Interpretation of the $\Delta I=2$ bands in $^{109}$In: possible antimagnetic rotation

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Two $\Delta I=2$ rotational bands were identified at CIAE, Beijing, using $^{100}$Mo($^{14}$N, 5n)$^{109}$In fusion-evaporation, however, their interpretation remains unclear. The systematic discussion has been made and the dynamic moment of inertia has been analyzed in this work. Furthermore, the $\Delta I=2$ rotational bands are compared with the tilted-axis cranking calculations based on a relativistic mean-field approach. The theoretical results based on the corresponding configuration, which involve the $1p1h$ excitation to the $\pi g_{7/2}$ orbital, show that $^{109}$In can be a candidate nucleus for antimagnetic rotation.

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I. INTRODUCTION

The rotational bands consisting of electric quadrupole transitions are usually related to the rotation of the deformed nucleus around an axis perpendicular to the symmetry axis of the deformed density distribution. With the development of theoretical and experimental research, a novel rotation has been found in weakly deformed or near-spherical nuclei, and is interpreted as a result of shears mechanism, i.e., the gradual closing of the angular momentum vector of relatively few high-$j$ proton particles ($j_p$) and high-$j$ neutron holes ($j_n$). Such kind of rotation is introduced as magnetic rotation considering that the magnetic moment is the order parameter inducing a violation of rotational symmetry. Up to now, numerous magnetic rotational bands have been observed in $A \sim 110$ mass region using the HI-13 tandem accelerator at the China Institute of Atomic Energy (CIAE), such as $^{106}$Ag, $^{107}$Ag, $^{112}$In, $^{113}$In, $^{115}$In, $^{118}$Cd, $^{119}$Cd, $^{120}$Cd, $^{121}$Cd, $^{122}$Cd, $^{123}$Cd, $^{124}$Cd.

Antimagnetic rotation (AMR) is also an exotic rotation observed in near-spherical or weakly-deformed nuclei $^{106}$In, $^{107}$In, $^{112}$In, $^{115}$In. The angular momentum is increased by simultaneous closing of the two blades of protons and neutrons toward the total angular momentum vector, which is so called “two-shears-like mechanism”. Because the transverse magnetic moments of the valence nucleons are anti-aligned, there are no $M1$ transitions in antimagnetic rotational bands. AMR is characterized by weak $E2$ transitions and decreasing $B(E2)$ values with increasing spin, which reflects the nearly spherical core. The large $j(2)/B(E2)$ ratio ($100 \ h^2 \text{MeV}^{-1} \text{e}^{-2} \text{b}^{-2}$), comparing with ($10 \ h^2 \text{MeV}^{-1} \text{e}^{-2} \text{b}^{-2}$) for well-deformed nucleus is also a typical feature.

The antimagnetic rotations are expected to be realized in the same mass region with magnetic rotation, and have been observed in the $A \sim 110$ mass region mostly. Especially for Cd isotopes, the positive parity yrast bands after the alignment of neutrons at sufficiently high frequencies are perfect candidates for the two-shears-like mechanism. Up to now, the antimagnetic rotational bands have been identified in $^{105}$Cd, $^{106}$Cd, $^{107}$Cd, $^{108}$Cd, $^{109}$Cd, $^{110}$Cd, $^{112}$Cd. In isotopes, when the additional proton is occupying the $g_{7/2}$ or $d_{5/2}$ orbitals, the “two-shears-like mechanism” can also be expected. In fact, the rotational bands in $^{108,110}$In, $^{112}$In and $^{115}$In have been taken as candidates for antimagnetic rotation.

In our previous work, the triaxial deformation, shape evolution, and possible chirality for the dipole bands in $^{109}$In were discussed in detail. However, it was unclear for the underlying nuclear structure of the $\Delta I=2$ bands. In this paper, two $\Delta I=2$ rotational bands in $^{109}$In are reinvestigated based on the systematic discussion. The experimental results are compared with the tilted axis cranking relativistic mean-field (TAC-RMF) approach. A candidate antimagnetic rotational band in $^{109}$In will be discussed.

