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LETTER TO THE EDITOR

A two-band interpretation of the high-spin states in even–even Pt isotopes

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Abstract. The high-spin states of even Pt isotopes are described within the conventional interacting boson approximation and the two-quasiparticle model. It was found that the first backbendings of the yrast levels of ^{192}Pt and ^{190}Pt can be reproduced reasonably. The main features of the calculated $B(E2)$ values for ^{184}Pt yrast band against the spin of the depopulating states are also in agreement with the observed values.

It is known that the high-spin states in the even Pt isotopes exhibit an anomaly, i.e. the 10^+ to 12^+ level spacing is remarkably small in the heavier isotopes whilst the transition energies in the lighter Pt isotopes show a nearly monotonic increase with spin (Funke *et al* 1975, Piiparinen *et al* 1975). This anomaly can be interpreted as a band crossing within a model in which two $i_{13/2}$ neutron quasiparticles or two $h_{9/2}$ or $h_{11/2}$ proton quasiparticles may be excited and coupled to the rotation of the core (Beshai *et al* 1976). Besides, a hybrid model for coupling the motion of particles to that of a quadrupole collective core is also proposed to calculate the excitation energies of $^{190,192}\text{Pt}$ (Raduta *et al* 1983). Recent measurements of the lifetimes for levels in the yrast band of ^{184}Pt up to a spin 16^+ showed that the observed $B(E2)$ values exhibit a marked increase in going from spin 2 to 10 (Larabee *et al* 1986, Garg *et al* 1986). This observation reveals a two-band mixing at low spin and it may be assumed that a coexistence of levels built on both prolate and oblate shapes is occurring at the low excitation energies of ^{184}Pt . Therefore, it should encourage a more rigorous theoretical treatment of the even Pt isotopes. In order to investigate the extent to which the observed irregularity can be understood, a calculation with a more realistic model, which takes into account the interplay between single-particle and collective degrees of freedom, is desirable.

The IBA model (Arima and Iachello 1976, 1978a, b) has been applied successfully to the low-flying collective states in even–even nuclei. However, when applied to the high-spin states, the traditional model usually does not reproduce them very well. In order to describe levels of high spin and excitation energy, a model within the neutron–proton interacting boson model with the excitation of a proton pair from the core has been proposed (Duval and Barrett 1981, Heyde *et al* 1983). However, this model overemphasised the role of the collective degrees of freedom and completely ignored the single-particle excitations. Yoshida *et al* (1982) allowed one of the bosons of the neutron–proton IBA to change into a pair of nucleons. Using the weak coupling technique and making use of the results of the

previous IBA-II calculation, Alonso *et al* (1986) extended the IBA-II to include two-quasiparticle excitations. They applied this model successfully to describe the back-bending of Dy isotopes. However, as the proton number goes away from the closed shell value, the basic states of neutron-proton IBA increase greatly, and the calculations of the neutron-proton IBA plus two-quasiparticle model of Yoshida *et al* are no longer feasible. It has been shown (Chiang *et al* 1985) that for regions far from the closed shell the difference between the proton and neutron bosons is less important. Therefore, to incorporate the effect of a two-quasiparticle excitation within the framework of the traditional IBA should be rather realistic yet reasonably simple. Morrison *et al* (1981) admixed two-quasiparticle $i_{13/2}$ neutron states with the IBA model to understand the anomalies of the high-spin states in $^{194-199}\text{Hg}$ isotopes. This was the first trial to describe the high-spin anomaly within the framework of the traditional IBA incorporating two-quasiparticle states. Since these nuclei are not far from the closed shell of $Z = 82$, $N = 126$, it may not be suitable to replace the IBA-II with IBA-I. Therefore, it should be interesting to see to what extent the IBA-I plus two-quasiparticle excitation can be applied. In this work, the even Pt isotopes with mass number between 182 and 192 will be used as test samples.

We will mainly follow the idea of Morrison *et al* by assuming that the high-spin anomaly of Pt could be described by the traditional IBA plus one boson broken into a $i_{13/2}$ quasiparticle pair. However, there are some differences between the treatment of Morrison *et al* and ours. First, Morrison *et al* applied the quasiparticle transformation of BCS theory in their Hamiltonian. In this way, they obtained more additional coupling terms between the bosons and the quasiparticles than this calculation. Second, in the work of Morrison *et al* the number of particles (holes) distributed in the $i_{13/2}$ orbit is not explicitly defined, but can be calculated through the u , v factors. Third, the Hg isotopes appear to exhibit an almost pure O(6) limit symmetry for low-lying states (Morrison *et al* 1981) whilst the Pt region has been shown to correspond to a change in the boson Hamiltonian from an O(6) to an SU(3) character (Casten and Cizewski 1978).

