Nonadditivity in moments of inertia of high-K multiquasiparticle bands[*]

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Abstract The experimental high-K 2- and 3-quasiparticle bands of well deformed rare-earth nuclei are analyzed. It is found that there exists significant nonadditivity in moments of inertia (MOIs) for these bands. The microscopic mechanism of the rotational bands is investigated by the particle number conserving (PNC) method in the frame of cranked shell model with pairing, in which the blocking effects are taken care of exactly. The experimental rotational frequency dependence of these bands is well reproduced in PNC calculations. The nonadditivity in MOIs originates from the destructive interference between Pauli blocking effects.

Key words particle-number-conserving method, BCS theory, nuclear moments of inertia

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1 Introduction

In the independent quasiparticle (qp) description of nuclear structure[1, 2], assuming the energies of the qp vacuum $|0\rangle\rangle$, 1-qp states $\alpha_i^+|0\rangle\rangle$ $(i = 1, 2, \cdots, n)$, and n-qp state $\alpha_1^+\alpha_2^+\cdots\alpha_n^+|0\rangle\rangle$ are $E_0 = 0$, $E(i)$, and $E(1, 2, \cdots, n)$ respectively, it is well known that $E(1, 2, \cdots, n) = \sum_{i=1}^n E(i)$ (the additivity of qp energies). Similarly, if the moments of inertia (MOIs) of rotational bands built on these intrinsic states are denoted by J_0, $J(i)$, and $J(1, 2, \cdots, n)$ respectively, the additivity of MOIs is[3]

$$J(1, 2, \cdots, n) - J_0 = \sum_{i=1}^n (J(i) - J_0) . \qquad (1)$$

Define

$$R(1, 2, \cdots, n) = \sum_{i=1}^n [J(i) - J_0]/[J(1, 2, \cdots, n) - J_0], \quad (2)$$

and in the BCS qp description, we have

$$R(1, 2, \cdots, n)|_{\text{BCS}} = 1 . \qquad (3)$$

In recent years a lot of low-lying excited rotational bands built on well-deformed intrinsic multiquasiparticle states were observed[4, 5]. For the well-deformed rare-earth nuclei with $A \sim 170$—185 $(Z \sim 71-74, N \sim 98$—108) the single-particle spectrum near the Fermi surface is dominated by high-Ω (projection of angular momentum along the symmetry axis) orbits. This special situation gives rise to low-lying high-K $(= \sum_i \Omega_i)$ multiquasiparticle bands. Assuming the unpaired nucleons occupy the Nilsson energy levels with angular momentum projection along the symmetric axis, Ω_1 and Ω_2, respectively, then there exist two 2-qp bands with $K = |\Omega_1 \pm \Omega_2|$. Similarly, assuming the three unpaired nucleons occupy Nilsson levels with Ω_1, Ω_2 and Ω_3, then there exist four 3-qp bands with $K = |\Omega_1 \pm \Omega_2 \pm \Omega_3|$.

In Section 2 the experimental high-K 2-qp and 3-qp bands are systematically analyzed and we found for these observed high-K 2-qp and 3-qp bands, $R_{\text{exp}} > 1$, i.e., all of these experimental nuclear MOIs are nonadditive,

$$[J(1, 2, \cdots, n) - J_0]_{\text{exp}} < \sum_{i=1}^n [(J(i) - J_0)]_{\text{exp}} . \qquad (4)$$

In Section 3 the microscopic mechanism of multiquasiparticle band is investigated with the particle-number conserving (PNC) method in treating nuclear pairing interaction, in which the Pauli blocking effects are taken into account exactly. Two typical examples are analyzed in detail and we found the nonadditivity in MOIs comes from the destructive interference of Pauli blocking effects.

