Effect of γ Softness on the Stability of Chiral Geometry: Spectroscopy of ^{106}Ag

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(Received 26 September 2006; published 7 March 2007)

A study of the nucleus ^{106}Ag has revealed the presence of two strongly coupled negative-parity rotational bands up to the 19^- and 20^- states, respectively, which cross each other at spin $I \sim 14$. The data suggest that near the crossover point the bands correspond to different shapes, which is different to the behavior expected from a pair of chiral bands. Inspection of the properties of these bands indicates a triaxial and a planar nature of rotation for the two structures. Possible causes for this may be understood in terms of a shape transformation resulting from the large degree of γ softness of ^{106}Ag. These data, along with the systematics of the odd-odd structures in the mass 100 region, suggest that γ softness has marked implications for the phenomenon of nuclear chirality.

DOI: 10.1103/PhysRevLett.98.102501 PACS numbers: 21.10.Re, 21.60.Ev, 23.20.−g, 27.60.+j

Chirality is the study of left- or right-handed symmetry. The existence of this phenomenon in atomic nuclei was initially suggested by Frauendorf *et al.* [1] and the first experimental evidence was subsequently found in the $A \sim 130$ mass region [2]. In odd-odd triaxial nuclei, three angular momentum vectors may couple to each other in either a left- or a right-handed fashion giving rise to left- or right-handed systems, respectively. The two odd nucleons align their angular momentum vectors along the short and long axis of the nucleus if they have a particle- and holelike nature, respectively, while the collective rotation vector aligns along the intermediate axis in order to minimize the energy. A left- or a right-handed system will be generated in the intrinsic frame, depending upon which side of the short-long (s-l) plane the rotation vector projects from. In the laboratory frame this spontaneous formation of handedness or chirality can be observed as nearly degenerate identical spin and parity states. Furthermore, in an ideal situation, (i.e., perfectly orthogonal angular momentum vectors and a stable triaxial nuclear shape) a perfect degeneracy between the identical spin states should be observed. In fact, the attainment of degeneracy is one of the key fingerprints of chirality. However, states with different quantum numbers in two nonchiral bands can also show an accidental degeneracy. Thus, one of the important tests of chirality is that the degenerate states in the two bands should also have similar physical properties, such as moments of inertia, quasiparticle alignments, transition quadrupole moments, and the related $B(E2)$ values for the in-band $E2$ transitions [3]. Thus, detailed studies of the two structures in the region where the bands are degenerate (or cross) are important in terms of characterizing their nature.

To date, there have been several cases studied in the $A \sim 100$ region [4–7] where doublet bands based upon a $\pi g_{9/2}^{-1} \times \nu h_{11/2}$ configuration have been found. Although no case of true energy degeneracy or band crossing has been found in the intermediate spin region of these nuclei, the properties of the bands in the nondegenerate region were found to be reasonably in accordance with the predicted experimental fingerprints [8] for chirality. These being: (i) a smooth behavior of the parameter, $S(I)$, $(=[E(I) - E(I-1)]/2I)$ as a function of spin. This smoothness results from a highly reduced Coriolis interaction due to the three-dimensional coupling of the angular momentum vectors. The Coriolis interaction is proportional to the scalar product of the total spin, I, with the single-particle and hole spin vectors. For a chiral (three-dimensional coupling) configuration, the rotational spin, R (which is the dominant part of the total spin, I, for moderate and high spins), is perpendicular to the single-particle/hole-spin vectors and therefore, results in a much reduced Coriolis interaction. (ii) A characteristic staggering of the $B(M1)/B(E2)$ ratios for transitions from levels in both the bands and for the in-band and out of band, $B(M1)_{\mathrm{in}}/B(E2)_{\mathrm{out}}$, ratios for transitions from levels in the excited partner band. This ratio should stagger low (high) for the odd-spin members and high (low) for the even spin members of a negative (positive) parity configuration. (iii) An energy degeneracy for states of the same spin in the two bands. This feature has not been observed in any of the chiral structures identified to date.

