Longitudinal Wobbling Motion in $^{187}\text{Au}$

N. Sensharma,¹ U. Garg,¹ Q. B. Chen,² S. Fraudendorf,¹ D. P. Burdette,¹ J. L. Cozzi,¹ K. B. Howard,¹ S. Zhu,³ M. P. Carpenter,⁴ P. Copp,⁴ F. G. Kondev,⁴ T. Lauritsen,⁣ J. Li,⁣ D. Seweryniak,⁣ J. Wu,⁣ A. D. Ayangeakaa,⁵ D. J. Hartley,⁵ R. V. F. Janssens,⁶,⁷ A. M. Forney,⁸ W. B. Walters,⁸ S. S. Ghugre,⁹ and R. Palit¹⁰

¹Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA
²Physik-Department, Technische Universität München, D-85747 Garching, Germany
³National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA
⁴Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
⁵Department of Physics, United States Naval Academy, Annapolis, MD 21402, USA
⁶Department of Physics and Astronomy, University of North Carolina Chapel Hill, NC 27599, USA
⁷Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, USA
⁸Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA
⁹UGC-DAE Consortium for Scientific Research, Kolkata 700 064, India
¹⁰Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai 400 005, India

(Dated: February 13, 2020)

The rare phenomenon of nuclear wobbling motion has been investigated in the nucleus $^{187}\text{Au}$. A longitudinal wobbling-bands pair has been identified and clearly distinguished from the associated signature-partner band on the basis of angular distribution measurements. Theoretical calculations in the framework of the Particle Rotor Model (PRM) are found to agree well with the experimental observations. This is the first experimental evidence for longitudinal wobbling bands where the expected signature partner band has also been identified, and establishes this exotic collective mode as a general phenomenon over the nuclear chart.

PACS numbers: 27.70.+q, 23.20.-g, 23.20.En, 23.20.Gq, 21.60.Ev

The shape of a nucleus, determined via specific characteristic spectroscopic features observed in experiments, is a manifestation of the self-organization of a finite fermionic system. Studying the appearance of various shapes with changing of neutron-to-proton ratio or increasing angular momentum reveals new insights into fundamental principles governing finite fermionic systems in general. The range of shapes that nuclei can assume encompasses spherical symmetry and axial deformation about a symmetry axis is not possible for a system of identical fermions. Accordingly, the medium axis (m-) responds to minimal energy. At a somewhat larger energy, this axis precesses (wobbles) about the space-fixed axis $\vec{J}$. In a quantal system, such as the nucleus (or a molecule), $\vec{J}$ wobbles about the medium (m-) axis in the body fixed frame (as illustrated in Fig. 1 (a)). This mode manifests itself in the appearance of rotational bands that correspond to successive excitations of wobbling phonons, $\omega_n$, and alternating signature $\alpha = \alpha_0 + \omega_n$, which determines the spin sequence $I = \alpha + \text{even number}$. Adjacent wobbling bands $n_{\omega + 1}$ and $n_{\omega}$ are connected by $\Delta I = 1$ transitions with a collectively-enhanced E2 component, which is generated by the wobbling motion of the entire charged body.

Microscopic calculations give ratios between the three moments of inertia that are close to the ratios of rotational flow $\eta$. The reason is that collective rotation about a symmetry axis is not possible for a system of identical fermions. Accordingly, the medium axis (m-) has the largest moment of inertia, because deviation from axial symmetry is maximal. Although predicted quite sometime ago $\eta$, there is only fragmentary evidence for simple wobbling (Fig. 1 (a)) in even-even nuclei $\eta$. Instead, wobbling has been demonstrated for a few odd-A nuclei: $^{105}\text{Pd}$ $\eta$, $^{155}\text{Pr}$ $\eta$, $^{133}\text{La}$ $\eta$, $^{161}\text{Lu}$ $\eta$, $^{163}\text{Lu}$ $\eta$, $^{165}\text{Lu}$ $\eta$, and $^{167}\text{Ta}$ $\eta$.

All these nuclei have an odd nucleon (neutron in the case of $^{105}\text{Pd}$ $\eta$, and proton for all the other cases) occupying a high-$j$ orbital. Depending on the particle (hole) nature of the odd quasiparticle arising from the bottom (top) of a deformed $j$ shell, its angular momentum gets aligned with the short, s- (long, l-) axes of the triaxial rotor, because this maximizes (minimizes) the overlap of its density distribution with the triaxial core, which minimizes the energy. If the quasiparticle arises from the
rotor energy is given by:

$$J = \text{increase in the rotor energy by:}$$

It should be understood that the frozen alignment scenario discussed here is an idealization to illustrate the longitudinal and transverse coupling schemes in a transparent way. The odd particle responds to the inertial forces, changing its orientation to a certain degree. Nevertheless, the qualitative classification remains valid. Wobbling is characterized by collectively enhanced \( I \rightarrow I + 1 \), E2 transitions from the wobbling to the yrast band, where the wobbling energy increases (decreases) for LW (TW).

