Interacting boson approximation studies of the negative parity states of $^{172-180}$Os isotopes

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The negative parity states of $^{172-180}$Os are studied in the framework of the interacting boson approximation model. The negative parity states are formed by including one f boson or allowing one boson to break into two fermions which are placed in orbits with opposite parity. The calculated level energies and $B(E2)$'s are in reasonable agreements with experiments. From the comparison of intrinsic structure it suggests that the relative energy of the quasiparticles may be the most important factor in the calculations.

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I. INTRODUCTION

In recent years the study of nuclear structure has focused on the phenomena of shape evolution, shape coexistence, and moment of inertia anomaly, both experimentally and theoretically. The nuclei in the region of W-Os-Pt offer a great opportunity for such studies. Many experiments of light Os isotopes [1–6] have been carried out and this makes the data of Os isotopes rather complete. These rich and complete data of Os isotopes become the check source for existing theories and the testing field for new theoretical studies. Theoretical models such as the cranked-shell model, the rotating Bardeen-Cooper-Schrieffer model, and the rotor-plus-quasiparticle model have been used in the analysis of the complicated nuclear structure of the Os isotopes.

To study Os isotopes in the framework of the interacting boson approximation model has been the focus for one of us in the past few years [7–11]. The high-spin states in even $^{172-180}$Os isotopes and the anomalies of moments of inertia are well explained in the interacting-boson-plus-fermion-pair model [8]. The light Os isotopes are also rich in negative parity states, but these states have not been the focus of the previous studies. Nevertheless, in the process of shape change the negative parity states may also play an important role and they are worth of investigations. Most Os isotopes with $90 \leq N \leq 114$ have low-lying negative parity bands with small K [12]. We therefore propose to do a systematic study of the negative parity bands of $^{172-180}$Os isotopes. It is relatively easy to approach Os isotopes, which are located in the phase transition region, with the IBA model. Also, the present study can serve as the continuation of the previous IBA studies of Os isotopes.

II. THE MODEL

From the IBA point of view, to make negative parity states in even-even nuclei it is necessary to include f bosons in the standard s-d bosons IBA. We limit the number of f bosons to be 0 or 1 in order to keep the situation simple. Such a scheme has been successful in describing the octupole bands in the rare earth region [13]. On the other hand, based on the concept of quasiparticles, the negative parity states in even-even nuclei are formed by placing two quasiparticles in orbits with opposite parity. It is known that the quasiparticle nature is something that is not inherently built inside the IBA model. Gelberg and Zemel [14], Morrison, Fassler, and Lima [15], and Yoshida, Arima, and Otsuka [16,17] proposed a two-fermions-plus-IBA model, i.e., a model in which a boson is allowed to break into two fermions. Such an idea has been applied to many nuclei and a good overall reproduction of the spectra can be obtained. These studies show that such a model is especially useful in the high energy states and multiple band structure and suggest that quasiparticle nature is important. We thus employ the idea of quasiparticles in the study of the negative parity band. The result is that there are two kinds of basis states:

$$|n_s n_d \nu \alpha L, f; L_T M_T\rangle$$

and

$$|n_s n_d \nu \alpha L, j_1 j_2(J); L_T M_T\rangle \ .$$

For the latter basis state a boson is broken into two fermions. The Hamiltonian is expressed as

$$H = H_B + H_F + V_{BF} + V_N \ . \tag{1}$$

The first term is the standard boson Hamiltonian and can be expressed as

$$H_B = \varepsilon_d \hat{n}_d + a_1 P^+ \cdot P + a_2 L \cdot L + a_3 Q \cdot Q \ , \tag{2}$$

where $Q = (d^+ s + s^+ \tilde{d})^{(2)} - \frac{\sqrt{7}}{2}(d^+ \tilde{d})^{(2)}$ is the SU(3) generator quadrupole operator. The next three terms are

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the fermion Hamiltonian and the boson-fermion coupling term. They can be written as

$$H_F = \sum_{jm} E_j a^+_{jm} a_{jm} + \frac{1}{2} \sum_{j_1 j_2 j'_1 j'_2 JM} V_0 (a^+_{j_1} a^+_{j_2})^{JM} \times (\tilde{a}_{j'_1} \tilde{a}_{j'_2})^{JM} , \quad (3)$$

$$V_{BF} = \sum_{j_1 j_2} \alpha Q_B \cdot (a^+_{j_1} \tilde{a}_{j_2})^{(2)} , \quad (4)$$

$$V_N = \gamma Q_B \cdot (f^+ \tilde{f})^{(2)} + \delta \sum_{j_1 j_2 J} Q_B \cdot [(a^+_{j_1} a^+_{j_2})^{(J)} \tilde{f} - f^+ (\tilde{a}_{j_1} \tilde{a}_{j_2})^{(J)}]^{(2)} + \varepsilon_f \hat{n}_f . \quad (5)$$

