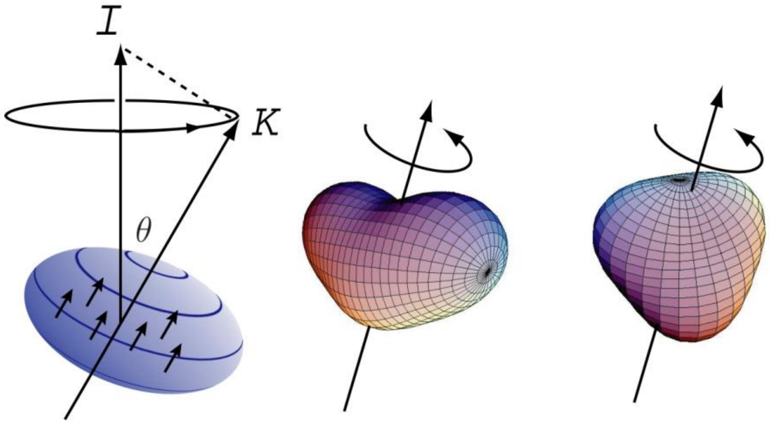
Explore new modes of vibrational and rotational excitations at high spin

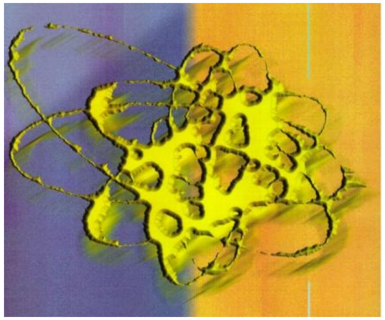


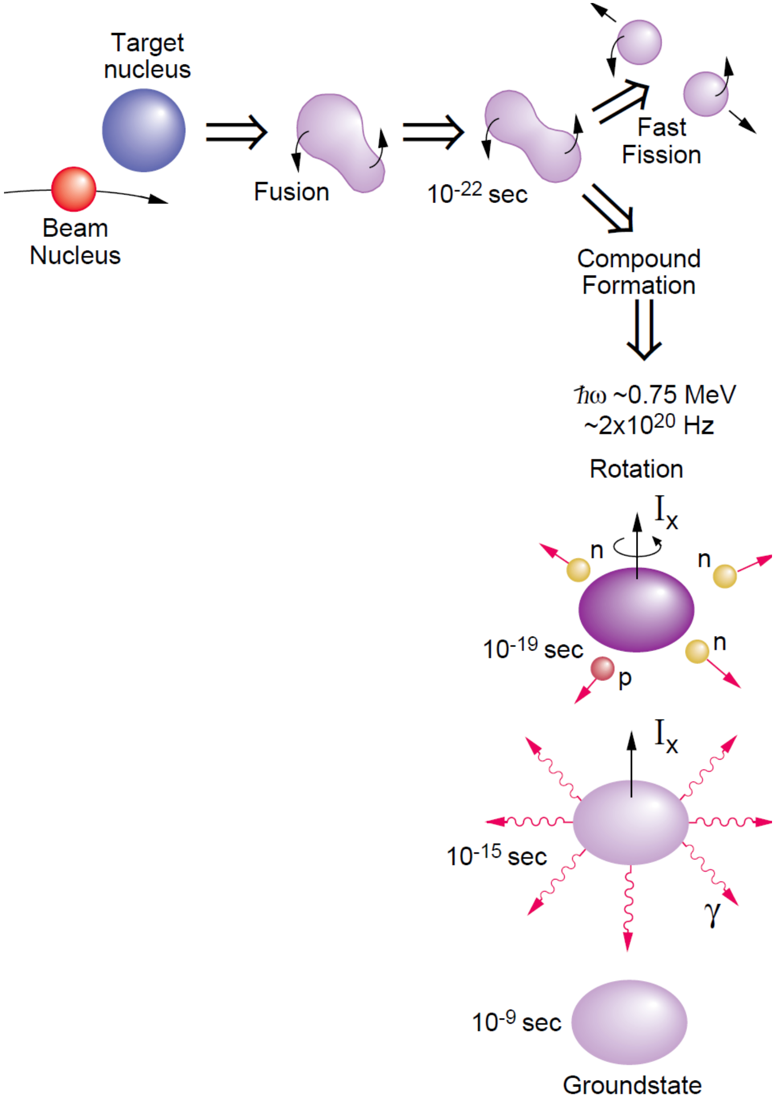
Emergence of new type of collective motion due to rapid rotation

Microscopic mechanism of generating collectivity (coherence) of soft collective modes of excitation

- Soft octupole vibration built on superdeformed bands
- Wobbling and Precession
- Chiral vibrations, Large-amplitude triaxial vibrations

Why do Nuclear Physics ?





Because we want to understand the character (dynamics) of the nucleus as a quantum droplet.

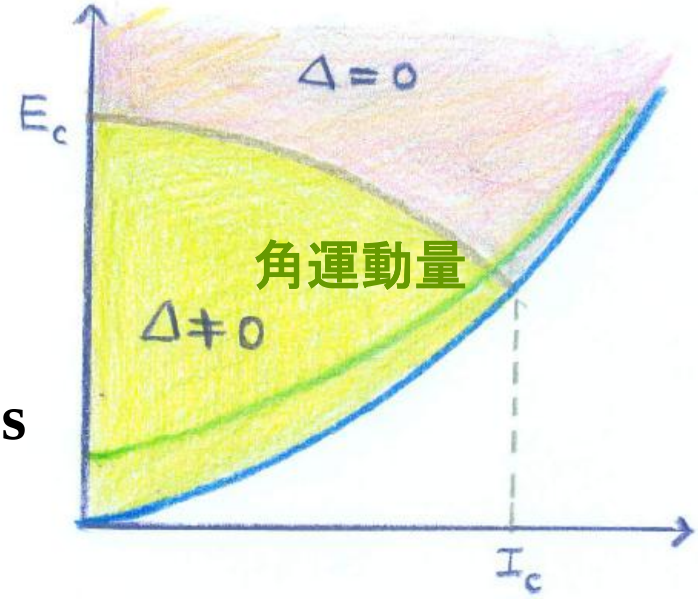
For this aim, we excite the nucleus in a variety of way and investigate its response.

Rotating it at extremely high speeds is quite fascinating and efficient to reveal its dynamical properties.

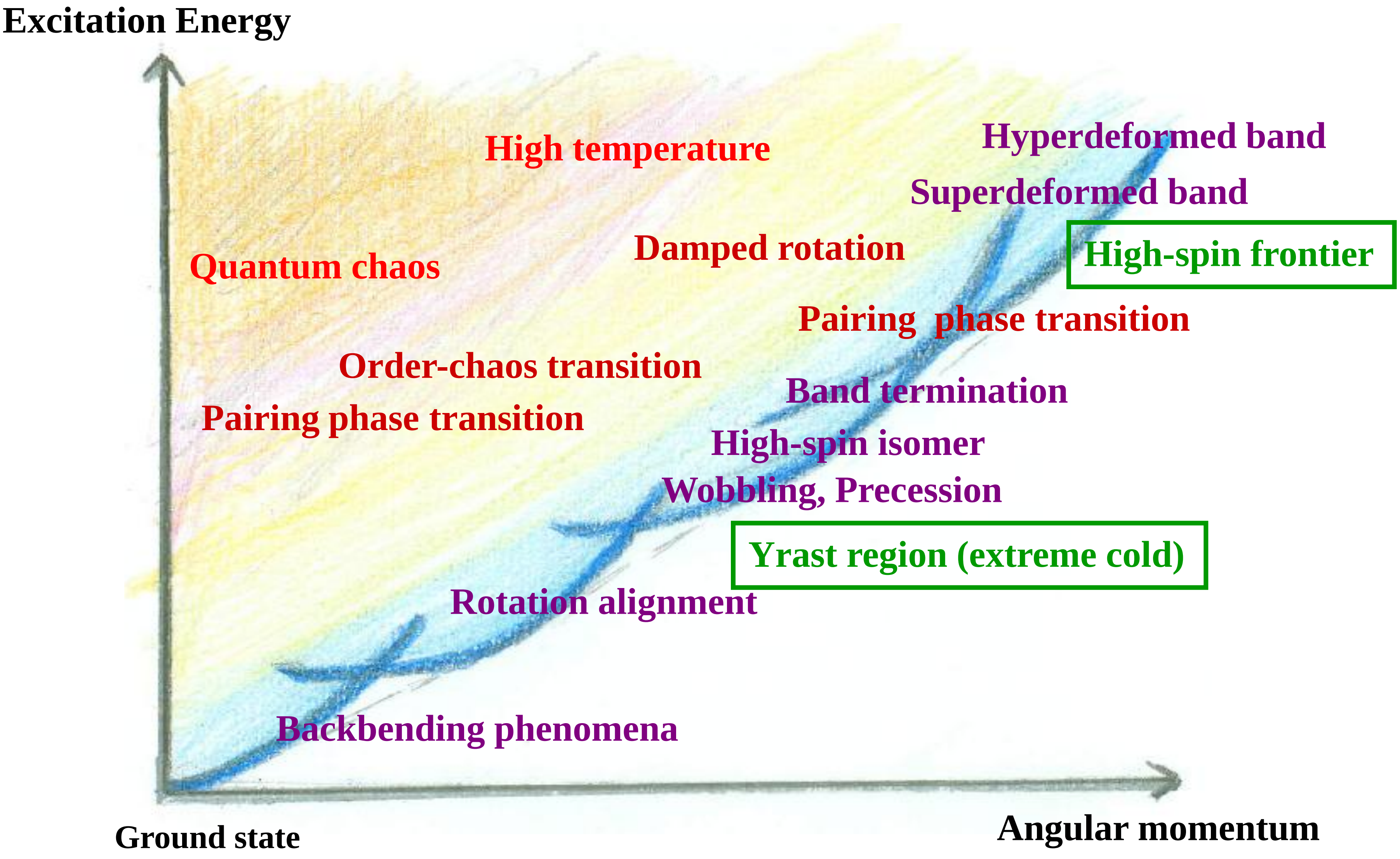
important !

Low-frequency quadrupole vibrations are normal modes of shape fluctuation of a finite superfluid (nucleus), whose characters are essentially different from the surface vibrations of a classical liquid drop.

Microscopic theory of these collective phenomena to understand why and how they emerge is one of the most difficult challenges in quantum many-body physics .



In spite of the enormous expansion in high spin frontier, vibrational modes at high spin are poorly known.



