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Rotational Bands in ^{169}Re *

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Abstract The excited states of ^{169}Re have been investigated by means of in-beam γ-ray spectroscopy techniques with the ^{144}Sm(^{28}Si, 1p2nγ) ^{169}Re reaction. X-γ and γ-γ-t coincidences, DCO ratios and intra-band B(M1)/B(E2) ratios were measured. 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]) have been established. Their configurations are proposed on the basis of B(M1)/B(E2) ratios and by comparing the band properties with known bands in neighboring odd-proton nuclei. The neutron AB crossings are observed at $\hbar\omega$ = 0.23 and 0.27 MeV for the $\pi 9/2^-$ [514] and $\pi 1/2^-$ [541] bands, respectively. Band properties of the neutron AB crossing frequencies, alignment gains and signature splittings are discussed, and compared with those in the heavier odd-A Re isotopes.

Key words γ-ray spectroscopy, rotational band, configuration

The very neutron deficient Re isotopes are expected to be rather soft with respect to β and γ deformations, and the polarizing effects of individual nucleons make the nuclear shapes strongly configuration-dependent[1-3]. For light odd-A Re isotopes, the proton Fermi surface is at the top of the $h_{11/2}$ and $d_{5/2}$ shells and just below the strongly down-sloping $1/2^-$ [541] and $1/2^+$ [660] Nilsson orbits from the $h_{9/2}$ and $i_{13/2}$ spherical states of the next shell. When the $9/2^-$ [514] and $5/2^+$ [402] orbitals, which have a positive slope of energy as a function of deformation, are occupied, a smaller deformation is favored. These strongly coupled bands have been observed systematically in the odd-A Re isotopes, and their electromagnetic properties have been determined through measurements of the B(M1)/B(E2) branching ratios[1-3]. These bands show small but distinct signature splitting at low spin before the AB neutron alignment[1-3], which might suggest some γ deformation. On the other hand, the $h_{9/2}$ and $i_{13/2}$ orbitals with $\Omega = 1/2$ are strongly down-sloping as a function of deformation and when occupied by the unpaired proton, will drive the nucleus towards larger deformation. Therefore, the AB neutron crossing should be delayed to higher frequencies, and lower alignment is associated with these low Ω bands. By increasing deformation, the Fermi surface is moved farther to low-Ω components of the $\nu i_{13/2}$ orbital, thereby reducing the Corioilis mixing. This results in an decreased alignment gain and higher crossing frequencies associated with the alignment of $i_{13/2}$ neutrons[4].

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In this article, we report experimental results on high-spin band structures in ^{169}Re. Before the present study, the rotational bands in ^{169}Re were reported in a symposium[5], but a high spin level scheme has not yet been published in the literature. The ground state of ^{169}Re was assigned to be the $\pi 9/2^-$ [514] Nilsson configuration[6]. In ^{173}Ir α-decay studies, the α-γ coincidence measurement revealed a 136 keV γ ray which was proposed to depopulate the 11/2 member of the $9/2^-$ [514] band in ^{169}Re[7].

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 1.3mg/cm^2 thickness with a 7mg/cm^2 Pb backing. A γ-ray detector array[8] comprising 12 HPGe's with BGO anti-Compton shields was used. The detectors were calibrated with ^{60}Co, ^{133}Ba, and ^{152}Eu standard sources; typical energy resolution was about 2.0—2.4keV at FWHM for the 1332.5keV γ rays.

