Search for Double γ-Vibrational Bands in Neutron-Rich ^{105}Mo Nucleus *

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Levels in the neutron-rich ^{105}Mo nucleus have been investigated by observing prompt γ-rays following the spontaneous fission fragments of ^{252}Cf with the Gammasphere detector array. The yrast band has been confirmed and updated. The other two collective bands with the band head levels at 870.5 and 1534.6 keV are newly observed, and they are suggested as the candidates for one-phonon $K = 9/2$ and two-phonon $K = 13/2$ double γ-vibrational bands, respectively. Systematic characteristics of these bands have been discussed.

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In the study of nuclear structure, the existence of one-phonon and two-phonon γ-vibrational bands in deformed nuclei is an important subject. In the $A = 100 \sim 110$ neutron-rich region, the rotational band built on the one-phonon γ-vibrational state in even–even nuclei has been observed in $^{102-108}$Mo,[1–5] $^{108-112}$Ru,[6–9] and $^{112-118}$Pd.[10,11] For the odd-A nuclei, the one-phonon γ-vibrational band has also been identified in $Z = 45$ $^{105-111}$Rh.[12–15] However, the experimental knowledge of the two-phonon γ-band is scarce, and it was only observed in the even–even ^{104,106}Mo[1–5] in $A = 100$ neutron-rich region. So far, no two-phonon γ-vibrational band structure has been found in odd-A nuclei. The ^{105}Mo nucleus is a better candidate to search for such a structure with its neutron number $N = 63$ lies between $N = 62$ (^{104}Mo) and $N = 64$ (^{106}Mo). In previous publications, some collective band structures of ^{105}Mo have been reported.[5,16,17] In this Letter, we briefly report on the observation of two new collective bands in neutron-rich ^{105}Mo, which are proposed as the rotational bands built on the one-phonon and two-phonon γ-vibrational states.

The identification of the prompt γ-rays from fission fragments produced by spontaneous and induced fissions is an effective method to study the high spin states of the neutron-rich $A = 100 \sim 110$ nuclei. The high spin states of ^{105}Mo were obtained by measuring the prompt γ-rays following the spontaneous fission of ^{252}Cf. The experiment was carried out at the Lawrence Berkeley National Laboratory. A ^{252}Cf source of strength $\sim$60 μCi was sandwiched between two Fe foils of thickness of 10 mg/cm^2, mounted in a 7.6-cm-diameter polyethylene ball to absorb β-rays and conversion electrons, and was 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 γ-coincidence events were collected. Thus, these data have higher statistics than our earlier measurements of Refs. [18–20] by a factor of about 15. More experimental details can be found in Refs. [15,19–21].

The partial level scheme of ^{105}Mo is shown in Fig. 1 and the collective bands observed are labelled on the top of each band. The yrast band (1) was identified with spin up to $31/2\hbar$ and we added three new $\Delta I = 1 M1$ linking transitions of 165.2, 680.6 and 145.2 keV inside this band comparing with those in Refs. [5,17]. Two new bands, band (2) based on the 870.5 keV level and band (3) based on the 1534.6 keV level, have been identified for the first time. Many new γ-transitions have also been observed. As an example, Fig. 2 shows a representative partial coincidence spectrum obtained by double gating on 94.9 and 775.6 keV γ-transitions. In this spectrum, one can see the main γ-transition peaks in bands (2) and (3) in ^{105}Mo and in $^{142-144}$Ba, the partner nuclei of ^{105}Mo.

