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Investigation of Rotational Properties in Even-Even Nobelium Isotopes

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Abstract: The rotational properties of the synthesized even-even $^{248-264}$No isotopes have been investigated by means of total Routhian surface calculations. The calculated ground-state properties (e.g. β_2, β_4) are in agreement with previous calculations. The behaviors of moment of inertia of $^{252,\ 254}$No are well reproduced by our calculations. The systematic upbending in moment of inertia is attributed to band crossing. It is found that the $j_{15/2}$ neutron rotation-alignment is preferred for the lighter No isotopes, but the $i_{13/2}$ proton alignment is favored in the heavier ones.

Key words: rotational properties; total Routhian surface calculation; moment of inertia; band crossing

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1 Introduction

The exploration of new nuclides, especially the predicted superheavy island of stability, is a hot topic and important goal in nuclear science. Only in 2011, 100 new nuclides were discovered[1]. There also has been a fast progress in synthesis of superheavy nuclei, where the binding is derived from the quantum shell effects. Different locations have been predicted for the next doubly-magic nucleus beyond the last one, $^{208}_{82}$Pb$_{126}$[2]. The essence of shell correction is the nonuniform distributions of single-particle levels. The single-particle levels of the next spherical shell, however, cannot be accessible to date. The deformation can usually bring the high-j down-sloping orbitals from the next shell across the predicted closure down to the Fermi surface. This can provide an indirect way to study the single-particle states of the next spherical shell[3]. In addition, rotational frequency and deformation play similar roles in determining the energies of orbitals. Therefore, it is significant to study the rotational properties of deformed heavy nuclei. Over the past decade or so, new experimental data on rotational bands, associated moments of inertia and alignment properties for the A≈ 250 nuclei have been observed due to the advances in instrumentation[4–8]. Very recently, the high-spin band structure of superheavy nucleus $^{256}_{104}$Rf has also been observed up to a tentative spinof $20\hbar$[9].

The transfermium No isotopes with $Z = 102$ are the gateway and the closest even-Z isotopes to so-called superheavy elements[9]. There has been experimental observation of high-spin bands of $^{252,\ 254}$No in present isotope chain by in-beam spectroscopy[6–7]. These high-spin states can bring more useful information on shell structure. In addition, they also may give information on the fission barrier at high angular momentum which is important for understanding the produced mechanism for the heaviest elements[8]. Prior to this work, the rotational properties of some transfermium nuclei, paying attention to different physical aims, have been studied using various theoretical methods (see Refs. [2, 10] and references therein). In this paper, a systematic calculation for the $Z = 102$ No isotopes

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synthesized experimentally has been carried out using total Routhian surface (TRS) approach, focusing on the rotational properties and their physical mechanism.

2 The model

The TRS approach[11−13], which is based on the cranked shell model (CSM)[14−15], accounts well for the overall systematics of high-spin phenomena in rapidly rotating medium and heavy mass nuclei. The total Routhian, which is called "Routhian" rather than "energy" in a rotating frame of reference, is the sum of the energy of the non-rotating state and the contribution due to cranking. The energy of the non-rotating state consists of a macroscopic part that is obtained from the standard liquid-drop model[16] and a microscopic term representing the Strutinsky shell correction[17].

Single-particle energies needed in the calculation of the quantal shell correction are obtained from the nonaxially deformed Woods-Saxon (WS) potential[18] with the parameter set widely used for cranking calculations. The nuclear shape is defined by the standard parametrization in which it is expanded in spherical harmonics[18]. The deformation parameters include β_2, γ, and β_4, where γ describes nonaxial shapes. The pairing correlation is treated using the Lipkin-Nogami (LN) approach[19] in which the particle number is conserved approximately. This avoids the spurious pairing phase transition encountered in the simpler BCS calculation. Not only monopole but also doubly stretched quadrupole pairings are considered. The quadrupole pairing is important for the proper description of moments of inertia, though it has negligible effect on energies[20]. The monopole pairing strength, G, is determined by the average gap method [21] and the quadrupole pairing strengths are calculated to restore the Galilean invariance broken by the seniority pairing force[13, 22]. The Strutinsky quantal shell correction is performed with a smoothing range $\gamma = 1.20\hbar\omega_0$, where $\hbar\omega_0 = 41/A^{1/3}$ MeV, and a correction polynomial of order $p = 6$.

