High Spin Band Structure in ^{112}Ru *

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Levels in the neutron-rich ^{112}Ru nucleus have been investigated by observing prompt gamma-rays from the spontaneous fission of ^{252}Cf with the Gammasphere detector array. The ground-state band and the one-phonon γ-vibrational band have been confirmed and extended with spin up to 16 $\hbar$ and 15 $\hbar$, respectively. The other two side bands, one proposed as two-phonon γ-vibrational band and the other proposed as two-quasiparticle band, have been observed for the first time. The total-Routhian-surface calculations show that rotational ^{112}Ru nucleus has triaxial deformation with parameters $\beta_2 \sim 0.27$ and $\gamma = -29°$. The observed band crossing in the yrast band is due to the alignment of a pair of $h_{11/2}$ neutrons according to the cranked shell model calculations. The possible configuration for the quasiparticle band has also been discussed.

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The neutron-rich ^{112}Ru nucleus with $Z = 44$ and $N = 68$ are located within the $A = 100$ deformed region. Study of the high spin states of neutron-rich nuclei in this region can provide valuable information of nuclear structures, such as the systematic shape change, and the single particle and collective motion characteristics.[1−6] However, it is difficult to investigate the high-spin states of the neutron-rich nuclei, because they cannot be formed by the usual heavy ion nuclear reaction. An effective method is to measure the prompt γ-rays of spontaneous fission from heavy nuclei such as ^{252}Cf or ^{248}Cm.[1] In previous publications, some collective band structures of neutron-rich even-A isotopes ^{108,110,112}Ru have been reported by using this method.[7−11] In this Letter, we briefly report on the observation of new high spin states in ^{112}Ru. The collective bands have been significantly extended and two new side bands have been established.

The ^{112}Ru nucleus was studied by measuring the prompt -rays in spontaneous fission of ^{252}Cf. The experiment was carried out at the Lawrence Berkeley National Laboratory. A ^{252}Cf source of activity ~ 60 μCi was sandwiched between two Fe foils in thickness of 10 mg/cm^2, and placed at the centre of the Gammasphere detector array which, for this experiment, consisted of 102 Compton-suppressed Ge detectors. A total of 5.7×10^{11} triple- and higher-fold coincidence events were collected. These data have statistics higher than the earlier measurements in Refs. [2,12] by a factor of about 15. Details of the experimental techniques have been described elsewhere.[2,12,13]

The new level scheme of ^{112}Ru based on our new data is shown in Fig. 1. The collective bands observed are labelled on the top of each band. The yrast band (1) is observed with spin up to 16$\hbar$, which confirms the previous result reported in Refs. [8,14]. The levels of band (2) have been significantly extended. Four $\Delta I = 1$ transitions of 233.2, 254.6, 334.7 and 271.0 keV inside band (2), which were not reported in Ref. [8], have been observed. Two new bands, band (3) based on the 1413.6 keV level and band (4) based on the 2230.3 keV level, have been identified. Moreover, many new linking transitions between both the bands were also observed. As examples, Fig. 2 shows two representative double-gated coincidence spectra. In addition to the γ-peaks from ^{112}Ru, γ-peaks from the corresponding fission partners can also be seen in each spectra.

Band (1) is the ground-state band and appears to be yrast to the highest spin observed, as can been seen from Fig. 1. An ratio of 2.72 shows that the ^{112}Ru lies in a deformed region. The kinematical moments of inertia $J^{(1)}$ as a function of rotational frequency for the band (1) along with the yrast bands in ^{108,110}Ru is presented in Fig. 3(a). It is shown that the backbendings (band crossing) of the ground-state bands in ^{108,110,112}Ru occur at a rotational frequency $\hbar\omega \approx 0.4$ MeV. However, the ^{110}Ru shows a sharp crossing while the ^{112}Ru shows a soft crossing, compared with that in ^{108}Ru. Meanwhile, we have carried out the cranked shell model (CSM) calculations[15,16]

