Collective Bands in Neutron-Rich ^{104}Mo Nucleus *

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Levels in the neutron-rich ^{104}Mo nucleus have been investigated by observing prompt γ-rays from the spontaneous fission of ^{252}Cf with the Gammasphere detector array. The ground-state band, the one-phonon and the two-phonon γ-vibrational bands as well as a quasiparticle band have been confirmed and expanded with spin up to 14$\hbar$. Other two side bands probably built on new quasiparticle states are identified. The possible configurations for the quasiparticle bands are discussed. Two of the quasiparticle bands show larger moments of inertia and may have pair-free characteristics. The levels of the ground-state band, the one-phonon γ-band and the two-phonon γ-band calculated from a general collective model are in close agreement with the experimental data.

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The neutron-rich ^{104}Mo nucleus lies on the edge of the region of well-deformed ground states on the reinforcing proton and neutron shell gaps at the same well-deformation, for $Z = 38, 40$ and $N = 60, 62$.[1] Study of levels in neutron-rich nuclei in this region can provide an important insight into the change in nuclear deformation and shape, single particle and collective motions and tests of nuclei models.[1−6] In an early report, the low excitation states of ^{104}Mo were measured through the β-decay.[7] However, it is difficult to investigate the high-spin states for these neutron-rich nuclei as 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 the heavy nuclei such as ^{252}Cf or ^{248}Cm. In several papers, the yrast rotational band of ^{104}Mo was identified and expanded[8−10] by using this method. The advent of large and efficient γ-ray detector arrays expands possibilities for observing high-spin states in the neutron-rich nuclei. Recently, an expanded level scheme of ^{104}Mo with the one-phonon γ-vibration band and two-phonon γ-vibration band as well as a quasiparticle band was reported.[6] In this letter, we report on the observation of the new high-spin states in ^{104}Mo. The collective bands have been significantly expanded and the new quasiparticle bands were identified.

The ^{104}Mo nucleus was studied in spontaneous fission of ^{252}Cf. Prompt γ–γ–γ-coincidence studies were carried out with a Gammasphere with 72 Compton-suppressed Ge detectors. A ^{252}Cf source of strength 25 μCi was sandwiched between two Ni foils of thickness 11.3 mg/cm^2, further sandwiched between a pair of 13.7 mg/cm^2 thick Al foils, and placed at the centre of the Gammasphere. Three-dimensional histograms (cubes) of the 2.9×10^{10} coincidence events were constructed. Details of the experimental techniques have been described elsewhere.[1,11−13]

The new level scheme of ^{104}Mo based on our new data is shown in Fig. 1. The collective bands observed are labelled on the top of every band. All the new transitions obtained in the present work are marked with an asterisk. All transitions reported in Ref. 6 were confirmed. A new level at 4115.8 keV was added to the yrast band (1). The levels of bands (2), (3) and (4) were expanded, too. Four $\Delta I = 1$ transitions at 215.8, 186.9, 259.9 and 250.3 keV inside band (2), which were not reported in Ref. 6, have been identified. A new side-band (5) based on the 2656.0 keV level is observed. In Ref. 6, only two levels at 2306.0 and 2886.9 keV along with a linked γ-transition at 560.9 keV in band (6) were reported. In our work, the band (6) constructed with four levels at 1884.2, 2306.0, 2866.9 and 3554.7 keV along with three $\Delta I = 2$ γ-transitions at 421.8, 560.9 and 687.8 keV inside the band was established. Moreover, many new side transitions between these bands were also observed. A total of thirty seven new transitions and ten new levels were identified.