Cranking indicates that the nuclear system is constrained to rotate around a fixed axis (the x-axis) at a given rotational frequency ω. Pairing correlations are dependent on rotational frequency and deformation. The resulting cranked-Lipkin-Nogami (CLN) equation takes the form of the well known Hartree-Fock-Bogolyubov-like (HFB) equation[13]. For a given rotational frequency and point of deformation lattice, pairing is treated self-consistently by solving this equation using a sufficiently large space of WS single-particle states. Certainly, symmetries of the rotating potential can be used to simplify the cranking equations. In the reflection-symmetric case, both signature, r, and intrinsic parity, π are good quantum numbers. The solution characterized by (π, r) provides simultaneously the energy eigenvalue from which it is straightforward to obtain the energy relative to the non-rotating state. After the numerical calculated Routhians at fixed ω are interpolated using cubic spline function between the lattice points, the equilibrium deformation can be determined by minimizing the calculated TRS.

3 Results and discussions

Our previous study[23] shows that there is no octupole correlations at normal deformed minima for these even-even nuclei $^{248-264}$No investigated here. We, therefore, perform the numerical calculations on (β_2, γ, β_4) deformation space. In order to test the validity of the TRS approach for these nuclei, in Fig. 1, we display the calculated ground-state deformations, comparing with the previous results given by Möller et al.[24] and by Sobiczewski et al.[25]. One can see that the ground-state β_2, β_4 deformations change gently with increasing neutron number. To some extent, our calculation is in agreement with other studies mentioned above, especially for β_4. Although the

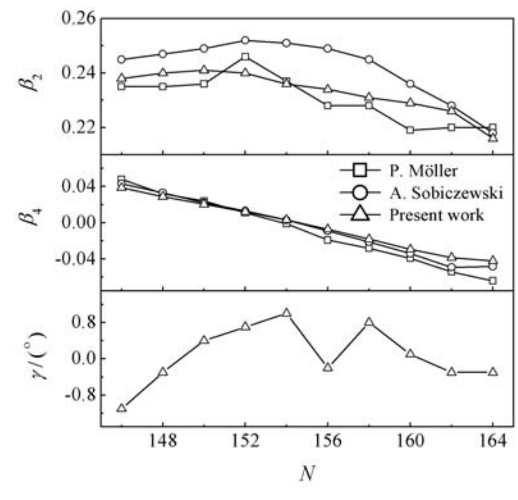

Fig. 1 Calculated ground-state deformations β_2 (top), β_4 (middle) and γ (bottom) for even-even nuclei $^{248-266}$No. The β_2 and β_4 deformations are compared with previous calculations.

most important β_2 deformations have quantitatively small differences, they consistently indicate these No nuclei are prolate deformed, and it has been confirmed experimentally for ^{254}No[8]. In Fig. 1, we also can see that these nuclei have very small triaxial deformation.

The excitation energy of the first 2^+ state in the ground-state band, E_{2^+}, is a sensitive indicator of nuclear excited mode. If the energy of such a state is found to be of about 40 $\sim$ 50 keV, as is expected in the A$\approx$250 mass region, the state cannot be of any other nature than rotational. Sobiczewski et al.[25] could reproduce and predict the E_{2^+} values of heavy nuclei very well. Their published E_{2^+} values for No isotopes are plotted versus neutron number in the upper panel of Fig. 2. In the lower panel of this figure, our calculated pairing-energy gaps for protons and neutrons are shown. From the systematics, one can see the E_{2^+} values have dips at N=152 and 162. It is possible that these energy changes are due to differences in the moments of inertia which are related to deformation and pairing correlation. However, there are no expected deformation maxima at N=152 and 162. These sharp decreases of E_{2^+} are explained to be mostly related to the deformed shell gaps[25], where the pairing energy gap becomes smaller, resulting in a larger moment of inertia. The present calculation also well reproduce the correlation between the neutron pairing gaps and the deformed shell gaps. It can be found that the neutron pairing gaps calculated by us have local minimum at $N = 152$ and minimum at $N = 162$.