In our model, it is assumed that one boson is broken to form a quasiparticle pair. The two quasiparticles may be excited to the $(i_{13/2})^2$ orbit with $J = 4, 6, \dots, 12$ and coupled to the rotation of the core. The couplings to angular momenta 0 and 2 are excluded in order to avoid double counting of states, because they are included through the s and d bosons respectively. The reason for including only the $i_{13/2}$ single-particle orbit is because the previous work (Schiffner and True 1976) showed the two-body matrix elements of $(i_{13/2})$, $(h_{9/2})$ and $(h_{11/2})$ orbits are nearly the same value providing that the $J = 0$ components are suitably normalised.

Our model space includes the IBA space with N bosons and states with $N - 1$ bosons plus two nucleons. The model Hamiltonian is

$$H = H_B + H_F + V_{BF}$$

where the boson Hamiltonian H_B can be expressed as

$$H_B = a_0 \varepsilon_d + a_1 P^+ \cdot P + a_2 L \cdot L + a_3 Q \cdot Q$$

the fermion Hamiltonian H_F takes the form

$$H_F = \sum_m \varepsilon_j a_{jm}^+ a_{jm} + \frac{1}{2} \sum_{JM} V^J (a_j^+ a_j^+)^{JM} (\tilde{a}_j \tilde{a}_j)^{JM}$$

with a_j^+ being the nucleon creation operator. The mixing Hamiltonian V_{BF} is assumed to be

$$V_{BF} = Q^B \cdot Q - Q^B \cdot Q^B$$

where

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

and

$$Q = Q^B + \alpha(a_j^+ a_j)^{(2)} + \beta[(a_j^+ a_j^+)^{(4)} \tilde{d} - d^+ (\tilde{a}_j \tilde{a}_j)^{(4)}]^{(2)}.$$

The Yukawa and surface delta potentials have been used for the radial dependence of the fermion potential. Both yield almost the same result. In the final calculation the Yukawa potential is employed and an oscillation constant $\nu = 0.96A^{-1/3} \text{ fm}^{-2}$ with $A = 160$ is assumed. The interaction strength is adjusted so that the $J=0$ state is lower than the $J=2$ state by 2 MeV. The values of the two-body matrix elements $\langle i_{13/2}^2 | V | i_{13/2}^2 \rangle_{J,T=1}$ are $-2.80, -0.80, -0.38, -0.18, -0.01, 0.06$ and 0.19 MeV respectively for $J=0, 2, 4, 6, 8, 10$ and 12 states. The single-particle energy and the parameters of the boson Hamiltonian and mixing Hamiltonian have been chosen to reproduce the energy level spectra of even Pt isotopes.

Table 1 lists the strengths and single-particle energies for isotopes Pt with mass numbers between 182 and 192. In general, the parameters for all isotopes can be categorised into two groups. The three lighter isotopes form a group while the three heavier ones form another group. In each group the parameters for the same term are very similar. In fact, a gap exists in the parameters of the ^{188}Pt and ^{186}Pt isotopes. An important feature exhibits in the strengths for $P^+ \cdot P$ and $Q \cdot Q$. The interaction strength for the pairing term decreases nearly monotonically from ^{192}Pt to ^{182}Pt . However, the strength for the quadrupole term increases from ^{190}Pt to ^{180}Pt . This reveals a transition from $O(6)$ symmetry to $SU(3)$ symmetry for even Pt isotopes, and is consistent with the results of Casten and Cizewski (1978). The calculated energy spectra (not shown here) agree with the experimental values (including β and γ bands). We have analysed the wavefunctions including two-quasiparticle excitation for each state. For the yrast states of ^{192}Pt and ^{190}Pt , the high-spin states with I higher than eight, the two-quasiparticle excitation configurations become dominant. The relative intensities for the pure boson configuration of the 8^+ state for these two isotopes are about 89%. For ^{184}Pt , the single-particle excitation configurations are dominant for the states with I greater than 14. Therefore our calculation seems to suggest that two bands of different deformations mix at low spin and that rotation-aligned bands originating from the $i_{13/2}$ nucleon quasiparticle state occur for the higher spin states.

The isotopes ^{192}Pt and ^{190}Pt show backbending at 8^+ and 10^+ . In order to see the change of the effective moment of inertia of the yrast band, we plot the conventional

Table 1. The interaction parameters in MeV for IBA plus two-quasinucleon excitation model.

