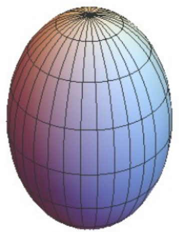
Wobbling motion in ^{187}Au

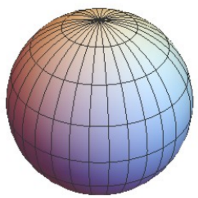
Nirupama Sensharma
Heavy-ion Discussions at Argonne National Laboratory
June 19, 2020
University of Notre Dame

Nuclear Shapes

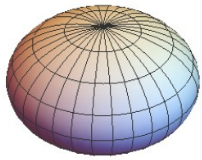
Prolate

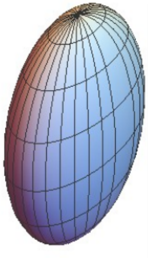


Spherical



Oblate



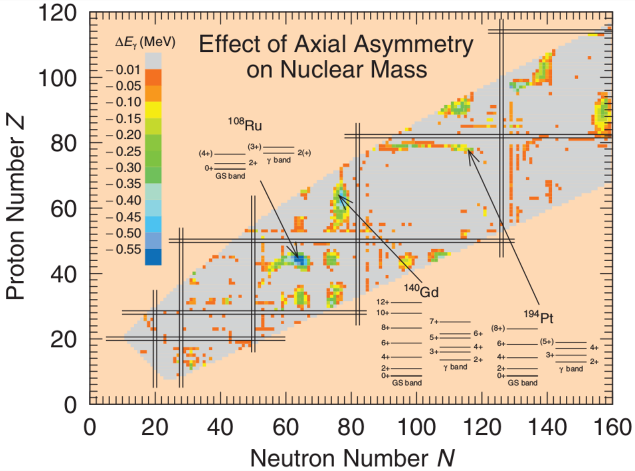


Triaxial

Triaxial Region

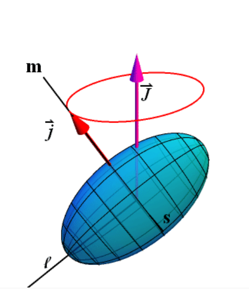
Triaxiality - A rare phenomenon!

P. Möller et. al. PRL 97, 162502 (2006)



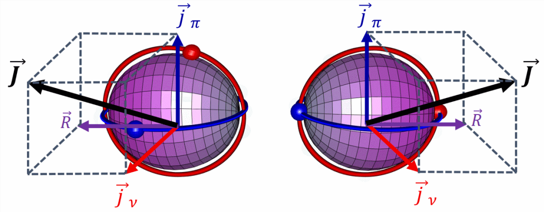
Experimental signatures of Triaxiality

Nuclear Wobbling Motion



Animation courtesy - J. T. Matta

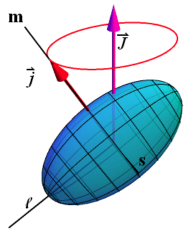
Chiral Rotation in nuclei

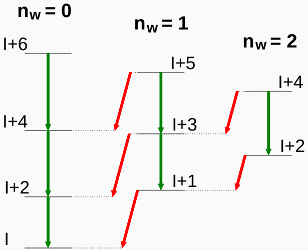


Animation courtesy - X. H. Wu

Observation of either of these modes constitute irrefutable evidence of triaxiality.

Wobbling - Unique fingerprint of Triaxiality



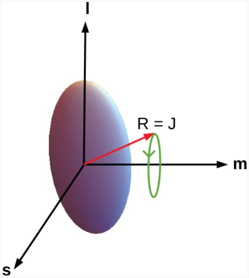


- Harmonic oscillation of one of the principal axes about the space fixed $\vec{J}$.
- Analog of the spinning motion of an asymmetric top.

Standard fingerprints for Wobbling bands:

- Rotational bands corresponding to n_w = 0, 1, 2, ...
- Transitions from $n_{w+1} \rightarrow n_w$ ($\Delta n_w = +1$)
- Interband Transitions are $\Delta \mathrm{I} = 1$, E2

Wobbling in even-even nuclei



- Simple Wobbling - as predicted by *Bohr and Mottelson*
- Small amplitude oscillations of $\vec{J}$ about the largest MOI axis (m-axis)

Energy of a rigid triaxial rotor: $E = A_l J_l^2 + A_s J_s^2 + A_m J_m^2$

Rotational parameters: $A_k = \dfrac{\hbar^2}{2\mathcal{J}_k}\,(\mathcal{J}_l < \mathcal{J}_s < \mathcal{J}_m \implies A_l > A_s > A_m)$

From conservation of angular momentum: $J^2 = J_l^2 + J_s^2 + J_m^2 = I(I+1)$

Wobbling energy, $\hbar\omega_w = 2I\left((A_l - A_m)(A_s - A_m)\right)^{1/2}$

$\implies$ Wobbling energy increases with increasing spin

Previous cases of Wobbling

VOLUME 86, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 2001

Evidence for the Wobbling Mode in Nuclei

S. W. Ødegård,[1,2] G. B. Hagemann,[1] D. R. Jensen,[1] M. Bergström,[1] B. Herskind,[1] G. Sletten,[1] S. Törmänen,[1] J. N. Wilson,[1] P. O. Tjøm,[2] I. Hamamoto,[3] K. Spohr,[4] H. Hübel,[5] A. Görgen,[5] G. Schönwasser,[5] A. Bracco,[6] S. Leoni,[6] A. Maj,[7] C. M. Petrache,[8,*] P. Bednarczyk,[7,9] and D. Curien[9]

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Physics Letters B 553 (2003) 197–203
PHYSICS LETTERS B
www.elsevier.com/locate/npe

The wobbling mode in ^{167}Lu

H. Amro[a,b,c], W.C. Ma[a], G.B. Hagemann[b], R.M. Diamond[d], J. Domscheit[e], P. Fallon[d], A. Görgen[d], B. Herskind[b], H. Hübel[e], D.R. Jensen[b], Y. Li[a], A.O. Macchiavelli[d], D. Roux[a], G. Sletten[b], J. Thompson[a], D. Ward[d], I. Wiedenhöver[f], J.N. Wilson[b], J.A. Winger[a]

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Physics Letters B 552 (2003) 9–16
PHYSICS LETTERS B
www.elsevier.com/locate/npe

One- and two-phonon wobbling excitations in triaxial ^{165}Lu

G. Schönwaßer[a], H. Hübel[a], G.B. Hagemann[b], P. Bednarczyk[c,d], G. Benzoni[e], A. Bracco[e], P. Bringel[a], R. Chapman[f], D. Curien[c], J. Domscheit[a], B. Herskind[b], D.R. Jensen[b], S. Leoni[e], G. Lo Bianco[g], W.C. Ma[h], A. Maj[d], A. Neußer[a], S.W. Ødegård[i], C.M. Petrache[g], D. Roßbach[a], H. Ryde[j], K.H. Spohr[f], A.K. Singh[a]

Eur. Phys. J. A 24, 167–172 (2005)
DOI 10.1140/epja/i2005-10005-7
THE EUROPEAN PHYSICAL JOURNAL A

Evidence for wobbling excitation in ^{161}Lu

P. Bringel[1,a], G.B. Hagemann[2], H. Hübel[1], A. Al-khatib[1], P. Bednarczyk[3,b], A. Bürger[1], D. Curien[3], G. Gangopadhyay[4], B. Herskind[2], D.R. Jensen[2], D.T. Joss[5], Th. Kröll[6,c], G. Lo Bianco[7], S. Lunardi[8], W.C. Ma[9], N. Nenoff[1], A. Neußer-Neffgen[1], C.M. Petrache[7], G. Schönwasser[1], J. Simpson[5], A.K. Singh[1,d], N. Singh[10], and G. Sletten[2]

PHYSICAL REVIEW C 80, 041304(R) (2009)

Wobbling mode in ^{167}Ta

D. J. Hartley,[1] R. V. F. Janssens,[2] L. L. Riedinger,[3] M. A. Riley,[4] A. Aguilar,[4,*] M. P. Carpenter,[2] C. J. Chiara,[2,5,6] P. Chowdhury,[7] I. G. Darby,[3] U. Garg,[8] Q. A. Ijaz,[9] F. G. Kondev,[5] S. Lakshmi,[7] T. Lauritsen,[2] A. Ludington,[1,†] W. C. Ma,[9] E. A. McCutchan,[2] S. Mukhopadhyay,[8] R. Pifer,[1] E. P. Seyfried,[1] I. Stefanescu,[2,6] S. K. Tandel,[7] U. Tandel,[7] J. R. Vanhoy,[1] X. Wang,[4] S. Zhu,[2] I. Hamamoto,[10] and S. Frauendorf[8]

Previous cases of Wobbling (cont..)

Breakthrough observation in 2015 – Wobbling found in A $\sim$ 130 region

PRL **114,** 082501 (2015) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2015

Transverse Wobbling in ^{135}Pr

J. T. Matta, U. Garg, W. Li, S. Frauendorf, A. D. Ayangeakaa,[†] D. Patel, and K. W. Schlax
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA

Note: First observation of wobbling at low deformation ($\epsilon \sim 0.16$) based on $\pi h_{11/2}$

whereas,

the previously observed cases involved an odd $\pi i_{13/2}$ and significantly larger deformations ($\epsilon \sim 0.40$).

Previous cases of Wobbling (cont..)