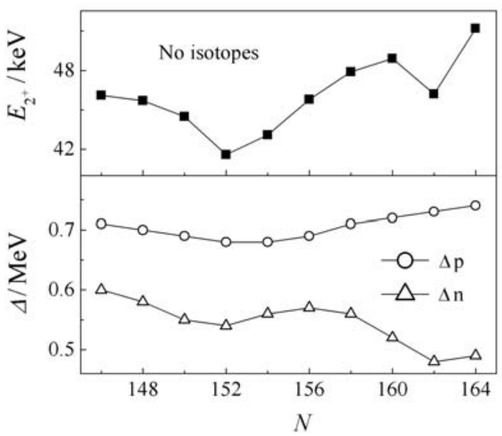

Fig. 2 Dependences of the energy E_{2^+} of the first rotational state 2^+ (the upper panel) and nucleon pairing-energy gaps (the lower panel) on neutron number N. Data of the energy E_{2^+} are taken from Ref.[25].

The variation of moments of inertia as functions of mass and rotational frequency can provide useful information on the energies of single-particle orbitals, particularly of those with high j (particle angular momentum). The calculated kinematic and dynamic moments of inertia, $J^{(1)}$ and $J^{(2)}$, for the ground-state bands of even-even nuclei $^{248-264}$No, drawn as the open symbols, are plotted as functions of rotational frequency in Fig. 3, together with the extracted experimental values (solid symbols) for $^{252,\,254}$No. One can see that the agreements of the moments of inertia for $^{252,\,254}$No between theory and experiment, which can provide a test of nuclear model[26], are to a great extent excellent, especially at low frequency. At high-spin region, the different rotational behaviors of ^{252}No and ^{254}No have recently been explained in terms of high-order β_6 deformation by Liu et al[2]. The moments of inertia of $^{248-264}$No increase with rotational frequency, as seen in Fig. 3, probably due to the gradual alignment of quasiparticles, specially those occupying the high-j orbitals. At low-spin region, they increase gently with spin, but climb more rapidly after a critical frequency, showing a upbending phenomenon. Moreover, the more sensitive moments of inertia $J^{(2)}$ show a irregular changing behavior that still need to be tested experimentally. The moment of inertia is an experimental quantity that is sensitive to shape changes, specially the quadrupole deformation. The ω dependences of β_2 for even-even $^{248-264}$No are shown in Fig. 4. We observe a nearly constant behavior for the low-spin region, but a sudden decrease in the high-spin states where rotation-alignment occurs. Obviously, the increase in moment of inertia, as shown in Fig. 3, cannot be explained by a increased deformation. It should be attributed to a decrease in the nucleon pairing correlations due to the Coriolis anti-pairing (CAP) effect. The reduction of β_2 as a function of rotational frequency may be explained in terms of the rotation-induced deoccupation of the antialigned high-j low-Ω quasiparticle orbitals[27]. For prolate deformed nuclei, the steep slop of high-j low-Ω orbital, as known, represents the strong driving force of this orbital to larger quadrupole deformation. On the contrary, the loss of antialigned high-j low-Ω orbits due to Coriolis plus centrifugal forces can cause the nucleus to become less deformed. In order to further analyze the mechanism behind the upbending in the moments of inertia, we display the calculated collective angular momenta in Fig. 5, together with proton and neutron components. The aligned angular momentum, which is equivalent to the moment of inertia

