Physics Letters B 828 (2022) 137010

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Probing the nature of the conjectured low-spin wobbling bands in atomic nuclei

S. Guo [a,b], X.H. Zhou [a,b,*], C.M. Petrache [c], E.A. Lawrie [d,e], S.H. Mthembu [d,e], Y.D. Fang [a,b], H.Y. Wu [f], H.L. Wang [g], H.Y. Meng [g], G.S. Li [a,b], Y.H. Qiang [a,b], J.G. Wang [a,b], M.L. Liu [a,b], Y. Zheng [a,b], B. Ding [a,b], W.Q. Zhang [a,b], A. Rohilla [a,b], K.R. Muhki [a,b], Y.Y. Yang [a,b], H.J. Ong [a,b], J.B. Ma [a,b], S.W. Xu [a,b], Z. Bai [a,b], H.L. Fan [h], J.F. Huang [i], J.H. Li [a,b], J.H. Xu [a,b], B.F. Lv [a,b], W. Hua [j], Z.G. Gan [a,b], Y.H. Zhang [a,b]

[a] *Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[b] *School of Nuclear Science and Technology, University of Chinese Academy of Science, Beijing 100049, China*
[c] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[d] *iThemba LABS, National Research Foundation, PO Box 722, 7131 Somerset West, South Africa*
[e] *Department of Physics & Astronomy, University of the Western Cape, P/B X17, Bellville ZA-7535, South Africa*
[f] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[g] *School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, China*
[h] *College of Engineering Physics, Shenzhen Technology University, Shenzhen 518118, China*
[i] *Guangzhou Municipal Ecological Environment Bureau Huadu District Branch, Guangzhou 510800, China*
[j] *Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, Zhuhai 519082, China*

A R T I C L E I N F O

Article history:
Received 24 September 2021
Received in revised form 3 February 2022
Accepted 2 March 2022
Available online 10 March 2022
Editor: B. Blank

Keywords:
Nuclear reaction: ^{175}Lu(^{18}O,6n)^{187}Au
Precession
Wobbling
Angular correlations
Linear polarization
Model calculation

A B S T R A C T

The precession of an atomic nucleus can be approximately described as wobbling motion, arising from the coupling of a rotation and a harmonic vibration. Recently, a number of wobbling bands were reported at low spin, which violate the wobbling approximation that can be valid only at high spin. In the present work, we explore the nature of the reported low-spin wobbling bands. Via a new experiment including both angular correlation and linear polarization measurements, we demonstrate that one such band in ^{187}Au is generated by dominant single-particle excitation rather than by the excitation of a wobbling phonon. Assessing the experimental proofs and discussions to assign the reported low-spin wobbling bands, we further point out that the imperfect research paradigm used previously would lead to unreliable identification of low-spin wobbling bands.

Precession is well known as a motion of a macroscopic rigid body, where its rotational axis describes a cone around a fixed direction. Actually, it appears in quite different scenes such as atomic nuclei of many-body quantum microscopic systems, for which the external force can be neglected and the moments of inertia are between hydrodynamic and rigid types. Nuclear precession was predicted by Davydov and Filippov [1], and described as nuclear wobbling in an approximate way by Bohr and Mottelsson [2]. When a triaxially deformed nucleus precesses, one of the three principal nuclear axes plays the role of the axle, and rotates around the space-fixed angular momentum. In the body-fixed frame of a nucleus, one can observe the precession of the angular momentum. As shown in Fig. 1, nuclear precession occurs when the rotational angular momentum R' is not oriented along a principal nuclear axis (shown with dashed line), but is tilted away and precesses. The total angular momentum J' resulting from the coupling of R' and the single-particle angular momentum j also precesses around the nuclear axis. Within the wobbling approximation, wobbling phonons are introduced to describe a quantized small-angle deviation of the axle with respect to the direction of J'. Such approximation is only valid at high spin, where it can be regarded as a harmonic vibration. At low spin, the deviation angle is too large to satisfy the wobbling approximation, and therefore the description

* Corresponding author at: Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail address: zxh@impcas.ac.cn (X.H. Zhou).

https://doi.org/10.1016/j.physletb.2022.137010
0370-2693/

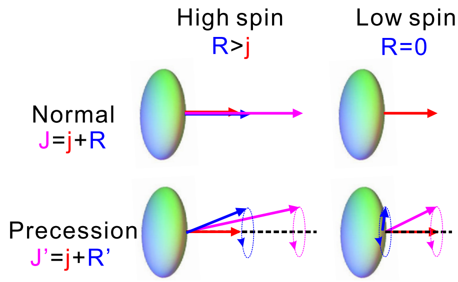

Fig. 1. Angular momentum geometry of nuclear precession. Normal (upper) and precession (lower) modes for high-spin (left) and low-spin (right) systems are sketched in the body fixed frame of an odd-A triaxial nucleus.

of the rotational bands in terms of wobbling phonon excitations is invalid.

