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Triaxial Deformation in very Neutron-deficient Re Nuclei*

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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. The $9/2^-[514]$ band in ^{169}Re shows the largest signature splitting at low spin among the known odd mass Re isotopes. For the $9/2^-[514]$ bands in light odd-A Re isotopes, the signature splitting of the Routhians and its relation with the signature dependence of M1 transition matrix elements are investigated in connection with the deviation of nuclear shape from axial symmetry, suggesting an appreciable negative γ deformation at low spin for the very neutron-deficient odd-A Re isotopes.

Key words: tiaxial deformation; signature splitting; odd-A nuclei
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The $9/2^-[514]$ bands were observed systematically in the rare-earth mass region[1-4]. The $9/2^-[514]$ bands are based on an $h_{11/2}$ spherical shell-model state and have a large value of the magnetic dipole transition operator. The decay sequences are characterized by mixed M1/E2 transitions, which connect the two signatures of the band and compete with stretched E2 transitions within each signature decay sequence. One of the striking phenomena associated with these $9/2^-[514]$ bands is that they show unexpectedly large signature splitting at low spins, whose amplitude increases considerably with decreasing neutron number to $N \approx 90$[1]. However, after the first backbending (which is attributed to the rotational alignment of a pair of $i_{13/2}$ neutrons), the signature splitting has been observed to disappear or become inverted. Cranked shell-model calculations of quasi-proton energies as a function of triaxial γ deformation[5-6] predict that the occupation of an orbit in the upper half of the $h_{11/2}$ shell tends to drive the nucleus towards negative γ deformation, leading to an apparent signature splitting at low frequencies. At higher frequencies, the alignment of $i_{13/2}$ neutrons favors shapes with positive γ values[7]. The observed disappearance or inversion of signature splitting after the $i_{13/2}$ neutron alignment might indicate that the opposite γ driving forces of the strongly coupled proton and the aligned $i_{13/2}$ neutrons may cancel each other to some extent or even result in positive γ deformation. Although it is very difficult to find conclusive experimental evidence for the existence of a negative γ deformed shape, such a suggestion has been made for the $9/2^-[514]$ bands in the light Lu and Ta isotopes[1]. This observation was based on signature splittings of the Routhians, M1 transition matrix elements, and the relation between them in connection with the triaxial γ deformation[1]. The high-spin level structure in the most neutron-defi-

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cient rhenium isotope investigated to date, ^{169}Re, combined with the available spectroscopic results of the other heavier odd-A Re isotopes [2–4,8], provides us an opportunity to investigate the evolution of triaxial deformation in neutron-deficient Re isotopes with decreasing the neutron number.

The excited states in ^{169}Re were populated via the ^{144}Sm (^{28}Si, 1p2n) reaction. The ^{28}Si beam was provided by the tandem accelerator at the Japan Atomic Energy Research Institute (JAERI). The target was isotopically enriched metallic foil with a thick Pb backing. The GEMINI [9] γ-ray detector array was used. To determine the optimum beam energy to produce ^{169}Re, and to identify the in-beam γ rays belonging to ^{169}Re, relative γ-ray yields were measured at different beam energies firstly. Then, γ-γ-t and X-γ-t coincidences were carried out at the optimum beam energy. After accurate gain matching, these coincidence events were sorted into symmetric total matrix and DCO matrix for off-line analysis. The measured relative γ-ray yields at different beam energies, combined with Re KX-ray coincident information, helped us assign γ-ray cascades to ^{169}Re. The level scheme of ^{169}Re is proposed from the present work as shown in Fig. 1. The ordering of transitions in each band is determined according to the γ-ray relative intensities, γ-γ coincidence relationships and γ-ray energy sums. The transition character is deduced from the measured DCO results. Since we do not have any direct measurement of the spins and parities for the states observed, the band-head assignments rely merely on the existing knowledge of band properties in neighboring odd-Z nuclei and the possible Nilsson states available for $Z=75$ at a prolate deformation. Band 2 was most strongly populated and extended up to $45/2^-$. Considering the alignment, band crossing frequency, experimental $B(M1)/B(E2)$ ratios, signature splitting, and level spacings, band 2 is presumed to be associated with the $9/2^-$ [514] configuration which was assigned to be the ground state of ^{169}Re. This configuration assignment is also supported by the α-decay studies of ^{173}Ir[10].

