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IBA-1 studies of strongly deformed nuclei near $A = 150$

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Abstract. A simple procedure to optimise the interaction parameters in IBA-1 is used to calculate the energy levels of strongly deformed nuclei $^{154-158}$Sm, $^{154-160}$Gd, $^{156-164}$Dy, $^{160-168}$Er, $^{162-172}$Yb and $^{168-176}$Hf. It is found that the variation in the interaction parameters for each isotope string can be kept to a minimum if one follows the guidance of the group symmetry limit. The energy levels calculated by this simple working procedure agree with the experimental data quite well. The B(E2) values are also calculated, and compared with the experimental data and previous work. Satisfactory agreement is obtained.

1. Introduction

Interacting boson approximation models have been applied to the study of low-lying collective states of heavy nuclei. These models are especially successful in describing the nuclear properties of those nuclei corresponding to the specific group symmetry limits. For those nuclei away from the symmetry limits, the interaction parameters contained in the Hamiltonian are usually extrapolated smoothly to fit the variation of nuclear properties. Such extrapolations are usually good in the vicinity of the symmetry limits. However, when one goes to regions not in the vicinity of symmetry limits, the search for the best-fit interaction parameters is usually a painstaking procedure, especially when the number of parameters is large such as in the case of IBA-2 model calculations.

It is known that in studying the nuclei corresponding to a specific symmetry, one may seek for a set of mass-number independent interaction parameters. This serves as an equivalence of finding an average set of best-fitted parameters corresponding to the individual nucleus. However, if one considers a set of nuclei which covers two or three symmetry limits, a large discrepancy may occur. In particular, when several sets of parameters produce equally good results, the determination of the most suitable set of interaction parameters becomes very difficult. In this paper, we present a simple procedure to optimise the interaction parameters of a set of nuclei in the strongly deformed region. The essence of our procedure is that we first determine the values of some parameters by experimental information, and then vary the values of other parameters by the guidance of the group limits. A good set

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of parameters can thus be determined in a systematic way that can be applied elsewhere. A similar procedure has been employed in the calculation of Os and Pt nuclei (Chiang *et al* 1988), satisfactory results were obtained. Since in IBA-1, the symmetry of the Hamiltonian is evident and the three symmetries can be easily recognised, it is easier to study our problem within the framework of IBA-1. It is known that, when the nuclei are far from the closed shell regions, IBA-1 works almost equally well as IBA-2 (Harter *et al* 1985). In particular, when the total number of the proton bosons and the neutron bosons of the nucleus, $N_\pi + N_\nu$, is quite large compared with the values of $|N_\pi - N_\nu|$, the IBA-1 is a valid approximation. Therefore, when the nuclei belonging to such regions are studied, one may use IBA-1 to replace IBA-2 to reduce the number of interaction parameters and the size of the model space. In IBA-1 the Hamiltonian for the three symmetry limits, SU(5), SU(3) and O(6), may be solved analytically with simple closed-form expressions for energy levels and transition rates.

