into two sequences of transition energies differing by 2ħ of angular momentum and the states in each sequence differ by 4ħ of angular momentum .The spin values in one sequence are I,I+4,I+8,… while in the other sequence are I+2,I+6,I+10,… Several theoretical attempts were done to explain the ΔI=2 energy staggering phenomenon [29-34] .

2. OUTLINE OF EXPONENTIAL MODEL WITH PAIRING ATTENUATION

The pairing energy Δ depends on the angular momentum I by the relation [35]

$$\Delta (I) = \Delta_0 \left(1 - \frac{I}{I_C}\right)^{\frac{1}{2}} \qquad (1)$$

where Δ_0 is the energy pairing gap and I_C is the critical spin value at which pairing correlations disappear completely (I_C =I). That is the pairing gap vanishes. Using the cranked model, it was found [36] that the nuclear moment of inertia J depends exponentially on pairing correlation parameter Δ

$$J (\Delta) = J_0 \exp [-\Delta] \qquad (2)$$

where the parameter J_0 can be determined from the (ln J) versus Δ plot. Inserting the moment of inertia J (Δ) in the I (I+1) rule of excitation energy

$$E (I) = (\hbar^2/2J)\, I (I+1) \qquad (3)$$

yield the exponential model with pairing attenuation [37]

$$E (I) = A\, I (I+1) \exp [\Delta_0 \left(1 - \frac{I}{I_C}\right)^{\frac{1}{2}}] \qquad (4)$$

with Afor SD bands. The γ – ray transition energy E_γ are the only quantity experimental measured, therefore, we can write E_γ between two levels differentiates by two units of angular momenta as

$$E_\gamma (I) = E (I) - E (I-2)$$

$$= A \{I (I+1) \exp [\Delta_0 (1-I/I_c)^{1/2}] – (I-1) (I-2) \exp [\Delta_0 (1-(I-2)/I_c)^{1/2}]\} \qquad (5)$$

Equation (5) can be used to fit the transition energies of SDRB's for fixed I_C and keeping A and Δ_0 as a free parameter.

3. SPIN ASSIGNMENT FOR SDRB's

The determination of spins and parity of states in all SD bands is one of most difficult and unsolved problems in the study of superdeformation. This is due to the difficulty of establishing the de excitation of a SD band into known yrast state. Several theoretical approaches [3] were attempted to assign the spins of the SD bands. Most of procedures begin with the Harris model [39]. The two parameter Harris formula for excitation energy it given by

$$E (\omega) = (1/2)\, \alpha\, \omega^2 + (3/2)\, \beta\, \omega^4 \qquad (6)$$

The dynamic moment of inertia $J^{(2)}$ for the Harris formula is

$$J^{(2)} = (1/\omega)\, (dE/d\omega) \qquad (7)$$

$$(J^{(2)} / \hbar^2) = \alpha + 3\beta\, \omega^2 \qquad (8)$$

where α corresponds to the bandhead moment of inertia. Integrating equation (8) yield the level spin I

$$\hbar I = \int J^{(2)}\, d\omega$$

$$= \alpha\, \omega + 3\beta\, \omega^3 + i \qquad (9)$$

where the intrinsic alignment i appears as a constant of integration and $\check{I}=\sqrt{I (I + 1)}$ is the intermediate nuclear spin.

The parameters α and β are obtained from the fitting procedure of $J^{(2)}$ with experimental data.

The kinematic moment of inertia $J^{(1)}$ for Harris formula is

$(J^{(1)}/\hbar^2) = \hbar\,(1/\omega) = \alpha + \beta\,\omega^2$ (10)

Eliminating ω from the two equations (9) and (10) we get a cubic equation for the energy of the rotational band levels.

