第 27 卷　第 2 期
2010 年 6 月

原 子 核 物 理 评 论
Nuclear Physics Review

Vol. 27，No. 2
June，2010

Article ID：1007－4627(2010)02－0140－06

Analysis of High-spin Rotational Band in Odd-odd ^{170}Re*

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Abstract：One high-spin rotational band in neutron deficient odd-odd nucleus ^{170}Re has been identified and assigned to the $\pi h_{1/2}\otimes\nu i_{13/2}$ configuration through the ^{142}Nd(^{32}S，1p3nγ)^{170}Re reaction. The band is analyzed on the basis of the arguments of energy systematics，signature inversion systematics，intra-band B(M1)/B(E2) ratios，quasiparticle Routhians，dynamic moment of inertia and Total Routhian Surface(TRS) calculations. From detailed analyses on its structural properties，the configuration，spins and parity have been further assigned for this rotational band.

Key words：rotational band；odd-odd nuclei；in-beam γ-ray spectroscopy

CLC number：O571.21　　　**Document code**：A

1　Introduction

During the past few years the experimental information on the band structure in rotating nuclei has expanded rapidly，mostly due to the availability of heavy-ion beams and multi-detector anti-Compton (AC) spectrometers. Investigations of the band structure in doubly odd nuclei carried out in recent years have led to the establishment of a general classification scheme for the coupling modes of two nonidentical valence nucleons[1]. A number of interesting nuclear structure features，including semidecoupled，doubly decoupled and compressed structures[2]，have been discovered and discussed in the A=170 mass region. Prior to this work，only a few low spin states，populated through the β^+/EC decay of ^{170}Os and α decay of ^{174}Ir，were known in ^{170}Re[3—5]，but no high-spin information was available. Partial analytic results from this work have been reported elsewhere[6]. In this paper，further analysis and discussion from band structural systematics of odd-odd nuclei and the crank shell model(CSM)[7] calculations is presented.

2　Experimental Procedures and Analysis

The optimal projectile-target combination and the fusion-evaporation excitation function of reaction system were analyzed according to theoretical calculations of CASCADE and ALICE codes. Based on these analyses and the measurement of excitation function，a beam energy of 166 MeV

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* **Received date**：5 Aug. 2009；**Revised date**：16 Oct. 2009

* **Foundation item**：National Natural Science Foundation of China(10805040)；Major State Basic Research Development Program (973 program) of China(2007CB815000)；Postdoctoral Program of Zhengzhou University

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was chosen to populate the high-spin states via the heavy-ion fusion-evaporation reaction ^{142}Nd(^{32}S, 1p3nγ)^{170}Re. The ^{32}S beam was provided by the tandem accelerator at the China Institute of Atomic Energy, Beijing. The ^{142}Nd target was a metallic foil of about 2.2 mg/cm^2 thickness of with a 7.0 mg/cm^2 Pb backing to stop the recoiling nuclei. At this optimum energy, the X-γ and γ-γ coincidence measurements were carried out with twelve BGO (AC)HPGe detectors, having energy resolution of 1.9—3.1 keV at 1332.5 keV γ-ray energy of ^{60}Co source. A total of 150 million coincidence events were recorded. The detector energies and efficiencies were calibrated using standard radioactive ^{133}Ba and ^{152}Eu sources. In the off-line analysis, the gains of the detectors were adjusted so that all the spectra had the same energy calibration, then the raw event data from all detectors were sorted into symmetric E_γ-E_γ as well as asymmetric matrices for determination of γ-ray multipolarities based on the directional correlation of decays from oriented states(DCO) method. Analysis of the coincidence relationships was carried out using standard Mxa105 software. The more detailed experimental conditions were described in the preceding paper[6].

3 Results and Dissusion

The yrast and near-yrast structures of ^{170}Re are expected to possess a near-prolate deformation with $\beta \approx 0.20$. The excited states can therefore be explained as two-quasiparticle states with a collective rotation added. Moreover, different configurations (orbitals) will give rise to rotational bands with different specific spectroscopic characters. The rotational band level scheme and its quasiparticle configuration and spins of ^{170}Re have been proposed briefly in our previous work[6]. It is well known rotational bands in odd-odd nuclei often cannot be linked to other known states in the level scheme, it is common to use CSM and systematics analyses, similar to the one described in Refs. [6, 8] to deduce the probable configurations and spin values. As usual, in order to identify the proton and neutron orbitals involved in the high-spin rotational band, a further analysis of band properties mentioned below, such as level energy systematics in isotonic chain, $B(\mathrm{M1})/B(\mathrm{E2})$ ratios, experimental routhians, dynamic moment of inertia, signature inversion, etc., has been performed.