Clearly, it is very important to look for cases where the two bands attain near degeneracy over a sufficient range of spin, since it is only in the degenerate regime that the true chiral (identical) nature of the two bands can be tested. The nucleus ^{106}Ag contains two protons more than ^{104}Rh (where degeneracy within 2 keV has been observed [4]) and hence was the first choice for further investigation, since it was expected that the larger proton number would increase the holelike nature of the last odd proton in the $g_{9/2}$ subshell, which is an important ingredient for sustaining the chiral geometry [9,10].

Previous work on ^{106}Ag identified two strongly coupled negative-parity bands; however, they disagreed on the spin assignments. The most recent work [10] identified the bands up to spins 16^- and 19^-. In both cases the yrast band was interpreted to be built upon $\pi g_{9/2}^{-1} \times \nu h_{11/2}$ configuration while no interpretation was given for the partner band. The present experiment to study ^{106}Ag was performed with the Gammasphere array at Argonne National Laboratory using the ^{100}Mo(^{10}B, $4n$)^{106}Ag reaction at a beam energy of 42 MeV. A thin self-supporting ^{100}Mo target of 550 μg/cm^2 thickness was used in the experiment. Fourfold and higher prompt γ ray coincidence events were recorded and these were unpacked into triples (E_γ-E_γ-E_γ) events before being sorted into a cube which was analyzed using the RADWARE [11] package. Figure 1 shows the partial level scheme of ^{106}Ag deduced in the present work. Both the negative-parity yrast band (band 1) and the side band (band 2) contain strong M1 transitions in addition to crossover $E2$ transitions of moderate intensity. The 10^- state bandhead of band 2 lies ~850 keV above the yrast 10^- state of band 1. However, the energy gap between the two bands closes very rapidly and beyond spin 14^- the sideband becomes the yrast structure. The sideband is connected to the yrast band through strong mixed $M1/E2$ and $E2$ transitions. In view of the previous conflict over the spin assignments we have performed a detailed analysis of the data (the results of which will be published in a full paper) and conclude that the revised spin assignments given in Ref. [9] are correct. From the present work the yrast and sidebands have been extended up to a spin of 19^- and 20^-, respectively, and several new transitions linking the two bands have been observed. The latter suggests an underlying similarity in the quasiparticle configurations of the bands.

The observation of a sideband which is connected to the yrast band via several $M1$ and $E2$ transitions is similar to the earlier reported systematic observation of doublet bands in neighboring $^{102-106}$Rh and ^{100}Tc nuclei, which were interpreted as having a common origin, namely, chirality [4–7]. The similar nature of the bands in ^{106}Ag has also led us to use the same arguments as those presented previously (e.g., see [4]); consequently, we assign the identical single-particle configurations to both the bands. However, in addition to sharing similarities with the bands in the Rh and Tc isotopes, the two bands in ^{106}Ag also show some marked differences from the systematics expected of chiral structures. Indeed, one of the chiral fingerprints, namely, the staggering pattern of the $B(M1)/B(E2)$ ratios, is found not to agree with the expectations [see (ii) page 1] for chiral structures in this region (see Fig. 2). Furthermore, the two bands in ^{106}Ag are observed to cross each other near $I = 14$. Such a crossing between two similar structures of the same spin and parity has not been observed in the other doublet bands seen in the $A \sim 100$ region. A crossover or degeneracy is one of the most sought after features of potential chiral partner bands since it is precisely in this region that the identical nature of the two bands can be tested.

In order to examine the properties of the bands around the crossing region we have plotted their energies along with their kinematic moments of inertia (MOI), quasiparticle alignments, and $S(I)$ values in Fig. 3. The MOI is indicative of the collective shape of the nucleus while the quasiparticle alignments are related to the alignment of the angular momentum vectors of quasiparticles with respect to the collective rotation vector and, therefore, suggest the

