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Experimental evidence for chirality in the odd-A ^{105}Rh

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Abstract

High-spin states in ^{105}Rh were populated by the ^{96}Zr(^{13}C, p3n) reaction at beam energies of 51 and 58 MeV, and studied using the EUROBALL IV γ-ray spectrometer and the DIAMANT charged particle array. A pair of nearly degenerate $\Delta I = 1$ three-quasiparticle bands with the same spins and parity have been observed. Comparison of the experimental results with tilted axis cranking calculations confirms the chiral character of the two bands, while arguments based on the excitation of particles within the $\pi g_{9/2}\nu(h_{11/2})^2$ configuration of the yrast band and comparison with the previously observed γ band exclude the other possible interpretations. This is the first experimental evidence for three-quasiparticle chiral structure in the A $\sim$ 100 region, and the first simultaneous observation of a γ band and chiral partner bands in one nucleus.

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A unique feature of triaxial nuclei is the possibility of uniform rotation around an axis which is out of the three symmetry planes of the mean-field ellipsoid. In this case the projections of the angular momentum vector on the three principal axes can form a left- or a right-handed system. The two possible linear combinations of these left- and right-handed systems manifest themselves as a pair of degenerate rotational bands [1,2]. Such chiral partner bands were first observed in the A $\sim$ 130 region in the odd–odd nuclei [3,4]. Recently chirality has also been reported in odd–odd nuclei in the A $\sim$ 104 Rh isotopes [5,6], thereby demonstrating that chiral features are of a general nature and not just related only to a specific mass region.

In odd–odd chiral nuclei one of the unpaired nucleons is a high-j particle-type, while the other is a high-j hole-type quasiparticle and they align their angular momenta with the short and the long axis, respectively, in order to minimize the interaction energy with the core. The core-rotation angular momentum is oriented along the intermediate axis because it has the largest moment of inertia. The above odd–odd systems present the simplest cases where substantial angular momentum components are oriented along all the three principal axes, which is necessary for nuclear chirality. Three perpendicular angular momentum components can, however, also be formed in more complex systems. For example, in three-quasiparticle configurations of odd-A nuclei, the two like valence nucleons can have a significant angular momentum component perpendicular to the angular momentum of the odd valence nucleon and to the rotational angular momentum of the triaxial core. In odd-A nuclei two types of chiral three-quasiparticle configurations can be expected. One is formed by a high-j hole and an aligned pair of high-j particles (type A), the second occurs when a low-j particle (which acts as a spectator) is coupled to the neighbouring odd–odd chiral configuration (type B).

The first evidence for chirality in a three-quasiparticle configuration was reported recently in ^{135}Nd [7] in a type A configuration. In this Letter, we report on the first observation of the type A chiral partner bands in odd–even ^{105}Rh nucleus in the mass 100 region. The chiral partner bands in ^{105}Rh involve a different configuration to that observed in ^{135}Nd, and therefore provide further support for the geometrical interpretation of the chirality observed in nuclei. Furthermore, the chiral partner band in ^{105}Rh is better developed experimentally than the band in ^{135}Nd. In the present work both the interconnecting M1 and the cross-over E2 transitions have been observed, thereby allowing a comparison to be made of the electromagnetic properties of the two bands. A γ band is also observed in ^{105}Rh, making this the first nucleus where the behaviour of the chiral bands and a γ band can be directly compared.

The observation of chiral partner bands of negative parity has been reported very recently for this nucleus by Alcántara-Núñez et al. [8]. The tentatively suggested configuration for these structures, $\pi g_{9/2}\nu h_{11/2}(g_{7/2}d_{5/2})$, can be understood as a combination of the $\pi g_{9/2}\nu h_{11/2}$ configuration, which is responsible for the chiral partner bands in the odd–odd neighbor ^{104}Rh [5], coupled with a normal parity low-j $(g_{7/2}d_{5/2})$ quasineutron, which according to the calculations, acts as a spectator. However, in such type B configurations, excitation of the spectator quasiparticle to the next available low-j state usually requires a relatively small amount of energy, thus in this case, nearly degenerate band structures with similar characteristics to the chiral partner bands can also be formed by quasiparticle excitation. Consequently it is difficult to prove experimentally that a type B chiral configuration exists, while the near degeneracy, electromagnetic properties and a comparison with the γ-band observed at low spins/excitation energies point clearly towards the chiral interpretation for the partner bands built on a type A configuration in ^{105}Rh as reported in the current Letter.

