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PROPERTIES OF ATOMIC NUCLEI
Experiment

Collective Bands in ^{104,106,108}Mo*

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Abstract—We have used our analysis of γ–γ–γ data (5.7×10^{11} triples and higher folds) taken with Gammasphere from prompt γ rays emitted in the spontaneous fission of ^{252}Cf to study the collective bands in ^{104,106,108}Mo. The one-phonon and two-phonon γ-vibrational bands and known two-quasiparticle bands in neutron-rich ^{104,106}Mo were extended to higher spins. The one- and two-phonon γ-vibrational bands have remarkably close energies for transitions from the same spin states and identical moments of inertia. Several new bands are observed and are proposed as quasiparticle bands in ^{104,106}Mo, along with the first β-type vibrational band in ^{106}Mo. The quasiparticle bands have essentially constant moments of inertia near the rigid-body value that indicate blocking of the pairing interaction. Candidates for chiral doublet bands in ^{106}Mo are strong. These are the first reported chiral vibrational bands in an even–even nucleus.

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A γ–γ–γ coincidence study of prompt γ rays emitted in the spontaneous fission of ^{252}Cf was carried out using Gammasphere with 102 Compton-suppressed Ge detectors. In spontaneous fission, ^{252}Cf fissions into two primary fragments, which emit neutrons and become secondary fragments, which emit γ rays. In our experiment, these γ rays were detected by Gammasphere. By using a ^{252}Cf source of strength 62 mCi sandwiched between two Fe foils of thickness 10 mg/cm^2 and mounted in a 3-inch-diameter plastic ball, approximately 6×10^{11} triple- and higher-fold coincidence events were recorded with a 1-μs time window. Further experimental details are found in Luo et al. [1]. Our 2000 experiment utilizing the spontaneous fission of ^{252}Cf yielded about 50 times greater statistics than previous experiments. Coincidence data were analyzed with the RADWARE [2] software package.

In our work, collective bands in ^{104,106,108}Mo were investigated by measuring the prompt γ rays emitted in the spontaneous fission of ^{252}Cf. The ground and one- and two- phonon γ-vibrational bands were extended and new bands were observed. In ^{106}Mo, two sets of $\Delta I = 1$ bands were observed, which are proposed to be chiral doublets.

Figure 1 shows the level scheme of ^{104}Mo. The ground band (1) is extended in our work from 12^+ up to 16^+. Band (2) is extended from 10^+ up to 14^+ and crossing transitions at 394.3, 604.9, 1283.7, and 940.6 keV between bands (2) and (1), respectively, were found from our analysis, as well as transitions at 215.8, 168.9, 259.9, and 250.3 keV within band (2). Band (3) is extended from 7^+ up to 9^+, and crossing transitions at 368.6, 609.1, 358.8, and 898.6 keV between bands (3) and (2), respectively, as well as crossing transition at 1022.4 keV between bands (3) and (1), were found from our work. Bands (5) and (8), with two levels each, and band (7), with four levels, and their depopulating transitions, were observed for the first time. Band (6) is extended from 9^- up to 13^-, and an additional level is identified at 5^-, The odd-spin level energies in band (2) are seen to be somewhat closer to the next higher even-spin level than to the next lower even-spin level in ^{104}Mo.