2 Phenomenological analysis of non-additivity of nuclear MOIs

In Table 1 we present the experimental $R_0(1,2)$ ratio for the bandhead MOIs of some high-K 2-qp rotational bands of the rare-earth nuclei

$$R_0(1,2)_{\exp} = \frac{[J_0(1)-J_0]_{\exp}+[J_0(2)-J_0]_{\exp}}{[J_0(1,2)-J_0]_{\exp}}, \quad (5)$$

where J_0 is the bandhead MOI of the ground-state band (qp vacuum $|0\rangle\rangle$ band) in an even-even nuclei, $J_0(1,2)$ is the MOI of 2-qp band $(\sim \alpha_1^+\alpha_2^+|0\rangle\rangle)$, $J_0(1)$ and $J_0(2)$ are the MOIs of 1-qp bands $(\sim \alpha_1^+|0\rangle\rangle$, $\alpha_2^+|0\rangle\rangle)$ in the adjacent odd-A nuclei. In Table 2, we present the experimental $R_0(1,2,3)$ of some high-K 3-qp bands whose intrinsic 3-qp configurations have been assigned[4]

$$R_0(1,2,3)_{\exp} = \frac{\sum_{i=1}^{3}[J_0(i)-J_0]_{\exp}}{[J_0(1,2,3)-J_0]_{\exp}}, \quad (6)$$

where $J_0(1,2,3)$ is the bandhead MOI of the high-K 3-qp band built on the intrinsic configuration $\alpha_1^+\alpha_2^+\alpha_3^+|0\rangle\rangle$ and $K = (\Omega_1+\Omega_2+\Omega_3)$.

From Table 1 and 2 it is found that for all these high-K 2-qp and 3-qp bands the experimental values of $R_0(1,2)$ and $R_0(1,2,3)$ are systematically larger than 1, i.e.

$$[J_0(1,2)-J_0]_{\exp} < [(J_0(1)-J_0)+(J_0(2)-J_0)]_{\exp}, \quad (7)$$

$$[J_0(1,2,3)-J_0]_{\exp} < \left[\sum_{i=1}^{3}(J_0(i)-J_0)\right]_{\exp}, \quad (8)$$

which implies a significant deviation from the addi-

tivity relation of nuclear MOIs (1) predicted by the BCS independent qp description.

Moreover, the experimental results also show that the nonadditivity relation (4) holds not only at bandhead, but also at higher angular momenta (see Fig. 3). In Secion 3 we will give a microscopic interpretation for the nonadditivity in MOIs, which turns out to originate from the destructive interference between Pauli blocking effects on nuclear pairing.

3 Microscopic mechanism of high-K multiquasiparticle bands

Now we investigate the microscopic mechanism of the variations in MOIs of high-K multiquasiparticle bands, including the angular momentum (rotational frequency ω) dependence of MOI, which depends sensitively on the configuration assignment of multiquasiparticle states, particularly on the Coriolis response of the Nilsson levels blocked by unpaired nucleons. It is well known that the pairing interaction plays an essential role in the description of collective motion of deformed nuclei at low spins, e.g., the pairing interaction is responsible for the observed reduction of MOI compared with that of a rigid rotor[1]. Usually, the BCS theory of superconductivity of metal is transplanted to treat the nuclear pairing correlation[2]. There is no doubt that the BCS theory had many achievements in the description of nuclear pairing correlation, but there exist some serious defects which should be dealt with

Table 1. The experimental $R(1,2)$ for the bandhead MOIs of some high-K 2-quasiparticle bands in the well-deformed even-even rare-earth nuclei.