Nuclear wobbling was first reported in the 160-mass region, where all identified wobbling bands were observed at high spin [3–8]. However, a number of rotational bands were interpreted recently as wobbling excitations at low spin [9–15]. These bands were described as transverse or longitudinal wobbling by Frauendorf and Dönau [16], which is achieved when the angular momentum of the odd quasiparticle is rigidly aligned with one of the principal axes of the rotating triaxial core. The spins of the lowest observed states in most of those bands are $J = j + 1$, where j is the angular momentum of the single quasi-particle (see Fig. 1). This means that in such low-spin states the wobbling motion can occur for an extremely slow collective rotation (R'). However, this is in contradiction with the approximation condition for wobbling motion, which requires large angular momentum, as pointed out by Bohr and Mottelsson for even-even nuclei [2] and by Frauendorf and Dönau for odd-mass nuclei [16], and recently demonstrated in the work of Lawrie et al. [17].

It is therefore necessary to explore the true excitation mechanisms generating the low-spin bands interpreted as wobbling excitations. The reported longitudinal wobbling band in ^{187}Au is re-investigated in the present work, since the assignment seems contradictory. The geometry of the longitudinal wobbling cannot be fulfilled for $h_{9/2}$ bands in ^{187}Au, since the proton Fermi surface is near the bottom of the intruder $h_{9/2}$ subshell [18], while for longitudinal wobbling the quasi-proton should stay at the middle of a j-shell [14].

In order to unveil the nature of the low-spin bands in ^{187}Au, an experiment was carried out at the Heavy Ion Research Facility in Lanzhou (HIRFL) [19,20], China. The excited states of ^{187}Au were populated using the ^{175}Lu(^{18}O,6n) reaction with a 108-MeV ^{18}O beam and a stack of two self-supported natural Lu targets with a thickness of 0.7 mg/cm^2 each. The γ rays were detected with a detector array consisting of 8 segmented clover detectors and 16 coaxial High-Purity Germanium (HPGe) detectors. Eight of the HPGe detectors were equipped with anti-Compton shields. All clover detectors were placed in a ring perpendicular to the beam direction. The 16 HPGe detectors were placed in four rings at 26°, 51°, 129° and 154° with respect to the beam direction. Approximately, 5×10^{10} double- or higher-fold events were recorded using a general-purpose digital data acquisition system [21].

Fig. 2a shows a partial level scheme of ^{187}Au built in the present work, together with a partial level scheme of ^{188}Pt. Bands 1-4 established in previous work [18,22] are confirmed. The structure in pink was reported in Ref. [14], and interpreted as the unfavored signature branch of the $\pi h_{9/2}$ band (Band 1) in ^{187}Au. It is worth noting that the 265-, 405-, 412-, and 549-keV transitions have very similar energies to those of the 265-, 405-, 414-, 551-keV transitions of ^{188}Pt [23] (the sequence in green in Fig. 2a), which is also populated in the reaction. Our data show no sign for the existence of the previously proposed 429- and 437-keV link-