To illustrate the procedure of optimisation for the interaction parameters, we systematically study the nuclear properties of nuclei in the transitional symmetry limits, $^{154-158}$Sm, $^{154-160}$Gd, $^{156-164}$Dy, $^{160-168}$Er, $^{162-172}$Yb and $^{168-176}$Hf, as the computation samples. These nuclei are all in the strongly deformed region because their first excitation energies are all less than 0.1 MeV. The refined calculation in this region was carried out and it was found that both IBA-1 and IBA-2 could produce reasonable agreement with the observed data. The group symmetry properties of these nuclei have also been extensively studied. In most cases, they are either quite close to SU(3) or the extent of deviation from SU(3) is due to a degree of freedom and structure outside the IBA-1. For example, the Sm isotopes have provided a good example that reveals the transition from the vibrational, SU(5), limit to the rotational, SU(3), limit (Scholten *et al* 1978), and thus have been studied extensively by many different approaches (Tamura and Weeds 1979, Gupta 1983, Castanos *et al* 1982 and Yen *et al* 1984). The Gd isotopes under study are close to SU(3) limit (Arima and Iachello 1978). Van Isacker *et al* (1982) presented extended s′, d′, and g bosons to study the even–even Gd isotopes. It was found (Van Isacker *et al* 1982) that the isotopes $^{156-158}$Gd are closer to the SU(3) limit than the ^{154}Gd nucleus and the neutron-rich Gd isotopes become O(6)-like with increasing neutron number. The Dy and Er isotopes belong to the SU(5) to SU(3) transition region (Scholten *et al* 1978, Casten 1980, Casten *et al* 1987, Casten and Warner 1982, Van Isacker *et al* 1982) and have been studied by many other authors (Chuu *et al* 1988, Guidry *et al* 1979, Hubert *et al* 1978, Sayer 1978, Madueme 1981, Ronningen *et al* 1977, Kistner *et al* 1978, Ichihara *et al* 1984, Faessler and Ploszajzak 1977). The broken SU(3) calculation of the nucleus ^{168}Er was well discussed (Warner *et al* 1980, 1981). Most of the Yb and Hf nuclei under study have broken SU(3). However, it is well known the rare earth nuclei near $N = 106$, especially the heavy Yb and Hf are good examples of SU(3) due to their high-lying β and γ bands and low $\beta \rightarrow \gamma$ and $g \rightarrow \gamma$ B(E2) values. The purpose of the present paper is to test the effects of fine-tuning of the symmetry limits across these nuclei by IBA-1. In the practical calculation, a core with $Z = 50$ and $N = 82$ is taken for isotopes of Sm, Gd and Dy. Thus the boson numbers for the isotope strings Sm, Gd and Dy range, respectively, from 11 to 13, 12 to 15 and 12 to 16. For isotopes Er, Dy and Hf, a core with $Z = 82$ and $N = 82$ is considered; therefore, the boson hole and particle numbers for isotope strings Er, Dy and Hf range, respectively, from 12 to 16, 11 to 16 and 13 to 16.

2. The model

The most important part of the IBA-1 Hamiltonian can be written as

$$H = \varepsilon_d n_d + a_0 P^+ \cdot P + a_1 L \cdot L + a_2 Q \cdot Q$$

where

$$Q = (d^+ \times \tilde{s} + s^+ \times \tilde{d})^{(2)} - \sqrt{7/2}(d^+ \times \tilde{d})^{(2)}.$$

The octopole term $T_3 \cdot T_3$ and the hexadecapole term $T_4 \cdot T_4$ have been omitted since they are generally believed to be less important.

In searching for the interaction parameters, it is helpful to take advantage from the experimental information and by the guidance of the group symmetry limits. The relations between the four-term interaction and the pure symmetries are as follows: in the SU(5) symmetry only ε_d and $L \cdot L$ terms appear; in the SU(3) limit only the $L \cdot L$ and $Q \cdot Q$ terms appear and in the O(6) symmetry only $P^+ \cdot P$ and $L \cdot L$ terms appear. Note for all three symmetry limits the $L \cdot L$ terms appears. Therefore, it would be helpful if we can fix this part of the Hamiltonian. This term has the effect of changing the relative level spacings corresponding to different angular momentum states. Guided by the average of the general level spacings of the six isotope strings, we select the value a_1 as 0.3 keV, 2.8 keV, 3.6 keV, 6.0 keV, 5.0 keV and 5.0 keV for the Sm, Gd, Dy, Er, Yb and Hf isotope string respectively. Since the energy spectra of most of the isotopes considered in this work are quite close to the SU(3) limit, the parameter a_2 which is the effective parameter of SU(3) should be varied. The general trend for varying a_2 is to decrease its average absolute value as we go away from the SU(3) limit. With these guides in mind, the optimisation of the parameters becomes much more efficient and the parameters are determined by a least-squares fit calculation on the energy spectra of the isotopes we considered. In the practical calculation we first determined the interaction parameters of the lightest-mass nucleus in each isotope string by a least-squares fit calculation. Once the strength parameters of the lightest mass were determined, they were used as initial values to reproduce the energy spectra of the other nuclei belonging to the same isotope string by varying only the parameter a_2 while the other parameters were kept as constant as possible. During the parameter searching procedure, the pre-determined interaction strengths of the lightest-mass nucleus might also be tuned slightly until suitable parameters for all nuclei in an isotope string were finally searched. From this viewpoint of parameter fittings, we simply keep all possible terms, and it will be justified *a posteriori* after the suitable parameters are obtained. The results obtained can be just as good as those obtained by varying all four terms randomly.