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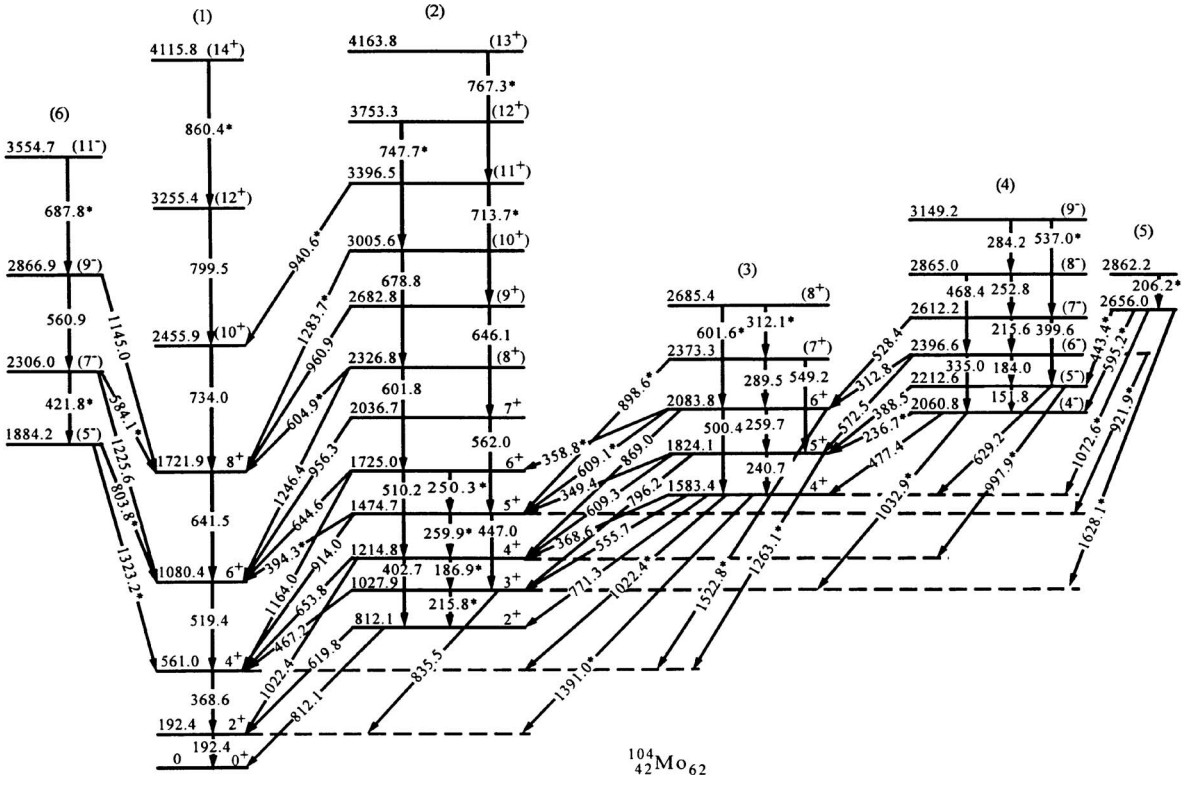


Fig. 1. Level scheme in ^{104}Mo. The new transitions in this letter are indicated with an asterisk.

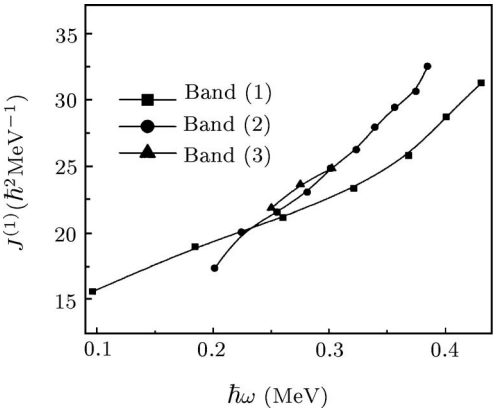


Fig. 2. Plots of J_1 versus $\hbar\omega$ for bands (1), (2) and (3) in ^{104}Mo.

The yrast band (1) was expanded with spin up to $14\hbar$ without backbending being observed. An $E_{4_1^+}/E_{2_1^+}$ ratio of 2.92 shows that the ^{104}Mo lies in a region of deformation. A $\beta = 0.35$ value for ^{104}Mo has been obtained from the lifetime measurement of the 2^+ states.[14] The spins and parities (I^π) for bands (2), (3) and (4) have been assigned in Ref. 6 based on systematics and some angular correlation measurements. As discussed in Ref. 6, band (2) is a rotational band based on the one-phonon γ-vibration state at 812.1 keV level and band (3) is a two-phonon γ-vibration band with the band head at 1583.4 keV level. Plots of the moments of inertia J_1 against $\hbar\omega$ for bands (1), (2) and (3) are shown in Fig. 2. As expected, the ground-state band (1), the one-phonon γ-band (2) and the two-phonon γ-band (3) have similar moments of inertia. Moreover, the four new $\Delta I = 1$ γ-transitions at 215.8, 186.9, 259.9 and 250.3 keV inside band (2) observed in the present work also give strong evidence of the characteristics of the γ-vibration band.

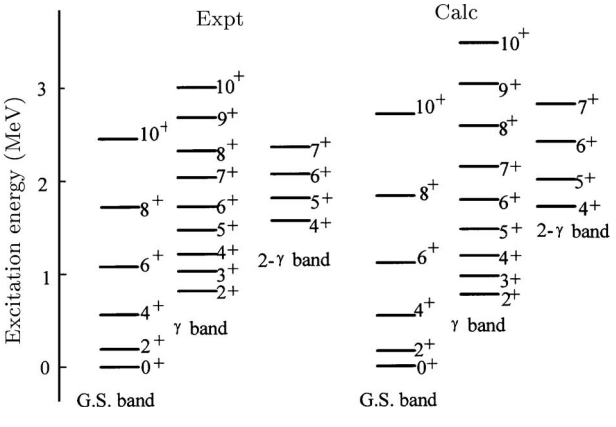


Fig. 3. Calculated (GCM) levels in comparison with experimental levels for ^{104}Mo.

