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High spin structure and multi-phonon γ-vibrations in very neutron-rich ^{114}Ru

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High spin levels of the neutron-rich ^{114}Ru have been investigated by measuring the prompt γ-rays in the spontaneous fission of ^{252}Cf. The ground state band and one-phonon γ-vibrational band have been extended up to 14^+ and 9^+, respectively. Two levels are proposed as the members of a two-phonon γ-vibrational band. A backbending (band crossing) has been observed in the ground state band at $\hbar\omega \approx 0.40$ MeV. Using the triaxial deformation parameters, the cranked shell model calculations indicate that this backbending in ^{114}Ru should originate from the alignment of a pair of $h_{11/2}$ neutrons. Triaxial projected shell model calculations for the γ-vibrational band structures of ^{114}Ru are in good agreement with the experimental data. However, when using the oblate deformation parameters, both the above calculated results are not in agreement with the experimental data.

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I. INTRODUCTION

The very neutron-rich ^{114}Ru nucleus with $Z = 44$ and $N = 70$ is located between the well-deformed Sr and Zr ($Z = 38, 40$; $N = 60, 62$) and the spherical double-magic ^{132}Sn. Study of the high spin states in this region can provide important insight into the nuclear structures [1]. Previously, the high spin collective band structures in even-even ^{108,110,112}Ru have been studied by measuring the prompt γ-rays emitted from the spontaneous fission or the induced fission of heavy nuclei [2–10]. Besides the ground state bands, some collective bands such as one-phonon and two-phonon γ-vibrational bands, and chiral doublet bands have been observed in ^{108,110,112}Ru. The level scheme of ^{114}Ru was first established by Shannon *et al.* [2] from the spontaneous fission of ^{248}Cm. The ground state band and a one-phonon γ-vibrational band have been observed to 10^+ and 5^+ respectively in that work. When this work was nearly finished, a low spin level scheme of ^{114}Ru was investigated from the β decay of ^{114}Tc by using the Penning-trap-assisted γ spectroscopy in a very recent publication [11], and six new levels were established compared to the work in Shannon *et al.* [2]. Several theoretical calculations were also published [11–14] and gave valuable results. However, compared to the neighboring Ru isotopes, the high spin data in ^{114}Ru are still lacking.

In this paper, we report on the observation of new high spin states in ^{114}Ru. A backbending in the ground band is observed. With triaxial deformation parameters, cranked shell model calculations indicate this backbending originates from the alignment of a pair of $h_{11/2}$ neutrons. Triaxial projected shell model calculations are in good agreement with our extended one-phonon γ-vibrational band and for our newly proposed two-phonon γ-vibrational band. The experimental data are not in agreement with the calculations when an oblate deformation is assumed.

II. EXPERIMENT AND RESULTS

To study the high spin states of ^{114}Ru, the prompt γ-rays emitted after their formation in the spontaneous fission of ^{252}Cf were measured. The experiment was carried out at the Lawrence Berkeley National Laboratory. Prompt γ-γ-γ coincidence studies were performed with the Gammasphere detector array consisting of 102 Compton-suppressed Ge detectors. A ^{252}Cf source of strength ~ 60 μCi was placed at the center of the Gammasphere. A three-dimensional histogram of 5.7×10^{11} coincidence events was constructed. The coincidence data were analyzed with the RADWARE software package [15].

It is very difficult to observe the high spin band structures for the very neutron-rich nuclei like ^{114}Ru, because their yield is low in fission experiments. By carefully examining the coincidence relationships and γ-ray rela-

