New high-spin level scheme of neutron-rich ^{112}Rh

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The neutron-rich nucleus ^{112}Rh has been reinvestigated by examining the prompt γ rays emitted in the spontaneous fission of ^{252}Cf with the Gammasphere detector array. A new side band was built in ^{112}Rh. Total Routhian surface calculations have been performed and confirm the role of triaxiality in the negative-parity structure of ^{112}Rh.

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Odd-odd neutron-rich Rh isotopes are located in the $A \approx 110$ region where the nuclear structures are characterized by shape coexistence and shape transitions [1–3]. The appearance of triaxial deformations has been found for nuclei $Z \geqslant 41$ [3–12] in this mass region. A remarkable similarity in the high-spin, negative-parity yrast states of odd-odd $^{104-114}$Rh is seen throughout a large range of neutron numbers from 59 (^{104}Rh) to 69 (^{114}Rh) [7–11,13–15]. These negative-parity yrast bands have been found to be built on a 6^- state with a 7^- intermediate state from $N = 59$ to $N = 65$ and then the band head becomes 7^- at $N \geqslant 67$. These $\Delta I = 1$, negative-parity yrast bands, which are believed to originate from the coupling of a proton in the $g_{9/2}$ orbital with a strongly aligned $h_{11/2}$ neutron, are present at low and moderate excitations and influenced by the triaxial deformation.

Our recent publication [11] reported the first high-spin level scheme of ^{114}Rh from the spontaneous fission (SF) of ^{252}Cf where a side band was found. The existence of such an yrare band may be used as an indicator of triaxial deformations [16]. Similar side bands have been reported in odd-odd ^{104}Rh [9] and ^{106}Rh [10] where chiral geometry has been found and discussed within the doublet of the yrast and yrare bands with nearly maximum triaxiality, $\gamma \approx -30^\circ$. The high-spin states in ^{108,110}Rh have been studied in either fusion-fission experiments [7,14,15] or ^{252}Cf SF experiments [8]. In these papers, no such a side band was identified, which may be due to low fission rates of these isotopes.

In ^{112}Rh, Luo *et al.* [8] found two levels at 802.4 and 1230.0 keV, where (10^-) and (11^-) were assigned, respectively, on the grounds of their decay pattern, in addition to the $\Delta I = 1$, yrast band (Band 1 in Fig. 2). The 802.4-keV level decays to the 402.8-keV, (9^-) yrast state and is fed by a 427.5-keV transition from the 1230.0-keV level (energies from Ref. [8]). These two levels may be part of a side band in ^{112}Rh. Thus, it is worth further exploring the existence of an yrare band and higher-spin states in ^{112}Rh.

To obtain additional experimental knowledge of the high-spin structure of ^{112}Rh, we re-examined our high-statistics data collected using a ^{252}Cf SF source of 62 μCi α activity and the Gammasphere detector array at Lawrence Berkeley National Laboratory. A total of 5.7×10^{11} triple- and higher-fold γ-ray coincidence events were obtained. These data were analyzed with the RADWARE software package [17].

A new transition of energy 337.9 keV is seen in the spectra double gated on the known 60.6-keV transition in ^{112}Rh and on the known 159.3-keV transition in ^{112}Rh, the 1133.8-keV transition in ^{135}I [18], and the 1111.8-keV transition in ^{136}I [19], respectively. This transition should belong to ^{112}Rh. Figure 1(a) supports this proposal where the gates are set on the known 60.6-keV transition in ^{112}Rh and the new 337.9-keV transition. In Fig. 1(a), the known transitions of energies 159.3 keV in ^{112}Rh, 1133.8 keV in ^{135}I, 1111.8 keV in ^{136}I and strong transitions in ^{137}I [20] are seen. Note that the 427.5-keV (427.6-keV here) transition in ^{112}Rh reported in Ref. [8] is observed in Fig. 1(a). New transitions of energies 244.9, 284.9, 672.5, and 712.5 keV are shown. Figure 1(b) presents the coincidence spectrum gated on the new 337.9- and 224.9-keV transitions where the known transitions of energies 60.6, 159.3, and 427.6 keV are seen along with strong transitions in $^{135-137}$I. Shown in Fig. 1(b) are the new transitions of energies 284.9, 422.9, and 712.5 keV. A new transition of energy 497.2 keV, equal to the sum of 337.9 and 159.3 keV, is confirmed by double gating on the 60.6- and 244.9-keV transitions, and on the 244.9- and 427.6-keV transitions. Another new transition of energy 582.8, equal to the sum of 337.9 and 244.9 keV and that of 399.6 and 183.2 keV, is seen by double gating on the 159.3- and 712.5-keV transitions, and on the 159.3- and 427.6-keV transitions. These data enable us to establish a new side band (yrare band) in ^{112}Rh in addition to the yrast band reported in Ref. [8], as shown in Fig. 2. All the levels and transitions in the yrast band reported in Ref. [8] have been confirmed in the present work where we cannot add any lower- or higher-spin level.