3. Results

The searched interaction strengths for the six isotope strings are listed in table 1. It can be seen from table 1 that the general trend for varying the interaction parameters for the isotopes $^{154-158}$Sm, $^{156-160}$Gd, $^{158-164}$Dy and $^{162-168}$Er can be obtained successfully by the above mentioned working procedure of optimisation for the interaction strengths. However, one can also note in table 1 that the values of ε_d

Table 1. The interaction parameters (in MeV) of the Hamiltonian for the Sm, Gd, Dy, Er, Yb and Hf isotopes.

	Parameter (MeV)			
Nuclei	ε_d	a_0	a_1	a_2
^{154}Sm	0.3800	−0.0020	0.0003	−0.0206
^{156}Sm	0.3800	−0.0020	0.0003	−0.0192
^{158}Sm	0.3800	−0.0020	0.0003	−0.0192
^{156}Gd	0.3800	0.0230	0.0028	−0.0140
^{158}Gd	0.3800	0.0230	0.0028	−0.0140
^{160}Gd	0.3800	0.0230	0.0028	−0.0108
^{158}Dy	0.4700	0.0400	0.0036	−0.0100
^{160}Dy	0.4700	0.0400	0.0036	−0.0096
^{162}Dy	0.4700	0.0400	0.0036	−0.0087
^{164}Dy	0.4700	0.0400	0.0036	−0.0062
^{162}Er	0.3700	0.0630	0.0060	−0.0095
^{164}Er	0.3700	0.0630	0.0060	−0.0085
^{166}Er	0.3700	0.0630	0.0060	−0.0065
^{168}Er	0.3700	0.0630	0.0060	−0.0068
^{164}Yb	0.4500	0.0390	0.0050	−0.0108
^{166}Yb	0.4200	0.0390	0.0050	−0.0108
^{168}Yb	0.3700	0.0335	0.0050	−0.0102
^{170}Yb	0.3700	0.0210	0.0050	−0.0108
^{172}Yb	0.3700	−0.0050	0.0050	−0.0136
^{170}Hf	0.3800	0.0080	0.0050	−0.0085
^{172}Hf	0.4000	0.0080	0.0050	−0.0118
^{174}Hf	0.4000	−0.0020	0.0050	−0.0125
^{176}Hf	0.4000	−0.0020	0.0050	−0.0137