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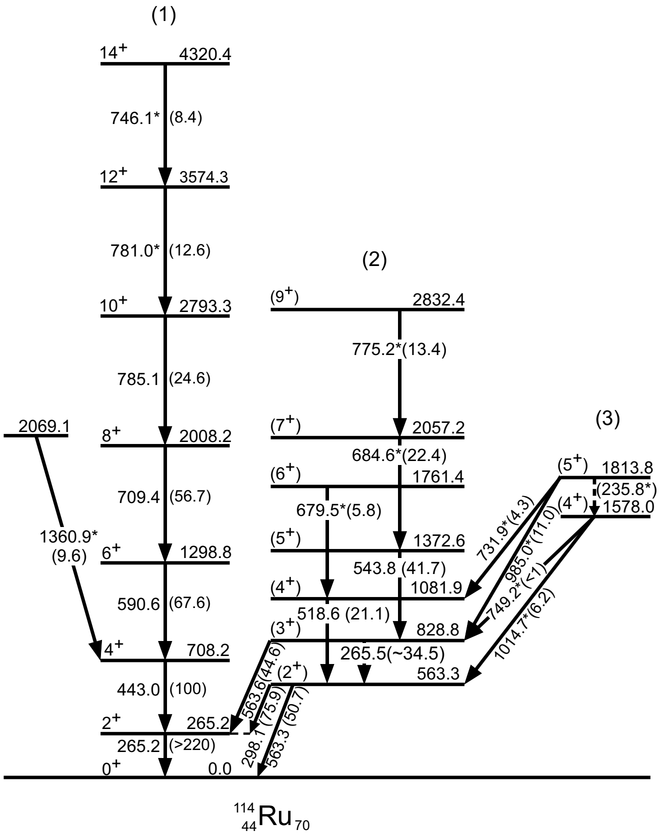

FIG. 1: Level scheme of ^{114}Ru obtained in the present work. Energies are in keV. The new transitions have been marked with an asterisk (*). The relative transition intensities are given in brackets after the transition energies as percentages of the 443.0 keV transition intensity. The errors of the transition energies are about 0.5 keV.

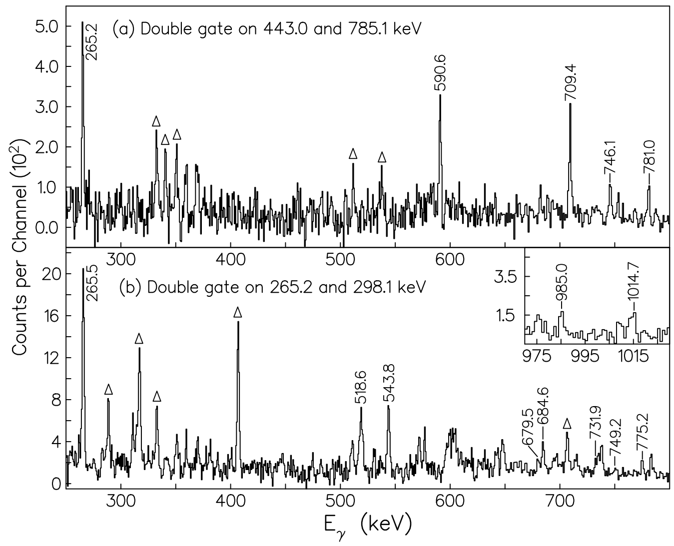

FIG. 2: Portion γ-ray spectra by: (a) double gating on 443.0 and 785.1 keV transitions, and (b) double gating on 265.2 and 298.1 keV transitions in ^{114}Ru. The peaks marked with the symbol(Δ) come from contaminants.

tive transition intensities, a new level scheme of ^{114}Ru obtained in the present work is shown in Fig. 1. As examples to illustrate the basis of Fig. 1, Fig. 2 shows two coincidence γ-ray spectra in ^{114}Ru. In Fig. 2(a), by double gating on 443.0 and 785.1 keV γ-transitions, one can see all the γ-peaks in band (1), except for the gating peaks of 443.0 and 785.1 keV. In Fig. 2(b), by double gating on 265.2 and 298.1 keV γ-transitions, one can see all the γ-peaks in band (2) as well as the new γ-transitions of 731.9, 749.2, 985.0, and 1014.7 keV.

