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Configuration-Dependent Bands in ^{169}Re *

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Abstract High-spin states in ^{169}Re were studied and resulted in the identification of a strongly coupled band based on the 9/2$^-$ [514] Nilsson state and a decoupled band built on the $h_{9/2}$ intruder proton orbital (nominally 1/2$^-$ [541]). The cranked shell nodel calculations present configuration-dependent deformations that can explain the different band crossing frequencies. The experimental 9/2$^-$ [514] band in ^{169}Re shows the largest signature splitting at low spin among the known odd mass Re isotopes. After the alignment of a pair of the $i_{13/2}$ neutrons, the phase of the splitting is inverted with a significantly reduced amplitude. Additionally, a three-quasiparticle band was observed and assigned to be built likely on the π9/2$^-$ [514] $\otimes$ AE configuration.

Key words rotational bands, configuration, cranked shell model

1 Introduction

The systematic study of spectroscopies in odd-Z isotopes can provide specific information about the influence of neutron shell fillings on nuclear level structure[1—3]. Neutron orbital fillings can change nuclear deformations, the characters of quasineutron excitations and therefore the features of spectroscopies. Particularly, these changes can be dramatic in the transitional mass region. The very neutron deficient odd-Z nuclei in the mass 170 region are located on the outer edge of the deformed rare earth nuclei. These nuclei are expected to be rather soft with respect to β and γ deformations. Therefore, the shape-polarizing effects of individual nucleons can be significant. Nuclear shapes can be strongly dependent on configurations and neutron numbers[1—3]. For light odd-A Re isotopes, the proton Fermi surface is at the top of the $h_{11/2}$ and $d_{5/2}$ subshells and close to the $h_{9/2}$ 1/2$^-$ [541] and $i_{13/2}$ 1/2$^+$ [660] intruder orbits[2,3]. A less deformed shape is favored with the 9/2 [514] and 5/2$^+$ [402] orbits occupied. On the other hand, the $h_{9/2}$ and $i_{13/2}$ orbits with Ω = 1/2 are strongly down-sloping as a function of deformation. The nucleus will be driven towards larger deformation when the down-sloping orbits are occupied by the unpaired proton. In this paper, we present the configuration-dependent band structure in ^{169}Re.

2 Experiment and results

The excited states in ^{169}Re were populated via the ^{144}Sm (^{28}Si, 1p2n)^{169}Re reaction. The ^{28}Si beam was provided by the tandem accelerator at the Japan Atomic Energy Research Institute (JAERI). The target is an isotopically enriched ^{144}Sm metallic foil of 1.3 mg/cm^2 thickness with a 7.0 mg/cm^2 Pb backing. A γ-ray detector array comprising 12 HPGe's with BGO anti-Compton (AC) shields was used in the measurements. The experimental information and level scheme construction have been described in detail in Refs. [4,5]. The level scheme of ^{169}Re, including three rotational bands, is shown in Fig. 1. The cranked shell model (CSM) is very successful in describing high-spin features like band-crossing fre-

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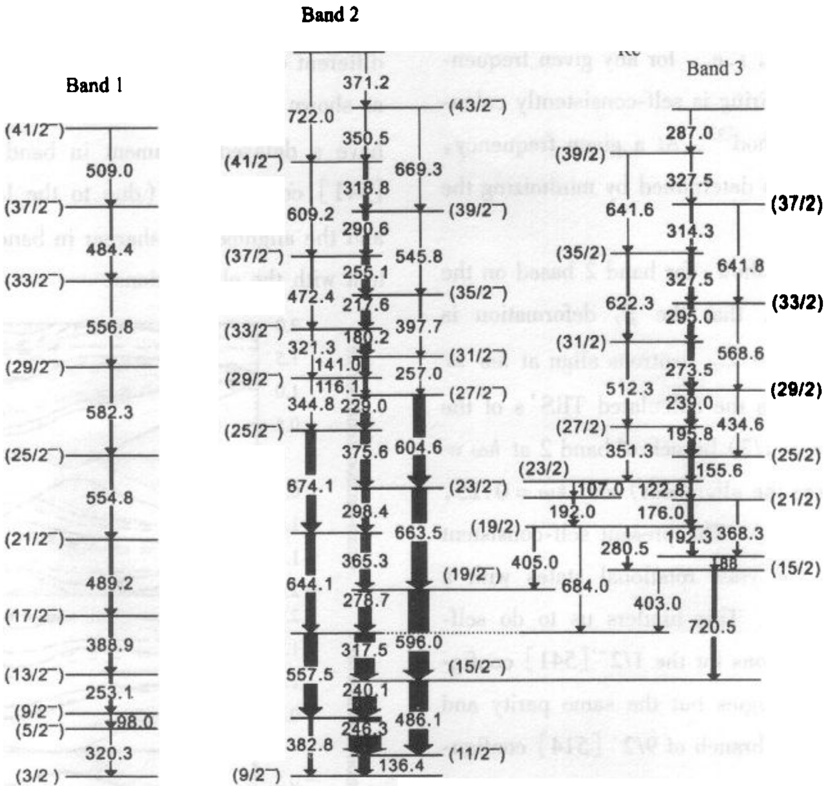