According to the participating valence proton (neutron) in the yrast band of the neighboring odd-Z (odd-N) nuclei and the high-j Nillson orbitals at the prolate deformation region, the configuration $\pi h_{1/2}[514]9/2^- \otimes \nu i_{13/2}[651]3/2^+$ was assigned to the present rotational band [6]. As is known, there are two ways to couple the proton and the neutron states, with intrinsic spins parallel and antiparallel. The Gallagher-Moszkowski rules specify that in an odd-odd nucleus the parallel coupling lies lower than the antiparallel(at the band head), with the splitting in the range of 50 to 200 keV[9]. Usually, the γ-ray deduced to band-head level cannot be seen due to the low energy and detection efficiency. The spin and parity assignments cannot be made by usual spectroscopic methods due to the suspending nature of the level scheme. The I^π values of the levels have been suggested on the basis of the available spin vs level energy systematics of the similar configuration bands in the neighboring nuclei[6]. The level spacing and level staggering in

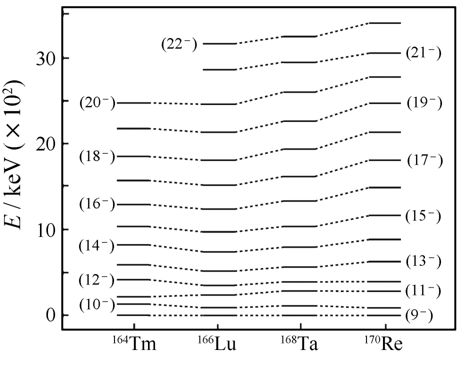

Fig. 1 Excitation energy systematics of $\pi h_{1/2} \otimes \nu i_{13/2}$ band in $N=95$ isotones. Data sources are ^{170}Re(this work), ^{168}Ta[10], ^{166}Lu[11], ^{164}Tm[12]. (9$^-$) levels are taken as the reference.

this band are very similar to the $\pi h_{1/2}\otimes\nu i_{13/2}$ bands observed in the neighboring odd-odd Re isotopes[6] (see Fig. 4 in Ref. [6]). In our present work, as is shown in Fig. 1, the proposed spins for the levels have been further investigated on the basis of the available spin vs the level energy systematics of the similar configuration band in $N = 95$ isotones[10—12]. As one can see, an excellent agreement has been achieved.

If the adopted level spin values in ^{170}Re can be used according to the systematics in level spacing, it will consequently lead to a low spin signature inversion consistent with the systematics of level staggering pattern discussed in Ref. [6]. It is known that the phenomenon of signature inversion has systematically been observed in almost all $\pi h_{1/2}\otimes\nu i_{13/2}$ bands in the neighborhood of $A=170$. The behavior of the signature inversion for different chains of isotopes and isotones has been recently analyzed and general trends have been found for nuclei with $Z=63$—75, $N=89$—95[13—17]. According to the method in Refs. [13, 17], the signature-inversion point I_c can be concluded. Although the reversion point is not reached in ^{170}Re because of the lack of higher spin data, the tendency towards reversion at about $I=19.5\hbar$ is evident. Here we present a systematic study extended with the new experimental data and plot the inversion point I_c vs proton number Z as shown in Fig. 2. The signature inversion point $I=19.5\hbar$ proposed in ^{170}Re nearly agrees with systematics. Moreover, we can see, the signature inversion point shifts to lower spins with increasing N in different chains of isotopes and to higher spins with increasing Z in different chains of isotones. Interestingly, an additional(N-Z) effect can be seen in Fig. 2, for the same(N-Z) value, the signature inversion point remains practically unchanged and decreases when N-Z increases. The phenomenon of anomalous signature splitting and the inversion observed in the $\pi h_{1/2}\otimes\nu i_{13/2}$ structures has been extensively studied through a variety of theoretical approaches[18—21]. Since the signature inversion point varies over a large range ($I=11.5$—$21\hbar$), any one explanation for the complex phenomenon is probably insufficient, the essential mechanism for the signature inversion in the bands is still an open question. In order to establish a reliable understanding of the observed trends, more comprehensive efforts are needed.

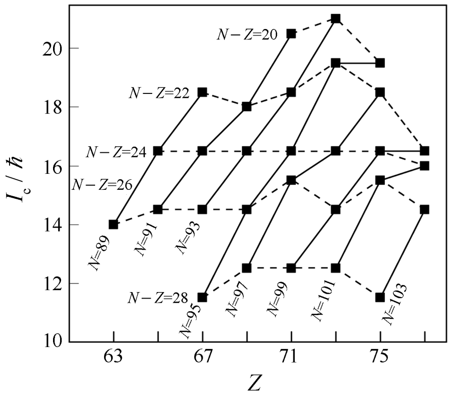

Fig. 2 Systematics of the signature inversion point for the $\pi h_{1/2}\otimes\nu i_{13/2}$ bands in the odd-odd nuclei in $A=170$ mass reigion. Solid lines correspond to nuclei with same N and dotted lines correspond to nuclei with same N-Z, as labeled in the figure.