In the present work, all transitions reported in Ref. [2] were confirmed. Two new transitions of 781.0 and 746.1 keV were observed above the level at 2793.3 keV in the ground state band (1), hence, the ground state band (1) was extended up to 14^+. In Ref. [2] band (2) was identified only with three levels at 563.9, 829.3 and 1373.3 keV along with two transitions of 265.4 and 544.0 keV. These levels and transitions along with the level at 1081.9 keV and the transition of 518.6 keV were also observed in Ref. [11]. Band (2) was tentatively assigned as a positive parity band based on 2^+ in Ref. [2]. The spin and parity (I^π) for the 828.8, 1081.9 and 1372.6 keV levels have been tentatively assigned as 3^+, 4^+ and 5^+ respectively [2, 11]. In this work, three new levels at 1761.4, 2057.2 and 2832.4 keV, along with three new γ-transitions of 679.5, 684.6 and 775.2 keV have been identified in this band. The I^π of these new levels in band (2) are tentatively assigned as 6^+, 7^+ and 9^+, respectively, based on the regular level spacings. Three linking transitions of 563.3, 298.1 and 563.6 keV between bands (1) and (2) which were reported in Refs. [2, 11] are confirmed. Two new levels at 1578.0 and 1813.8 keV along with four linking transitions of 1014.7, 749.2, 985.0 and 731.9 keV from these levels to band (2) are also observed in the present work comparing with the results in Ref. [2]. These levels are assigned to be members of a new band (3) built on the 1578.0 keV level in this work. The 1578.0 keV level along with a transition of 870.3 keV between 1578.0 and 708.2 keV levels was reported in Ref. [11]. But the 870.3 keV transition is not observed in our fission data. Through our triple γ-γ-γ coincidence analysis, the 1014.7 keV transition does not come from the ^{27}Al(n, n′) γ-ray. By double gating on 265.2 and 298.1 keV γ-transitions, the 1014.7 keV peak can be seen, as shown in Fig. 2(b). In the same way, we have checked that by double gating on the 1014.7 and 298.1 keV, the 265.2 keV peak can be seen, and by double gating on 1014.7 and 265.2 keV γ-transitions, the 298.1 keV peak can been seen also. But when we check the other cascade coincidence relationships, for example, in 1014.7-563.6-265.2 keV cascade, we can not see such coincidence relationships. A very weak 235.8 keV transition in band (3) has some uncertainty. Comparing with the neighboring $^{108-112}$Ru [10], the spins and parities for the two levels at band (3) are tentatively assigned as 4^+ and 5^+. A total of 7 new levels and 11 new transitions are identified in the present work, comparing to the results in Refs. [2, 11].

III. DISCUSSION

Shannon *et al.* [2] proposed that ^{114}Ru shows triaxial deformation with $\gamma = 27.2°$ in the ground state based on the rigid triaxial rotor (RTR) model [16]. This value is near to those in ^{108,110,112}Ru with $\gamma = 22.5°$, 24.2° and 26.4°, respectively [2]. However, in Refs. [13, 14], Xu *et al.* and Faisal *et al.* have made total-Routhian-surface (TRS) calculations based on cranked shell model with nonaxial deformed Woods-Saxon potential, and the results indicated that ^{114}Ru should have an oblate shape with β_2 = 0.236, and γ = -59°, whereas ^{108,110,112}Ru show triaxial shapes. They indicated that shape evolution from triaxial to oblate occurs in $^{108-114}$Ru. They note, however, that the minima of these nuclei are very shallow, suggesting that the deformation is soft and a small perturbation near the Fermi surface would drive the system from one shape to another.