$e^3 + 2e^2 + (1+36\,d)e - 4(1+27\,d)d = 0$ (11)

where $e = (4\beta/\alpha^2)\,E$, $d = (\beta/2\alpha^3)\,I(I+1)$

Equation (11) give the excitation energy E as a function of spin. Putting $\gamma = 2d$ we have

$E(I)=(\hbar^2/2\alpha)(I\,(I+1)\,[1-\gamma+4\,\gamma^2 -24\,\gamma^3 +\ldots]$ (12)

The rotational frequency ħω ,The dynamic $J^{(2)}$ and kinematic $J^{(1)}$ moments of inertia are related to the transition energy $E_\gamma(I)$ by the relations

$\hbar\omega = (1/4)[E_\gamma(I+2\rightarrow I) + E_\gamma(I\rightarrow I-2)]$ (MeV) (13)

$J^{(2)} = 4/[\,E_\gamma(I+2\rightarrow I) - E_\gamma(I\rightarrow I-2)]\ (\hbar^2\,\mathrm{MeV}^{-1})$ (14)

$J^{(1)} = (2I-1) / E_\gamma(I\rightarrow I-2)$ $(\hbar^2\,\mathrm{MeV}^{-1})$ (15)

It is seen that the dynamic moment of inertia $J^{(2)}$ can be extracted from the energy difference between two consecutive transition energies in the band ,it does not depend on the spin while the kinematic moment of inertia $J^{(1)}$ depend on the spin proposition . The two moments of inertia $J^{(2)}$, $J^{(1)}$ are related as follows.

$J^{(2)}/\hbar^2 = (1/\hbar)(dI/d\omega) = (1/\hbar^2)[J^{(1)}+(dJ^{(1)}/d\omega)]$ (16)

3. Analysis of energy staggering in SDRB'S

The ΔI=1 staggering phenomenon, several pairs of signature partners SDRB's exhibit a ΔI=1 energy staggering [17]. these signature partners show signature splitting with large amplitude.

To exhibit the ΔI=1 energy staggering. we consider EGOS staggering function, It represents the gamma transition energy over the spin

$EGOS\,(I) = E\gamma(I) / 2I$ (17)

with $E\gamma(I) = E\gamma(\,I\,) - E\gamma(\,I-2)$

when EGOS is plotted against (2I) for pure rotator E (I) = A I (I+1) it represents a straight line parallel to the spin axis.

4. NUMERICAL RESULTS AND DISCUSSION

Our selected data set includes twelve super deformed rotational bands (SDRB's) for Thallium nuclei The γ-ray transition energies in a band is assumed as the difference in energies between two levels separated by two units of angular momentum .The experimental transition energies of our SDRB's are taken from Ref [3].The level spins of each band are determined by fitting the dynamic moments of inertia for each rotational frequency ħω extracted from experimental transition energies with the Harris two parameter α and β equation (10) in order to obtain a minimum root mean square deviation by the common definition of the $\chi(J^{(2)})$

$$\chi(J^{(2)}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{J^{(2)}_{exp}(\omega i)-J^{(2)}_{cal}(\omega i)}{\delta J^{(2)}_{exp}(\omega i)}\right)^2}$$

where N is the total number of the experimental points entering into the fitting procedure and $\delta J^{(2)}_{exp}\,(\omega i)$ is the experimental errors in $J^{(2)}$.

A computer simulated search program is used in fitting procedure. The calculated assigned bandhead spins and the best adopted Harris parameters α and β are listed in Table (1).

After knowing the level spins for each band, another fitting procedure has been performed to adjust the two parameters Δ and A of the exponential model with pairing attenuation by fitting the experimental transition energies with the corresponding theoretical one to minimize $\chi(E\gamma)$

$$\chi\,(E\gamma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{E\gamma\exp(I) - E\gamma cal(I)}{\delta\,E\gamma\exp(I)}\right)^2}$$

where δE_γ^{exp} (I) is the experimental error in transition energy Eγ(I).

Table (1) show the adopted best model parameters Δ, A and the rms deviation ((Eγ). The experimental lowest transition energy $E_\gamma\,(I_0 +2\rightarrow I_0)$. For each (SD) band is also indicated in Table (1). The calculated transition energy E_γ^{Cal} (I) are compared to experimental ones E_γ^{exp} (I). and the results are shown in Table (2). We see that a very good agreement between calculation and experiment is obtained, which give good support to the proposed exponential model with pairing attenuation

The moments of inertia $J^{(1)}$ and $J^{(2)}$ for the three pairs of identical bands (IB's) in ^{193,194,195}Tl are shown in Figure (1), they display similarities in the frequency range 0.10 MeV < ħω < 0.35 MeV for the pair [^{193}Tl (SD1), ^{194}Tl (SD3)], and 0.10 MeV < ħω < 0.40 MeV for the two pairs [^{193}Tl (SD1), ^{195}Tl (SD1)],and[^{193}Tl (SD2),^{195}Tl (SD2)].