Excitation Energy

High temperature

Hyperdeformed band

Superdeformed band

Damped rotation

High-spin frontier

Quantum chaos

Pairing phase transition

Order-chaos transition

Band termination

Pairing phase transition

High-spin isomer

Wobbling, Precession

Yrast region (extreme cold)

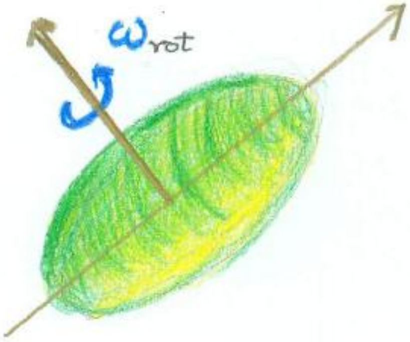
Rotation alignment

Backbending phenomena

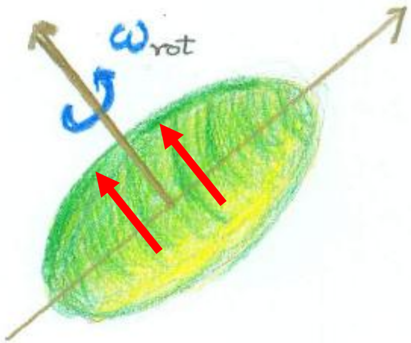
Ground state

Angular momentum

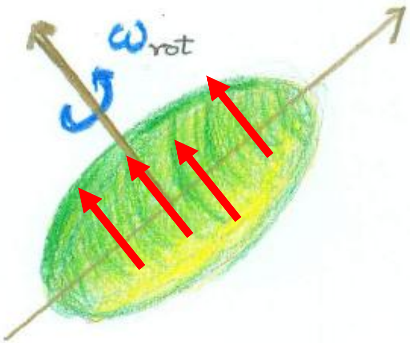
Change of nuclear structure along the yrast line



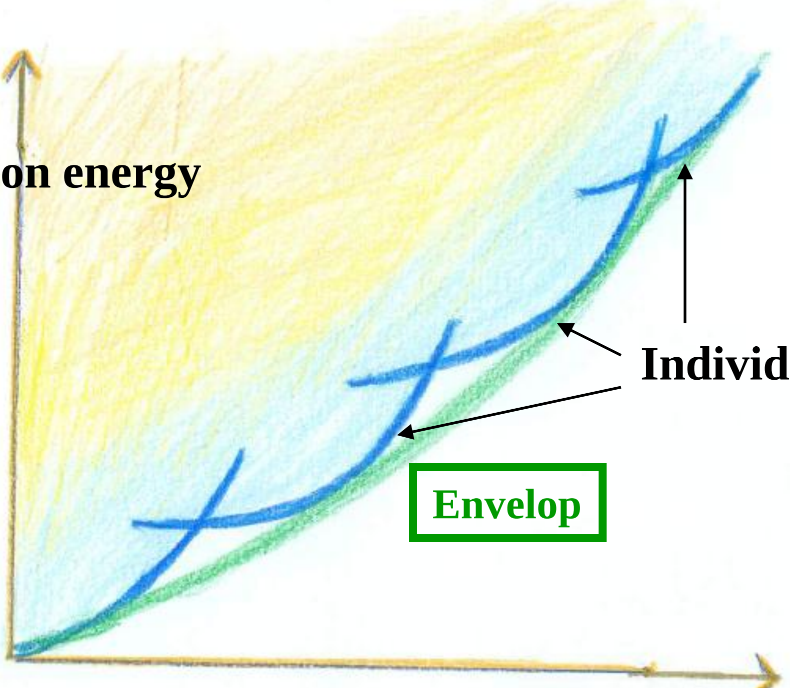
Prolate deformation



Alignment of 2QP



Alignment of 4QP



Excitation energy

Individual bands

Envelop

Angular momentum (spin)

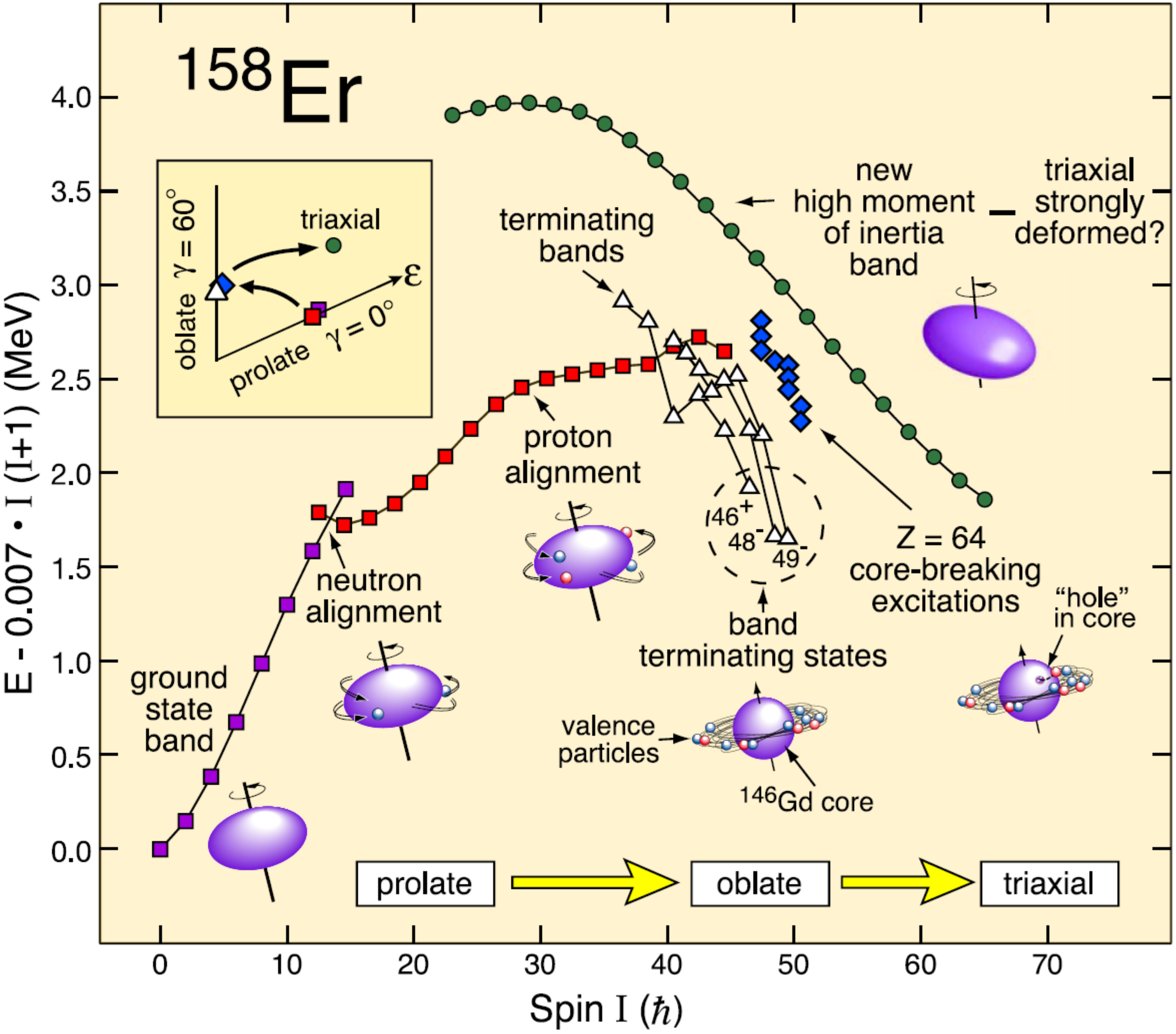
Growth of triaxiality

Band termination

Oblate deformation

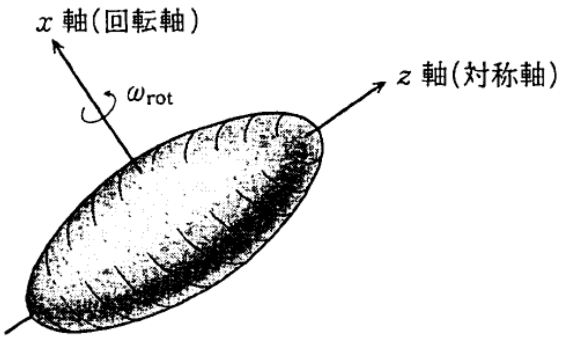
High Spin Frontier

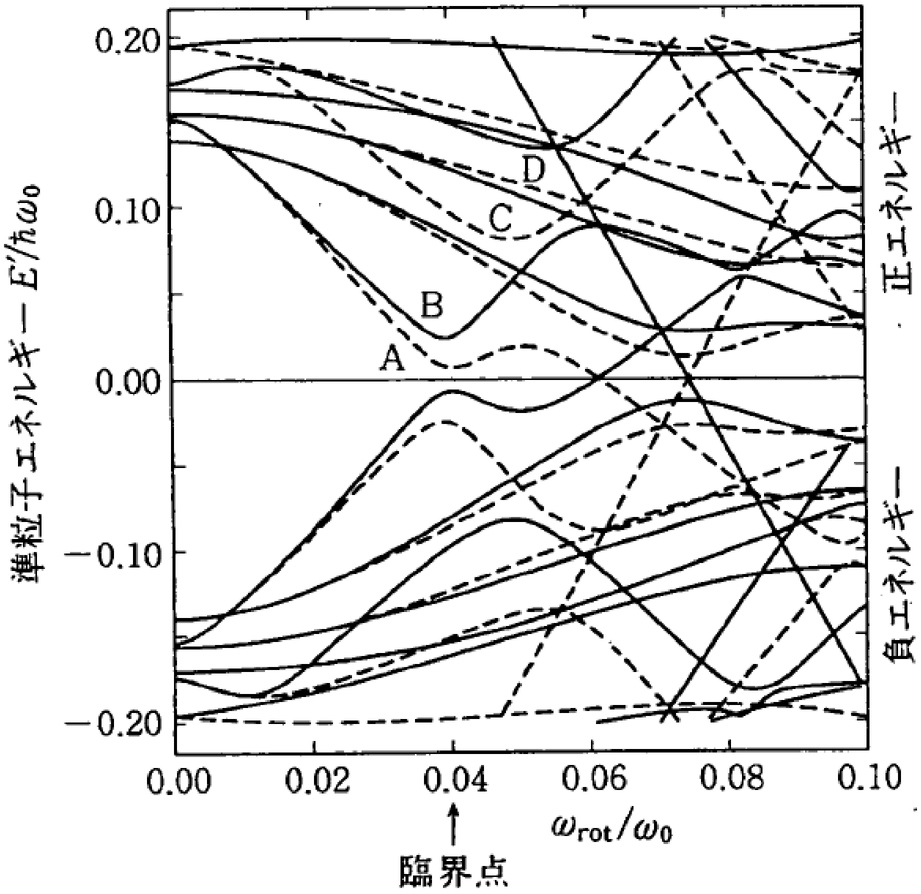
E.S. Paul et al., Phys. Rev. Lett. 98 (2007) 012501



Quasiparticle Shell Model in the Rotating Frame

$$
\begin{aligned}
H &= \sum_i (e_i - \lambda) c_i^\dagger c_i - \Delta \sum_i (c_i^\dagger c_{\bar{i}}^\dagger + c_{\bar{i}} c_i) - \omega_{\mathrm{rot}} \sum_{i,j} < i|J_x|j > c_i^\dagger c_j \\
&= \sum_\mu E_\mu a_\mu^\dagger a_\mu + \sum_{\bar{\mu}} E_{\bar{\mu}} a_{\bar{\mu}}^\dagger a_{\bar{\mu}}
\end{aligned}
$$