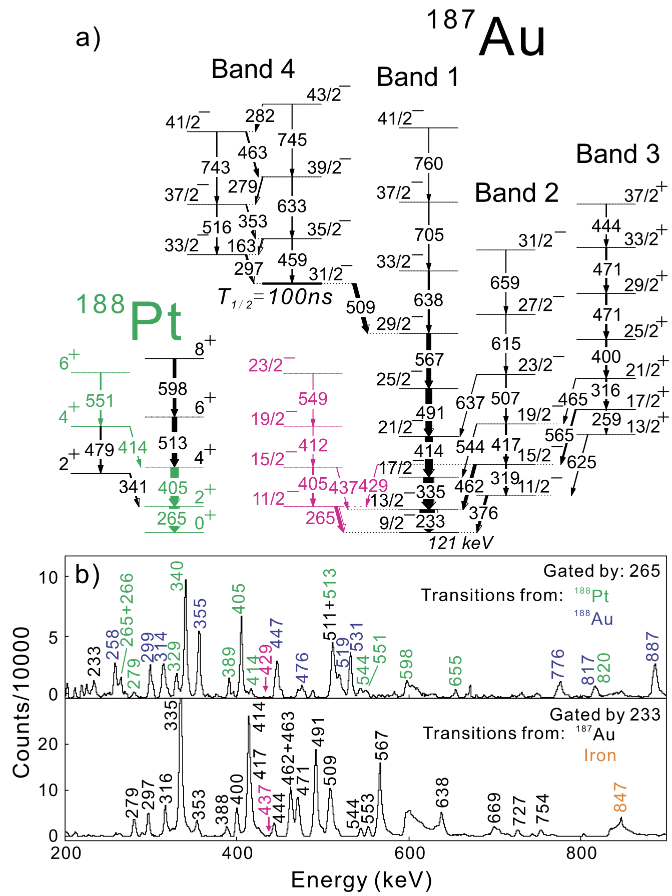

Fig. 2. a): Partial level scheme of ^{187}Au and ^{188}Pt. The structure in pink was reported in Ref. [14], but not observed in the present data. Instead, a similar sequence in green was assigned to ^{188}Pt. b): Spectra gated by the 265- and 233-keV transitions.

ing transitions, as shown in Fig. 2b. In addition, this structure was not identified in the detailed β-decay study of ^{187}Ag performed by Rupnik et al. [24], in which plenty of excited states in ^{187}Au with spin up to $I = 19/2$ were observed. If this band did belong to ^{187}Au and did have the features reported in Ref. [14] in terms of quasi-particle configuration, spin, parity, and very low excitation energy, it would be present in our data and would have been observed by Rupnik et al. [24].

Band 2 was first proposed as the unfavored signature branch of Band 1 built on a single-particle excitation [18], but interpreted later as a collective wobbling band [14]. Band 2 consists of a series of excited states with spin increasing in steps of 2, and decays to Band 1 via several $\Delta I = 1$ transitions. Usually, $\Delta I = 1$ transitions are mixed, with mainly electric quadrupole (E2) and magnetic dipole ($M1$) components, in proportion described by the $E2/M1$ mixing ratio (δ). If Band 2 is a wobbling band, the $\Delta I = 1$ transitions are expected to be dominated by the $E2$ components, giving rise to larger than one absolute values of δ. This is contrary to the expectation of $M1$ dominated character of the transitions between signature partner branches.

In this work, the δ values of the transitions linking Band 2 to Band 1 were determined using two complementary measurements of a two-point angular correlation ratio, R_{ac}, and of linear polarization, P. R_{ac} was deduced from the ratio of the γ-ray intensities in the spectra measured by the 154° and 90° detectors, gated on transitions observed in all detectors. P was deduced from the Compton scattering events in perpendicular and horizontal directions in adjacent crystals of the clover detectors (see the supplementary material for the procedures). The measured polarization

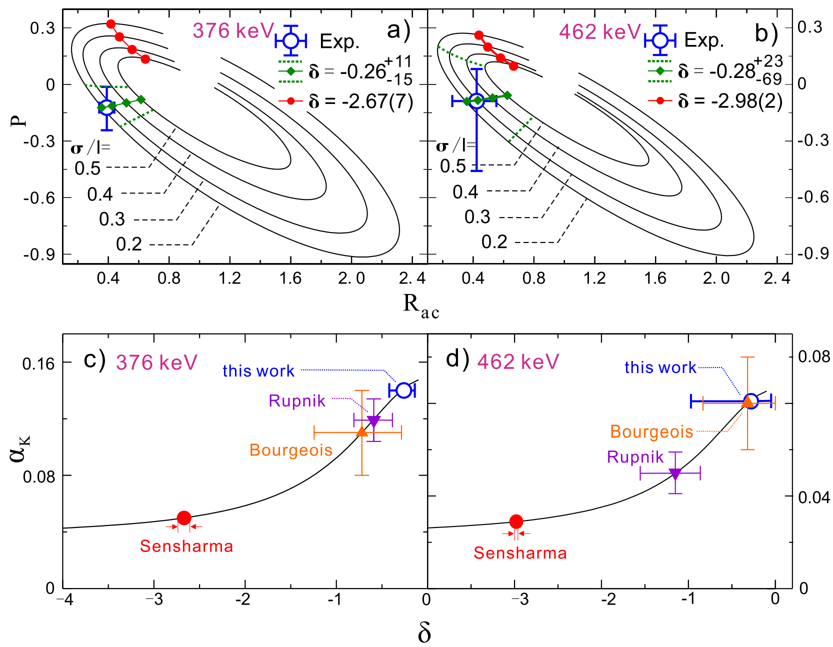

Fig. 3. a) and b): Plots of polarization P versus R_{ac} for different values of δ and σ/I, together with experimental results and estimated results for certain δ values. c) and d): Internal conversion coefficients α_K as a function of δ, together with the experimental results from the present work and those from Sensharma et al. [14], Rupnik et al. [24], and Bourgeois et al. [25]. The δ values for the Refs. [24] and [25] were deduced from the reported internal conversion values using the BrIcc code [26].