Breakthrough observation in 2015 – Wobbling found in A $\sim$ 130 region

PRL **114,** 082501 (2015) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2015

Transverse Wobbling in ^{135}Pr

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Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA

Note: First observation of wobbling at low deformation ($\epsilon \sim 0.16$) based on $\pi h_{11/2}$

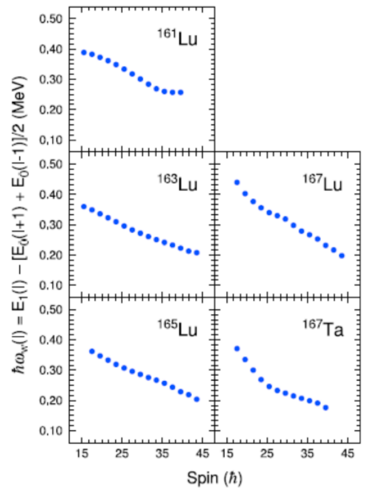
whereas,

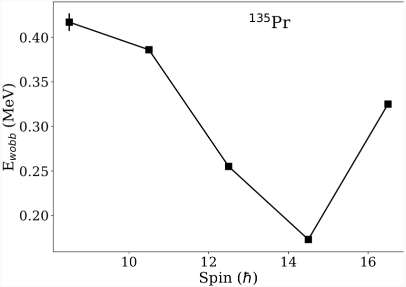
the previously observed cases involved an odd $\pi i_{13/2}$ and significantly larger deformations ($\epsilon \sim 0.40$).

But wait, there was a problem!

Wobbling Energy (*from previously known wobblers*)

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.

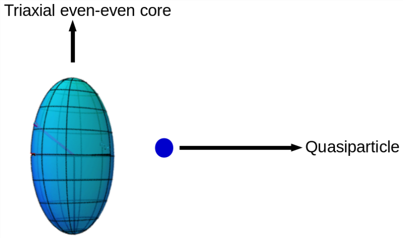




Revaluation was required to determine why E_{wobb} was found to decrease with increasing spin.

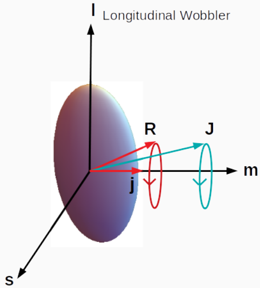
Quasiparticle Triaxial Rotor Calculations

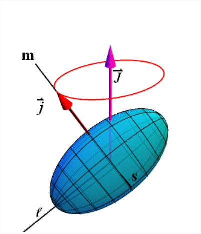
Discrepancy resolved by S. Frauendorf and F.Dönau by utilizing the QTR model to study triaxiality in odd-mass nuclei.



- Triaxial even-even core coupled to an odd quasiparticle.
- Odd quasiparticle – high *j* unpaired proton/neutron – couples with the triaxial core and provides necessary alignment.
- This coupling modifies the wobbling motion considerably.

Wobbling in odd-A nuclei - Types of Wobbling (1/2)





- Odd-particle aligned with axis with max. MOI (m-axis)
- $\mathcal{J}_3 > \mathcal{J}_2$ and $\mathcal{J}_3 > \mathcal{J}_1$
- Longitudinal wobbling: $\mathcal{J}_3 = \mathcal{J}_m$

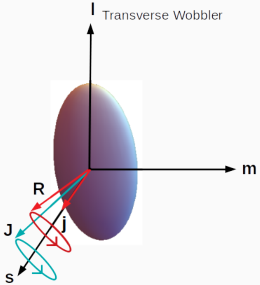
Animation Courtesy - Dr. J. T. Matta

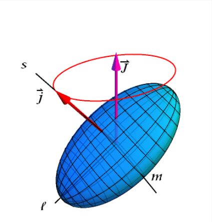
Wobbling energy, $\hbar\omega_w = \frac{j}{\mathcal{J}_3}\left[\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_1}-1\right)\right)\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_2}-1\right)\right)\right]^{1/2}$

$\implies$ E_{wobb} increases with J

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

Wobbling in odd-A nuclei - Types of Wobbling (2/2)





- Odd-particle aligned perpendicular to axis with max. MOI (s- or l-axis)
- $\mathcal{J}_3 < \mathcal{J}_2$ and $\mathcal{J}_3 > \mathcal{J}_1$
- Transverse wobbling: $\mathcal{J}_3 = \mathcal{J}_s$

Animation Courtesy - Dr. J. T. Matta

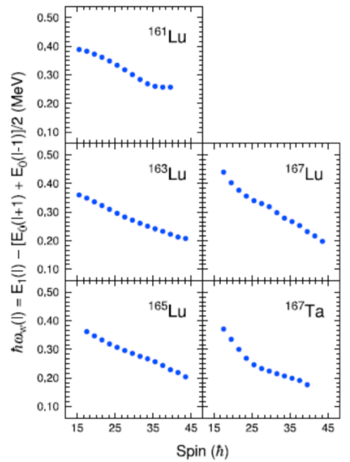
$$\text{Wobbling energy, } \hbar\omega_w = \frac{j}{\mathcal{J}_3}\left[\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_1}-1\right)\right)\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_2}-1\right)\right)\right]^{1/2}$$

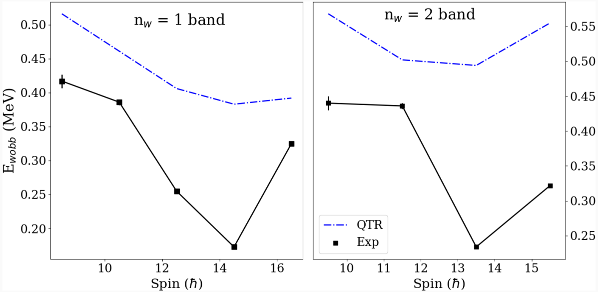
$\implies$ E_{wobb} decreases with J

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

Wobbling Energy (*from previously known wobblers*) – Revaluated

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.





J. T. Matta et al., Phys. Rev. Lett. 114, 082501 (2015)

N. Sensharma et al., Phys. Lett. B 792 (2019)

Transverse Wobbling

Odd particle aligns ⊥ to axis with maximum M.O.I

Previous cases of Wobbling (cont..)

PRL **114,** 082501 (2015) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2015

Transverse Wobbling in ^{135}Pr

J. T. Matta, U. Garg, W. Li, S. Frauendorf, A. D. Ayangeakaa,[†] D. Patel, and K. W. Schlax
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA

Further confirmation obtained by the existence of $n_\omega = 2$ wobbling band

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Two-phonon wobbling in ^{135}Pr

Check for updates

N. Sensharma[a], U. Garg[a,*], S. Zhu[b], A.D. Ayangeakaa[b,1], S. Frauendorf[a], W. Li[a,c], G.H. Bhat[d], J.A. Sheikh[e], M.P. Carpenter[b], Q.B. Chen[f], J.L. Cozzi[a], S.S. Ghugre[g], Y.K. Gupta[a,h], D.J. Hartley[i], K.B. Howard[a], R.V.F. Janssens[j,k], F.G. Kondev[b], T.C. McMaken[a,2], R. Palit[l], J. Sethi[b], D. Seweryniak[b], R.P. Singh[m]

Previous cases of Wobbling (cont..)

Another observation in A $\sim$ 130 region

Eur. Phys. J. A (2019) **55**: 159
DOI 10.1140/epja/i2019-12856-5

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

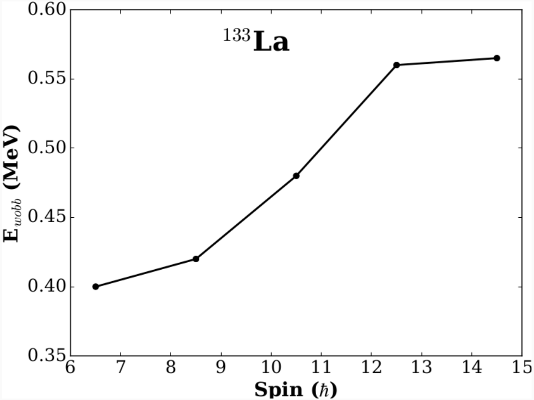
Longitudinal wobbling in ^{133}La

S. Biswas[1], R. Palit[1,a], S. Frauendorf[2], U. Garg[2], W. Li[2], G.H. Bhat[3,4], J.A. Sheikh[3,4], J. Sethi[1], S. Saha[1], Purnima Singh[1], D. Choudhury[1], J.T. Matta[2], A.D. Ayangeakaa[2], W.A. Dar[3], V. Singh[5], and S. Sihotra[5]

[1] Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Colaba, Mumbai, 400 005, India
[2] University of Notre Dame, Notre Dame, IN 46556, USA
[3] Department of Physics, University of Kashmir, Srinagar, 190 006, India
[4] Cluster University of Srinagar, Jammu and Kashmir, Srinagar, 190001, India
[5] Department of Physics, Panjab University, Chandigarh 160014, India

Wobbling Energy for ^{133}La

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.



First case of Longitudinal Wobbling

Also based on a $\pi h_{11/2}$ configuration.
Odd particle aligns parallel to axis with maximum M.O.I

S. Biswas et al., Eur. Phys. J. A 55, 159 (2019)

More on wobbling...

