Extended collective bands in neutron-rich ^{109}Ru*

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Abstract Levels in the neutron-rich ^{109}Ru have been studied by observing the prompt γ-rays following the spontaneous fission fragments of ^{252}Cf. The ground state band and the negative parity bands have been confirmed and extended. A positive parity band with the band head level at 332.5 keV is newly identified and suggested as a single-neutron excitation band built on the $7/2^+[404]$ Nilsson orbital. Some structural characteristics of these bands are discussed.

Key words collective levels, γ-transitions and level energies, neutron-rich nucleus, spontaneous fission

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1 Introduction

High-spin level structural studying of odd-A Ru deformed nuclei in the $A \sim$100 neutron-rich region can provide many interesting characters, such as the single-particle orbital characters, the rotation-alignments, and triaxial deformations and possible shape transitions[1—4]. Several rotational bands built on the single-particle levels have been observed, for example, in ^{107}Ru[3, 4], ^{111}Ru[2, 5, 6] and ^{113}Ru[7]. For ^{109}Ru, high-spin collective band based on the $5/2^+$ state ($\nu g_{7/2}/\nu d_{5/2}$ subshells) and a side band based on the $9/2^-$ state ($\nu h_{11/2}$ subshell) have been established through studying the prompt γ-rays from the spontaneous fission of ^{252}Cf[1, 4, 5, 8] and ^{238}U(α,f) fusion-fission reaction[2]. In this paper, we report on identification of a new single-neutron excitation band and some new γ-transitions in ^{109}Ru.

2 Experiments and results

We investigated the high-spin structures of ^{109}Ru via the spontaneous fission of ^{252}Cf. The experiment was carried out at the Lawrence Berkeley National Laboratory. High-fold coincidences between prompt γ-rays were measured using the Gammasphere detector array which consisted of 102 Compton-suppressed Ge detectors. A total of 5.7×10^{11} triple- and higher fold- γ-coincidence events were collected. The high-quality coincidence data were analyzed with the Radware software package[9] using γ-γ-γ coincidence methods.

Level scheme of ^{109}Ru derived from the present work is shown in Fig. 1. The three collective bands observed are labeled as (1) — (3) above the scheme. The relative intensities of γ-transitions are also given in parentheses. For the ground state (GS) band, we have confirmed most of the transitions with spin up to $29/2^+$ observed in our previous work[5] and a recent report.[2] However, in Ref. [2], a 729 keV transition was added between the 764 and 652 keV cascade transitions in the GS band comparing with those in our previous work[5]. The result in the present work supports our assignment in Ref. [5] that the 729 keV transition is not a member of band (1) but a linking transition between band (1) and the new side band

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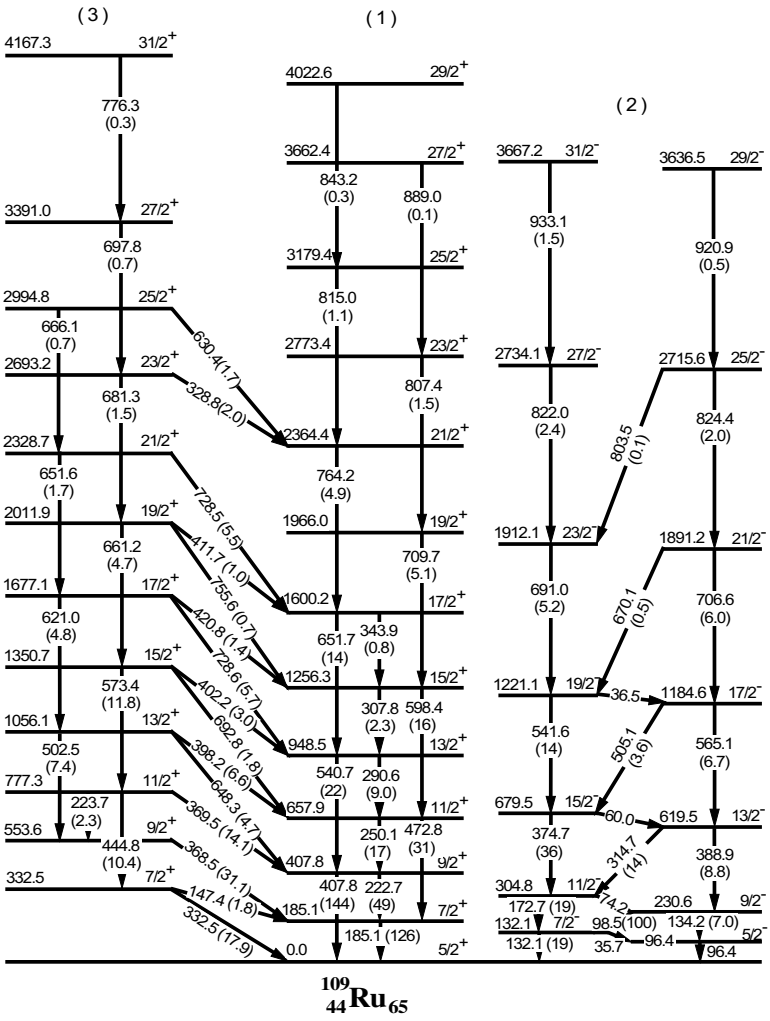