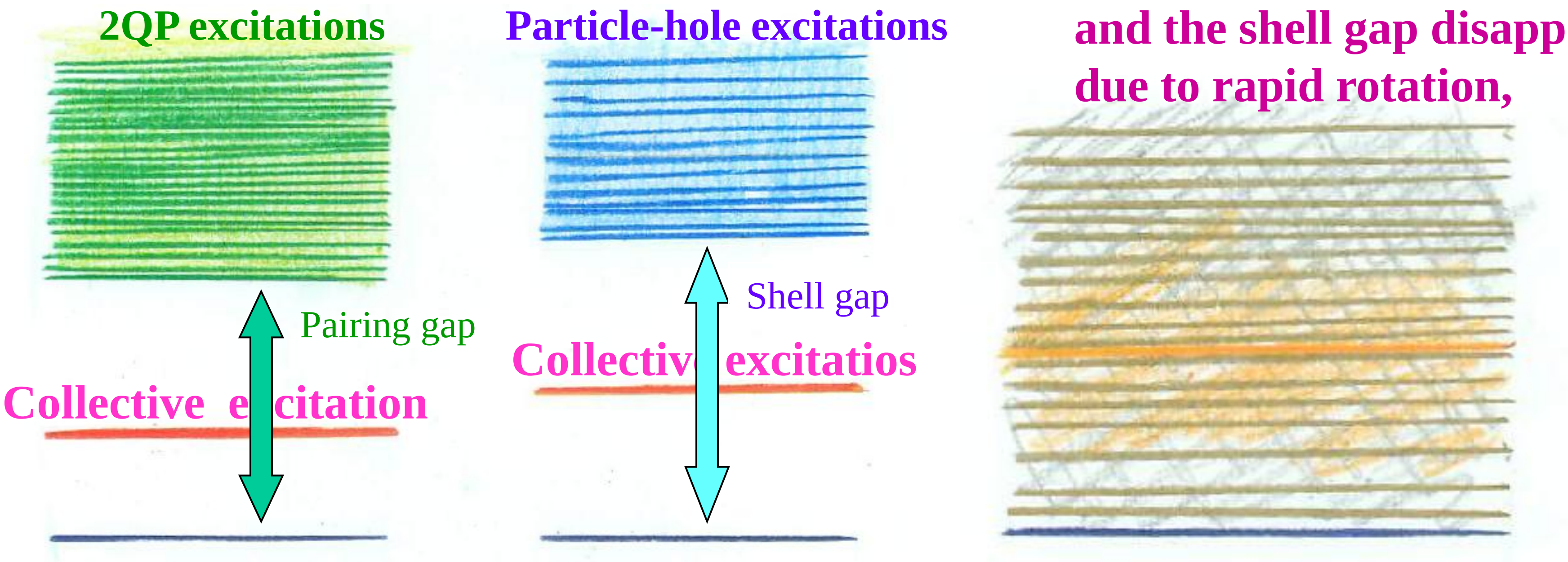


Breaking of spherical symmetry, gauge symmetry and time-reversal symmetry

Generalization of the concept of single-particle mode

1970s-1980s

Almost all high-spin spectra supposed to be explainable in terms of the quasiparticle shell model in the rotating frame.
Does the low-frequency vibrations disappear at high spin ?



If both the pairing gap and the shell gap disappear due to rapid rotation,

2QP excitations

Pairing gap

Collective excitation

Ground state

（pairing）

Particle-hole excitations

Shell gap

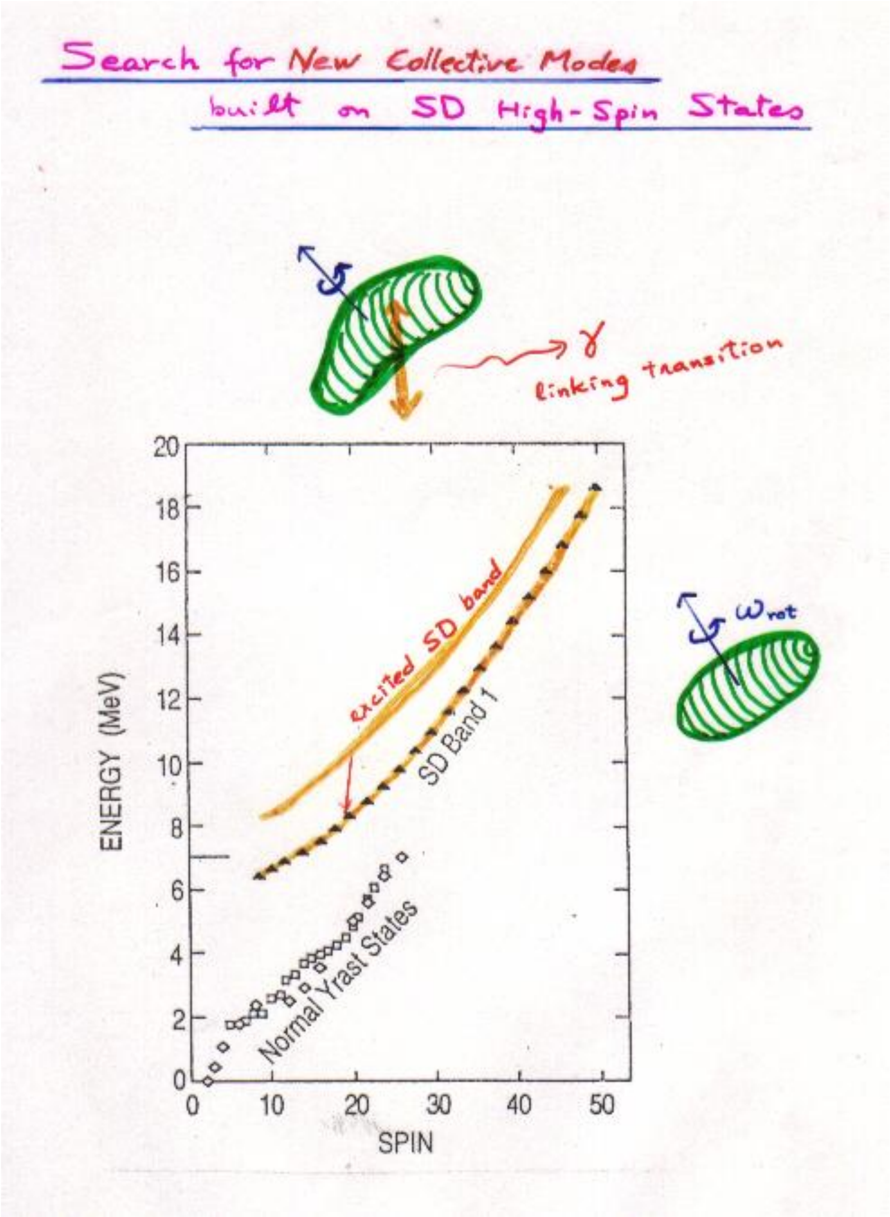
Collective excitatios

Gound state

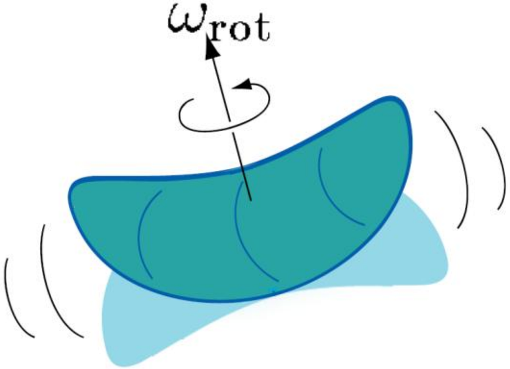
（closed shell）

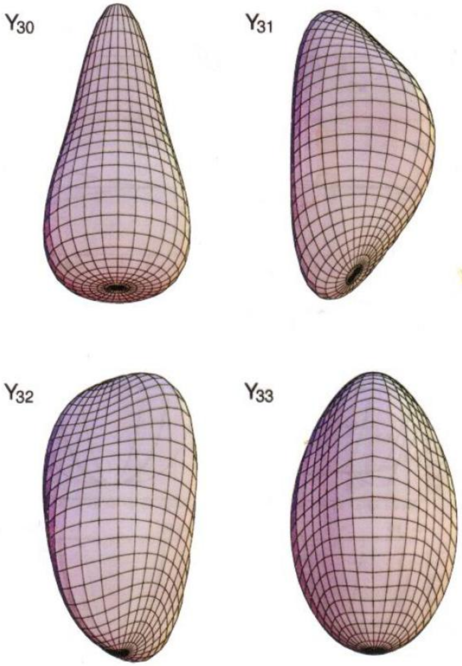
Yrast state

New collective vibrations built on superdeformed states



Search for New Collective Modes
built on SD High-Spin States





PHYSICAL REVIEW C **83**, 044309 (2011)

Structure changes in ^{160}Er from low to ultrahigh spin

J. Ollier,[1] J. Simpson,[1] M. A. Riley,[2] E. S. Paul,[3] X. Wang,[2] A. Aguilar,[2] M. P. Carpenter,[4] I. G. Darby,[5,*] D. J. Hartley,[6] R. V. F. Janssens,[4] F. G. Kondev,[4] T. Lauritsen,[4] P. J. Nolan,[3] M. Petri,[3,†] J. M. Rees,[3] S. V. Rigby,[3] C. Teal,[2] J. Thomson,[3] C. Unsworth,[3] S. Zhu,[4] A. Kardan,[7,8] and I. Ragnarsson[8]

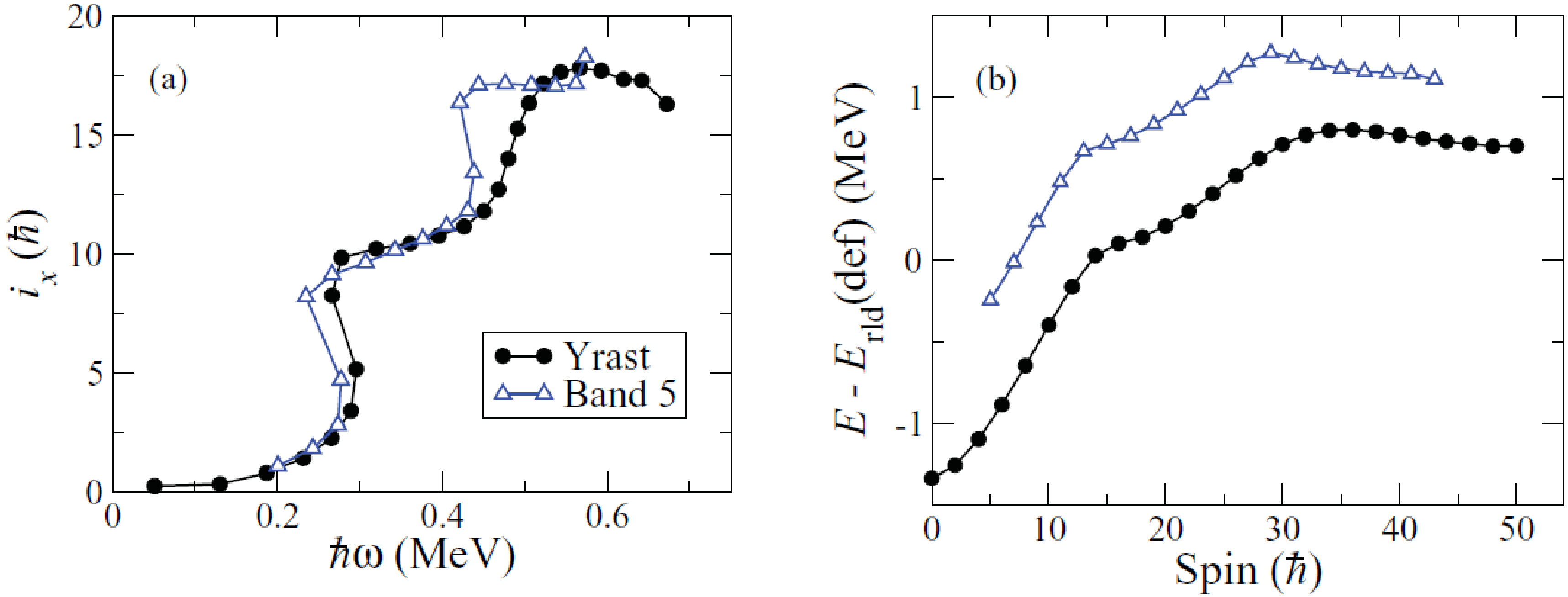


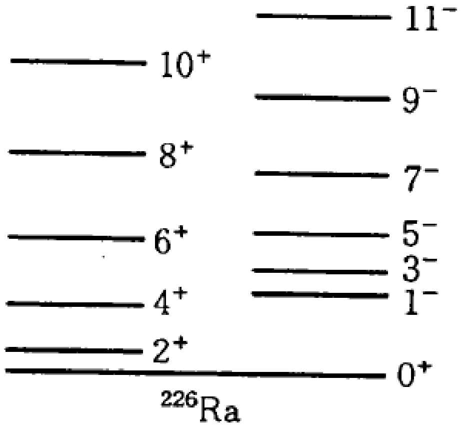
FIG. 9. (Color online) (a) The aligned angular momentum (alignment) as a function of rotational frequency for the yrast band and band 5 ($K = 2$). (b) Energy relative to a rotating liquid drop as a function of spin for these bands.