The signature-partner bands represent another type of excitation involving a partial de-alignment of the odd particle with respect to its preferred axis (Fig. 1(b)); for those, the connecting \( \Delta I = 1 \) transitions are of predominant M1 character, with very little, if any, E2 admixture.

In all of the cases mentioned above (except \(^{133}\text{La}\))\(^{10}\)), the wobbling bands have been identified as corresponding to TW, because \( E_{\text{wobb}} \) decreases with increasing angular momentum. In this Letter, we report on the observation of band structures corresponding to longitudinal wobbling motion in the nucleus \(^{187}\text{Au}\). This is the first case of observation of bands corresponding to longitudinal wobbling, clearly distinguished from the associated signature-partner band. Further, these results open up a new mass region, and a different set of orbitals, where this exotic collective motion is established. Occurrence of triaxiality at low spins has been established in this mass region by observation of chiral band pairs in several nuclei \(^{185,186}\text{Au}\)\(^{15,20}\) and suggested by large-scale, mean-field calculations (see, for example, Refs. 3, 21, 22). Also, earlier studies of the coupling of an odd number of particles to a rotor had revealed substantial deviations from an axial shape \(^{23,24}\).

To populate the levels of interest in \(^{187}\text{Au}\), a \(^{19}\text{F}\) beam was used with an enriched \(^{174}\text{Yb}\) target (13 mg/cm\(^2\)-thick foil with a 33 mg/cm\(^2\)\(^{208}\text{Pb}\) backing) at the ATLAS facility of the Argonne National Laboratory. Data were collected with the Gammasphere array in two separate runs using the same beam and target combination. For
the first run, a total of 57 Compton-suppressed Germanium detectors of the Gammasphere array were employed and the beam energy was 105 MeV. For the second, the number of detectors was 73, and the beam energy 115 MeV. Data were acquired in the triple-coincidence mode, with the combined total of three- and higher-fold $\gamma$-ray coincidence events being $1.08 \times 10^9$.

To take advantage of higher statistics, the data from both measurements were combined, and the analyses performed using the RADWARE suite of codes [25]. Energy and efficiency calibrations were performed for the added data set and the calibrated data was sorted into $\gamma-\gamma$ coincidence matrices and $\gamma-\gamma-\gamma$ coincidence cubes. A partial level scheme for $^{187}$Au relevant to the focus of this work is presented in Fig. 2; additional information on the level structure, along with details of the coincidence relationships, as well as the relevant coincidence spectra, will be presented in a forthcoming publication [26]. The arrangement of Gammasphere detectors into 17 different angular rings around the beam line has enabled high statistics angular distribution measurements for the relevant transitions of Fig. 2. The analysis procedure followed for these measurements is the same as that described in Refs. 8, 9. The validity of the method has been established by examining the angular distributions for two known stretched E2 transitions (333.8- and 413.7-keV) in the Yrast band (shown in Figs. 3(g) and (h)). As expected, the mixing ratios extracted for these stretched E2 transitions are extremely small: $\delta = -0.04(1)$ and -0.03(1), respectively. Further details, including a discussion of the various factors that might affect the extraction of final results—efficiency corrections, spin alignment, attenuation coefficients etc.—will be provided in Ref. 20.

Spins and parities of the bandheads as well as some low-lying levels of Bands (1) and (2) had been established previously [27, 28]. In addition to these, the present work has identified a new band [Band (3)] built on an 11/2$^-$ state at 386.3 keV. The spins and parities for the levels in Band (3) have been assigned on the basis of angular distribution measurements as well as coincidence relationships, details of which will be provided in Ref. 20.