For our new result in ^{114}Ru, we have carried out an analysis of the kinetic moment of inertia for the ground state band (1). Plots of these kinetic moments of inertia $J^{(1)}$ as a function of rotational frequency $\hbar\omega$ for band (1) in ^{114}Ru along with the ground state bands in ^{108,110,112}Ru [4–6, 9, 10] are shown in Fig. 3. It shows that the backbending (band crossing) of ground state bands in ^{108,110}Ru and ^{114}Ru all occur at a rotational frequency $\hbar\omega \sim 0.4$ MeV, with ^{112}Ru having only a smooth upbending behavior. In order to make an interpretation of the observed backbend of band (1) in ^{114}Ru, we have carried out cranked shell model (CSM) calculations [17–19] to determine whether the proton orbital ($g_{9/2}$) or the neutron orbital ($h_{11/2}$) is responsible for the backbending at the observed rotational frequencies. As different deformation parameters in ^{114}Ru have been suggested in Refs. [2, 13, 14], we took two sets of parameters in the calculations: (A) taking the triaxial deformation parameters with $\beta_2 = 0.236$, $\gamma = 27.2°$ [2], and (B) taking the oblate ones with $\beta_2 = 0.236$, γ = -59° [13, 14]. The calculated quasi-particle energies (Routhians) for ^{114}Ru are shown in Fig. 4. The calculations using both sets of parameters predict the band crossing as: (A) the alignment of two $g_{9/2}$ protons at $\hbar\omega > 0.60$ MeV and the alignment of two $h_{11/2}$ neutrons at $\hbar\omega \sim 0.39$ MeV using triaxial deformation parameters, and (B) the alignment of two $g_{9/2}$ protons at $\hbar\omega \sim 0.40$ MeV and the alignment of two $h_{11/2}$ neutrons at $\hbar\omega \sim 0.28$ MeV using oblate deformation parameters. The calculations indicate that in both cases in ^{114}Ru, the neutron alignments should happen first corresponding to the first backbending, and the proton alignments should correspond to a second backbending. So the observed backbending in band (1) of ^{114}Ru should be caused by $h_{11/2}$ neutron alignments, just like in neighboring isotopes ^{108,110,112}Ru [4–6]. However, using the oblate deformation parameters, the calculated neutron band crossing frequency at $\hbar\omega \sim 0.28$ MeV is much smaller than the experimental value at $\hbar\omega \sim 0.4$ MeV, whereas using the triaxial deformation parameters, the calculated neutron band crossing frequency at $\hbar\omega \sim$ 0.39 MeV is in excellent agreement with the experimental value.

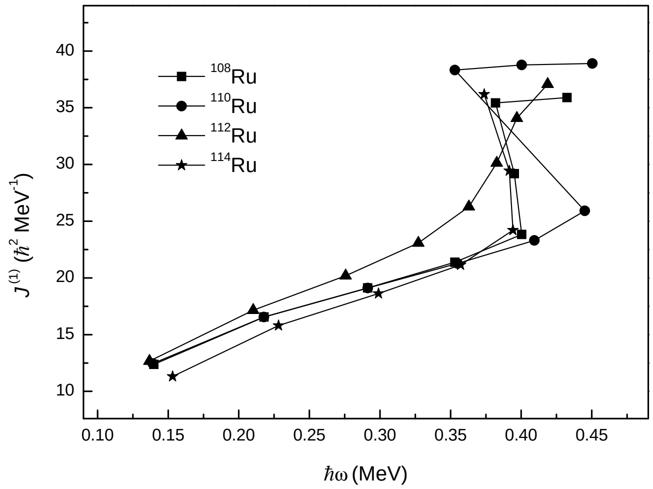

FIG. 3: Plots of kinetic moment of inertia $J^{(1)}$ versus rotational frequency $\hbar\omega$ for ground state bands in ^{108,110,112,114}Ru.

TABLE I: Energies (keV) and ratios between two- and one-phonon γ-vibrational bands.

	^{108}Ru	^{110}Ru	^{112}Ru	^{114}Ru
$E_{4_3^+}$	1643.9	1618.4	1413.9	1578.0
$E_{2_2^+}$	707.9	612.7	523.6	563.3
$E_{4_3^+}/E_{2_2^+}$	2.32	2.64	2.70	2.80

Band (2) has been assigned as a one-phonon γ-vibrational band [2]. The ground state band and one-phonon γ-vibrational band are expected to exhibit similar inertia parameters [20]. The inertia parameter A can be obtained from the second-order rotational energy formula:

$$E(I,K) = E_K + A[I(I+1) - K^2] + B[I(I+1) - K^2]^2. \quad (1)$$

Using our new observed data, the values of the inertia parameter A obtained in ^{114}Ru are 35.5 and 35.7 keV for the ground state band and band (2), respectively. The similar values of the inertia parameter support the assignment of band (2) as a one-phonon γ-vibrational band.

Band (3) is built on the 1578.0 keV level. As the energy of the band head level of band (3) is much less than the neutron paring-gap energy $2\Delta_n \sim 2.1$ MeV and the proton paring-gap energy $2\Delta_p \sim 1.7$ MeV [21] in this region, band (3) should not be a two-quasiparticle band. We assign the band (3) as a two-phonon γ-vibrational band. Similar two-phonon γ-vibrational bands have also been observed in neighboring isotopes ^{108,110,112}Ru [4, 6, 10]. Table I shows the excitation energies and energy ratios between the band head levels of the 4^+ two-phonon γ-vibrational band and the 2^+ one-phonon γ-vibrational band in ^{108,110,112}Ru [10] and in ^{114}Ru (present work).

