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Proton Orbital [541]1/2 and Backbending in ^{178}W*

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Abstract *The microscopic mechanism of nine experimentally observed bands in ^{178}W is investigated using the particle-number conserving method of the cranked shell model with monopole and quadrupole paring interactions. The experimental results, including the moments of inertia and angular momentum alignments of nine bands in ^{178}W, are reproduced well by the particle-number conserving calculations, in which no free parameter is involved. Calculations demonstrate that occurrence of sharp backbending comes mainly from the contribution of high-j intruder orbitals $\nu i13/2$ or $\pi h11/2$ and their interference effect with orbitals near the Fermi surface. The ω variation of the occupation probability of each cranked orbital and the contribution to moment of inertia from each cranked orbital are analyzed.*

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Key words: backbending, cranked shell model, moment of inertia, pairing interaction

1 Introduction

High-K low excited states in deformed nuclei are often interpreted as generated by the aligning a few nucleons in the vicinity of the Fermi surface, i.e. $K = \sum \Omega_i$, where K is the projection on the symmetry axis of the total angular momentum and Ω_i is the projection of the angular momentum of the i-th nucleon, hence the prerequisite for occurrence of high-K states is the existence of high-Ω orbitals near the Fermi surface. In the $A \sim 180$ mass region, while $Z \approx 74$, $N \approx 104$, the high-K multi-quasiparticle spectrum is dominated by high-Ω orbitals close to the Fermi surface, such as $\pi[514]7/2$, $\pi[512]5/2$, $\nu[633]7/2$, $\nu[642]5/2$, etc., hence high-K multi-quasiparticle structures in the $A \sim 180$ region can be formed at relatively low excitation energies. The first high-K isomer in deformed nuclei with seniority higher than three was identified in this region.[1] With the development of techniques utilizing heavy-ion-induced reactions in high-spin spectroscopy, considerable quantities of experimental and theoretical researches with regard to high-K states are concentrated on the nuclei of the $A \sim 180$ region, such as $^{176-180}$W[2–11] and ^{178}Hf.[12,13] Many features of W isotopes, such as shape coexistence,[5] potential energy surface,[6] limiting moment of inertia (MOI),[7] static quadrupole moment,[8] Fermi alignment[9] and high-K isomer states,[10,11] have stroked people's interests and have been investigated in detail. Previous researches have already proposed that $\nu i13/2$ is mainly responsible for the backbending in $A \sim 180$ region.[4,14] However, $\pi[541]1/2$ has not been specifically identified for its influences to backbending in ^{178}W, the present paper shows the effect of proton orbital [541]1/2 at the region of backbending in $K^\pi = 15^+$ bands of ^{178}W.

For the high-K multi-quasiparticle bands, due to the rapid rotation and multi-quasiparticle excitations, the influence of pairing interactions would weaken significantly. It has been noted that nuclear MOI depends sensitively on the blocking effects of unpaired particles. Therefore, treating the blocking effect exactly and consistently is crucial in analyzing the microscopic mechanism of the ω variation of MOI of high-K multi-quasiparticle bands. To date, there have been several methods microscopically treating the paring interaction. The cranked Hartree–Fock–Bogoliubov method is adopted to treat paring correlation.[15–17] In the angular momentum projection shell model,[18,19] where the 0-, 2-, and 4-quasiparticle configurations could be involved, the defect of angular momentum non-conservation inherent in the cranked shell model would be remedied. With the total routhian surface method, the Lipkin–Nogami approximate particle-number projection is performed,[20] thus the defect of particle-number non-conservation is partly remedied. In the particle-number-conserving (PNC) method,[14,21,22] the particle number is conserved from beginning to end in the process of the calculation. The blocking effects resulting from the unpaired particles, which are crucial in studying the mechanism of the ω variation of MOI of high-K multi-quasiparticle bands, would be taken into account strictly and consistently. In this paper, the PNC treatment of pairing interaction is adopted to investigate the mechanism of the ω variation of MOI of the 0-, 2-, and 4-quasiparticle bands in ^{178}W, including the detailed calculations of occupation probability of each cranked Nilsson orbital and their contributions to the total alignment and MOI.