High-spin states in ^{105}Rh were populated using the ^{96}Zr(^{13}C, p3n) reaction at beam energies of 51 and 58 MeV. The ^{13}C beam, provided by the Vivitron accelerator at IReS, Strasbourg, impinged upon a stack of two targets, each having a thickness of 558 μg/cm^2 and being enriched to 86% in ^{96}Zr. The emitted γ-rays were detected by the EUROBALL IV spectrometer equipped with 15 Cluster and 24 Clover detectors at backward angles and around 90°, respectively, relative to the beam direction. Contaminants from the stronger (^{13}C, xn) reaction channels were eliminated using the highly efficient DIAMANT charged-particle detector array consisting of 88 CsI detectors [9,10] as an off-line filter. A total of $\sim 2\times 10^9$ triple- and higher-fold coincidence events were obtained and stored onto magnetic tapes, among which $\sim 5\times 10^7$ belonged to the ^{105}Rh reaction channel. The level scheme was constructed with the aid of the Radware analysis package [11] on the basis of the triple-coincidence relations, as well as energy and intensity balances of the observed γ-rays. A partial level scheme derived from the present experiment and a typical coincidence spectrum are shown in Figs. 1 and 2, respectively. Directional correlation from oriented states (DCO) ratios and linear polarizations [12–14] were derived for the transitions of sufficient intensity in order to determine their multipolarities. The observed values for key transitions are compared in Fig. 3(a), (b) with the values of different multipolarities and mixing ratios calculated for the experimental geometry. For the M1 + E2 multipolarity the plotted mixing ratios vary in the $-0.1 \leqslant \delta \leqslant 0.45$ range, while for the E1 + M2 multipolarity the plotted range is $-0.05 \leqslant \delta \leqslant 0.05$. The attenuation coefficients of incomplete alignment were fitted to strong transitions with known multipolarities in the calculations (see Fig. 3(c)).

Band 1 and the bottom part of band 4 were previously reported in Ref. [15] and the $\pi g_{9/2}$ and $\pi g_{9/2}\nu(h_{11/2})^2$ configurations have been assigned to them, respectively. In addition to the above two bands, bands 2 and 3 were also reported in Ref. [8]. They assigned band 2 as a γ-vibrational band, while the $\pi 1/2^+[431]$ configuration was assigned to band 3. The upper part of band 4, and band 5 were observed for the first time in the present work. In the level scheme construction, we have accepted the spins and parities for band 1 from Ref. [15] and determined the spins and parities of the other bands on the basis of the multipolarities of transitions connecting them to this band. The values obtained agree well with the assignments given in Refs. [8,15] for the previously known states. The spins and parities of band 5 are firmly established by the multipolarities of the linking 466, 821 and 1015 keV transitions. The 466 and 821 keV transitions have unambiguous $\Delta I = 1$ M1 + E2 multipolarity. Although the multipolarity of the 1015 keV transition could in principle be $\Delta I = 2$ E2 or M1 + E2 with $\Delta I = 0$, we accept the $\Delta I = 2$ E2 character because if we assume the second possibility then the expected branching ratios for states in band 5 would be inconsistent with the observed decay-out pattern, i.e., the spin I states of band 5 would decay systematically to the $I+1$ states of band 4 without there being any observed decay to the $I-1$ states. The latter decay to the $I-1$ states should, however, be strongly favoured by the energy of the corresponding transition. The linking 1015 and 466 keV transitions have been observed previously in Ref. [8]. The E2 multipolarity is in agreement with the spins and parities proposed in Ref. [8] for the initial and final states of the 1015 keV transition.

The experimental characteristics of bands 1 and 2 were compared with core-quasiparticle coupling calculations using the model described in Refs. [16,17]. The parameters of the rigid triaxial rotor core of Davydov–Filippov type [18] were adjusted to reproduce the available experimental data on ^{106}Pd [19]; core energies were fitted using the Variable Moment of Inertia model [20]. The coupling constant for the quadrupole–quadrupole interactions between the core and the odd proton, as well as the position of the proton Fermi level were adjusted to reproduce the experimental energies of states in band 1. Fig. 4(a), (b) shows that the model provides a good description of the two bands assuming a triaxial core with $\beta = 0.243$ and $\gamma = 26.5°$ rotating around the intermediate axis. According to the calculations, band 1 corresponds to the $\pi g_{9/2}$ configuration, while in band 2 this configuration is coupled to the γ band of ^{106}Pd. These assignments are in agreement with the assignments in Refs. [8,15] for band 1, and with the assignment for band 2 in Ref. [8].