| Nucleus | Parameters (MeV) | | | | | | |
|-------------------|------------------|--------|--------|---------|----------|---------|--------------|
| | a_0 | a_1 | a_2 | a_3 | α | β | ϵ_j |
| ^{192}Pt | 0.5380 | 0.0970 | 0.0105 | 0.0012 | 0.04 | 0.03 | 1.36 |
| ^{190}Pt | 0.5124 | 0.0711 | 0.0105 | -0.0003 | 0.04 | 0.03 | 1.36 |
| ^{188}Pt | 0.5124 | 0.0541 | 0.0091 | -0.0030 | 0.04 | 0.03 | 1.36 |
| ^{186}Pt | 0.4630 | 0.0316 | 0.0081 | -0.0072 | 0.11 | 0.03 | 1.17 |
| ^{184}Pt | 0.4630 | 0.0226 | 0.0081 | -0.0072 | 0.11 | 0.03 | 1.14 |
| ^{182}Pt | 0.4630 | 0.0202 | 0.0081 | -0.0072 | 0.11 | 0.025 | 1.14 |

$2\mathcal{J}/\hbar^2$ against $(\hbar\omega)^2$ curve, with

$$2\mathcal{J}/\hbar^2 = \frac{4I-2}{E_{I+2} - E_I}$$

and

$$(\hbar\omega)^2 = \left(\frac{E_{I+2} - E_I}{[I(I+1)]^{1/2} - [(I-2)(I-1)]^{1/2}} \right)^2,$$

which is the most sensitive expression for the backbending behaviour. Figures 1 and 2 show the calculated and the observed $2\mathcal{J}/\hbar^2$ against $(\hbar\omega)^2$ curve for ^{192}Pt and ^{190}Pt . The calculated curves agree with the observed ones except at $I=12^+$ for both nuclei. For ^{192}Pt , the calculated $2\mathcal{J}/\hbar^2$ for $I=12^+$ state is smaller than the corresponding observed one, whilst the theoretical $2\mathcal{J}/\hbar^2$ value for $I=12^+$ state for ^{190}Pt is larger than the experimental one. The reason for these discrepancies is that the energy level spacing between $I=12$ and $I=10$ for these two nuclei mainly comes from the difference in the two-body matrix elements for $J=12$ and $J=10$ components of the fermion configuration. The calculated values for this difference are 0.14 MeV for ^{192}Pt and 0.15 MeV for ^{190}Pt , while the observed values are 0.11 MeV and 0.19 MeV respectively. Considering the rather sensitive nature of these curves, this agreement is still very surprising. The energy level spectrum for ^{184}Pt is shown in figure 3. In order to make a clear comparison, the ground band, β band and γ band are separated in different columns. It can be seen that the agreement between

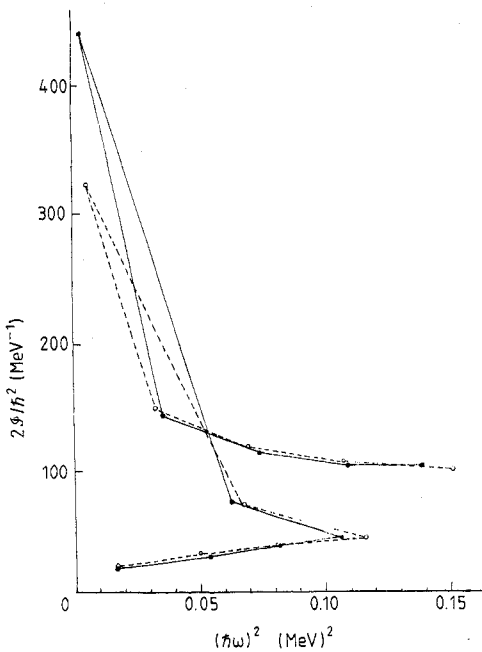


Figure 1. The calculated and experimental moment of inertia, $2\mathcal{J}/\hbar^2$ against $(\hbar\omega)^2$ for the positive-parity levels of ^{192}Pt . Open circles, calculated values; full circles, experimental values.

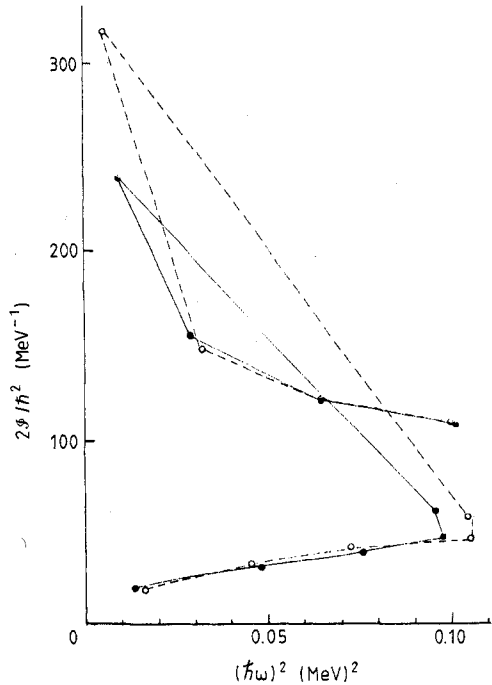


Figure 2. The calculated and experimental moment of inertia, $2\mathcal{J}/\hbar^2$ against $(\hbar\omega)^2$ for the positive-parity levels of ^{190}Pt . Open circles, calculated values; full circles, experimental values.