Band (1) is the ground-state band with the band head $K^\pi = 5/2^-$ built on $5/2^-[532]$ orbital of the $\nu h_{11/2}$ subshell.[5,17] The $\nu h_{11/2}$ negative parity band structure has also been identified in $N = 63$ isotones ^{103}Zr,[5] ^{107}Ru[22] as well as in ^{103}Mo[5,23] and ^{107}Mo.[24] These bands show decoupled characteristics. They have large signature splitting between $\alpha = +1/2$ and $\alpha = -1/2$ components. The level energy difference of the $\nu h_{11/2}$ bands as a function of the spin I in the $Z = 42$ isotopes ^{103,105,107}Mo and $N = 63$ isotones ^{103}Zr, ^{105}Mo and ^{107}Ru are shown

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in Fig. 3. One can see that in the Mo isotopes, they show the similar behaviour. The signature splitting of ^{103}Mo is larger, whereas those of the ^{105,107}Mo are almost identical. However, in ^{103}Zr, ^{105}Mo and ^{107}Ru, it increases with the increasing Z number. On the other hand, the trend of signature splitting of the $\nu h_{11/2}$ orbitals in odd-A nuclei is very sensitive to the γ-degree of freedom, according to the particle-rotor model calculations.[5] The γ-values are $\sim 0°$ in Zr, $\sim -19°$ in Mo,[5] and ~ -22–$-29°$ in Ru.[6,7,25] From Fig. 3, we can see that the signature splitting of the nuclei increases with the increasing γ-value.

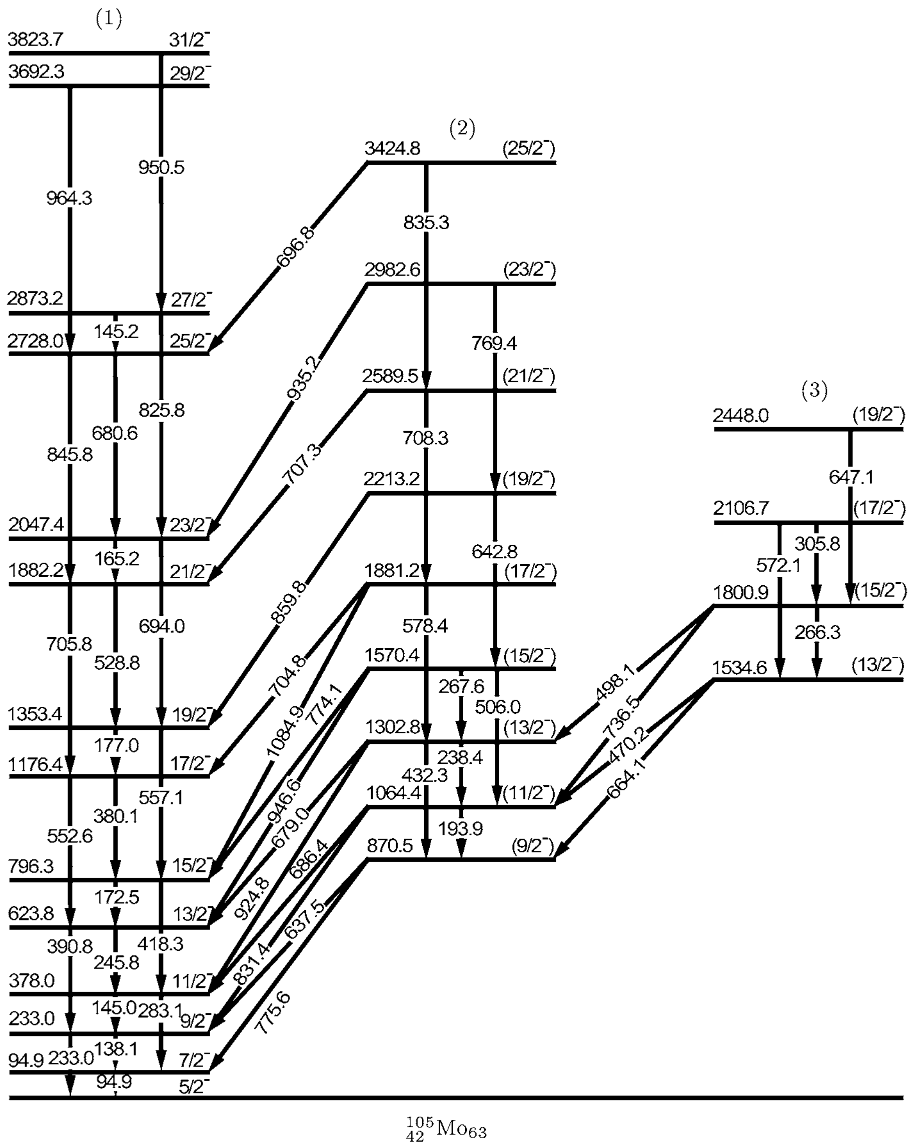

Fig. 1. Partial level scheme of ^{105}Mo obtained in the present work. Energies are taken in units of keV.