are slightly varied for the low-mass Yb and Hf isotopes. Furthermore, the parameter a_0 changes drastically for the heavier mass Yb and Hf isotopes. This drop of parameter a_0 reflects a real change in structure of these nuclei. The energy levels of the heavy Yb and Hf nuclei approach those of the SU(3) symmetry. The calculated and observed energy spectra are shown in figures 1–6. To save space, we present only the results for nuclei ^{154}Sm, ^{156}Gd, ^{158}Dy, ^{164}Er, $^{164-172}$Yb and $^{170-176}$Hf. For these nuclei, the experimental data are abundant. For clear comparison, the different quasi-bands are displayed in different columns. The energy states marked with asterisks are not included in the fitting. The high-spin states of the isotopes we considered exhibited anomaly shrinking of level spacings around $I \simeq 12$. In addition, the observed B(E2) values for these nuclei exhibited a decrease beyond spin $I \simeq 12$. These two phenomena are usually interpreted as a band crossing, and are ascribed to the contribution of those components with a boson breaking into two quasi-fermions (Yoshida and Arima 1985, Alonso *et al* 1986, Chuu and Hsieh 1988). Since boson breaking is beyond our model space, therefore, in the present calculation energy levels with angular momentum higher than 14 are not included in the fittings. It can be seen from the figures that the energy levels are reproduced quite well especially the ground-state band and the quasi-γ band. The fittings of quasi-β bands are slightly worse. However, they are still in correct order and agree reasonably well with the observed data, except for a very few levels. It can be seen from figures 5 and 6 that the fittings become worse for the heavier-mass Yb and Hf isotopes. This is because there is a structural change for these nuclei as we mentioned above. For the other Sm, Gd, Dy and Er isotopes not shown in the figures the calculated energy

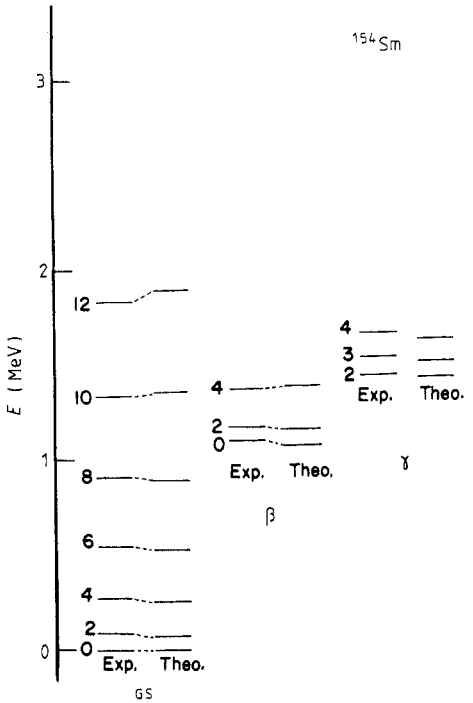

Figure 1. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for the ^{154}Sm nucleus.

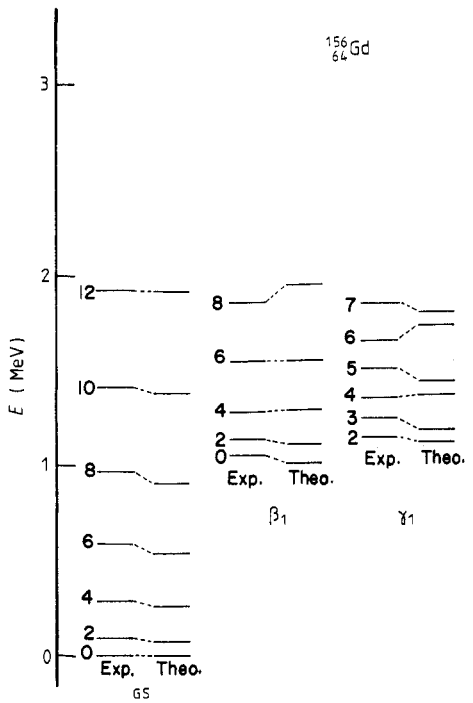

Figure 2. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for the ^{156}Gd nucleus.

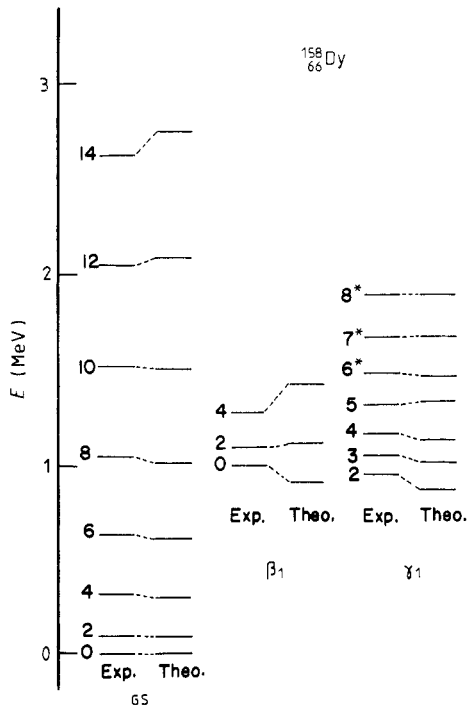

Figure 3. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for the ^{158}Dy nucleus.

