STUDY OF NUCLEAR STRUCTURE OF ^{146}SM USING INTERACTING BOSON MODEL-1

Satendra Sharma
Department of Physics
Yobe State University
Damaturu, Nigeria
ss110096@gmail.com

***Abstract*— The interacting boson model hamiltonian is used to describe the energy spectrum, B(E2) value and B(E2) branching ratios for inter-band and intra-band transitions for three quasi-bands in ^{146}Sm. It is found that IBM-1 reproduces the observed complex nuclear structure very well. The agreement between the theoretical results and the observed data are satisfactory for all possible observed nuclear properties. Present results are compared with the dynamic pairing-plus-quadrupole model, IBM-2 and previous interacting boson approximation calculations.**

***Index Terms*— Nuclear structure of ^{146}Sm, interacting boson model-1, energy spectrum, B (E2) values, B(E2) ratios and Q_2+.**

I. INTRODUCTION

The ^{146}Sm has interesting features because it provides interaction of two neutrons added to the N = 82 magic n^0 shell and two protons missing from the Z = 64 p^+ subshell for N ≤90. This nucleus has been studied extensively and large number of its levels up to 6^+ have been observed in the radioactive decay[1-4] of ^{146}Eu and ^{146}Pm. The experimental data is also available from the reaction works [1, 4-9] and coulomb excitation [2]. Kracikova et al. [10] carried out radioactive decay of ^{146}Eu and measured angular distribution of 68 γ–rays. They [10] deduced the spin parity assignment in ^{146}Sm. Peker [11] also compiled the experimental data for A = 146.

Several theoretical calculations were carried out to explain the structure of ^{146}Sm. Such calculations [7, 10, 12-18] contain various amount of shell model and collective ingredient of complex properties. The compilations [10, 11] of experimental data enable us to present more elaborate analysis.

Scholten et al. [12] used the H_{IBM-1} (with 4 parameters) with 4 (E_{2g}, E_{4g}, $E_{0\beta}$, $E_{2\beta}$) states as input for PHINT program [19] and predicted only these 4 states (see Fig. 3 of [12]). However, Gupta and Sharma [20] pointed out that only the inclusion up to high spin states in the H_{IBM-1} make a significant contribution to the proper transition from SU(5) to SU(3) limit. Gupta [13] applied the DPPQ model [21] for ^{146}Sm and achieved a partial success, but the model was unable to reproduced the small B(E2;2g→0g) value and B(E2;3γ→2γ/4g), B(E2;3γ→2g/2γ) and B(E2;3γ→2g/4g) branching ratios. Kracikova et al. [10] used H_{IBM-1} with ratio R = E2DD/E2SD = 4.087±3.773. However, the physical limit is –2.958≤ R ≤0 for SU(3) and O(6) limit respectively[22]. Thus, the work of Kracikova et al. [10] seems to be *unpredictable*. In the present work this ratio R is –1.17.

II. THE INTERACTING BOSON MODEL AND CALCULATION

The two body effective Hamiltonian for a system of s- and d- bosons can be written as:

$$H = E_0 + \varepsilon_s'(s^\dagger.\tilde{s}) + \varepsilon_s'(d^\dagger\tilde{d}) + \sum_{L=0,2,4} (1/2)\sqrt{(2L+1)}\, c_L[(d^\dagger x\, d^\dagger)^{(L)}(\tilde{d}\, x\tilde{d})^{(L)}]_0^{(0)} + \frac{1}{\sqrt{2}}\tilde{v}_2[(d^\dagger x d^\dagger)^{(2)} x\,(\tilde{d}\, x\tilde{s})^{(2)} + (d^\dagger x s^\dagger)^{(2)} x\,(\tilde{d}x\tilde{d})^{(2)}]_0^{(0)}$$

$$+ \frac{1}{2}\tilde{v}_0[(d^\dagger x\, d^\dagger)^{(0)}(\tilde{s}\, x\tilde{s})^{(0)} + (s^\dagger x\, s^\dagger)^{(0)}(\tilde{d}\, x\tilde{d})^{(0)}]_0^{(0)} + u_2[(d^\dagger x\, s^\dagger)^{(2)} x(\tilde{d}\, x\tilde{s})^{(2)}]_0^{(0)} + \frac{1}{2}u_0[(s^\dagger x\, s^\dagger)^{(0)} x(\tilde{s}\, x\tilde{s})^{(0)}]_0^{(0)}$$