In Fig. 2, spins and parities in the yrare band are tentatively assigned by assuming the 337.9-keV transition having a

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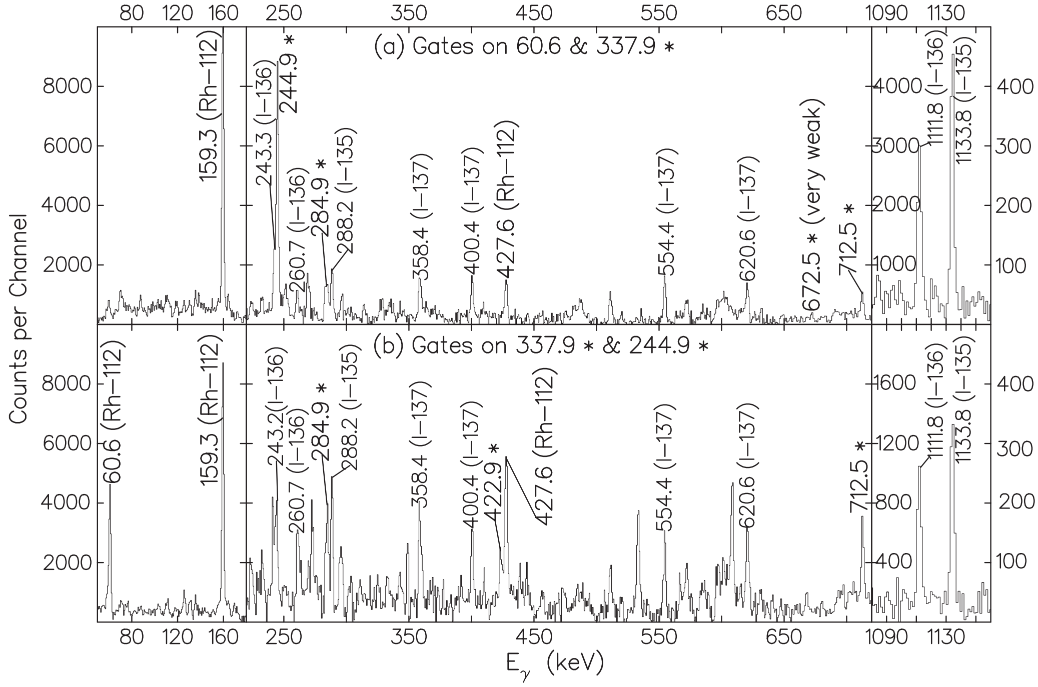

FIG. 1. Coincidence spectra double gated on the known 60.6-keV and new 337.9-keV transitions, and on the new 337.9- and 244.9-keV transitions in ^{112}Rh. New transitions are marked with an asterisk. Other unlabeled strong peaks are from random coincidence or contamination.

$\Delta I = 1$, $E2/M1$ character and the crossover transitions being $E2$ and taking into account the similarity between the side bands in ^{112}Rh and ^{114}Rh as shown in Fig. 3. These tentative assignments are also supported by the decay patterns in band 2, for example, the 557.8-keV level in band 2 decaying to the 60.6-keV [(7$^-$)], 219.9-keV [(8$^-$)], and 403.1-keV [(9$^-$)] levels in band 1, which confines the spin-parity of the 557.8-keV level to (9$^-$). Spin-parity assignments in the yrast band are adopted from Ref. [8], except for the labeled 0-keV level because more definite measurements are required to determine the multipolarity of the 60.6-keV transition. The similarities of the yrast structures of odd-odd $^{104-114}$Rh have been discussed in Ref. [11,15] to support the spin-parity assignments.

