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Soft chiral vibrations in ^{106}Mo

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Abstract. High-spin states in neutron-rich ^{106}Mo were investigated by detecting the prompt γ-rays in the spontaneous fission of ^{252}Cf with Gammasphere. Several new bands are observed. Two sets of $\Delta I = 1$ bands in ^{106}Mo are found to have all the characteristics of a new class of chiral vibrational doublets. Tilted axis cranking calculations support the chiral assignment and indicate that the chirality is generated by neutron $h_{11/2}$ particle and mixed $d_{5/2}$, $g_{7/2}$ hole coupled to the short and long axis, repectively.

PACS. 21.10.Re Collective levels – 23.20.Lv γ transitions and level energies – 27.60.+j $90 \leq A \leq 149$ – 25.85.Ca Spontaneous fission

Evidence for triaxial shapes is found in neutron-rich nuclei in the $A = 100$–114 range [1,2,3,4]. Low-lying one- and two-phonon states of the gamma vibration indicate the softness of ^{106}Mo with respect to triaxial deformations [5]. In such a soft nucleus the excitation of quasiparticles will strongly modify the shape and may induce a stable triaxial shape [6,7]. A pair of chiral doublet rotational bands, which consist of two sets of $\Delta I = 1$ sequences of states with the same parity and very close energies can occur in triaxial nuclei. Chiral doubling emerges when the angular momentum has substantial components along all three principal axes of the triaxial density distribution. Then there are two energetically equivalent orientations of the angular momentum vector. In one case the short, intermediate and long axes form a right-handed system with respect to the angular momentum, in the other case a left-handed system [6].

Such chiral pairs of bands have been found in odd-odd nuclei around $Z = 59$ and $N = 75$ [8] where the angular momentum is composed of a component from the odd $h_{11/2}$ proton along the short axis, a component from the $h_{11/2}$ neutron hole along the long axis and a collective component along the intermediate axis. Chiral bands predicted for odd-odd nuclei around $Z = 43$ and $N = 65$, where the odd $h_{11/2}$ neutron generates the angular momentum along the short and the $g_{9/2}$ proton hole along the long axis [7] were recently observed in ^{104}Rh [9].

To establish the general nature of chirality, it is important to find examples of chiral bands with a different quasiparticle composition. Here we report the first evidence of a pair of chiral vibrational bands in ^{106}Mo where the chiral structure is due to the neutrons with $h_{11/2}$ particle coupled to the short axis and mixed $d_{5/2}$, $g_{7/2}$ hole coupled to the long axis.

The levels of ^{106}Mo were investigated by measuring the prompt γ-rays emitted in the spontaneous fission (SF) of ^{252}Cf. A 62 μCi ^{252}Cf source was sandwiched between two 10 mg/cm^2 Fe foils and mounted in a 7.62 cm diameter plastic (CH) ball and placed at the center of Gammasphere with 102 Compton-suppressed Ge detectors at Lawrence Berkeley National Laboratory. A total of 5.7×10^{11} triple- and higher-fold coincidence events were collected, factors of 10–100 higher than earlier

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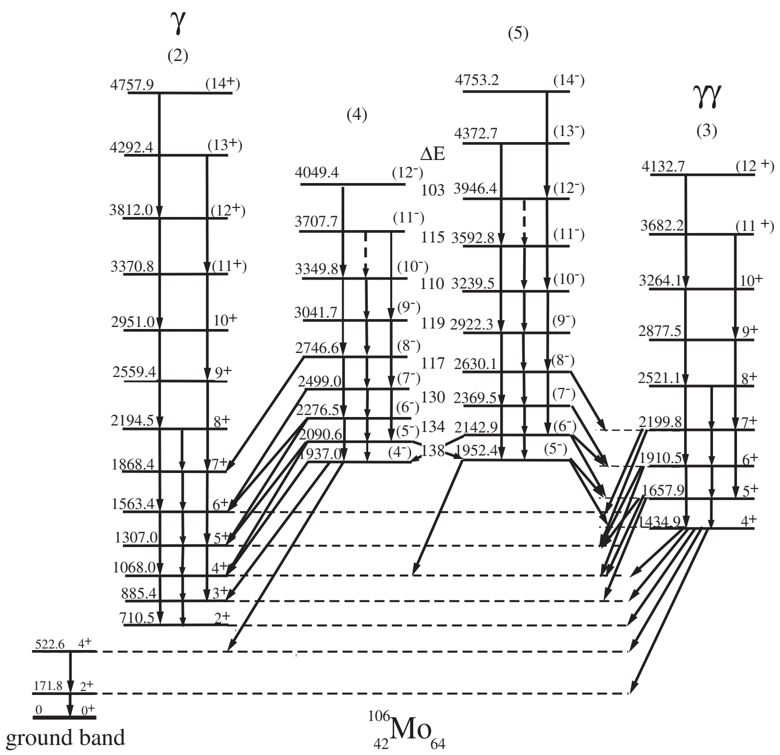