First observation of wobbling in A $\sim$ 100 region

PHYSICAL REVIEW LETTERS **122,** 062501 (2019)

Experimental Evidence for Transverse Wobbling in ^{105}Pd

J. Timár,[1,*] Q. B. Chen,[2] B. Kruzsicz,[1] D. Sohler,[1] I. Kuti,[1] S. Q. Zhang,[3] J. Meng,[3] P. Joshi,[4] R. Wadsworth,[4] K. Starosta,[5] A. Algora,[1,6] P. Bednarczyk,[7] D. Curien,[8] Zs. Dombrádi,[1] G. Duchêne,[8] A. Gizon,[9] J. Gizon,[9] D. G. Jenkins,[4] T. Koike,[10] A. Krasznahorkay,[1] J. Molnár,[1] B. M. Nyakó,[1] E. S. Paul,[11] G. Rainovski,[12] J. N. Scheurer,[13] A. J. Simons,[4] C. Vaman,[14] and L. Zolnai[1]

First experimental evidence for TW bands based on a one-neutron configuration ($\nu h_{11/2}$).

More on wobbling...

First observation of wobbling in A $\sim$ 100 region

PHYSICAL REVIEW LETTERS **122,** 062501 (2019)

Experimental Evidence for Transverse Wobbling in ^{105}Pd

J. Timár,[1,*] Q. B. Chen,[2] B. Kruzsicz,[1] D. Sohler,[1] I. Kuti,[1] S. Q. Zhang,[3] J. Meng,[3] P. Joshi,[4] R. Wadsworth,[4] K. Starosta,[5] A. Algora,[1,6] P. Bednarczyk,[7] D. Curien,[8] Zs. Dombrádi,[1] G. Duchêne,[8] A. Gizon,[9] J. Gizon,[9] D. G. Jenkins,[4] T. Koike,[10] A. Krasznahorkay,[1] J. Molnár,[1] B. M. Nyakó,[1] E. S. Paul,[11] G. Rainovski,[12] J. N. Scheurer,[13] A. J. Simons,[4] C. Vaman,[14] and L. Zolnai[1]

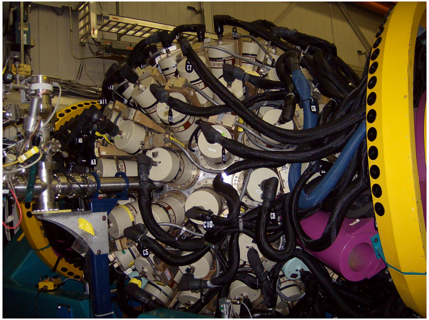
Are there other regions of nuclear chart where wobbling bands may be observed?

Exploring in A $\sim$ 190 region

- Significant triaxiality suggested for nuclei at low spins in this mass region.
  (T. Nikšic, et. al. Part. Nucl. Phys. 66 (2011))
- Clear evidence for triaxiality provided by observation of chiral band pairs in ^{188}Ir, ^{194}Tl and ^{198}Tl.
- Our choice - ^{187}Au
  - The nucleus ^{186}Pt known to exhibit triaxial behavior.
  - Wobbling observed so far mostly in odd-Z nuclei.
  - The $\pi h_{9/2}$ orbital expected to lead to stabilization of triaxial shapes in this region.

Experiment

- Gammasphere array
- Reaction: ^{174}Yb(^{19}F,6n)^{187}Au
- Target: 13 mg/cm^2 ^{174}Yb deposited on 33 mg/cm^2 ^{208}Pb backing



	Run #1	Run #2
Beam Energy (MeV)	105	115
No. of detectors	57	73
No.of triple coincidence events	4.4×10^8	6.3×10^8

Experiment

- Gammasphere array
- Reaction: ^{174}Yb(^{19}F,6n)^{187}Au
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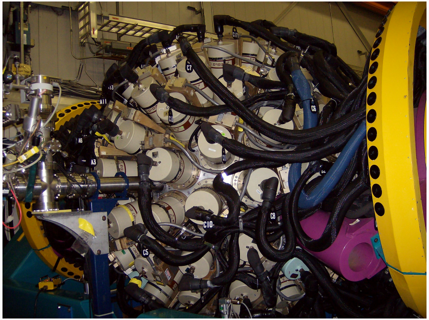

	Run #1	Run #2
Beam Energy (MeV)	105	115
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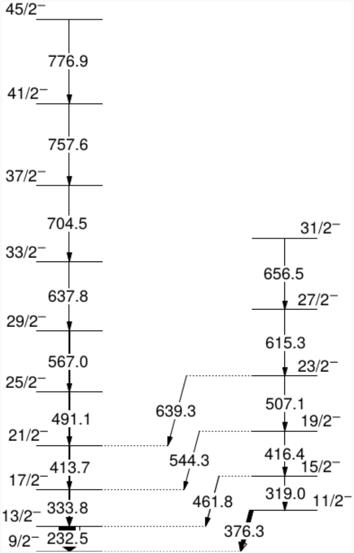
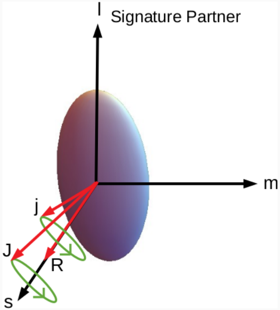
Partial Level Scheme of ^{187}Au (Previous Measurements)

C. Bourgeois et al., Z. Physik A - Atomic Nuclei 333, 5 (1989)

- Spin and Parity of bandhead at $\frac{9}{2}^-$, E_x = 121.0 keV firmly established.
- Yrast band built on the lowest $\pi h_{9/2}$ structure.
- The two bands reported as two signatures, $\alpha = (\mp\frac{1}{2})$ of the $\pi h_{9/2}$ state.



Signature Partner (SP) Band (A short review)

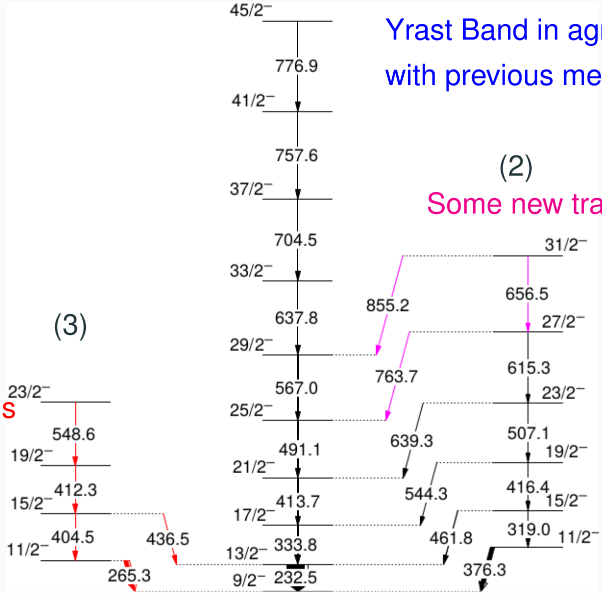


A principal axis rotation leads to sequences of $\Delta I = 2$ bands having alternate signatures (α).

For odd-A nuclei, α takes values $\pm 1/2$.

- Triaxial core coupled with a quasiparticle – yrast and SP bands observed.
- Angular momentum of quasiparticle not aligned with the s-axis anymore, but moves around the s-axis.
- SP $\rightarrow$ Yrast connecting transitions are pure M1 in nature.

Partial Level Scheme of ^{187}Au (extended from the present work)



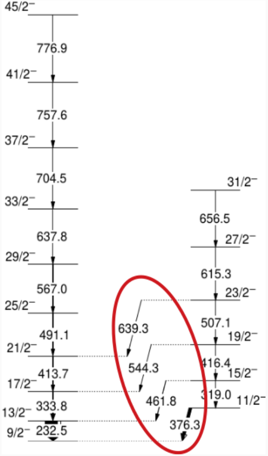
Yrast Band in agreement with previous measurement

(2)
Some new transitions found

A new band with 2 connections to Yrast Band

Spectroscopic Properties (Previous Measurements)

C. Bourgeois et al., Z. Physik A - Atomic Nuclei 333, 5 (1989)

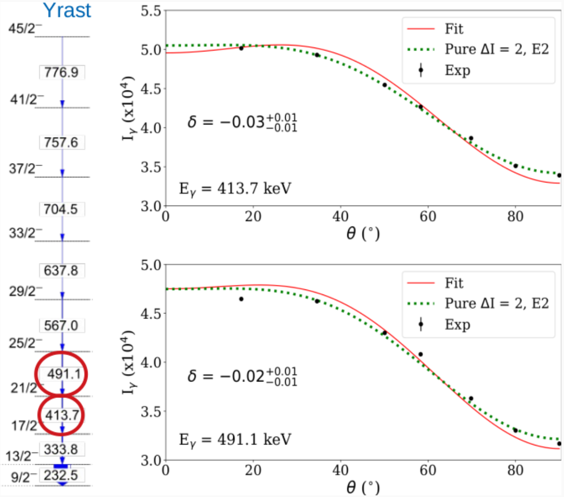


- Band 2 $\rightarrow$ Band 1 γs reported as M1/E2 in nature.
- Angular distributions at 12°, 33° and 90°.
- Precise δ values missing.