Bands 4 and 5 form a $\Delta I = 1$ partner band structure which has similar characteristics to the best examples of the known chiral partner bands in the odd–odd nuclei, especially to the chiral bands in the neighbouring ^{104}Rh. Both bands have the same (positive) parity, and the energy difference between the same-spin states decreases with increasing spin from ~ 400 to ~ 50 keV (see Fig. 5). Their $B(\mathrm{M1}; I \to I-1)/B(\mathrm{E2}; I \to I-2)$ values are close to each other, and the difference between them is also diminishing

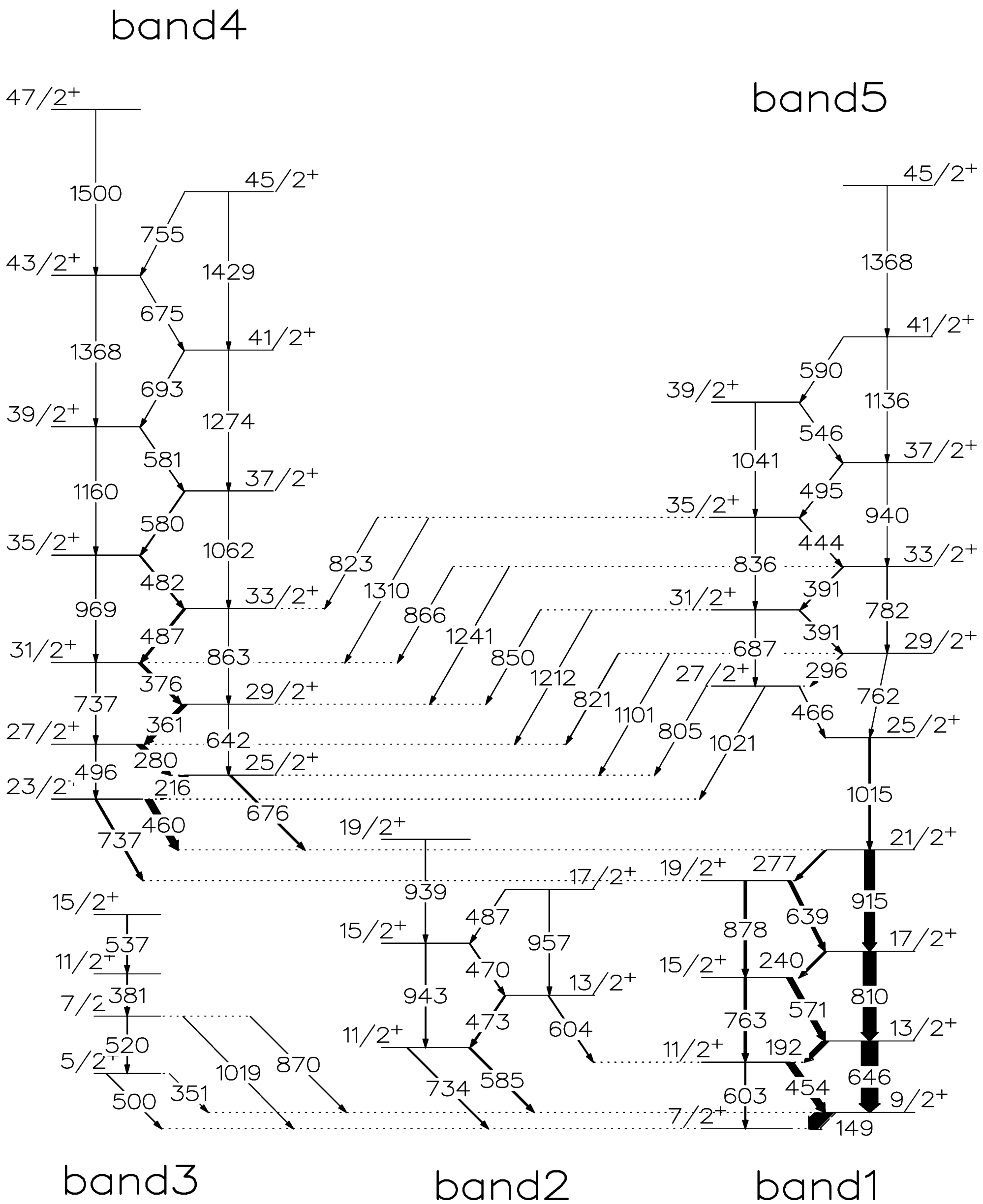

Fig. 1. Partial level scheme of ^{105}Rh obtained in the present work.

at the highest spins (see Fig. 5). Furthermore, there are strong M1 + E2 and E2 transitions from band 5 to the yrast band 4. These facts suggest that they have the same $\pi g_{9/2}\nu(h_{11/2})^2$ quasiparticle configurations. However, in order to assign chiral character to the two bands other possible explanations, which in principle could also result in a partner band structure, need to be excluded. There are two such possibilities. The first possibility is that one of the $h_{11/2}$ neutrons can be excited to the next $h_{11/2}$ Nilsson orbital in band 5, whilst the second is that band 5 is a γ band belonging to band 4. The first possibility can be excluded on the basis of the results of cranking calculations using a triaxially deformed Woods–Saxon potential. These

