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# Gamma Vibrational Bands and Chiral Doublet Bands in $A\approx100$ Neutron-rich Nuclei*

ZHU Sheng-jiang[1], DING Huai-bo[1], J. H. Hamilton[2], A. V. Ramayya[2], CHE Xing-lai[1], J. K. Hwang[2], Y. X. Luo[2,3], J. O. Rasmussen[3], K. Li[3], WANG Jian-guo[1], XU Qiang[1], GU Long[1], YANG Yun-yi[1], S. Frauendorf[4], V. Dimitrov[4]

(1 *Department of Physics, Tsinghua University, Beijing* 100084, *China*;
2 *Department of Physics, Vanderbilt University, Nashville, TN* 37235, *USA*;
3 *Lawrence Berkeley National Laboratory, Berkeley, CA* 94720, *USA*;
4 *Physics Department, Notre Dame University, Notre Dame, IN* 46556, *USA*)

**Abstract**: The level structures of neutron-rich $^{105}$Mo, $^{106}$Mo, $^{108}$Mo and $^{110}$Ru nuclei in $A\approx100$ region have been carefully investigated by coincidence measurements of the prompt γ-rays populated in the spontaneous fission of $^{252}$Cf with the Gammasphere detector array. In $^{105}$Mo, one-phonon $K=9/2$ and two-phonon $K=13/2$ γ-vibrational bands have been identified. In $^{108}$Mo, one-phonon γ-vibrational band is expanded and two-phonon γ-vibrational band has been identified. Two similar sets of bands in $^{106}$Mo and $^{110}$Ru are observed to high spins, which have been proposed as the soft chiral γ-vibrational bands. The characteristics for these γ-vibrational bands and chiral doublet bands have been discussed.

**Key words**: high spin state; neutron-rich nucleus; γ-vibrational band; chiral doublet band

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## 1 Introduction

In study of nuclear structure, search for the γ-vibrational bands and chiral doublet bands are very important subjects. In $A\approx100$ neutron-rich region, the rotational band built on the one-phonon γ-vibrational state has been observed in some nuclei, such as, in even-even $^{104-108}$Mo[1-4], $^{108-112}$Ru[5-8] etc.. However, the experimental knowledge of the two-phonon γ-vibrational band is scarce, and it was only observed in the even-even $^{104,106}$Mo[1-4] and $^{112}$Ru[8] in this region. So far, no two-phonon γ-vibrational band structure was found in odd-$A$ nuclei. For the chiral doublet bands, according to the theoretical model[9], when a nucleus has a triaxial shape with significant deformation, and a pair of unpaired nucleon angular momenta are along both the shortest principal axis (particle) and longest principal axis (hole), and the collective rotational angular momentum of the core is along the axis of intermediate length, the chiral symmetry breaking may occur, and the chiral doublet bands may be observed. In experimental studies,

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**Biography**: Zhu Sheng-jiang(1946－), male(Han Nationality), Binhai, Jiangsu, China, Professor, working on the field of nuclear and particle physics; E-mail: zhushj@mail.tsinghua.edu.cn

the chiral doublet bands have been observed in several nuclei, for examples, in $^{134}$Pr[10], $^{104}$Rh[11] etc.. In the present work, we report on the high spin state research for the neutron-rich $^{105}$Mo, $^{106}$Mo, $^{108}$Mo and $^{110}$Ru. The one-phonon γ-vibrational bands are identified in $^{105}$Mo and expanded in $^{108}$Mo, and the two-phonon γ-vibrational bands are discovered in $^{105}$Mo and $^{108}$Ru. The chiral doublet bands are identified in $^{106}$Mo and $^{110}$Ru.

