# Direct chiral geometry measurement, the proof of concept

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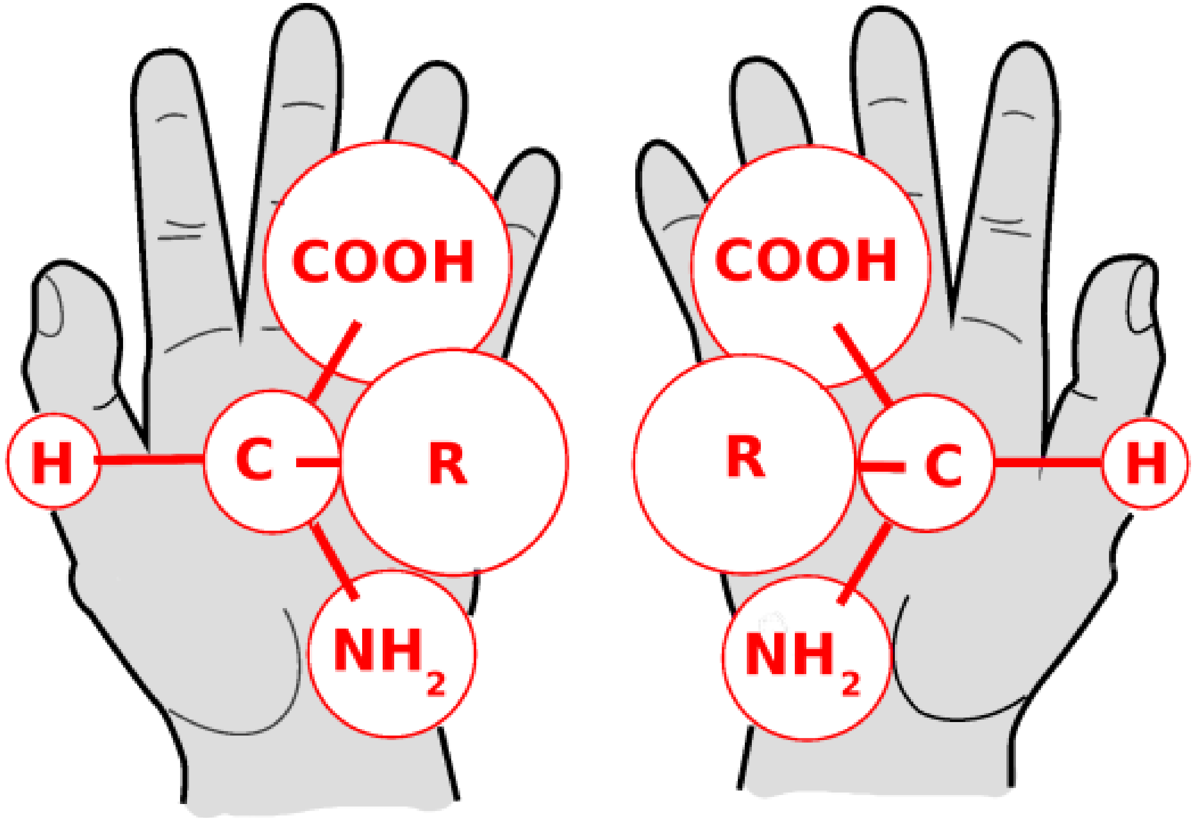
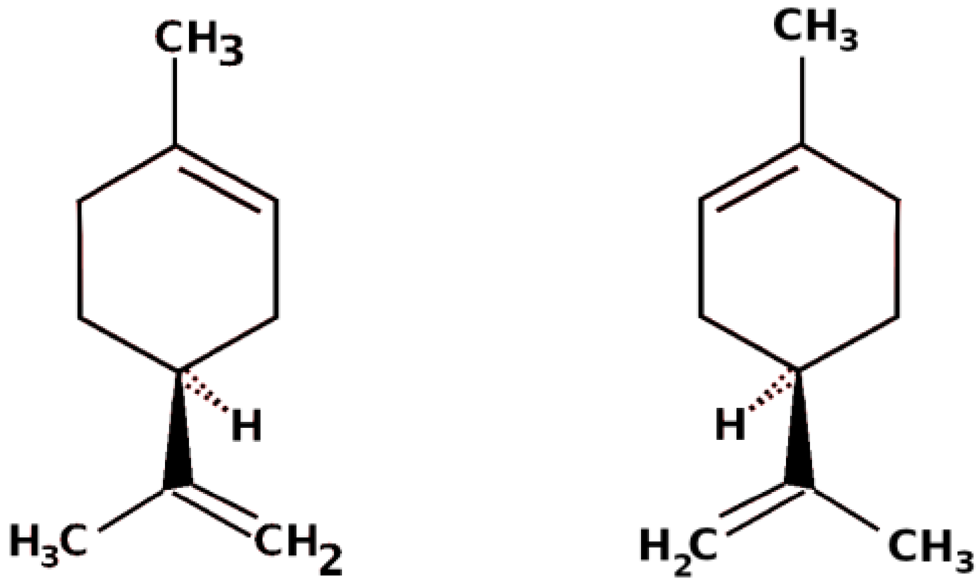
Left- and right-handed molecules