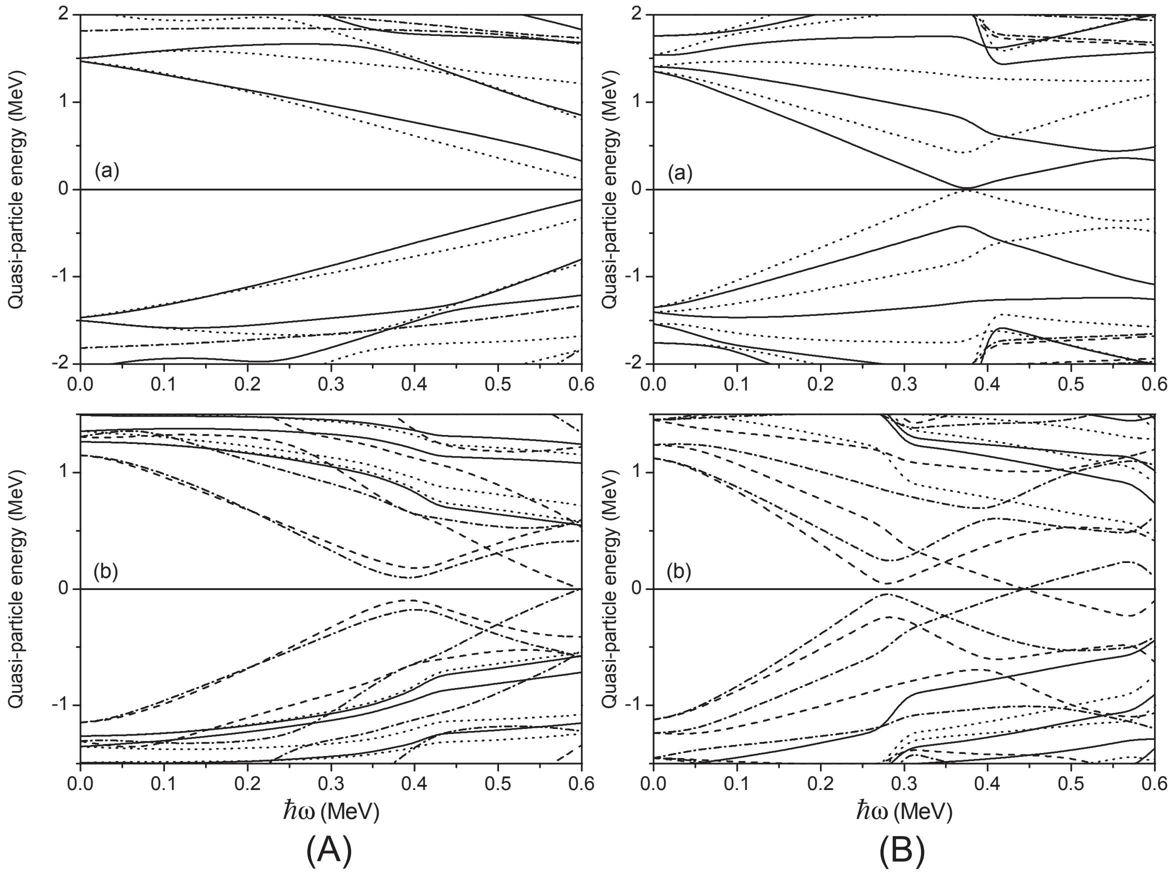

FIG. 4: The calculated Routhians by (A) (left part) taking the triaxial deformation parameters with $\beta_2 = 0.236$, $\gamma = 27.2°$ and (B) (right part) taking the oblate ones with $\beta_2 = 0.236$, γ = -59° against rotational frequency $\hbar\omega$ in ^{114}Ru. In each part, (a) is for quasi-protons, and (b) for quasi-neutrons. The parity and signature (π, α) of the levels are: solid lines (+1/2, +1/2); dotted lines (+1/2, -1/2); dot-dashed lines (-1/2, +1/2); dashed lines (-1/2, -1/2).