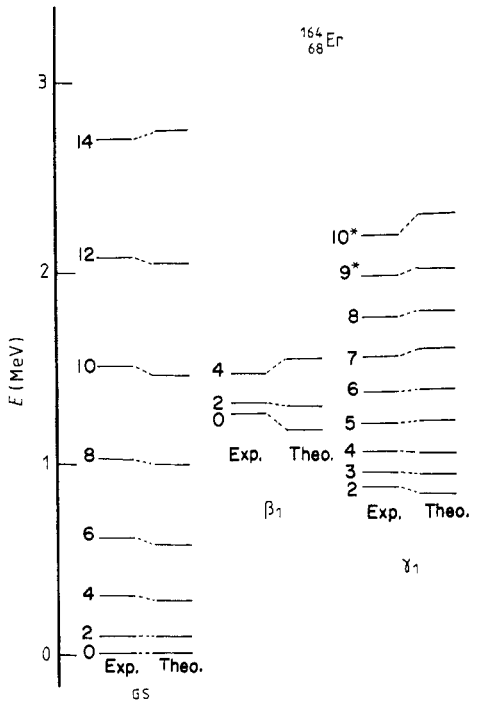

Figure 4. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for the ^{164}Er nucleus.

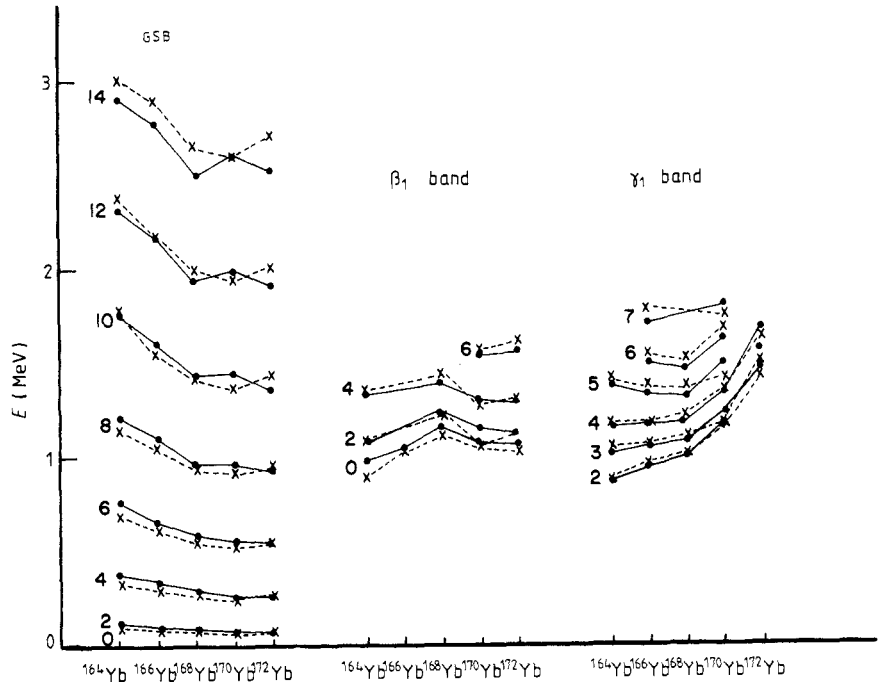

Figure 5. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for Yb isotopes. The calculated values are connected by broken lines and the observed data are connected by full lines.

