β_4 systematics in rare-earth and actinide nuclei: *sdg* interacting boson model description

Y. D. Devi and V. K. B. Kota
Physical Research Laboratory, Ahmedabad, 380 009, India
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The observed variation of hexadecupole deformation parameter β_4 with mass number A in rare-earth and actinide nuclei is studied in the *sdg* interacting boson model (IBM) using single j-shell Otsuka-Arima-Iachello mapped and IBM-2 to IBM-1 projected hexadecupole transition operator together with $SU_{sdg}(3)$ and $SU_{sdg}(5)$ coherent states. The $SU_{sdg}(3)$ limit is found to provide a good description of data.

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Coulomb excitation, electron scattering, Coulomb/nuclear interference, etc., generated data on hexadecupole deformation parameter β_4 all across the rare-earth region and the latest compilation of these data are due to Janecke [1]. Similarly Bemis *et al.* [2], employing Coulomb excitation with ^{4}He ions, and Zumbro *et al.* [3,4], analyzing muonic K, L, and M x rays, produced β_4 data for some of the actinide nuclei. An important feature of the β_4 data in rare-earth and actinide regions is the change in the sign of β_4 after some value of the mass number A. Bertsch's [5] polar cap model gives a qualitative understanding of the variation in β_4 with A. The Nilsson-Strutinsky renormalization method [6] and its variants [7,8] and the more microscopic Hartree-Fock + BCS method [9] are so far employed for the description of β_4 data.

Recently considerable progress was made in establishing that the *sdg* interacting boson model (*sdg*IBM or simply *g*IBM) is a viable and powerful tool for the analysis and understanding of $E4$ data (i.e., select $E4$ matrix elements [10], $E4$ strength distributions [11,12], hexadecupole vibrational bands [13], etc.) which has started accumulating in the past few years. Therefore it is important and essential to understand the β_4 systematics using *sdg*IBM. As demonstrated in [14], the *sd*IBM fails to describe the β_4 systematics in rare-earth nuclei. In Refs. [15,11] it is shown that the inclusion of g bosons together with the OAI (Otsuka, Arima, and Iachello) [16] mapped hexadecupole ($E4$) transition operator can in principle explain the change in sign of β_4 with A. However, as the formalism in [15,11] is strictly confined to *sdg*IBM-1, so far the experimental data are not analyzed. To this end one should start with proton-neutron *sdg*IBM (*pn-sdg*IBM or *sdg*IBM-2). Therefore OAI mapping of the $E4$ transition operator in p,n spaces is carried out separately and the resulting IBM-2 $E4$ operator is projected onto IBM-1 space. The $E4$ operator thus obtained is used in the $SU_{sdg}(3)$ and $SU_{sdg}(5)$ limits of *sdg*IBM [17] to analyze β_4 data in rare-earth and actinide nuclei.

In *sdg*IBM-2 quadrupole ($\lambda=2$) and hexadecupole ($\lambda=4$) transition operators T^{λ}_{μ} are written as

$$T^{\lambda}_{\mu}(\pi\nu)=\sum_{\rho=\pi,\nu} e^{(\lambda)}_{\rho} Q^{\lambda}_{\mu;\rho} ,\qquad Q^{\lambda}_{\mu;\rho}=\sum_{l,l'=0,2,4} q^{(\lambda)}_{l,l';\rho}(b^{\dagger}_{l;\rho}\tilde{b}_{l';\rho})^{\lambda}_{\mu} , \tag{1}$$

where π (ν) represents proton (neutron) bosons. In (1) $q^{(\lambda)}_{l,l';\pi}$ ($q^{(\lambda)}_{l,l';\nu}$) are effective charges that define the one-body transition operators $Q^{(\lambda)}_{\pi}$ ($Q^{(\lambda)}_{\nu}$) and $e^{(\lambda)}_{\pi}$ ($e^{(\lambda)}_{\nu}$) are the overall effective charges, respectively, in proton (neutron) boson space. Using the OAI correspondence [16,18],