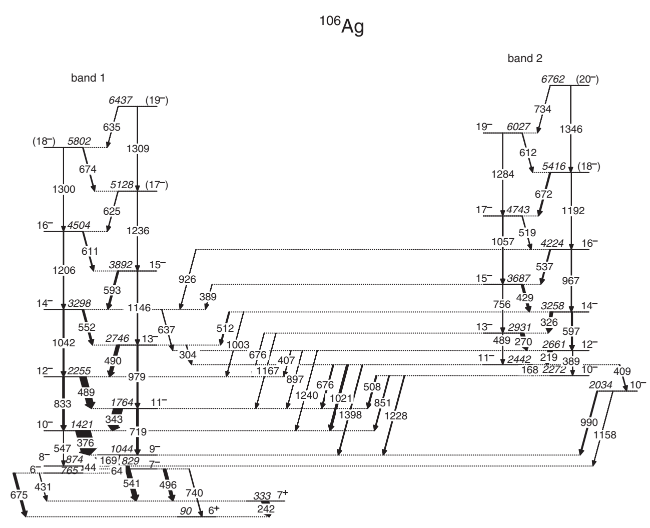

FIG. 1. Partial level scheme for ^{106}Ag from present work.

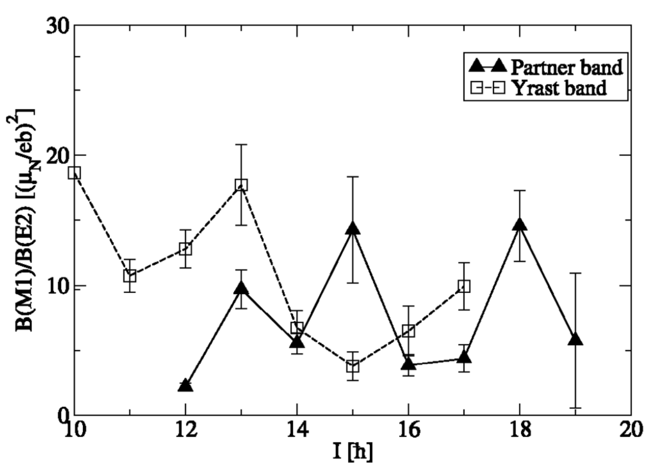

FIG. 2. $B(M1)/B(E2)$ values as a function of spin, I, for the negative-parity bands in ^{106}Ag.

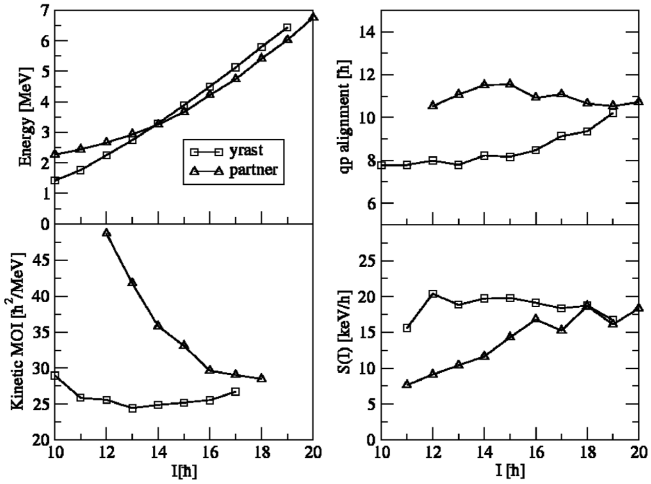

FIG. 3. Plot of excitation energy, kinematic moments of inertia, quasiparticle alignments, and the $S(I)$ parameter as a function of spin for bands 1 and 2 in ^{106}Ag.

nature of rotation. The staggering parameter, $S(I)$, is a measure of the Coriolis interaction in the odd-odd nucleus which, as indicated above, can be highly reduced for triaxial and hence chiral rotation. It is clear from the figure that near the crossing ($I = 14$) the MOI of the partner band is very different (40% higher) to that of the yrast band. The different values of MOI, combined with the unchanging quasiparticle alignments in this spin region (see Fig. 3), clearly suggest that the two bands may correspond to different shapes. Figure 4 shows a potential energy surface plot from total Routhian surface (TRS) calculations for ^{106}Ag at a rotational frequency of $\hbar\omega = 0.40$ MeV. The arrow shows the direction in which the nuclear shape is unstable, which is indeed the direction of triaxiality. The two points A and B with equal energy lying on the innermost contour correspond to the deformation parameters $\beta, \gamma = (0.20, 0°)$ and $(0.12, -28°)$, respectively. It is apparent from this figure that an axial prolate ($\gamma = 0°$) as well as a triaxial shape ($\gamma \neq 0°$) are both close in energy. Thus the calculations also indicate that it is possible for the