The bandhead moments of inertia which depends on the intrinsic structure of the rotational band for these three pairs of IB's are nearly identical.

From the analysis of $J^{(1)}$ and $J^{(2)}$ moments of inertia we observed that the lowest values of $J^{(2)}$ for the yrast superdeformed bands in Tl isotopes exhibit a zigzag moments of inertia staggering .Table(3) and Figure(2) shows the calculated and the experimental lowest values of $J^{(2)}$ versus the neutron number of the yrast SD bands in $^{191-195}$Tl nuclei .

The main results of present paper are the observation of a ΔI=1 energy staggering effect in five pairs of signature partners in odd A and odd-odd ^{192,194}Tl nuclei namely:

^{191}Tl (SD1, SD2), ^{192}Tl (SD1, SD2), ^{193}Tl (SD1, SD2), ^{194}Tl (SD1, SD2), and ^{195}Tl (SD1, SD2). We investigated this Effect by calculating the staggering function EGOS equation (17). The results are plotted versus nuclear spin I in Figure (3). Zigzag pattern with large amplitude is shown. The numerical values are listed in Table (4)

Table (1) The estimated bandhead spin I_0 and the adopted best model parameters α, β , Δ, A obtained from the fitting produce for studied SDRB'S in Tl the nuclei. The experimental lowest transition energy Eγ (I_0+2→I_0)) for each (SD) band is also given. The rms deviation χ is indicated

SD band	($\hbar^2 MeV^{-1}$)α	β ($\hbar^4 MeV^{-3}$)	I_0 (ħ)	Δ(10^{-1})	A(Kev)	χ	E_(^exp (KeV)
^{191}Tl(SD1)	92.7007	55.5565	11.5	3.3009	3.9958	0.754	276.5
^{191}Tl(SD2)	92.1013	60.1692	12.5	5.2868	3.5564	0.338	296.3
^{192}Tl(SD1)	102.7981	1.5499	11	3.77642	3.9097	1.100	283.0
^{192}Tl(SD2)	103.5797	9.7379	14	3.12090	4.1003	1.495	337.5
^{193}Tl(SD1)	96.4098	54.4976	8.5	3.17970	3.9123	0.693	206.6
^{193}Tl(SD2)	96.4333	4.6144	9.5	2.6883	4.0853	0.491	227.3
^{194}Tl(SD1)	96.9760	150.5479	12	2.19465	4.1104	0.658	268
^{194}Tl(SD2)	99.900	45.0435	9	2.15538	4.1178	0.510	209.3
^{194}Tl(SD3)	90.7109	203.8071	10	2.88292	4.0276	0.533	240.5
^{194}Tl(SD5)	100.4390	93.8086	8	1.91747	4.1322	0.454	187.9
^{195}Tl(SD1)	95.5000	45.3292	5.5	2.8735	4.0470	0.360	146.2
^{195}Tl(SD2)	95.0010	64.9352	6.5	3.51009	3.8300	1.414	167.5

Table (2). The calculated transition energy Eγ(I) for our calculated. SDRB's and comparison with experimental data. The model parameters and the band head spins are listed in Table (1)