$$\begin{aligned}
&|(j_\rho)^{2N_\rho}, v_\rho=0, J_\rho=0\rangle \leftrightarrow |n_{s;\rho}=N_\rho, L_\rho=0\rangle ,\\
&|(j_\rho)^{2N_\rho}, v_\rho=2, J_\rho=2\rangle \leftrightarrow |n_{s;\rho}=N_\rho-1, n_{d;\rho}=1, L_\rho=2\rangle ,\\
&|(j_\rho)^{2N_\rho}, v_\rho=2, J_\rho=4\rangle \leftrightarrow |n_{s;\rho}=N_\rho-1, n_{g;\rho}=1, L_\rho=4\rangle ,\\
&\qquad\qquad \rho=\pi \text{ or } \nu ,
\end{aligned} \tag{2}$$

where N_π (N_ν) is proton (neutron) boson number, $j_\rho=(2\Omega_\rho-1)/2$ with $2\Omega_\pi$ ($2\Omega_\nu$) being the shell degeneracy for protons (neutrons), and equating the matrix elements of multipole operators in fermion $[r^{\lambda}_{\rho}Y^{\lambda}_{\mu}(\theta_\rho,\phi_\rho)]$ and boson ($Q^{\lambda}_{\mu;\rho}$) spaces one obtains the effective charges $q^{(\lambda)}_{l,l';\rho}$. Note that ($j_\pi, j_\nu$) takes values ($\frac{31}{2},\frac{43}{2}$) and ($\frac{43}{2},\frac{57}{2}$) for rare earths and actinides, respectively. Now carrying out IBM-2 to IBM-1 projection [19] by assuming that the low-lying levels belong to F spin $F=F_{\max}=(N_\pi+N_\nu)/2$ and using the simple result that $\langle FF_z|e_\pi(b^{\dagger}_{\pi}\tilde{b}_{\pi}) + e_\nu(b^{\dagger}_{\nu}\tilde{b}_{\nu})|FF_z\rangle = [(e_\pi N_\pi + e_\nu N_\nu)/N]\langle FF|b^{\dagger}\tilde{b}|FF\rangle$; $F_z=(N_\pi-N_\nu)/2$ (IBM-1 states correspond to $F=F_z=N/2; N=N_\pi+N_\nu$) which follows from the Wigner-Eckart theorem in F-spin space, the OAI mapped and IBM-2 to IBM-1 projected transition operator T^{λ}_{μ} is

$$\begin{aligned}
T^{\lambda}_{\mu} &= \sum_{l,l'} e^{(\lambda)}_{l,l'}(b^{\dagger}_{l}\tilde{b}_{l'})^{\lambda}_{\mu} ;\\
e^{(\lambda)}_{l,0} &= e^{(\lambda)}_{0,l}\\
&= \mathbf{e}^{(\lambda)}_{\pi}\sqrt{2(\Omega_\pi-N_\pi)}N_\pi/N + \mathbf{e}^{(\lambda)}_{\nu}\sqrt{2(\Omega_\nu-N_\nu)}N_\nu/N ,\\
e^{(\lambda)}_{l,l'} &= e^{(\lambda)}_{l',l}\\
&= (\mp)\sum_{\rho=\pi,\nu}(\mathbf{e}^{(\lambda)}_{\rho}\mathbf{q}^{(\lambda)}_{l,l';\rho}N_\rho/N), \quad (l,l')\neq 0 ,\\
\mathbf{q}^{(\lambda)}_{l,l';\rho} &= \frac{\sqrt{\Omega_\rho(\Omega_\rho-1)}}{(\Omega_\rho-2)}(\Omega_\rho-2N_\rho)\\
&\quad \times\sqrt{4(2l+1)(2l'+1)}\begin{Bmatrix} l & l' & \lambda\\ j_\rho & j_\rho & j_\rho\end{Bmatrix} ,\\
\mathbf{e}^{(\lambda)}_{\rho} &= e^{(\lambda)}_{\rho}\frac{\langle j_\rho\|r^{\lambda}_{\rho}Y^{\lambda}_{\mu}(\theta_\rho,\phi_\rho)\|j_\rho\rangle}{\sqrt{(2\lambda+1)\Omega_\rho(\Omega_\rho-1)}} ,\\
q^{(\lambda)}_{l,l';\rho} &= \mathbf{q}^{(\lambda)}_{l,l';\rho}\mathbf{e}^{(\lambda)}_{\rho}/e^{(\lambda)}_{\rho} .
\end{aligned} \tag{3}$$