nuclei	bandhead-energy/keV	K^{π}	2-qp configuration	reference 1-qp bands	$R(1,2)_{\exp}$
^{162}Dy	1485.67	5^-	$\nu5/2^+ + \nu5/2'^-$	^{161}Dy$+^{161}$Dy*	1.78
^{170}Yb	1258.46	4^-	$\nu7/2^+ + \nu1/2^-$	^{171}Yb*$+^{171}$Yb	1.96
^{170}Hf	1773.36	6^+	$\pi7/2^+ + \pi5/2^+$	^{169}Lu$+^{169}$Lu*	1.94
^{170}Hf	2183.8	8^-	$\pi7/2^+ + \pi9/2^-$	^{169}Lu$+^{169}$Lu*	2.29
^{172}Hf^a	1686.0	6^+	$\pi7/2^+ + \pi5/2^+$	^{171}Lu$+^{171}$Lu*	1.92
^{172}Hf	2006.0	8^-	$\pi7/2^+ + \pi9/2^-$	^{171}Lu$+^{171}$Lu*	2.28
^{172}Hf	1858.0	6^-	$\nu7/2^+ + \nu5/2^-$	^{171}Hf$+^{171}$Hf*	1.39
^{174}Hf^b	1549.18	6^+	$\pi7/2^+ + \pi5/2^+$	^{173}Lu$+^{173}$Lu*	2.19
^{174}Hf	1713.41	6^-	$\nu7/2^+ + \nu5/2^-$	^{173}Hf*$+^{173}$Hf*	1.67
^{174}Hf	1797.47	8^-	$\pi7/2^+ + \pi9/2^-$	^{173}Lu$+^{173}$Lu*	2.27
^{180}Hf^c	1141.5	8^-	$\pi7/2^+ + \pi9/2^-$	^{181}Ta$+^{181}$Ta*	1.03
^{176}W	1973.1	8^-	$\pi7/2^+ + \pi9/2^-$	^{175}Ta$+^{175}$Ta*	1.16
^{178}W^d	1665.0	6^+	$\nu7/2^- + \nu5/2^-$	^{177}W*$+^{177}$W*	1.25
^{178}W	1738.0	7^-	$\nu7/2^- + \nu7/2^+$	^{177}W*$+^{177}$W*	2.04
^{182}W^e	1757.0	6^+	$\pi7/2^+ + \pi5/2^+$	^{181}Ta$+^{181}$Ta*	1.95
^{182}W	1978.0	7^-	$\pi9/2^- + \pi5/2^+$	^{181}Ta*$+^{181}$Ta*	1.57

∗ denotes the excited 1-qp band. The experimental data are taken from the Nuclear Data Sheets, except: a) D. M. Cullen et. al., Phys. Rev., 1995, **C52**: 2415; b) N. L. Gjørup et. al., Nucl. Phys., 1995, **A582**: 369; c) S. -C. Wu and H. Niu, Nucl. Data Sheets, 2003, **100**: 483; R. D'Alarcao et. al., Phys. Rev., 1999, **C59**: R1227.; d) C. S. Purry et. al., Nucl. Phys., 1998, **A632**: 229; e) T. Shizuma et. al., Nucl. Phys., 1995, **593**: 247.

Table 2.   The same as Table 1, but for some high-K the 3-qp bands in the odd-A rare-earth nuclei. All the experimental data are from Ref. [4] and references therein.