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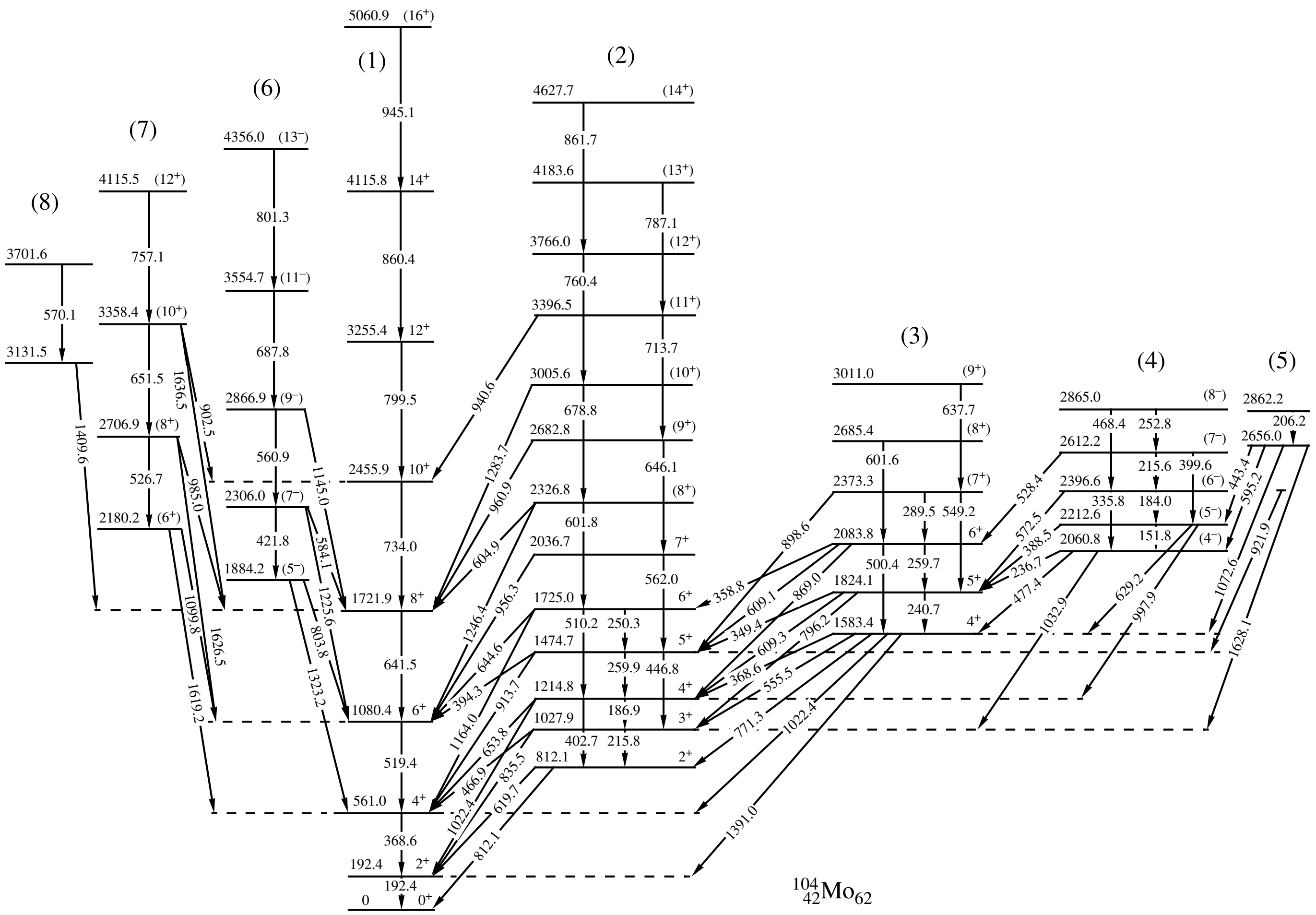

Fig. 1. New level scheme of ^{104}Mo (energy in keV).

In Fig. 2 is the level scheme of ^{106}Mo. From our analysis, the ground band is extended from 10^+ up to 16^+. Bands (7) and (8) are identified for the first time by our work. The γ band, band (2), is extended from 8^- up to 12^-, and new cascade transitions at 182.6, 256.4, 305.5, and 326.1 keV within band (2) were identified. Also, new crossing transitions at 545.4, 273.5, 506.1, 871.0, 1262.6, and 898.3 keV between bands (2) and (1) are seen. Band (3), the $\gamma-\gamma$ band, is extended from 7^+ up to 12^+, and crossing transitions at 1263.1 and 912.3 keV between bands (3) and (1) and at 892.8 and 636.4 keV between band (3) and the γ band (2) are found. Band (4) was extended from 8^- up to 12^- and a new (5^-) state added at 2090.6 keV. New transitions from known states within this band are at 185.9, 295.0, 308, tentatively 358, 247.9, 408.4, and 542.7 keV. New crossing transitions are seen at 1414.4 keV between bands (4) and (1), at 1022.6 and 783.6 keV between band (4) and the γ band (2), and at 137.2 keV between band (4) and the one-phonon band (5). Band (5) is extended in our work from 10^- up to 14^- and a new transition is seen at 670.5 keV, as well as crossing transitions at 884.4 keV between band (5) and the γ band (2), at 205.9 keV between band (5) and the zero-phonon band (4), and at 294.5 and 232.4 keV between band (5) and the $\gamma-\gamma$ band (3). Band (6) is extended from 8^+ up to 10^+ and from 0^+ up to 6^+, and crossing transitions are seen at 1150.0, 978.2, 1364.9, 1014.1, and 1492.4 keV between band (3) and the ground band (1).