Fig.1.　Level scheme of ^{169}Re.

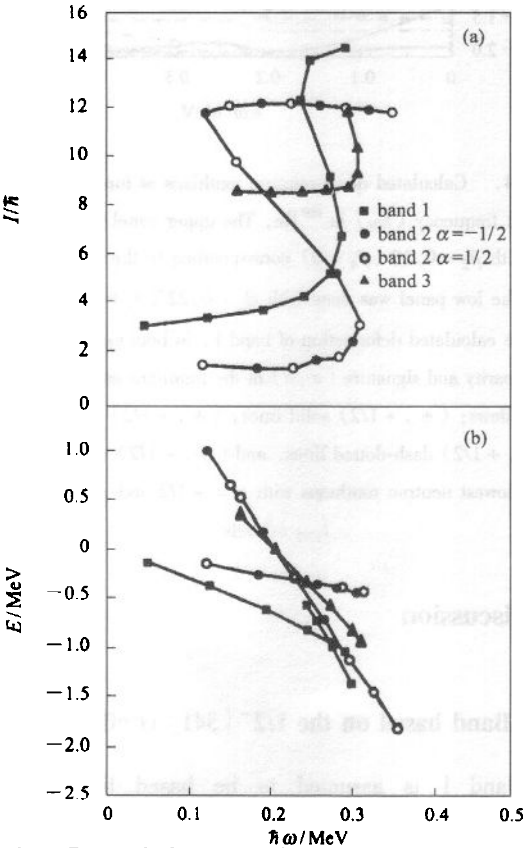

Fig.2.　Extracted alignment and routhian energy for measured rotational bands in ^{169}Re (panels (a) and (b), respectively). The labels in the legends indicate the bands as they are labeled in Fig. 1. The Harris reference parameters are chosen to be $J_0 = 20$ $\hbar^2$ MeV^{-1} and $J_1 = 60$ $\hbar^4$ MeV^{-3}

quencies, rotational aligned angular momenta and signature splittings of many nuclei. In order to study the effect of rotation on the single-particle motion and compare the properties of the observed rotational bands to the results of CSM calculations, we must transform the experimental excitation energies and spins into the rotating frame. The quasiparticle alignment and Routhian energy for all bands observed in ^{169}Re are extracted and plotted vs rotational frequency in Fig. 2.

3 Theoretical calculations

In order to have a deeper understanding of the band structures in ^{169}Re, we have performed cranked-shell-model (CSM) calculations by means of Total-Routhian-Surface (TRS) method[6] in the three-dimensional deformation β_2, β_4, γ space. The nonaxial deformed Woods-Saxon (WS) potential[7] was employed. Both monopole and quadrupole pairings[8] were included. To avoid the spurious pairing phase transition encountered in the BCS approach, we used the approximate particle number projection named the Lipkin-Nogami pairing[9]. The pairing correlation is dependent on rotational frequency ($\hbar\omega$) and deformation . In order to include such dependence in the

TRS, we have done pairing-deformation-frequency self-consistent TRS calculations, i.e., for any given frequency and deformation, the pairing is self-consistently calculated by the HFB-like method[9]. At a given frequency, the deformation of a state is determined by minimizing the calculated TRS.