^{191}Tl (SD1)			^{191}Tl (SD2)			^{192}Tl (SD1)			^{192}Tl (SD2)		
I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)	
	EXP	CAL		EXP	CAL		EXP	CAL		EXP	CAL
13.5	276.5	278.687	14.5	296.3	294.725	13	283	282.121	16	337.5	332.139
15.5	317.7	319.431	16.5	337.2	336.487	15	320.8	320.898	18	374.9	372.608
17.5	359	359.574	18.5	377.8	377.249	17	359	359.928	20	413.4	412.489
19.5	398.8	399.100	20.5	416.9	416.995	19	397.8	397.599	22	451.1	451.767
21.5	438.3	437.993	22.5	455.7	455.704	21	437.1	437.433	24	489.6	490.427
23.5	476.8	476.238	24.5	492.8	493.354	23	476.1	476.253	26	527.4	528.450
25.5	514.5	513.815	26.5	529.6	529.921	25	515.2	515.521	28	565.5	565.816
27.5	551.4	550.706	28.5	566.1	565.380	27	554.4	553.840	30	603.1	602.505
29.5	587.5	586.888	30.5	600.1	599.701	29	593	592.606	32	640.9	638.491
31.5	621.8	622.336	32.5	633.4	632.852	31	632	631.352	34	677.6	673.546
33.5	656.3	657.026	34.5	665.9	664.75	33	670	671	35	715.3	708.983
35.5	689.8	691.19	36.5	697.5	695.43	35	707	706			

^{193}Tl(SD1)			^{193}Tl(SD2)			^{194}Tl(SD1)			^{194}Tl(SD2)		
I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)		I(ħ)	Eγ (I) (KeV)	
	EXP	CAL		EXP	CAL		EXP	CAL		EXP	CAL
10.5	206.6	209.066	11.5	227.3	229.038	14	268	269.062	11	209.3	210.251
12.5	247.3	249.341	13.5	267.9	269.263	16	307	307.569	13	248.4	249.253
14.5	287.7	289.077	15.5	308.2	309.028	18	345.1	345.701	15	287.5	287.901
16.5	327.4	328.262	17.5	348	348.321	20	384.2	383.448	17	326	326.187
18.5	366.4	366.885	19.5	387	387.129	22	421	420.799	19	364.4	364.1
20.5	405.3	404.931	21.5	425.4	425.441	24	457	457.743	21	401.7	401.63
22.5	442.9	442.385	23.5	463.7	463.242	26	494.9	494.266	23	439.3	438.766
24.5	479.7	479.231	25.5	501.1	500.518	28	530.9	530.355	25	475.9	475.496
26.5	516.1	515.450	27.5	537.5	537.250	30	567	565.993	27	512	511.807
28.5	551.6	551.023	29.5	573.4	573.421	32	601.2	601.849	29	548	547.684
30.5	586.5	585.930	31.5	608.8	609.010	34	634.9	635.849	31	583.5	583.110
32.5	620.3	620.145	33.5	643.8	643.997	36	669.8	670.675	33	617.5	618.070

Table (3). The lowest dynamic moment of inertia J $^{(2)}$ for the yrast SDRB'S in $^{191\text{-}195}$Tl [N is the neutron number]

SD band	N	$J^{(2)}_{exp}$ ($\hbar^2$ MEV^{-1})	$J^{(2)}_{cal}$ ($\hbar^2$ MEV^{-1})
^{191}Tl(SD1)	110	97.083	98.1739
^{192}Tl(SD1)	111	105.8201	103. 1539
^{193}Tl(SD1)	112	98.2800	99.3171
^{194}Tl(SD1)	113	102.5641	103.8732
^{195}Tl(SD1)	114	95.2380	96.6673

Table (4). The calculated ΔI=1 staggering function EGOS (I) versus nuclear spin I for the signature partners ^{191}Tl (SD1, SD2), ^{192}Tl (SD1, SD2), ^{193}Tl (SD1, SD2), ^{194}Tl (SD1, SD2), ^{195}Tl (SD1- SD2)