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to understand the band structures in ^{112}Ru. Similar calculations were employed in ^{108}Ru in our earlier work.[11] The calculated results for ^{112}Ru are presented in Fig. 4, from which the minima in the total Routhian surfaces (TRS) can be found, corresponding to $\beta_2 = 0.236$, $\beta_4 = -0.008$, $\gamma = -58.9^\circ$ at $\omega = 0.0\,\mathrm{MeV}/\hbar$, $\beta_2 = 0.281$, $\beta_4 = -0.008$, $\gamma = -30.2^\circ$ at $\omega = 0.2\,\mathrm{MeV}/\hbar$ and $\beta_2 = 0.236$, $\beta_4 = -0.032$, $\gamma = -40.4^\circ$ at $\omega = 0.5\,\mathrm{MeV}/\hbar$. It is also shown that after the band crossing, nuclear deformation parameters have changed. The calculations show that the β_2 and γ average values are close to 0.27 and -29° respectively, when the rotational frequency varies between 0 and $0.4\,\mathrm{MeV}/\hbar$. These calculation results indicate that the ^{112}Ru nucleus has oblate deformation in the ground state, and possesses triaxial deformation with the increasing rotational frequency. Then we have carried out the calculations of Routhians for

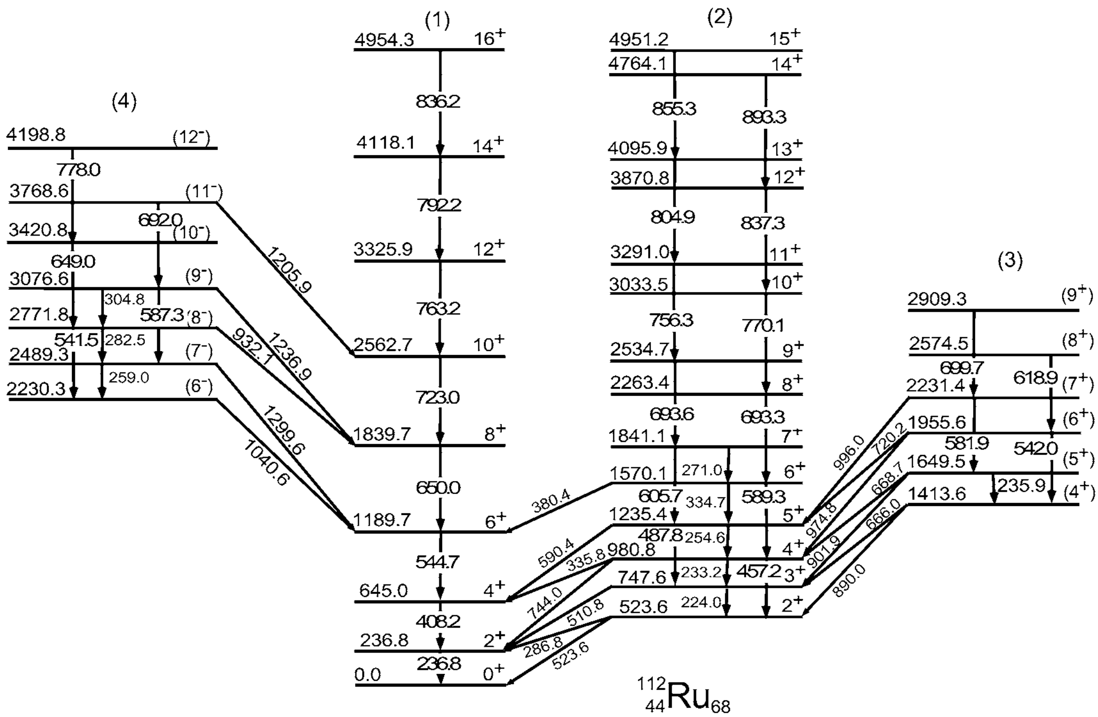

Fig. 1. Level scheme in ^{112}Ru.