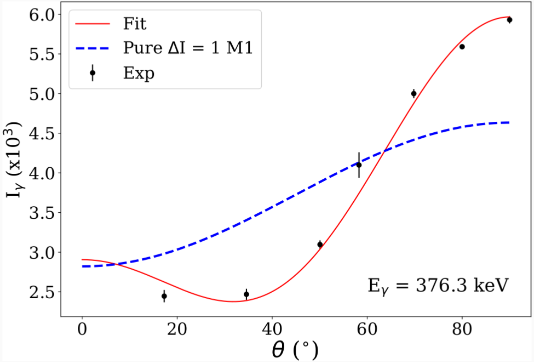
E_γ (keV)	Location[a]	P[b]	R[b]	Adopted multipolarity
133	7		0.5 (2)	$M1+E2$[c]
150	7		0.6 (2)	$M1$[c]
163	8		0.5 (1)	$M1+E2$
167	7		0.6 (2)	$M1+E2$[c]
279	8			$M1+E2$
281	8	−0.19 (7)	0.7 (1)	$M1+E2$
297	8	−0.35 (10)	0.5 (1)	$M1+E2$
325	8		0.5 (2)	$M1+E2$
353	8	−0.07 (2)	0.3 (1)	$M1+E2$
376	2→1	−0.10 (5)	0.3 (1)	$M1+E2$
384	6		0.7 (3)	$(L=1)$
407	7		0.6 (2)	$L=1$
462	2→1		0.20 (5)	$M1+E2$
464	8	−0.25 (10)	0.3 (1)	$M1+E2$
465	4→2		0.6 (2)	$E1$
474	6		0.6 (4)	$(L=1)$
509	8→1		0.4 (1)	$M1+E2$[c]
544	2→1	−0.2 (1)	0.2 (1)	$M1+E2$
565	4→2	0.4 (2)	0.6 (2)	$E1$

Spectroscopic Properties (Present Measurement)

- Present work performed a complete angular distribution analysis (17.3°, 34.6°, 50.1°, 58.3°, 69.8°, 80.0° and 90.0°).
- Precise δ values were extracted using a Markov-Chain Monte Carlo (MCMC) sampling technique.
- Method benchmarked by establishing distribution of a known pure-E2 transition.



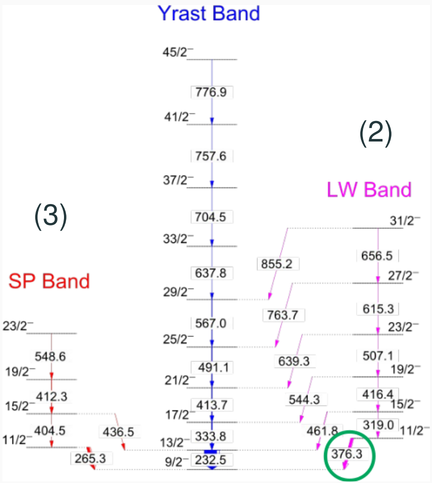
Angular Distributions (1/7)



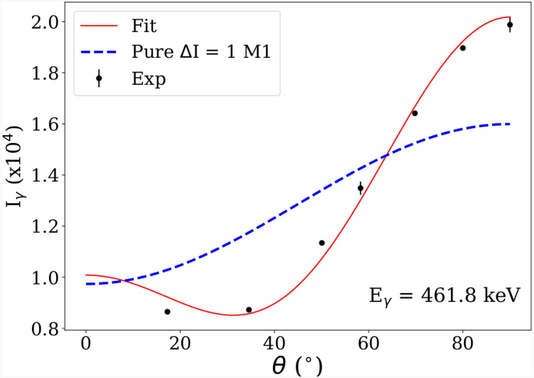
$$\delta = -2.67^{+0.07}_{-0.07}$$

$$E2\% = 87.7^{+0.5}_{-0.6}$$

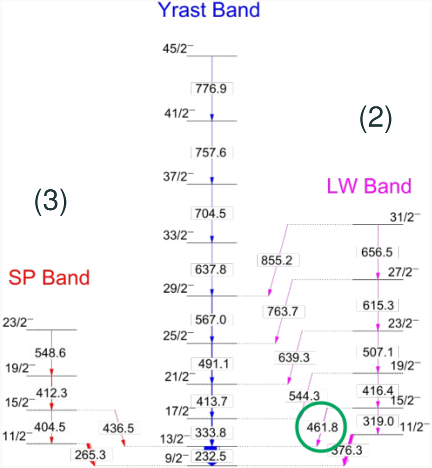
E_γ = 376.3 keV



Angular Distributions (2/7)



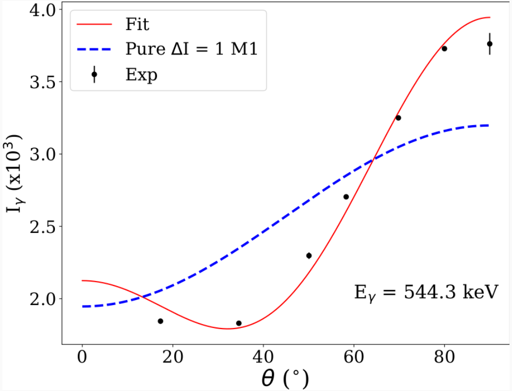
E_γ = 461.8 keV



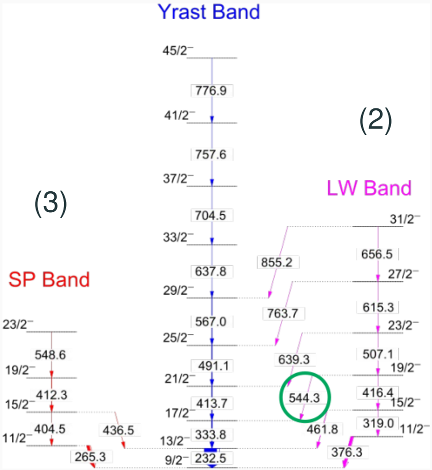
δ = **-2.98**$^{+0.02}_{-0.02}$

E2% = 89.9$^{+0.1}_{-0.1}$

Angular Distributions (3/7)

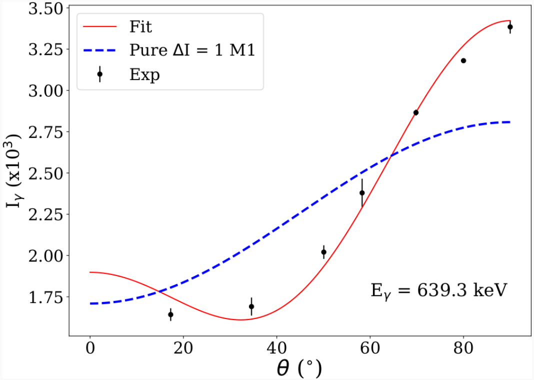


E_γ = 544.3 keV



$$\delta = \mathbf{-3.44}^{+0.03}_{-0.03}$$

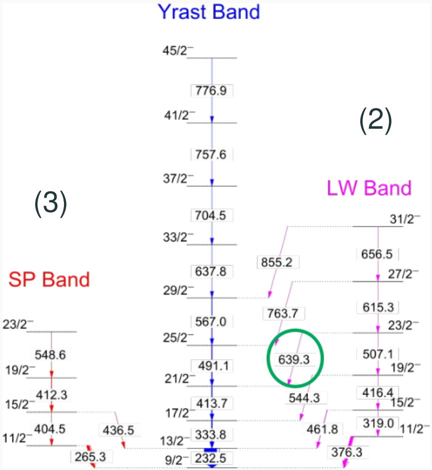
$$\mathbf{E2\%} = \mathbf{92.2}^{+0.1}_{-0.1}$$



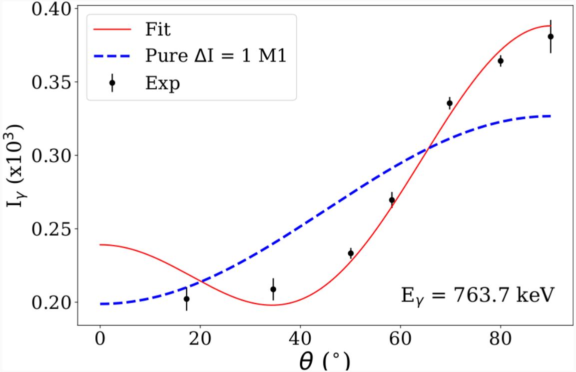
$\delta = -3.72^{+0.11}_{-0.12}$

E2% = $93.3^{+0.4}_{-0.4}$

E_γ = 639.3 keV



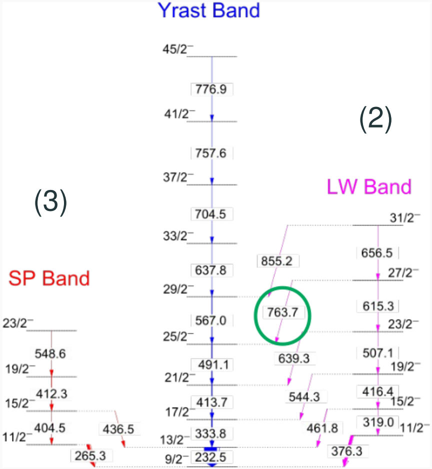
Angular Distributions (5/7)