of the 376-keV, $11/2^- \rightarrow 9/2^-$ transition is in good agreement with the value of -0.10(5) reported previously [18]. The δ values were deduced from the measured values of R_{ac} and P, as shown in Fig. 3. The curves are sensitive to the σ/I parameter in which σ is the variance of the projection of the angular momentum I along the beam direction. The σ/I parameter might be affected by states with lifetimes of the order of a picosecond or larger. In the present work, δ values are deduced with the σ/I parameter not restricted. This induces a larger uncertainty in the measured δ, however the result does not depend on an assumed value for σ/I. Despite the large error bars, it is clear that the absolute values of the deduced δ values are smaller than 1, indicating dominant $M1$ nature of these transitions. Data points that correspond to the large δ values deduced in Ref. [14] are shown in red in Fig. 3. They are in distinct disagreement with both the presently deduced values and the values obtained from previous internal conversion coefficient measurements [24,25]. Considering the measured $B(E2)$ in values of 100 - 200 W.u. in the collective bands of ^{187}Au and the ^{186}Pt core [27,28], the values of B(E2)out are estimated to be only a few W.u., which is inconsistent with the proposed wobbling interpretation for Band 2 [14], and even with any interpretation that involves a collective type of excitation of Band 2 with respect to Band 1.

In order to study further the nature of Band 2, one-quasi-particle-plus-triaxial-rotor (QTR) model calculations using the code of P. Semmes and I. Ragnarsson [29] were carried out (for more details see the supplementary material). Standard parameters are used for the Nilsson potential [30] and for the pairing strength. The γ-dependence of the moments of inertia of the core has irrotational-flow nature, as suggested by an empirical evaluation [31]. The spin dependence is taken into account assuming variable moments of inertia described by the Harris parameters J_0 = 25 $\hbar^2$ MeV^{-1} and J_1 = 8 $\hbar^4$ MeV^{-3}. The adopted quadrupole deformation of $\varepsilon_2 = 0.21$ is similar to that previously used in Refs. [24,14]. The adopted triaxial deformation is γ = 12°, as suggested in the theoretical calculations for the ^{186}Pt core [32]. The calculated proton Fermi level is near the highest $h_{11/2}$ and lowest $h_{9/2}$ orbitals,

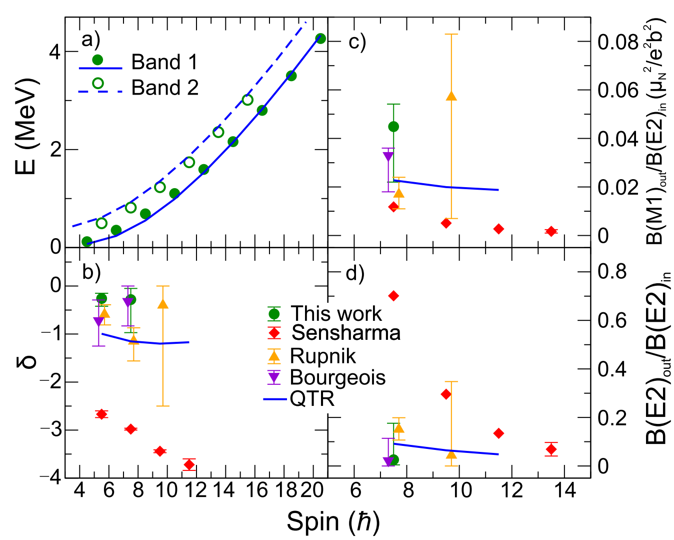

Fig. 4. Comparison between experimental and calculated a) Excitation energies (E), b) mixing ratios (δ), c) $B(M1)_{out}/B(E2)_{in}$ ratios, and d) $B(E2)_{out}/B(E2)_{in}$ ratios. The values associated with the previously measured δ values [14,18,24,25] are also shown. Some points are slightly shifted horizontally to avoid overlapping.

as in Ref. [18]. Nine negative-parity orbitals adjacent to the Fermi level are included in the calculations.

The calculated excitation energies of the two lowest-energy rotational bands with $h_{9/2}$ nature are shown in Fig. 4a. The wave functions clearly indicate that Bands 1 and 2 are based primarily on the lowest and second-lowest energy orbitals originating from the $h_{9/2}$ subshell, respectively, suggesting that the excitation between the two bands has a single particle character. The calculated δ values, $B(M1)_{out}/B(E2)_{in}$ and $B(E2)_{out}/B(E2)_{in}$ ratios are in good agreement with our data and with the data from Refs. [18,24,25], but in contrast with those from Ref. [14] (see Figs. 4b, 4c and 4d). This agreement further supports the proposed non-collective character of the excitation, for more details, see the supplementary material.