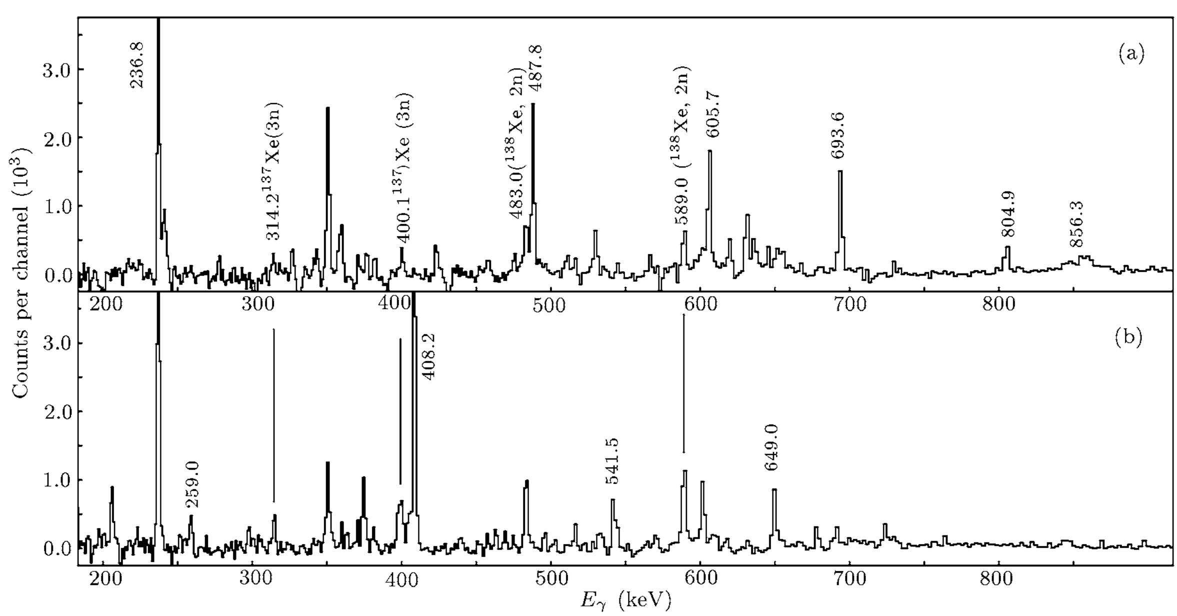

Fig. 2. Coincidence spectra obtained (a) by double gating on the 510.8 and 756.3 keV (b) by double gating on the 544.7 and 1040.6 keV in ^{112}Ru.

^{112}Ru using CSM by taking the above calculated β_2 and γ parameters. Here, parings are self-consistently calculated by the HFB-like method, and more details about parings can be found in Refs. [17–19]. The calculated quasi-particle energies (Routhians) for ^{112}Ru are presented in Fig. 5(a) for protons and Fig. 5(b) for neutrons, respectively. The calculations predict that a band crossing caused by the alignment of two $h_{11/2}$ neutrons occurs at $\hbar\omega \approx 0.40$ MeV, which is in excellent agreement with the experimental value of $\hbar\omega \approx 0.40$ MeV, whereas the band crossing related to the alignment of two $g_{9/2}$ protons can not be seen in the calculations. Therefore, we believe that the $h_{11/2}$ neutron is responsible for the backbending in the ground-state band in ^{112}Ru.

Band (2) belongs to the one-phonon γ-vibrational band[8] and is extended with spin from $9\hbar$ to $15\hbar$ in the this work. Several new $\Delta I = 1$ γ-transitions inside band (2) observed in the present work give strong evidence for characteristics of the γ-vibration band. The plot of $J^{(1)}$ versus $\hbar\omega$ for band (2) is shown in Fig. 3(a). As can be seen, the curve shows staggering, i.e., obviously signature splitting. This may be caused by the triaxial deformation. Band (3) is newly observed. Based on a systematic comparison with similar structures observed in the neighbouring nuclei ^{104,106}Mo[5] and ^{108}Ru[11], we propose that band (3) is a two-phonon γ-vibration band. The plot of $J^{(1)}$ against $\hbar\omega$ for band (3) is also presented in Fig. 3(a). As is expected, the ground-state band (1), the one-phonon γ-vibration band (2) and the two-phonon γ-vibration band (3) have similar moments of inertia.

The new band (4) in ^{112}Ru has the structure similar to the two-quasi-neutron bands in the neighbouring nuclei ^{102}Zr,[4] ^{106}Mo,[6] and ^{110}Ru,[10] so we also tentatively assign it as two-quasi-neutron band. The plot of $J^{(1)}$ versus $\hbar\omega$ for band (4) in ^{112}Ru along with the two-quasi-neutron bands in ^{102}Zr, ^{106}Mo and ^{110}Ru are shown in Fig. 3(b). The curves for these bands are