Band (2) in Fig. 2 is found to decay to Band (1) (the Yrast band) via six $\Delta I = 1$ transitions. Previous work [29, 30] has identified this band as the unfavored signature partner of Band (1). However, based on the high-statistics angular distribution measurements for the connecting transitions between the two bands, this sequence has been identified in the present work as the first wobbling ($n_\omega = 1$) band. Figs. 3(a) – (d) provide the angular distributions for the four lowest $n_\omega = 1 \rightarrow$ Yrast ($n_\omega = 0$) connecting transitions. The mixing ratio, $\delta$, and the percentage of E2 mixing are noted on each plot. These transitions have an 87%-93% E2 component, clearly identifying them as $\Delta I = 1$, E2 in nature, which is the hallmark of wobbling bands [12]. The present work has not been able to identify any other wobbling bands corresponding to higher phonon numbers ($n_\omega = 2$ and above). The absence of these bands can be attributed to reasons discussed previously in Ref. 17.

Band (3) is found to decay to the yrast band via two $\Delta I = 1$ transitions (265.3- and 436.5-keV). The angular distributions for these transitions (Figs. 3(e) and (f)) reveal a very small E2 component ($\approx 0.4$% and 1.0% E2 admixture, respectively), identifying these transitions as being essentially of a pure M1 character. Angular distribution measurements for the in-band transitions have revealed a stretched E2 character. Moreover, a $\Delta I = 2$ crossover transition (429.2-keV) was also identified, connecting the 15/2$^-$ level in Band (2) to the 11/2$^-$ level in Band (3). The spin and parity of the 15/2$^-$ level in Band (2) have been established previously [27, 28]. The observed $\Delta I = 2$ nature of the in-band transitions, as well as of the 429.2-keV transition, along with the pure $\Delta I = 1$ nature of the two connecting transitions (265.3- and 436.5-keV) have led to the spin and parity assignments in Fig. 2 Band (3), with its two almost pure M1 connecting transitions to the Yrast band, has, thus, been identified as the unfavored signature partner (SP) of the Yrast band.

Fig. 2(d) displays the variation of $E_{\text{wobb}}$ with spin.
The increasing trend clearly identifies $^{187}\text{Au}$ as a longitudinal wobbler. This is different from all the other known wobblers, which have been identified as being of the transverse type. Thus, $^{187}\text{Au}$ represents the first clear observation of longitudinal wobbler motion in nuclei.

To further understand the nature of wobbling, we have carried out calculations in the framework of the Particle Rotor Model (PRM) \cite{17, 31, 32} for the $h_9/2$ band structures, with the deformation parameters $\beta = 0.29$, $\gamma = 23^\circ$, the pairing gap $\Delta = 0.88$ MeV, and the chemical potential located at $\lambda = -1.32$ MeV, 0.38 MeV below the second level of the $h_9/2$ shell. The $h_9/2$ proton is described by a single-$j$ shell Hamiltonian. Including the $f_7/2$ orbital into the PRM calculations provided results that agree with Figs. 1 and 5 within the shown accuracy, because the admixture of the $f_7/2$ proton to the eigenstates is lower than 5%. We have also carried out cranking calculations based on the configuration-fixed covariant density functional PC-PK1 \cite{33, 37}. The equilibrium deformations changed only slight from $\beta = 0.28$, $\gamma = 22^\circ$ at $I = 9/2$ to $\beta = 0.28$, $\gamma = 25^\circ$ at $I = 29/2$, which justifies the assumption of a constant deformation for the PRM calculations. The analogue calculations for the $^{186}\text{Pt}$ core provided quite similar equilibrium deformations. As input for the PRM, we used the smaller deformation $\beta = 0.23$, $\gamma = 23^\circ$ found by the HFB-D1S calculations for $^{186}\text{Pt}$ \cite{38} because it accounts for the experimental values of $B(E2, 13/2^- \rightarrow 9/2^-) = 1.49 (eb)^2$ for $^{187}\text{Au}$ \cite{39} and $B(E2, 22/2^+ \rightarrow 0^+) = 0.84 (eb)^2$ for $^{186}\text{Pt}$\cite{38}.

The moments of inertia are of the irrotational-flow type: $J_k = J_0 \sin^2(\gamma - 2k\pi/3)$, with $J_0 = 38.0 \ h^2/\text{MeV}$. The PRM calculations locate the chemical potential in the middle of the $h_9/2$ shell. Frauendorf and Dönnic \cite{17} had predicted the appearance of LW for quasiparticles from half-filled shells.
The results for the transitions from the SP to the Yrast band are presented in Figs. 5 (c) and (d). The \( B(E2)_{\text{out}}/B(E2)_{\text{in}} \) ratios for these transitions are much smaller than those for LW \( \rightarrow \) Yrast linking transitions, which further supports the wobbling and signature-partner interpretations for the LW and SP bands. The PRM calculations overestimate the \( B(M1)/B(E2) \) ratios for the LW band and underestimate it for the SP bands. This may be attributed to an incorrect mixing between the wobbling and SP states, which is sensitive to the excitation energies and the ratios between the moments of inertia.