^{191}TL (SD1, SD2)		^{192}TL (SD1, SD2)		^{193}TL (SD1, SD2)		^{194}TL (SD1, SD2)		^{195}TL (SD1, SD2)	
I(ħ)	EGOS	I(ħ)	EGOS	I(ħ)	EGOS	I(ħ)	EGOS	I(ħ)	EGOS
14.5	1.060	16	0.7029	11.5	1.7366	14	1.4149	8.5	2.5223
15.5	1.5939	17	1.6346	12.5	1.6242	15	1.2557	9.5	2.0988
16.5	1.0336	18	0.7044	13.5	1.4757	16	1.2292	10.5	2.0111
17.5	1.3192	19	1.3679	14.5	1.3664	17	1.0951	11.5	1.7207
18.5	0.9554	20	0.6945	15.5	1.2871	18	1.0841	12.5	1.5714
19.5	1.1205	21	1.1878	16.5	1.1656	19	0.9683	13.5	1.5362
20.5	0.8729	22	0.6515	17.5	1.1462	20	0.9674	14.5	1.3884
21.5	0.9766	23	1.0037	18.5	1.0034	21	0.8658	15.5	1.2769
22.5	0.7871	24	0.4972	19.5	1.0381	22	0.8713	16.5	1.1798
23.5	0.8737	25	0.9403	20.5	0.8683	23	0.7811	17.5	1.14
24.5	0.6996	26	0.4277	21.5	0.9539	24	0.7907	18.5	1.01
25.5	0.8823	27	0.9237	22.5	0.753	25	0.7101	19.5	1.0365
26.5	0.6077	28	0.3299	23.5	0.8875	26	0.7219	20.5	0.86464
27.5	0.7558	29	0.9305	24.5	0.6526	27	0.6496	21.5	0.9572
28.5	0.5148	30	0.223	25.5	0.8347	28	0.6624	22.5	0.7648
29.5	0.729	31	0.9571	26.5	0.5634	29	0.5975	23.5	0.896
30.5	0.42	32	0.108	27.5	0.7927	30	0.6103	24.5	0.6371
31.5	0.7185	33	1.0008	28.5	0.4832	31	0.5521	25.5	0.8486
32.5	0.3235	34	-0.0146	29.5	0.7592	32	0.5641	26.5	0.5489
33.5	0.7216	35	0.7029	30.5	0.4101	33	0.5123	27.5	0.8121
34.5	0.2253	36	1.6346	31.5	0.7326	34	0.5224	28.5	0.4535
35.5	0.736			32.5	0.3426	35	0.4769	29.5	0.7844
36.5	0.1253			33.5	0.712	36	0.4857	30.5	0.3732
37.5	0.7601			34.5	0.2796	37	0.4453	31.5	0.7638
38.5	0.0236			35.5	0.6961	38	0.4518	32.5	0.2984
				36.5	0.2202			33.5	0.7492
				37.5	0.6862			34.5	0.2282
				38.5	0.162			35.5	0.7396
				39.5	0.678			36.5	0.1615
				40.5	0.108			37.5	0.7341
				41.5	0.6729			38.5	0.0977
								39.5	0.7323
								40.5	0.0362
								41.5	0.7338
								42.5	-0.0233