The same chemical composition

Handedness reversion not possibe with rotation

$$R_\pi P|L\rangle = |R\rangle$$





**Citrus fruits aroma molecule**
**The right-handed molecules |R> - fresh fruits smell**
**The left-handed molecule |L> - petrol, turpentine smell**

Mans H. Boelens, Harrie Boelens & Leo J. van Gemert, Perfumer & Flavorist, Vol.18, No. 6, 1-15 (1993)

$$\vec{s} \cdot \vec{p},$$

**Chirality based on helicity concept**

## Chirality in optical physics

$$\chi = \hbar c k \left( \hat{N}^L - \hat{N}^R \right)$$

J. Enrique Vazquez-Lozano, Alejandro Martinez, *"Optical Chirality in Dispersive and Lossy Media"*, Physical Review Letters **121**, 043901 (2018)

## Chirality in weak interaction

$$J_\mu^W = \bar{\psi}\gamma_\mu(1+\gamma_5)\psi = 2\bar{\psi}_L\gamma_\mu\psi_L$$

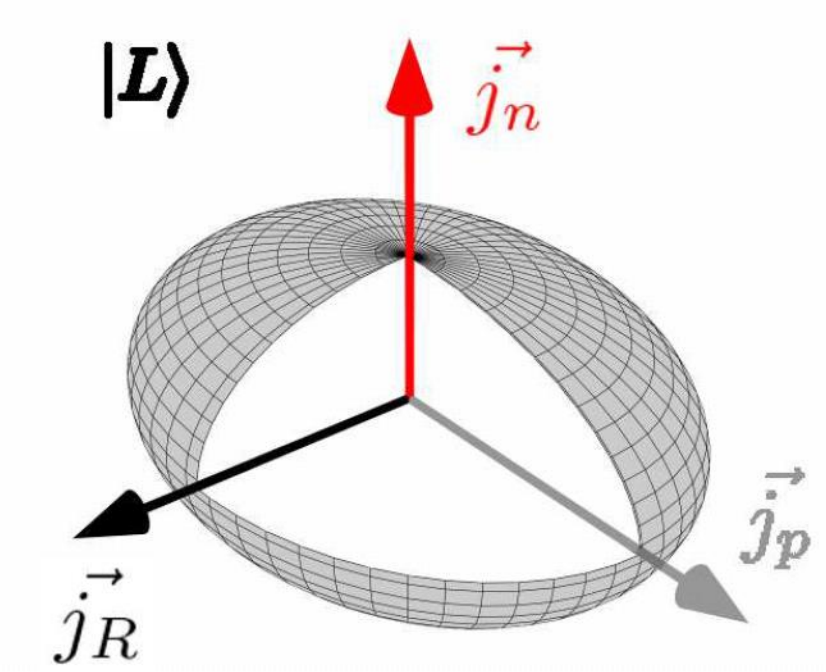
**Still based on space inversion (involves parity)**