Figure 3 shows a double gate on the 171.8-keV transition between the 2^+ and 0^+ levels of the ground band and the 1051.6-keV transition between the 4^- level of band (4) and the 3^+ level of the one-phonon γ band in ^{106}Mo. In this spectrum, we can see higher lying 153.6-, 185.9-, 222.5-, 339.5- 408.4-, 470.1-, 603.2-, and 666.0-keV transitions of band (4) and the 487.2-keV transition of band (5), as well as the crossing transition at 205.9 keV between bands (4) and (5), in addition to the crossing transition at 713.6 keV

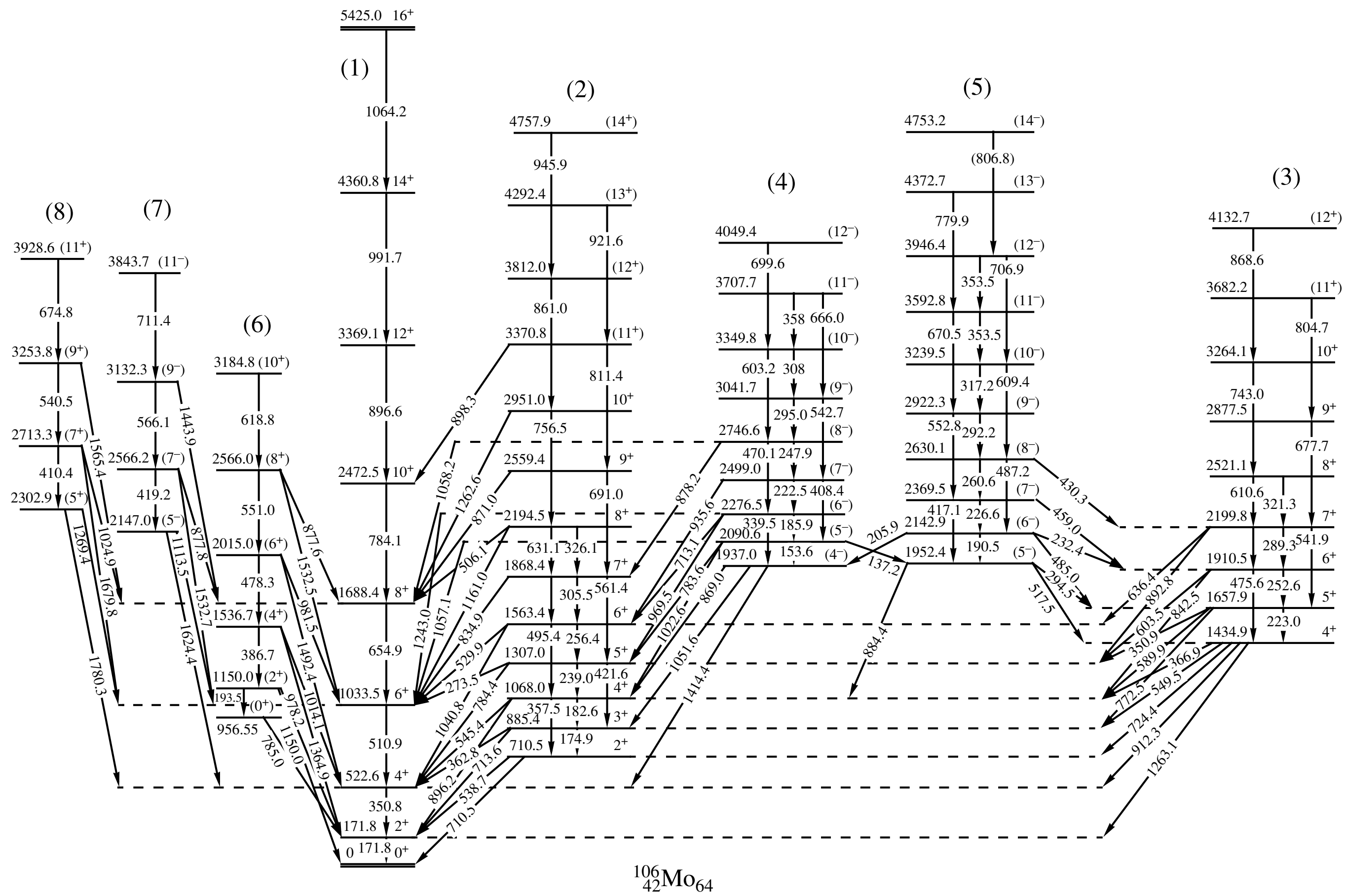

Fig. 2. New level scheme of ^{106}Mo (energy in keV).

between the ground band (1) and the γ band (2) of ^{106}Mo.

We can see the new $\Delta I = 1$ doublet bands (4), (5) and the one- and two-phonon γ bands in ^{106}Mo in Fig. 2. The tilted axis cranking model predicts chiral vibrational bands in ^{106}Mo such that band (4) is a zero-phonon chiral vibrational band and band (5) is a one-phonon chiral vibrational band. Bands (4) and (5) have the properties of chiral doublets. Chirality is a geometrical concept that derives only from the orientation of the angular momentum with respect to the triaxial shape. As Frauendorf et al. [3] noted, chiral bands can occur in a triaxial nucleus when there are substantial components of the angular momentum along all three axes.

Characteristics of chiral doubling include the following: Two $\Delta I = 1$ bands with the same parity and very close energy occur when the angular momentum has substantial components along all three axes of the triaxial nucleus. Then there are two energetically equivalent orientations of the angular momentum vector with the short, intermediate, and long axes forming right- or left-handed systems with respect to the angular momentum.

Examples of chiral doublets include odd–odd nuclei ($Z \sim 59$, $N \sim 65$), where the angular momentum is composed of an odd $h_{11/2}$ proton along the short axis, an $h_{11/2}$ neutron hole along the long axis, and collective rotation along the intermediate axis. It has recently been reported by Vaman et al. [4] that "The best chiral properties observed to date were discovered in the ^{104}Rh nucleus, involving the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration, where the valence proton and neutron play opposite roles to those in the $A = 130$ region."

In order to demonstrate the general nature of chirality, it is important to find examples of chiral sister bands with quasiparticle configurations different from previous examples. Here, we report the first observation of a pair of chiral vibrational bands in an even–even nucleus. From our new ^{106}Mo work [5], we have found that the chirality is generated by a neutron $h_{11/2}$ particle coupled to the short axis and a mixed