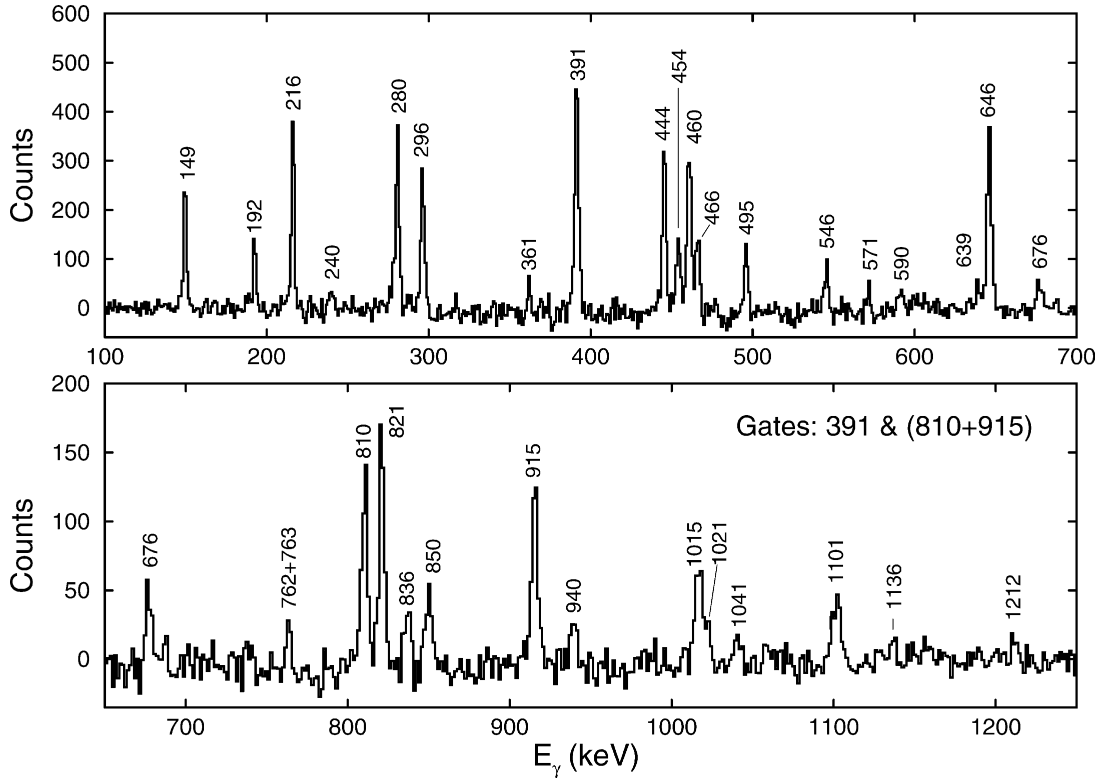

Fig. 2. Background subtracted γ–γ–γ coincidence spectrum showing the transitions which are in simultaneous coincidence with the 391 keV doublet in band 5 and either the 810 keV or the 915 keV transition in band 1.

calculations predict that the separation between the occupied and the lowest empty $h_{11/2}$ orbital increases constantly with increasing rotational frequency. This is clearly opposite to what is observed experimentally. Indeed, the calculated difference between the relevant $h_{11/2}$ orbitals increases to ~ 500 keV, which is almost an order of magnitude larger than the observed experimental separation between the two bands at the highest spins. The observation of a γ band (band 2) in ^{105}Rh allows us to estimate the behaviour of the γ band belonging to band 4. As it is shown in Fig. 4(c), the energy of the γ band is on average ~ 400 keV higher than that of band 1, and this energy difference does not decrease with increasing spin. This energy separation is also almost an order of magnitude larger than the observed energy difference between bands 4 and 5 at the highest spins. Based on these comparisons, we believe that chirality remains the only realistic possibility to explain the characteristics of the observed partner band structure.