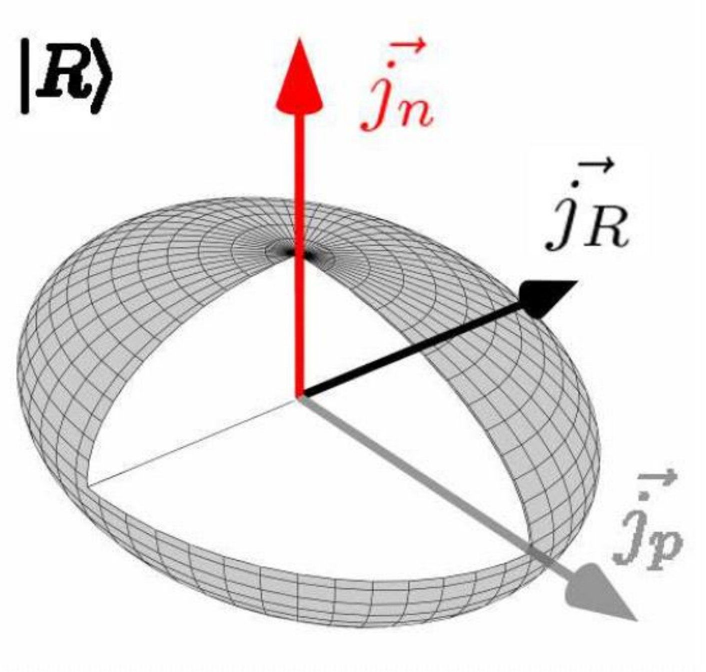
$$R_\pi P|L\rangle = |R\rangle$$

## Nuclear chirality

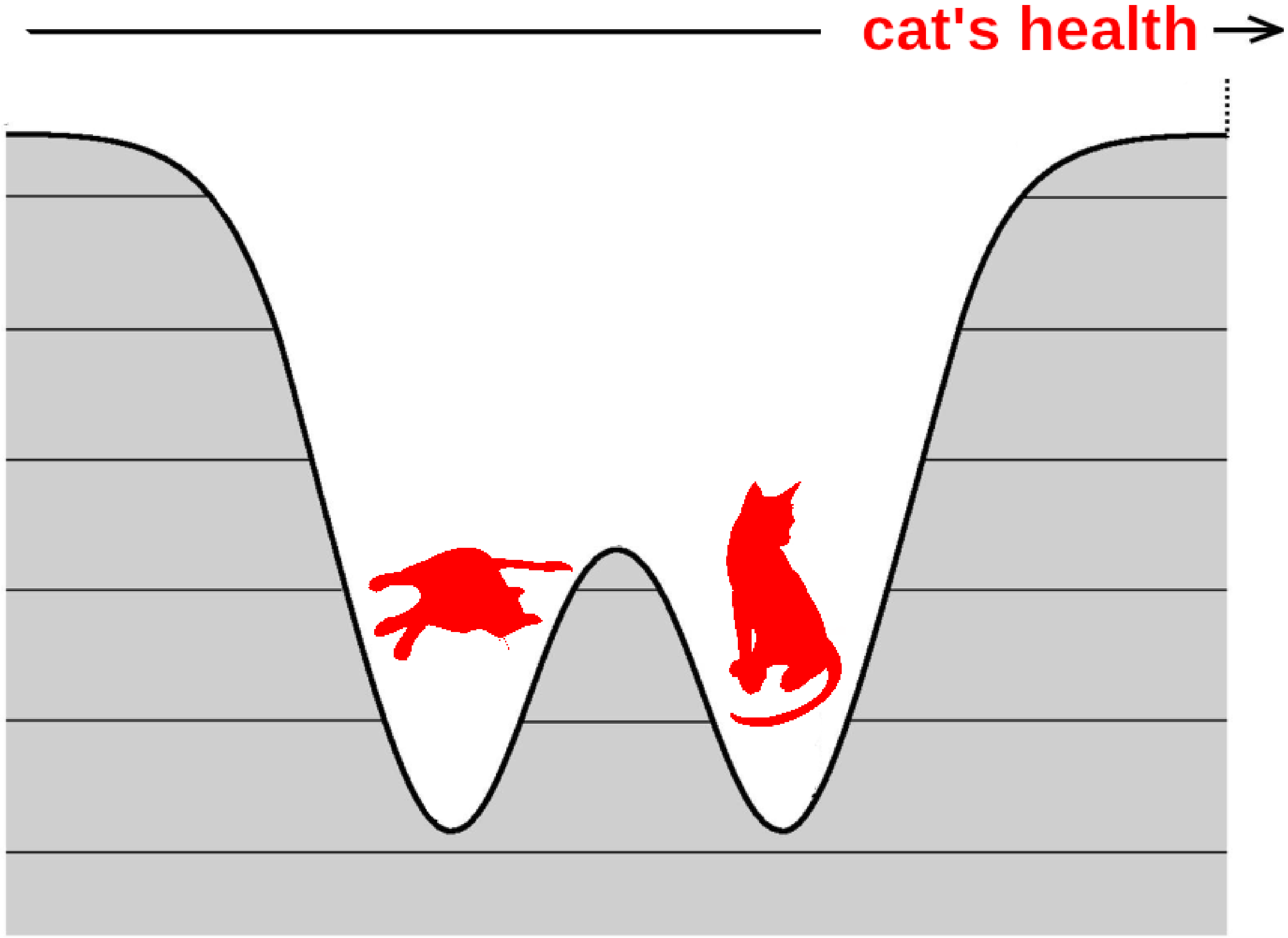
$$R_\pi T|L\rangle = |R\rangle$$

**odd-odd nuclei**
**even-even core (triaxially