The TRS calculations show, for band 2 based on the $9/2^-$ [514] configuration, that the β_2 deformation is about 0.18 and a pair of the $i_{13/2}$ neutrons align at $\hbar\omega \approx 0.22$ MeV. Fig. 3 displays the calculated TRS's of the negative signature ($\alpha = -1/2$) branch of band 2 at $\hbar\omega = 0.10, 0.15$ MeV (before the alignment) and $\hbar\omega = 0.25, 0.30$ MeV (after alignment). The present self-consistent CSM works well only for yrast rotational states with a given parity and signature. This hinders us to do self-consistent cranked calculations for the $1/2^-$ [541] configuration that has higher energies but the same parity and signature as the $\alpha = +1/2$ branch of $9/2^-$ [514] configuration. However, we did the configuration-constraint deformation calculation[10] for the $1/2^-$ [541] configuration. The calculitions show that $1/2^-$ [541] configuration has a larger deformation with $\beta_2 = 0.22$ ($\gamma = 0°$). With the different deformations, we plotted quasi-neutron routhians as shown in Fig. 4. It can be seen that the $i_{13/2}$ neutrons have a delayed alignment in band 1 built on the $1/2^-$ [541] configuration (due to the larger β_2 deformation) and the alignment is sharper in band 2. These are consistent with the observations.

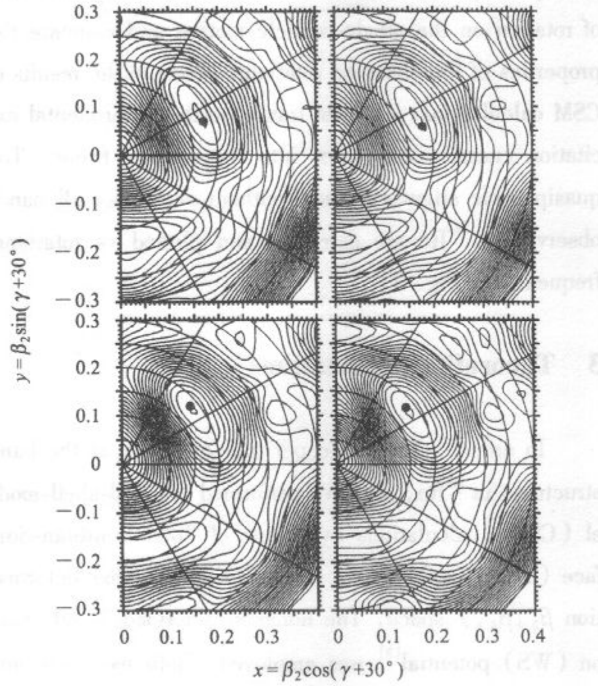

Fig.3. Calculated TRS for the $(\pi, \alpha) = (-, -1/2)$ branch of band 2. The up-left and up-right panels corresponding to $\hbar\omega = 0.10$ and 0.15 MeV (before the $i_{13/2}$ neutron alignment); low-left and low-right panels corresponding to $\hbar\omega = 0.25$ and 0.30 MeV (after the alignment). The energy difference between contours is 200 keV.