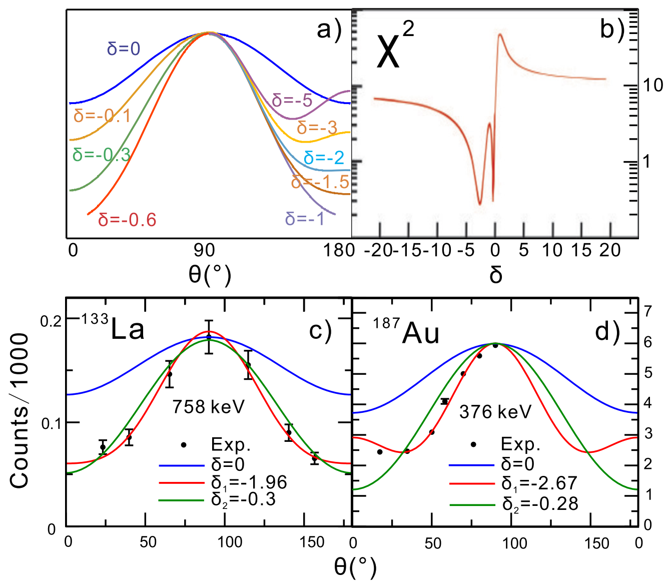

Fig. 5. a): Angular distribution curves with different δ values. Since all curves are symmetric about 90°, only the left part for those with ($-1 < \delta < 0$), and only the right part for those with ($\delta < -1$) are shown to avoid overlapping. b): A sketch figure of the χ^2 as function of δ. c) and d): Estimated angular distribution curves and experimental results for the reported wobbling bands in ^{133}La and ^{187}Au. The curves for pure $M1$ transition (in blue) and large δ (in red) are taken from the original figures in Refs. [13,14], and those with smaller δ values and same σ/I are also plotted (in green) for comparison.

In order to check if the risk of misinterpretation also exists in other reported low-spin wobbling bands, we assessed the published experimental and theoretical evidence. The critical experimental proof in favor of the wobbling interpretation is the observation of predominant $E2$ character for the $\Delta I = 1$ transitions linking the proposed one-phonon wobbling bands to the corresponding zero-phonon bands, which is determined by measuring the $\delta(E2/M1)$ mixing ratios. Additional support for wobbling motion is provided by a comparison between calculated and experimental results on excitation energies and ratios of transition probabilities.

The δ values can be deduced from angular distribution and/or linear polarization measurements. Angular distribution curves are calculated assuming appropriate values for δ and σ/I. The suitable δ values, which correspond to good agreement between the calculated curves and the experimental points, are obtained. As shown in Fig. 5a, the angular distribution curves become steeper and steeper with decreasing δ value below 0. However, for $\delta < -1$ the slope decreases. There are usually two minima for the χ^2 values corresponding to two δ solutions $|\delta_1| > 1$ and $|\delta_2| < 1$ (see Fig. 5b). In some cases, almost equally good fits are obtained for both solutions (see Fig. 5c), leading to similar χ^2 minima. Sometimes, one solution can fit the experimental results better than the other one (see Fig. 5d). It is therefore important to discuss the confidence level of χ^2, and check whether the second solution for δ can be confidently excluded based on the χ^2 fit. It is worth noting that the number of counts in the peaks used to obtain the angular distribution are not measured directly, but deduced from the $\gamma-\gamma$ coincidence matrices. Both the central values and the uncertainties can be affected by the selection of parameters in the process of creating and analyzing the gated spectra. The resulting uncertainties of χ^2 should be considered.

Mixing ratios for the linking transitions of the low-spin wobbling bands in ^{135}Pr [9,10], ^{133}La [13] and ^{187}Au [14] were extracted from angular distribution measurements, but the possible $|\delta_2| < 1$ solutions were not mentioned or discussed, and the curves for $|\delta_1| > 1$ were only compared with those for pure $M1$