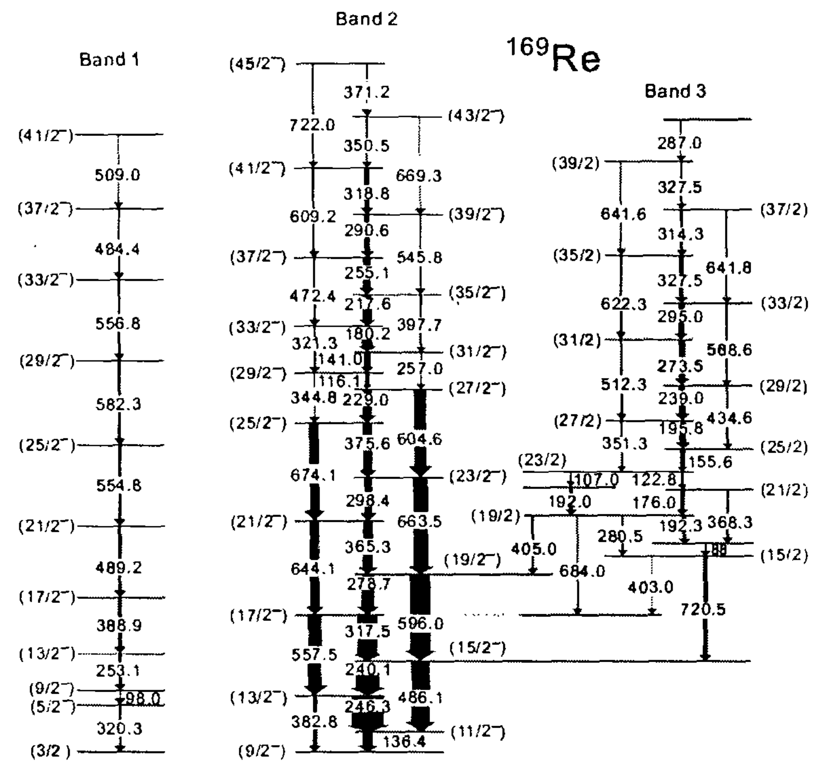

Fig. 1　Level scheme of ^{169}Re deduced from the present work. The widths of the arrows indicate the relative transition intensities.

Band 2 experiences a strong backbending at $\hbar\omega = 0.23$ MeV with gain of 10.5 $\hbar$ in alignment, corresponding well to the AB neutron crossing in the 9/2$^-$[514] bands of the neighboring odd-A Re isotopes[2–4]. The TRS calculation shown in Fig. 2 corresponds to this band, as it comprises the ground state. 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 quadruple deformation, but at small positive γ deformation.

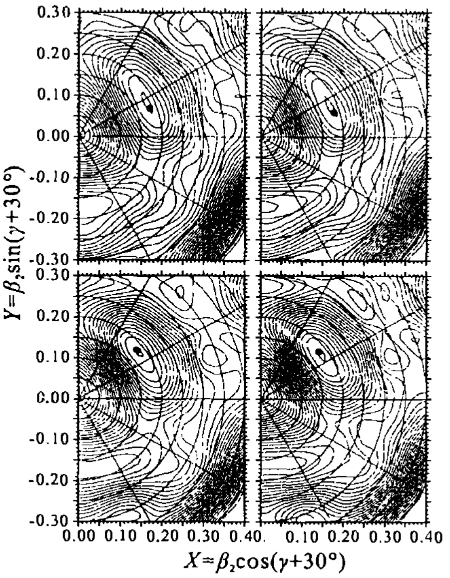

Fig. 2 Calculated total Routhian surfaces for the $(\pi, \alpha) = (-, -1/2)$ branch of Band 2. The up-left and up-right panels corresponding to $\hbar\omega = 0.10$ and 0.15 MeV (before the $i_{13/2}$ neutron alignment); low-left and low-right panels corresponding to $\hbar\omega = 0.25$ and 0.30 MeV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

The observation of the 9/2$^-$[514] band in the most neutron-deficient rhenium isotope investigated to date, ^{169}Re, combined with the available spectroscopic results of the other light odd-A Re isotopes[2–4,8], provides us an opportunity to investigate the evolution of triaxial deformation in neutron-deficient Re isotopes while decreasing the neutron number. We will discuss the nuclear shape deviation from an axial symmetry associated with the 9/2$^-$[514] configuration in very light odd-A Re nuclei on the basis of the signature splittings of the Routhians and M1 transition matrix elements and the relation between them in connection with the triaxial (γ) deformation.