II. EXPERIMENT AND RESULTS

The experiment was carried out using the HI-13 tandem accelerator at the China Institute of Atomic Energy...
Band 8

43/2$^+$ 8782.5

1143.4

39/2$^+$ 7639.1

973.0

35/2$^+$ 6666.1

816.3

31/2$^+$ 5849.8

631.1

27/2$^+$ 5218.7

463.0

23/2$^+$ 4755.7

658.6

19/2$^+$ 4097.1

941.6

15/2$^+$ 3155.5

837.0

11/2$^+$ 2318.5

1099.6

13/2$^+$ 1218.9

1428.3

9/2$^+$ 1026.3

0.0

Band 7

Band 7

(45/2$^+$) 8979.8

1000.4

41/2$^+$ 7979.4

886.2

37/2$^+$ 7091.2

829.6

33/2$^+$ 6261.6

864.8

29/2$^+$ 5396.8

443.6

25/2$^+$ 4499.2

443.6

21/2$^+$ 4299.2

4749.8

17/2$^+$ 804.8

469.7

27/2$^-$

FIG. 1: Partial level scheme of $^{109}$In proposed in our previous work [28].

Band 8 is a weakly populated decoupled band and was interpreted as a rotational band built on the $1p1h$ proton excitation from the $\pi g_9/2$ to the $\pi g_7/2$ orbital, i.e., the $1p2h \pi g_9/2 g_7/2$ configuration. Similar bands observed in $^{107,111,113}$In [13, 29, 30] are summarized in Fig 2. Even though the bandhead of band 8 in $^{109}$In and several corresponding levels in $^{107}$In have not been observed, the isotopic regularity of the level energies is significant. It is worth noting that the excitation energies of $1p1h$ proton excitation from $g_9/2$ to $g_7/2$ orbital in $^{111,113}$In are within 1~2 MeV relative to the ground state, and decreases with the increasing neutron number. The $7/2^+$ was not observed in $^{109}$In, but the excitation energy of this state should be less than 2318.5 keV, which is the energy of $11/2^+$ state. The proton-neutron residual in-

(CIAE) in Beijing. Excited states in $^{109}$In were populated using the $^{100}$Mo($^{14}$N, 5$n$)$^{109}$In fusion-evaporation reaction at beam energy of 78 MeV. The target consists of a 0.5 mg/cm$^2$ foil of $^{100}$Mo with a backing of 10 mg/cm$^2$-thick $^{197}$Au. The $\gamma$ rays were detected by an array composed of nine BGO-Compton-suppressed HPGe detectors, two low-energy photon (LEP) HPGe detectors, and one clover detector. A total of $84 \times 10^6 \gamma-\gamma$ coincidence events were recorded in an event-by-event mode. The data were sorted into a fully symmetrized $E_\gamma E_\gamma$ matrix and an asymmetric DCO matrix to obtain the $\gamma$-ray coincidence relationship and the multipolarities of $\gamma$-rays. The level scheme of $^{109}$In was extended by 46 new $\gamma$ rays.

The partial level scheme focused on the $\Delta I=2$ bands in $^{109}$In is redrawn in Fig. 1. Band 7 is built upon the $21/2^{(+)}$ state with excitation energy of 4299.2 keV, and extended to $(45/2^{+})$ state at energy of 8979.8 keV. It decays out through $\gamma$-rays with energies of 1304.2, 893.0 and 673.7 keV to the well known $13/2^+_2$ state at 1428.3 keV. The spins of the levels in band 7 can be determined experimentally. Although band 7 links to a negative-parity band (band 5) through the $\gamma$-ray with energy of 469.7 keV, band 7 feeds mostly to the positive-parity states. Thus band 7 is most likely a positive parity band. Band 8 consists of eight $\Delta I=2$ transitions and is extended to the $43/2^{(+)}$ state at 8782.5 keV. With the help of the linking 475.9-keV transition, which connects band 8 to band 7, the spins of the levels in band 8 can be determined, and most likely the parity is positive. Due to the weak intensity of the 1099.6-keV transition, the spin of level at 1218.9 keV could not be determined. Furthermore, the energy of the transition from $11/2^+$ state to a supposed $7/2^+$ state should be much smaller than 1099.6 keV according to the systematics comparison, as will be discussed below. Therefore the $\gamma$-ray with energy of 1099.6 keV should not be an intraband transition of band 8. A detailed description of the experiment and level scheme can be found in Ref. [28].