One can see that the $E_{4_3^+}/E_{2_2^+}$ values in all the isotopes are in accord with the systematics, but they are larger than the harmonic ratio 2, and progressively increase toward heavy isotopes. The larger ratio indicates an increasing anharmonicity in the γ vibration.

To gain a deeper understanding for the multi-phonon γ band structure, we have performed triaxial projected shell model (TPSM) [22] calculations for ^{114}Ru. It has been shown that TPSM calculations with triaxially deformed basis can naturally describe multi-phonon γ-vibrations [23]. TPSM with multi-quasiparticle (qp) configurations in the model has recently been developed and applied successfully in different mass regions for even-even [24, 25] and odd-mass nuclei [26]. It has been shown that the model can quantitatively reproduce the observed data of the multi-phonon γ-vibrational bands built on top of various multi-qp states.

In the TPSM calculation, one starts from the triaxially-deformed Nilsson-BCS bases. The Nilsson potential is given by

$$\hat{H}_0 - \frac{2}{3}\hbar\omega \left[\varepsilon \hat{Q}_0 + \varepsilon' \frac{\hat{Q}_{+2} + \hat{Q}_{-2}}{\sqrt{2}} \right] \quad (2)$$

where $\hat{H}_0$ is the spherical single-particle Hamiltonian with inclusion of appropriate spin-orbit forces parametrized by Bengtsson and Ragnarsson [27]. The axial and triaxial parts of the Nilsson potential in Eq. (2) contain the deformation parameters ε and ε', which are related to the conventional triaxiality parameter by $\gamma = \tan^{-1}(\varepsilon'/\varepsilon)$. As we shall show, the choice of deformation parameters $\varepsilon = 0.25$ and $\varepsilon' = 0.13$ will reproduce the data nicely. The corresponding γ value is 27°. Thus these deformation parameters are consistent with the values suggested by Shannon *et al.* [2]. The pairing correlation in the Nilsson states is taken into account by a standard BCS calculation, within a model space of three major shells for each kind of nucleon (N= 3, 4, 5 for neutrons and N= 2, 3, 4 for protons).

In the TPSM calculation, we use the same Hamiltonian as for the earlier PSM calculations [28].

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_\mu \hat{Q}^\dagger_\mu \hat{Q}_\mu - G_M \hat{P}^\dagger \hat{P} - G_Q \sum_\mu \hat{P}^\dagger_\mu \hat{P}_\mu, \quad (3)$$

The strength of the quadrupole-quadrupole force χ is determined in a self-consistent manner so that it is related to the deformation of the basis [28]. The monopole-

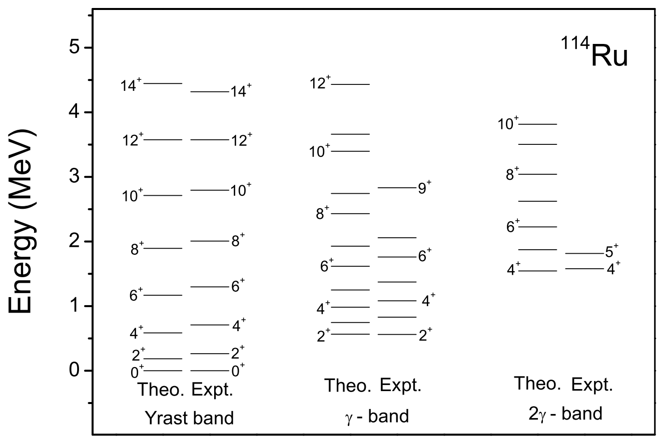

FIG. 5: Calculated energy levels for ^{114}Ru and comparison with available data.