In order to determine the optimum beam energy to produce ^{169}Re and to identify the in-beam γ rays belonging to ^{169}Re, first, we measured the relative γ-ray yields at the beam energies of 140, 145, and 150MeV. Then, the beam energy of 145MeV, at which the yield of the 136keV γ ray was a maximum, was chosen to populate the high-spin states in ^{169}Re. γ-γ-t and X-γ-t coincidence measurements were performed at this optimum beam energy. A total of 250×10^6 coincidence events were accumulated. After accurate gain matching, these coincidence events were sorted into a symmetric total matrix for off-line analysis. To obtain the DCO (Directional Correlations of γ rays deexciting the Oriented states) ratios, the detectors were divided into 3 groups positioned at 32° (148°), 58° (122°), and 90° with respect to the beam direction. A non-symmetrized matrix with detectors at $\theta_2 = 90°$ against those at $\theta_1 = 32°$ (and ± 148°) was constructed. The experimental DCO ratio was calculated by $R_{DCO}(\gamma) = I_\gamma(\theta_1)/I_\gamma(\theta_2)$, where $I_\gamma(\theta_1)$ represents the intensities of an unknown γ ray along the θ_1 axis in coincidence with the stretched E2 transitions along θ_2 direction. Similarly, with the same gates on θ_1 axis, coincidence spectra along the θ_2 axis were projected to determine $I_\gamma(\theta_2)$. In the present geometry, stretched quadrupole transitions were adopted if $R_{DCO}(\gamma)$ ratios were close to unity, and dipole transitions were assumed if $R_{DCO}(\gamma) \leq 0.6$. The measured relative γ-ray yields, combined with Re K X-ray coincident information, helped us assign γ-ray cascades to ^{169}Re.

The level scheme of ^{169}Re, including two rotational bands, is proposed from the present work and 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 character of transitions is deduced from the measured DCO results. Band 1 has a typical character of decoupled band. A γ-ray spectrum gated on the 320.3keV transition is shown in Fig.2. The lowest state of this band is most likely the state depopulated by the 320.3keV line having a dipole character. The 98keV transition was observed very weakly because of its highly converted nature. The DCO values for transitions in the cascade above the proposed band head are consistent with $\Delta I = 2$ character. The transitions above the 320.3keV transition are in coincidence with the 136.4keV line which is believed to decay to the ground state, but the linking transitions are too weak to be observed. Gated spectrum demonstrating the existence of band 2 is shown in Fig.3. Band 2 arises presumably from the $9/2^-$ [514] Nilsson orbital, which is supported by the α-γ coincidence measurement in ^{173}Ir α-decay study[7]. For band 2, the branching ratios, which are defined as

$$\lambda = \frac{T_\gamma(I \rightarrow I-2)}{T_\gamma(I \rightarrow I-1)}, \tag{1}$$

are extracted for the most transitions. Here $T_\gamma(I \rightarrow I-2)$ and $T_\gamma(I \rightarrow I-1)$ are the γ-ray

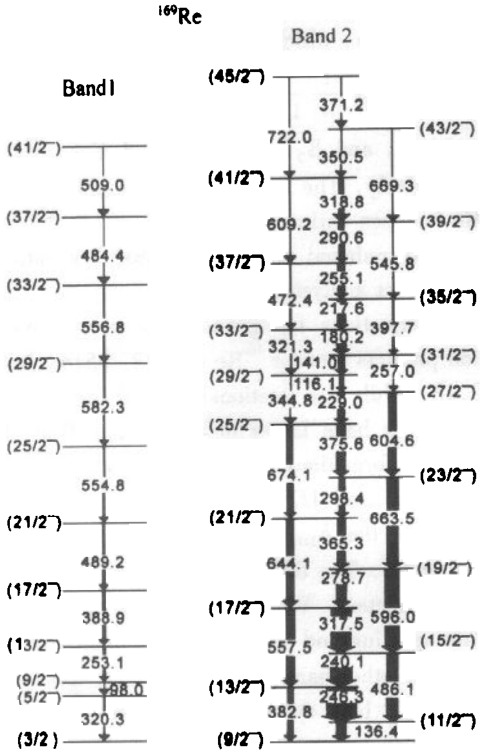

Fig. 1.　Level scheme of ^{169}Re deduced from the present work.