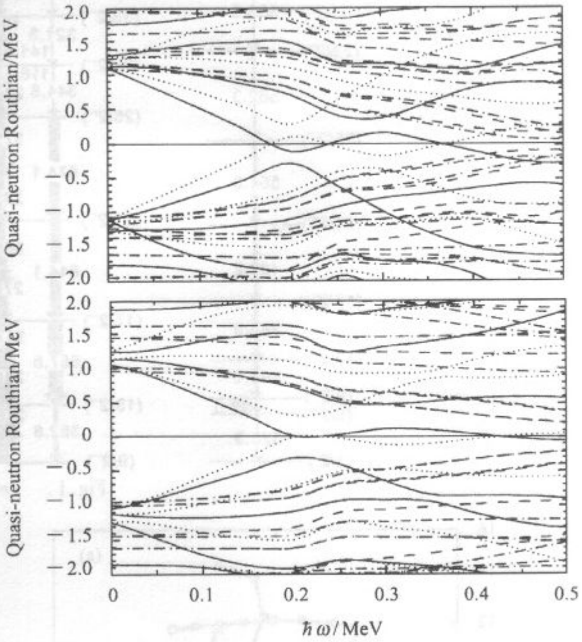

Fig.4. Calculated quasi-neutron routhians as function of rotational frequency ($\hbar\omega$) in ^{169}Re. The upper panel was calculated with $\beta_2 = 0.18$ ($\beta_4 = 0$) corresponding to the case of band 2. The low panel was done with $\beta_2 = 0.22$ ($\beta_4 = 0.026$) that is the calculated deformation of band 1. In both cases, $\gamma = 0°$. The parity and signature (π, α) of the routhians are represented as follows: $(+, +1/2)$ solid lines, $(+, -1/2)$ dotted lines, $(-, +1/2)$ dash-dotted lines, and $(-, -1/2)$ dashed lines. The lowest neutron routhians with $\alpha = +1/2$ and $-1/2$ are the $i_{13/2}$ orbitals.

4 Discussion

4.1 Band based on the $1/2^-$ [541] configuration

Band 1 is assumed to be based likely on the $1/2^-$ [541] Nilsson orbit and the band head has a spin-parity of $5/2^-$[4,5]. This band has an alignment of approximately $3.5\hbar$ before the backbend (see Fig.2), in agreement with what is expected for an aligned proton state occupying the $1/2^-$ [541] orbit. As shown in Fig.2, the band crossing takes place at $\hbar\omega = 0.27$ MeV, where the gain in the alignment is about $10.5\hbar$. The AB neutron crossing is delayed by about 40 keV in band 1 compared with the strongly coupled band[1]. Similar shifts have been observed for the 1/2$^-$ [541] bands in a large number of odd-Z nuclei in this mass region and can be qualitatively attributed to the larger quadrupole deformation for the 1/2$^-$ [541] configuration[1-3], which has a negative slope in the Nilsson diagrams and thus drive the nucleus toward larger deformation. Theoretical calculation predicted that the quadrupole deformation β_2 values were 0.22 and 0.18 for the 1/2$^-$ [541] and 9/2$^-$ [514] configurations, respectively. Since the neutron Feimi level, λ_ν, is above the highly alignable low-Ω $i_{13/2}$ neutron orbits, an increased deformation corresponds to a increased quasineutron energy, E_ν, for the $i_{13/2}$ quasineutron:

$$E_\nu = \sqrt{\Delta^2 + (\varepsilon_\nu - \lambda_\nu)^2}, \qquad (1)$$

resulting in a delayed AB neutron band crossing[11]. Fig. 4 displays that the neutron AB crossing frequency increases with increasing quadrupole deformation.

4.2　Band based on the 9/2$^-$ [514] configuration

Band 2 is associated with the 9/2$^-$ [514] configuration. It experiences a strong backbending at $\hbar\omega = 0.23$ MeV with gain of $10.5\hbar$ in alignment (see Fig. 2), corresponding well to the AB neutron crossing in the 9/2$^-$ [514] bands of the neighboring odd-A Re isotopes[2,3]. The experimental neutron AB crossing frequency is well reproduced by the CSM calculation as shown in Fig. 4. The TRS calculation shown in Fig. 3 is corresponding to the 9/2$^-$ [514] configuration. This configuration is γ soft at low rotational frequencies with potential minimum at $\beta_2 \approx 0.18$ and $\gamma \approx -10°$. After the first band crossing the predicted nuclear shape is still γ soft with the energy minimum at about the same quadrupole deformation, but at small positive γ deformation.

For systems with odd particle number, the signature defined by $\alpha_f = 1/2(-1)^{j-1/2}$ (favored signature) is lowered in energy with respect to the $\alpha_u = 1/2(-1)^{j+1/2}$ (unfavored) signature, where the angular momentum of the odd particle is expressed by j. The signature splitting Δe is defined as the difference in energies at a given rotational frequency for the pair of signature partners. Fig. 5 presents plots of the signature splittings for the 9/2$^-$ [514] bands in the light odd-A Re nuclei[2,3,12], defined as[13]

$$S(I) = [E(I) - E(I-1)] - \frac{1}{2}[E(I+1) - E(I) + E(I-1) - E(I-2)], \qquad (2)$$

Here $E(I)$ is the level energy of state I; $S(I)$ is directly proportional to the signature splitting Δe, but magnified by approximately a factor of two. There is a clear energy splitting between the two signatures at low frequencies, and after the $i_{13/2}$ neutron alignment the phase of signature splitting is inverted with a much reduced amplitude (see the insets of Fig. 5). As shown in Fig. 5, the experimentally observed signature splitting in the very neutron-deficient isotopes is unexpectedly large, and increases rapidly with decreasing neutron number. The signature splitting as high as about 30 keV is observed at low spins in ^{169}Re.