To corroborate the observed chirality in ^{105}Rh, three-dimensional tilted axis cranking (TAC) calculations were performed for the $\pi g_{9/2}\nu(h_{11/2})^2$ configuration using the model described in Ref. [21]. The results of the calculations are presented in Table 1, where $\hbar\omega$ denotes the rotational frequency, and θ, ϕ denote the two polar angles of the rotational axis with respect to the principal axes of the triaxial core. The deformation parameters $\epsilon_2 = 0.224$, $\epsilon_4 = 0.004$, and $\gamma = 29^\circ$ were obtained as self-consistent values at $\hbar\omega = 0.25$ MeV and turned out to be weakly frequency dependent. These values are similar to the deformation parameters found in Ref. [8] for the configuration $\pi g_{9/2}\nu h_{11/2}(g_{7/2}d_{5/2})$. We carried out the TAC calculations assuming that the proton and neutron pairing is zero. According to the table, below $\hbar\omega = 0.55$ MeV the rotation axis lies in the plane spanned by the long and short axis. There, one expects two well separated bands, the zero and the one phonon chiral vibrational states [4]. At $\hbar\omega = 0.55$ MeV the

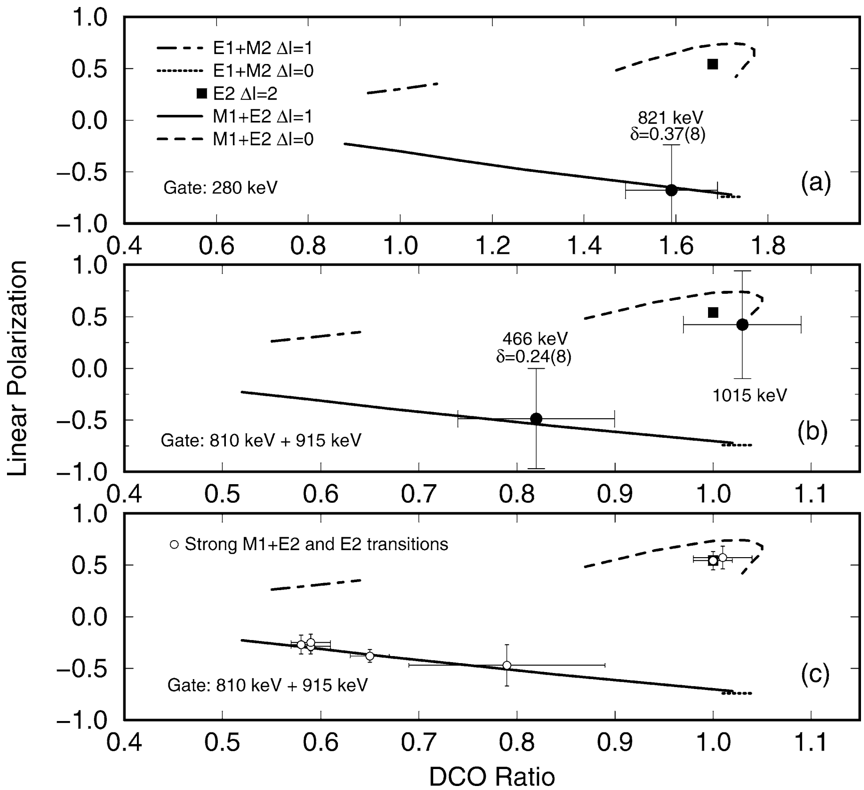

Fig. 3. (a), (b) Experimental (circles with X and Y error bars) and calculated (square and lines defined in the legend) DCO and linear polarization values for the key transitions determining the spins and parities in the new band 5 transitions; (c) similar data/calculations for known-multipolarity transitions.

solution becomes unstable and a second minimum appears which becomes yrast. In this second minimum the orientation of the rotation axis is aplanar ($\phi \neq 0^\circ$), thus it corresponds to stable chirality where two degenerate bands are expected with the same inband $B(\mathrm{M1})/B(\mathrm{E2})$ ratios [21]. The tunneling between the left-handed and the right-handed configurations is substantial in nuclei and makes the two bands less alike. The onset of chirality at $I \approx 21\hbar$ is visible in the upper panel of Fig. 6 as the increase of the slope of the curve $I(\omega)$. In the chiral regime the angular momentum grows due to the increase of its component along the intermediate axis, which has a larger moment of inertia than the short and the long axes, which provide the angular increment in the planar regime (cf. Fig. 4 in Ref. [1]). The experimental curve $I(\omega)$ of band 4 shows a comparable kink at $I \approx 20\hbar$. At this spin the energy difference between band 4 and 5 becomes as small as 120 keV. Since the rotational frequency is about 700 keV, the nucleus has turned 6 times before it has tunneled from the left-handed into the right-handed configuration, which may be considered as being sufficiently close to the static limit of weak tunneling. In the region $15 < I < 20$, the experimental curves $I(\omega)$ of the two chiral partners are shifted by about $1\hbar$, which is consistent with our interpretation of band 4 and 5 as zero and one phonon states of the soft chiral vibrational mode, respectively. The rotational and vibrational frequencies become about equal for $I \approx 16$. In this regime of soft vibration, the $B(\mathrm{M1})/B(\mathrm{E2})$ ratios need not to be equal. However, the experimental ratios seem to approach each other for $\hbar\omega > 0.5$ MeV, as expected for approaching the chiral regime.