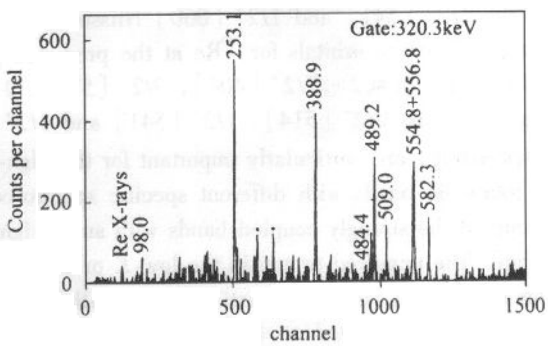

Fig. 2.　Typical coincidence spectrum with gate on selected transition in band 1 as indicated on the panel. The * symbols indicate contaminations.

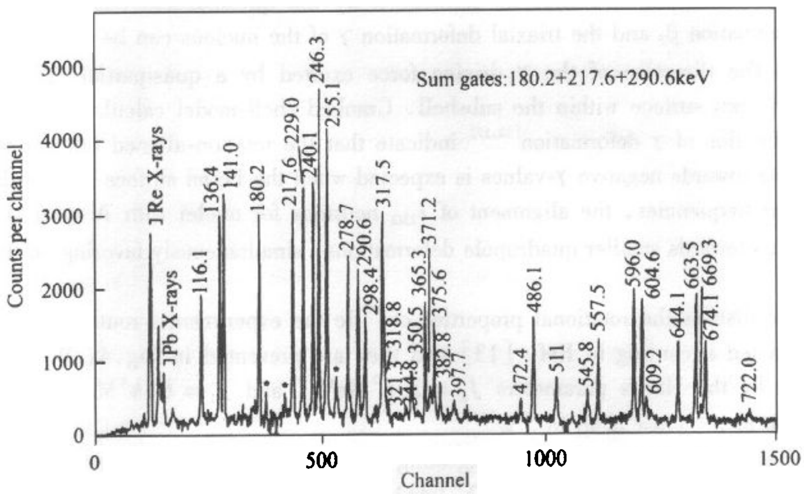

Fig. 3.　Representative spectrum illustrating band 2 from a sum of gates as indicated on the panel. The * symbols indicate contaminations.

intensities of the $\Delta I = 2$ and $\Delta I = 1$ transitions, respectively. These intensities are measured in a summed coincidence spectrum gated by the transitions above the state of interest. The branching ratios are used to extract the reduced transition probability ratios, which are defined as[9]

$$\frac{B(\mathrm{M1};I\to I-1)}{B(\mathrm{E2};I\to I-2)}=0.697\frac{[E_\gamma(I\to I-2)]^5}{[E_\gamma(I\to I-1)]^3}\frac{1}{\lambda}\frac{1}{1+\delta^2}\left(\frac{\mu_N^2}{e^2b^2}\right),\qquad(2)$$

where δ is the E2/M1 mixing ratio for the $\Delta I=1$ transitions, and $E_\gamma(I\to I-1)$ and $E_\gamma(I\to I-2)$ are the $\Delta I=1$ and $\Delta I=2$ transition energies, respectively. The mixing ratio δ deduced from angular correlation coefficients in the heavier odd-A Re isotopes varies between 0.0 and 0.2[1—3]. This small values has hardly any effect on the extracted reduced transition probability ratios. Consequently, the value $\delta=0.0$ has been used in the present analysis.