Bands (2) and (3) are newly established in the present work. According to the level spacings comparing with the neighbouring nuclei and the transition selection rule from band (2) to band (1), the possible spin of the band head level of the band (2) could be 9/2 or 11/2. The excitation energy at 870.5 keV of the band head level indicates that this level possibly originates from the single-neutron orbital or belongs to the one-phonon γ-vibrational state. If it belongs to a single-neutron excitation, we can exclude the $9/2^+$ or $11/2^+$ states as one can not find a suitable orbital in Nilsson diagram around the Fermi surface.[26] For the consideration of negative-parity state, the possible choice is $9/2^-[514]$ or $11/2^-[505]$ orbital excitation. However, these two orbitals may be still too far from the Fermi surface to be possible. Thus the band (2) must probably be an one-phonon γ-vibrational band with $K = 9/2$ and the state of the 870.5 keV level could be assigned as $9/2^-$. Band (3) has the band head excitation energy at 1534.6 keV. The possible spin of the band head level can be assigned as 11/2 or 13/2. Based on the same reason, we can exclude the single-particle configuration. Moreover, as the band head energy of 1534.6 keV is well below the neutron pairing gap $2\Delta_n \sim 2.1$ MeV and the proton pairing gap $2\Delta_p \sim 1.7$ MeV[1], we can rule out the three quasiparticle configuration for it. Thus we think that this band must belong to a two-phonon γ-vibrational band with $K = 13/2$ and the state of the 1534.6 keV level could be assigned as $13/2^-$. These double γ-vibrational bands can be explained as the coupling of the single-particle $5/2^-[532]$ orbital with one- and two-phonon γ-vibrational cores in the neighbouring even–even ^{104}Mo nuclei.

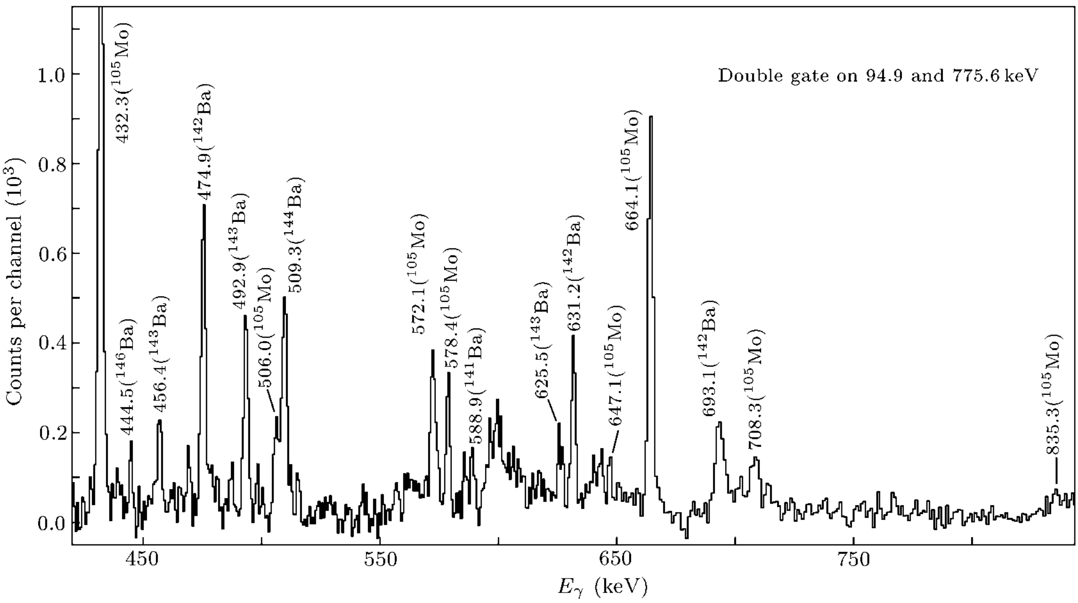

Fig. 2. Portion of coincidence γ-ray spectrum obtained by double gating on 94.9 and 775.6 keVγ-rays of ^{105}Mo.