The two free parameters $e_\rho^{(\lambda)}$ (or equivalently $\mathbf{e}_\rho^{(\lambda)}$) are defined in (1) and the OAI mapped expressions for the effective charges $q_{l,l';\rho}^{(\lambda)}$ appearing in (1) are defined by the last equation in (3). The ($-$) sign for $e_{l,l'}^{(\lambda)}$ in (3) is for particle bosons (fermion number $N_f \le \Omega; N = N_f/2$) and the (+) sign is for hole bosons [fermion number $N_f \ge \Omega; N = (2\Omega - N_f)/2$].

In *sdg*IBM, the N-boson coherent state [17] is written as

$$|N;\alpha\rangle = \left[\left[\sum_{\substack{l=0,2,4\\ -l\le\mu\le l}} \alpha_{l\mu} b^\dagger_{l\mu}\right]^N \Big/ [N!\,\alpha^{2N}]^{1/2}\right]|0\rangle \quad (4)$$

where $\alpha^2 = 1 + \alpha_2\cdot\alpha_2 + \alpha_4\cdot\alpha_4$, $\alpha_{l,-\mu} = (-1)^{l+\mu}\alpha_{l,\mu}$, $b_0^\dagger = s_0^\dagger$, $b_{2\mu}^\dagger = d_\mu^\dagger$, $b_{4\mu}^\dagger = g_\mu^\dagger$. Using the coherent state $|N;\alpha\rangle$, the intrinsic quadrupole and hexadecupole moments M_2 and M_4 are given by

$$\begin{aligned} M_2 &= \langle N;\alpha|T_0^2|N;\alpha\rangle \\ &= \frac{N}{\alpha^2}\sum_{l,l'} (\alpha_l\alpha_{l'})_0^2 e_{ll'}^{(2)} , \\ M_4 &= \langle N;\alpha|T_0^4|N;\alpha\rangle \\ &= \frac{N}{\alpha^2}\sum_{l,l'} (\alpha_l\alpha_{l'})_0^4 e_{ll'}^{(4)} . \end{aligned} \quad (5)$$

In [20,17] $\alpha_{\lambda\mu}$ are parametrized in terms of the quadrupole and hexadecupole deformation parameters β_2^c, β_4^c and the asymmetry angle γ^c (c denotes coherent state),

$$\begin{aligned} &\alpha_{20} = \beta_2^c \cos\gamma^c , \\ &\alpha_{21} = \alpha_{2-1} = 0 , \\ &\alpha_{22} = \alpha_{2-2} = \frac{\beta_2^c \sin\gamma^c}{\sqrt{2}} , \\ &\alpha_{40} = \tfrac{1}{6}\beta_4^c (5\cos^2\gamma^c + 1) , \\ &\alpha_{41} = \alpha_{4-1} = 0 , \\ &\alpha_{42} = \alpha_{4-2} = \tfrac{1}{6}\sqrt{\tfrac{15}{2}}\,\beta_4^c \sin 2\gamma^c , \\ &\alpha_{43} = \alpha_{4-3} = 0 , \\ &\alpha_{44} = \alpha_{4-4} = \tfrac{1}{6}\sqrt{\tfrac{35}{2}}\,\beta_4^c \sin^2\gamma^c , \\ &\beta_2^c \ge 0, \quad -\infty \le \beta_4^c \le +\infty, \quad 0^\circ \le \gamma^c \le 60^\circ . \end{aligned} \quad (6)$$