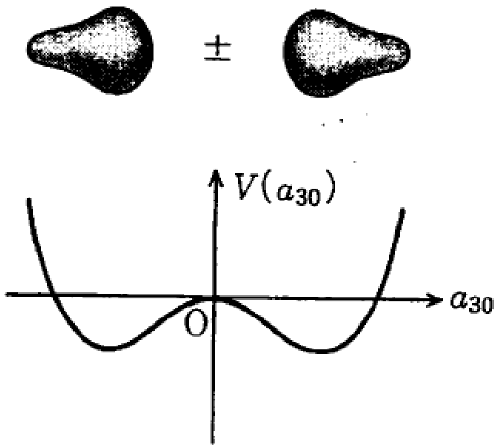
Typical spectra indicating symmetry breaking

- Breaking of axial symmetry → Wobbling motion
- Breaking of chiral symmetry → Chiral doublet

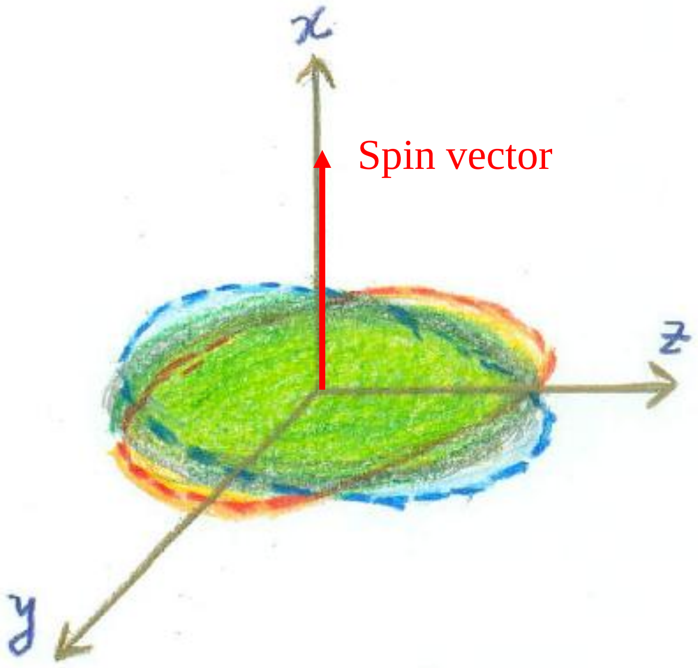
Macroscopic quantum tunneling

- Breaking of reflection symmetry → Parity doublet

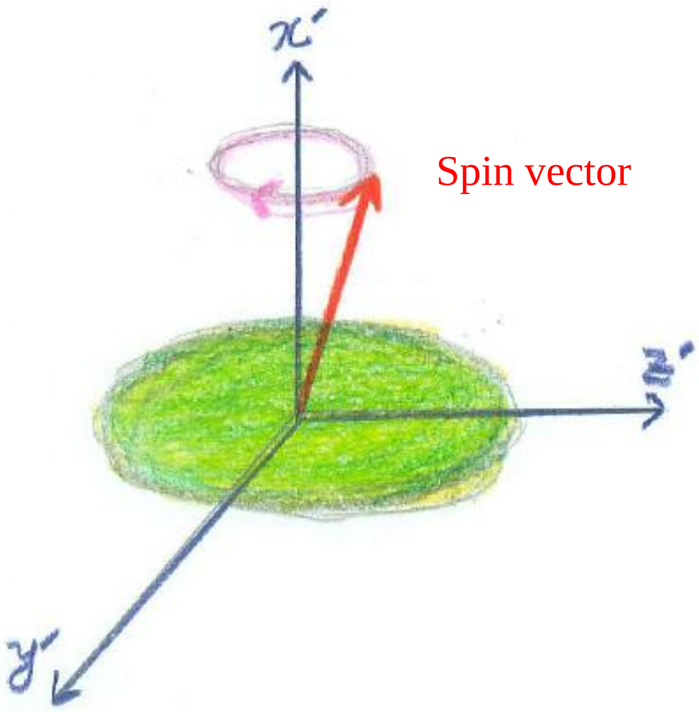




Alternative pictures of Wobbling Motion



Shape viewed from the uniformly rotating frame fluctuates

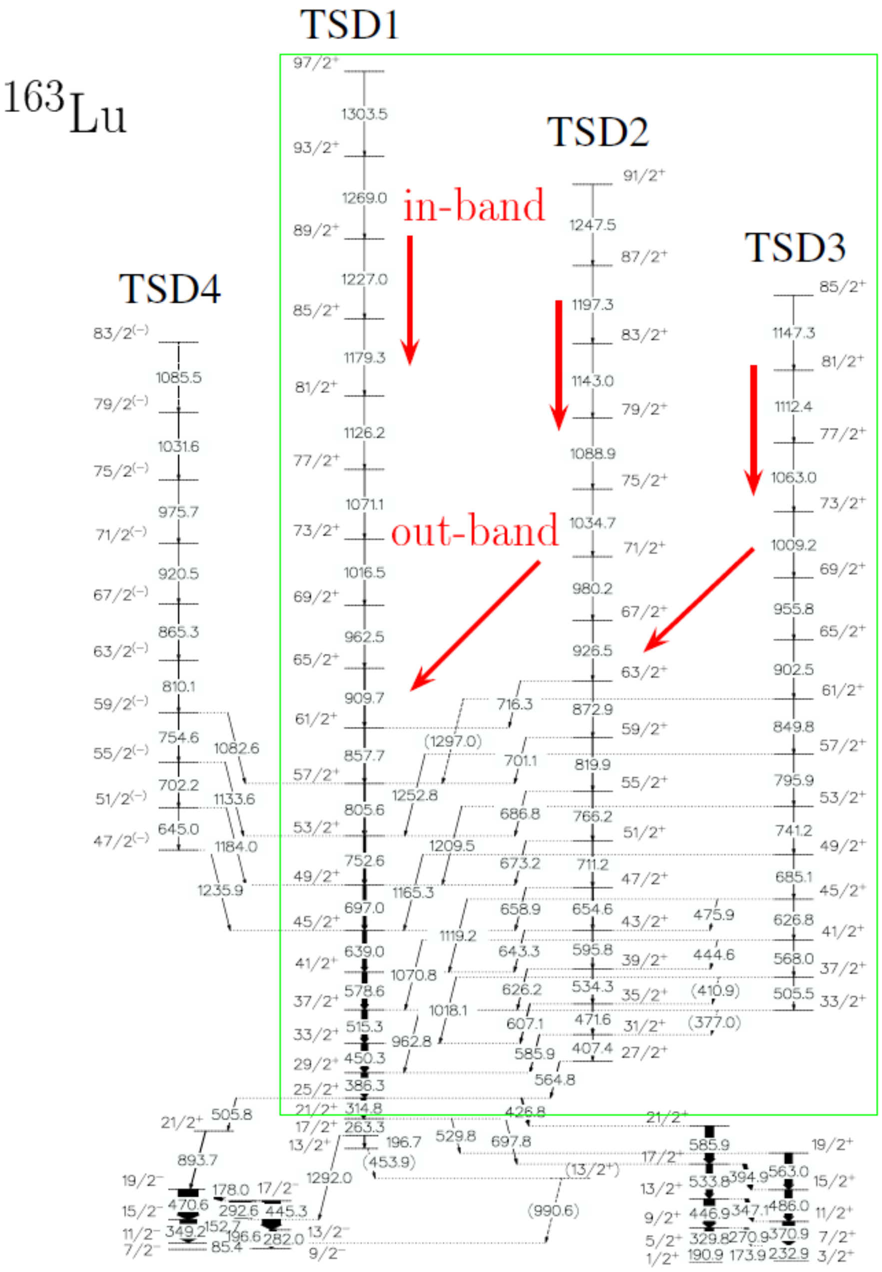


Spin viewed from the principal axis frame precesses

Deformed nucleus breaking the axial symmetry

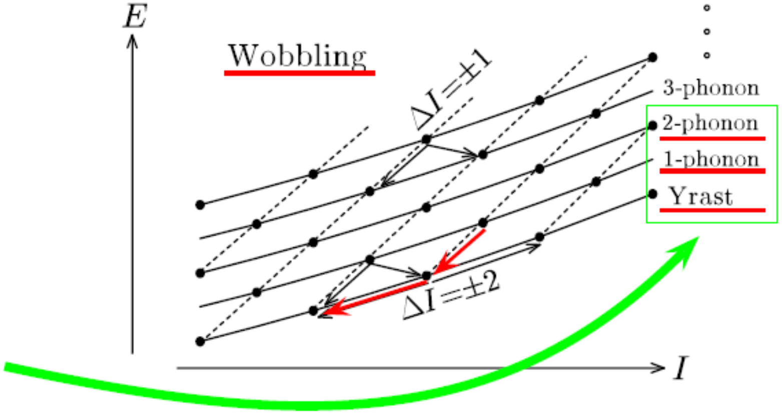
Wobbling Spectra

D. R. Jensen at al., Eur. Phys. J. **A19** (2004), 173

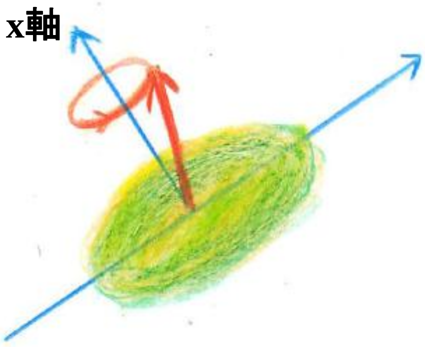


First identified by Ødegård et al. (2001)

Why observed only in odd-A nuclei ?