The TAC calculations give too small values of ω for given I, which may indicate that zero pairing is a too extreme assumption. We have also carried out TAC calculations assuming a strong neutron pairing

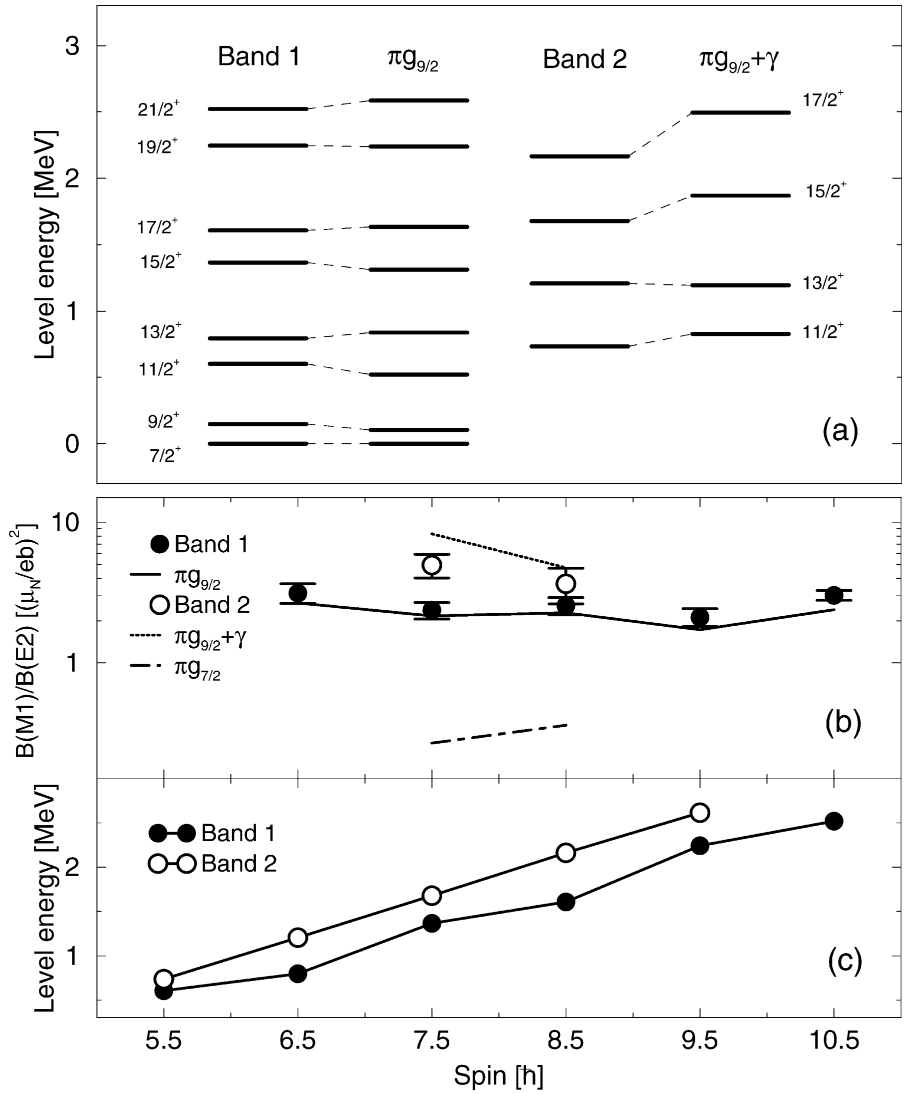

Fig. 4. (a) Experimental level energies and (b) $B(\mathrm{M1})/B(\mathrm{E2})$ ratios of bands 1 and 2 compared with the values calculated using the core-quasiparticle coupling model for the configurations shown. (c) Shows the energy separation between the bands 1 and 2 as a function of spin.

($\Delta_n = 1.39$ MeV). The results are presented in Table 1 and Fig. 6 as well. With this choice the calculated ω for given I is too high as compared to the experiment. Probably, weak dynamical pair correlations will generate a curve in between our two extreme ones, which would be close to experiment. In the considered case of strong pairing, the calculated onset of chirality at $I \approx 14$ seems to be too early. For $\hbar\omega > 0.475$ MeV, the rotational axis is predicted to move to the intermediate axis ($\theta = 90^\circ$, $\phi = 90^\circ$). This is due to a band crossing with a 5 quasiparticle configuration. Indeed, no band crossing has been observed in bands 4 and 5, pointing to a strong reduction of pairing. We tried to follow the three-qusiparticle chiral solution after the crossing as an excited configuration. However we were not able to identify it among the other excited configurations because of strong mutual interaction. Since assuming a weak pair field engraves this