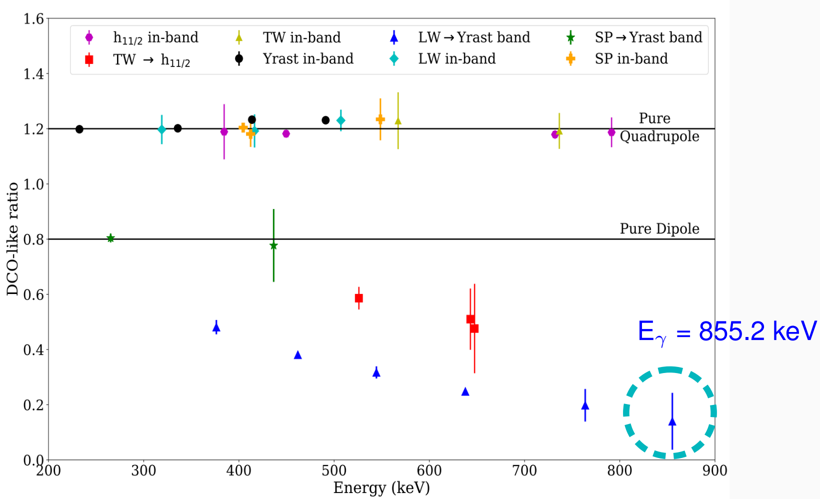
δ = $-4.51^{+0.24}_{-0.26}$

E2% = $95.3^{+0.5}_{-0.5}$

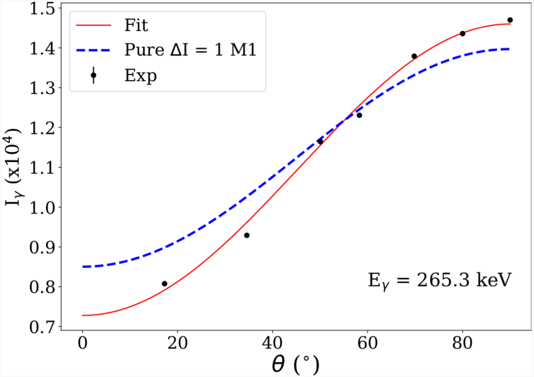
E_γ = 763.7 keV



DCO-like Ratios



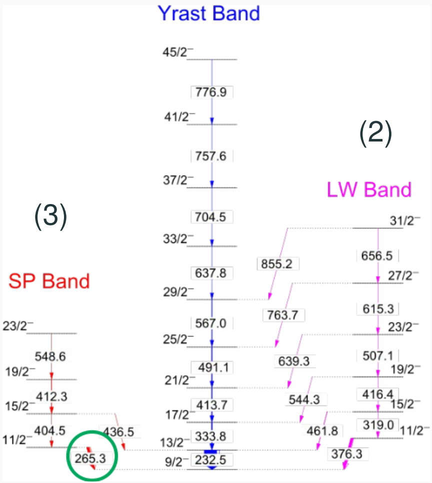
Angular Distributions (6/7)



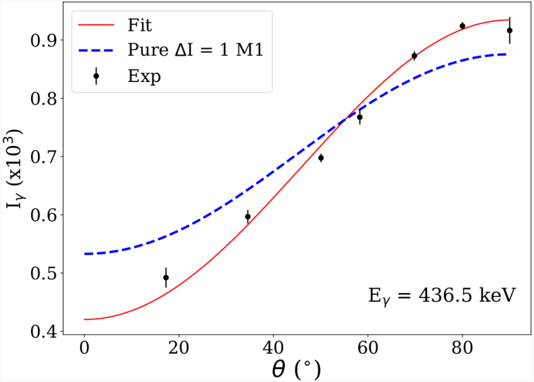
δ = **-0.06**$^{+0.01}_{-0.01}$

E2% = 0.4$^{+0.1}_{-0.1}$

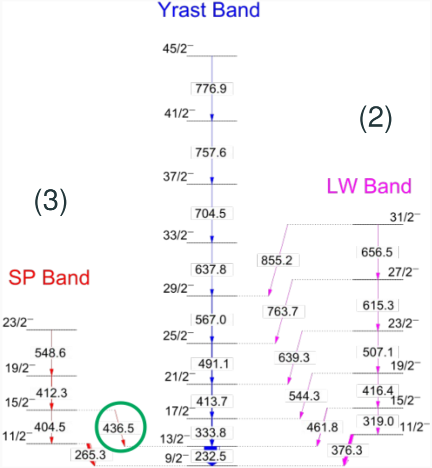
E_γ = 265.3 keV



Angular Distributions (7/7)



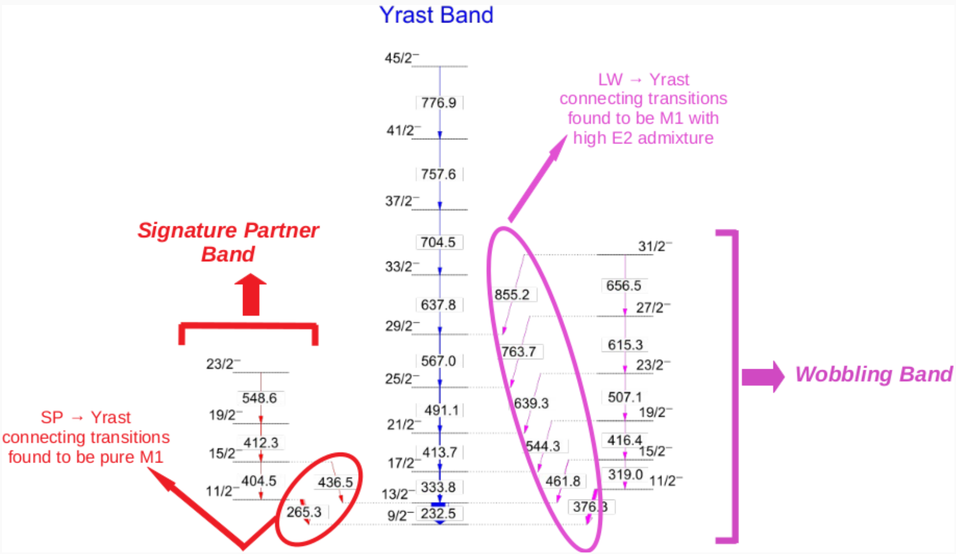
E_γ = 436.5 keV



δ = $-0.10^{+0.01}_{-0.01}$

E2% = $1.0^{+0.2}_{-0.1}$

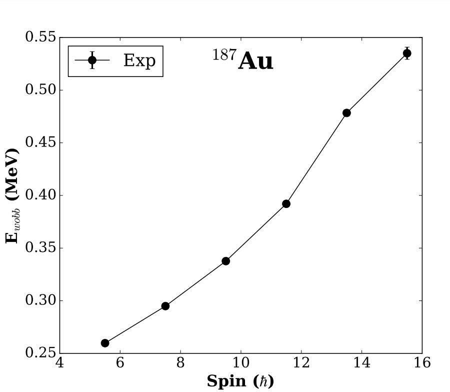
Partial Level Scheme of ^{187}Au (from the present work) Part I



Wobbling Energy for ^{187}Au

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.

$$E_{\text{wobb}}(I) = E(I, n_\omega = 1) - \left(\frac{E(I-1, n_\omega = 0) + E(I+1, n_\omega = 0)}{2} \right) \tag{1}$$

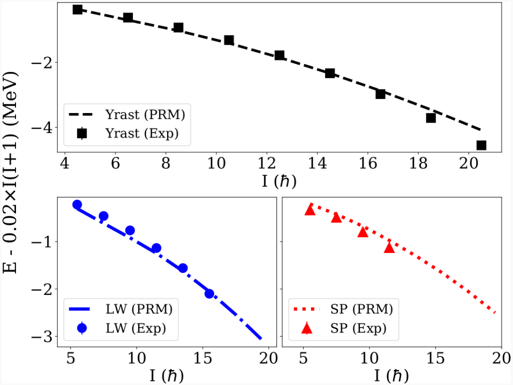


^{187}Au - Only the second case of Longitudinal Wobbling!

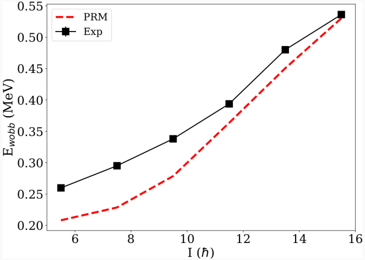
Particle Rotor Model (PRM) Calculations ($h_{9/2}$ *band structures*)

Deformation parameters β = 0.23, γ = 23°, pairing gap Δ = 0.88 MeV.

Excitation Energies



Wobbling Energy



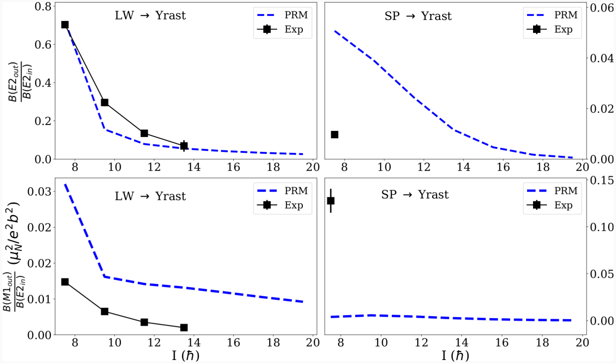
PRM reproduces the increasing trend in E_{wobb}, but value slightly underestimated compared to experiment.

N. Sensharma et al., Phys. Rev. Lett. 124, 052501 (2020)

Particle Rotor Model (PRM) Calculations ($h_{9/2}$ *band structures*) (cont.)

High reduced E2 transition probability, B(E2), for connecting transitions – indicative of wobbling bands.

Reduced Transition Probability Ratios



- Large $B(E2)_{out}/B(E2)_{in}$ – collective quadrupole excitation – characteristic of wobbling bands.
- $B(M1)_{out}/B(E2)_{in}$ overestimated for LW and underestimated for SP – incorrect mixing between states – sensitive to E_{ex} and MOI ratios.