(1)

In Eq. 1, E_0 is the core energy; ε'_s and ε'_d are the binding energies of s and d bosons; c_L, $\tilde{v}_L$ and u_L describe the two-boson interaction. Another form of H_{IBM} is:

$$H' = \varepsilon'' n_d + a_0(P^\dagger.P) + a_1(L.L) + a_2(Q.Q) + a_3(T_3.T_3) + a_4(T_4.T_4) \quad (2)$$

Where, $n_d = (d^\dagger.\tilde{d})$, $P = \frac{1}{2}\{(\tilde{d}\tilde{d}) - (\tilde{s}\tilde{s})\}$, $L = \sqrt{10}\,(d^\dagger x\,\tilde{d})^{(1)}$,

$$Q = [(d^\dagger x\,\tilde{s}) + (s^\dagger x\,\tilde{d})]^{(2)} - \frac{1}{2}\sqrt{7}[d^\dagger x\tilde{d}]^{(2)}$$

$T_3 = [(d^\dagger.\tilde{d})]^{(3)}$ and $T_4 = [(d^\dagger x\,\tilde{d})]^{(4)}$

A least square fitting technique is applied to obtain the optimized values of the four parameters i.e ε", a_0, a_1 and a_2, while a_3 and a_4 are kept zero in Eq. 2. The PHINT program [19] is used to fit the observed energy spectra. All levels with reliable spin [23] assignment ($I^{\pi} \leq 10^{+}$) are included up to the point that the first level with an uncertain spin assignment appears. In fitting of the energy spectra, we first determine the four parameters of H' as discussed above, that reproduce the best energy spectrum of g-, β- and γ-bands.

Table I: The Ibm-1 Parameters (In Kev)

N_B = Np+Nn	7
EPS	146.0
PAIR	-51.5
ELL	-18.4
QQ	-3.5
E2DD	-200.0
E2SD	170.0
E2DD/E2SD	-1.17

The optimized values of these four boson- boson interaction parameters are listed in Table I. These four parameters along with E2SD (= α_2) and E2DD (= $\sqrt{5}\beta_2$) are the input for the FBEM program [24]. The E2 transition operator depends upon these two parameters α_2 and β2 as given below:

$$T(E2) = \alpha_2 [d^{\dagger} \tilde{s} + s^{\dagger} \tilde{d}]^{(2)} + \beta_2 [d^{\dagger} \tilde{d}]^{(2)} \qquad (3)$$

Where, α_2 is called the boson effective charge and β_2 accounts for nuclear shape transition. The α_2 is simply the scaling parameter and affecting the B(E2) values. The ratio R (=E2DD/ E2SD) is equal to -2.958 in the SU(3) limit and reduced to zero in the O(6) limit. The FBEM gives the B (E2) values and branching ratios.

III. RESULT AND DISCUSSIONS

A. Energy Spectrum

For ^{146}Sm, the energy ratio R_4 (=E4g/E2g) is 1.85 which is close to the SU(5) limiting value 2. The triplet of 4^{+}_1-0^{+}_2-2^{+}_2 also lies at ~1.5 MeV (i.e., twice of E_{2g} = 0.746 MeV) and this triplet is slightly splited (see Table II). Thus, ^{146}Sm lies close to SU(5) limit. The energy spectrum of ^{146}Sm (N=84) for g- and γ– bands is similar to the N = 84 (^{138}Xe, ^{140}Ba, ^{142}Ce, ^{144}Nd and ^{148}Gd) isotones (see Fig. 1 [25]). The 2g, 4g and 2γ states increase very slowly on increasing Z from 54 to 64.

However, 0_β state increases as Z increases from 56 to 60 and decreases drastically for Z = 62. But 2_β state decreases linearly with Z changing from 58 to 62. The variation of energy (E) in MeV versus spin (I) for g-, β- and γ-band is shown in Fig 1-3. It is observed that present IBM-1 calculation gives the values close to experimental values[11,12] upto higer spins. Previous IBM1 [10] and DPPQ[13] values are having much deviations.

It evident from Table II, that the present approach gives a surprisingly good result in view of the expected marginal applicability of the model. The following points have been observed:

i) The triplet of 4^{+}_1, 2^{+}_2 and 0^{+}_2 states is at ~1.5 Mev.
ii) The quintuplet states 6^{+}_1, 2^{+}_3, 4^{+}_2, 3^{+}_1 and 0^{+}_2 are splited as in experiment.