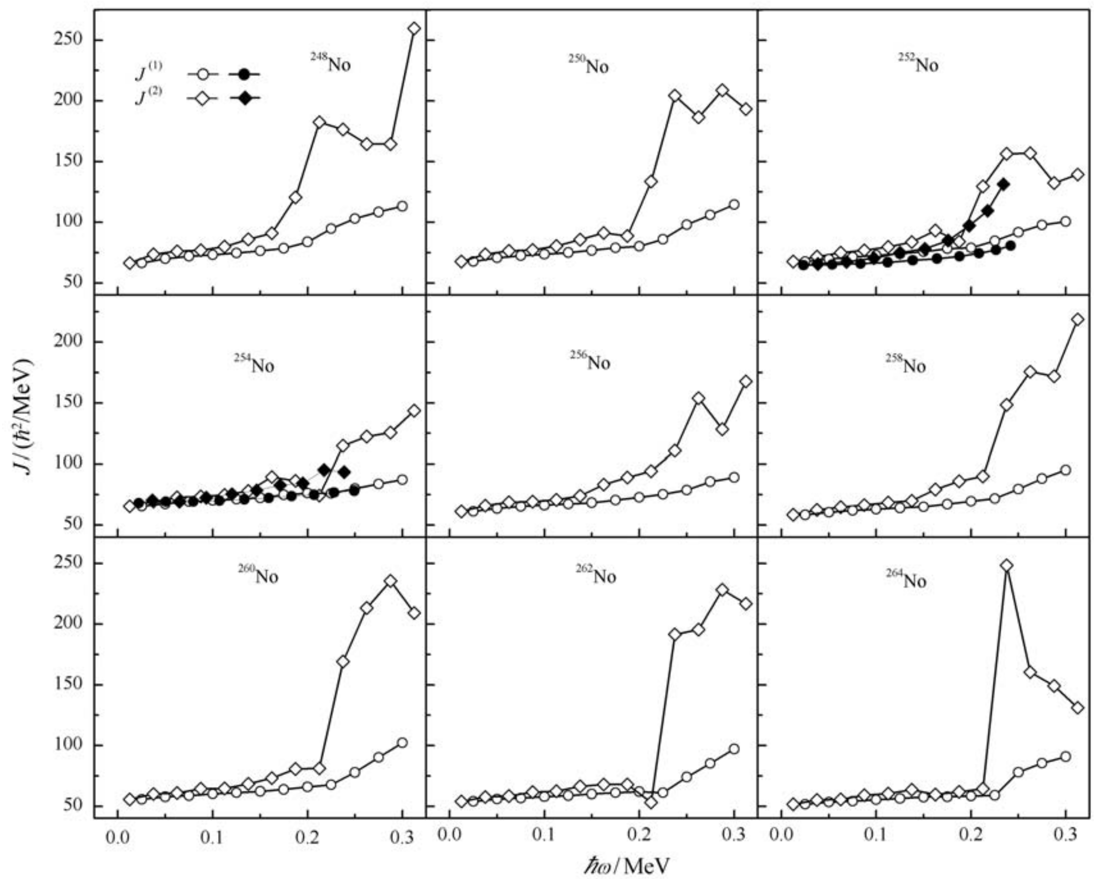

Fig. 3　Kinematic and dynamic moments of inertia $J^{(1)}$ and $J^{(2)}$ of even-even nuclei $^{248-264}$No vs the rotational frequency $\hbar\omega$ from experiments (filled symbols) and present calculations (open symbols).