A. Band 8

Band 8 is a weakly populated decoupled band and was interpreted as a rotational band built on the $1p1h$ proton excitation from the $\pi g_9/2$ to the $\pi g_7/2$ orbital, i.e., the $1p2h \pi g_9/2 g_7/2$ configuration. Similar bands observed in $^{107,111,113}$In [13, 29, 30] are summarized in Fig 2. Even though the bandhead of band 8 in $^{109}$In and several corresponding levels in $^{107}$In have not been observed, the isotopic regularity of the level energies is significant. It is worth noting that the excitation energies of $1p1h$ proton excitation from $g_9/2$ to $g_7/2$ orbital in $^{111,113}$In are within 1~2 MeV relative to the ground state, and decreases with the increasing neutron number. The $7/2^+$ was not observed in $^{109}$In, but the excitation energy of this state should be less than 2318.5 keV, which is the energy of $11/2^+$ state. The proton-neutron residual in-
interaction may play an important role in 1p1h excitation from $\pi g_{9/2}$ to $\pi g_{7/2}$ orbital at such low energy. It reduces the energy spacing between the $\pi g_{9/2}$ and $\pi g_{7/2}$ orbitals, and its impact is enhanced when more neutrons are occupying the midshell.

Angular momenta as a function of rotational frequency $\hbar\omega$ for those bands in $^{107,109,111,113}$In are shown in Fig. 2. Sharp backbends associated to the alignment of a pair of $h_{11/2}$ neutrons are evident at nearly 0.35 MeV/$\hbar$ for the rotational bands in $^{109,111,113}$In. After the backbend, the angular momenta of the rotational bands in $^{109,111,113}$In increase with the rotational frequency gradually and show a similar pattern with that of $^{107}$In. The regularity of those rotational bands in $^{107,109,111,113}$In further support the configuration assignment of band 8 in $^{109}$In. Therefore, the configuration of band 8 is assigned as $\pi[2g_{9/2}^2g_{7/2}]$ before the backbend and $\pi[2g_{9/2}g_{7/2}]\otimes\nu(h_{11/2})^2$ after backbend.

As mentioned above, the rotational bands arisen from the excitation of one proton across the shell-gap in odd-$A$ indium isotopes exhibit strong regularity. Such rotational bands have also exhibited rich structural information, for example, rotational bands in $^{108,110,112}$In have been identified as candidates for antimagnetic rota-

![Graph showing rotational bands involving the $\pi g_{7/2}$ orbital in $^{107,109,111,113}$In. Ground states of $9/2^+$ are shown as references.](image)

**FIG. 2:** Rotational bands involving the $\pi g_{7/2}$ orbital in $^{107,109,111,113}$In. Ground states of $9/2^+$ are shown as references.