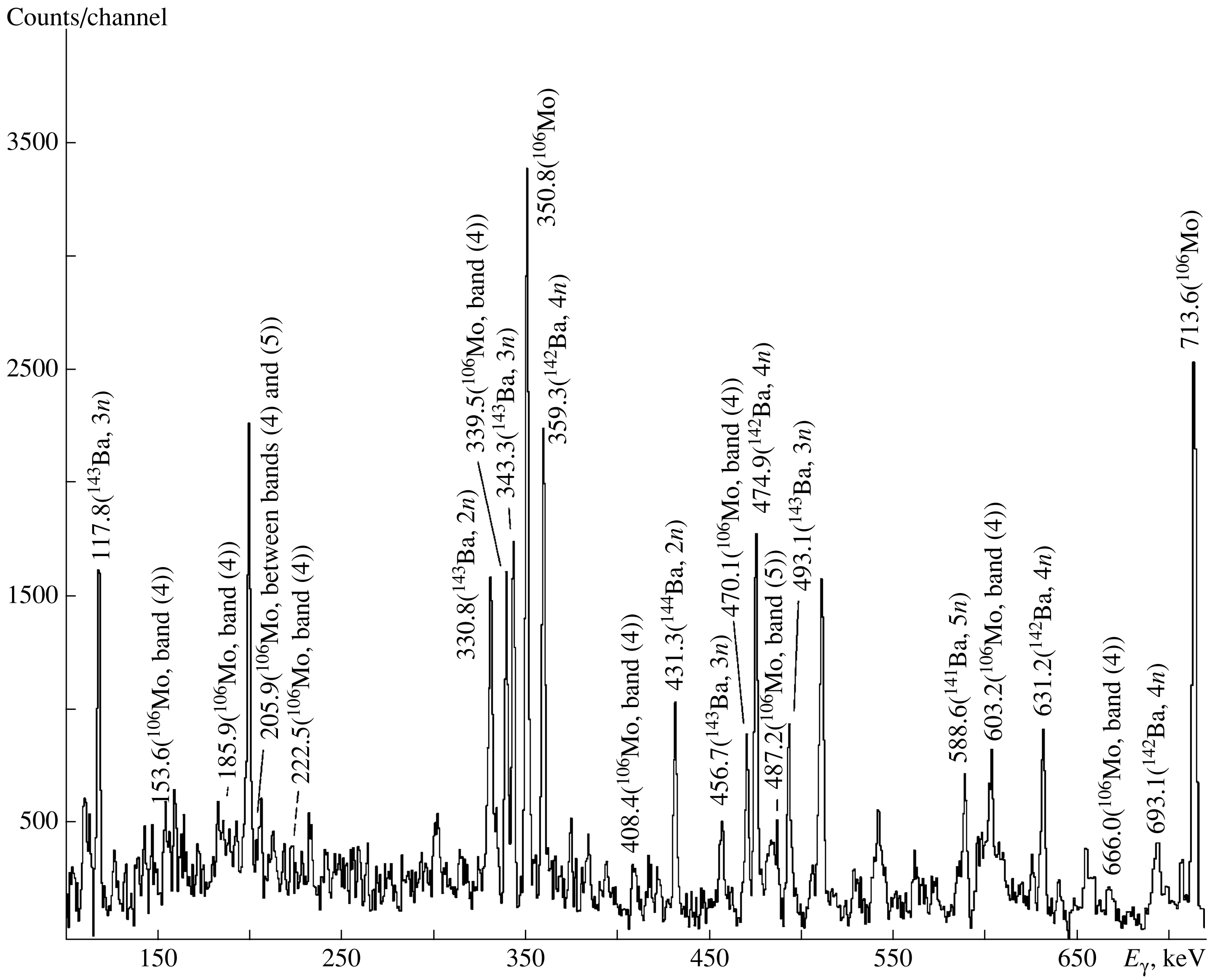

Fig. 3. Double gate on 171.8 and 1051.6 keV in ^{106}Mo.

$d_{5/2}$, $g_{7/2}$ hole coupled to the long axis with collective rotation along the intermediate axis. Tilted axis cranking calculations support the chiral assignment for ^{106}Mo from our analysis. Figure 4 is a graph of ΔE of the γ bands in ^{104,106,108}Mo vs. spin of the lower energy level. We can see the clear difference between ^{104}Mo and ^{106}Mo, with ^{104}Mo showing a marked staggering to spin 12^+. We can see a little of this effect at low spins in ^{106}Mo, but it smooths out at higher spins until spin 13^+. In ^{108}Mo, there is a decrease in the $4^+ \to 3^+$ energy level difference compared to the $3^+ \to 2^+$ difference, but the differences increase from there to 7^+, with less of an increase in the $9^+ \to 8^+$ difference. The moments of inertia of the new extended quasiparticle bands, i.e., bands (6) and (7) in ^{104}Mo and bands (7) and (8) in ^{106}Mo, are remarkably similar, as shown in Fig. 5, and near the rigid-body value.

In summary, we have extended the ground and γ bands, discovered new quasiparticle bands, and proposed a new type of chiral bands. We have found chiral vibrational bands in ^{106}Mo, an even–even nucleus. Tilted axis cranking calculations indicate that, in ^{106}Mo, chirality has a dynamical character. In ^{106}Mo, the two chiral bands are low-energy zero- and one-phonon chiral vibrations. This different mechanism of generating chirality helps prove the general nature of chirality in nuclei.