2 Calculations and Discussions

In our calculation, the cranked proton and neutron Nilsson orbitals near the Fermi surface of the well-deformed nucleus ^{178}W are shown in Fig. 1. The $\alpha = 1$ orbitals are plotted by solid and dashed lines respectively and the high-j intruder orbitals by bold lines. From Fig. 1, we can see that there are many high-Ω proton and neutron orbitals close to the Fermi surface, such as $\pi[514]9/2$, $\pi[404]7/2$, $\nu[633]7/2$, $\nu[512]5/2$, $\nu[514]7/2$, etc., hence high-K multi-quasiparticle bands can be formed easily at relatively low excitation energies in ^{178}W.

The Nilsson parameters (κ, μ) and the deformation parameters $(\varepsilon_2, \varepsilon_4)$ are taken from the Lund systematics.[15,23] Minor adjustments are made for the deformation parameters of $K^\pi = 7^-$ and $K^\pi = 15^+$ bands

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since both of them are based on deformation-driving high-j intruder orbital. The cranking-shell model Hamiltonian with pairing interactions, $H_{\rm CSM}$, is diagonalized in a truncated cranked many-particle configuration space, whose dimension is about 800 for neutrons and 600 for protons. The corresponding effective pairing interaction strengths, G_0 (monopole) and G_2 (quadrupole), are (in units of MeV) determined by the experimental odd-even differences in nuclear binding energy and bandhead moments of inertia, i.e., for neutron, $G_0 = 0.348$ and $G_2 = 0.006$; for proton, $G_0 = 0.358$, $G_2 = 0.009$. There is no free parameter involved in the PNC calculations.

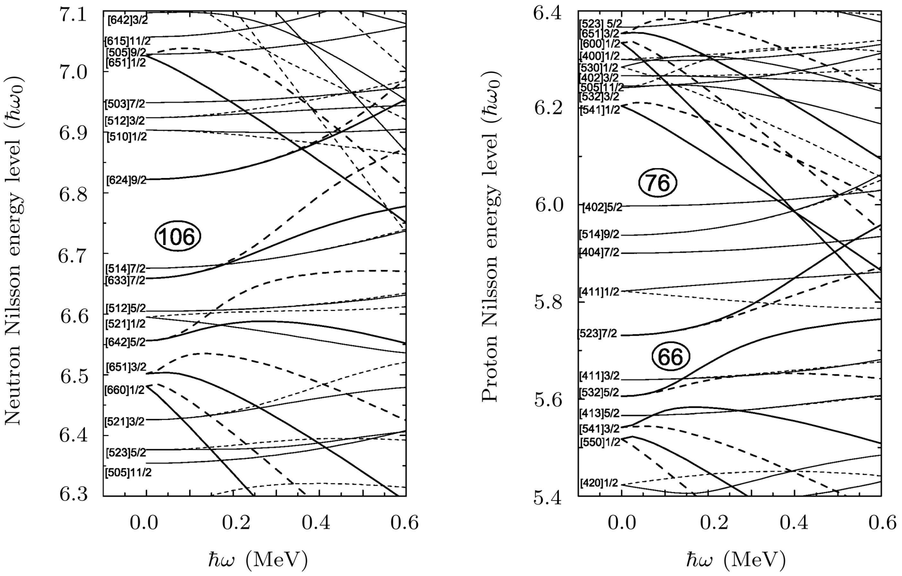

Fig. 1 Cranked neutron and proton Nilsson orbitals near the Fermi surface of ^{178}W. The signature $\alpha = 0$, 1 orbitals are denoted by solid and dashed lines, respectively. The high-j orbitals are denoted by bold lines.