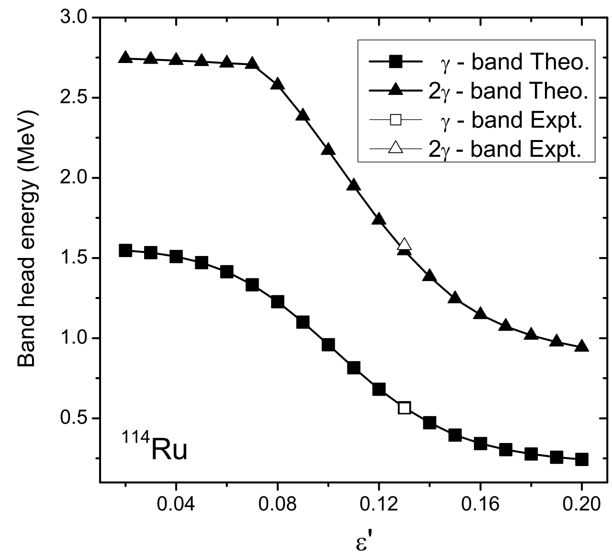

FIG. 6: Band head energies varying with the deformation parameter ε' and comparison with the experimental band head energies of the γ-vibrational bands in ^{114}Ru.

pairing strength is taken to be the standard form $G_M = G_{\nu,\pi}/A$, with $G_\nu = 16.22$ for the neutron and $G_\pi = 22.68$ for the proton coupling constant. The quadrupole-pairing strength G_Q is assumed to be proportional to G_M, the proportionality constant being 0.18.

The TPSM results compared with the experimental data are presented in Fig. 5. One can see that the experimental results are described reasonably well by the TPSM calculations. We note especially that the band head energies for bands (2) and (3) are precisely reproduced. The good agreement with the experimental data supports the interpretation for the bands (2) and (3) as 1-γ and 2-γ bands, respectively. The TPSM calculation suggests also that the data can only be quantitatively described when a positive quadrupole deformation combined with a large triaxiality ($\gamma = 27°$) is assumed. To understand the TRS results in Ref. [13, 14], we have performed TPSM calculations by assuming an oblate shape (negative quadrupole deformation) for ^{114}Ru. We find that such results cannot reproduce the current data, and in particular, the obtained γ-ray energies (moments of inertia) for the yrast band (band (1)) are not consistent with the data. We note that the TRS calculations for ^{114}Ru [13, 14] yield only very shallow minima, suggesting a γ-soft nature for this nucleus.

In order to understand the large anharmonicity observed in the ^{114}Ru vibrations, we present in Fig. 6 the calculated band head energies of the 1-γ and 2-γ bands varying with the triaxial deformation ε'. The axial deformation is fixed at $\varepsilon = 0.25$. It is interesting to observe that the band head energies of the γ-bands are nearly constant from $\varepsilon' = 0.02$ to $\varepsilon' = 0.08$ and the ratio $E_{4_3^+}/E_{2_2^+}$ is close to 2, indicating that the vibration is nearly harmonic. With increasing triaxiality ε', the ratio increases and an anharmonicity develops. The variation shows that the anharmonicity of the γ-vibration is related to triaxial deformation. This picture is consistent with the conclusion of the early work of Davydov and Filippov [16]. At $\varepsilon' = 0.13$ or $\gamma = 27°$, the agreement with the data becomes essentially perfect. Thus the TPSM calculation naturally describes the anharmonicity found by the experimental data, and suggests that the triaxial degree of freedom plays an important role in the γ-vibrational bands of ^{114}Ru.

From the CSM and TPSM calculations above, one can see that both calculated results suggest triaxial deformation in ^{114}Ru. Moreover, the TPSM calculation does not support the interpretation of an oblate deformation. So apparently the ^{114}Ru nucleus still keeps the triaxial deformation, just like in ^{108,110,112}Ru, and the shape transition from triaxial to oblate in neutron-rich Ru isotopes may not happen. This needs further theoretical study.

IV. SUMMARY

In the present work, the high-spin states of neutron-rich ^{114}Ru nucleus have been studied by measuring the prompt γ-rays in the spontaneous fission of ^{252}Cf. The ground state band and one-phonon γ-vibrational band have been extended and backbending observed in the ground state band. Two new levels at 1578.0 and 1813.8 keV were assigned as the members of the two phonon γ-vibrational band. Using different deformation parameters, CSM calculations were carried out to determine the origin of the observed band crossing in the ground state, and TPSM calculations were used to describe the multi-phonon γ-vibrational band energy levels. Both calculations indicate good agreement between theoretical and experimental results when using a triaxial deformation in ^{114}Ru but not for an oblate deformation.

V. ACKNOWLEDGMENTS

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