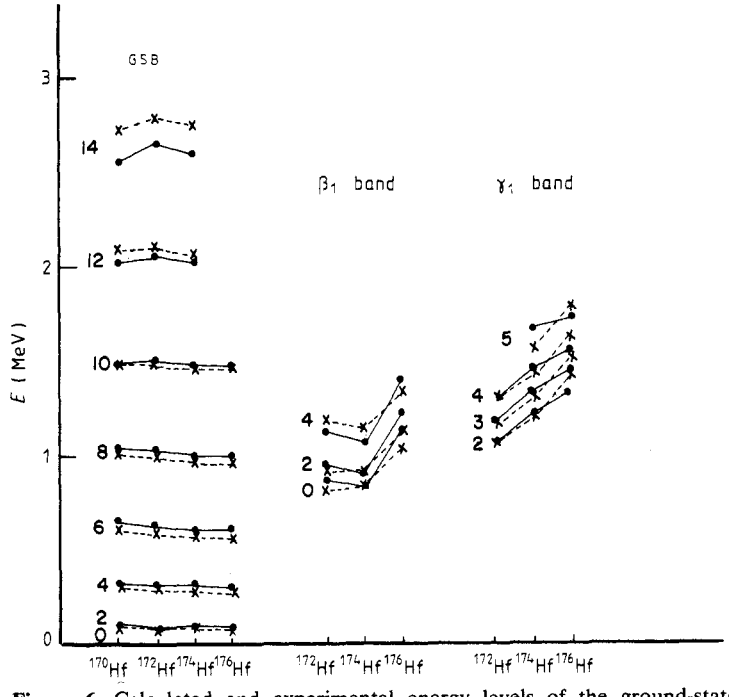

Figure 6. Calculated and experimental energy levels of the ground-state, quasi-β_1, quasi-γ_1 bands for Hf isotopes. The calculated values are connected by broken lines and the observed data are connected by full lines.

spectra agree very well with the experimental data. There are several experimental $B(E2)$ values for ^{154}Sm, ^{156}Gd, $^{162-164}Er$, ^{164}Yb and $^{170-172}Yb$ nuclei (Helmer 1985, 1987, Shurshikov 1986, Ignatochkin *et al* 1987, Lee 1980, Lee and Bunting 1985, Greenwood 1974, Zhou 1987 and Wang 1987). The study of these values provides us with a good test of the model wavefunctions. The electric quadrupole operator is

$$T(E2) = e^B[(d^+ \times \tilde{s} + s^+ \times \tilde{d})^{(2)} + \chi(d^+ \times \tilde{d})^{(2)}].$$

In the calculation the value of the boson effective charge e^B is determined by normalising the largest calculated $B(E2)$ value for each nucleus to the corresponding observed data. In order to allow theoretical counterparts of some experimental transitions in the SU(3) limit of IBA electromagnetic transition from the γ_1 (or β_1) band to the ground-state (g) band, the value of χ is sometimes treated as a free parameter (Warner and Casten 1982, Rikovska and Bonatsos 1988). However, in a recent review article, Casten and Warner (1988) have shown that, in particular for strongly deformed nuclei, a consistent-Q model makes more sense in that the quadrupole operator in the Hamiltonian and the one used to calculate E2 properties is taken to be the same. Therefore, in the present work, the value of χ is chosen as $-\sqrt{7/2}$ which is a generator of the SU(3) group and is consistent with the value of χ used in the Hamiltonian. It is found that $B(E2)$ values for the nuclei we considered can be reproduced satisfactorily. In the present calculation, the values of the boson effective charges e^B are chosen to be $0.116e$ to $0.145e$, which are close to the value $0.13e$ adopted in the previous calculation (Chuu and Hsieh 1988). Table 2 lists the calculated and observed $B(E2)$ values for the transitions of $g \rightarrow g$ and $\gamma \rightarrow g$ for comparison. In the table 2, the largest calculated $B(E2)$ value for each nucleus (e.g. $8 \rightarrow 6$ for nuclei ^{154}Sm, ^{156}Gd and ^{160}Dy; $10 \rightarrow 8$ for nuclei ^{162}Dy and ^{164}Dy etc) has been normalised to the corresponding observed data. Some previous theoretical $B(E2)$ values using a sixth-order boson expansion calculation, the rotational model and s′, d′ and g boson models are also listed in the final column of table 2 for comparison. One can note from table 2 that, in general, the important feature of the $B(E2)$ values can be reproduced quite well by the present work for the ground-state band transitions. For the interband transitions, the main feature of $B(E2)$ values can be reproduced satisfactorily. Because of the $B(E2)$ staggering, it is not possible to fit better. The noticeable reduction in $B(E2)$ occurring at band-crossing points is well known (Gelberg and Zemel 1980) and is interpreted as the result of the interplay of a collective phenomenon, i.e. the boson cutoff and the crossing of two bands (Gelberg and Zemel 1980). According to the FDSM, this reduction is ascribed to the band mixing induced by symmetry breaking terms (Guidry *et al* 1986). Our calculated $B(E2)$ values are in good agreement with the previous theoretical results on $B(E2)$ values although our model is considerably more simple than theirs.