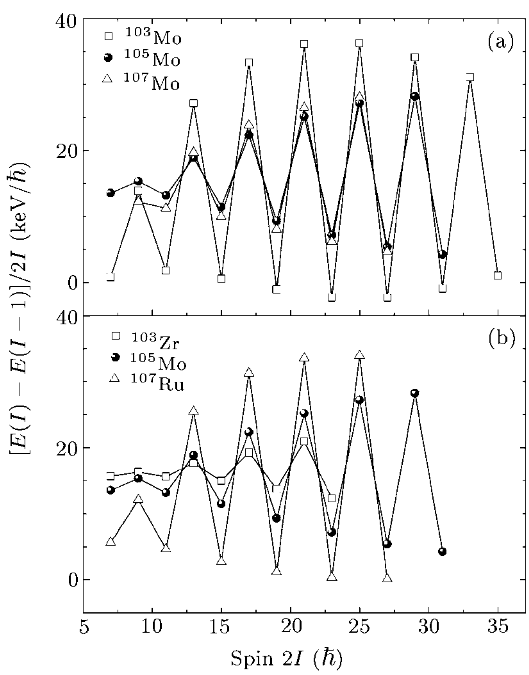

Fig. 3. Signature splitting of the $\nu h_{11/2}$ bands as a function of the spin I (a) in ^{103}Mo (square),[7,21] ^{105}Mo (circle, present work) and ^{107}Mo (triangle),[22] and (b) in ^{103}Zr (square),[7] ^{105}Mo (circle, present work) and ^{107}Ru (triangle).[23]

Figure 5 shows a systematical level comparison of the ground state bands and the one- and two-phonon γ-vibrational bands in ^{104}Mo,[3] ^{105}Mo (the present work) and ^{106}Mo.[4] One can see that the two new bands in ^{105}Mo have similar level feature with the one- and two-phonon γ-vibrational bands in ^{104}Mo and ^{106}Mo. They have closed band head excitation energies: 812 keV in ^{104}Mo, 871 keV in ^{105}Mo and 710 keV in ^{106}Mo for the one-phonon γ-band, and 1583 keV in ^{104}Mo, 1535 keV in ^{105}Mo and 1818 keV in ^{106}Mo for the two-phonon γ-band. The band head energy ratios of $E_{2\gamma}/E_{1\gamma}$ are 1.95, 1.76, and 2.56 for ^{104}Mo, ^{105}Mo, and ^{106}Mo, respectively. It seems that the characteristics of the γ-bands in ^{105}Mo are more similar with ^{104}Mo. The similarity of the linking de-excitation transitions between the one-phonon γ-band and the ground state band as well as between the one-phonon and the two-phonon γ-bands in ^{104,105,106}Mo may give another evidence for our assignment.

The kinematic moments of inertia J_1 as a function of the rotation frequency $\hbar\omega$ for the one- and two-phonon γ-vibrational bands in ^{104,105,106}Mo are presented in Fig. 6. The curves have similar slopes with the $\hbar\omega$ increasing in the γ-bands in each isotope. Such a feature has been suggested as a characteristic of multi-phonon γ-vibrational bands.[1] However, they are rather flat in ^{105}Mo, medium in ^{106}Mo and largest in ^{104}Mo. The phenomenon of nearly stable moments of inertia J_1 with the frequency variation in

^{105}Mo may be attributed by the blocking effect from the $h_{11/2}$ single neutron, which was also observed in the yrast band.