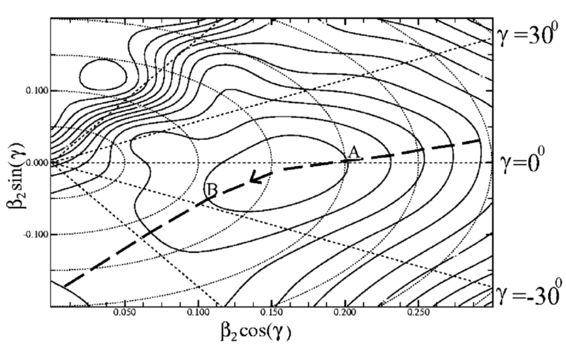

FIG. 4. TRS plot for the yrast negative-parity configuration in ^{106}Ag at a rotational frequency of 0.40 MeV. The contour separation is 0.35 MeV.

two bands to possess different (i.e., axial prolate and triaxial) nuclear shapes.

In order to investigate further we may look at the quasiparticle alignments and $S(I)$ plots which are also a good indicator of nuclear shapes in the $A \sim 100$ odd-odd triaxial nuclei. In this region the odd-odd quasiparticles, with their particle and hole nature, are believed to be aligned in the s-l plane of the nucleus. Therefore, the excited band with higher values of quasiparticle alignment may indicate a collective rotation in the s-l plane, suggesting a planar rotation and hence an axial shape, while lower values of quasiparticle alignments for the yrast band would indicate a rotation away from the s-l plane, thereby suggesting an aplanar rotation in a triaxial nucleus. Finally, the smoothness of the $S(I)$ plot (as discussed in the introduction and elsewhere) also suggests a triaxial nature for band 1 while the staggered nature of band 2 above spin 15 suggests it contains a large planar component of the collective rotation. The apparent smoothness of the $S(I)$ plot below this spin results from the fact that the Coriolis force, which depends on the inverse of the MOI for an ideal rotor, suppresses the magnitude of the staggering, and hence leads to a smooth curve even for an axial shape [see the $S(I)$ plot in Fig. 3].

From the above discussion the situation for the two bands in ^{106}Ag appears to suggest the coexistence of triaxial and axial shapes. This is an interesting observation since the quantal nature of chiral subsystems automatically demands that a chiral partner should have identical properties to an odd-odd triaxial rotational band. In ^{106}Ag, the data strongly suggest that we are observing a different (prolate) shape for the excited partner band (band 2). It is important to remember that similar properties for the two bands are expected only in certain ideal conditions when the two chiral formations have a sufficiently large potential barrier between them. For nuclei with smaller barriers, the rotation vector can tunnel across the two chiral wave functions and give rise to the phenomenon called chiral vibrations [2]. Furthermore, the nuclear shape should be sufficiently stable against these vibrations, otherwise the excited band, which corresponds to the one phonon state, may easily undergo a shape transformation. This could particularly be true in the case of ^{106}Ag where both the triaxial and axial prolate shapes are very close in energy.

The present work suggests that the two bands in ^{106}Ag are an example of the effect of large γ softness on the chiral geometry. In view of this it is interesting to examine the general systematics of the chiral nuclei in the $A \sim 100$ region. Figure 5 shows a plot of excitation energy, MOI, and quasiparticle alignments for the odd-odd nuclei studied to date in the $A \sim 100$ region. The nucleus ^{104}Rh, which is the only other nucleus showing near degeneracy in this mass region [4], has slightly different values of MOI and quasiparticle alignments, thereby suggesting the presence of slightly different shapes around the degeneracy region.