In summary, we have observed wobbling motion in the nucleus \(^{187}\text{Au}\). Two rotational bands have been identified as corresponding to \( n_\omega = 0 \) and \( n_\omega = 1 \) wobbling-bands pair. The signature partner of the \( n_\omega = 0 \) (yrast) band has also been identified. An increasing wobbling energy, \( E_{\text{wobb}} \), with spin establishes \(^{187}\text{Au}\) as the first nucleus in which longitudinal wobbling motion has been observed and clearly distinguished from the signature-partner band. Results from PRM calculations are in good agreement with experimental observations. These results open the \( A \sim 190 \) region as a new arena where this exotic collective mode has now been observed and establish this mode as a general phenomenon over the nuclear chart encompassing many different nuclear orbitals. Continuing experimental efforts are warranted to explore this behavior further.

UG acknowledges travel support from CUSTIPEN (China-U.S. Theory Institute for Physics with Exotic Nuclei) which was instrumental in the initiation of theoretical collaboration with QBC. This work has been supported in part by the U.S. National Science Foundation [Grants No. PHY-1713857 (UND) and No. PHY-1203100 (USNA)], and by the U. S. Department of Energy, Office of Science, Office of Nuclear Physics [Contract No. DE-AC02-06CH11357 (ANL), No. DE-FG02-95ER40934 (UND), No. DE-FG02-97ER41033 (UNC), DE-FG02-97ER41041 (TUNL), No. DE-FG02-94ER40834 (Maryland), and No. de-sc0009971 (CUSTIPEN)]. The work of QBC was supported by Deutsche Forschungsgemeinschaft (DFG) and National Natural Science Foundation of China (NSFC) through funds provided to the Sino-German CRC 110 “Symmetries and the Emergence of Structure in QCD” (DFG Grant No. TRR110 and NSFC Grant No. 11621131001). This research used resources of ANL’s ATLAS facility, which is a DOE Office of Science User Facility.

For references, see:

[1] A. Bohr and B. R. Mottelson, *Nuclear Structure Vol.II, Chap. 4* (W. A. Benjamin, New York, 1975).
[2] K. Heyde and J. L. Wood, Rev. Mod. Phys. 83, 1467 (2011).
[3] P. Möller, R. Bengtsson, B. G. Carlsson, P. Olivius, and T. Ichikawa, Phys. Rev. Lett. 97, 162502 (2006).
[4] S. Frauendorf and J. Meng, Nuclear Physics A 617, 131 (1997).
[5] S. Frauendorf, Phys. Rev. C 97, 069801 (2018).
[6] S. Frauendorf, Int. J. Mod. Phys. E 24, 1541001 (2015).
[7] J. Timár, Q. B. Chen, B. Kruzsicz, D. Sohler, I. Kuti, S. Q. Zhang, J. Meng, P. Joshi, R. Wadsworth, K. Starosta, et al., Phys. Rev. Lett. 122, 062501 (2019).
[8] J. T. Matta, U. Garg, W. Li, S. Frauendorf, A. D. Ayangeakaa, D. Patel, K. W. Slach, R. Palit, S. Saha, J. Sethi, et al., Phys. Rev. Lett. 114, 082501 (2015).
[9] N. Sensharma, U. Garg, S. Zhu, A. D. Ayangeakaa, S. Frauendorf, W. Li, G. H. Bhat, J. A. Sheikh, M. P. Carpenter, Q. B. Chen, et al., Phys. Lett. B 792, 170 (2019).
[10] S. Biswas, R. Palit, U. Garg, G. H. Bhat, S. Frauendorf, W. Li, J. A. Sheikh, J. Sethi, S. Saha, P. Singh, et al., Eur. Phys. J. A 55, 159 (2019).
[11] P. Bringel, G. B. Hagemann, H. Hübel, A. Al-khatib, P. Bednarczyk, A. Bürger, D. Curien, G. Gangopadhyay, B. Herskind, D. R. Jensen, et al., Eur. Phys. J. A 24, 167 (2005).
[12] S. W. Ödegård, G. B. Hagemann, D. R. Jensen, M. Bergström, B. Herskind, G. Sletten, S. Törnåne, J. N. Wilson, P. O. Tjøm, I. Hamamoto, et al., Phys. Rev. Lett. 86, 5866 (2001).
[13] D. R. Jensen, G. B. Hagemann, I. Hamamoto, S. W. Ödegård, B. Herskind, G. Sletten, J. N. Wilson, K. Spohr, H. Hübel, P. Bringel, et al., Phys. Rev. Lett. 89, 142503 (2002).
[14] G. Schönwalder, H. Hübel, G. B. Hagemann, P. Bednarczyk, G. Benzoni, A. Bracco, P. Bringel, R. Chapman, D. Curien, J. Domscheit, et al., Phys. Lett. B 552, 9 (2003).
[15] H. Amro, W. C. Ma, G. B. Hagemann, R. M. Diamond, J. Domscheit, P. Fallon, A. Görgen, B. Herskind, H. Hübel, and D. R. Jensen, Phys. Lett. B 553, 197.
[16] D. J. Hartley, R. V. F. Janssens, L. L. Riedinger, M. A. Riley, A. Aguilar, M. P. Carpenter, C. J. Chiara, P. Chowdhury, I. G. Darby, U. Garg, et al., Phys. Rev. C 80, 041304 (2009).