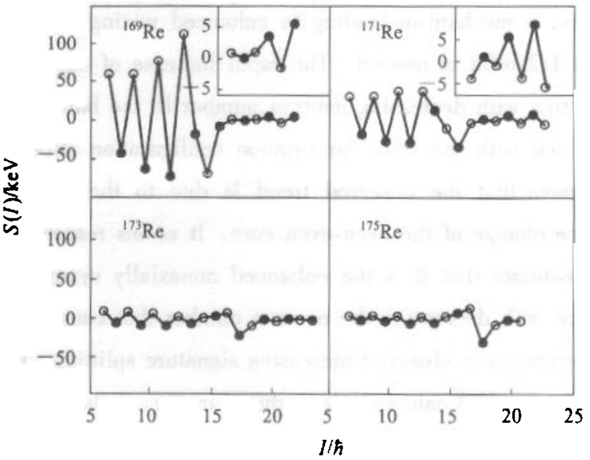

Fig.5.　Signature splitting $S(I)$ as a function of spin I for the 9/2$^-$ [514] bands in $^{169-175}$Re. The filled and open symboles correspond to the favored and unfavored signatures, respectively.

Signature splitting of the energies is considered generally as a consequence of the mixing of the $\Omega = 1/2$ orbits into the wave functions, duo to the Coriolis interaction. Since the proton Fermi level lies high in the $h_{11/2}$ subshell in Re isotopes with a proton number of 75, the mixing of the $\Omega = 1/2$ components into the wave functions should be very small for an axially symmetric nuclear shape. A signature splitting does not necessarily imply a triaxial nuclear shape, but the magnitude of Δe could offer a clue for possible γ deformation. It is well known that the magnitude of signature splitting is expected to be very dependent on several properties such as the nuclear deformation, paring, and shell filling[14]. For example, decreasing nuclear quadrupole deformation β_2 can result in an increased signature spitting since in the lowest order Δe is proportional to $(\beta_2)^{-2\Omega+1}$ if paring is neglected[14]. The increased signature splitting amplitudes for the lighter Re isotopes seem therefore to be explained in terms of the decreasing nuclear quadrupole deformation as indicated by the theoretical calculation[15]. However, changing the pairing gap, quadrupole deformation β_2, and hexadecapole deformation ε_4 in large intervals, the particle-rotor and Cranked shell-model calculations adopting an axially symmetric nuclear shape show that the predicted magnitude of the signature splitting is nevertheless much less than the observed value in the neutron-deficient isotopes[16]. Thus, in order to reproduce the large signature splitting in the $9/2^-$ [514] bands in light Re isotopes, a mechanism leading to enhanced mixing with an $\Omega = 1/2$ orbit is needed. The rapid increase of signature splitting with decreasing neutron number in the bands associated with the same quasiproton configuration strongly suggests that the observed trend is due to the nuclear shape change of the even-even core. It seems reasonably to postulate that it is the enhanced nonaxially symmetric shape with decreasing the neutron number that causes the experimentally observed increasing signature splitting. Indeed, the TRS calculations as shown in Fig. 3 show energy minimum with negative γ deformation at low frequencies, and the increasing γ softness with decreasing neutron number for odd-A Re isotopes can also be predicted.

R. Bengtsson et al.[17] pointed out that the positive γ deformation may cause signature inversion in the configuration of $\pi h_{11/2} \otimes \nu i_{13/2}^2$, where the aligned neutrons could produce a positive γ deformation. After the $i_{13/2}$ neutron alignment the predicted nuclear shape, as shown in Fig. 3, is γ soft with the energy minimum at apparent positive γ deformation. Therefore, the observed inversion of signature splitting with small amplitude at high frequencies might indicate that the γ driving force of the aligned $i_{13/2}$ neutrons, favoring positive direction, is stronger than that of the strongly coupled $h_{11/2}$ proton favoring negative γ value, and this might result in a nuclear shape with small positive γ deformation.