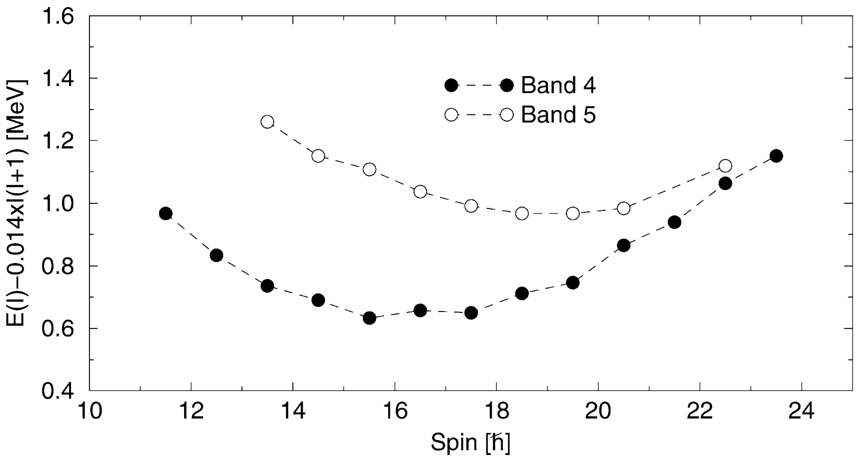

Fig. 5. Experimental energy separation between bands 4 and 5 obtained by subtracting a rigid rotor reference.

Table 1
Orientation angles and expectation values of the total angular momentum as a function of the rotational frequency from the TAC calculations. The horizontal line in the middle of the table separates the planar and aplanar solutions

$\hbar\omega$ [MeV]	θ	ϕ	$I(\omega)$ [$\hbar$]
Zero pairing			
0.15	72	0	13.2
0.20	72	0	14.2
0.25	73	0	15.2
0.30	73	0	16.1
0.35	74	0	17.0
0.40	74	0	17.9
0.45	74	0	18.7
0.50	75	0	19.6
0.55	76	0	20.4
0.60	76	0	21.3
0.65	78	0	22.3
0.70	79	0	23.3
0.75	79	0	24.2
0.55	75	0	20.4
0.60	75	18	21.6
0.65	80	29	23.3
0.70	80	34	24.4
0.75	85	40	25.8
Strong pairing			
0.25	69	0	12.5
0.35	69	0	13.5
0.45	74	0	14.5
0.45	79	20	14.9
0.475	74	34	15.7

problem we were not able to carry out such TAC calculations.

TAC permits us to calculate the electromagnetic transition rates only for a given chirality in a semiclassical way [22]. The tunneling mixes the left- and right-handed configurations, which distributes the semiclassical strength to intra-band and inter-band transitions of the chiral sister bands. To predict the distribution, one must calculate the tunneling. So far, the tunneling process has only be described in the framework of the model that couples two quasiparticles to a triaxial rotor [1,16,17]. Since a corresponding code for three quasiparticles was not at our disposal, we were not able to calculate how the strengths are distributed between intra- and inter-band transitions. For this reason we compared the ratios of the summed strengths $(B(\mathrm{M1}, 4 \to 4) + B(\mathrm{M1}, 4 \to 5))/(B(\mathrm{E2}, 4 \to 4) + B(\mathrm{E2}, 4 \to 5))$ and $(B(\mathrm{M1}, 5 \to 5) + B(\mathrm{M1}, 5 \to 4))/(B(\mathrm{E2}, 5 \to 5) + B(\mathrm{E2}, 5 \to 4))$ with the TAC calculations as given by the absolute square of the relevant matrix elements (see Ref. [22]). We note here, that the experimental summed strengths for band 4 are equal to the intra-band strengths, as no transitions were observed from band 4 to band 5. Above spin 19, the experimental ratios for the two bands agree as expected for static chirality and weak tunneling. The unpaired TAC calculations give slightly too large $B(\mathrm{M1})/B(\mathrm{E2})$ ratios. The inclusion of neutron pairing reduces the ratio and brings it closer to the