deformed)**
**odd proton (particle)**
**odd neutron (hole)**

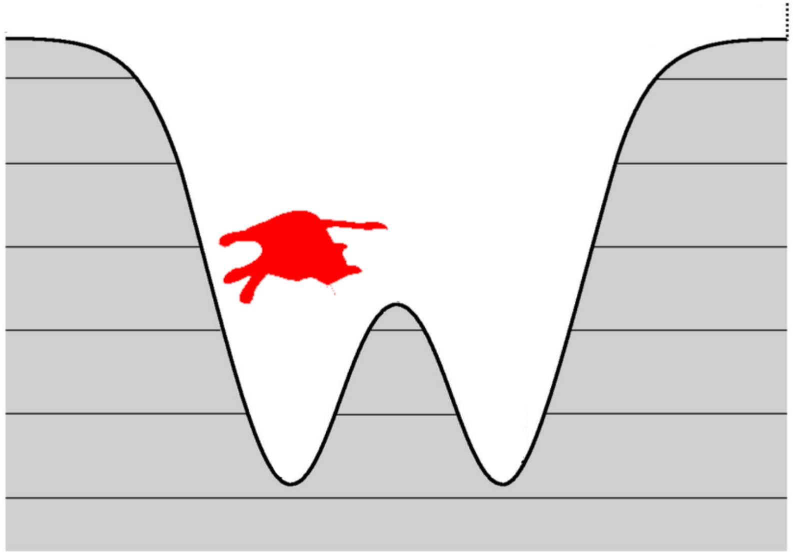


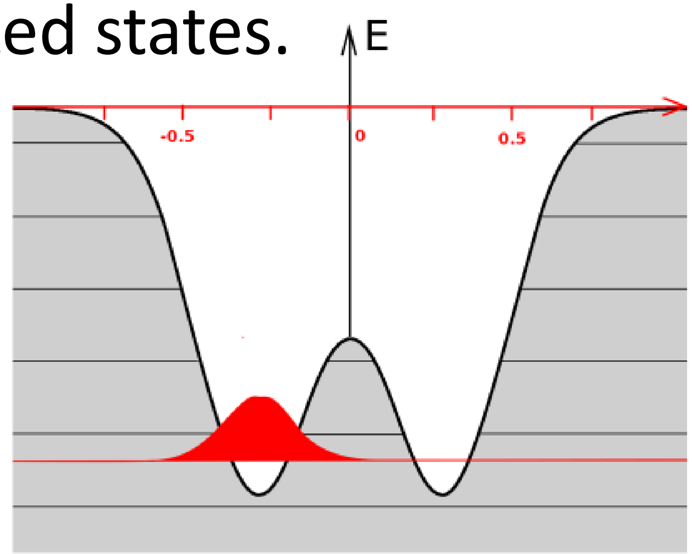



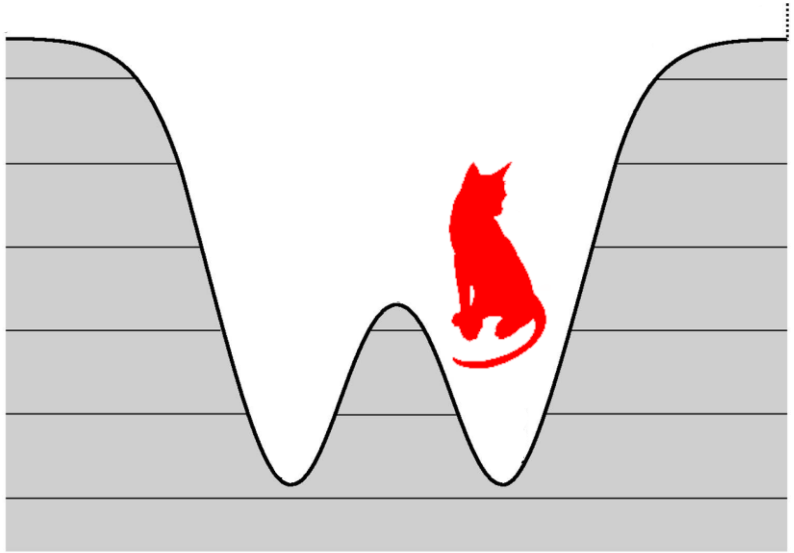