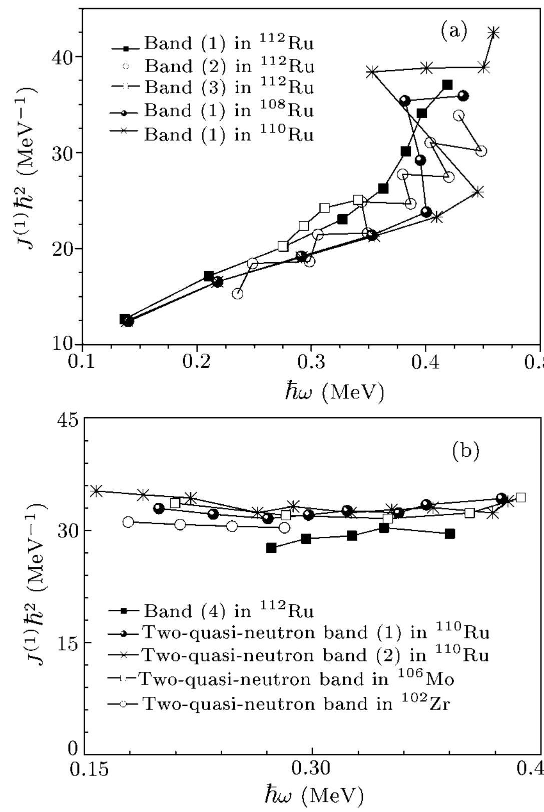

Fig. 3. (a) $J^{(1)}$ versus $\hbar\omega$ for bands (1), (2) and (3) in ^{112}Ru and the yrast bands in ^{108,110}Ru. (b) $J^{(1)}$ versus $\hbar\omega$ for bands (4) in ^{112}Ru and the two-quasi-neutron bands in ^{106}Mo, ^{102}Zr and ^{110}Ru.

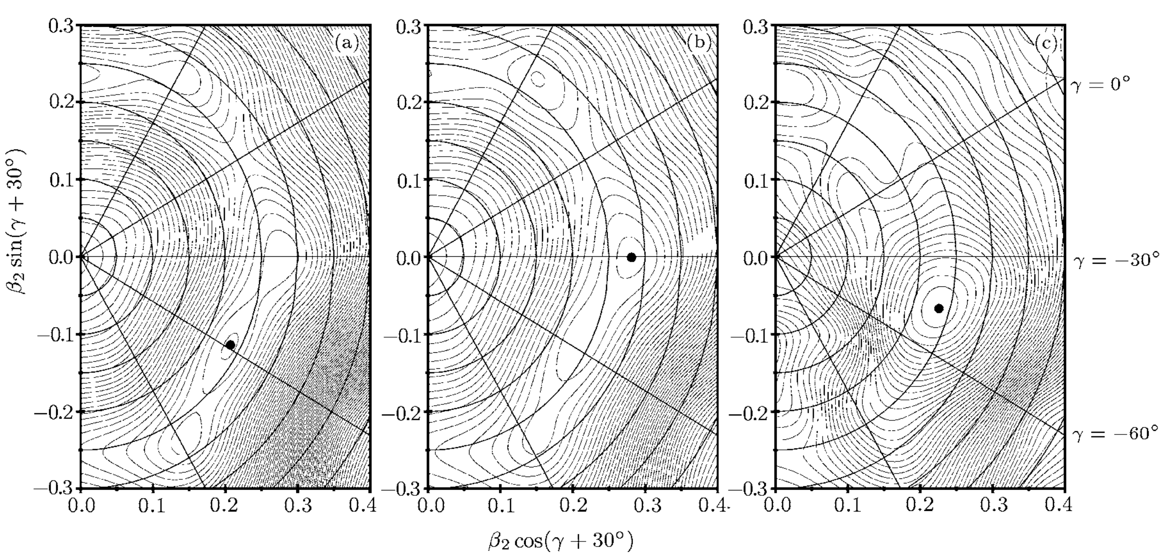

Fig. 4. Polar coordinate plots of total Routhian surface (TRS) calculated for ^{112}Ru (a) at $\hbar\omega = 0.0$ MeV, $\beta_2 = 0.236$, $\gamma = -58.9°$, $\beta_4 = -0.08$; (b) at $\hbar\omega = 0.2$ MeV, $\beta_2 = 0.281$, $\gamma = -30.2°$, $\beta_4 = -0.08$, and (c) at $\hbar\omega = 0.5$ MeV, $\beta_2 = 0.236$, $\gamma = -46.407°$, $\beta_4 = -0.032$.