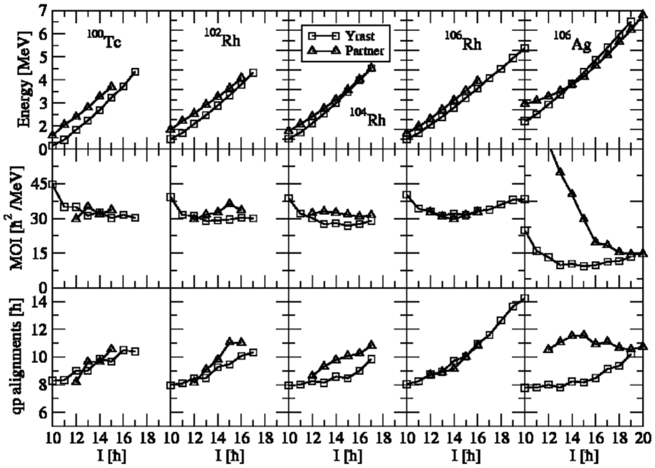

FIG. 5. Excitation energy, kinematic moments of inertia, and quasiparticle alignments as a function of spin for the doublet bands in odd-odd nuclei in $A \sim 100$ region.

On the other hand, ^{106}Rh shows an almost identical nature of the two bands in terms of their MOI as well as quasiparticle alignments, suggesting that they are true chiral partners and are least affected by the γ softness. This rapid change of the shape of the Rh isotopes with increasing neutron number has also been suggested from other studies [12].

From the above discussion we believe that there is evidence for two extreme types of doublet bands in the $A \sim 100$ region. The first type is best characterized by the pair of bands in ^{106}Rh where the two structures show very similar values of quasiparticle alignments as well as the MOI. The similar values of MOI clearly indicate a similarity of shape of the collective mean field while the similar quasiparticle angular momentum indicates a similarity of the intrinsic quasiparticle structure responsible for the two bands. This is very much supportive of the chiral and hence identical nature of the two bands. The second type of doublet band is characterized by the bands in ^{106}Ag where the two structures cross each other and hence suggests that they do not interact. In this case the two bands are found to possess very different MOI which suggests that they have different shapes. Moreover, the crossing or degeneracy is not due to the identical nature of the chiral wave functions but to the different nature of the wave functions for two different shapes. That is, the bands are still built on the same unique parity $\pi g_{9/2}^{-1} \times \nu h_{11/2}$ configuration, but the configurations will possess different K distributions. A detailed theoretical analysis of this complex picture is beyond the scope of the present Letter; however, these results provide new insight into our understanding of the origin of doublet bands.

A similar situation to that in ^{106}Ag has also been observed in the $A \sim 130$ region in the nucleus ^{134}Pr where two bands with very different MOI and quasiparticle alignments at the point of crossing have been observed. Recent lifetime measurements and other studies [13,14] in this nucleus provide direct evidence for different shapes for the two bands. One of these studies [13] suggests a new term ''dynamic-chirality'' to explain this phenomenon; however, this work seems to have overlooked the important requirement of the identical nature for the two bands at and around the crossing region.

In summary, the levels in nucleus ^{106}Ag were studied. These reveal a set of doublet bands of the same parity which are strongly connected to each other. An examination of these bands in the light of the systematics of chiral partner bands in the $A \sim 100$ region shows some marked differences from the ideal chiral behavior and suggests a strong influence of γ softness on the stability of the chiral geometry. As a result, the excited partner band (band 2) possesses properties which may be explained in terms of an axial nuclear shape, while for the yrast band the nucleus has a triaxial shape. A possible explanation for a planar axial rotational band as a partner to the triaxial yrast band can be shape transformation caused by the chiral vibrations resulting from a large degree of γ softness in this nucleus. In such γ-soft nuclei the one phonon chiral vibrational state, which is responsible for the excited band, may generate a transformation from a triaxial shape to an axial shape.

We thank the UK EPSRC and US NSF under Contract No. VUF 06/05 for the financial support, the ANL accelerator crew for producing the beam, and R. V. F. Janssens for assistance with the Gammasphere array.

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