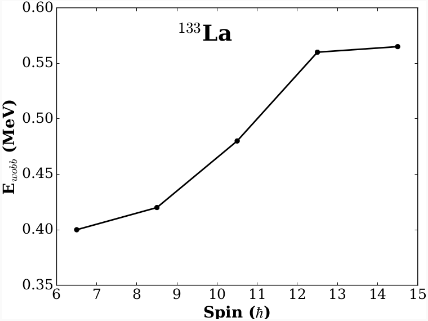
N. Sensharma et al., Phys. Rev. Lett. 124, 052501 (2020)

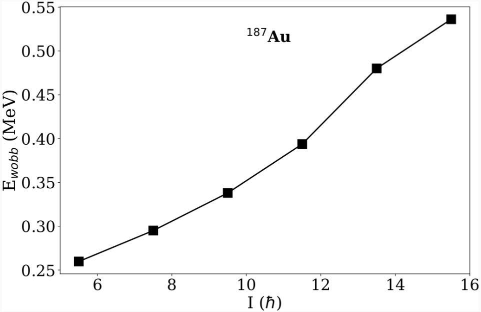
Summarizing results of the $h_{9/2}$ bands-pair

- ^{187}Au – first wobbling observation in the A $\sim$ 190 region.
- Two rotational bands have been identified as the $n_\omega = 0$ and $n_\omega = 1$ wobbling-bands pair.
- The signature partner of the $n_\omega = 0$ (yrast) band has also been identified.
- An increasing E_{wobb} with spin establishes ^{187}Au as a *longitudinal wobbler*.

Longitudinal Wobbling in ^{133}La and ^{187}Au (Summary - cont.)

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.





Longitudinal wobbling band observed but its associated signature partner not observed.

First case of a longitudinal wobbling band, clearly distinguished from the associated signature partner band.

Publicity...

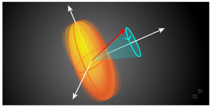
Physics ABOUT BROWSE PRESS COLLECTIONS

SYNOPSIS

Gold Nucleus is Wobbly

February 5, 2020 • *Physics* 13, s17

A rare kind of nuclear spinning motion has been detected in an isotope of gold.



APS/Alan Stonebraker

Planets, footballs, and even some large molecules have something in common: they rotate as rigid, classical bodies. Atomic nuclei are another matter, in that quantum mechanics allows strange new modes of motion. In experiments involving a short-lived isotope of gold, ^{187}Au, Nirupama Sensharma at the University of Notre Dame, Indiana, and colleagues have observed an unusual rotational mode, predicted in 2014, called longitudinal wobbling. Seeing this wobbling mode in such a heavy nucleus puts constraints on theories of nuclear structure.

Like other nuclei with an odd number of nucleons, ^{187}Au can be modeled as a spinning ellipsoid with an independent nucleon orbiting within it. In its ground state, the system rotates smoothly about one of the ellipsoid's axes. But at higher energies, ^{187}Au, like other ellipsoidal nuclei with three unequal axes, can exhibit a more complex motion. This motion comes from the nucleon tugging on the nucleus, making its rotation axis wobble like an unbalanced spinning top. Alignment between the nucleon's orbital axis and the nucleus's long or short dimensions produces transverse wobbling, which has been seen in a handful of nuclei. Sensharma and colleagues' study provides the first clear detection of longitudinal wobbling, in which the nucleon's orbital axis aligns with the nucleus's intermediate-length axis.

The researchers spotted the new mode's signature in the nuclear debris created by firing fluorine ions at an ytterbium target. Among the isotopes produced in the collision were a host of ^{187}Au nuclei in various excited states. By analyzing the gamma rays emitted as these excited states decayed, the team reconstructed the initial population —including the predicted longitudinal wobbling states. They expect further examples of heavy triaxial nuclei to show up in future studies.

This research is published in *Physical Review Letters*.

–Marric Stephens

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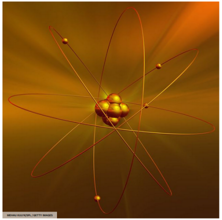
Sad: This Isotope Lives for Just 8 Minutes and Leaves Behind a Wobbly Nucleus

But the ramifications could be huge.

// BY CAROLINE DELBERT FEB 12, 2020



MEHAU KULYK/SPL / GETTY IMAGES

- **An isotope of gold has given scientists their first glimpse of longitudinal nuclear wobbling.**
- **The documented wobbling is similar to the way the Earth wobbles, caused by things like unequal axes.**
- **The nucleus is a prolate spheroid, like a rugby ball, and should lead to discovery of more wobbly isotopes.**

Scientists have identified a short-lived isotope of gold with a wobbly nucleus. The isotope is created by a nuclear reaction, and the research team believes the nucleus wobbles because of one extra nucleon. A large team from the U.S. and India has published its findings in *Physical Review Letters*.

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Science News *from research organizations*

Physicists see nuclear wobbling in one isotope of gold

Date: February 18, 2020

Source: University of Notre Dame

Summary: Researchers recently discovered that some nuclei wobble on their intermediate axes.

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FULL STORY

Nuclei can be round, like a soccer ball, or oblong, like a football. Others are slightly oblong but misshapen, like a potato. One of the only two ways to observe the third shape, rarely encountered, is when the nucleus wobbles like a lopsided top.

Researchers had previously seen these rare triaxial nuclei wobble on their shorter, transverse axes. But University of Notre Dame researchers and collaborators recently discovered that the nuclei also wobble on their intermediate axes. Their research, "Longitudinal Wobbling Motion in 187Au," was published recently in the premier physics journal, *Physical Review Letters*.

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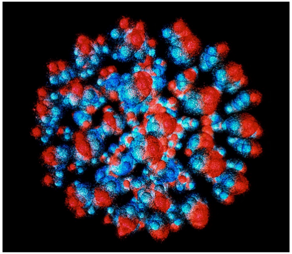

A gold atom's nucleus (pictured, artist's impression) has been observed executing an unusual type of spinning motion. Credit: ARSCIMED/SPL

ATOMIC AND MOLECULAR PHYSICS · 13 FEBRUARY 2020

Rarer than gold: wobbling gold

Scientists catch their first glimpse of an intricate type of nuclear movement.

For the first time, physicists have clearly observed a rare and complex motion of atomic nuclei called longitudinal wobbling.

An atomic nucleus is composed of protons and neutrons, collectively called nucleons. In an excited state, some nuclei with an odd number of nucleons exhibit a complex wobble – like that of a spinning top – because of their imbalanced geometry. Previous observations detected wobbling around only either the longest or shortest axis of nuclei having fewer than 170 nucleons.

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NUCLEAR PHYSICS

A wobbly nucleus

Jelena Stajic

+ See all authors and affiliations

Science 28 Feb 2020:
Vol. 367, Issue 6481, pp. 996-997
DOI: 10.1126/science.367.6481.996-g

Article | Info & Metrics | eLetters | PDF

Atomic nuclei consist of nucleons—protons and neutrons. The composition of the nucleus affects its overall shape, ranging from spherical to ellipsoidal with three unequal axes. Nuclei with the latter shape—referred to as triaxial—are prone to wobbling, behaving not unlike a spinning top. Sensharma *et al.* studied a particular kind of wobble in a gold nucleus, ^{187}Au. They found that this nucleus exhibits longitudinal wobbling, a phenomenon that has been theorized but not observed experimentally before.

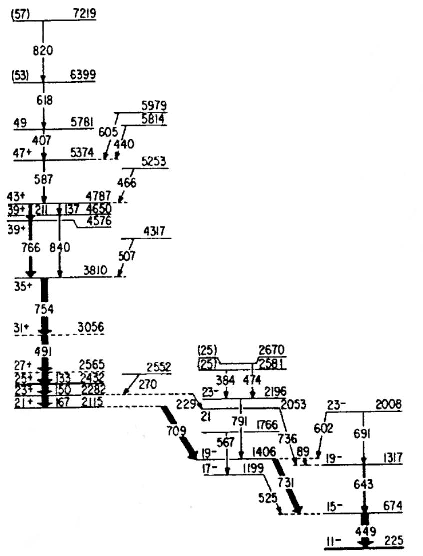
Phys. Rev. Lett. **124**, 052501 (2020).

- Editor's Suggestion on PRL
- phys.org, Sciencenewsnet.in, Newswise, Yahoo! News
- 25 tweets across 9 countries

Partial Level Scheme of ^{187}Au (Previous Measurement) Part II

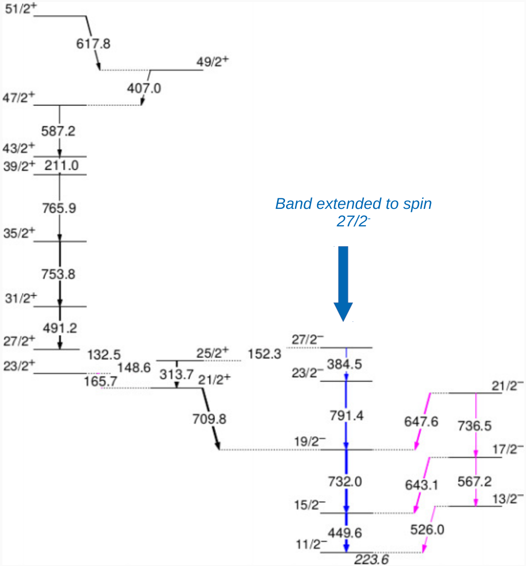
C. Bourgeois et al., Z. Physik A - Atomic Nuclei 333, 5 (1989)

- Band structure arising from $(\pi h_{11/2})^{-1}$ shape-coexisting with the $(\pi h_{9/2})$ structure.
- Spin and parity for the bandhead $\frac{11}{2}^{-}$, E_x = 223.6 keV firmly established.