For the $\pi h_{1/2}\otimes\nu i_{13/2}$ rotational bands in this mass region, the coupling between a normal orbital ($\pi h_{11/2}$) and a Coriolis distorted orbital($\nu i_{13/2}$) leading to a compressed structure[22]. Its electromagnetic properties, which are relatively insensitive to assumptions of spin, were studied and compared with model predictions[8]. One could deduce the empirical B(M1)/B(E2) ratios using the usual rotational model expressions from the observed γ-ray energies E_γ and branching ratios λ as the method described in Ref. [15]. The theoretical estimates of the B(M1)/B(E2) ratios could be obtained from the semiclassical formula of the cranking model developed by Donau and Frauendorf[23]. The extracted experimental and calculated theoretical B(M1)/B(E2) ratios for this band are presented in Fig. 3 from which one can see that the assignment of $\pi h_{1/2}[514]9/2^{-}\otimes\nu i_{13/2}[651]3/2^{+}$ configuration is reasonable to some extent.

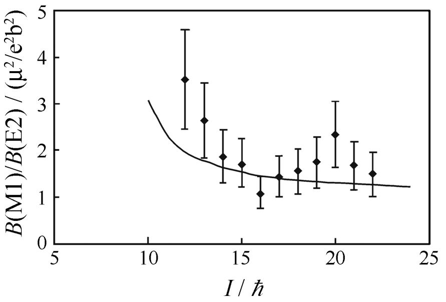

Fig. 3　Experimental B(M1)/B(E2) ratios extracted from $\pi h_{1/2}\otimes\nu i_{13/2}$ band of ^{170}Re. The calculated values using the geometric model of Donau and Frauendorf [23] are shown in solid curves.

In order to study the effect of rotation on the qusiparticle motion, we shall transform the measured excitation energies into the intrinsic rotating frame[24]. The experimental routhians plotted as functions of the rotational frequency for ^{170}Re, ^{169}W, ^{171}Re are displayed in Fig. 4. We can see that the signature-active particle in this band is also the $h_{11/2}$ proton. In the $\pi h_{1/2}\otimes\nu i_{13/2}$ band, the experimental routhians show a obvious change at a rotational frequency $\hbar\omega=0.3$ MeV, indicating the occurrence of band crossing. As shown in Fig. 4, the crossing frequency $\hbar\omega=0.3$ MeV can be extracted from the routhians and is consistent with the breaking of a pair of $i_{13/2}$ neutrons in ^{169} W . Compared to ^{171}Re, the $\nu i_{13/2}$ produces a delay in the crossing frequency most likely due to blocking (AB crossing is blocked), so that the band crossing should be the two-$i_{13/2}$-quasi neutron BC crossing.

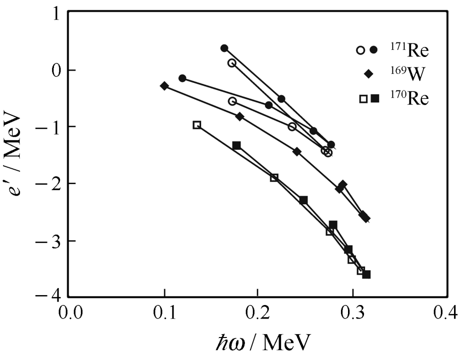

Fig. 4　Experimental routhians extracted from $\pi h_{1/2}\otimes\nu i_{13/2}$ band of ^{170}Re. and its odd-Z ^{171}Re[25] and odd-N ^{169}W[26] neighbours according to Ref. [24]. A core reference with $J_0=15\ \hbar^2\ \mathrm{MeV}^{-1}$ and $J_1=90\ \hbar^4\ \mathrm{MeV}^{-3}$, used for ^{168}W[27], is subtracted from the data set. The open(filled) symbols correspond to the favored(unfavored) signature.

A sensitive indicator of band crossing is also provided by dynamical moments of inertia $J^{(2)}$. Fig. 5 shows the dynamical moments of inertia $J^{(2)}$ of this band. The experimental result for ^{170}Re shows a sharp increase around 0.30 MeV. It provides a rather strong suggestion of band crossing, although it do not thoroughly rule out the possibility of other explanations such as coexisting collective structures. The crossing frequency, which has been estimated from the dynamical moments of inertia, agrees with the value obtained from the experimental routhians.