## 2 Experiment and Data Analysis

As the $^{105}$Mo, $^{106}$Mo, $^{108}$Mo and $^{110}$Ru lie in the $A\approx100$ neutron-rich region, it is difficult to study the high-spin states of these neutron-rich nuclei using the usual heavy ion nuclear reactions. A practical method is to measure the prompt γ-rays of spontaneous fission of $^{252}$Cf[12]. The experiment was carried out at the Lawrence Berkeley National Laboratory. Prompt γ-γ-γ coincidence studies were performed with the Gammasphere detector array, which, for this experiment, consisted of 102 Compton-suppressed Ge detectors. A $^{252}$Cf source of strength ~60 μCi was placed at the center of the Gammasphere. A total of $5.7\times10^{11}$ triple and higher fold γ-coincidence events were collected. The coincidence data were analyzed with the Radware software package[13]. Detailed information of the experiment can be found in other articles[12, 14, 15].

## 3 Results and Discussion

### 3.1 The γ-vibrational bands in $^{105}$Mo and $^{108}$Mo

By carefully examining many coincidence relationships and the transition intensities, partial level schemes of $^{105}$Mo and $^{108}$Mo have been established, as shown in Figs. 1 and 2. The collective bands observed are labeled on the top of the scheme.

For $^{105}$Mo, the yrast band (1) is identified with spin up to 31/2 ħ. We add 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. [16, 17]. Two new bands, band (2) based on the

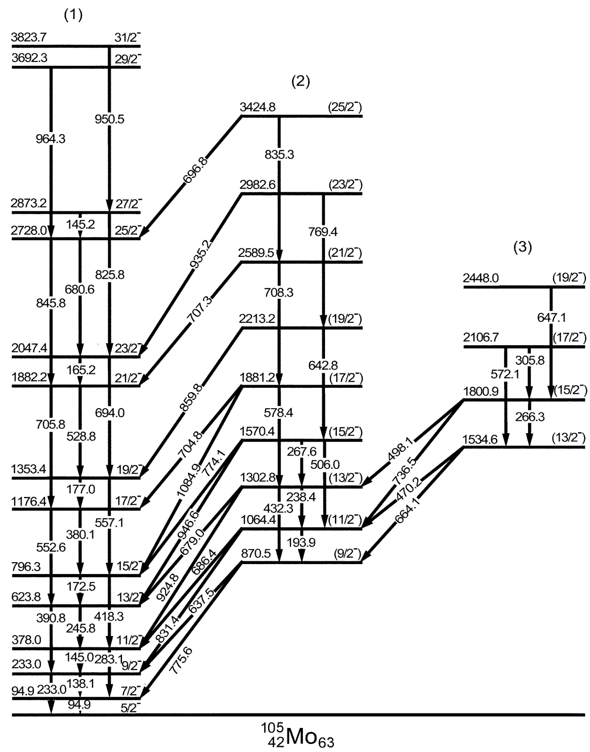


Fig. 1 The partial level scheme of $^{105}$Mo obtained in the present work. Energies are taken in keV.

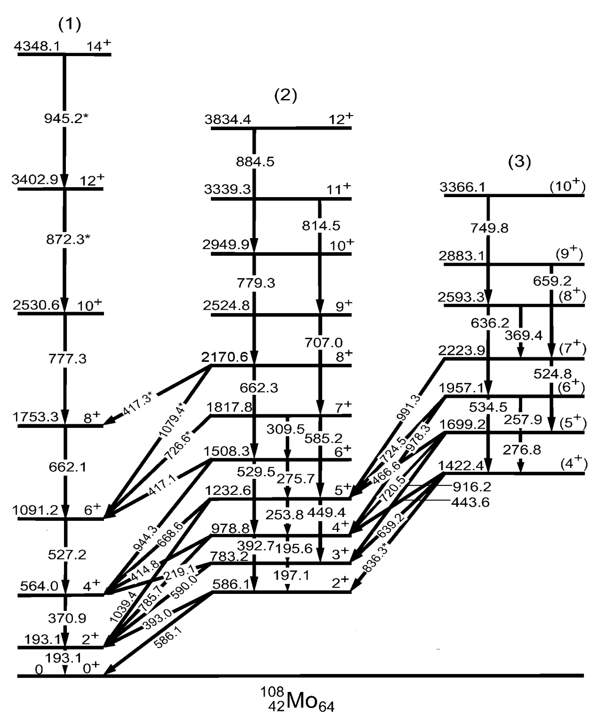


Fig. 2 The partial level scheme of $^{108}$Mo obtained in the present work. Energies are taken in keV.