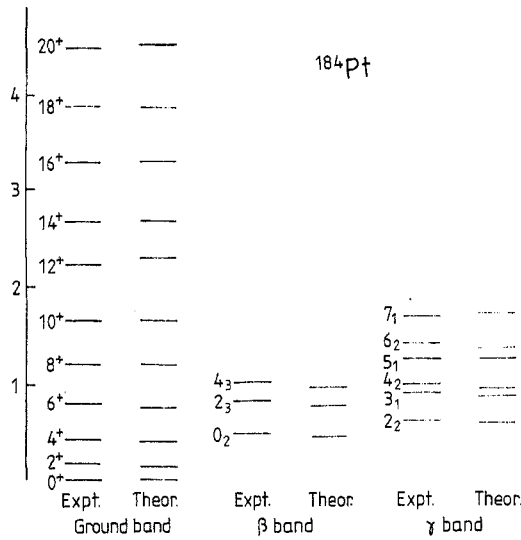


Figure 3. The calculated and experimental energy levels for the ^{184}Pt nucleus. The experimental data are taken from Sakai (1984).

the calculated and the observed energy levels is very convincing. For ^{184}Pt , there is experimental information on $B(E2)$. The study of these values will give us a good test of the model wavefunctions. The electric quadrupole operator can be written as

$$T(E2) = e^B Q + e^F \alpha (a_j^+ \tilde{a}_j)^{(2)} + \beta e^B [(a_j^+ a_j^+)^{(4)} \tilde{d} - d^+ (\tilde{a}_j \tilde{a}_j)^{(4)}]^{(2)}$$

where Q is taken as

$$Q = (d^+ \tilde{s} + s^+ d)^{(2)} - \chi (d^+ \tilde{d})^{(2)}.$$

For the fermion effective charge e^F , an average value 0.37 of those of proton and neutron obtained by Alonso *et al* is assumed. The boson effective charge in the $T(E2)$ operator has been determined by adjusting the experimental value of $B(E2, 10^+ \rightarrow 8^+)$. The parameters α and β are assumed to have the values used in the mixing Hamiltonian. The parameter χ is fixed to be $-\sqrt{7}/2$ which is the value of the generator of the $SU(3)$ group. Figure 4 shows the calculated and the observed $B(E2)$ values against the spin of the depopulating state. The observed $B(E2)$ values exhibit an increase in going from spin 2^+ to 10^+ and then decrease beyond spin 10^+ . Our calculated $B(E2)$ values reproduce this basic feature reasonably. Garg *et al* (1986) have used a rigid rotor model and a simple band-mixing calculation proposed by Dracoulis *et al* (1986) to study the $B(E2)$ values for ^{184}Pt . Both treatments cannot yield the decline feature beyond spin 10^+ .

In summary, a general way to incorporate the two-quasiparticle excitation within the framework of a traditional IBM is applied to the even Pt isotopes. Backbendings of the moment inertia of the yrast states for ^{192}Pt and ^{190}Pt are reproduced. The calculated interaction parameters reveal a transition from $O(6)$ symmetry to $SU(3)$ symmetry for even Pt isotopes. The relative intensity for the pure boson configuration and the two-quasi nucleon excitation configuration shows a coexistence of levels built on both prolate and oblate shapes at low excitation energies and thus two-band crossing occurs at low spin. The main feature of the $B(E2)$ values against the spin curve for ^{184}Pt can be reproduced reasonably. The model will be particularly useful in the region with numerous valence

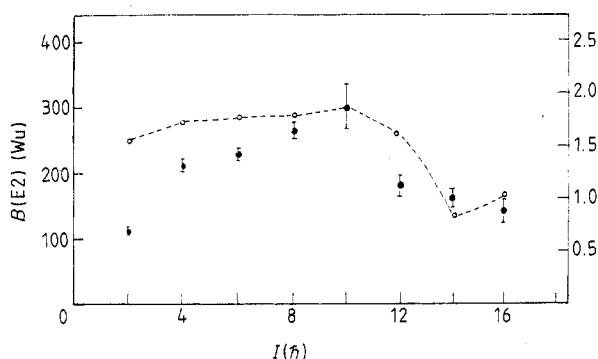


Figure 4. The calculated and the experimental $B(E2)$ values for the ^{184}Pt yrast band against the spin of the depopulating state. The experimental data are taken from Garg *et al* (1986). Open circles, calculated results; full circles, experimental values.

bosons when a similar calculation with the neutron-proton IBA is not feasible. The model may be applied to analyse the double backbending observed in the high-spin states of some nuclei. It is conjecture that for describing such double backbending behaviour, it might be necessary to assume that more bosons break into quasiparticle pairs or to include more single-particle orbits other than $i_{13/2}$ in the calculations.

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