In order to understand the band structures, we have employed the general collective model (GCM) to calculate the collective bands in ^{104}Mo. The details of the calculation method and the parameters taken will be published elsewhere.[15] Here we only give the calculated levels and a comparison with the experimental

data, as shown in Fig. 3. The general agreement between theoretical and experimental levels is evident. It shows that bands (2) and (3) in ^{104}Mo indeed belong to the one-phonon γ-band and the two-phonon γ-band, respectively. Our calculation results also indicate that the ^{104}Mo has an axial symmetric deformation which is in agreement with the recent report,[6] but differs from the viewpoint of the triaxial rotor[16] or $\gamma-$soft deformation[17] in early reports.

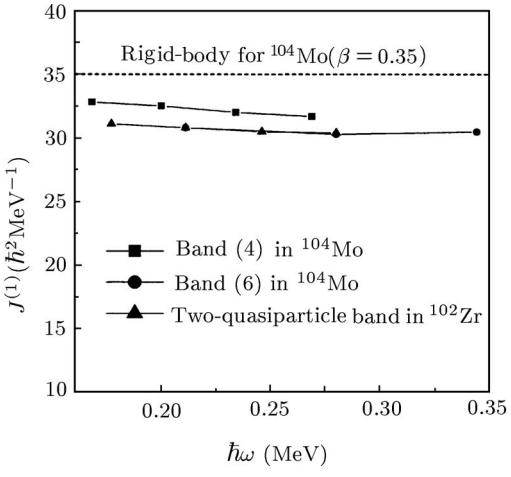


Fig. 4. Plots of J_1 versus $\hbar\omega$ for bands (4) and (6) in ^{104}Mo.

It was suggested that band (4) in ^{104}Mo has two-quasiparticle characteristics[6], as observed in ^{106}Mo (Ref. 5) and ^{102,104}Zr.[4] According to the $|(g_k - g_R)/Q_0|$ value analysis,[6] the 2060.8 keV level in band (4) has two quasineutron configurations with $K = 4$: the $\nu\{[411]^{3/2^+}[532]^{5/2^-}\}4^-$ or $\nu\{[411]^{3/2^+}[413]^{5/2^+}\}4^+$ configurations. Examining the collective bands in the $N = 62$ isotone ^{102}Zr, a two-quasiparticle band with the band head $\nu\{[411]^{3/2^+}[532]^{5/2^-}\}4^-$ configuration has been observed.[4] Based on the systematical comparison with ^{102}Zr, the 2061.8 keV level in ^{104}Mo probably has a similar configuration with that in ^{102}Zr; that is, $\nu\{[411]^{3/2^+}[532]^{5/2^-}\}4^-$. The band (5) built on the 1884.2 keV level probably does not belong to the β-vibration band as no lower excitation band member was observed. The I^π of the 1884.2 keV level may be assigned as 5^- or 6^+. As a negative parity band based on the 5^- state in the $N = 62$ isotone ^{108}Pd, which is similar to band (6) in ^{104}Mo, has been observed,[18] we tentatively assigned band (6) as the negative parity band with a $I^\pi = 5^-$ band head. The band head energy at 1864.3 keV in band (6) is lower than the 2060.8 keV level in band (4). As the proton pairing gap energy is lower than the neutron pairing gap energy,[5] the band head in band (6) may be considered as a quasi-proton configuration; that is, a possible configuration of the 1884.2 keV level is $\pi\{[422]^{5/2^+}[303]^{5/2^-}\}5^-$. The similarity of moments of inertia of both bands (4) and (6) in ^{104}Mo (see discussion below) may give further evidence for a two-quasiparticle characteristic in band (6).

The moments of inertia (J_1) versus $\hbar\omega$ for bands (4) and (6) in ^{104}Mo along with the quasiparticle band in ^{102}Zr are shown in Fig. 4. The J_1 values of the three quasiparticle bands are very large and essentially constant. They are very close to the rigid-body values. The rigid body moment of inertia is calculated from the formula

$$I_{\text{rigid}} = 0.4AM_nR^2[1 + (5/16\pi)^{1/2}\beta] \qquad (1)$$

for a nucleus with a mass number A, a nucleon mass M_n and a radius $R = 1.2 \times A^{1/3}$fm. For $\beta = 0.35$ in ^{104}Mo,[14] the calculated J_{rigid} value is $35.0/\hbar^2$. The J_1/J_{rigid} ratios are 0.92 for band (4) and 0.87 for band (6). The results indicate that the two quasiparticle bands in ^{104}Mo, as well as in ^{102}Zr, may belong to the pairing-free bands as observed in ^{98}Y, ^{102}Nb (Ref. 19) and ^{145}Ba (Ref. 20). The origin of these pair-free bands in ^{104}Mo and ^{102}Zr is not clear, but definitely offers a new challenge for theory.

The new band (5) based on the 2556.0 keV level may belong to another two-quasiparticle or four-quasiparticle band. Only one weak transition 206.2 keV was observed inside the band. From the side feedings observed between the bands, I^π of the 2656.0 keV level may be assumed as 4^+, 4^- or 5^+. To determine the characteristics of this band, more experimental work is needed.

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