Physical condition for an appearance of the wobbling motion



$$H = \frac{I_x^2}{2\mathcal{J}_x} + \frac{I_y^2}{2\mathcal{J}_y} + \frac{I_z^2}{2\mathcal{J}_z}$$

for $I_x \gg I_y,\ I_z$

$$E(n, I) = \frac{I(I+1)}{2\mathcal{J}_x} + \hbar\omega(n + \frac{1}{2}) \ , \qquad n = 0, 1, 2, \ldots$$

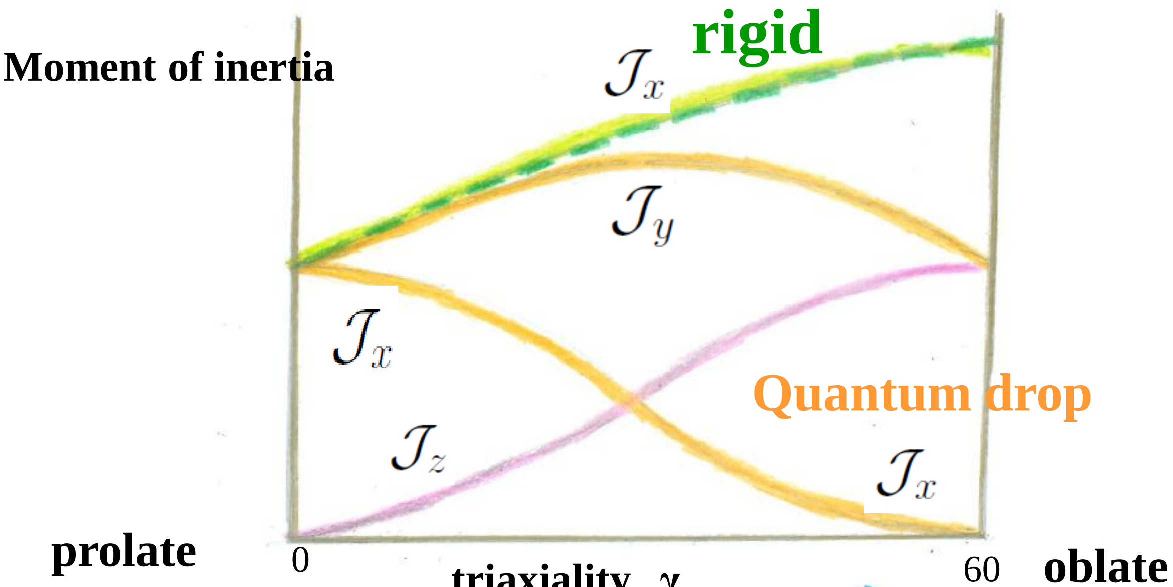
$$\hbar\omega = I\sqrt{(\frac{1}{\mathcal{J}_y} - \frac{1}{\mathcal{J}_x})(\frac{1}{\mathcal{J}_z} - \frac{1}{\mathcal{J}_x})}$$

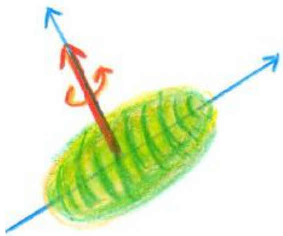
このモードが存在するためには $\mathcal{J}_x \geq \mathcal{J}_y,\ \mathcal{J}_x$ が必要

Evaluate the moments of inertia $\mathcal{J}_x$, $\mathcal{J}_y$, $\mathcal{J}_z$
by means of the QRPA in the rotating frame

M. Matsuzaki et al., Phys. Rev. C 69 (2004) 034325

Paradox of the wobbling motion



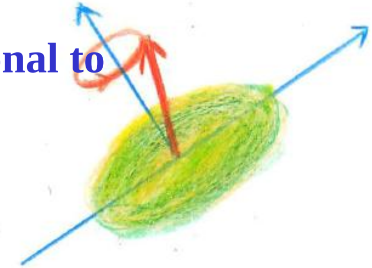


Quantum rotation restoring the broken symmetry

Alignment of individual spins (quantum rotation disappears）

The rotation axis is orthogonal to the symmetry axis

The rotation axis is parallel to the symmetry axis



imaginary for quantum drop！

$\mathcal{J}_x \geq \mathcal{J}_y, \mathcal{J}_x$ が必要

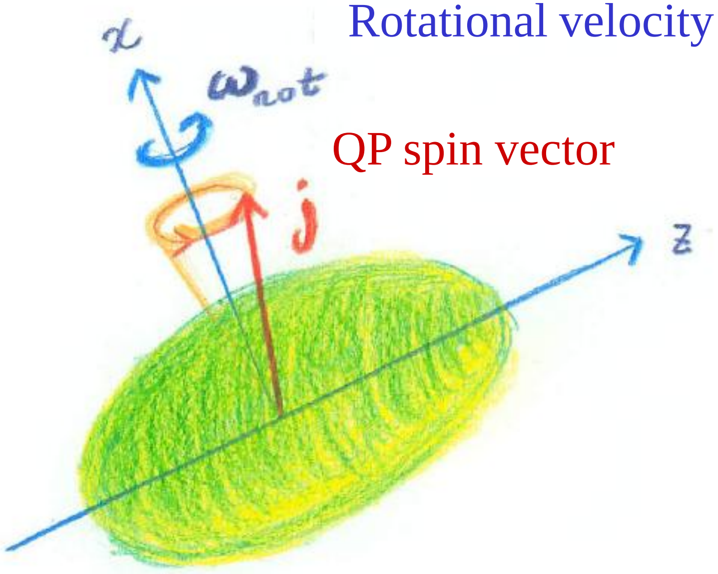
required

Wobbling frequency

$$\hbar\omega = I\sqrt{\left(\frac{1}{\mathcal{J}_y}-\frac{1}{\mathcal{J}_x}\right)\left(\frac{1}{\mathcal{J}_z}-\frac{1}{\mathcal{J}_x}\right)}$$

Important conclusion

Unable to explain in terms of the classical concept, because it is the quantum dynamics involving quasiparticle spin alignment and shell structure that generates the wobbling modes in question.



Rotation axis

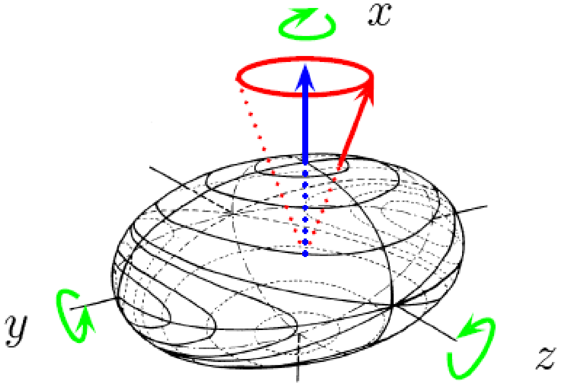
Rotational velocity

QP spin vector

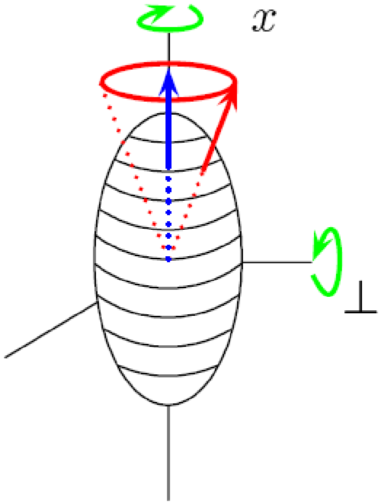
Symmetry axis

M. Matsuzaki, Y.R. Shimizu and K. Matsuyanagi, Phys. Rev. C 69 (2004) 034325

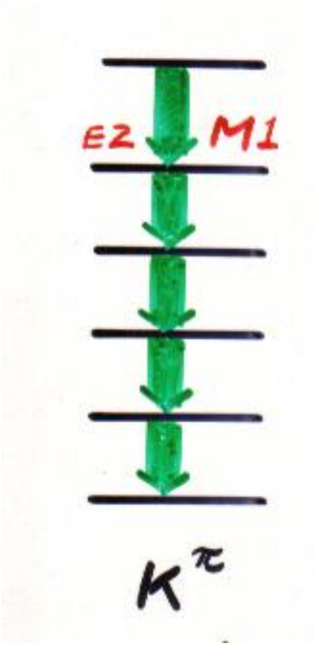
Wobbling and Precession



$I_x \gg I_y, I_z$



$I_x \gg I_\perp$

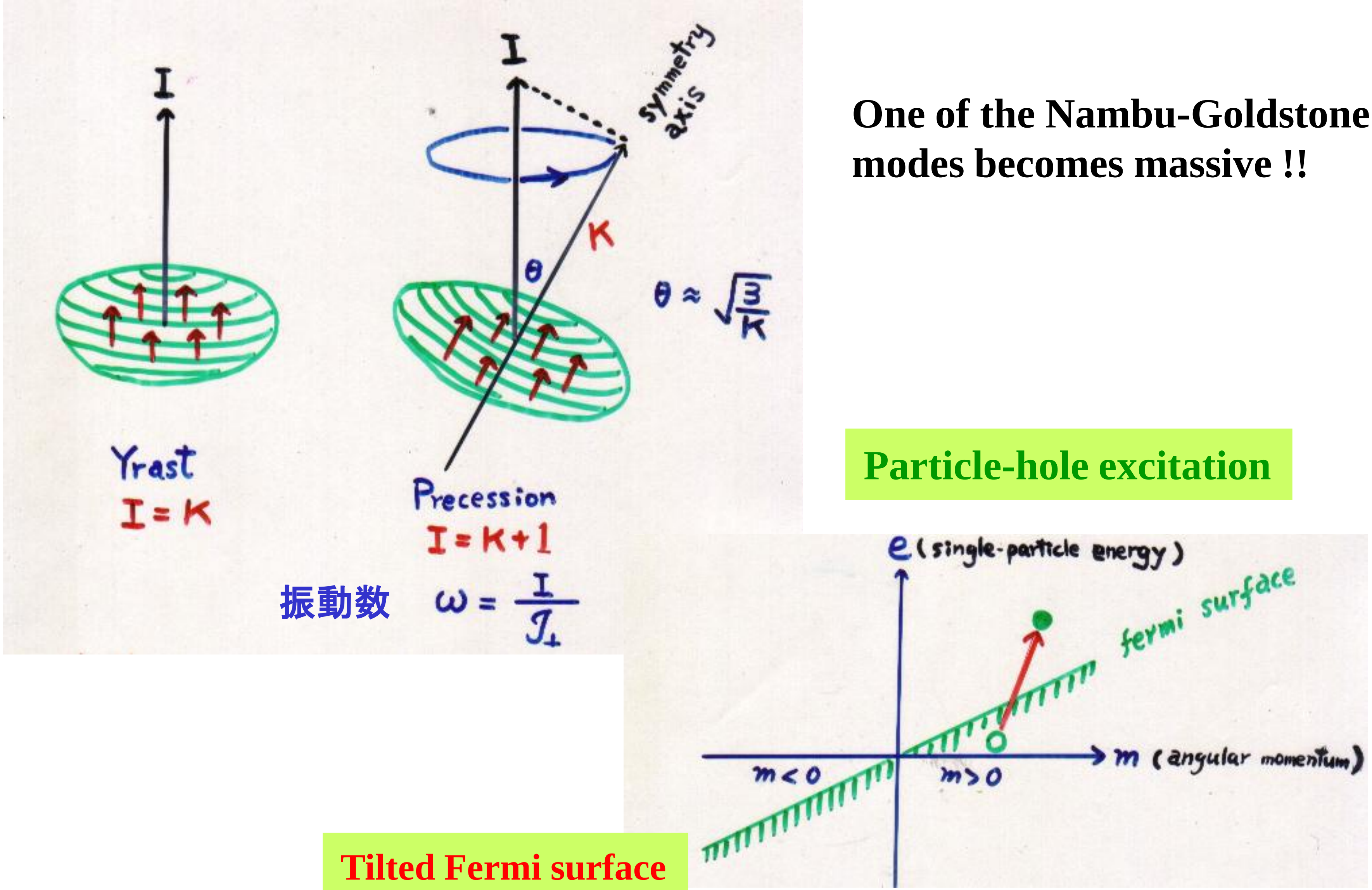


Precession mode built on high-K isomer

Y.R. Shimizu, M. Matsuzaki and K. Matsuyanagi, Phys. Rev. C 72 (2005) 014306

Microscopic structure of the precession excitation

One of the Nambu-Goldstone modes becomes massive !!