nuclei	bandhead-energy/keV	K^π	3-qp configuration	reference 1-qp bands	$R(1,2,3)_{\exp}$
^{163}Ho	1504.9	$17/2^+$	$\pi7/2^-+\nu5/2^++\nu5/2'^-$	^{163}Ho+ ^{161}Dy +^{161}Dy*	1.50
^{165}Tm	1633.3	$17/2^-$	$\pi7/2^++\nu5/2'^-+\nu5/2^+$	^{165}Tm*+ ^{165}Yb +^{165}Yb*	2.59
^{165}Tm	1740.8	$17/2^+$	$\pi7/2^-+\nu5/2'^-+\nu5/2^+$	^{165}Tm*+ ^{165}Yb +^{165}Yb*	2.58
^{171}Lu	1240.9	$15/2^-$	$\pi7/2^++\nu1/2^-+\nu7/2^+$	^{171}Lu+ ^{171}Yb +^{171}Yb*	1.82
^{177}Lu	970.0	$23/2^-$	$\pi7/2^++\nu7/2^-+\nu9/2^+$	^{177}Lu+ ^{177}Hf +^{177}Hf*	2.04
^{177}Lu	1325.0	$25/2^+$	$\pi9/2^-+\nu7/2^-+\nu9/2^+$	^{177}Lu*+ ^{177}Hf +^{177}Hf*	1.87
^{175}Ta	1565.9	$21/2^-$	$\pi7/2^++\pi9/2^-+\pi5/2^+$	^{175}Ta+ ^{175}Ta* +^{175}Ta*	1.61
^{175}Ta	1729.3	$21/2^+$	$\pi9/2^-+\nu5/2^-+\nu7/2^+$	^{175}Ta*+ ^{175}Hf +^{175}Hf*	1.77
^{177}Ta	1698.5	$23/2^+$	$\pi9/2^-+\nu7/2^++\nu7/2^-$	^{177}Ta*+ ^{177}W* +^{177}W*	2.07
^{177}Ta	2098.2	$25/2^+$	$\pi9/2^-+\nu7/2^-+\nu9/2^+$	^{177}Ta*+ ^{177}Hf +^{177}Hf*	1.07
^{179}Ta	1317.8	$25/2^+$	$\pi9/2^-+\nu7/2^-+\nu9/2^+$	^{179}Ta*+ ^{177}Hf +^{177}Hf*	1.85
^{179}Ta	1327.0	$23/2^-$	$\pi7/2^++\nu7/2^-+\nu9/2^+$	^{179}Ta+ ^{177}Hf +^{177}Hf*	2.16
^{163}Er	1845.6	$19/2^-$	$\nu5/2^++\pi7/2^-+\pi7/2^+$	^{163}Er*+^{163}Tm*+^{163}Tm*	2.66
^{163}Er	1982.9	$19/2^+$	$\nu11/2^-+\nu3/2'^-+\nu5/2^+$	^{163}Er*+ ^{163}Er* +^{163}Er*	4.42
^{163}Er	2120.5	$19/2^+$	$\nu5/2'^-+\pi7/2^-+\pi7/2^+$	^{163}Er+^{163}Tm*+^{163}Tm*	1.33
^{171}Hf	1645.3	$19/2^+$	$\nu7/2^++\pi7/2^++\pi5/2^+$	^{171}Hf+ ^{169}Lu +^{169}Lu*	1.41
^{171}Hf	1984.8	$23/2^-$	$\nu7/2^++\pi7/2^++\pi9/2^-$	^{171}Hf+ ^{169}Lu +^{169}Lu*	1.74
^{173}Hf	1077.4	$13/2^+$	$\nu7/2^++\nu1/2^-+\nu5/2^-$	^{173}Hf*+ ^{173}Hf +^{173}Hf*	2.51
^{173}Hf	1699.7	$19/2^+$	$\nu7/2^++\pi7/2^++\pi5/2^+$	^{173}Hf*+ ^{171}Lu +^{171}Lu*	1.25
^{173}Hf	1981.3	$23/2^-$	$\nu7/2^++\pi7/2^++\pi9/2^-$	^{173}Hf*+ ^{171}Lu +^{171}Lu*	1.53
^{175}Hf	1433.3	$19/2^+$	$\nu7/2^++\pi7/2^++\pi5/2^+$	^{175}Hf*+ ^{175}Ta +^{175}Ta*	1.20
^{175}Hf	1766.5	$23/2^-$	$\nu7/2^++\pi7/2^++\pi9/2^-$	^{175}Hf*+ ^{175}Ta +^{175}Ta*	1.26
^{177}Hf	1315.0	$23/2^+$	$\nu7/2^-+\pi7/2^++\pi9/2^-$	^{177}Hf+ ^{177}Lu +^{177}Lu*	1.33
^{177}Hf	1343.0	$19/2^-$	$\nu7/2^-+\pi7/2^++\pi5/2^+$	^{177}Hf+ ^{177}Lu +^{177}Lu*	1.31
^{177}Hf	1713.3	$25/2^-$	$\nu9/2^++\pi7/2^++\pi9/2^-$	^{177}Hf*+ ^{177}Lu +^{177}Lu*	1.45
^{179}Hf	1106.0	$25/2^-$	$\nu9/2^++\pi7/2^++\pi9/2^-$	^{179}Hf+ ^{177}Lu +^{177}Lu*	1.70
^{179}Hf	1310.5	$17/2^+$	$\nu7/2^-+\nu9/2^++\nu1/2'^-$	^{179}Hf*+ ^{179}Hf +^{179}Hf*	1.87
^{179}Hf	1405.0	$23/2^+$	$\nu7/2^-+\pi7/2^++\pi9/2^-$	^{179}Hf*+ ^{179}Ta +^{179}Ta*	1.28
^{177}W	1645.5	$19/2^+$	$\nu7/2^++\nu5/2^-+\nu7/2^-$	^{177}W*+ ^{177}W* +^{177}W*	2.70
^{179}W	1832.1	$23/2^-$	$\nu7/2^-+\nu7/2^++\nu9/2^+$	^{179}W+ ^{179}W* +^{179}W*	1.80
^{179}W	2011.9	$23/2^+$	$\nu7/2^-+\pi7/2^++\pi9/2^-$	^{179}W+ ^{179}Ta +^{179}Ta*	1.40
^{179}W	2088.4	$23/2^-$	$\nu9/2^++\pi5/2^++\pi9/2^-$	^{179}W*+ ^{179}Ta* +^{179}Ta*	2.13
^{183}W	1900.3	$19/2^+$	$\nu1/2'^-+\nu7/2^-+\nu11/2^+$	^{183}W+ ^{183}W* +^{183}W*	1.58