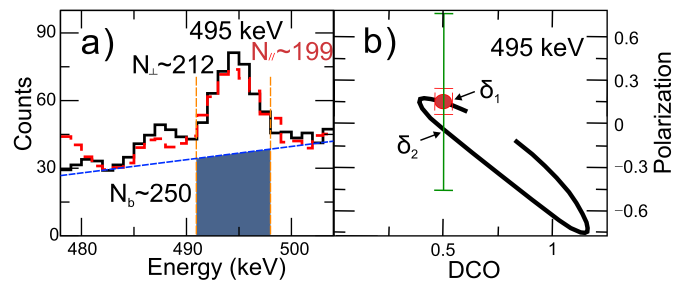

Fig. 6. Statistical error on polarization for a reported transition in ^{183}Au. a): Reported spectra used in polarization measurement for ^{183}Au in Ref. [12]. $N_\perp$ and $N_\parallel$ represent the peak area of the 495-keV transition in spectra showing γ rays observed to scatter perpendicular or parallel to the reaction plane, respectively. N_b is the background below the peak. The spectra are adopted from Fig. 1c in Ref. [12]. b): Experimental (red symbol) and calculated (black line) DCO and linear polarization values for the 495-keV transition are taken from Fig. 2d in Ref. [12]. The error bar in green is the statistical error estimated from the spectra.

transitions ($\delta = 0$). Generally, the two solutions are expected to correspond to different polarization values, and therefore linear polarization (P) measurements can help to identify the correct one. Such measurements were performed for ^{135}Pr [9] and ^{133}La [13], but not for ^{187}Au [14]. In addition, the $|\delta_1| > 1$ solutions for two transitions in ^{135}Pr were only selected based on their positive sign, but not on the magnitude of the measured P [9], which is insufficient since the $|\delta_2| < 1$ solutions for those two transitions can also correspond to positive polarization values. Alternative to angular distribution analysis, the δ values can be extracted using the measured directional correlation ratios of oriented states (DCO) and polarization values [33]. Such analysis was carried out for the transitions in ^{105}Pd [11], ^{183}Au [12], ^{133}La [13], and ^{127}Xe [15]. As shown in Fig. 5b, based on only measured DCO values two solutions for δ are possible, while the additional precise measured polarization can exclude one of them. For the polarization measurement, only the γ rays detected by two adjacent crystals of clover detectors are used, and consequently the uncertainty of the measured polarization value is relatively large. It is thus essential to carefully evaluate the uncertainty on the polarization value to confidently select the correct solution for δ. However, in some published work, the uncertainties seem to be significantly underestimated. For example, a small uncertainty was reported for the polarization value of the 495-keV transition in ^{183}Au [12], while the experimental data suggest much larger statistical errors (see Fig. 6 and the supplementary material), leading to larger uncertainty and insufficient precision to distinguish between the two possible solutions for δ.

According to the overall assessment, the experimental results on several nuclei do not offer unambiguous evidence in support of the proposed low-spin wobbling bands.

The assigned wobbling nature was also based on the comparison between the experimental results on reduced transition probability ratios, (which strongly depend on the extracted δ values) and theoretical calculations. If the experimental δ values are considerably smaller than the theoretical expectation for wobbling bands, the wobbling interpretation is ruled out. On the other hand, only the measured $|\delta_1| > 1$ values cannot constitute sufficient unambiguous evidence for the existence of wobbling motion. It is noticeable that in the work reporting the identification of low-spin wobbling bands, only interpretations in terms of signature partner band and wobbling band were considered. Actually, other mechanisms can also induce collective motion and thus induce enhanced $E2$ component of the linking transitions, such as β-vibration, γ-vibration [34], and tilted precession [17,35]. Such collective excitations are well known in the low-spin domain.

As an approximation, the wobbling motion is invalid at low spin. Therefore, its low-spin limit should be quantitatively investigated. On the other hand, low-spin precession is still expected to exist in nuclei, which need to be further investigated in a way other than wobbling. Actually, the interpretation in terms of tilted precession [17] of a low-spin rotational band was recently reported in ^{135}Nd [35].

However, to make reliable conclusions on this topic, the problems hidden in the research paradigm should be solved. It is insufficient to exclusively adopt only the large δ solutions from the measured data and based on this to determine the type of excitation. In fact, the low-spin wobbling interpretation was adopted without exploring other possible modes of excitation. In further studies, the experimentally measured δ values, which are of critical importance for establishing the collectivity of the excitation, should be evaluated with better accuracy. The predicted measurable quantities, which can distinguish the different excitation modes, such as wobbling, tilted precession, vibrations, etc., need to be identified and properly treated in order to unambiguously assign the nature of such low-spin rotational bands.