Fig. 1. Decay patterns of chiral bands into γ and $\gamma\gamma$ bands in ^{106}Mo. The energy differences in keV of the same spin states in bands (4) and (5) are given between the bands. Transitions depopulating the γ-band (2) are omitted.

measurements. Coincidence data were analyzed with the RADWARE software package.

In addition to previous work [5], 78 new transitions and 34 new levels in ^{106}Mo are identified. The partial level scheme in fig. 1 shows 45 of the new transitions and 20 of the new levels including bands (4) and (5) in ^{106}Mo which are proposed to be chiral doublets along with the one- and two-phonon γ vibrational bands and ground-band members to show their decay patterns. To illustrate the data, fig. 2 shows the spectrum double gated on the 1051.6 keV transition that depopulates band (4) and the 171.8 keV, 2-0 transition where the transitions in band (4) are shown along with the 205.9 keV transition from band (5) to (4) and the 117 keV transition in ^{143}Ba, the strong 3n partner. The β_2 value of the ^{106}Mo ground band is 0.34 [10]. The spins and parities of the γ vibrational band (2) and $\gamma\gamma$ band (3) have been assigned previously [5]. In ^{106}Mo, bands (4) and (5) are consistent only with 4^- and 5^- or 5^+ and 6^+ assignments, respectively, for the band heads. These assignments are based on the decay patterns out of each level including both the transitions seen and the absence of higher energy transitions to other band members. The decay patterns are only consistent with band (5) having one unit of spin higher than band (4). We could not measure the parity of the pair of bands directly.

The two-quasiproton states lie at higher energy than the two-quasineutron states, because of the larger pairing gap and the smaller level density. For this reason we interpret the bands as two-quasineutron excitations. The lowest neutron particle-hole excitations have negative parity. This is expected, because the single particle levels with opposite parity cross each other with increasing deformation, whereas the distance between levels with the same parity increases [11]. For this reason we adopt the negative parity. There are two configurations which correspond to the excitation of a neutron from the highest $h_{11/2}$ level to two close-lying mixed $d_{5/2}, g_{7/2}$ positive-parity levels. The lower configuration $h_{11/2}, (d_{5/2}, g_{7/2})^{-1}$ would correspond to [541]3/2[[413]5/2]$^{-1}$ in the case of an axial shape. However, it is found to have a triaxial deformation of $\beta_2 = 0.31$ and $\gamma = 31°$ in our TAC calculation. Our recently measured lifetimes of less than 8 ns for the decay out of the band heads support the triaxial shape. If the observed pair of bands was axial, one would expect a substantial retardation of the decay into the $K = 0$ ground band, because $\Delta K > 3$ corresponds to a large retardation, which is not observed.

For interpretation, we carried out 3D Titled Axis Cranking calculations using the method of ref. [12]. The proton pairing gap was chosen to be equal to the even-odd mass difference. The neutron pair gap was set equal to zero, because blocking two states will substantially reduce the neutron pair correlations [13].