870.5 keV level and band (3) based on the 1 534.6 keV level, have been identified for the first time. Many new γ-transitions have also been observed. For the $^{108}$Mo, the ground-state band (1) is observed with spin to 14 ħ, which confirms and updates the previous results[2, 16]. All the transitions in band (2) reported in Refs. [2, 16] are confirmed. In addition, we observed a new transition 884.5 keV and extended the spin levels of the band (2) up to 12 ħ. Energy levels in the band (3) based on 1 422.4 keV have been firmly established with spin up to 10 ħ, in which only three levels were reported in the previous work[2].

The band (1) in $^{105}$Mo 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[16, 17]. For the bands (2) and (3) in $^{105}$Mo, according to the level spacings comparing with the neighboring nuclei and the transition selection rule from bands (2) to (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. For the consideration of negative-parity state, the possible choice is $9/2^-$[514] or $11/2^-$[505] orbital excitation. But these two orbitals may be still too far from the Fermi surface to be possible. So 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 $9/2^-$. The band (3) has the band head excitation energy at 1 534.6 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 excluded the single-particle configuration. Moreover, as the band head energy of 1 534.6 keV is well below the neutron pairing gap $2\Delta_n\approx2.1$ MeV and the proton pairing gap $2\Delta_p\approx1.7$ MeV[1], we can rule out the three quasiparticle configuration for it. So we think that this band must probably belong to a two-phonon γ-vibrational band with $K=13/2$ and the state of the 1 534.6 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 neighboring even-even $^{104}$Mo nuclei.

For the $^{108}$Mo, the band (2) based on 586.1 keV energy level was previously suggested as the one-phonon γ-vibrational band [2,16]. Here we agree with the assignments of the spins and parities. For the band (3), as the band head level at 1 422.4 keV is lower than the neutron pairing gap and the proton pairing gap also, the band could not be two neutron- or proton-excitation band. Based on the characters of the transition from band (3) to band (2), the spin of the head level could be $3^+$ or $4^+$. But in the neighboring nuclei $^{104}$Mo and $^{106}$Mo, there were two-phonon γ-vibrational bands found. The energy level space between the heads of bands (3) and (2) is 836.3 keV in $^{108}$Mo, which is very close with the level spaces between the band heads of two-phonon and one-phonon γ-vibrational bands in $^{104}$Mo (771 keV) and $^{106}$Mo (724 keV). So we assign the spin and parity of the 1 422.4 keV level in band (3) as $4^+$, and this band is a two-phonon γ-vibrational band in $^{108}$Mo.

Fig. 3 shows a systematical level comparison of the ground state bands and the one- and two-phonon γ-vibrational bands in $^{104,105,106,108}$Mo. One can see that the one- and two-phonon γ-vibrational bands in $^{105}$Mo and $^{108}$Mo have similar level feature with those in $^{104}$Mo and $^{106}$Mo. They have closed band head excitation energies: 812 keV in $^{104}$Mo, 871 keV in $^{105}$Mo, 710 keV in $^{106}$Mo and 589 keV in $^{108}$Mo for the one-phonon γ-band, and 1 583 keV in $^{104}$Mo, 1 535 keV in $^{105}$Mo, 1 818 keV in $^{106}$Mo and 1 422.4 keV in $^{108}$Mo for the two-phonon γ-band. The band head energy ratios of $E_{2\gamma}/E_{1\gamma}$ are 1.95, 1.76, 2.56 and 2.43 for $^{104}$Mo, $^{105}$Mo, $^{106}$Mo and

$^{108}$Mo respectively. It seems that the characteristics of the γ-bands in $^{105}$Mo are more similar with that in $^{104}$Mo, and the characteristics in $^{108}$Mo are more similar with that in $^{106}$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 $^{104-106,108}$Mo may give another evidence for our assignment.