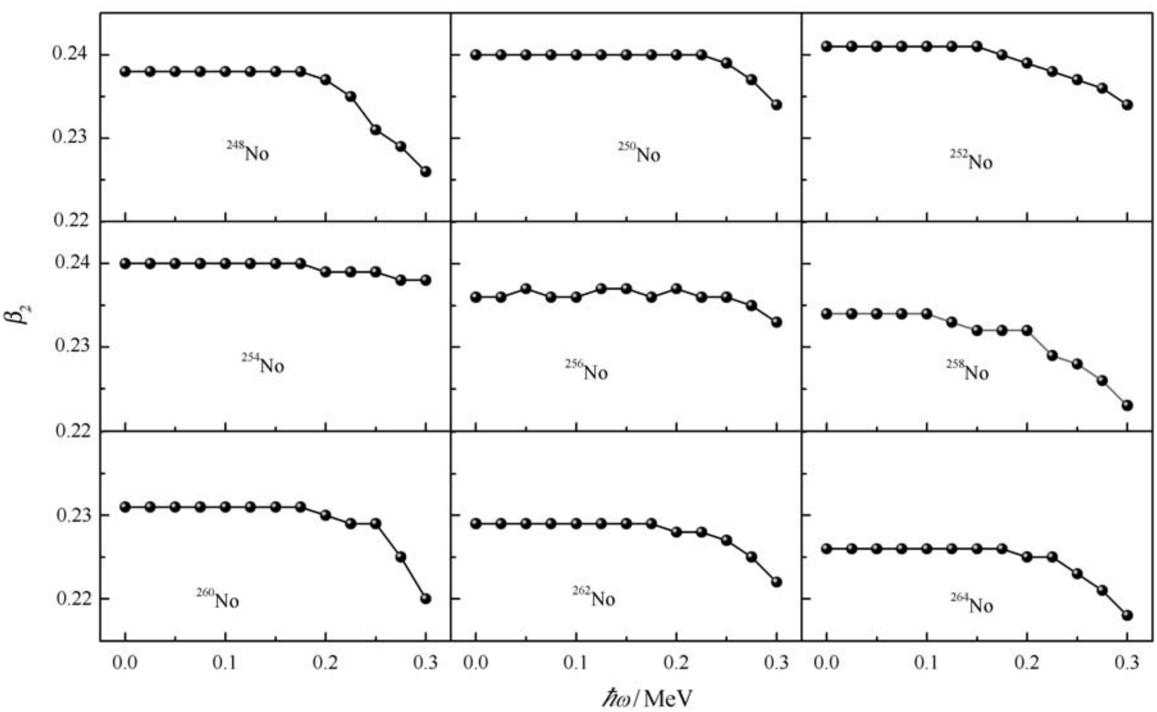

Fig. 4　Calculated quadrupole deformations β_2 vs the rotational frequency $\hbar\omega$ for even-even nuclei $^{248-264}$No.