4. Summary and discussion

In summary we have studied systematically the low-lying states and the $B(E2)$ values of the isotope strings of even–even Sm, Gd, Dy, Er, Yb and Hf with mass number changing between 154 to 176. These nuclei are in the strongly deformed region and thus belong to the SU(3) symmetry region. It is found that these deformed nuclei near $A = 150$ can be described globally by an IBA Hamiltonian that unavoidably breaks SU(3) symmetry. In most cases, this IBA Hamiltonian has the

Table 2. The calculated and experimental $B(E2)$ values (in e^2b^2). The largest calculated $B(E2)$ value for each nucleus has been normalised to the corresponding observed data.

Nucleus	e^B	I_i^+	I_f^+	Exp.	Theo.	
					Present work	Others
^{154}Sm	0.142	2_1	0_1	0.8532	1.0260	0.673[a]
		4_1	2_1	1.2013	1.4451	0.980[a]
		6_1	4_1	1.4219	1.5472	1.090[a]
		8_1	6_1	1.5494	1.5494	1.110[a]
		10_1	8_1	1.5347	1.4924	—
		12_1	10_1	1.3778	1.3911	—
		2_2	0_1	0.0046	0.0068	0.001[a]
		2_2	4_1	0.0216	0.0070	0.008[a]
		2_3	0_1	0.0137	0.0214	0.021[a]
		2_3	4_1	0.0049	0.0030	0.006[a]
^{156}Gd	0.134	2_1	0_1	0.9328	1.0312	0.914[b]
		4_1	2_1	1.2870	1.4600	1.286[b]
		6_1	4_1	1.4716	1.5811	1.380[b]
		8_1	6_1	1.5963	1.5963	1.380[b]
		10_1	8_1	1.5713	1.5714	1.340[b]
		12_1	10_1	1.5164	1.4971	1.260[b]
		5_1	4_1	0.0001	0.0030[b]	0.029[b]
		5_1	6_1	0.0001	0.0045[b]	0.025[b]
^{160}Dy	0.123	2_1	0_1	1.0061	1.1438	—
		4_1	2_1	1.4808	1.6361	—
		8_1	6_1	1.8575	1.8575	—
		10_1	8_1	1.7182	1.8621	—
		12_1	10_1	1.6046	1.8236	—
		14_1	12_1	1.6408	1.7480	—
		2_2	0_1	0.0144	0.0304	—
		2_2	2_1	0.0279	0.0780	—
^{162}Dy	0.119	2_1	0_1	1.0438	1.1140	1.077[c]
		4_1	2_1	1.5108	1.5961	1.538[c]
		6_1	4_1	1.5737	1.7553	1.694[c]
		8_1	6_1	1.8255	1.8221	1.773[c]
		10_1	8_1	1.8360	1.8360	1.821[c]
		12_1	10_1	1.7101	1.8112	1.835[c]
^{164}Dy	0.116	2_1	0_1	1.1145	1.1028	1.000[d]
		4_1	2_1	1.4451	1.5912	0.920[d]
		6_1	4_1	1.6530	1.7684	0.930[d]
		8_1	6_1	1.5997	1.8537	0.870[d]
		10_1	8_1	1.8876	1.8876	0.910[d]
		12_1	10_1	1.8983	1.8843	1.000[d]
		14_1	12_1	1.7383	1.8470	—
		2_1	0_1	0.0213	0.0322	—
		2_2	2_1	0.0427	0.0940	—
		2_2	4_1	0.0051	0.0032	—
^{162}Er	0.135	2_1	0_1	1.1646	1.1646	5.060[e]
^{164}Er	0.125	2_1	0_1	1.1624	1.1523	5.480[e]
		4_1	2_1	1.3757	1.6374	—
		8_1	6_1	1.8290	1.8290	—
		10_1	8_1	1.9090	1.8212	—
		12_1	10_1	1.4131	1.7738	—
		2_2	0_1	0.0277	0.0274	—
		2_2	2_1	0.0608	0.0560	—