The signature splitting Δe is defined as the difference in energies at a given rotational frequency for the pair of signature partners. Fig. 3 presents plots of the signature splittings for the 9/2$^-$[514] bands in the light odd-A Re nuclei[2–4,8], defined as[11]

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

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. 3). In the odd-A Re isotopes with

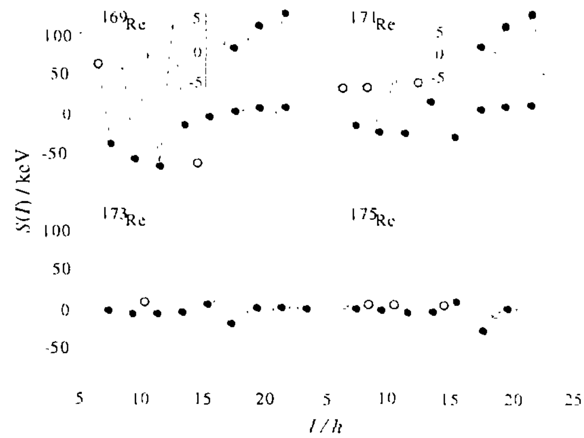

Fig. 3 Signature splitting $S(I)$ as a function of spin I for the 9/2$^-$[514] bands in $^{169-175}$Re. The filled and open symbols correspond to the favored and unfavored signatures, respectively.

mass number larger than 175, there is almost no signature splitting in the 9/2$^-$[514] bands. As shown in Fig. 3, the experimentally observed signature splitting in the very neutron-deficient isotopes is unexpectedly large, and increases rapidly with decreasing neutron number. A signature splitting as high as approximately 30 keV has been observed at low spins in ^{169}Re. Signature splitting of the energies is considered generally as a consequence of the mixing of the $\Omega=1/2$ orbits into the wave functions, due 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, pairing, and shell filling. For example, decreasing nuclear quadruple deformation can result in an increased signature spitting[12]. The increased signature splitting amplitudes for the lighter Re isotopes seem therefore to be explained in terms of the decreasing nuclear quadruple deformation as indicated by the theoretical calculation[13]. However, changing the pairing gap, quadruple deformation, and hexadecapole deformation 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[14]. 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 reasonable 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. 2 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.

In order to investigate the deviation of nuclear shape from axial symmetry and the direction of γ deformation, theoretical studies revealed that for axially symmetric nuclear shape a correlation between the signature splittings of the $B(\mathrm{M1})$ values and Routhians can be obtained as [15]

$$\frac{\Delta B(M1)}{\langle B(M1)\rangle}=\frac{4(\Delta e)\times(\hbar\omega)}{(\Delta e)^2+(\hbar\omega)^2}, \tag{2}$$

here, $\Delta B(\mathrm{M1})/\langle B(\mathrm{M1})\rangle$ is the relative signature splitting of the magnetic transition rates which can be calculated with the experimentally observed transition intensities. This equation is exact for axially symmetric shapes in the cranking model for any cranking frequency $\hbar\omega$, and valid if $I\gg1$ in the particle-rotor model for the one-quasiparticle deformation-aligned bands where K is good quantum number. For negative γ deformations the left-hand side of the equation has a lower value than the right-hand side, and for positive γ deformation a higher value[15]. On the basis of such a comparison, it has been suggested that the neutron-deficient Ho, Tm, Lu, and Ta isotopes deviate appreciably from an axially symmetric shape[15]. Fig. 4

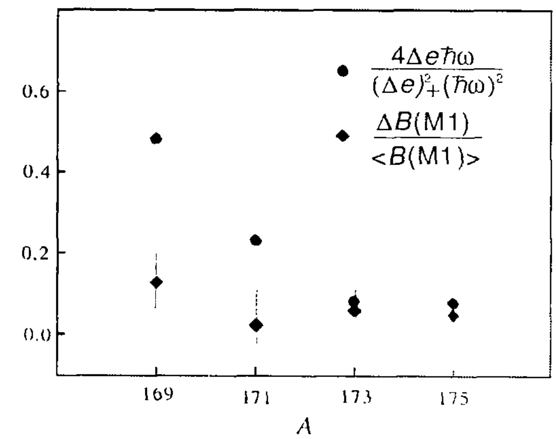

Fig. 4 Comparison between the quantities of the left- and right-hand sides of Eq. (2).

compares the left- and right-hand side values of Eq. (2) by choosing the data around $I=17/2$ before the $i_{13/2}$ neutron alignment for the $9/2^-[514]$ bands in the light odd-A Re isotopes[2-4]. We remark that the quantities shown in Fig. 4 are calculated by using the experimental observed Routhian splitting Δe and $B(M1)/B(E2)$ ratios. The increasing difference between the two sides with decreasing neutron number indicates a considerable negative γ deformation for ^{169}Re.

Bengtsson et al[16] 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. 2, 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.

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非常缺中子Re核的负三轴形变研究*

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摘 要：利用在束核谱学实验技术，建立了^{169}Re基于$9/2^-[514]$组态的强耦合转动带. 该带在已知的奇A Re核中具有最大的低自旋旋称劈列. 对于奇A Re中的$9/2^-[514]$转动带，研究了它们的能量旋称劈列和M1跃迁矩阵元相对旋称劈列与核形状偏离轴对称的关系，揭示了非常缺中子的奇A Re核具有相当的负三轴形变.

关 键 词：三轴形变；旋称劈列；奇A核

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