∗ the excited 1-qp band.

seriously[3, 6—8], including the particle-number non-conservation and the blocking effects. Just as Rowe emphasized[7], while the blocking effects are straight-forward, it is very difficult to quantify them in the BCS formalism because BCS introduces different quasiparticle bases for different blocked levels.

In this article the large variations in MOIs of high-K multiquasiparticle bands, including the ω-dependence and the nonadditivity of MOIs, are investigated by particle-number-conserving (PNC) method in the frame of Cranked Shell Model (CSM)[9, 10], in which the particle number is conserved intrinsically and the Pauli blocking is strictly kept. The key point of PNC treatment for nuclear pairing is that a many-particle configuration (MPC) truncation (or many-body Fock-space basis cut-off) is used instead of the more common single-particle level (SPL) truncation. The superiority of the MPC trun-

cation over the SPL truncation has been discussed in detail in Refs. [11, 12], particularly, the stability of the MPC basis cut-off has been demonstrated profoundly in an article by H. Molique and J. Dudek[8].

The CSM Hamiltonian of an axially symmetric nucleus in the rotating frame is expressed as[9, 10]

$$H_{\rm CSM} = H_{\rm Nil} - \omega J_x + H_{\rm P} , \qquad (9)$$

where $H_{\rm Nil}$ is the Nilsson Hamiltonian, $-\omega J_x$ is the Coriolis interaction with cranking frequency ω about the x axis perpendicular to the nuclear symmetry z axis, and $H_{\rm P}$ is the pairing interaction

$$\begin{aligned} H_{\rm P} &= H_{\rm P}(0) + H_{\rm P}(2) , \\ H_{\rm P}(0) &= -G_0 \sum_{\xi\eta} a_\xi^+ a_{\bar\xi}^+ a_{\bar\eta} a_\eta, \qquad (10) \\ H_{\rm P}(2) &= -G_2 \sum_{\xi\eta} q_2(\xi) q_2(\eta) a_\xi^+ a_{\bar\xi}^+ a_{\bar\eta} a_\eta, \end{aligned}$$

where $\bar{\xi}(\bar{\eta})$ is the time-reversal state of the Nilsson state $\xi(\eta)$, $q_2(\xi) = \sqrt{\dfrac{16\pi}{5}}\langle\xi|r^2Y_{20}|\xi\rangle$ is the diagonal element of the stretched quadrupole operator, and G_0 and G_2 are the effective strength of monopole and quadrupole pairing interaction. For details of the solution to the eigenvalue problem of H_{CSM}, please refer to Refs. [9, 10]. Assuming that an eigenstate of H_{CSM} is

$$|\psi\rangle = \sum_i C_i|i\rangle \qquad (C_i\text{ real}),\qquad(11)$$

where $|i\rangle$ is a cranked MPC, then the angular momentum alignment of $|\psi\rangle$ is

$$\langle\psi|J_x|\psi\rangle = \sum_i C_i^2\langle i|J_x|i\rangle + 2\sum_{i<j}C_iC_j\langle i|J_x|j\rangle,\quad(12)$$

and the kinematic moment of inertia for the state $|\psi\rangle$ is

$$J = \frac{1}{\omega}\langle\psi|J_x|\psi\rangle.\qquad(13)$$

The PNC calculations for two typical examples, the MOIs of the 3-qp band of ^{171}Hf (bandhead energy 1645.3 keV, $K^\pi = 19/2^+$) and the 2-qp band of ^{172}Hf (bandhead energy 1858.0 keV, $K^\pi = 6^-$) are given below. In Fig.1 we present the cranked Nilsson orbital near the Fermi surface of ^{170}Hf. The deformation parameters $\varepsilon_2 = 0.245$, $\varepsilon_4 = 0.014$, and κ and μ are taken from the Lund systematics[13, 14].