Partial Level Scheme of ^{187}Au (from the present work) Part II

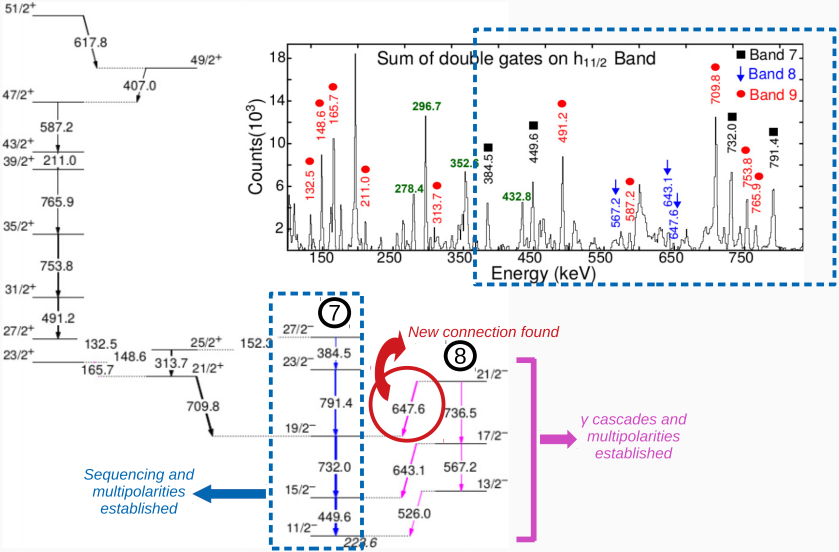
Band in agreement with previous measurements



Band extended to spin 27/2⁻

Some γ placements have been revised and band extended to spin 21/2⁻

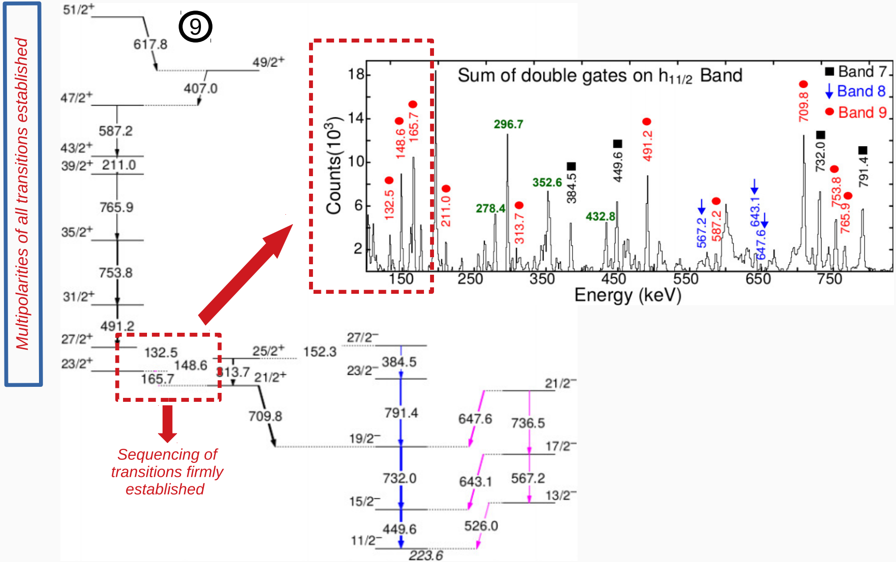
Partial Level Scheme of ^{187}Au (from the present work) Part II



Sequencing and multipolarities established

γ cascades and multipolarities established

Partial Level Scheme of ^{187}Au (from the present work) Part II

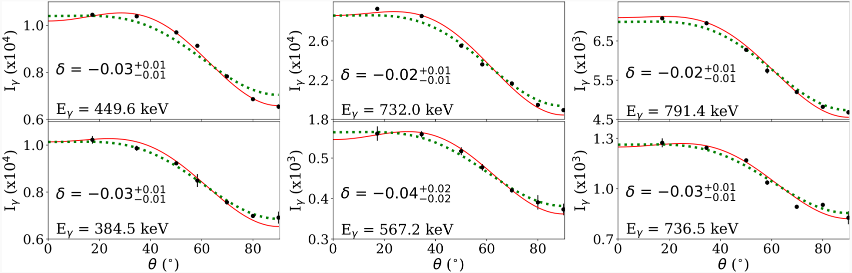


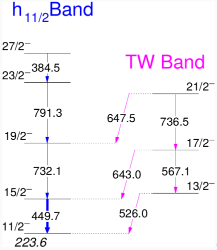
Spectroscopic Properties (Previous and Present Measurements)

E_γ (keV)	1	2	3	E_γ (keV)	1	2	3
449.7	E2	*Unknown*	E2	384.5	*Unknown*	L = 1	E2 + M1
732.1	E2	*Unknown*	(E2)	567.1	*Unknown*	E1	*Unknown*
791.3	E2	*Unknown*	M1	736.5	*Unknown*	L = 1	M1

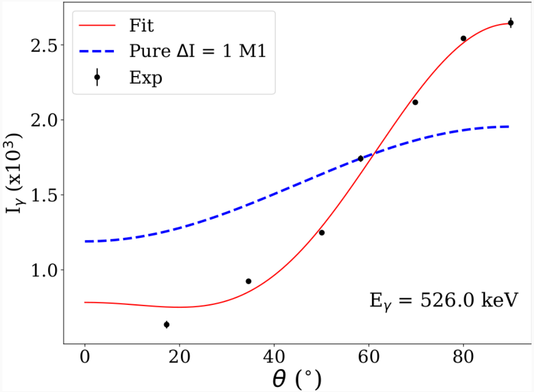
1 – PRC 40, 132 (1989), 2 – Z. Phys. A 333, 5 (1989), 3 – PRC 58, 2 (1997)

Results from present work





Angular Distributions (1/2)

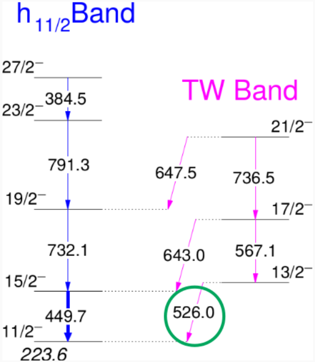


δ = $-1.88^{+0.03}_{-0.03}$

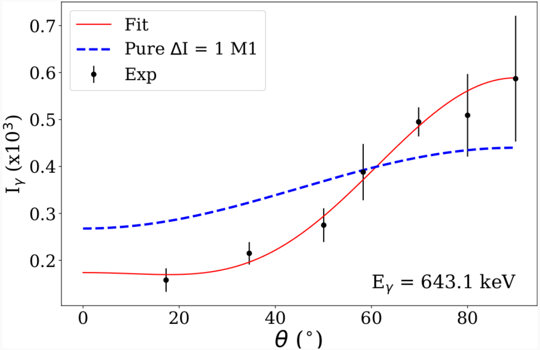
E2% = $77.9^{+0.6}_{-0.6}$

E_γ = 526.0 keV

Previously reported as M1+E2 (δ not reported) PRC 40, 132 (1989)



Angular Distributions (2/2)

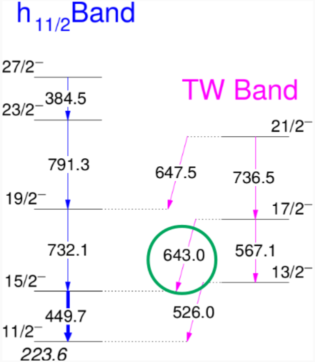


δ = **-1.96**$^{+0.22}_{-0.25}$

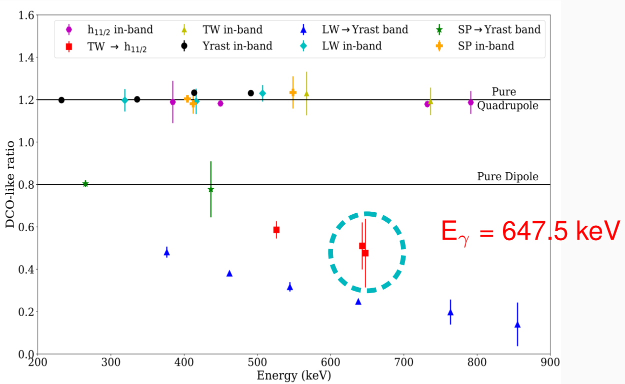
E2% = 79.3$^{+3.7}_{-4.2}$

E_γ = 643.1 keV

Previously reported as M1+E2 (δ not reported) PRC 40, 132 (1989)



DCO-like Ratios

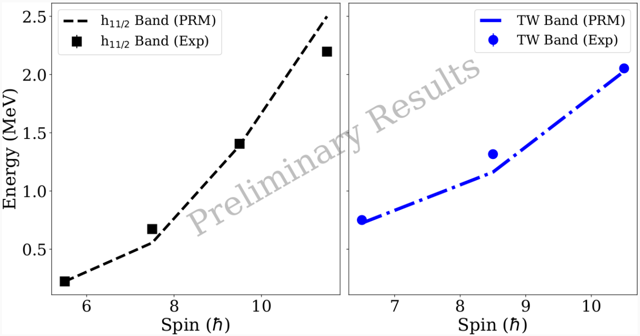


$\Delta I = 1$, E2 nature of the connecting transitions for the $h_{11/2}$ bands-pair (similar to that for the $h_{9/2}$ bands-pair) – another pair of wobbling bands associated with the $\pi h_{11/2}$ structure.