In the $SU_{sdg}(3)$ and $SU_{sdg}(5)$ limits, which are appropriate for deformed nuclei [17,21], the equilibrium shape parameters $(\beta_2^0, \beta_4^0, \gamma^0)$ are given by

$$\begin{aligned} &SU_{sdg}(3){:}\ \ \beta_2^0 = \sqrt{\tfrac{20}{7}},\ \beta_4^0 = \sqrt{\tfrac{8}{7}},\ \gamma^0 = 0^\circ , \\ &SU_{sdg}(5){:}\ \ \beta_2^0 = \sqrt{\tfrac{10}{7}},\ \beta_4^0 = \sqrt{\tfrac{18}{7}},\ \gamma^0 = 60^\circ . \end{aligned} \quad (7)$$

The coherent state matrix elements M_2 and M_4 are related to the geometric model deformation parameters (β_2, β_4) for axially symmetric shapes [as is the case with $SU_{sdg}(3)$ and $SU_{sdg}(5)$ limits [17]] by the relation [22]

$$\begin{aligned} \beta_2 &= \left[\frac{4\pi}{3ZeR_0^2}\right] M_2 , \\ \beta_4 &= \left[\frac{4\pi}{3ZeR_0^4}\right] M_4 - \frac{9}{7\sqrt{\pi}}\beta_2^2 . \end{aligned} \quad (8)$$

In the geometric model analysis [22] that gives rise to (8), the surface diffuseness corrections are neglected. Note that $R_0 = r_0 A^{1/3}$ and r_0 is chosen to be 1.2 fm.

The mapped $E4$ operator T_μ^4 with $\mathbf{e}_\pi^{(4)}, \mathbf{e}_\nu^{(4)}$ as the two free parameters (3) is used to calculate the coherent state matrix element M_4 via (5) and (6) in the $SU_{sdg}(3)$ and $SU_{sdg}(5)$ limits by using the equilibrium shape parameters $(\beta_2^0, \beta_4^0, \gamma^0)$ given in (7). The M_4's thus obtained and the experimental or theoretical [using (3) and (5)] β_2 values when used in (8) give β_4 values. The calculated β_4's are fitted to experimental data and the two free parameters