In our calculation, H_{CSM} is diagonalized in a sufficiently large cranked many-particle configuration (CMPC) space, then we can obtain sufficient accurate solutions $|\psi\rangle$ to the low-lying eigenstates of H_{CSM}. The dimension of CMPC space is 700 for neutron

and 600 for proton. The corresponding effective pairing interaction strengths $G_{n0} = 0.35$ MeV, $G_{n2} = 0.005$ MeV and $G_{p0} = 0.30$ MeV, $G_{p2} = 0.007$ MeV are determined by the experimental odd-even differences in binding energies, and no other free parameters are involved. It is noted that for the low-lying excited bands the number of involved important CM-PCs (with weight $> 10^{-3}$) is very limited (usually < 20), so the obtained results are accurate enough. It is found that the large number of experimental data of MOIs at various rotational frequencies for the low-lying excited bands of ^{171}Hf and ^{171}Lu can be reproduced rather well by the PNC calculations. It is expected that more satisfactory results may be obtained by using more realistic single-particle levels than the Nilsson levels (e.g. Woods-Saxon) and by slightly modifying the effective pairing interaction strength.

In Fig. 2(a) we present the experimental and calculated ω-dependence of two low-lying excited 1-quasiparticle bands, $\nu7/2^+[633]$ and $\nu5/2^-[512]$ of ^{171}Lu and ^{171}Hf. As a reference, the experimental ω-dependence of the ground-state band MOI of ^{170}Hf is also given in Fig. 2(a). Fig. 2(b) is the same as Fig. 2(a), but for the 1-qp bands of ^{171}Lu, $\pi7/2^+[404]$ and $\pi5/2^+[402]$ bands. Fig. 2(c) is for the 2-qp bands of ^{172}Hf, 1858.0 keV, $K^\pi = 6^-$ with configuration $\nu7/2^+[633]\otimes\pi5/2^-[512]$. Fig. 2(d) is the 3-qp bands of ^{171}Hf, 1645.3 keV, $K^\pi = 19/2^+$ with configuration $\nu7/2^+[633]\otimes\pi7/2^+[404]\otimes\pi5/2^+[402]$. It is seen that the experimental MOIs of all these rotational bands and their ω dependence are well reproduced by the PNC calculations.
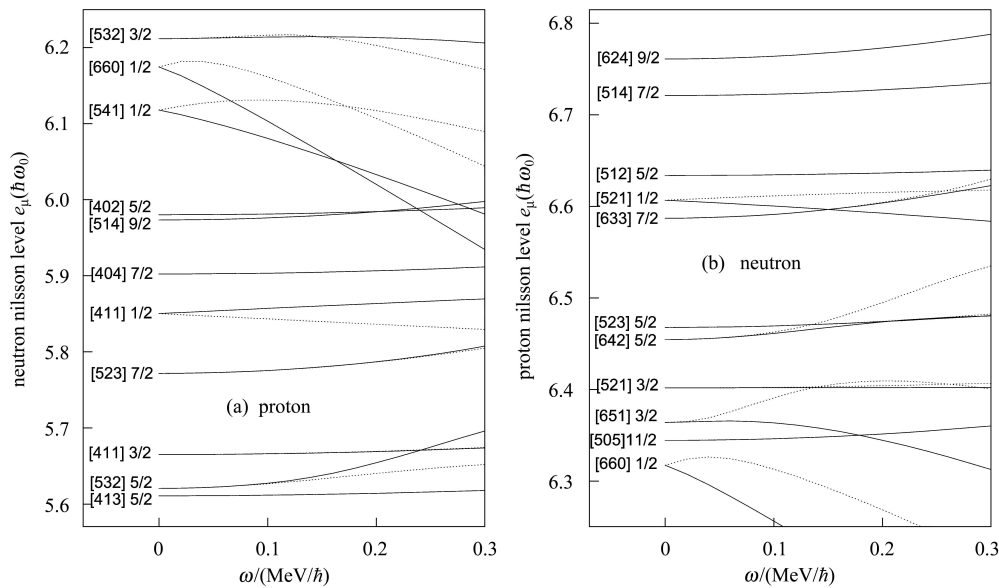