[17] S. Frauendorf and F. Dönau, Phys. Rev. C 89, 014322 (2014).

[18] D. L. Balabanski, M. Danchev, D. J. Hartley, L. L. Riedinger, O. Zeidan, J. ye Zhang, C. J. Barton, C. W. Beausang, M. A. Caprio, R. F. Casten, et al., Phys. Rev. C 70, 044305 (2004).

[19] P. L. Masiteng, E. A. Lawrie, T. M. Ramashidza, R. A. Bark, B. G.Carlsson, J. J. Lawrie, R. Lindsay, F. Komati, J. Kau, P. Maine, et al., Phys. Lett. B 719, 83 (2013).

[20] E. A. Lawrie, P. A. Vymers, J. J. Lawrie, C. Vieu, R. A. Bark, R. Lindsay, G. K. Mabala, S. M. Maliage, P. L. Masiteng, S. M. Mullins, et al., Phys. Rev. C 78, 021305 (2008).

[21] M. P. Carpenter, C. R. Bingham, L. H. Courtney, V. P. Janzen, A. J. Larabee, Z. M. Liu, L. L. Riedinger, W. Schmitz, R. Bengtsson, T. Bengtsson, et al., Nucl. Phys. A 513, 125 (1990).

[22] T. Nikšić, D. Vretenar, and P. Ring, Prog. Part. and Nucl. Phys. 66, 519 (2011).

[23] J. Meyer-ter Vehn, Nucl. Phys. A249, 111 (1975).

[24] F. Dönau and S. Frauendorf, Phys. Lett. B 71, 263 (1977).

[25] D. C. Radford, Nucl. Instrum. and Methods in Phys. Res. A 361, 297 (1995).

[26] N. Sensharma et al., To be published.

[27] M. A. Deleplanque, C. Gerschel, M. Ishihara, N. Perrin, V. Berg, C. Bourgeois, M. G. Desthuilliers, J. P. Husson, P. Kilcher, and J. Letessier, J. Phys. (Paris) 36, L (1975).

[28] C. Bourgeois, P. Kilcher, J. Letessier, V. Berg, and M. G. Desthuilliers, Nucl. Phys. A 295, 424 (1978).

[29] C. Bourgeois, M. G. Porquet, N. Perrin, H. Sergolle, F. Hannachi, G. Bastin, and F. Beck, Z. Physik A - Atomic Nuclei 333, 5 (1989).

[30] 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, and L. L. Riedinger, Phys. Rev. C 40, 132 (1989).

[31] I. Hamamoto, Phys. Rev. C 65, 044305 (2002).

[32] E. Streck, Q. B. Chen, N. Kaiser, and U.-G. Meißner, Phys. Rev. C 98, 044314 (2018).

[33] P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng, Phys. Rev. C 82, 054319 (2010).

[34] J. Meng, J. Peng, S. Q. Zhang, and S.-G. Zhou, Phys. Rev. C 73, 037303 (2006).

[35] J. Meng, ed., Relativistic Density Functional for Nuclear Structure (World Scientific, 2016).

[36] J. Meng, J. Peng, S. Q. Zhang, and P. W. Zhao, Front. Phys. 8, 55 (2013).

[37] R. Rodriguez-Guzmán, P. Sarriguren, L. M. Robledo, and J. E. García-Ramos, Phys. Rev. C 81, 024310 (2010).

[38] M. S. Basunia, Nucl. Data Sheets 110, 599 (2009).

[39] C. M. Baglin, Nucl. Data Sheets 99, 1 (2003).