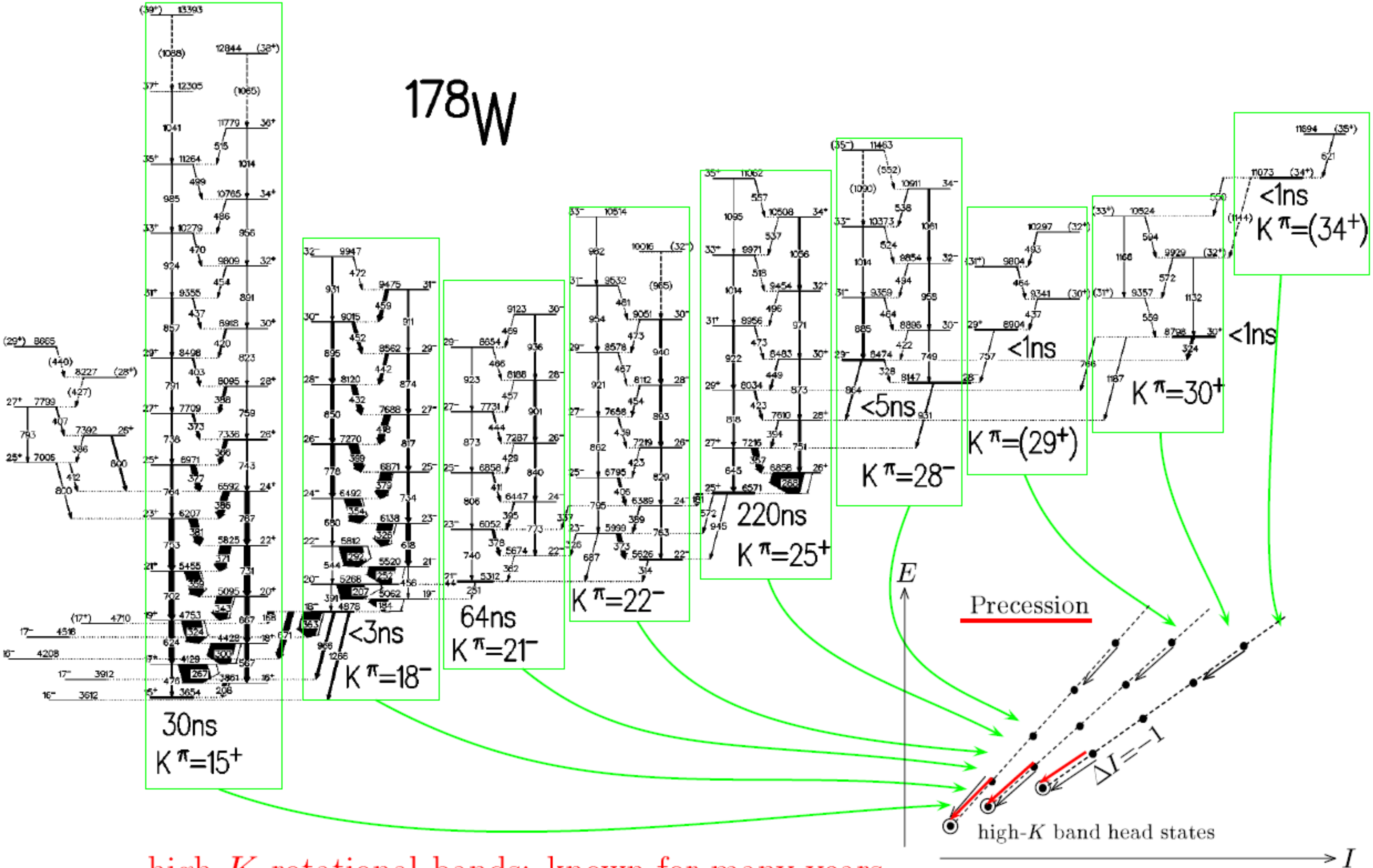


Particle-hole excitation

Tilted Fermi surface

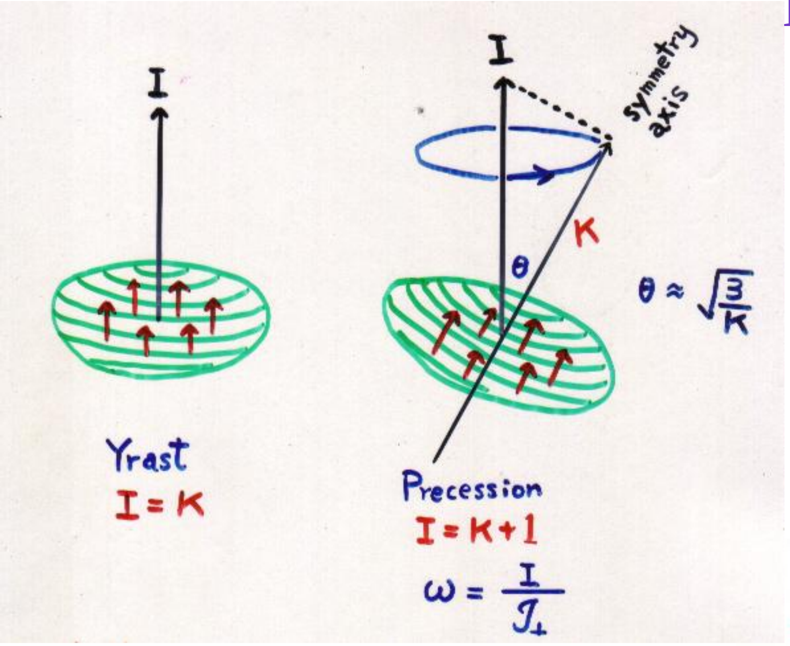
Precession Spectra

D. M. Cullen et al., Phys. Rev. **C60** (1990), 064301.



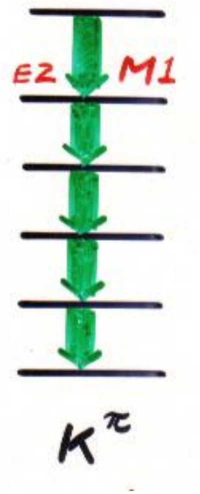
high-K rotational bands: known for many years

Open Problem; Whether or not the precession mode emerges on a high-K oblate isomer .

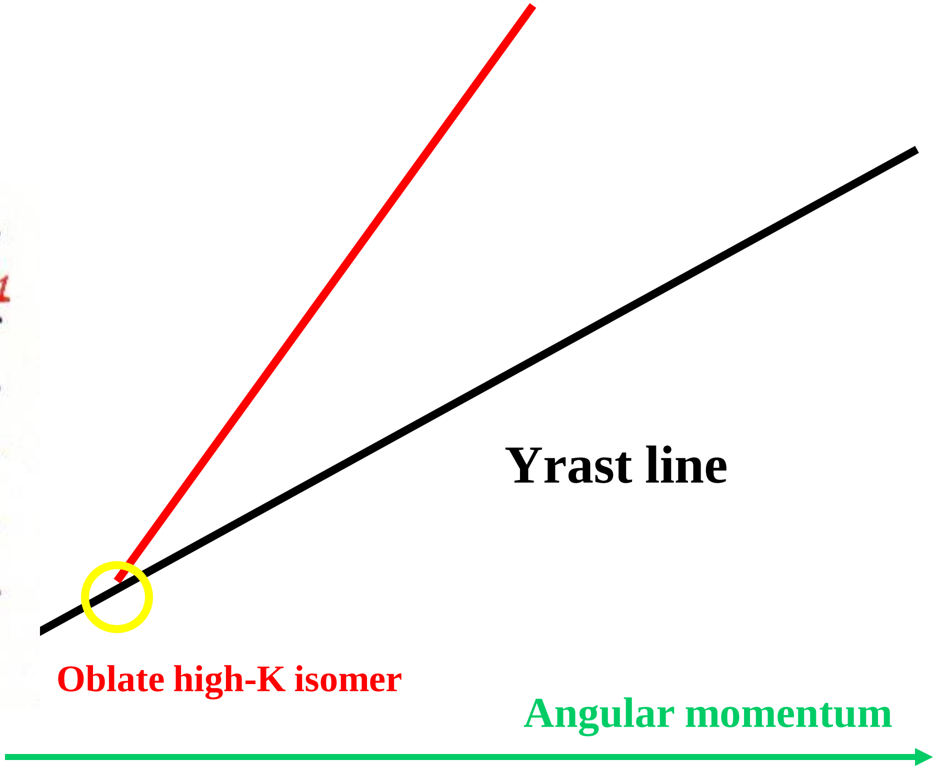


Note that

Collective mass parameters (inertia functions) in the phenomenological collective model reveal the dynamical properties of the system



Precession Band

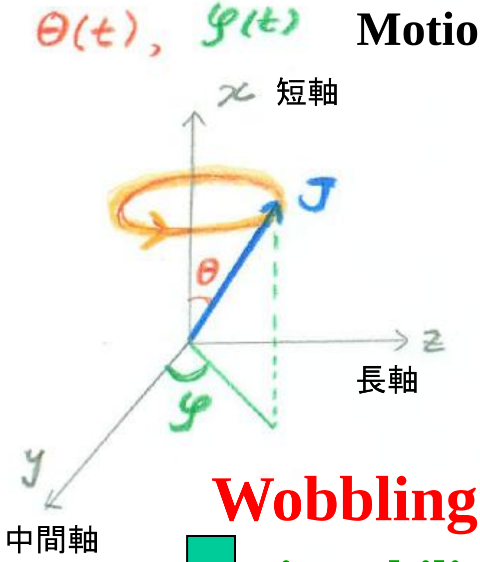


Yrast line

Oblate high-K isomer

Angular momentum

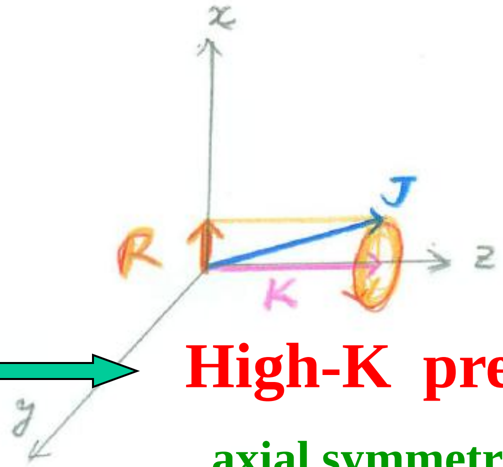
Unified view of Spin dynamics of a 3D quantum drop