The typical antimagnetic rotational bands in $^{106,108,109,110}$Cd, $^{106,108}$Sn 

The dynamic moment of inertia $\mathcal{J}^{(2)}$ is a sensitive probe of the nuclear collectivity. The $\mathcal{J}^{(2)}$ and rotational frequency can be extracted experimentally,

$$\hbar\omega_{\exp} = \frac{1}{2} E_\gamma(I \rightarrow I - 2)$$

$$\mathcal{J}^{(2)} \approx \frac{dI}{d\omega} = \frac{4}{E_\gamma(I + 2 \rightarrow I) - E_\gamma(I \rightarrow I - 2)}$$

$\gamma$ of band 8 in $^{109}$In is shown in Fig. 4. The typical antimagnetic rotational bands in $^{106,108,109,110}$Cd, $^{106,108}$Sn, $^{109}$Sb are also shown for comparison. As for smooth terminated bands, the nuclei undergo a smooth transition from a collective prolate shape at low rotational frequencies to a non-collective particle-hole oblate shape. Such reduction in collectivity leads to a decrease in the dynamic moment of inertia. As shown in Fig. 4, $\mathcal{J}^{(2)}$ decreases with increasing rotational frequency for the smoothly terminating bands in $^{107}$In, $^{108}$Sn, $^{109}$Sb. For band 8 after backbend in $^{109}$In, $\mathcal{J}^{(2)}$ stays around 23 MeV$^{-1}$h$^2$ as increasing rotation frequency and has a similar pattern with that of AMR bands in $^{106,108}$Cd. Such small and stable value of $\mathcal{J}^{(2)}$ indicates that band 8 after backbend in $^{109}$In is much less collective, and may be a candidate antimagnetic rotational band.

**B. Band 7**

The $1p1h$ excitation from $\pi g_{9/2}$ to $\pi d_{5/2}$ orbital is also expected for indium isotopes though it is unfavored comparing to the $\pi g_{7/2}$ orbital, considering the $-\omega_{js}$ term in the cranking Hamiltonian. Collective bands built on the $1p1h$ excitation from $\pi g_{9/2}$ to $\pi d_{5/2}$ orbital have been observed in isotope $^{111}$In in which the configuration

**FIG. 3:** (Color online) Angular momentum as a function of rotational frequency $\hbar\omega$ for bands involving the $\pi g_{7/2}$ orbital in $^{107,109,111,113}$In.
of band 1 in $^{111}$In is suggested as $\pi g_9/2d_5/2$ and band 2 is interpreted as a mixing of $\pi g_7/2$ and $\pi d_5/2$ orbitals.

In order to qualitatively understand the structure of band 7 in $^{109}$In, the angular momentum as a function of rotational frequency for band 7 is shown in Fig. 5 together with that of band 1 and band 2 in $^{111}$In. The angular momentum of band 7 has an initial value of around $13 \hbar$ and increases with the rotational frequency. Band 2 in $^{111}$In has a small initial angular momentum, which increases rapidly with the rotational frequency before the backbend. Backbends occur for band 7 in $^{109}$In and band 2 in $^{111}$In at around $0.43 \text{ MeV}/\hbar$. The backbends at nearly same rotational frequency usually indicate the similar change of the intrinsic structure, so that band 7 after backbend in $^{109}$In may invoke a mixing of $\pi d_5/2$ and $\pi g_7/2$ orbitals as band 2 in $^{111}$In. Band 7 before the backbend has been suggested as $\pi d_5/2g_9/2 \otimes \nu h^2_{11/2}$ with the help of aligned angular momenta [28]. Nevertheless, the limited extent for band 1 of $^{111}$In restricts the comparison, no convincing conclusion can be made for the configuration of band 7 before the backbend.