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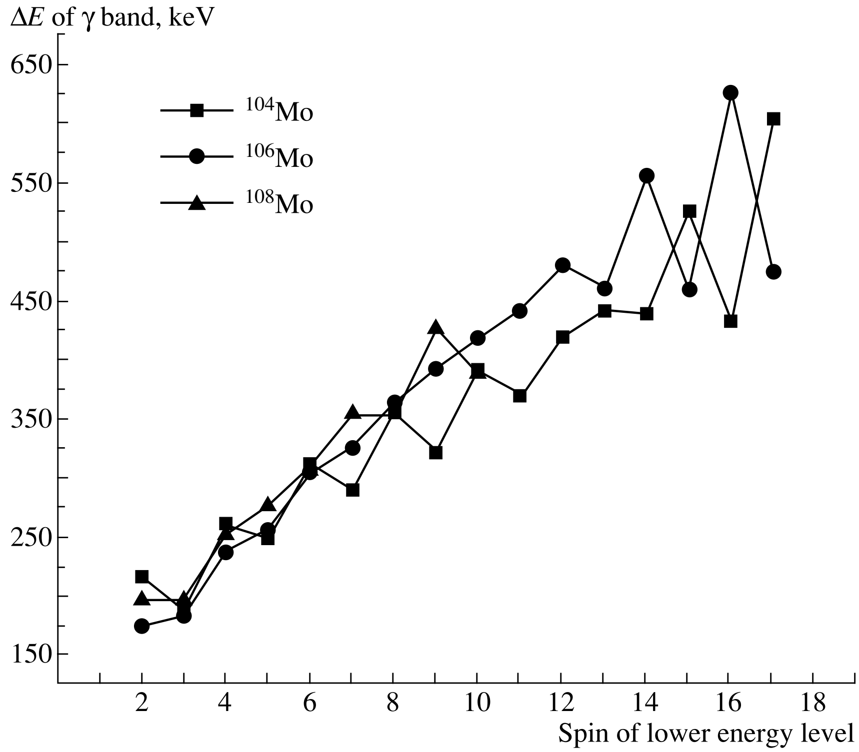

Fig. 4. Plot of ΔE of the γ bands in ^{104,106,108}Mo vs. spin of the lower energy level.

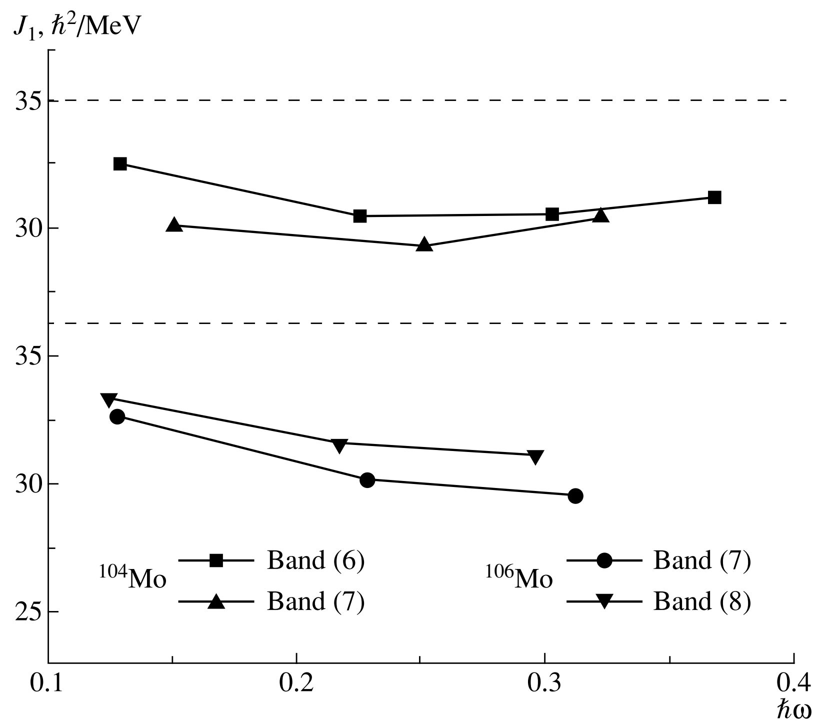

Fig. 5. Plot of moment of inertia J_1 vs. $\hbar\omega$ of the extended quasiparticle bands in ^{104,106}Mo. Dashed lines indicate the rigid body values for ^{104,106}Mo, respectively.

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