B. The B(E2) Values For G-Band

In case of ^{146}Sm (N=84 isotones) the experimental data is available only for B(E2; Ig+2→Ig), Ig =0g, 2g and 4g . So we have compared the B(E2) values of present IBM-1 calculation with N = 84 (^{138}Xe, ^{142}Ce, ^{144}Nd) isotones for most possible transitions (see Table III). The calculated value of Q_{2g} is -0.186 which close to the experimental value [27] of ^{144}Nd [= -0.15(6)] and ^{142}Ce [= -0.16(5)]. The theoretical B(E2) value for (2g→0g) transition lies within the observed range and for (4g→2g) transition the value is close to the recoil distance value [26]. However, in the decay of ^{146}Eu, B(E2;4g→2g) is very small [10]. The theoretical B(E2) values for (2γ→2g), (2_β→2g), (0g→2γ), (0g→2_β), (2_β→4g), (2γ→4g) and (2_β→2γ) transitions lie within the experimental range of N = 84 isotones (see Table III).

Table II: The Values of Energy (In Mev) For ^{146}sm.

State	Expt. [23]	Present IBM-1	IBM-1 [10]	DPPQ [13]
2g	0.74724	0.7804	0.733	0.756
4g	1.38126	1.4648	1.353	1.375
6g	1.8117	2.0500	1.869	-
8g	2.7376	2.5331	2.287	-
10g	(3.7232)	2.9064	2.615	-
0_β	1.452	1.4481	1.459	1.430
2_β	(2.15572)	2.0966	2.173	2.310
4_β		2.2573	2.790	-
6_β		2.8146	-	-
2γ	1.64833	1.5969	1.610	1.725
3γ	(2.269)	2.3333	2.417	-
4γ	2.439	2.6387	2.256	-
5γ	2.898 [10]	2.9296	-	-
6γ		3.0599	2.800	
7γ		3.4158		
8γ		3.6043		
9γ	3.5675 [10]	3.8007		

C. The B(E2) Branching Ratios For G-Band

In the SU(5) limit the B(E2;4g→ 2g)/B(E2;2g→ 0g) ratio is 1.71 and our theoretical value lies within the observed range, however, DPPQ [13] and IBM-1 [12] values lie outside the observed range (see Table IV). The decay of ^{146}Eu [10] had the overlapping of 0.633 and 0.634 Mev γ -rays representing (3^{-}, 1.3802→2g) and (4g→2g) transitions, respectively, which may affect the B(E2) ratio for (6g→4g)/(4g→2g) transition. The observed value [10] of this ratio is 0.98(4) compared to the theoretical value 1.26. Peker [11] listed the B(E2) values in Weisskopf Unit for (8g→6g) and (6g→4g) transitions, which gives the B(E2) ratio ~0.16(5) compared to the theoretical value 1.09 (see Table IV).

D. The B(E2) Branching Ratios For Γ –Band

The experimental data [1, 10, 11] have the doublet of 0.8995 and 0.9011 MeV γ–rays representing (2.281→4g) and (2_γ→2g) transitions, respectively. Thus the B(E2) ratios for

($2_\gamma \rightarrow 0g/2g$) and ($4^+;2.281 \rightarrow 2g/4g$) transitions were not reliable, our IBM-1 value is 0.005 and lying within the factor of four. The spin assignment of 2.281 MeV state was doubtful in the Table of Isotopes [1]. However, Peker [11] and Kracikova et al. [10] assigned this state as 4^+. For ($3_\gamma \rightarrow 2g/4g$), ($3_\gamma \rightarrow 2g/2\gamma$) and ($3_\gamma \rightarrow 2_\gamma/4g$) transitions, theoretical B(E2) ratios lie within the observed range (see Table IV). From recent compilation [11] the B(E2) ratios for ($5_\gamma \rightarrow 4g/6g$) and ($9_\gamma \rightarrow 8g/8_2$) transitions are also available for which the theoretical results lie within the factor of 7.

E. The B(E2) Branching Ratios For B –Band

In ^{146}Sm the β –band has only 0^+ and 2^+ states [1, 10, 11]. The experimental B(E2) ratio for ($2_\beta \rightarrow 0g/2g$) is ranging from 0.014 to 0.066(13) and our theoretical value approaching to the lower limit (see Table IV).