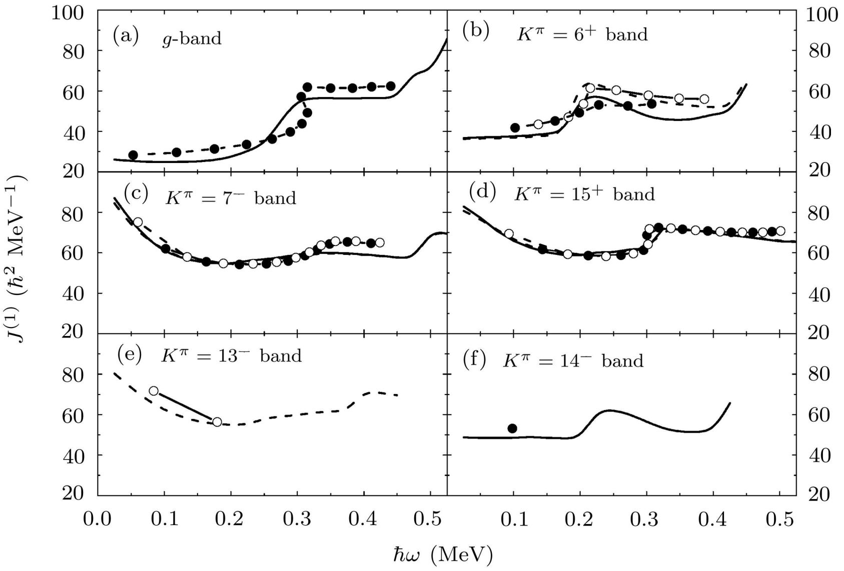

Fig. 2 Comparison between experimental and calculated kinetic MOIs of the eight bands in ^{178}W. The experimental data are denoted by solid circles for $\alpha = 0$ and open circles for $\alpha = 1$. The calculated results are denoted by solid and dashed lines.

The comparison between the experimental and calculated MOIs of the nine bands in ^{178}W are shown in Fig. 2, in which the solid ($\alpha = 0$) and the open ($\alpha = 1$) lines represent the experimental results, the calculated results are shown by the solid ($\alpha = 0$) and the dashed ($\alpha = 1$) lines. As seen from Fig. 2, the overall agreement between the results of the PNC calculations and those of the experiments is satisfactory. The frequencies of backbending for ground band, $K^\pi = 6^+$ and $K^\pi = 15^+$ bands are reproduced very well by our PNC calculations. D.L. Balabanski *et al.* discovered that for high-K bands in ^{179}W, the static quadrupole moments differ significantly from the ground-state quadrupole moments.[8] In the framework of cranking shell model, the difference from the deformation of ground band is due to the existence of deformation-driving orbitals on which the high-K bands are based. For $K^{\pi} = 7^{-}$ bands, the configuration is based on such deformation-driving orbital [633]7/2 and [514]7/2. After a minor adjustment of deformation parameter, i.e. ε_2 from 0.24 to 0.23, the agreement of PNC calculation results with that of experiment is much better. In this paper, we focus on discussing the contributions of the proton and neutron intruder orbital to the MOI of the multi-quasiparticle bands in ^{178}W. Detailed information could be seen from the occupation probabilities of single particle and their contributions to the total MOI, which are shown in Fig. 3 and Fig. 4, respectively.