Motion of spin vector

Wobbling

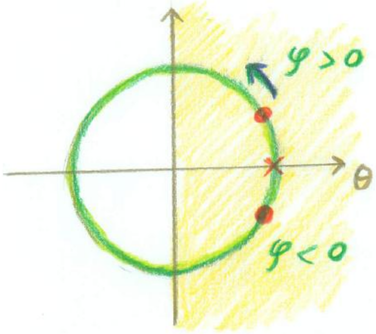
instability

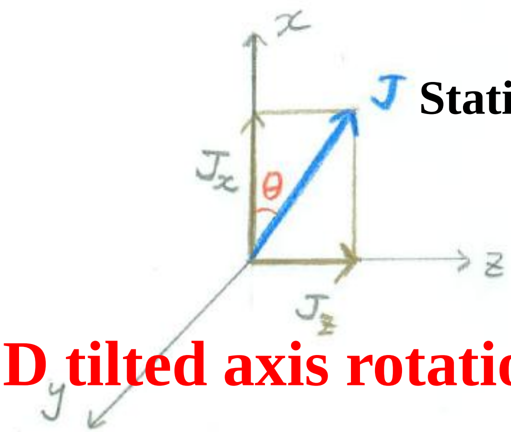


High-K precession

axial symmetry limit

Chiral doublet

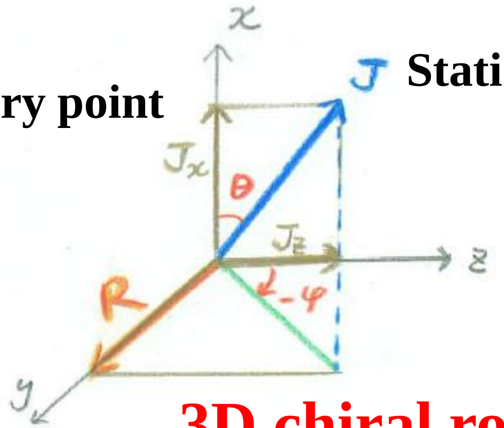




Stationary point

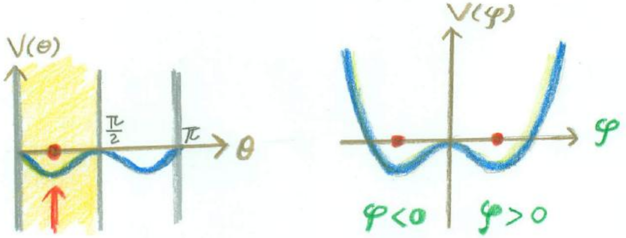
2D tilted axis rotation

instability



Stationary point

3D chiral rotation



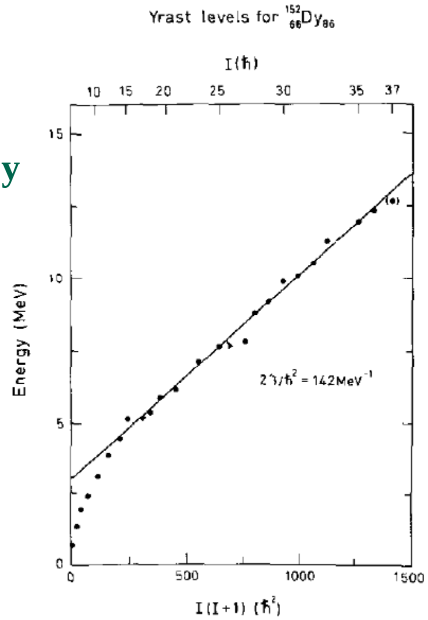
Directions of R
are opposite to
each other

Nuclear Physics A354(1981)303c-316c.

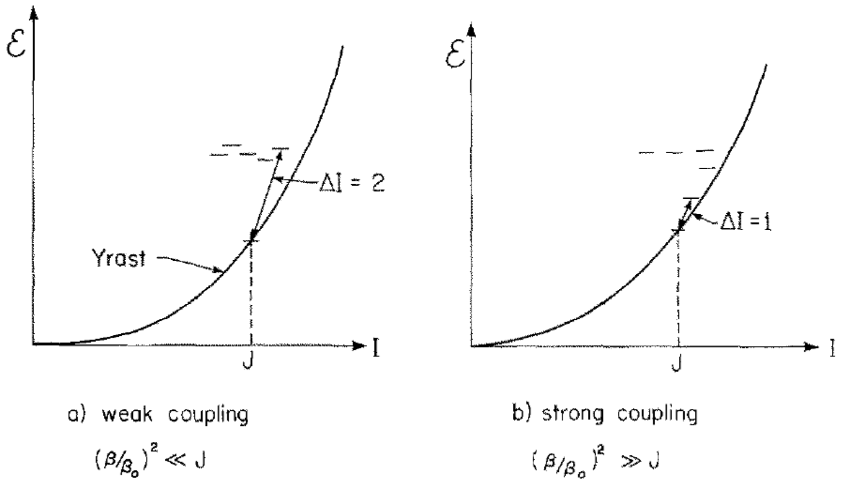
THE STRUCTURE OF ANGULAR MOMENTUM IN RAPIDLY ROTATING NUCLEI

A. Bohr and B. R. Mottelson
Niels Bohr Institute and Nordita
Copenhagen, Denmark

Oblate high-K isomer in 152Dy



We are being presented here with a fascinating new form of nuclear matter in which the internal motion gives rise to a "macroscopic" amount of time reversal violation. This situation provides us with new opportunities to test our understanding of bulk terms in the nuclear energy as well as the modificaton in the average potentials produced by the significant circulating currents.



a) weak coupling

$(\beta/\beta_0)^2 \ll J$

b) strong coupling

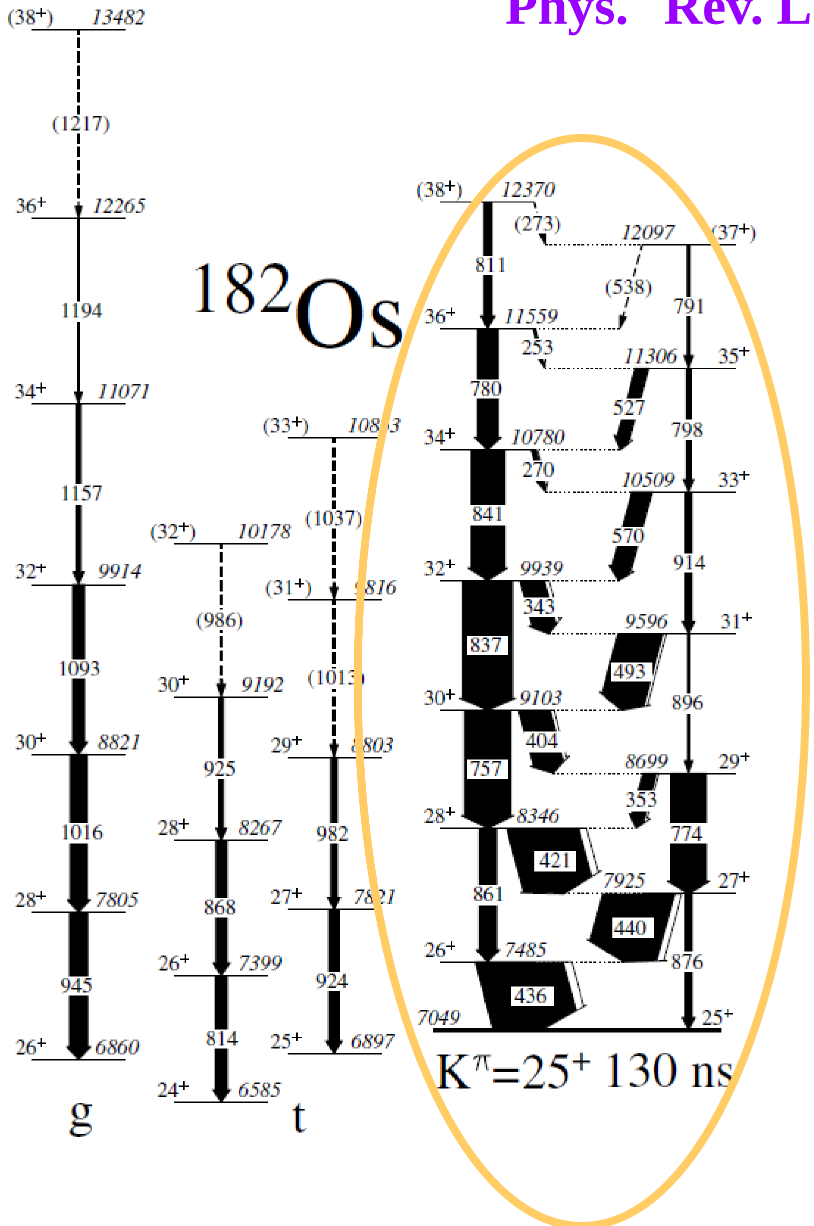
$(\beta/\beta_0)^2 \gg J$

suggested

possible competition between precession and gamma vibration

Many-phonon states of gamma vibration built on High-K isomer?

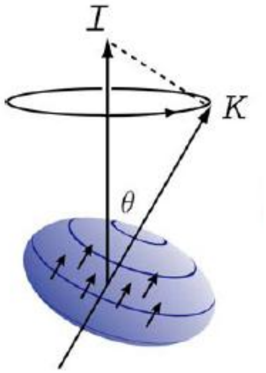
Phys. Rev. Lett. 91 (2003) 182501



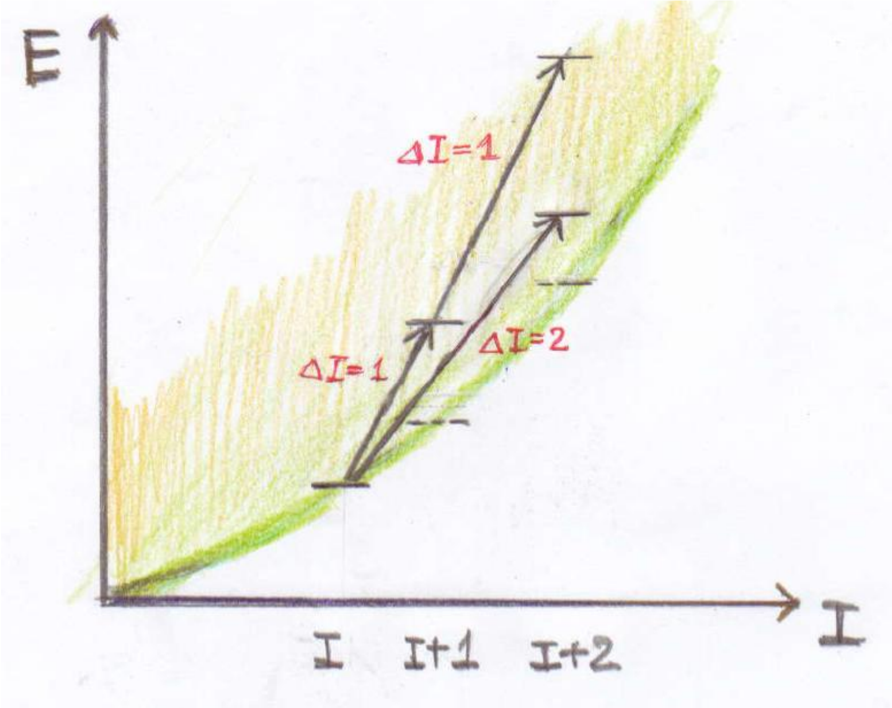
Interesting Question :

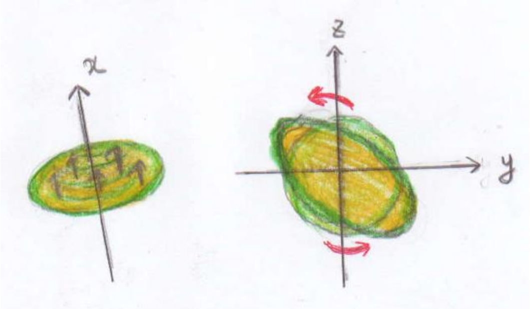
Precession vs Gamma vibration

Do they exist ? If affirmative, which is favored energetically ?