Note that an yrare band has been observed in ^{104}Rh [9], ^{106}Rh [10], and ^{114}Rh [11], respectively, which are interpreted as triaxially deformed. The existence of such an yrare band has been discussed in odd-even $^{107-115}$Rh, which demonstrates typical features of nuclei with triaxiality, and their structures have been reproduced very well by the rigid triaxial rotor plus particle model [8,12,21]. Thus, the presence of an yrare band in ^{112}Rh may be understood to have triaxial deformation.

Note that the phenomenon of signature inversion in the negative-parity yrast band of ^{114}Rh has been reported

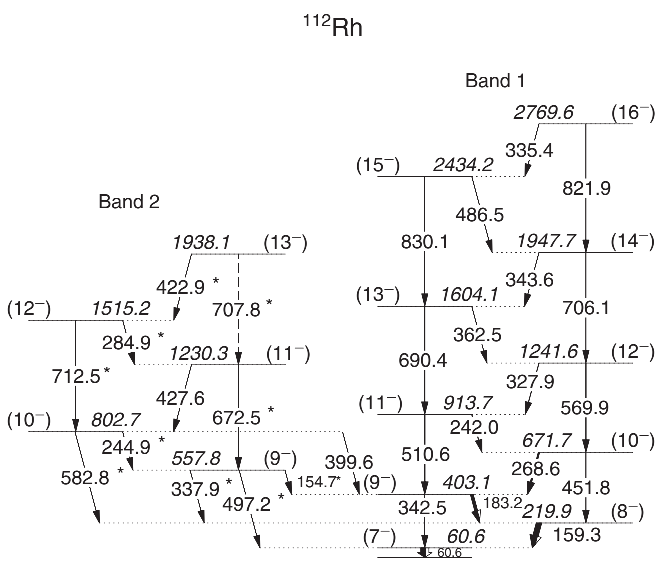

FIG. 2. Partial level scheme of ^{112}Rh established in the present work. The newly identified transitions are marked with an asterisk. All level energies are relative to the energy of the lowest state which is labeled as zero keV.

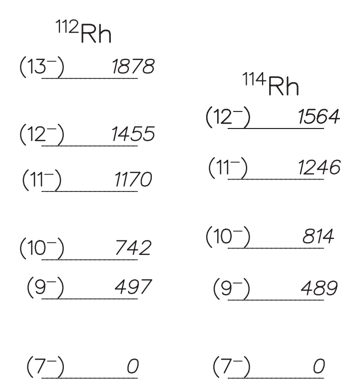

FIG. 3. Similarity in the yrare bands in ^{112,114}Rh. All level energies are relative to the (7$^-$) state in the yrast bands.

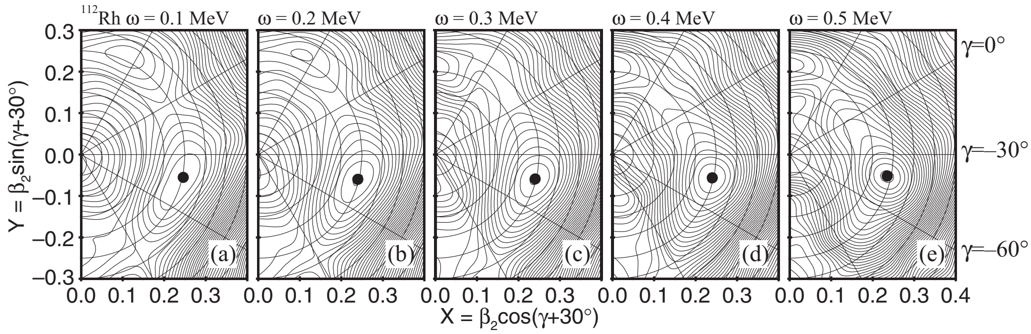

FIG. 4. TRS calculations based on the configuration of $[(+,+\frac{1}{2})\otimes(-,-\frac{1}{2})]$ [(π,α) for the 45th proton coupling to (π,α) for the 67th neutron] for the negative-parity yrast band of ^{112}Rh. The interval of energy contours is 200 keV. The deformation parameters for all minima are nearly constant at $\beta_2 = 0.25$, $\gamma = -43^\circ$, and $\beta_4 = -0.03$.