The TAC calculations showed that the angular momentum of the $d_{5/2}, g_{7/2}$ neutron hole is strongly aligned with the long axis. 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 total angular momentum moves from the long-short plane through the aplanar region to the short-intermediate

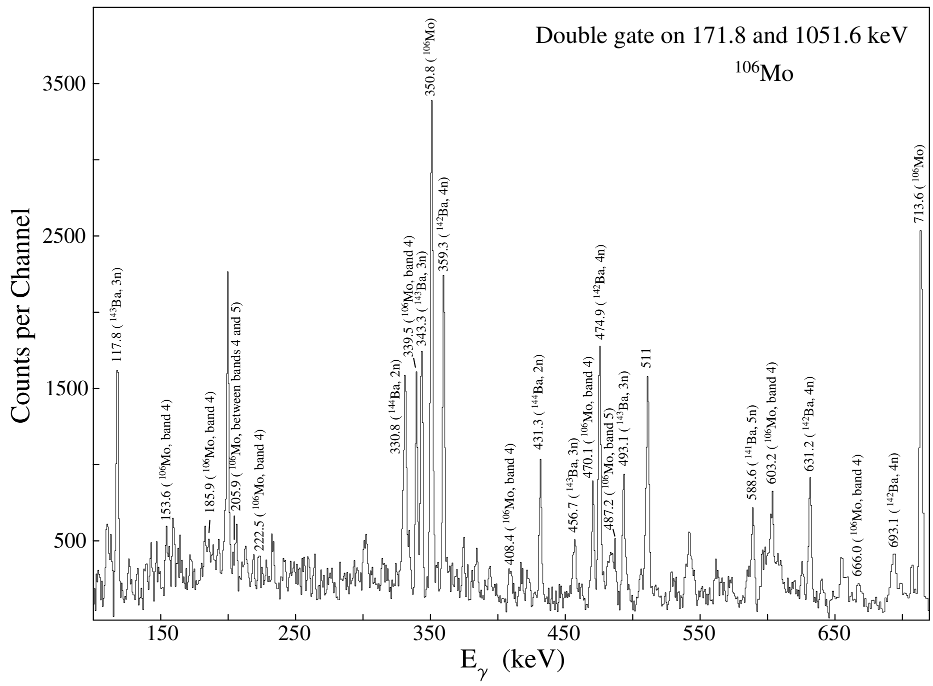

Fig. 2. Coincidence spectrum obtained by double gates on the 171.8 keV 2 → 0 transition and the 1051.6 keV one depopulating band (4) in ^{106}Mo.

plane. The motion of the total angular momentum vector cannot be completely explained in terms of a particle angular momentum aligned with the short axis, hole angular momentum aligned with the short axis and collective angular momentum aligned with the intermediate axis. The microscopic structure of the core favors a path through the aplanar region.

This mechanism is quite different from the known chiral examples, where the high-j particle(s) generates angular momentum along the short axis, the high-j hole along the long axis, and the remaining nucleons generate collective angular momentum along the intermediate axis.

The microscopic TAC results cannot be reduced to the simple picture of a particle aligned with the short axis, a hole aligned with the long axis and collective angular momentum along the intermediate axis. It comes about as the interplay of the neutrons in the open shell. Although we could not come up with a simple picture as in the case of chiral bands based on the intruder orbitals, the TAC calculations do give angular momentum projections on all three axes when the rotational axis moves from the long-short to the intermediate-short plane. The TAC calculations give constant J^1. In the case of axial prolate symmetry, the orbitals with high K have a large component of angular momentum aligned with the long axis. This component remains large at finite rotational frequency, which introduces some K-mixing. Triaxiality introduces more mixing, but there are still normal parity orbitals that retain a certain amount of angular momentum aligned with the long axis. TAC that has all these ingredients finds chiral examples, like the one we present here.

The following facts speak in favor of associating the observed bands as a chiral pair:

a) Triaxiality is known for this nucleus and the lifetimes for the decays out of the bands give it further support.

b) The ΔE values between like spin levels decrease with increasing angular momentum.

c) Both bands have regular $\Delta I = 1$ sequences with $M1$ transitions between their even and odd spin members. The signature splitting is very small, as indicated by the very small staggering of the kinematic moment of inertia commonly denoted as $J^1 = I/((E(I) - E(I-1))$ shown in fig. 3. (very small compared to even the “best ”chiral bands in ^{104}Rh [9] in fig. 3).

d) The moments of inertia in fig. 3 are equal as expected for a chiral pair. They remain almost constant with increasing spin.