Mueller et al. have calculated the equilibrium deformations for ground-state and intruder configurations in odd-A Re isotopes[10]. The calculation predicts that for ^{169}Re the 9/2⁻ [514] band is expected to have quadrupole deformations around 0.18, while the rotational-aligned band based on the 1/2⁻ [541] and 1/2⁺ [660] Nilsson orbitals tend to have larger deformations. Thus the available Nilsson orbitals for ^{169}Re at the predicted prolate deformations are the 1/2⁺ [411], 1/2⁺ [400], 5/2⁺ [402], 7/2⁺ [404], 9/2⁻ [514], 1/2⁻ [541] and 1/2⁺ [660], among which the high-j orbitals 9/2⁻ [514], 1/2⁻ [541] and 1/2⁺ [660] of the $h_{11/2}$, $h_{9/2}$ and $i_{13/2}$ parentages, respectively, are particularly important for the high-spin states. The different orbitals will give rise to rotational bands with different specific spectroscopic characters. When the high-K orbitals are occupied the strongly coupled bands with small signature splitting and strong $\Delta I=1$ transitions will occur. The unpaired proton in the low-K orbitals will on the other hand easily align their spins and the bands with large signature splittings will be observed. At high spins a pair of intruder high-j particles are expected to break up and align their angular momentum along the rotation axis producing an up-bend or a backbend. In the mass region around ^{169}Re, the experimental results and theoretical calculations[1—3,9,11] have demonstrated that the aligned $i_{13/2}^2$ neutron configuration is responsible for the first band crossing.

Nuclei in this mass region are known to be rather soft with respect to β and γ deformations. The nuclear shape of ^{169}Re will thus be influenced by the quasiparticle configuration. Both the quadrupole deformation β_2 and the triaxial deformation γ of the nucleus can be different for different configurations. The direction of the γ driving force exerted by a quasiparticle is related to the position of the Fermi surface within the subshell. Cranked shell-model calculations of quasi-proton energies as a function of γ deformation[12,13] indicate that the rotation-aligned orbitals favor positive γ, and a driving towards negative γ-values is expected when the Feimi surface lies on the top of the shell. At higher frequencies, the alignment of $i_{13/2}$ neutrons for nuclei with $N\leqslant 96$ is expected to drive the nucleus towards smaller quadrupole deformations, simultaneously favoring positive values of γ[14,15].

In order to discuss the rotational properties of ^{169}Re the experimental routhians and alignments have been extracted according to Ref. [13] and they are presented in Fig.4. We have chosen a reference given by the Harris parameters $J_0=20\hbar^2\mathrm{MeV}^{-1}$ and $J_1=60\hbar^4\mathrm{MeV}^{-3}$, which give a good description to the yrast band in ^{168}W[16].

Band 1 has a decoupled structure suggesting that the configuration includes protons from an $\Omega=1/2$ orbital. Candidate orbitals are 1/2⁺ [411], 1/2⁺ [400], 1/2⁻ [541] and 1/2⁺ [660]. Considering the systematics of the level spacings in the neighboring odd-Z nuclei[1—3], band 1 is assumed to be based on the 1/2⁻ [541] Nillson orbital and the lowest state has a spin value of 5/2. For the $\pi h_{9/2}$ subshell the Fermi level is close to the 1/2⁻ [541] orbital, leading to large signature-split sequences of which we have observed only the favored ($\alpha=+1/2$) component. As shown in