Fig. 1.   Nilsson levels near the Fermi surface of ^{170}Hf. $\varepsilon_2 = 0.245$, $\varepsilon_4 = 0.014$, κ and μ are taken from the Lund systematics[13, 14]. (a) proton, (b) neutron.
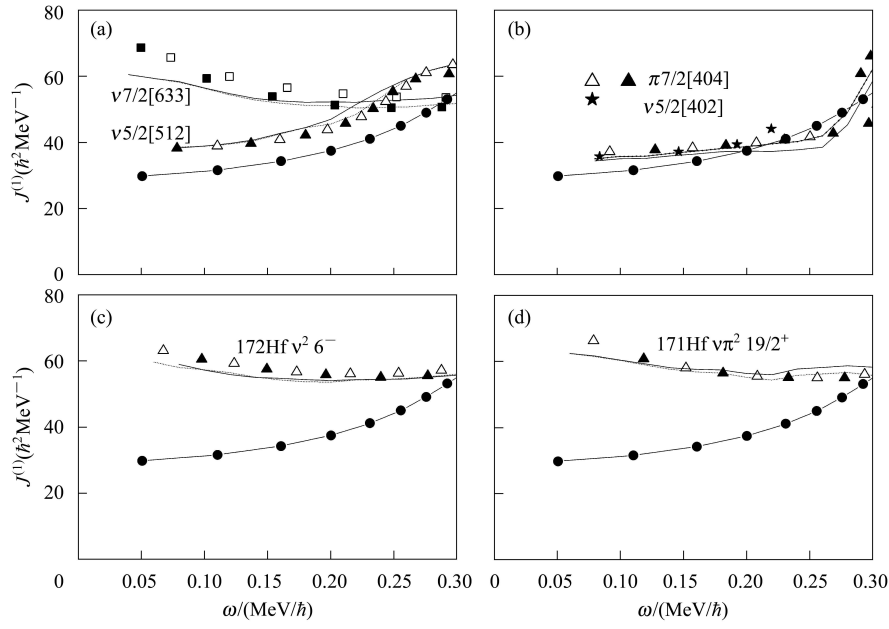
Fig. 2.   Comparison of the calculated and experimental MOIs of the quasiparticle bands of ^{171}Lu and ^{171}Hf. The experimental ground state band of ^{170}Hf is also presented (solid circles ●) as a reference. (a) The 1-qp band of ^{171}Hf, $\nu5/2^-[512]$ and $\nu7/2^+[633]$. The solid (open) triangles and squares are for $\alpha = 1/2$ ($\alpha = -1/2$). (b) The 1-qp band of ^{171}Lu, $\pi7/2^+[404]$, $\pi5/2^+[402]$. (c) The 2-qp band of ^{172}Hf, 1858.0 keV, $K^\pi = 6^-$, $\nu7/2^+[633] \otimes \nu5/2^-[512]$. (d) The 3-qp band of ^{171}Hf, 1645.3 keV, $K^\pi = 19/2^+$, $\nu7/2^+[633] \otimes \pi7/2^+[404] \otimes \pi5/2^+[402]$.
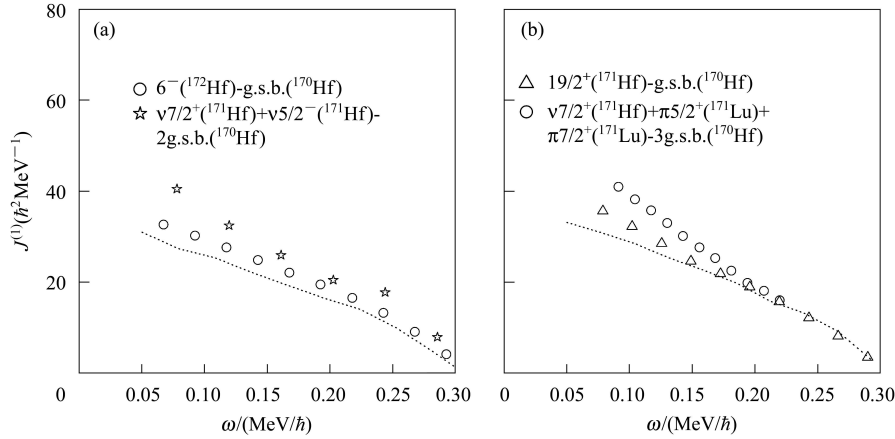