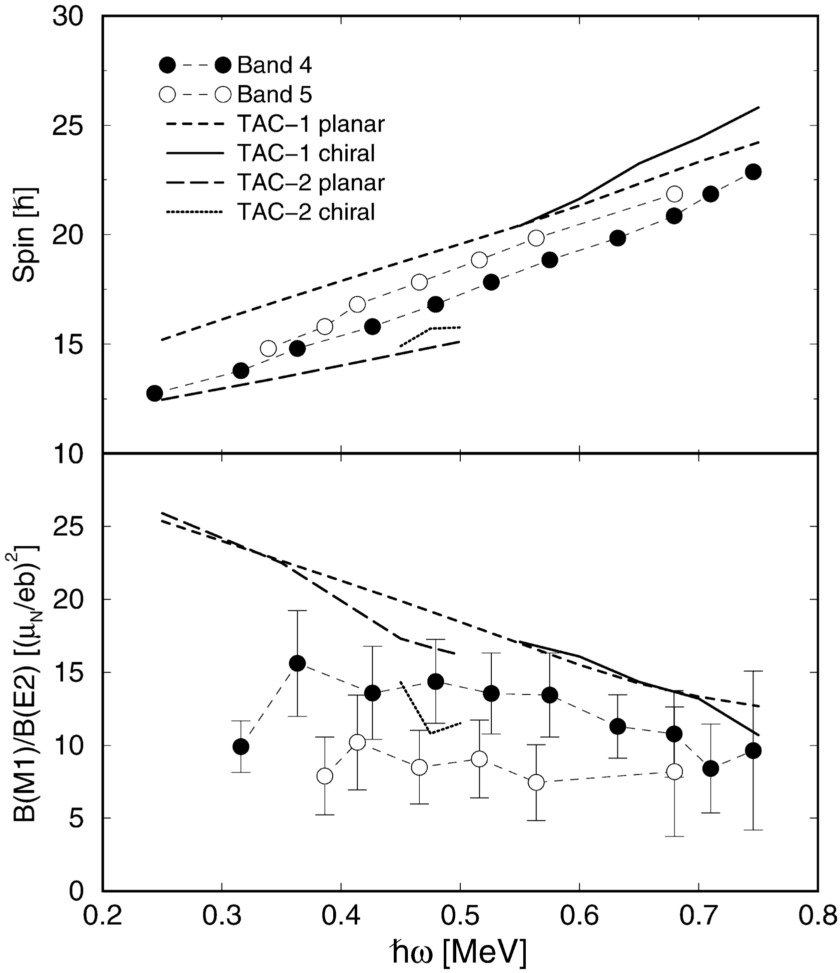

Fig. 6. Experimental and calculated total spin (top panel) and summed $B(\mathrm{M1}; I \to I-1)/B(\mathrm{E2}; I \to I-2)$ strengths, as defined in the text (bottom panel), for bands 4 and 5. TAC-1 and TAC-2 correspond to calculations without neutron pairing and with neutron pairing, respectively.

experiment for the chiral solution. However since it appears at a relatively low spin, the direct comparison with experiment is somewhat problematic. In the region $15 < I < 20$ of chiral vibration, the TAC calculation must be compared with the intra-band transitions of the zero-phonon state, i.e., band 4. The corresponding experimental $B(\mathrm{M1})/B(\mathrm{E2})$ ratios are the same as the ones for the summed strengths shown in Fig. 6. The unpaired TAC calculations give somewhat large ratios. The paired calculations come closer to the experiment, which may be another evidence for weak dynamical pair correlations. However, it should also be noted that one has to calculate rather accurately the deformation in order to reproduce the $B(\mathrm{M1})/B(\mathrm{E2})$ ratios. A separate comparison of the experimental $B(\mathrm{M1})$ and $B(\mathrm{E2})$ values with the TAC calculations would be more instructive. Hence a measurement of lifetimes seems highly desirable. We note here also that the TAC calculations predict $B(\mathrm{M1})/B(\mathrm{E2})$ ratio values for the planar and for the chiral scenarios close to each other compared to the experimental errors, thus they do not allow to distinguish between the two scenarios.

Studies of odd–odd nuclei in this region indicate that well defined chiral geometry exists in ^{104}Rh, and that this nucleus possesses the best chiral properties observed to date in odd–odd nuclei. Similarly, ^{105}Rh shows the best chiral properties observed so far in odd-A nuclei, indicating the importance of this region from the chiral studies point of view. The neighbouring odd–odd ^{106}Rh isotope shows the characteristics of chiral vibration [6]. The boundaries of this new region of chirality remain unexplored. Investigations of chirality based on three-quasiparticle structures similar to those observed in ^{105}Rh could provide a good means to map out these borders.

In summary, nearly degenerate $\Delta I = 1$ partner bands have been observed in ^{105}Rh. They are assigned as chiral partner bands. ^{105}Rh is the first odd-A nucleus in which the chiral nature of the partner band structure is supported also by the electromagnetic properties of the partner band, and by comparison of the behaviour of the partner band with a γ band. It belongs to the newly found A $\sim$ 104 chiral region where only chirality generated by a high-j particle and a high-j hole has been reported previously. The results provide strong support for the concept that chirality has a primarily geometric character, and hence it is not restricted to odd–odd nuclei.

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