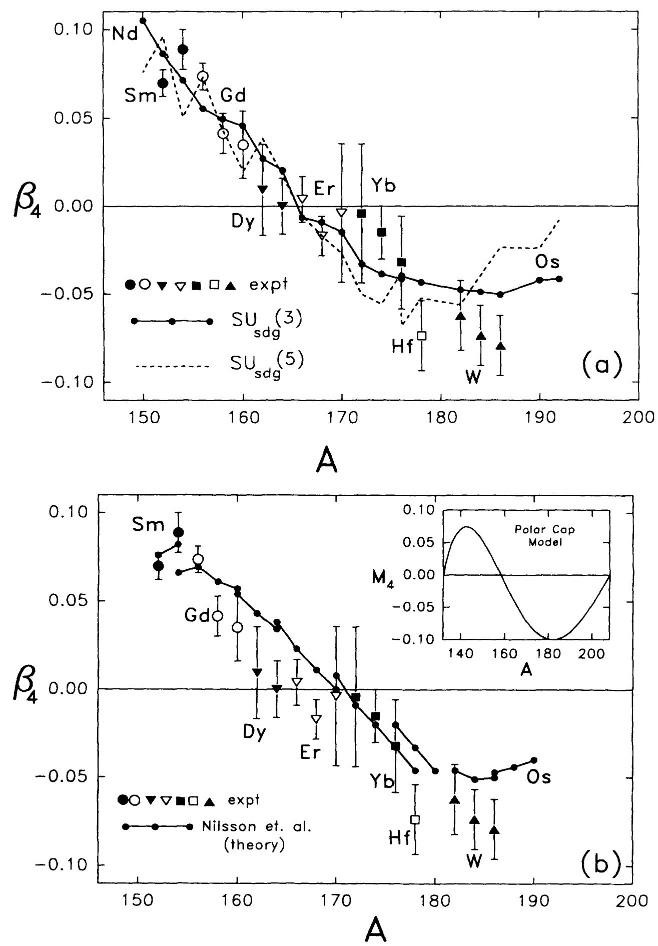

FIG. 1. Hexadecupole deformation β_4 vs mass number for rare-earth nuclei. (a) The $SU_{sdg}(3)$ and $SU_{sdg}(5)$ predictions are compared with data. (b) The theoretical results due to Nilsson *et al.* [6] are compared with data. In the inset to (b), the polar cap model prediction for the variation in M_4 with A is also shown. The experimental data are taken from Janecke [1].

$e_\pi^{(4)}, e_\nu^{(4)}$ are determined. In the present analysis experimental β_2 values are used, which is equivalent to comparing the calculated and experimental $E4$ matrix elements ($M_4 = \langle 4^+_{\text{g.s.}} \| T^4 \| 0^+_{\text{g.s.}} \rangle$; g.s. stands for ground state $K^\pi = 0^+$ band). The results for rare-earth and actinide nuclei are shown in Figs. 1(a) and 2(a), respectively.

For rare-earth nuclei the β_4 data are taken from Janecke's compilation [1] and the β_2 data are taken from the adopted values given by Raman *et al.* [23]. The effective charges ($e_\pi^{(4)}, e_\nu^{(4)}$) in $e\,\text{b}^2$ units are determined to be (0.0121,0.0045) and (0.0396,−0.0181) in the $\text{SU}_{sdg}(3)$ and $\text{SU}_{sdg}(5)$ limits, respectively. It is seen from the results in Fig. 1(a) that the $\text{SU}_{sdg}(3)$ limit provides a good description of experimental data. In Fig. 1(b) the results of Nilsson *et al.* [6] are shown. Here the potential energy surfaces are constructed as a function of quadrupole (β_2) and hexadecupole (β_4) deformation parameters including Coulomb and pairing energies and then minimizing the potential energy, the ground state deformation parameters are determined. In the inset to Fig. 1(b) Bertsch's polar cap model [5] prediction for M_4 vs A is shown. Where, with $\mathcal{N}$ the sum of proton and neutron shell degeneracies (for rare earths $\mathcal{N}=76$), $m(A)$ the number of valence nucleons [for rare earths $m(A) = A - 132$] and the Legendre polynominal $P_4(x) = (35x^4 - 30x^2 + 3)/8$,

$$M_4(A) \propto \int_{\mu(A)}^{1} P_4(x)dx, \quad \mu(A) = 1 - \frac{m(A)}{\mathcal{N}} .$$

It is to be noted that the variation of β_4 with A is similar to that of M_4 with A. It is seen from Figs. 1(a) and 1(b) that the $\text{SU}_{sdg}(3)$ limit results are similar to those of Nilsson *et al.* [6].

For actinide nuclei the β_4 data are taken from Bemis *et al.* [2] and Zumbro *et al.* [3,4] and the β_2 data are taken from Ref. [2]. The effective charges ($e_\pi^{(4)}, e_\nu^{(4)}$), in $e\,\text{b}^2$ units, are determined to be (−0.078,0.066) and (−0.0133,0.026) in the $\text{SU}_{sdg}(3)$ and $\text{SU}_{sdg}(5)$ limits, respectively. Once again the results given in Fig. 2(a) show that $\text{SU}_{sdg}(3)$ limit provides a good description of data. In Fig. 2(b) the Hartree-Fock + BCS results of Libert and Quentin [9] and the Nilsson-Strutinsky calculations of Brack *et al.* [8] are shown and the $\text{SU}_{sdg}(3)$ results are somewhat better than the microscopic calculations.