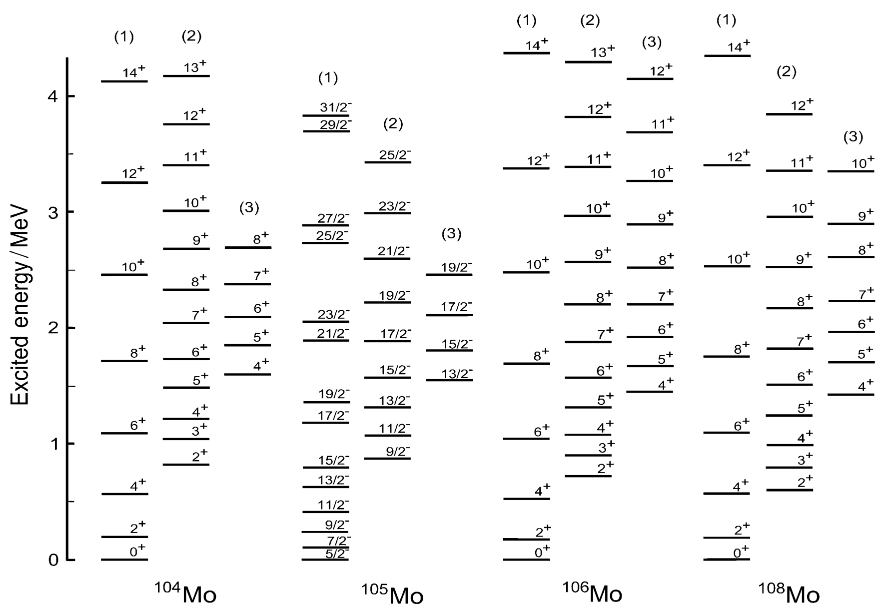


Fig. 3　Systematical comparison of the levels of one- and two-phonon γ-vibrational bands in $^{104-106,108}$Mo.

## 3.2　The chiral doublet bands in $^{106}$Mo and $^{110}$Ru

Partial level schemes of $^{106}$Mo and $^{110}$Ru are shown in Figs. 4 and 5, in which only the two sets of bands with bands (1) and (2) labeled on top of the schemes are shown in each nucleus. Some levels of the ground bands and one phonon γ-bands in $^{106}$Mo and $^{110}$Ru, as well as the two phonon γ-band in $^{106}$Mo are also shown in the figures in order to see the de-excitation transitions from the bands (1) and (2). The details of the ground bands and the γ-bands can be found in Refs. [4, 7]. Partial levels and structures of the bands in $^{106}$Mo and $^{110}$Ru showed in Figs. 4 and 5 have been observed in Refs. [4, 7], but here we update and expand them. Furthermore, we recently have made γ-γ(θ) angular correlation measurements described in Ref. [18] to determine the spins and parities of some levels in $^{106}$Mo and $^{110}$Ru which are not done in our previous works[4, 7].

From Figs. 4 and 5, one can see that the two similar sets of bands (1) and (2) are observed to high spins in $^{106}$Mo and $^{110}$Ru, and they have similar structural characters. We propose that they belong to chiral doublet bands.

In our previous reports, we have indicated that the $^{106}$Mo and $^{110}$Ru have triaxial shapes[4, 7] which are the basic conditions for the chiral doublet bands. Then the proposed chiral doublet bands in even-even $^{106}$Mo and $^{110}$Ru with higher excitation energies of the band head levels should originate from two quasi-particle configurations. As the two quasi-proton states lie at higher energy than the two quasi-neutron states, so these doublet bands are interpreted as two quasi-neutron excitations. We propose that these chiral bands in even-even nuclei are with configurations of the $\nu h_{11/2}$ (particle state) and the $\nu d_{5/2}$ (mixed with the $g_{7/2}$) (hole state), that is, $\nu h_{11/2}\otimes[d_{5/2}/g_{7/2}]^{-1}$.