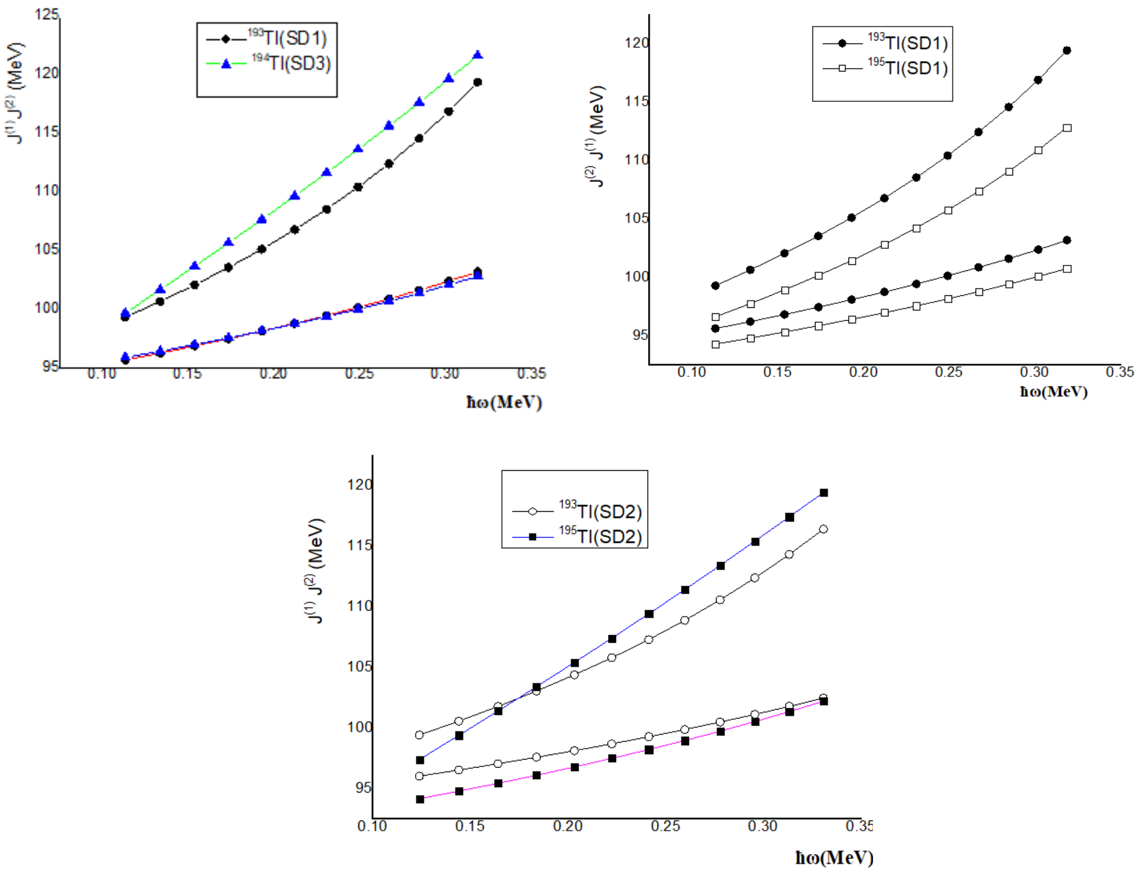

Figure (1). The kinematic $J^{(1)}$ and dynamic $J^{(2)}$ moment of inertia verses rotational frequency ħω for the three pairs of identical bands in ^{193,194,195}Tl

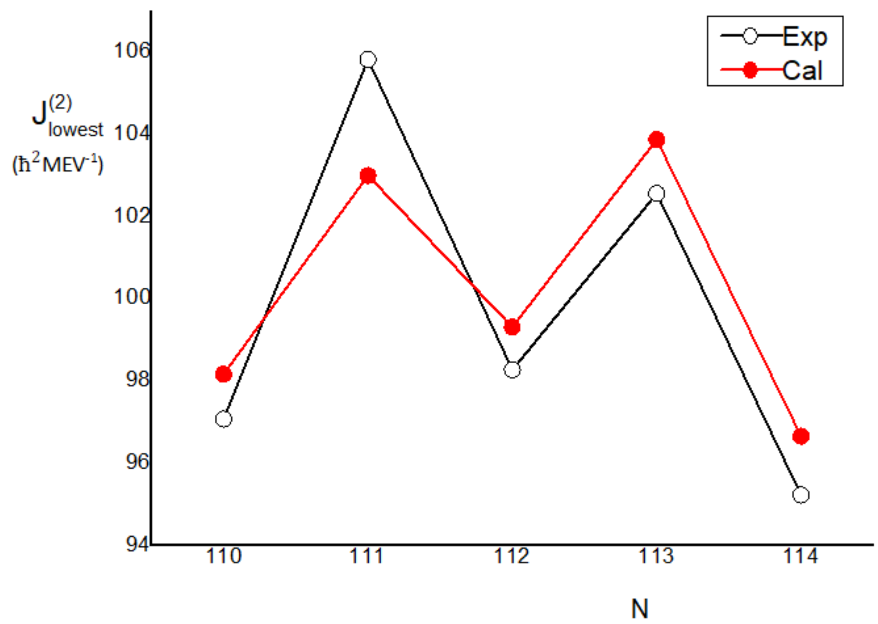

Figure (2). The lowest dynamic moments of inertia $J^{(2)}$ for the yarst SDRB'S in $^{191-195}$Tl