and discussed recently [11]. A further examination of the negative-parity yrast bands in odd-odd $^{104-112}$Rh reveals that signature inversion exists in all of these bands (more details will be presented elsewhere) where the spin-parities in the yrast band of ^{104}Rh have been uniquely determined. In Ref. [11], calculations in the framework of triaxial projected shell model [22] indicates a drift of the rotational axis at $I = 12$, coincident with $I_{\rm rev}$ (the even spin at which the normal signature splitting ordering is restored, for details see Ref. [11]), from the longest principal axis to the intermediate one as the ^{114}Rh nucleus is rotating. Therefore, signature inversion in ^{114}Rh was proposed to be caused by this drift which is related to the change of the rotational mode, from the quasiparticle aligned rotation along the longest axis to the collective rotation along the intermediate axis [11]. More theoretical work is under way to understand this phenomenon in lighter odd-odd Rh isotopes in this mass region.

It is useful to know if triaxiality plays an important role in the shape deformation of the odd-odd ^{112}Rh nucleus. Calculations based on the cranked shell model have been performed where the nonaxial deformed Woods-Saxon (WS) potential [23] was employed. Collective rotation was investigated by means of total Routhian surface (TRS) calculations in a three-dimensional deformation space of β_2, γ, and β_4. At a given frequency, the deformation of a state was determined by minimizing the calculated TRS. More details can be found in Refs. [24]. The present calculations support that the negative-parity yrast and yrare bands of ^{112}Rh are built on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration, which is consistent with the previous conclusions based on the systematics.

We obtain $\beta_2 = 0.26$, $\gamma = -36^\circ$, and $\beta_4 = -0.02$ for the ground state of ^{112}Rh in the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration from the present TRS calculations, where the γ value is close to $\gamma = -30^\circ$ in ^{106}Rh [10] and $\gamma = -32^\circ$ in ^{114}Rh [11]. Our calculations also show that triaxiality is consistent and persists in the negative-parity yrast band in ^{112}Rh up to at least $\hbar\omega = 0.5$ MeV when the nucleus is cranked. Figure 4 demonstrates some TRS calculation results for the negative-parity yrast band of ^{112}Rh for $\hbar\omega = 0.1, 0.2, 0.3, 0.4$, and 0.5 MeV, respectively, where the β_2 and γ values remain constant, 0.25 and -43°, respectively. Therefore, our TRS calculations support that triaxiality plays an important role in the negative-parity structure in ^{112}Rh. However, more detailed calculations are needed to figure out how triaxiality can result in its anomalous signature splitting and thus signature inversion.

It is interesting to see that a triaxial oblate shape ($-60^\circ < \gamma < -30^\circ$) is present in the TRS calculations in ^{112}Rh ($N = 67$). This is consistent with the observation of both experiment and theory in even-odd Ru (one proton less than Rh) that the triaxial oblate shape appears at $N = 67$ [25]. The authors in Ref. [25] also provide experimental and theoretical evidence for a triaxial prolate to triaxial oblate shape transition at $N = 68$ in even-even Ru. A recent work on β- and γ-coincidence spectroscopy of ^{111}Tc ($Z = 43$ and $N = 68$) [26] shows that an assumption of a triaxial oblate deformation is required in the quasiparticle-rotor-model calculations to interpret low-lying states with $K = 1/2^+$ and $5/2^+$. It is worth recalling that a so-called $N = 68$ effect was proposed in neutron-rich odd-even Rh isotopes as well as even-even Ru isotopes by investigating their yrast level energies in our recent publication [12]. Therefore, one may propose that a triaxial prolate to triaxial oblate shape transition be expected at $N = 68$ in the Rh isotopic chain.

In conclusion, a new side band in ^{112}Rh was established by studying the prompt γ rays emitted from the ^{252}Cf spontaneous fission with Gammasphere. The properties of this yrare band in ^{112}Rh is consistent with triaxiality in this region of the nuclear landscape. TRS calculations have been carried out and indicate a unchanged triaxial oblate deformed shape in ^{112}Rh. A triaxial prolate to triaxial oblate shape transition in Rh may be expected at $N = 68$ based on the known data. More experimental efforts are required to explore the side band structures in ^{108,110}Rh and populate higher-spin levels in neutron-rich Rh isotopes.

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