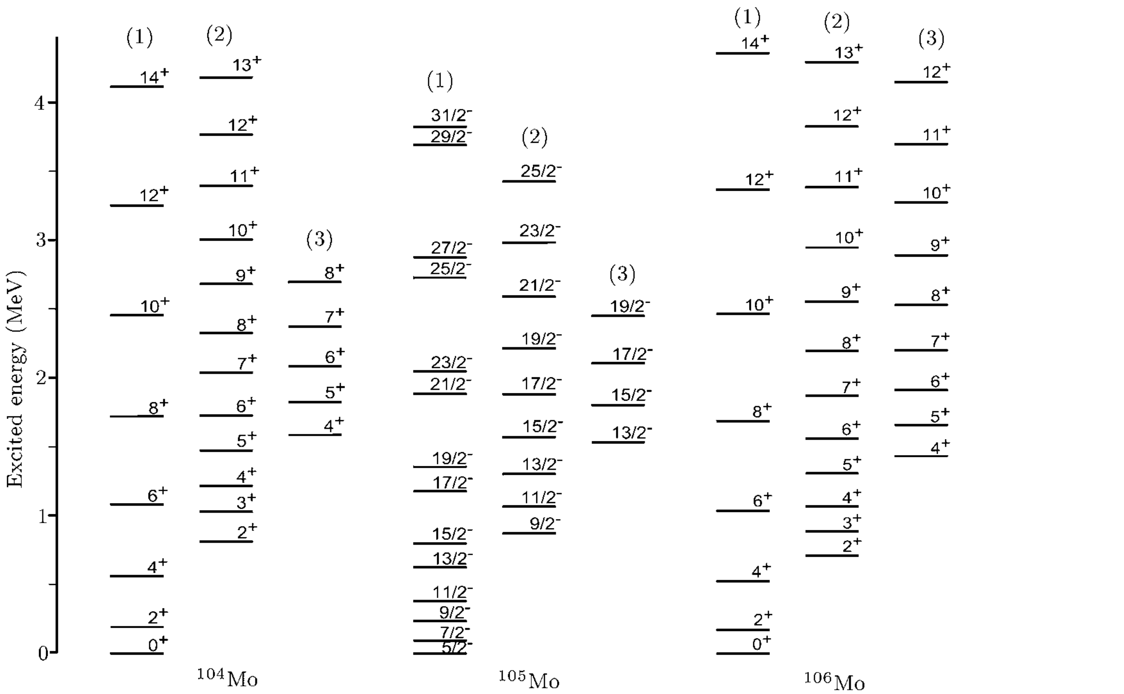

Fig. 4. Systematical comparison of the levels of the yrast bands, one- and two-phonon γ-vibrational bands in ^{104,105,106}Mo.

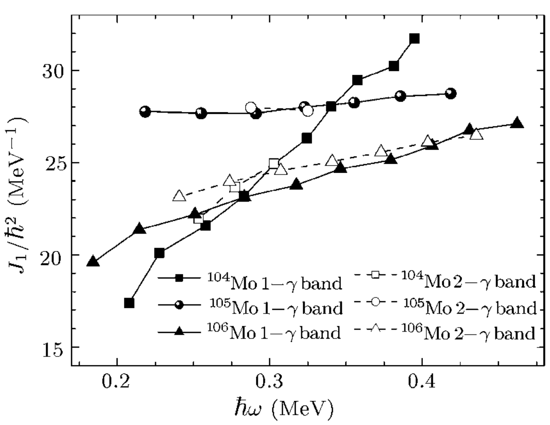

Fig. 5. Plot of moment of inertia J_1 versus frequency $\hbar\omega$ for the γ-vibrational bands in ^{104}Mo, ^{105}Mo and ^{106}Mo.

In summary, high spin states in neutron-rich ^{105}Mo nucleus have been re-investigated. The Yrast band based on the $5/2^-[532]$ Nilsson orbital has been confirmed and updated. Two new negative parity bands are observed and they are suggested as one- and two-phonon γ-vibrational bands, respectively. This is the first observation of such kind of γ-vibrational collective band structures in the odd-A nuclei in this region. Systematical band characteristics have been discussed.

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