III. THEORETICAL INTERPRETATION

In the following, the structure of rotational bands in $^{109}$In are investigated by tilted axis cranking relativistic mean-field (TAC-RMF) approach. In contrast to its non-relativistic counterparts, the CDFT, including relativistic mean-field (RMF) framework with point-coupling or mesonic exchange interaction, takes the fundamental Lorentz symmetry into account from the very beginning so that naturally takes care of the important spin degree of freedom, resulting in great successes on many nuclear phenomena [18, 33, 37, 40]. Moreover, without any additional parameters, the rotation excitations can be described self-consistently with the tilted axis cranking relativistic mean-field (TAC-RMF) approach [17, 18]. In particular, the TAC-RMF model has been successfully used in describing magnetic rotation (MR) and AMR microscopically and self-consistently in $A \sim 60, 80, 130$ and 190 regions [17, 18], and especially the 110 region, such as the AMR bands in $^{105,109,110}$Cd [41, 42] and $^{108,110,112}$In [23, 27], and also the MR bands in $^{113,115}$In [13, 46]. In the present TAC-RMF calculations, the point-coupling interaction PC-PK1 [47] is used for the Lagrangian without any additional parameters. A basis of 10 major oscillator shells is adopted for the solving of the Dirac equation and pairing correlations are neglected. In order to describe band 8 and band 7 in $^{109}$In, the configuration $\pi g_7/2g_9/2 \otimes \nu h^2_{11/2}$ and $\pi(g_7/2d_5/2)^1 g_9/2 \otimes \nu h^2_{11/2}$ are adopted in the TAC-RMF calculations respectively.
The calculated results for the $\pi g_{9/2}^2 g_{7/2} \otimes \nu h_{11/2}^2$ configuration are shown in Fig. 6 in comparison with the experimental data for band 8 after the backend. For a direct comparison, the angular momentum $J$ is defined as $J = I - 1/2$. It could be seen that the TAC-RMF calculations based on the assigned configuration are in a good agreement with the experimental data, supporting the configuration assignment.

After the backend in band 8, the calculated $3J(2)$ well reproduce the data and the $3J(2)$ values are around 20-25 MeV$^{-1}h^2$, which are much smaller than the typical values ($\sim 35$ MeV$^{-1}h^2$) for the $A = 110$ rigid spherical rotor. This indicates that band 8 is not based on a collective behavior, but is most likely based on antimagnetic rotation, as discussed in Section II A.

Typical characteristics of AMR include weak $E2$ transitions, reflecting the small deformation of the core and resulting in large ratios of $3J(2)$ to the reduced transition probability $B(E2)$ values. Moreover, the $B(E2)$ values rapidly decrease with the angular momentum. The $B(E2)$ and $3J(2)/B(E2)$ ratios as functions of the rotational frequency in the TAC-RMF calculations for the assigned configurations are given respectively in the upper and lower panels of Fig. 7. $B(E2)$ value decreases smoothly with the increasing rotational frequency, while the $3J(2)/B(E2)$ ratio shows an increasing tendency. In addition, the calculated $3J(2)/B(E2)$ ratios are around 100 - 120 $h^2$MeV$^{-1}e^{-2}b^{-2}$, which is about an order of magnitude larger than that for a typical deformed rotational band ($\sim 10$ $h^2$MeV$^{-1}e^{-2}b^{-2}$ [14]) and is also in agreement with characteristic properties of AMR bands [26, 27, 41].

The decrease of the $B(E2)$ value can be understood by the evolution of the nuclear deformation. As shown in the inset of Fig. 7 (a), with increasing rotational frequency, the nucleus undergoes a slow and small decrease of $\beta$ deformation with a rather small triaxiality ($\gamma \leq 10^\circ$). Indeed, it could been seen that the decrease of $\beta$ will result in the decreasing tendency of $B(E2)$.

In order to examine the two-shears-like mechanism for the band, showing in Fig. 8 are $J_{π^+\nu}$ (the angular momentum vectors of neutrons and the low-Ω $g_{7/2}$ proton) and $j_{π}$ (the two high-Ω $g_{9/2}$ proton holes) at rotational frequencies from 0.2 to 0.6 MeV. The angular momentum $J_{π^+\nu}$ is related to all the neutron levels and the occupied low-Ω $g_{7/2}$ protons in the intrinsic system. At the bandhead ($\hbar\omega = 0.2$ MeV), the two $j_{π}$ are nearly perpendicular to $J_{π^+\nu}$ and pointing opposite to each other, which form the blades of the two shears. As the rotational frequency increases, the gradual alignment of the $g_{9/2}$ proton hole vectors $j_{π}$ toward $J_{π^+\nu}$ generates angular momentum, while the direction of the total angular momentum stays unchanged. This leads to the closing of the two shears simultaneously by moving one blade toward the other, demonstrating the two-shears-like mechanism in band 8.