In the practical calculation the fermion potential is assumed to be the Yakawa type with Rosenfeld mixture. Harmonic oscillator wave function is adopted. The oscillator constant $\nu = 0.96A^{-1/3}\,\mathrm{fm}^{-2}$ with $A = 180$ is assumed. The potential strength V_0 is taken to be -50 MeV. Equation (5) represents the Hamiltonian including the f boson. To reduce the number of parameters and to keep the calculations simple, $\varepsilon_d = 0.475$ MeV and $a_3 = -0.0066$ MeV determined by Hsieh *et al.* [18] are used for the present study. a_1 and a_2 are mass dependent and are slightly modified from the previously determined values. The chosen a_1 and a_2, along with ε_d and a_3, are able to explain the yrast bands and they are listed in Table I. The parameters α and δ in the mixing Hamiltonian are kept constant at 0.1 and -0.06 MeV, respectively. The f-boson and s-d boson interaction strength is taken as $\gamma = 0$.

Recall that to form the negative parity states, the two quasiparticles should be placed in orbits with opposite parity. Here we consider $h_{11/2}$ and $g_{7/2}$ orbits for quasiprotons and $i_{13/2}$ and $h_{9/2}$ orbits for quasineutrons. The reason to choose these quasiparticle orbits is that they are near the Fermi surface and they can form high spin negative parity states. The two quasiprotons can couple to angular momentum $2, 3, \ldots, 9$ and the two quasineutrons can couple to angular momentum $2, 3, \ldots, 11$. In this way, the effect of the f boson and higher spin bosons are included to a certain extent. Therefore, an IBA plus two-quasiparticle calculation can better describe higher spin states. The total single particle energies of the two quasiproton orbits are constant at 2.38 MeV, while those of quasineutron orbits are mass dependent and they were chosen to given the best overall fit to all the known negative parity states. They are 2.38, 2.51, 2.64, 2.73, and 2.78 MeV, respectively, for $^{172-180}$Os isotopes.

TABLE I. Mass-dependent interaction parameters in MeV. See text for the meaning and/or the values of parameters.

Nuclides	Boson number	a_1	a_2
^{172}Os	10	0.020	0.0010
^{174}Os	11	0.035	0.0010
^{176}Os	12	0.035	0.0017
^{178}Os	13	0.035	0.0024
^{180}Os	14	0.035	0.0033

III. RESULTS AND DISCUSSIONS

There is at least one well-developed negative parity band in $^{172-180}$Os. The yrast negative parity states starts at low spin (5^- for ^{172}Os and 4^- for $^{174-180}$Os) and at excitation energy around 1.5 MeV. The results of calculations of the negative parity states of $^{172-180}$Os are compared to experiment in Figs. 1–5, where the energy of the 5^-_1 states of each isotope is set to be zero. The interacting-boson-plus-fermion-pair model is able to reproduce the energies reasonably well.

The transition probability is a more stringent test for the model than the level energy. Unfortunately, there is very little data for Os isotopes. Only for ^{174}Os is there complete experimental $B(E2)$ values for the whole negative parity band [19]. The effective charges, e_F and e_B, used in the present calculations are 0.5 and 0.25, respectively. The e_B value chosen is somewhat larger than the value commonly used. The predicted values are compared with experimental ones (taken from Ref. [19]) in Fig. 6 below. Note that the experimental $B(E2)$ of $6^-_1 \to 4^-_1$ and $7^-_1 \to 5^-_1$ are derived by us based on the estimated conversion coefficient and other necessary data from Ref. [19]. Although some of the data have