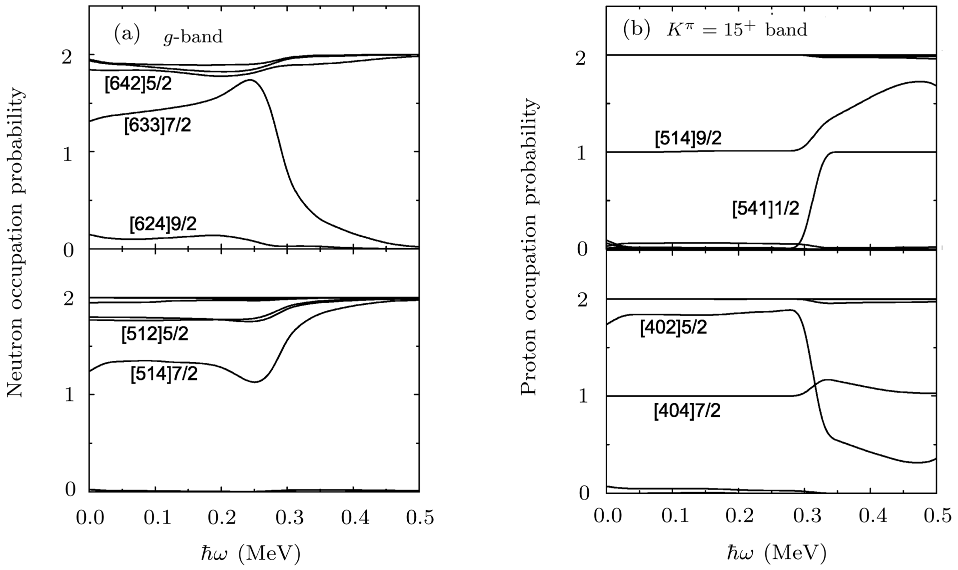

Fig. 3 Occupation probability n_{μ} of each orbital μ near the Fermi surface for the ground and $K^{\pi} = 15^{+}$ bands of ^{178}W.

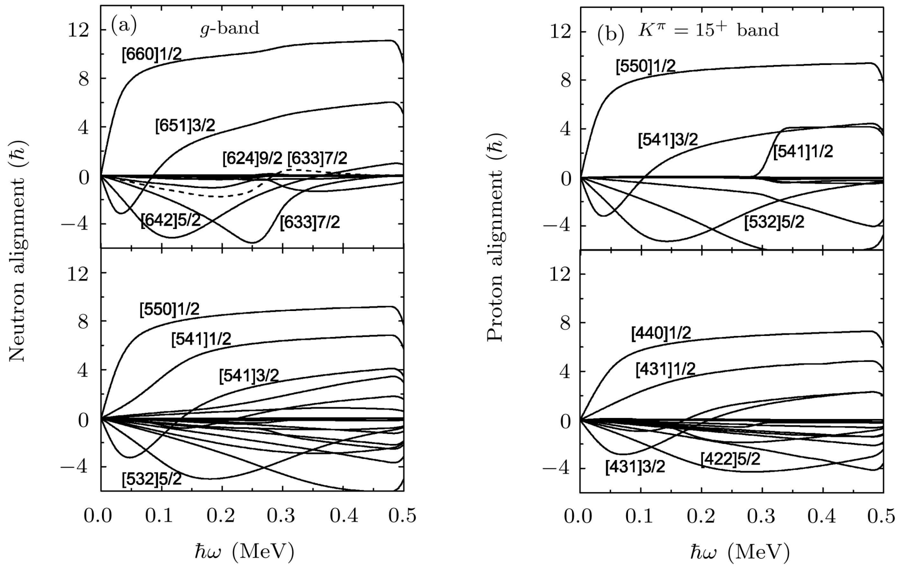

Fig. 4 The direct contributions to the alignment from the particle in the cranked orbital μ, $j_X(\mu)$ and the interference term $j_X(\mu\nu)$ between cranked orbitals μ and ν, for the ground and $K^{\pi} = 15^{+}$ bands of ^{178}W.

The occupation of each cranked orbitals (Both signatures $\alpha = 0, 1$, are included) near the Fermi surface and their ω variation is shown in Fig. 3. For the ground band of ^{178}W, due to the strong pairing correlation, both the cranked orbital [633]7/2 (below the Fermi surface) and [514]7/2 (above the Fermi surface) are partially occupied at low frequency. At higher frequency, however, the stronger Coriolis anti-pairing interaction acting on the high-j intruder neutron orbital [633]7/2 would result in a partial excitation from [633]7/2 to [514]7/2, i.e., the occupation probability of [633]7/2 drops suddenly from 1.7 to 0.4 at $\hbar\omega = 0.31$ MeV, while that of [514]7/2 increases from 1.1 to 1.8. This result could also be interpreted from the neutron Nilsson energy levels shown in Fig. 1, in which we could see that the orbitals [514]7/2 and [633]7/2 are close to each other, the interchange of configurations related to these two orbitals could take place more easily. In contrast to the neutron configuration interchanging responsible for the backbending of the ground band, excitation of proton high-j orbital [541]1/2 would be responsible for the backbending of $K^\pi = 15^+$ bands occurring at $\hbar\omega = 0.3$ MeV. As shown in Fig. 3(b), in the region of backbending, i.e., $\hbar\omega = 0.3$ MeV, the occupation probability of high-j orbital $\pi[541]1/2$ increases suddenly from 0.0 to 1.0, while that of $\pi[402]5/2$ decreases from 1.88 to 0.54, and continues to decrease gradually. More detailed information concerning the contributions of single particle orbital to total angular alignments could be seen from Fig. 4.