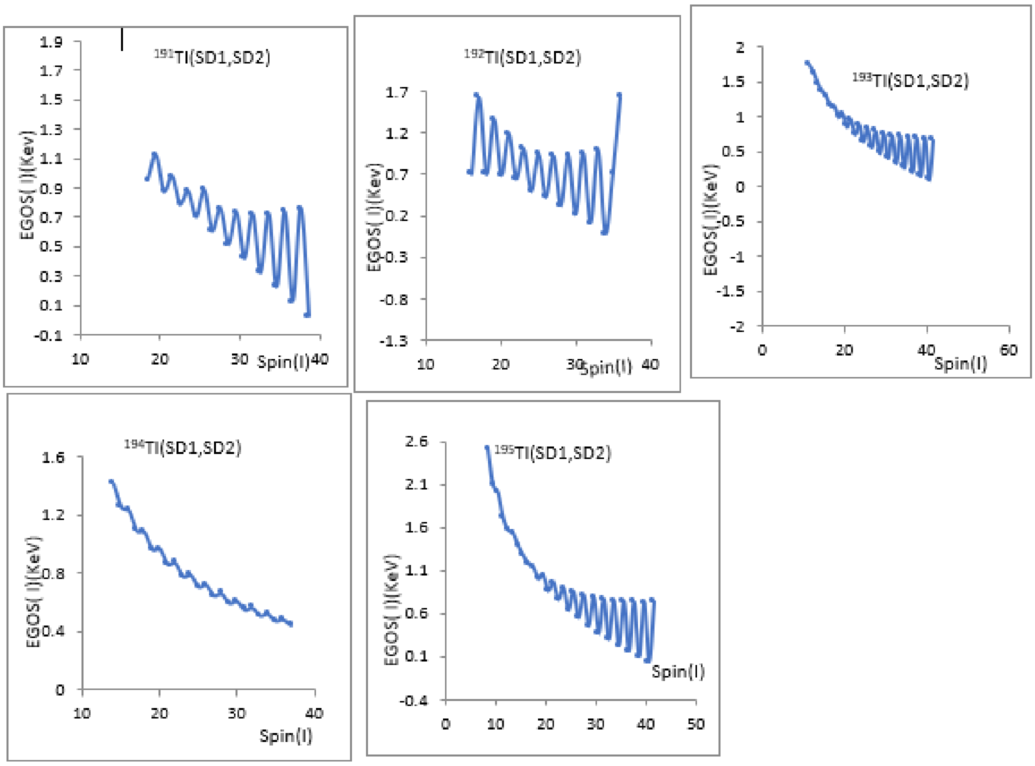

Figure (3). The Δ I=1 staggering parameter EGOS(I) in (KeV) as a function of nuclear spin I for the Five pairs of signature partners in Tl nuclei.

5. CONCLUSION

SDRB's in Tl isotopes with mass number between 191and 195 have been studied in the framework of exponential model with pairing attenuation. The existence of identical bands and EGOS(I) staggering behaviors are discussed. All the studied SD bands exhibit significant amounts of staggering. We have succeeded in making very good fit γ-ray transition energies E_γ by using a simulated search program

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تركيب وسلوك الحزم الدورانية فائقة التشوه فى منطقة رقم الكتلة 190 باستخدام النموذج الأسى مع توهين الازدواج

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الملخص العربى

تم دراسة تركيب الحزم فائقة التشوة ذات اقل طاقة والمثارة لانوية الثاليوم في منطقة رقم الكتلة 190في اطارنموذج مقترح لامتداد النموذج الاسي مع توهين الازدواج الحزم الدورانية فائقة التشوة. وباستخدام الغزل المعين ضبطت البارامترات المثالية للنموذج المقترح لامتداد النموذج الاسي مع توهين الازدواج لكل حزمة علي حدة بواسطة برنامج مضاهاة باحث اخر لتوفيق الطاقات الانتقالية النظرية مع نظيراتها التجريبية ولقد قيست جودة التوفيق بين الطاقات النظرية والطاقات التجريبية للحزم فائقة التشوة .استخدمت البارامترات المثلي للنموذج المقترح في حساب الطاقات الانتقالية رباعية الاقطاب الكهربي.الترددات الدورانية وعزوم القصور الذاتية الكيناماتيكية والديناميكية .توافقت جيدا النتائج النظرية المحسوبة مع نظيراتها التجريبية. فحص سلوك عزوم القصور الذاتية الكيناماتيكية والديناميكية مع التردد الدوراني لجميع الحزم فائقة التشوة المختارة . وتم التحقق من ظهور التعرج الشاذ في طاقات جاما الانتقالية.