The kinematic moment of inertia remains constant if the angular momentum gain is caused by adding angular momentum along the axis perpendicular to the plane in which the particle and hole angular momentum lie. This is analogous to high-K bands, where the particle-hole angular momentum is parallel to the symmetry axis and the collective angular momentum perpendicular to it. If the particle, the hole and the total angular momentum lay in one plane (planar tilt) the kinematic moment of inertia is a decreasing function of I, like in the familiar case of rotational alignment of a high-j particle in an axial nucleus. The I-independence of J^1 as an evidence for an aplanar geometry of the angular momentum as was first pointed out by Vaman *et al.* [9], who used $S(I) = 1/(2J^1)$ as a measure.

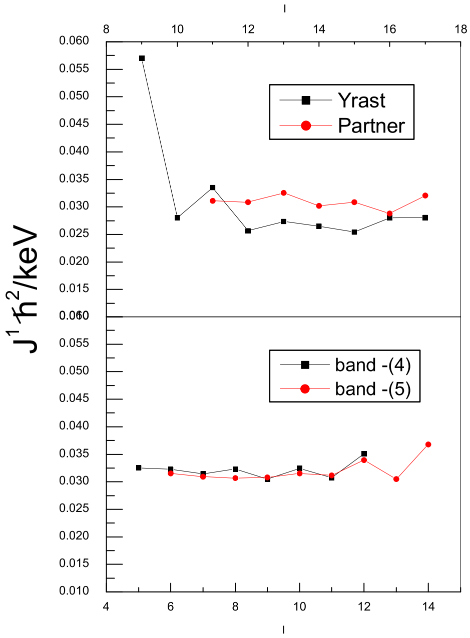

Fig. 3. Plots of moment of inertia (J^1) *versus* I for ^{104}Rh (top pannel) and ^{106}Mo (bottom pannel).

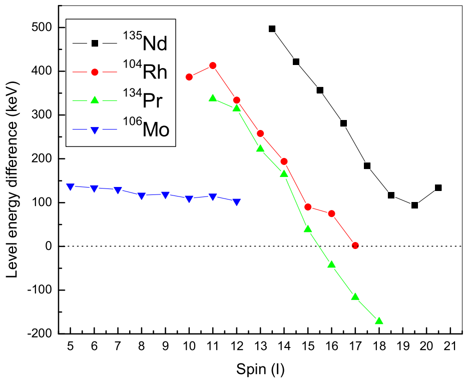

Fig. 4. Energy level differences (keV).

Figure 4 shows that the energy difference between the same spin levels in the two doublet bands is small at the bottom and decreases slowly with I. This is consistent with the observation that J^1 is constant for the band. For the known examples of chirality, one sees a transition from chiral vibrations at the bottom to stable chirality at the top of the bands: the energy difference is large at the bottom and decreases to a small value, where simultaneously the kinematic moment of inertia approaches a constant value. Our case looks like a very soft chiral vibration or a chiral configuration with substantial left-right tunneling, which do not change very much with I.

The pattern of the electromagnetic decays depends sensitively on the the mixing matrix element that couples the left-handed with the right-handed configuration. Since the left- and right-handed configurations have the same energy, already a small matrix element determines the phase of the mixing amplitude. If this phase is similar in the initial and final states, the transitions remain in the bands and there is no cross talk, as observed in our case. If the phases differ substantially, then there will be strong interband transitions. Koike *et al.* [14] discussed recently such a case. However, the peculiar staggering pattern reflects the special symmetry of their model and cannot be expected to be observed in other chiral configurations that do possess the symmetry, like the one suggested in this paper.

In summary, bands (4) and (5) in ^{106}Mo are proposed as the first chiral vibrational bands in an even-even nucleus. The TAC calculations strongly support this interpretation. A different mechanism (as compared to the known cases) generates chirality, which proves the general nature of the concept.

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