In summary, the nature of the conjectured low-spin wobbling bands is probed in the present work since the wobbling motion is invalid at low spin. The present new experimental results on the previously proposed wobbling band in ^{187}Au, unequivocally show that the band is generated by dominant single-particle excitation and cannot be associated with wobbling. Furthermore, from an overall assessment, we conclude that the experimental and theoretical evidence for the reported low-spin wobbling bands is generally insufficient. To understand the mechanisms giving rise to those bands, convincing experimental and theoretical examinations are required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the accelerator crew of HIRFL for providing the stable ^{18}O beam during the pandemic of COVID-19. S.G. expresses his gratitude to Prof. P.W. Zhao for useful discussions. This work has been supported by the Strategic Priority Research Program of Chinese Academy of Sciences, (Grant No. XDB34000000), the National Key R&D Program of China (Contract Nos. 2018YFA0404402 and 2018YFA0404400), the Key Research Program of the Chinese Academy of Sciences (Grant No. XDPB09-02), the National Natural Science Foundation of China (Grant Nos. U1932137, U1732139, U1832134, 11775274, 11975209, and 11805289), the Cai YuanPei 2018 Project No. 41458XH, and the National Research Foundation of South Africa, GUN: 109134 and 116666.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2022.137010.

References

[1] A.S. Davydov, G.F. Filippov, Rotational states in even atomic nuclei, Nucl. Phys. 8 (1958) 237–249.
[2] A. Bohr, B.R. Mottelson, Nuclear Structure, vol. II, Benjamin, New York, 1975.
[3] S.W. Ødegård, G.B. Hagemann, D.R. Jensen, M. Bergström, B. Herskind, G. Sletten, et al., Evidence for the wobbling mode in nuclei, Phys. Rev. Lett. 86 (Jun 2001) 5866–5869.
[4] D.R. Jensen, G.B. Hagemann, I. Hamamoto, S.W. Ødegård, B. Herskind, G. Sletten, et al., Evidence for second-phonon nuclear wobbling, Phys. Rev. Lett. 89 (Sep 2002) 142503.
[5] P. Bringel, G.B. Hagemann, H. Hübel, A. Al-khatib, P. Bednarczyk, A. Bürger, et al., Evidence for wobbling excitation in ^{161}Lu, Eur. Phys. J. A 24 (2) (May 2005) 167–172.
[6] G. Schönwaßer, H. Hübel, G.B. Hagemann, P. Bednarczyk, G. Benzoni, A. Bracco, et al., One- and two-phonon wobbling excitations in triaxial ^{165}Lu, Phys. Lett. B 552 (1) (2003) 9–16.
[7] H. Amro, W.C. Ma, G.B. Hagemann, R.M. Diamond, J. Domscheit, P. Fallon, et al., The wobbling mode in ^{167}Lu, Phys. Lett. B 553 (3) (2003) 197–203.
[8] D.J. Hartley, R.V.F. Janssens, L.L. Riedinger, M.A. Riley, A. Aguilar, M.P. Carpenter, et al., Wobbling mode in ^{167}Ta, Phys. Rev. C 80 (Oct 2009) 041304.
[9] J.T. Matta, U. Garg, W. Li, S. Frauendorf, A.D. Ayangeakaa, D. Patel, et al., Transverse wobbling in ^{135}Pr, Phys. Rev. Lett. 114 (Feb 2015) 082501.
[10] N. Sensharma, U. Garg, S. Zhu, A.D. Ayangeakaa, S. Frauendorf, W. Li, et al., Two-phonon wobbling in ^{135}Pr, Phys. Lett. B 792 (2019) 170–174.
[11] J. Timár, Q.B. Chen, B. Kruzsicz, D. Sohler, I. Kuti, S.Q. Zhang, et al., Experimental evidence for transverse wobbling in ^{105}Pd, Phys. Rev. Lett. 122 (Feb 2019) 062501.
[12] S. Nandi, G. Mukherjee, Q.B. Chen, S. Frauendorf, R. Banik, Soumik Bhattacharya, et al., First observation of multiple transverse wobbling bands of different kinds in ^{183}Au, Phys. Rev. Lett. 125 (Sep 2020) 132501.
[13] S. Biswas, R. Palit, S. Frauendorf, U. Garg, W. Li, G.H. Bhat, et al., Longitudinal wobbling in ^{133}La, Eur. Phys. J. A 55 (9) (Sep 2019) 159.
[14] N. Sensharma, U. Garg, Q.B. Chen, S. Frauendorf, D.P. Burdette, J.L. Cozzi, et al., Longitudinal wobbling motion in ^{187}Au, Phys. Rev. Lett. 124 (Feb 2020) 052501.