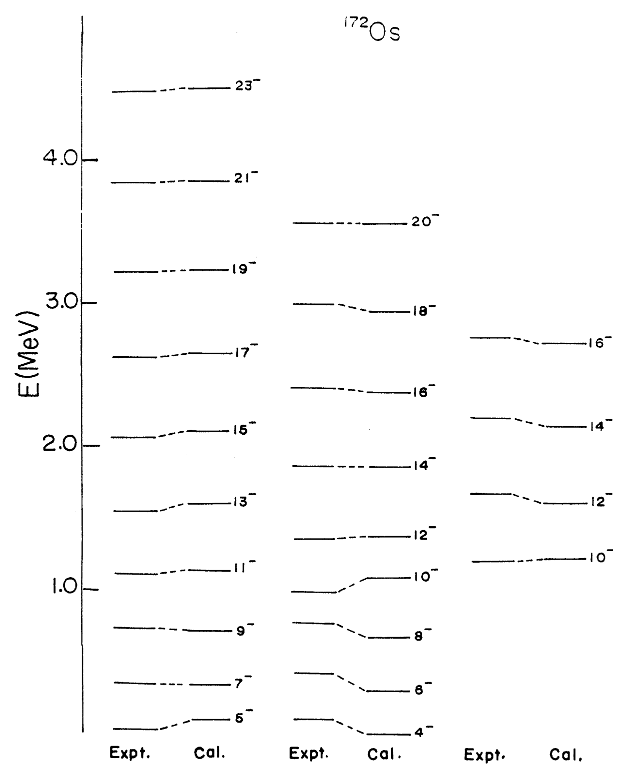

FIG. 1. Calculated and observed energy spectra for the nucleus ^{172}Os. The experimental data are taken from Refs. [1,2].

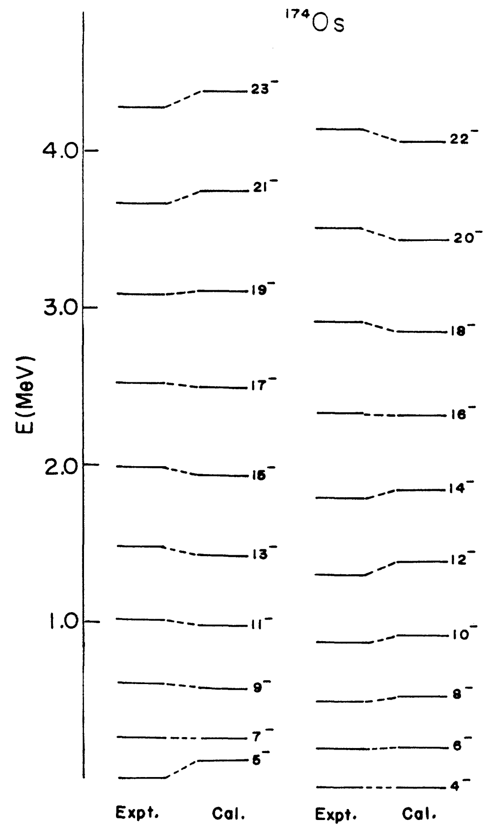

FIG. 2. Calculated and observed energy spectra for the nucleus ^{174}Os. The experimental data are taken from Refs. [3,4].

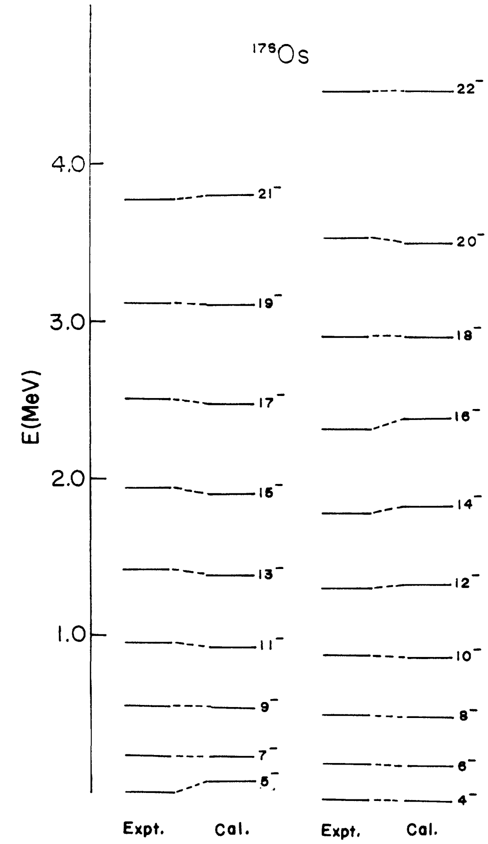

FIG. 3. Calculated and observed energy spectra for the nucleus ^{176}Os. The experimental data are taken from Ref. [5].