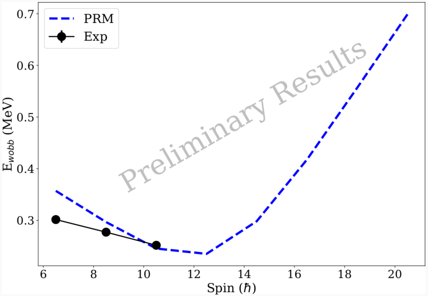
Particle Rotor Model (PRM) Calculations ($h_{11/2}$ *band structures*)

Deformation parameters β = 0.26, γ = 40°.

Excitation Energies



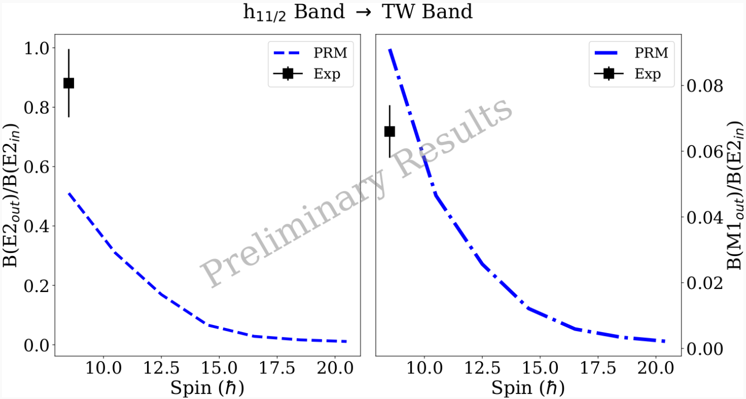
Wobbling Energy



- Excitation energies reproduced well for both bands.
- Decreasing trend of E_{wobb} reproduced – *Transverse wobbling*.
- PRM predicts the collapse of TW at I = 25/2.

Particle Rotor Model (PRM) Calculations ($h_{11/2}$ *band structures*) (cont.)

Reduced Transition Probability Ratios



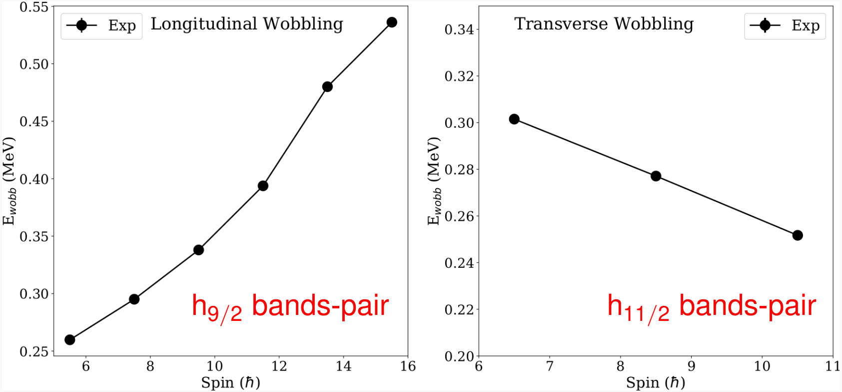
Large value of $B(E2)_{out}/B(E2)_{in}$ and small value of $B(M1)_{out}/B(E2)_{in}$ suggest a very promising wobbling candidate of this $h_{11/2}$ bands-pair. *More statistics needed*

Summarizing results of the $h_{11/2}$ bands-pair

- Two rotational bands have been identified as the $n_\omega = 0$ and $n_\omega = 1$ wobbling-bands pair arising from a $(\pi h_{11/2})^{-1}$ configuration.
- This is also the very first case of hole-like wobbling.
- A decreasing E_{wobb} with spin establishes these bands as exhibiting *transverse wobbling*.

Wobbling Energy (Summary - cont.)

Wobbling energy (E_{wobb})- energy associated with wobbling excitations.



^{187}Au – First case of coexistence of longitudinal and transverse wobbling!

Conclusion and Future Work

- Wobbling motion investigated in the ^{187}Au nucleus.
- Angular distribution measurements – enabled extraction of precise δ values.
- ^{187}Au - first established case of *Longitudinal wobbling* clearly distingushed from the associated signature partner band.
- Identification of the $h_{11/2}$ band structure in ^{187}Au – possible *Transverse wobbling* candidate.
- PRM calculations found to be in good agreement with experiment.

^{187}Au - First nucleus indicating the coexistence of *Longitudinal* and *Transverse* wobbling. *(Further experimental efforts are needed to establish this claim)*

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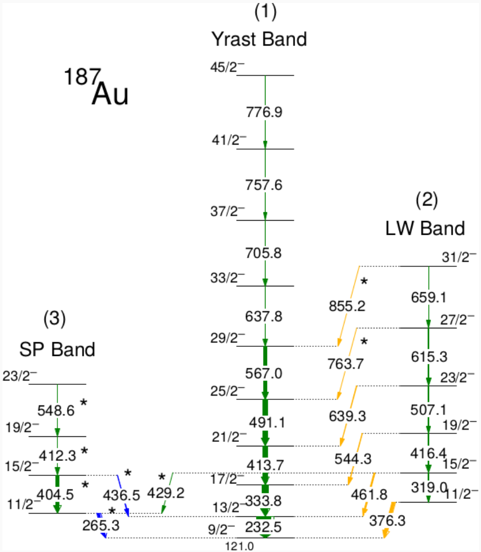
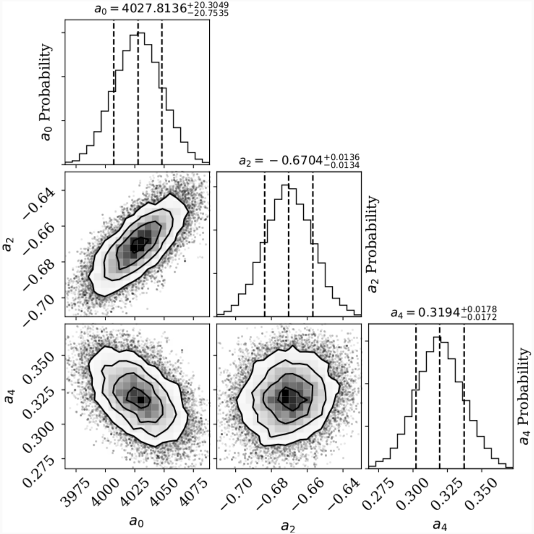
Backup

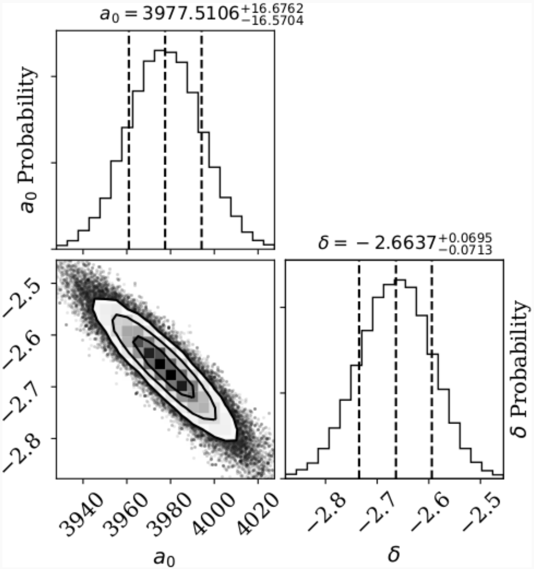
Level Scheme of ^{187}Au



A_2-A_4 Probability distribution plot for E_γ = 376.3 keV



δ Probability distribution plot for E_γ = 376.3 keV



Simple Wobbler theory

Hamiltonian of a rigid triaxial rotor (in the body fixed frame): $H = A_3\hat{J}_3^2 + A_1\hat{J}_1^2 + A_2\hat{J}_2^2$

Rotational parameters: $A_k = \dfrac{\hbar^2}{2\mathcal{J}_k}$

From conservation of angular momentum: $J^2 = J_l^2 + J_s^2 + J_m^2 = I(I+1)$

and energy: $E = A_3J_3^2 + A_1J_1^2 + A_2J_2^2$

Wobbling excitations are small amplitude oscillations of the a.m. vector (J_1, J_2, J_3) about the 3-axis of the largest MoI. Their energy is given by a harmonic spectrum of wobbling quanta

$H = A_3I(I+1) + \left(n + \frac{1}{2}\right)\hbar\omega_w$ where, n is the no. of wobbling quanta and,

Wobbling energy, $\hbar\omega_w = 2I\left(\left(A_l - A_m\right)\left(A_s - A_m\right)\right)^{1/2}$

DCO-like Ratios

DCO Ratios

- $R_{\text{DCO}} = \frac{I_{\theta_1}^{\gamma 2}(\text{Gate}_{\theta_2}^{\gamma 1})}{I_{\theta_2}^{\gamma 2}(\text{Gate}_{\theta_1}^{\gamma 1})}$
- Selective gate at two angles - exclusive.
- Transition of interest has lower intensity.
- Gate dependent

DCO-like Ratios

- $R_{\text{DCO-like}} = \frac{I_{\theta_1}^{\gamma 2}(\text{Gate}_{\text{all detectors}}^{\gamma 1})}{I_{\theta_2}^{\gamma 2}(\text{Gate}_{\text{all detectors}}^{\gamma 1})}$
- Involves the same gate at all angles, thereby making it more inclusive.
- Transition of interest has greater intensity.
- Gate independent