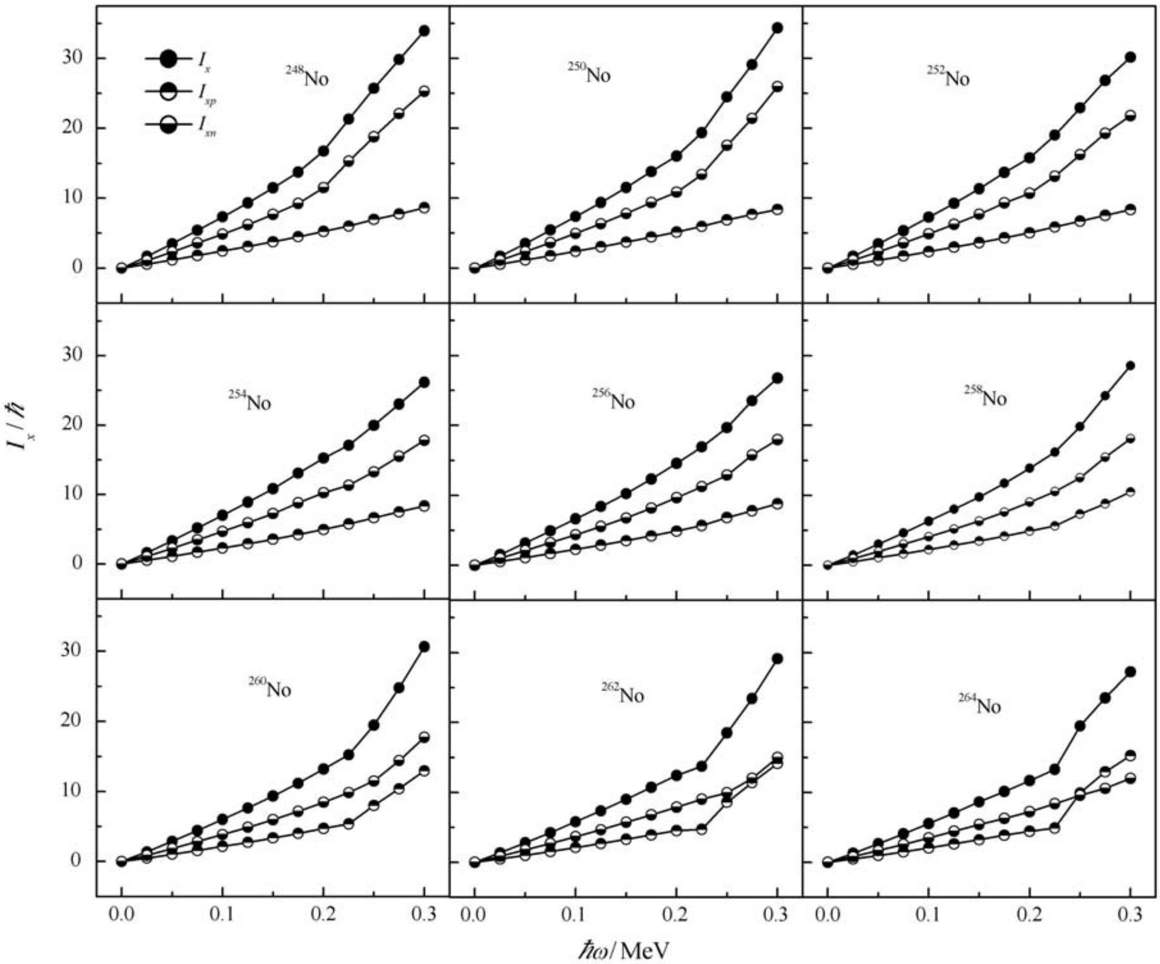

Fig. 5　Calculated angular momentum as a function of rotational frequency $\hbar\omega$ for even-even nuclei $^{248-264}$No. Proton and neutron contributions are shown simultaneously.

here, shows the upbending behavior where the rotation-alignment of a pair of high-j nucleons occurs. In this transfermium region, the related high-j single-particle states are proton $i_{13/2}$ and neutron $j_{15/2}$ orbitals. Several previous studies[28–30] indicated the alignments of $i_{13/2}$ proton and $j_{15/2}$ neutron pairs are strongly competitive. For example, it was pointed out that the proton and neutron alignments take place simultaneously in the lighter No isotopes (e.g in $^{252,\ 254}$No), while the $j_{15/2}$ neutrons win in the competition between proton- and neutron-alignment in the heavier No isotopes (e.g. in ^{256,258}No)[30]. As shown in Fig. 5, the present calculations reproduce the competitive beha-vior well, but also show some differences with the studies mentioned above. One can find that the neutron angular momentum is larger than the proton component and upbends earlier with rotation in the lighter $^{248-256}$No. The proton and neutron alignments take place simultaneously in ^{258}No due to the emergence of the almost same upbending frequencies. After ^{258}No nucleus, the upbending in the collective angular momentum is similar to the proton component, and the relative proton contribution in the angular momentum become larger and larger. As seen in ^{264}No, the proton component even becomes the main contribution to the total angular momentum at high-spin region. Therefore, it can be concluded that the first band crossing are mainly ascribed to rotation-alignment of a pair of $j_{15/2}$ neutrons for the lighter No isotopes and $i_{13/2}$ protons for the heavier ones. The different rotation-alignments are related to the relative positions of the relevant orbitals to the Fermi surface. With increasing neutron number, the Fermi surface of No isotope moves to aligned higher-Ω orbitals, Where the alignment of a neutron broken pair may be delayed (become unfavored). However, experimental searches where the have so far not provided convincing evidence.

4 Summary

In conclusion, the deformations and moments of inertia of even-even $^{248-264}$No nuclei have been calculated using TRS method in (β_2, γ, β_4) deformation space. Our calculations are compared with previous calculations and available experiments. It is suggested that there are deformed shell gaps at $N = 152$ and 162. The upbending in moments of inertia is attributed to rotation-alignment of high-j neutron (proton) pair for the lighter (heavier) No isotopes. Our prediction of rotational properties for $^{248-264}$No awaits future experimental confirmation.

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偶偶No同位素转动性质研究

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摘要: 通过总Routhian 面计算方法研究了$Z = 102$号元素已实验合成的偶偶$^{248-264}$No同位素的转动性质。计算的基态形变β_2, β_4与前人的计算相符。$^{252, 245}$No两核基态带的转动惯量特征能得到基本再现。偶偶$^{248-264}$No同位素转动惯量系统上弯的现象可归因于带交叉。研究还表明，推转时质子与中子顺排有强烈竞争，在较轻的No同位素中$j_{15/2}$中子拆对顺排较为优先，而在较重的No核中$i_{13/2}$质子顺排更加优先。

关键词: 转动特征；总Routhian 面计算；转动惯量；带交叉

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