Fig. 3.   The nonadditivity of MOIs for multiquasiparticle bands. (a) The 2-qp $K^\pi = 6^-$ band, $\nu7/2^+[633] \otimes \nu5/2^-[512](\alpha = 0)$. The stars are for the experimental $[J(7/2^+[633]) - J_0] + [J(5/2^-[512]) - J_0]$ band. The circles are for the experimental $[J(6^-) - J_0]_{\alpha=0}$ band, and the dotted line is the calculated result by PNC method. (b) The 3-qp $K^\pi = 19/2^+$ band, $\nu7/2^+[633] \otimes \pi7/2^+[404] \otimes \pi5/2^+[402](\alpha = -1/2)$. The stars are for the experimental $[J(7/2^+[633]) - J_0] + [J(7/2^+[404]) - J_0] + [J(5/2^+[402]) - J_0]$. The circles are for the experimental $[J(19/2^+) - J_0]_{\alpha=-1/2}$, and the dotted line is the calculated result by the PNC method.

Even with no free parameters, our calculation can still well reproduce so large a number of experimental data of MOIs for various qp bands. The main reason is that the Pauli blocking effects on pairing are taken care of exactly, which is impossible in the BCS formalism. Fig. 2(a) shows that the MOIs of $\nu7/2^+[633]$ band of ^{171}Hf are much larger than those of the ground state band (gsb) of ^{170}Hf at low frequencies ($\hbar\omega < 0.30$ MeV), because the high-j intruder

neutron orbital $(i_{13/2})$ $\nu7/2^+[633]$ is blocked. The MOI of the $\nu5/2^-[512]$ ($h_{9/2}$) band of ^{171}Hf is moderately larger than the gsb of ^{170}Hf, because the Coriolis response of a $5/2^-[512]$ particle is smaller than that of a $7/2^+[633]$ ($i_{13/2}$) particle. Fig. 2(b) shows that the MOIs of $\pi7/2^+[404]$ and $\pi5/2^+[402]$ bands of ^{171}Lu are comparable to the gsb of ^{170}Hf. This is because both orbitals are of deformation aligned[1] and have very small Coriolis response. From this we can under-

stand why a lot of 1-qp bands of this kind are almost "identical" to the gsb of adjacent even-even nuclei[15]. The MOIs of the 2-qp $K^\pi = 6^-$ band of ^{172}Hf and the 3-qp $K^\pi = 19/2^+$ band of ^{171}Hf are much larger than the gsb of ^{170}Hf at low spins, because the high-j intruder neutron orbit $\nu 7/2^+[633]$ is involved in both bands.

The nonadditivity of MOIs of high-K multiquasiparticle bands is shown in Fig. 3. Fig. 3(a) is for the 2-qp $K^\pi = 6^-$ bands of ^{172}Hf. The stars are for the experimental $[J(7/2^+[633]) - J_0] + [J(5/2^-[512]) - J_0]$ (denoted by stars), which is expected to be equal to $[J(6^-) - J_0]$ according to the BCS prediction (1). However, the experimental $[J(6^-) - J_0]_{\exp}$ (denoted by circles in Fig. 3(a)) is smaller than

$[J(7/2^+[633]) - J_0]_{\exp} + [J(5/2^-[512]) - J_0]_{\exp}$. The calculated $[J(6^-)_{\text{cal}} - J_0]$ results are denoted by a dotted line, which is in agreement with the $[J(6^-) - J_0]_{\exp}$. Fig. 3(b) is the same as Fig. 3(a), but for the 3-qp $K^\pi = 19/2^+$ band of ^{171}Hf.

In summary, the experimental high-K 2- and 3-quasiparticle bands of the rare-earth nuclei are analyzed in detail. The observed large variations in MOIs with the quasiparticle configurations are investigated by the PNC treatment for the CSM with pairing. The large number of experimental data of MOIs can be reproduced well by the PNC calculations without free parameters. The observed nonadditivity of MOIs for multiquasiparticle comes from the destructive interference between the Pauli blocking effects on pairing.

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