We have carried 3D-Tilted Axis Cranking (TAC) calculations. The calculations show that the angular momentum of the $d_{5/2}/g_{7/2}$ neutron hole is strongly aligned with the long axis, and the angular momentum of the $h_{11/2}$ neutron lies in the short-intermediate plane. It prefers the direction of the short axis, but not very strongly. The remaining "core" angular momentum prefers the intermediate axis. The calculations indicated that the bands (1) and (2) $^{106}$Mo belong to a type of new chiral doublet bands, that is, they are zero- and one-phonon chiral vibrational bands respectively. For the $^{110}$Ru , they have similar characters.

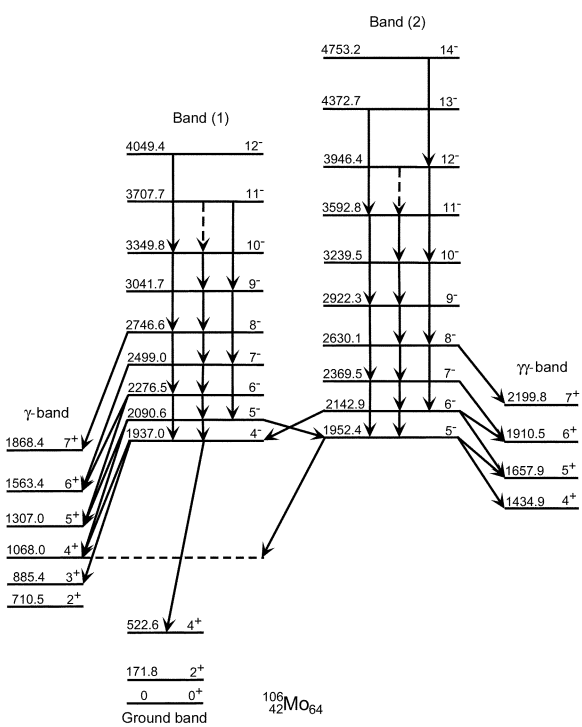


Fig. 4 The partial level scheme of $^{106}$Mo obtained in the present work. Energies are taken in keV.

Our calculations are made further test whether observed $\Delta I=1$ doublet bands in $^{106}$Mo and $^{110}$Ru could be accidentally degenerate bands from the coupling of an $h_{11/2}$ neutron to other single-neutron orbitals. The calculations show that in all cases, the $B$(E2)/$B$(M1) ratios of the two lowest bands differ typically by one order of magnitude. The experimental branching ratios of E2 to M1(E2) transitions within the two sets of doublet bands in $^{106}$Mo and $^{110}$Ru are given in Table 1. It shows that the equal order of magnitude in bands (1) and (2) in these nuclei. The clear disagreement of the calculated $B$(E2)/$B$(M1) ratios based on various quasi-particle configurations with the experimental data is strong evidence that these doublet bands do not arise from the couplings of different quasi-particle configurations which are just accidentally degenerate. It indicates that the doublet bands in each nucleus have very similar structures as required for chiral doublets.