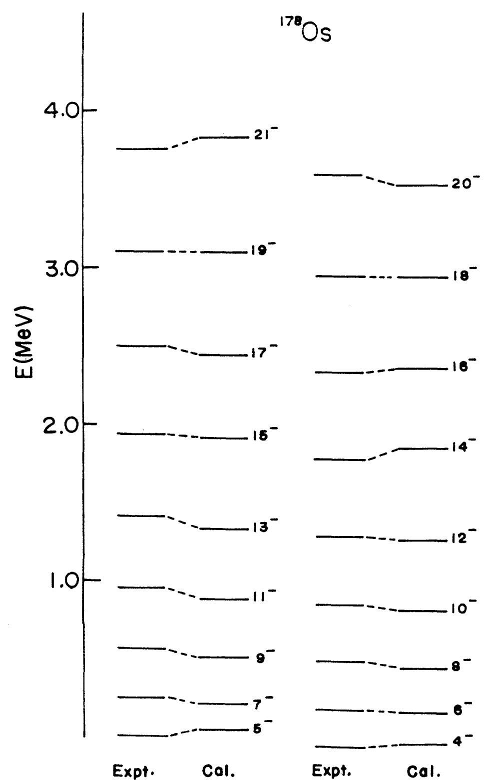

FIG. 4. Calculated and observed energy spectra for the nucleus ^{178}Os. The experimental data are taken from Ref. [5].

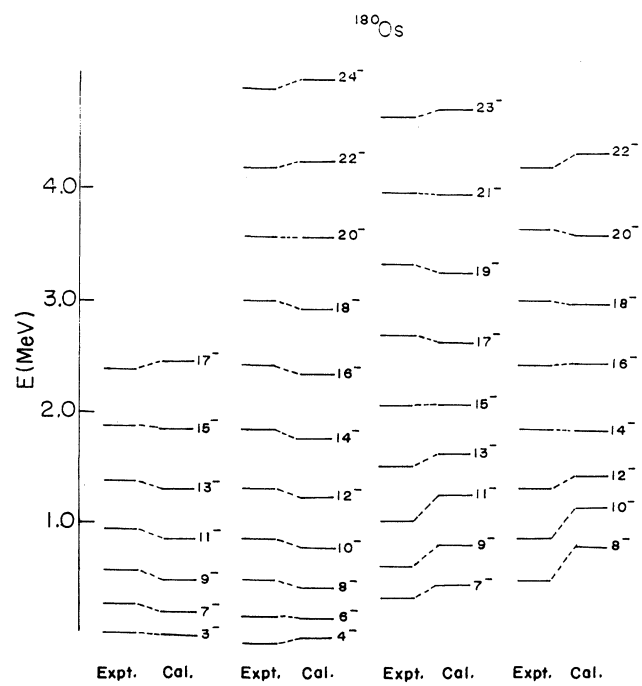

FIG. 5. Calculated and observed energy spectra for the nucleus ^{180}Os. The experimental data are taken from Refs. [5,6].

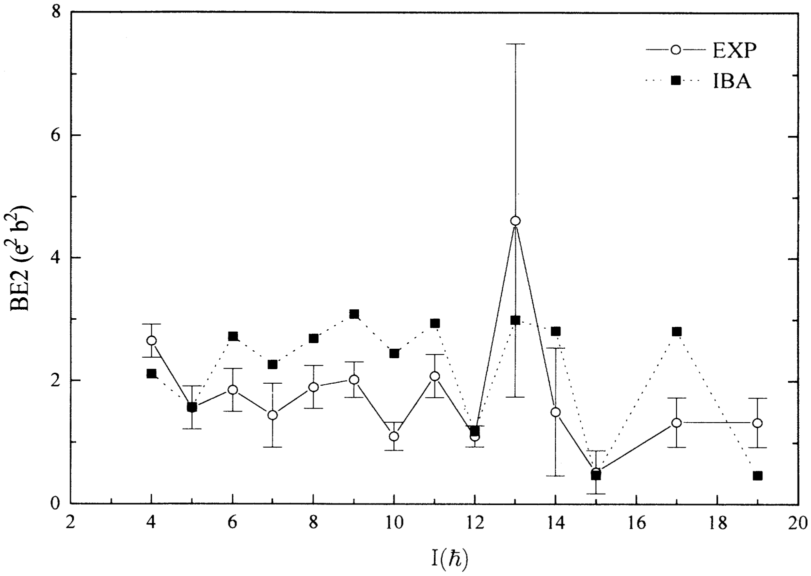

FIG. 6. IBA calculated $B(E2)$ values for $I+2 \to I$ transitions for the yrast negative parity states in ^{174}Os compared with experimental values. The experimental values are taken from Ref. [19].

a very large uncertainty, there are good correlations between IBA calculated and experimental values. That is, the IBA calculated values are in general larger than experimental ones due to the use of an e_B value which is slightly larger than usual.