4.3 Band based possibly on the $\pi 9/2^-$ [514] $\otimes\nu AE$ configuration

As shown in Fig. 2, band 3 has the largest aligned angular momentum with a value of about $8.5\hbar$ at low spins. The alignment was deduced by assuming a band-head K value of 4.5; the alignment in such high-spin levels is expected to be less influenced by the uncertainty of the K value. This band shows an upbend at $\hbar\omega \approx 0.31$ MeV, and there is no signature splitting up to the highest level observed. In view of such a large alignment, band 3 must be based on a configuration of at least three quasiparticles. The band crossing frequency of $\hbar\omega \approx 0.31$ MeV is much higher than the AB neutron crossing in the neighboring nuclei[2,3,18—20], indicating that band 3 involves an $i_{13/2}$ neutron. A one-quasiparticle occupation of the lowest $\nu i_{13/2}$ state would inhibit the normal $\nu i_{13/2}$ alignment from occurring at the expected rotational frequency. This well-known blocking effect can be seen in odd-N nuclei throughout the rare-earth region. Inspecting the level structure in the nuclei around ^{169}Re[18—21], we propose that band 3 is likely based on the $\pi 9/2^-$ [514]$\otimes\nu AE$ configuration. Here, $A(\pi = +, \alpha = +1/2)$ and $E(\pi = -, \alpha = +1/2)$ are the conventional Cranked Shell Model orbits labelling the lowest configurations in the $\nu i_{13/2}$ and $\nu f_{7/2}\, h_{9/2}$ subshells[18], respectively. The A and E orbits were observed at very low excitation energies at the neighboring odd-N nuclei[19,18,21]; the AE configurations were also identified at excitation energies around 1.6 MeV in the neighboring even-even nuclei[18—21], which are comparable with the band-head energy of band 3. Thus, the $\pi 9/2^-$ [514] $\otimes\nu AE$ configuration would be expected to be energetically favorable in ^{169}Re. Most of the alignment in band 3 would be contributed by the $\nu i_{13/2}$ quasiparticle, while the rest might be associated with the other two quasiparticles. The upbend at $\hbar\omega \approx 0.31$ MeV may be caused by the BC neutron alignment because the crossing frequency is similar to those for the BC neutron alignments observed in the nuclei around ^{169}Re[18—21].

5 Summary and conclusions

For ^{169}Re, the $i_{13/2}$ neutron alignments have been observed in the $1/2^-$ [541] and $9/2^-$ [514] bands at $\hbar\omega = 0.27$ and 0.23 MeV, respectively. The difference between the crossing frequencies can be interpreted in terms

of shape effects since the different proton orbits favor different nuclear shapes. There is a quite large energy splitting between the two signatures of the 9/2$^-$[514] band at low frequencies, and after the $i_{13/2}$ neutron alignment the phase of signature splitting is inverted with a much reduced amplitude. The TRS calculations show that the 9/2$^-$[514] configuration tends to have nonaxial shape with negative γ values at low frequencies, and after the $i_{13/2}$ neutron alignment the predicted positive γ deformation may cause signature inversion in configuration of $\pi h_{11/2}\otimes\nu i^2_{13/2}$. Systematics of the signature splitting for the 9/2$^-$[514] bands at low spin in the light odd-A Re isotopes suggests that the nucleus becomes more γ soft and has larger γ deformation while decreasing the neutron number. By referring to the level structure in the nuclei around ^{169}Re, it is proposed that the three-quasiparticle band is likely built on the π9/2$^-$[514]$\otimes\nu AE$ configuration.

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^{169}Re 的转动带结构组态相关性研究*

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摘要　研究了^{169}Re 的高自旋态能级结构，建立了组态为 π9/2$^-$[514]的强耦合带和组态为 π1/2$^-$[541]的退耦合带. 推转壳模型(Cranked shell model)计算结果表明组态相关的不同形变能够解释这些转动带的不同带交叉频率. 在已知的奇 ARe 核中，^{169}Re 的 9/2$^-$[514]转动带在低自旋时具有最大的能量旋称劈裂. 当一对 $i_{13/2}$ 中子顺排后，旋称劈裂发生了反转，并且劈裂的幅度非常显著地减少了. 另外，还观测到了一个三准粒子激发带，并指定了它的最可能组态为 π9/2$^-$[514]$\otimes\nu AE$.

关键词　转动带　组态　推转壳模型

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