IV. CONCLUSION

In this paper we have studied the lower and higher states of g, β- and γ- bands, absolute B(E2) values and B(E2) branching ratios of ^{146}Sm, which is close to SU(5) of limit of IBM-1. The calculated energy spectrum, Q^+_{2g}, B(E2) values and B(E2) ratios present a coherent and varied picture of the change in nuclear shape and dynamics. It is found that the inclusion of energy states up to higher spins in the PHINT program provides the proper values of boson- boson interaction parameters. It is also observed that present IBM-1 theoretical B(E2) values for ($2\gamma \rightarrow 2g$), ($2_\beta \rightarrow 2g$), ($0g \rightarrow 2\gamma$), ($0g \rightarrow 2_\beta$), ($2_\beta \rightarrow 4g$), ($2\gamma \rightarrow 4g$) and ($2_\beta \rightarrow 2\gamma$) transitions lie within the experimental range of N = 84 isotones.

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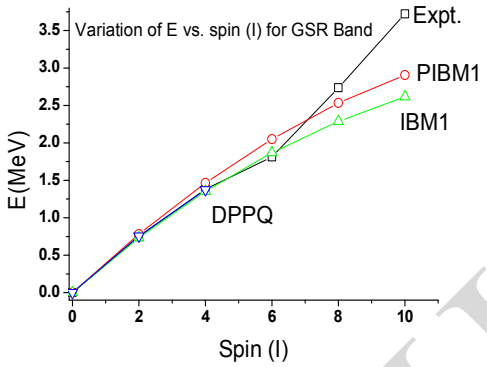

Fig. 1: The variation of energy (E) in MeV versus spin (I) for ground state rotational band. The experimental data[11,23] is shown by black rectangle (□), present IBM (PIBM1) calculation by red hollow circles (O), earlier IBM1 calculation[10] (IBM1) by green upright hollow triangle (Δ) and DPPQ[13] by inverted blue hollow triangle (∇).

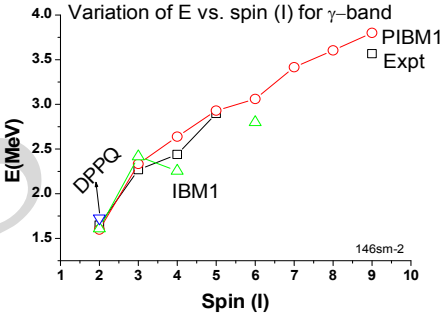

Fig. 2: Same As Fig.1 For The Γ- Vibrational Band.

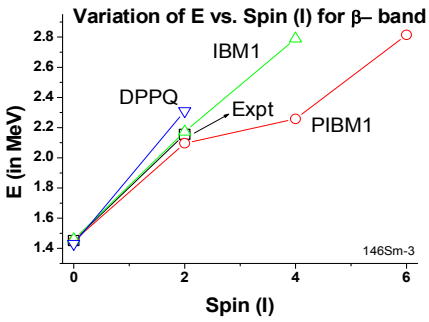

Fig. 3: Same As Fig.1 For The B- Vibrational Band.

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Table III: Comparison of Experimental and Calculated Electromagnetic Properties of N = 84 Isotones.