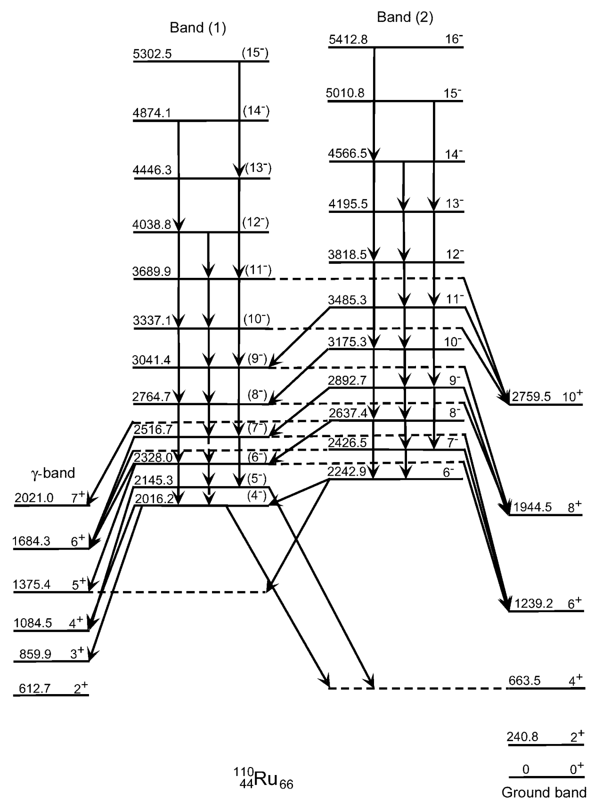


Fig. 5 The partial level scheme of $^{110}$Ru obtained in the present work. Energies are taken in keV.

**Table 1 Experimental branching ratios of the E2 to M1(E2) transitions**

| Spin | $^{106}$Mo | | $^{110}$Ru | |
|---|---|---|---|---|
| | Band(1) | Band(2) | Band(1) | Band(2) |
| 12 | >6.0 | >4.8 | >4.4 | 6.4 |
| 11 | 4.7 | >3.9 | 9.2 | 11.4 |
| 10 | 6.8 | 8.5 | 5.9 | 4.9 |
| 9 | 8.3 | 5.8 | 6.9 | 7.9 |
| 8 | 6.4 | 2.7 | 3.3 | 3.4 |
| 7 | 3.2 | 1.3 | 2.6 | |

Varman et al.[11] pointed out a test for chiral bands in which $S(I)=1/(2J_1\})=[E(I)-E(I-1)]/2I$, where $J_1$ is the kinetic moment of inertia, should be constant and identical with $I$ for two chiral bands. The $S(I)$ values for $^{106}$Mo and $^{110}$Ru are shown in Fig. 6. They are much more constant and more equal than found for this reported 'best' case of chiral bands in $^{104}$Rh[11]. The TAC calculations also predict a constant $J_1$.

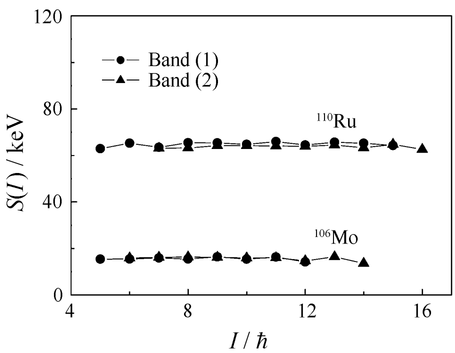


Fig. 6 $S(I)$ for $^{106}$Mo and $^{110}$Ru. The energy values are separated by 50 keV for display between nuclei.

The research on the energy differences between the levels with the same spin and the variations of excitation energies $E(I)$ vs. spin $I$ for bands (1) and (2) in $^{106}$Mo and $^{110}$Ru comparing with the chiral doublet bands in $^{104}$Rh also were carried out. All the results show the chiral characteristics in these three even-even nuclei.

## 4 Conclusions

High spin band structures in $^{105}$Mo, $^{108}$Mo and $^{110}$Ru have been studied. One-phonon and two-phonon γ-vibrational bands have been identified in $^{105}$Mo. This is a first identification of such kind of band structure in odd-$N$ nuclei. In $^{108}$Mo, one-phonon γ-vibrational band is expanded and two-phonon γ-vibrational band has been identified. Pairs of band structures in $^{106}$Mo and $^{110}$Ru have been observed. These bands are proposed as the chiral vibrational bands. The characteristics for these γ-vibrational bands and chiral doublet bands have been discussed.

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