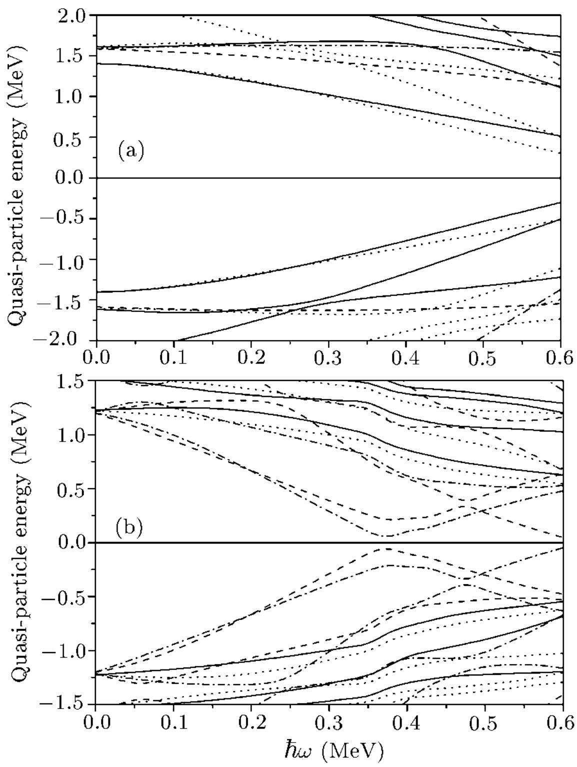

Fig. 5. The Calculated Routhians for quasi-protons (a) and quasi-neutrons (b) against rotational frequency $\hbar\omega$. The parity and signature (π, α) of the levels are illustrated. Solid lines: $(+, +1/2)$; dotted lines: $(+, -1/2)$; dot-dashed lines: $(-, +1/2)$; dashed lines: $(-, -1/2)$.

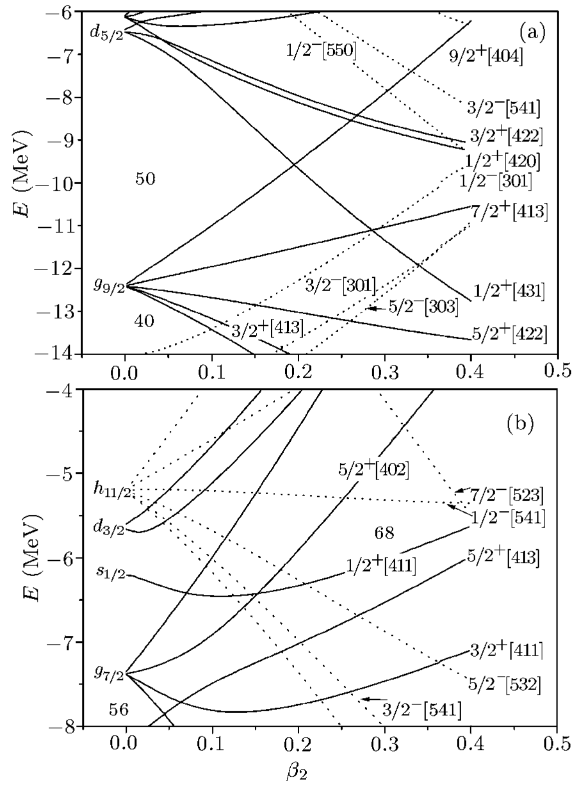

Fig. 6. Nilsson diagrams of (a) protons and (b) neutrons in ^{112}Ru calculated with the deformed Woods–Saxon potential.

very alike. Based on the systematic comparison, the selection rule of the feeding transitions and the level spacings, we tentatively assign the spin and parity I^{π} of the band head level at the 2230.3 keV in band (4) as 6^-. Thus, according to the regular level spacings inside the band, I^{π}'s of the other levels in band (4) were assigned. The Nilsson diagrams calculations were carried out with the deformed Woods–Saxon potential for protons and neutrons in ^{112}Ru as shown in Fig. 6. According to the calculation (Fig. 6(b)), band (4) probably originates from $\nu\{[402]5/2^+ \otimes [523]7/2^-\}6^-$ configuration. The identification of the proper configuration for band (4) requires more experimental data and theoretical calculations.

In summary, high spin states in ^{112}Ru have been studied. The ground-state band and the one-phonon γ-vibrational band have been confirmed and extended. The two-phonon γ-vibrational band and a two-quasiparticle band, which is most probably built on the $\nu\{[402]5/2^+ \otimes [523]7/2^-\}6^-$ configuration, have been observed. The TRS calculations indicate that the rotational ^{112}Ru nucleus has triaxial deformation with $\gamma \sim -29°$ and the band crossing in the yrast band is due to the alignment of a pair of $h_{11/2}$ neutrons.

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