Quantity		^{146}Sm	^{144}Nd	^{142}Ce	^{138}Xe
Q(2g+)	Expt.		-0.15(6)[c] -0.39(21)[j,k]	-0.16(5)[c] -0.12(9)[g]	
	Th.	-0.186[a] -0.61[b] -0.63[u]	-0.38[f] -0.40[d] -0.11[h], -0.07(15)[i]	-0.11[h]	
B(E2; 2g→0g)	Expt.	$0.048^{+\infty}_{-0.01}$ [l] >0.034[m]	0.110(6)[m], 0.116(2)[n] 0.0982(8)[c], 0.0998(34)[o] 0.084(4)[v]	0.0958(8)[c] 0.090(2)[m] 0.084(2)[v]	0.0047(6)[m]
	Th.	0.131[a] 0.025(17)[l] 0.148[u], 0.032[w]	0.142[f] 0.104[h] 0.028[w]	0.104[h] 0.026[w]	
B(E2; 4g→2g)	Expt.	≥0.061[t] 0.045(31)[i]	0.100(9)[c] 0.086(16)[p], 0.08(1)[j,k]	0.117(10)[c]	
	Th.	0.228[a] 0.33[b] 0.262[u]	0.17[h] 0.122[d] 0.27[f]	0.17[h]	
B(E2; 2γ→2g)	Expt.		0.095(30)[p] 0.095(21)[j,k]	0.162(37)[c]	
	Th.	0.225[a] 0.143[b]	0.140[f] 0.17[h], 0.073[d]	0.17[h]	
B(E2; 2β→2g)	Expt.		0.023(15)[q,r] 0.02(1)[j,k]	0.033(11)[c]	
	Th.	0.0007[a] 0.059[b]	0.016[h], 0.018[d] 0.000051[s] 0.0038[t]	0.016[h] 0.000046[s] 0.0044[t]	
B(E2; 0g→2γ)	Expt.		0.0030(6)[p] 0.005(5)[j,k]	<0.008[c]	
	Th.	0.005[a] 0.035[b] 0.012[u]	0.0[h] 0.01[f] 0.005[d]	0.0[h]	
B(E2; 0g→2β)	Expt.		0.065(16)[q,r], 0.065(15)[j,k]	0.070(11)[c]	
	Th.	0.0005[a] 0.0045[b] 0.004[u]	0.058[h], 0.0004[f] 0.15[s], 0.19[t] 0.035[d]	0.058[h] 0.14[s] 0.16[t]	
B(E2; 2γ→4g)	Expt.				
	Th.	0.002[a] 0.008[b]	0.001[b]		
B(E2; 2β→4g)	Expt.				
	Th.	0.043[a] 0.023[b]	0.026[d]		
B(E2; 2β→2γ)	Expt.				
	Th.	0.081[a]	0.001[d]		

[a] Present IBM-1 calculation.
[b] DPPQ model calculation [13].
[c] Coulomb excitation experiment using ^{4}He, ^{12}C & ^{16}O projectiles [27].
[d] Cluster vibration model calculation [28].
[e] Coulomb excitation with ^{16}O projectiles [25].
[f] IBM-1 calculation [29].
[g] Coulomb excitation with ^{16}O projectiles [30].
[h] IBM-2 U(5) calculation [31].
[i] Coulomb excitation ^{16}O projectiles (τ -ray yield measurements +particle data) [30].
[j] Using (t, p) reaction [32].
[k] Using in-beam particle – τ – (τ-/e- conversion) time multi-parameter coincidence experiment [33].
[l] From the ^{144}Eu decay [10].
[m] Adopted values [34].
[n] Coulomb excitation with ^{4}He projectiles [35].
[o] Weighted mean of 4 values [25, 36, 37 38].
[p] From coulomb excitation [38].
[q] [39].
[r] [40].
[s] Using an extension of the Vibrational model with large bases of single particle (sp) states [41].
[t] Using an extension of the VM with small bases of sp state [41].
[u] [12].
[v] [36].
[w] [16]

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Table IV. The B (E2; Ii→If/If') Ratios in ^{146}sm.

Transition (Ii → If/ If')	Experimental B(E2) Ratios			Present	Others Calculations	
	[10]	[11]	[1, 13]	IBM1	DPPQ [13]	IBM-1 [12]
4g→2g/2g→0g	≥1.27(26)	≥1.30		1.74	1.94	1.82
6g→4g/4g→2g	0.98(4)	<0.74		1.26		
8g→6g/6g→4g		~0.16(5)		1.09		
2γ→0g/2g*	0.0012(4)	>0.01	0.015	0.005	0.018	0.01
2γ→2g/4g				30.5	1.73	5.0
3γ→2g/4g	0.038(6)	0.054	0.038	0.025	0.22	0.06
3γ→2g/2γ	0.019(5)	0.049	0.018	0.01	0.10	
3γ→2γ/4g	2.00(99)	1.10	2.11	2.5	0.78	
4γ→2g/4g	0.007	0.007		0.15	0.1	
5γ→4g/6g		0.21		0.03		
9γ→8g/8_2		0.023		0.15		
2_β→0g/2g	0.066(13)	0.02	0.014	0.014	0.051	0.12
4_2→2g/4g	0.26(5)*	>0.33*	0.25*	0.011	0.02	

*Multiple assignments

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