Fig. 1. Level scheme of ^{109}Ru. Energies of γ-rays are given in keV and relative transition intensities are given in parenthesis.

(3) as shown in Fig. 1. Comparing with Ref. [5], we added a new 343.9 keV $\Delta I = 1$ M1 linking transition between 1600.2 and 1256.3 keV levels. For bands (2), besides the γ-transitions found in Refs. [1, 4, 5], we also identified two linking ones 60.0 keV and 36.5 keV. Band (3) based on 332.5 keV level is identified for the first time in the present work. A total of 12 energy levels and 26 γ-transitions in this band and between bands (1) and (3) have been observed.

3 Discussion

The positive parity GS band (1) has been assigned as $K^\pi = 5/2^+$ based on the $5/2^+[413]$ orbital of the $\nu d_{5/2}$ subshell mixed with the $5/2^+[402]$ orbital of the $\nu g_{7/2}$ subshell[1, 4, 9]. The negative parity band (2) was identified as $\nu h_{11/2}$ unique parity (intruder) band based on $9/2^-$ state. Structural characters of these two bands have been discussed detailed in Refs. [1, 4, 5]. For the newly identified band (3), based on the strong linking transitions between bands (3) and (1), we assigned it as a positive parity band. According to the observed patterns of decay transitions from band (3) to band (1) as well as the level spacings inside band (3) comparing with those in band (1), we assigned the spin and parity (I^π) of the 332.5 keV band head level as $7/2^+$. The I^π of other levels in band (3) are assigned as seen in Fig. 1. In order to have more confirmation for our assignments above, we carried out $\gamma - \gamma(\theta)$ angular correlation measurements based on our data set divided into angular bins[10]. The $\gamma - \gamma(\theta)$ for the 369.5—407.8 keV cascade yielded $A_2 = -0.080 \pm 0.073$ and $A_4 = -0.055 \pm 0.112$. Theoretical values $A_2 = -0.0714$ and $A_4 = 0.0$ for a $11/2^+(D)9/2^+(Q)5/2^+$ cascade are consistent with our assignments that the 777.3 keV level with $I^\pi = 11/2^+$.

For band (3), as the band head energy 332.5 keV is much lower than the ones of the one-phonon γ-vibrational bands (∼600—800 keV) observed in even-even $^{108-112}$Ru[2, 11—13], $^{112-118}$Pd[14, 15], $^{104-108}$Mo[16—20] and odd-A ^{105}Mo[21, 22] in this region, the band (3) should originate from a single-quasi-neutron configuration. From Nilsson diagram[23] for neutron of this region, the positive parity single-neutron orbitals expected near the Fermi level are $5/2^+[413]$, $1/2^+[411]$, $5/2^+[402]$ and $7/2^+[404]$. So to assign the configuration for the 332.5 keV band head as $7/2^+[404]$ of $\nu g_{7/2}$ subshell is reasonable. Moreover, we have calculated the $|g_{\rm K}-g_{\rm R}|/Q_0$ value of this band from the γ-ray branching ratio based on the formulas from Ref. [24]. For the $\nu g_{7/2}$ $7/2^+[404]$ sub-orbital, the experimental value is $|g_{\rm K}-g_{\rm R}|/Q_0 = 0.026(5)(b)^{-1}$. By using the corresponding formula and parameters in Refs. [25, 26], the calculated theoretical value is 0.030 $(\rm b)^{-1}$. The experimental value is consistent with the theoretical one, and it confirms our assignment.