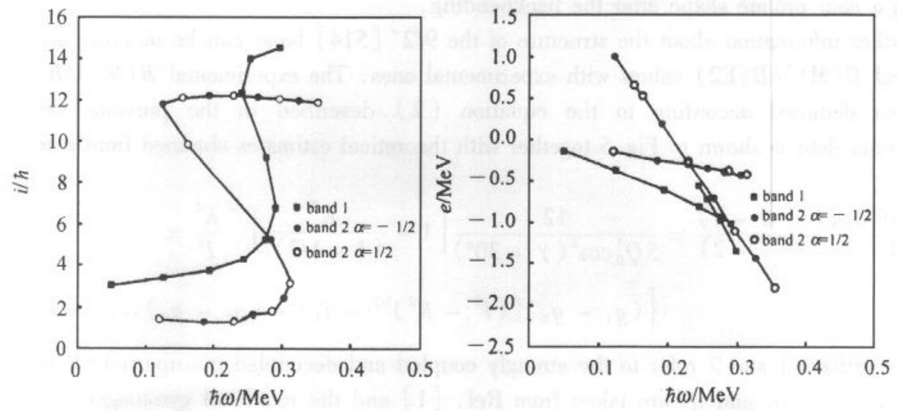

Fig.4. Extracted alignment i and Routhian energy e for measured rotational bands in ^{169}Re. The labels in the legends indicate the bands as they are labeled in Fig.1. The Harris reference parameters are chosen to be $J_0 = 20\hbar^2 \mathrm{MeV}^{-1}$ and $J_1 = 60\hbar^4 \mathrm{MeV}^{-3}$

Fig.4 band 1 shows a upbend at $\hbar\omega = 0.27$MeV, where the gain in the alignment is about $10.5\hbar$. The crossing frequency is almost same as those in the heavier odd-A Re isotopes[1—3]. The delayed AB neutron crossing in the 1/2⁻[541] bands with respect to the strongly coupled bands suggests a larger quadrupole deformation for the 1/2⁻[541] configuration in light Re isotopes[4]. Inspecting the alignment gains in the 1/2⁻[541] bands caused by the first AB neutron crossing in the odd-A Re isotopes[1—3], it is found that the alignment gain increases while decreasing the neutron number. By decreasing the neutron number, the neutron Fermi surface is moved closer to low-Ω components of the $\nu i_{13/2}$ orbital, resulting in an increased gain in aligned angular momentum associated with the alignment of $i_{13/2}$ neutrons. In the present work, the 1/2⁻[541] band head energy in ^{169}Re is observed to be higher than 320keV above the ground state, which might explain the low population for the 1/2⁻[541] band in ^{169}Re comparing those in the heavier odd-A Re isotopes[1—3].

Band 2 experiences a strong backbending at $\hbar\omega = 0.23$MeV with gain of $10.5\hbar$ in alignment, which are consistent with the crossing frequencies and alignment gains in the 9/2⁻[514] bands associated with the first AB neutron alignment in the light odd-A Re isotopes[1—3]. There is a clear energy splitting between the two signatures at low rotation frequencies and that the splitting disappears quite suddenly when the alignment increases. The calculations[12,13] predict that the 9/2⁻[514] configuration in light Re isotopes tends to drive the nucleus towards negative γ-deformation, which can cause a small signature splitting at low frequencies. At higher frequencies, the alignment of $i_{13/2}$ neutrons in very neutron deficient Re isotopes favors positive values of γ[14,15]. The observed disappearance in 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 and

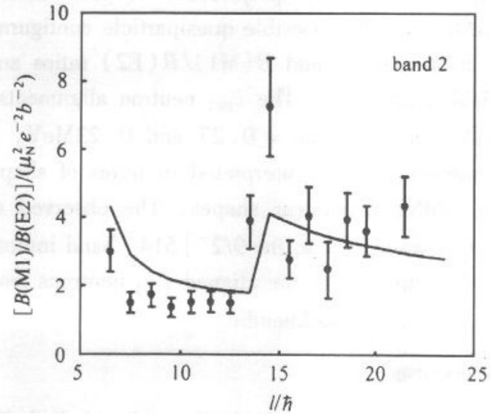

Fig.5. Experimental $B(\mathrm{M1})/B(\mathrm{E2})$ ratios for band 2, and theoretical prediction described in the text.

resulting a near prolate shape after the backbending.