High-j intruder orbital is characterized by its large contributions to alignment at low frequency and large Coriolis response. Thus the change of alignment at the region of backbending is mainly due to the excitations of high-j orbitals. The backbending of the ground band, $K^\pi = 6^+$ bands and $K^\pi = 15^+$ bands serves as such typical examples. The contributions of each proton and neutron orbital to the total alignment of the ground and $K^\pi = 15^+$ bands are shown in Fig. 4. According to the PNC calculations, in the region of backbending, the total increase of alignment of the ground band is $7.3\hbar$, the direct contribution of $\nu[633]1/2$ is $4.75\hbar$, that of $\nu[642]5/2$ is $1.46\hbar$, that of the interference term $\nu[633]7/2 \otimes [624]9/2$ and $\nu[633]7/2 \otimes [651]3/2$ is $1.57\hbar$ and $-0.5\hbar$ respectively, as shown in Fig. 4(a). Therefore, the contributions to the backbending come mainly from $\nu i13/2$ orbitals. As for the $K^\pi = 15^+$ bands, whose results of calculations are shown in Fig. 4(b), at $\hbar\omega = 0.3$ MeV, the total increase of alignment is $3.11\hbar$, the direct contribution of $\pi[541]1/2$ is $4\hbar$, while that of $\pi[514]7/2$ and $\pi[514]9/2 \otimes [523]7/2$ is $-0.5\hbar$ and $-0.4\hbar$ respectively. Backbending mainly results from the proton high-j orbital [541]1/2. In the same way, backbending of $K^\pi = 6^+$ bands is due to double excitations from two $N = 6$ orbitals [633]1/2 and [642]5/2 to two $N = 5$ neutron orbitals [514]7/2 and [512]5/2 occurred at about $\hbar\omega = 0.275$ MeV.

Experimentally, there are two four-quasiparticle bands whose configurations are reliably established, but the data for them are too few to analyze the ω variations of MOI.[4] The results of our PNC calculations of these bands and their comparisons with the experimental results are shown in Fig. 2(e) and 2(f), from which we can see that the agreement of the calculated and experimental results at low frequency is satisfactory. Moreover, our results of PNC calculations predict the behavior of these two bands at higher frequencies.

3 Summary

The MOI of the series of high-K multi-quasiparticle bands in ^{178}W are investigated in detail using the PNC method for treating the cranked shell model with monopole and quadrupole pairing interactions. The experimentally variation of $J^{(1)}$s of the multi-quasiparticle bands are reproduced very well by the PNC calculations, in which no free parameter is involved. It is found that the backbending of ground, $K^\pi = 6^+$ and $K^\pi = 14^-$ bands mainly comes from the influence of high-j $\nu i13/2$ orbitals. For $K^\pi = 7^-$ band $K^\pi = 13^-$ bands, large alignments at low frequency also come from the contributions of $\nu i13/2$ orbitals. In contrast, $\pi[541]1/2$ is responsible for the backbending of $K^\pi = 15^+$ bands at $\hbar\omega = 0.3$ MeV. The deformation of bands with higher seniority, i.e. bands of six-quasiparticle, eight-quasiparticle, might display more complicated scenarios.[8] Analysis of the microscopic mechanism of these bands is under consideration.

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