Precession mode





gamma vibration
about the aligned
angular momentum

Conclusion:

Discovery of a new collective excitation built on an oblate high-K isomer will reveal how the nuclear dynamics is affected by macroscopic alignment of angular momenta of protons and neutrons.

Appendix

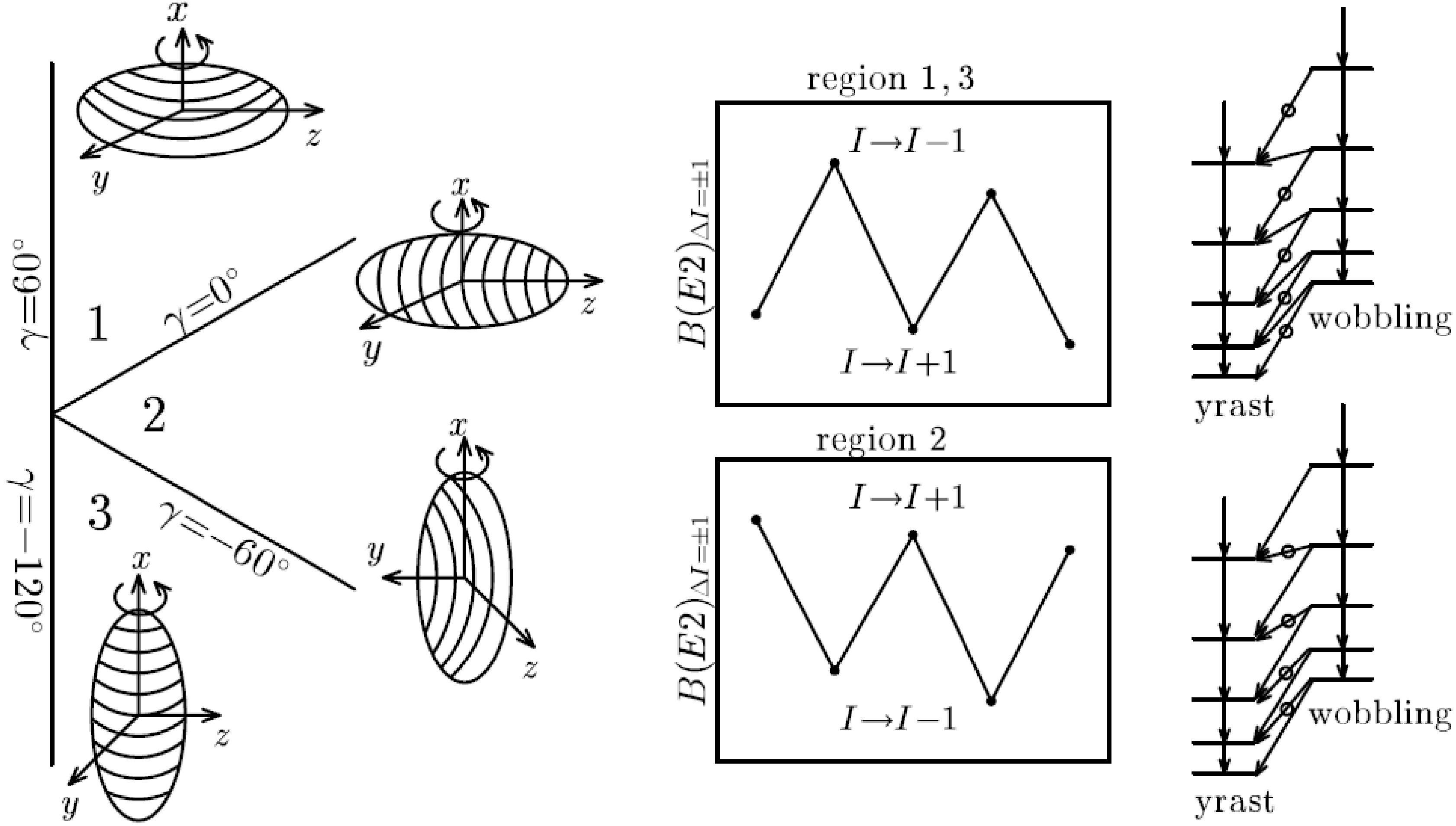


Figure 2: Schematic figure depicting the relation between the triaxial deformation and the properties of the out-of-band E2 transition. The shape corresponding to the triaxiality parameter γ (Lund convention) is shown relative to the main rotation axis, which is chosen to the x-axis in the left panel. In the middle, the out-of-band B(E2) values with $\Delta I = \pm 1$ are plotted as functions of the angular momenta or the rotational frequency, for which stronger transitions are marked in the right panel.

Courtesy of T.Koike

Which candidates are truly chiral?
Experimental confirmation

Bottom line:

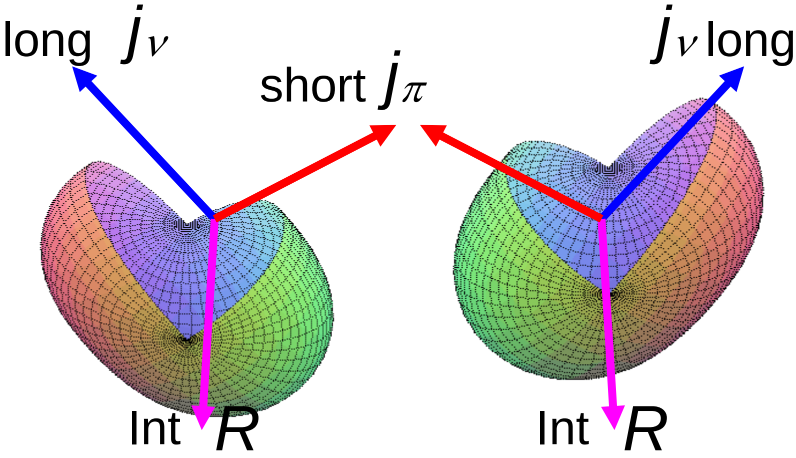
Ideally identical and practically very similar characters between chiral pairs →TWINS

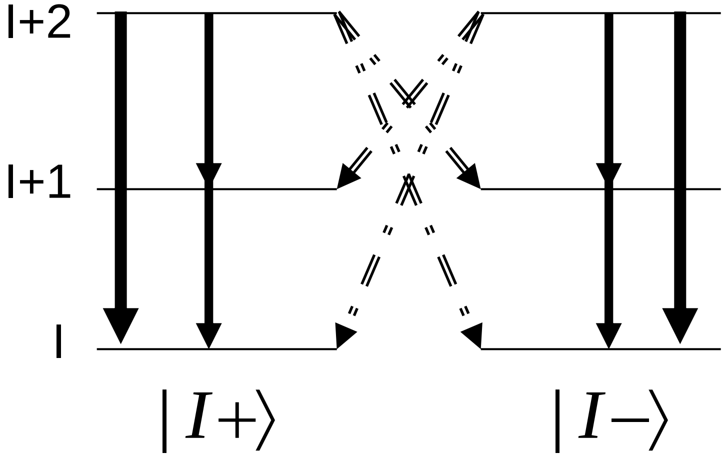
- Degeneracy
- Single particle configuration
  - Unique parity (experimentally pure)
  - q.p alignment
- Collective aspects
  - Moment of inertia
  - Shape/deformation
- Electromagnetic properties (most sensitive to wave functions)

$$B(EM; I_i+ \to I_f+) \approx B(EM; I_i- \to I_f-)$$

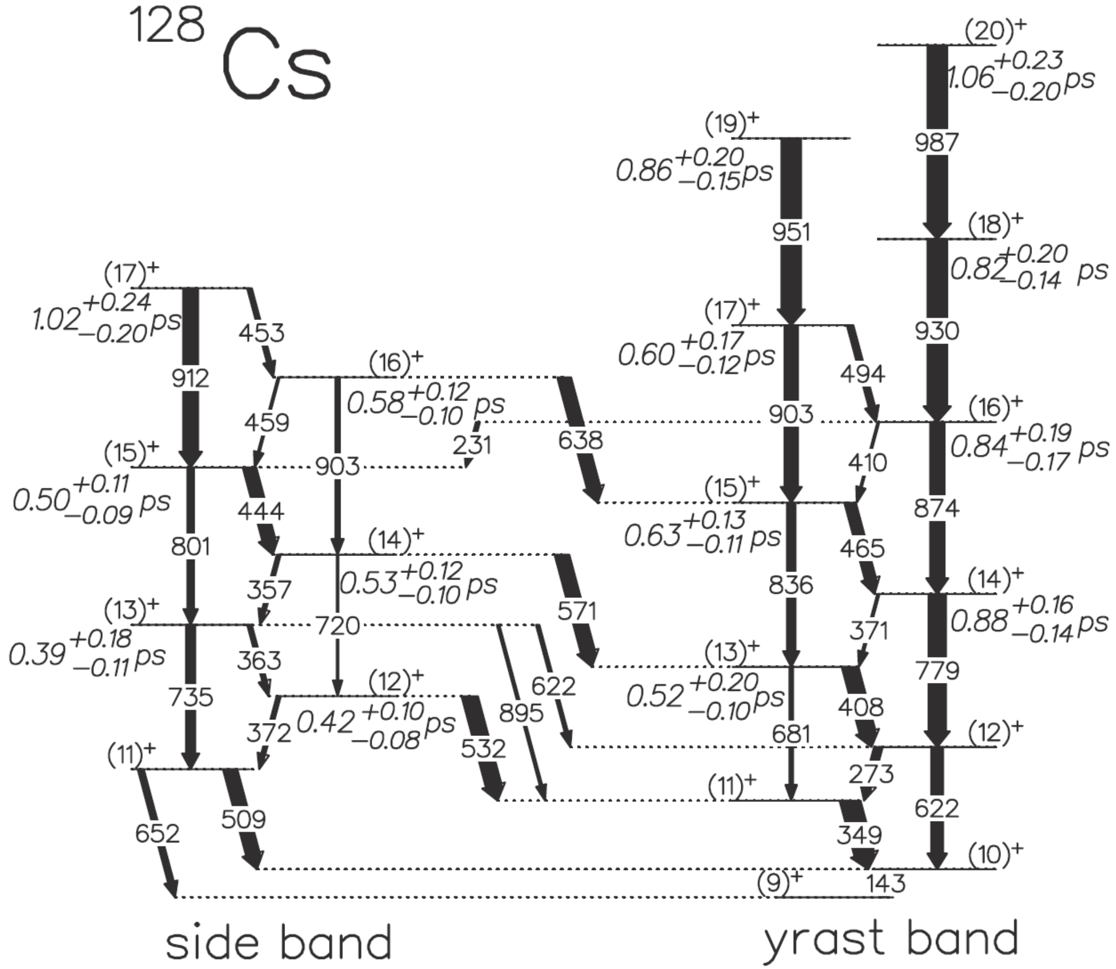
$$B(EM; I_i+ \to I_f-) \approx B(EM; I_i- \to I_f+)$$

- Small Coriolis interaction
  - Smooth and identical variation of S(I)=[E(I)-E(I-1)]/2





Candidate for the Chiral doublet



E. Grodner et al., Phys. Rev. Lett. 97 (2006) 172501