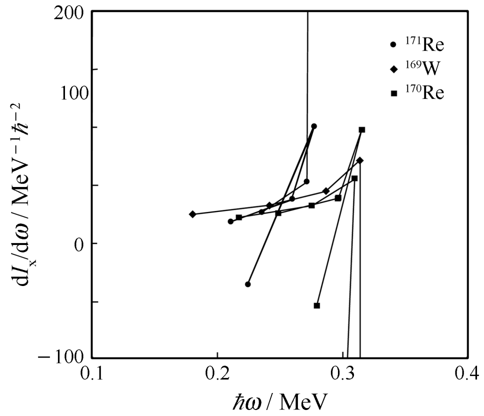

Fig. 5　Dynamic moment of inertia $J^{(2)}$ as a function of rotational frequency $\hbar\omega$. In this plot, we set a common reference $J_0=15\ \hbar^2\ \mathrm{MeV}^{-1}$ and $J_1=90\ \hbar^4\ \mathrm{MeV}^{-3}$, which is an appropriate choice for ^{168}W[27].

Nuclei in the $A=170$ mass region are known to be soft and do easily change deformation. The nuclear shape of ^{170}Re will thus be influenced by the quasiparticle configuration. Both the quadrupole deformation β_2 and the triaxial deformation γ of this nucleus can be different for different configurations. In order to have a better understanding of the collective properties of ^{170}Re, we have performed the deformation and pairing self-consistent Total Routhian Surface (TRS) calculations using the Woods-Saxon potential[28—30]. Both monopole and quadrupole components of the pairing interaction are considered with odd-particle blocking effects included. The calculations minimize the total energy of the nucleus with respect to the deformation parameters β_2 and γ at different rotational frequencies for this configuration. Fig. 6 shows the calculated TRS of the favored signature at $\hbar\omega=$ 0.0, 0.1, 0.2 and 0.3 MeV. As we can see in this figure, the resulting energy surfaces of ^{170}Re have γ-soft minima in the (β_2, γ) plane, their position change with rotational frequencies. It is meaningful to investigate if this is the partial reason of the signature inversion. Moreover, it is worth studying the systematics of these collective properties for this mass region in future.

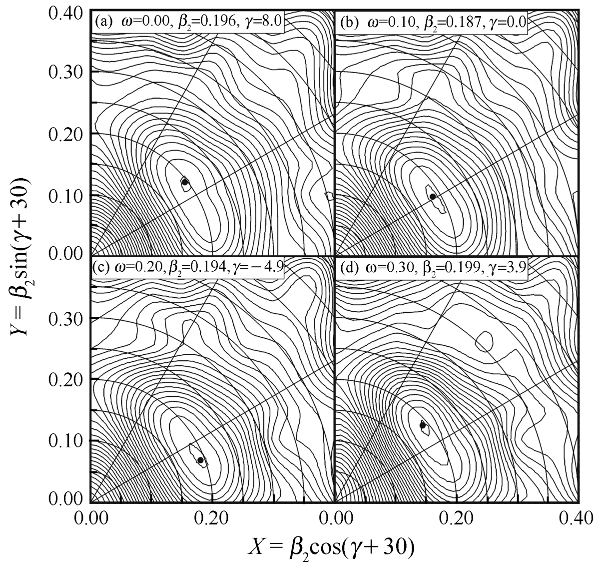

Fig. 6 The TRS for ^{170}Re, calculated for the favored signature of $\pi h_{1/2}\otimes\nu i_{13/2}$ configuration (the unfavored signature sequence is similar to this one). The energy difference between contours is 200 keV.

4 Conclusions

In this paper we report on the further investigation results of the high-spin rotational band in ^{170}Re. The structural properties were analyzed on the basis of several considerations (for example: systematics of level spacing and signature inversion, quasiparticle Routhians, etc.). The present work further extends high-spin studies of the $A=$ 170 region to the lightest rhenium isotope investigated to date.

Acknowledgment The authors wish to thank the staffs in the tandem accelerator at the China Institute of Atomic Energy, Beijing for their help and hospitality during the experiment.

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双奇核^{170}Re 高自旋转动带分析*

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摘　要：通过重离子熔合蒸发反应^{142}Nd(^{32}S，1p3nγ)^{170}Re 布居了缺中子双奇核^{170}Re 的高自旋激发态，识别出了该核的一条转动带并建议了其组态为 $\pi h_{1/2}\otimes\nu i_{13/2}$。基于对同中子素能级系统性、旋称反转系统性、带内 B(M1)/B(E2)、准粒子 Routhians、动力学转动惯量和 Total Routhian Surface(TRS)等带结构特征的详细分析和讨论，进一步确认了对 A=170 核区目前最缺中子双奇核高自旋转动带组态、宇称和自旋值的指定。

关 键 词：转动带；双奇核；在束 γ 谱学

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* **收稿日期**：2009-08-05；**修改日期**：2009-10-16

* **基金项目**：国家自然科学基金资助项目(10805040)；国家重点基础研究发展规划资助项目(973 计划项目)(2007CB815000)；郑州大学博士后项目

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