Further information about the structure of the $9/2^-[514]$ band can be obtained by comparing theoretical $B(M1)/B(E2)$ values with experimental ones. The experimental $B(M1)/B(E2)$ ratios have been deduced according to the equation (2) described in the previous section. The experimental data is shown in Fig.5 together with theoretical estimates obtained from a semiclassical formula[17,18]

$$\frac{B(M1;I\to I-1)}{B(E2;I\to I-2)}=\frac{12}{5Q_0^2\cos^2(\gamma+30°)}\left[1-\frac{K^2}{(I-1/2)^2}\right]^{-2}\frac{K^2}{I^2}\times$$
$$\left\{(g_1-g_R)\left[(I^2-K^2)^{1/2}-i_1\right]-(g_2-g_R)i_2\right\}^2\left(\frac{\mu_N^2}{e^2b^2}\right). \quad (3)$$

The suffixes 1 and 2 refer to the strongly coupled and decoupled quasiparticles, respectively. The gyromagnetic g_1 and g_2 are taken from Ref. [1] and the rotational gyromagnetic factor g_R is taken here as $Z/A=0.443$. The alignment of the strongly coupled particle is set to $i_1=0.0\hbar$ and for the three quasiparticle band a value $i_2=10.5\hbar$ as deduced from experiment is used for the decoupled neutron pair. The nominal band head K-value of 4.5 is used. The quadrupole moment is set to $Q_0=5.5$ e·b, which corresponds to the quadrupole deformation of the even-even core nucleus ^{168}W[19]. By assuming $\gamma=0°$ the experimentally observed trend of $B(M1)/B(E2)$ ratios for the $9/2^-[514]$ band is reproduced by the theory if the alignment gain is attributed to the AB neutron crossing. At low spin the theoretical values for $\gamma=0°$ overestimate experiment, and improved agreement could be obtained for negative γ deformation. The $B(M1)/B(E2)$ ratios for the $9/2^-[514]$ band show a pronounced increase of a factor of 2 at the spin where the alignment first reaches its maximum. The ratios of the reduced transition probabilities at low spins and the increase after the backbending for the $9/2^-[514]$ band in ^{169}Re are comparable to those obtained in the $9/2^-[514]$ bands in the odd-proton Re nuclei[1,3]. The increase in the branching ratio can be due both to a loss of the collectivity and an increase in the M1 transition strength. Assuming a constant quadrupole moment the model predicts an increase in the branching ratio when a pair of $i_{13/2}$ neutrons align. The experimentally observed increase in the $B(M1)/B(E2)$ ratios is in qualitative agreement with the proposed neutron origin of the backbend in the $\pi 9/2^-[514]$ band.

In summary, the odd-proton nucleus ^{169}Re has been produced in the bombardment of the ^{144}Sm target with the ^{28}Si projectiles. A level scheme consisting of two rotational bands has been established. The possible quasiparticle configurations of these bands have been suggested based on the measured in-band $B(M1)/B(E2)$ ratios and the existing knowledge of band structures in the neighboring nuclei. 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 0.23MeV, respectively. The difference between the crossing frequencies can be interpreted in terms of shape driving effects since the different proton orbitals favor different nuclear shapes. The observed disappearance in signature splitting after the $i_{13/2}$ neutron alignment in the $9/2^-[514]$ band indicates that the opposite γ driving forces of the strongly coupled proton and the aligned $i_{13/2}$ neutrons may cancel each other, and resulting in a near prolate shape after the backbending.

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^{169}Re 的转动带结构研究*

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摘要　利用在束 γ 谱学方法,通过反应^{144}Sm(^{28}Si,1p3n)^{169}Re 研究了^{169}Re 的激发态能级结构.实验进行了 X-γ 符合、γ-γ 符合、DCO 系数和带内 B(M1)/B(E2)比率测量.基于这些测量,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.通过比较^{169}Re 的转动带与邻近奇质子核已知转动带的结构和 B(M1)/B(E2)比率,指定了^{169}Re 转动带的组态.实验观测到 π9/2$^-$[514]和 π1/2$^-$[541]转动带的中子 AB 带交叉的转动频率分别为 0.23 和 0.27MeV.着重讨论了^{169}Re 转动带的中子 AB 带交叉频率、转动角动量顺排和旋称劈列等,并讨论了奇 A Re 核转动带结构的系统性.

关键词　在束 γ 谱学　转动带　组态

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