[15] S. Chakraborty, H.P. Sharma, S.S. Tiwary, C. Majumder, A.K. Gupta, P. Banerjee, et al., Multiphonon longitudinal wobbling in ^{127}Xe, Phys. Lett. B 811 (2020) 135854.
[16] S. Frauendorf, F. Dönau, Transverse wobbling: a collective mode in odd-A triaxial nuclei, Phys. Rev. C 89 (Jan 2014) 014322.
[17] E.A. Lawrie, O. Shirinda, C.M. Petrache, Tilted precession and wobbling in triaxial nuclei, Phys. Rev. C 101 (Mar 2020) 034306.
[18] C. Bourgeois, M.G. Porquet, N. Perrin, H. Sergolle, F. Hannachi, G. Bastin, F. Beck, Shape coexistence at high spin in ^{187}Au, Z. Phys. A At. Nucl. 333 (1) (Mar 1989) 5–14.
[19] J.W. Xia, W.L. Zhan, B.W. Wei, Y.J. Yuan, M.T. Song, W.Z. Zhang, et al., The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou, Nucl. Instrum. Methods Phys. Res., Sect. A 488 (1) (2002) 11–25.
[20] Z. Sun, W.-L. Zhan, Z.-Y. Guo, G. Xiao, J.-X. Li, RIBLL, the radioactive ion beam line in Lanzhou, Nucl. Instrum. Methods Phys. Res., Sect. A 503 (3) (2003) 496–503.
[21] H.Y. Wu, Z.H. Li, H. Tan, H. Hua, J. Li, W. Hennig, et al., A general-purpose digital data acquisition system (GDDAQ) at Peking University, Nucl. Instrum. Methods Phys. Res., Sect. A 975 (2020) 164200.
[22] J.K. Johansson, D.G. Popescu, D.D. Rajnauth, J.C. Waddington, M.P. Carpenter, L.H. Courtney, V.P. Janzen, A.J. Larabee, Z.M. Liu, L.L. Riedinger, Shape coexistence in ^{187}Au, Phys. Rev. C 40 (Jul 1989) 132–144.
[23] S. Mukhopadhyay, D.C. Biswas, S.K. Tandel, S. Frauendorf, L.S. Danu, P.N. Prashanth, et al., Semi-decoupled band and other high-spin band structures in ^{188}Pt, Phys. Rev. C 96 (Jul 2017) 014315.
[24] D. Rupnik, E.F. Zganjar, J.L. Wood, P.B. Semmes, P.F. Mantica, Levels of ^{187}Au: a detailed study of shape coexistence in an odd-mass nucleus, Phys. Rev. C 58 (Aug 1998) 771–795.
[25] C. Bourgeois, P. Kilcher, J. Letessier, V. Berg, M.G. Desthuilliers, Étude par spectroscopie "en ligne" des états d'énergie de ^{187}Au: interprétation en termes de déformations nucléaires triaxiales, Nucl. Phys. A 295 (3) (1978) 424–444.
[26] T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Evaluation of theoretical conversion coefficients using bricc, Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 589 (2) (2008) 202–229.
[27] Coral M. Baglin, Nuclear data sheets for A = 186, Nucl. Data Sheets 99 (1) (2003) 1–196.
[28] M.S. Basunia, Nuclear data sheets for A = 187, Nucl. Data Sheets 110 (5) (2009) 999–1238.
[29] P.B. Semmes, I. Ragnarsson, in: J.X. Saladin, R.A. Sorenson, C.M. Vincent (Eds.), Proceedings of the International Conference on High-Spin Physics and Gamma-Soft Nuclei, Pittsburg, 1990, World Scientific, Singapore, 1991, p. 500, in: J. Dudek, B. Haas (Eds.), Future Directions in Nuclear Physics with 4π Gamma Detection Systems of the New Generation, in: AIP Conf. Proc., vol. 259, 1992, p. 566.
[30] Tord Bengtsson, Ingemar Ragnarsson, Rotational bands and particle-hole excitations at very high spin, Nucl. Phys. A 436 (1) (1985) 14–82.
[31] J.M. Allmond, J.L. Wood, Empirical moments of inertia of axially asymmetric nuclei, Phys. Lett. B 767 (2017) 226–231.

[32] R. Rodríguez-Guzmán, P. Sarriguren, L.M. Robledo, J.E. García-Ramos, Mean field study of structural changes in Pt isotopes with the Gogny interaction, Phys. Rev. C 81 (Feb 2010) 024310.
[33] K. Starosta, T. Morek, Ch. Droste, S.G. Rohoziński, J. Srebrny, A. Wierzchucka, et al., Experimental test of the polarization direction correlation method (PDCO), Nucl. Instrum. Methods Phys. Res., Sect. A 423 (1) (1999) 16–26.
[34] J.P. Davidson, Rotations and vibrations in deformed nuclei, Rev. Mod. Phys. 37 (Jan 1965) 105–158.
[35] B.F. Lv, C.M. Petrache, E.A. Lawrie, A. Astier, E. Dupont, K.K. Zheng, et al., Tilted precession bands in ^{135}Nd, Phys. Rev. C 103 (Apr 2021) 044308.