Table 2. (*Continued*)

Nucleus	e^B	I_i^+	I_f^+	Exp.	Theo. Present work	Theo. Others
^{164}Yb	0.145	2_1	0_1	0.9332	1.0662	—
		4_1	2_1	1.3811	1.5331	—
		6_1	4_1	1.4824	1.6851	—
		8_1	6_1	1.7330	1.7330	—
		10_1	8_1	1.6157	1.7138	—
		12_1	10_1	1.5944	1.6445	—
		14_1	12_1	1.2800	1.5372	—
		16_1	14_1	1.1251	1.3814	—
		18_1	16_1	1.5997	1.1842	—
^{170}Yb	0.121	2_1	0_1	1.1300	1.1849	—
		8_1	6_1	2.0138	2.0138	—
		10_1	8_1	1.9914	2.0094	—
		12_1	10_1	1.4936	1.9654	—
^{172}Yb	0.116	2_1	0_1	1.1818	1.4042	—
		4_1	2_1	1.8976	1.9890	—
		6_1	4_1	1.8523	2.1621	—
		8_1	6_1	2.2159	2.2159	—
		10_1	8_1	2.1307	2.2108	—
		12_1	10_1	2.4432	2.1663	—
		2_2	2_1	0.0001	0.0023	—
		2_2	4_1	0.0001	0.0058	—
		4_2	2_1	0.0001	0.0009	—
		4_2	2_2	2.2387	1.5756	—
		4_2	6_1	0.0001	0.0056	—

(a) Tamura and Weeds 1979.
(b) Van Isacker *et al* 1982.
(c) Guidry *et al* 1979.
(d) Sayer 1978.
(e) Ronningen *et al* 1977.

property that the coefficients of the symmetry breaking terms remain constant or almost constant except the cases where the real structural changes are going on. The energy spectra for the deformed region isotopes can be reproduced quite reasonably by varying only one or two parameters guided by symmetries. We also calculated B(E2) values for different isotopes. Our calculation yields satisfactory agreement between the theoretical and experimental B(E2) values. Our calculated B(E2) values are also in good agreement with the previous theoretical results obtained by different approaches.

In conclusion, our calculation suggests a simple procedure for the fine-adjustment of interaction parameters to obtain the energy spectra and B(E2) values for nuclei in some particular symmetry region. The fine tuning of the interaction parameters can be achieved by taking the average value of some parameter suggested by the experimental information and varying the others by the guidance of group symmetry limits. Such a procedure, which makes use of the symmetry guidance and the observed information, will definitely reduce the work and the ambiguity involved in parameter searching.

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