On the other hand, we have analyzed the total angular-momentum alignment I_x to obtain more information about the underlying single particle structure of the nucleus. Fig. 2. shows the I_x for positive-parity bands (1) and (3) in ^{109}Ru and the GS bands in ^{108}Ru, ^{110}Ru. For GS band (1) in ^{109}Ru, the alignment shows a similar trend with these for the yrast bands in ^{108}Ru and ^{110}Ru when $\hbar\omega \leqslant 0.41$ MeV, and then it shows an obvious energy level splitting when $\hbar\omega > 0.41$ MeV. One can see the back-bending (band-crossing) occurs in every band: for the yrast bands in ^{108,110}Ru, the crossing frequencies are $\hbar\omega \approx 0.40$ MeV, for the GS band (1) in ^{109}Ru, $\hbar\omega \approx 0.43$ MeV, and for the band (3) in ^{109}Ru, $\hbar\omega \approx 0.33$ MeV. The yrast band crossings of even-even ^{108,110}Ru are caused by alignment of a pair of $h_{11/2}$ neutrons according to the cranked shell model calculations[2, 12, 13]. So the band crossings for the bands (1) and (3) in ^{109}Ru are most probably caused by alignment of a pair of protons because the neutron alignment should be delayed due to the single neutron blocking effect as discussed in Ref. [2,5]. We have noticed that the crossing frequency of the band (3) is much lower than those in yrast bands of ^{108,110}Ru. It may be caused by the occupied different single-neutron orbital.

The signature splitting and band staggering of positive parity bands (1) and (3) in ^{109}Ru are shown in Fig. 3, in which $\Delta E = E_\gamma(I+1 \to I) - E_\gamma(I \to I-1)$ as a function of spin I. From the figure, one can see not only the signature splitting but also the signature inversion that occurs at $I \approx 21/2\hbar$ for band (1) and $I \approx 17/2\hbar$ for band (3). These signature inversions may be caused by structural variation at middle spins as also observed in the GS band of ^{107}Ru.

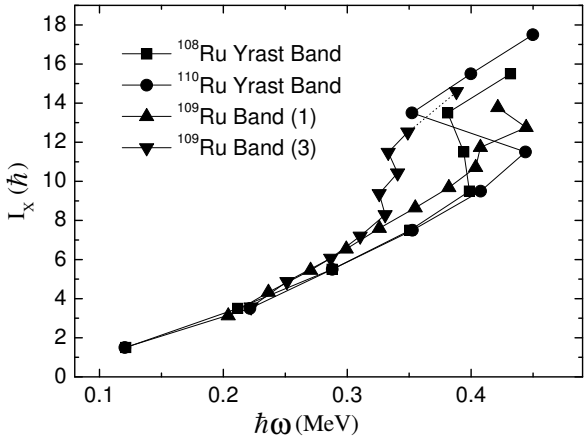

Fig. 2. Total angular-momentum alignment I_x for positive-parity bands (1) and (4) in ^{109}Ru and the GS bands in ^{108}Ru, ^{110}Ru.

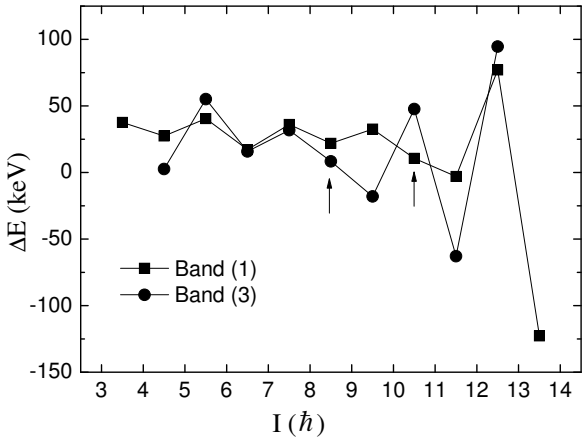

Fig. 3. Plots of the ΔE against spin I for bands (1) and (4) in ^{109}Ru illustrating the presence of signature splitting and inversion.

4 Summary

Excited states of neutron-rich ^{109}Ru were populated in the spontaneous fission of ^{252}Cf. The level scheme of ^{109}Ru has been investigated. The GS band (1) and the negative parity band (2) are confirmed and updated. A positive parity side band built on the $7/2^+[404]$ Nilsson orbital is newly identified. The band crossing of the side band (3) may be caused by proton alignment. Other characters of these bands have been discussed.

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