By comparing the $\text{SU}_{sdg}(3)$ and $\text{SU}_{sdg}(5)$ results with experimental and other theoretical calculations shown in Figs. 1 and 2 the following conclusions can be drawn: (1) With two free parameters the data for rare earths and actinides are described very well. (2) $\text{SU}_{sdg}(3)$ limit provides a good description of data and it is much better than $\text{SU}_{sdg}(5)$ limit. This is in conformity with the fact that the $\text{SU}_{sdg}(3)$ limit gives a good description of various properties of rotational nuclei [21,24]. (3) In actinides $\text{SU}_{sdg}(3)$ limit shows change in sign of β_4 for Cm isotopes which is consistent with data; other theoretical calculations do not produce the change in sign. (4) The free parameters $e_\pi^{(4)}$ and $e_\nu^{(4)}$ should be determined by microscopic theories involving multi-j-shell mappings (see, for example, Ref. [25]) and this is being pursued. The results of this exercise will be reported in a longer publication. (5) In the calculations experimental β_2 values are employed which amounts to comparing the calculated and experimentally determined M_4's rather than the deduced [via Eq. (8)] β_4 values. It is useful to note that the experimental M_4's are 4–8 times the single particle unit for rare earths and 6–10 times for actinides (except in a few cases).

The results given in this paper confirm that *sdg*IBM provides a good framework for describing $E4$ properties of nuclei. The present formalism is being extended to study the recently deduced $B(IS4{:}4^+_\gamma \to 0^+_{\text{g.s.}})$ systematics in rare-earth nuclei [26] and the results will be reported in a longer publication.

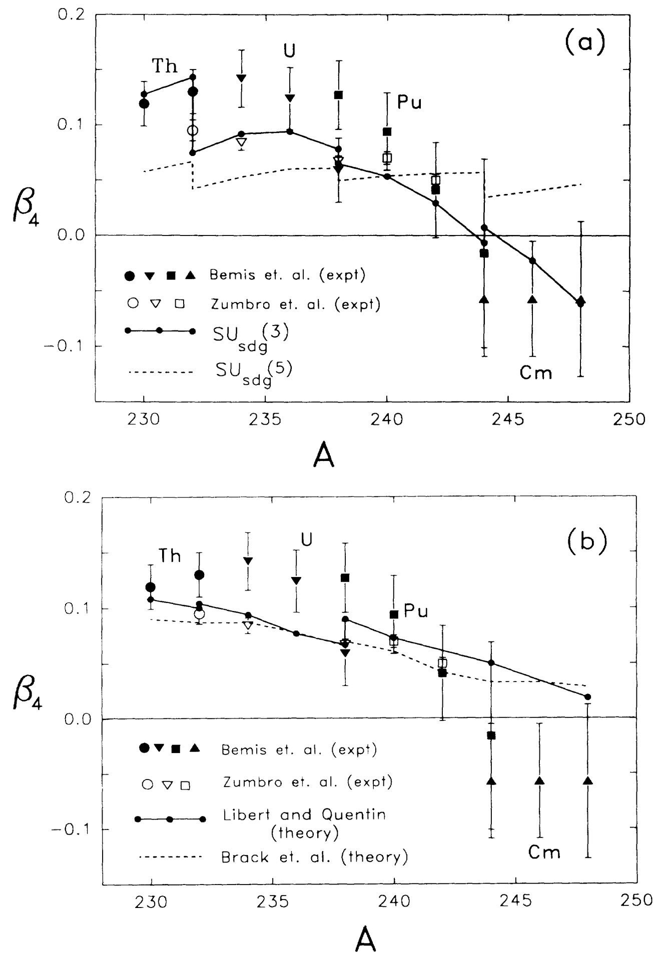

FIG. 2. Hexadecupole deformation β_4 vs mass number for actinides. (a) The $\text{SU}_{sdg}(3)$ and $\text{SU}_{sdg}(5)$ predictions are compared with data. (b) The theoretical results due to Brack *et al.* [8] and Libert and Quentin [9] are compared with data. The experimental data are due to Bemis *et al.* [2] and Zumbro *et al.* [3,4].

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