In order to learn the microscopic structure of the negative parity states being studied, we ought to examine the wave functions. In the calculations the lower spin, lower-lying negative parity states are formed by coupling the f boson to the positive parity s and d bosons. The contribution from the quasiparticles is negligible until the spin of the negative parity states is about 10^- or until the level energy is ~ 2 MeV above the 5_1^- state. Obviously, the contribution of the quasiparticles to the negative parity states strongly depends on their energies. The lower the quasiparticle energy is, the more important quasiparticles are in the wave function. In the present study it is seen that the lower lying, lower spin negative parity states are rather collective, while the higher spin states have significant quasiparticle nature.

Sood, Headly, and Sheline in their recent compilation [12] of even-even nuclei in the rare earth region have provided a detailed description of the intrinsic structures and associated rotational bands. The structure of the first negative parity band in ^{172}Os and $^{176-180}$Os is listed in Table II. It is obvious that the structures of Os iso-

TABLE II. The intrinsic structures of the first negative parity bands in $^{172-180}$Os.

	Intrinsic structure	
Nucleus	Compilation of Ref. [12]	IBA calculations
^{172}Os	Rotation aligned $i_{13/2}$ neutrons and octupole vibration at lower spin	f boson coupled to s-d bosons at low spin and quasineutrons at higher spin
^{174}Os	Not known	f boson coupled to s-d bosons at low spin and quasineutrons at higher spin
^{176}Os	Octupole-vibrational band, rotation aligned 5/2[402], $h_{9/2}$ protons predominating after $I \approx 7$	f boson coupled to s-d bosons at low spin, quasiprotons at higher spin, and quasineutrons at even higher spin
^{178}Os	Octupole-vibrational band, rotation aligned 5/2[402], $h_{9/2}$ protons predominating after $I \approx 7$	f boson at low spin, quasiprotons at higher spin, and quasineutrons at even higher spin
^{180}Os	Rotation aligned 7/2[514] and other orbital neutrons	f boson coupled to s-d bosons at low spin, quasiprotons at higher spin, and quasineutrons at even higher spin

topes are not simple at all and cannot be described by a single motion. Generally speaking, they are octupole-vibrational band in nature and have a significant contribution from quasiparticles at higher spin. The structure based on IBA calculations is also listed in Table II for comparison. As mentioned earlier, the wave functions of these negative parity states are dominated by f boson at lower spin and by quasiparticles at higher spin. This feature is consistent with the compilation of Sood, Headly, and Sheline. From comparison it suggests that it is necessary to allow a boson to break into one fermion pair in the model space in order to describe the negative parity states of $^{172-180}$Os isotopes. For ^{172}Os, ^{176}Os, and ^{178}Os the type of particles (quasiproton or quasineutron) that contributes to the structure is correctly reproduced. We also notice that the quasiparticle orbits included in the calculations are somewhat different than that in Ref. [19]. The agreement of the type of quasiparticles in the intrinsic structure seems to suggest that the energy of the quasiparticles is a far more important factor. That is, if the relative energies of quasiprotons and quasineutrons are chosen correctly, the relative significance of the quasiprotons and quasineutrons in the wave function is determined. The energies of the quasiparticles will decide at which spin value the contribution of quasiparticles in the negative parity states becomes important with respect to that of the f boson. Which quasiparticle orbits are actually included in the calculations does not affect the qualitative agreement we are seeking here.

IV. SUMMARY

To describe the negative parity states in $^{172-180}$Os isotopes, the interacting-boson-plus-fermion-pair model is chosen, in which one f boson is coupled to normal s-d boson states or a boson is allowed to break into two fermions. Reasonable agreements in excitation energies and $B(E2)$ values are obtained. As far as the structure is concerned, the calculations achieve acceptable, qualitative agreement for the complex negative parity states: the lower lying, lower spin negative parity states are collective, while higher spin states have significant contribution of quasiparticles. From comparison with experimental evidence it also suggests that the relative energies of the quasiprotons and quasineutrons are the most important factor in determining their importance in structure of the negative parity states.

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