The TAC-RMF calculations for band 7 have also been performed. In the TAC-RMF calculation for band 8 with configuration $\pi g_{7/2} g_{9/2} \otimes \nu h_{11/2}^2$, the proton above $Z = 50$ shell occupies the lowest orbit of $g_{7/2}$ subshell, and the main component of proton wave function belongs to $\pi g_{7/2}$. Different from that, in the calculation for band 7 with configuration $\pi (g_{7/2}d_{5/2})^1 g_{9/2} \otimes \nu h_{11/2}^2$, the proton above $Z = 50$ shell occupies another orbit and there is no main component due to the strong configuration mixing between $g_{7/2}$ and $d_{5/2}$ orbitals. In Fig. 9 the cal-

![FIG. 7: $B(E2)$ values (a) and $3J(2)/B(E2)$ ratios (b) as functions of the rotational frequency in the TAC-RMF calculations for the assigned configurations. Insert: Deformation parameters $\beta$ and $\gamma$ driven by the increasing rotational frequency in the TAC-RMF calculations. The arrow indicates the increasing direction of the rotational frequency.](image)

![FIG. 8: Angular momentum vectors of neutrons and the low-Ω $g_{7/2}$ proton, $j_{π}$, and the high-Ω $g_{9/2}$ proton holes, $j_{π^+\nu}$, at rotational frequencies from 0.2 to 0.6 MeV.](image)
calculation results based on the $\pi (g_7/2 d_5/2) v h_{11/2}^2$ configuration, including excitation energies, angular momenta, $B(E2)$ values and deformation parameters, are shown together with the corresponding data. It should be noted that we could not find converged results for $h \omega < 0.32$ MeV based on the $\pi (g_7/2 d_5/2) v h_{11/2}^2$ configuration, due to the level crossing as discussed in Ref. [3].

It could be seen that the energies and the angular momenta in the TAC-RMF calculations achieve good agreement with the data for $I < 37/2$, supporting the configuration assignment. The $B(E2)$ values show a decreasing tendency with increasing rotational frequency, which corresponds to the decrease of $\beta$ deformation with a small triaxiality in the calculations. While for the data with $I \geq 37/2$, there might be an additional excitation responsible for the large aligned spin.

FIG. 9: Energy spectrum (a), angular momenta (b), $B(E2)$ values and deformation parameters (c) obtained from the TAC-RMF calculations in comparison with available data. The arrow indicates the direction towards increasing rotational frequency.

**IV. SUMMARY**

In summary, two $\Delta I = 2$ rotational bands populated in the $^{100}$Mo($^{14}$N, $5n$)$^{109}$In reaction have been investigated. The rotational bands arise from the excitation of the proton from the $\pi g_{9/2}$ to $\pi g_7/2$ orbital in odd-A indium isotopes exhibit strong regularity, and the dynamic moment of inertia shows that band 8 after backbend is much less collective. The configuration of band 8 is assigned as $\pi [g_{9/2} g_{7/2}]$ before the backbend and $\pi [g_{9/2} g_{7/2}] \otimes \nu (h_{11/2})^2$ after backbend.

The experimental data of the $\Delta I = 2$ rotational bands in $^{109}$In have been compared with the TAC-RMF calculations, and good agreement has been obtained. The predicted $B(E2)$, deformation $\beta$ and $\gamma$, as well as $\bar{J}^2 / B(E2)$ ratios in TAC-RMF calculations based on the $\pi g_{9/2} g_{7/2} \otimes h_{11/2}^2$ configuration have been discussed and the characteristic features of AMR for the band after the backbend have been shown. The two-shears-like mechanism for band 8 shows that it can be a candidate antimagnetic rotational band. Further experimental investigation such as life-time measurements are expected for a conclusive interpretation.

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