Nuclear chirality is a today's nuclear spectroscopy Schrodinger's cat box problem.

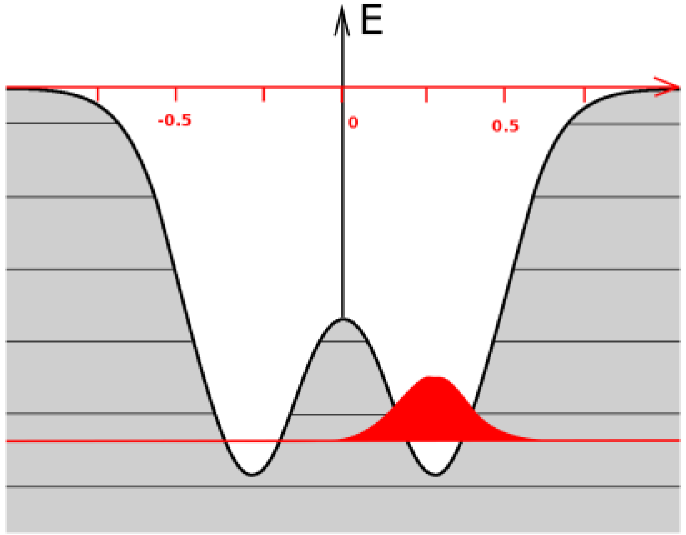


Taking a look into the cat's box allowed, then cats state can be measured. We deal with localized states.

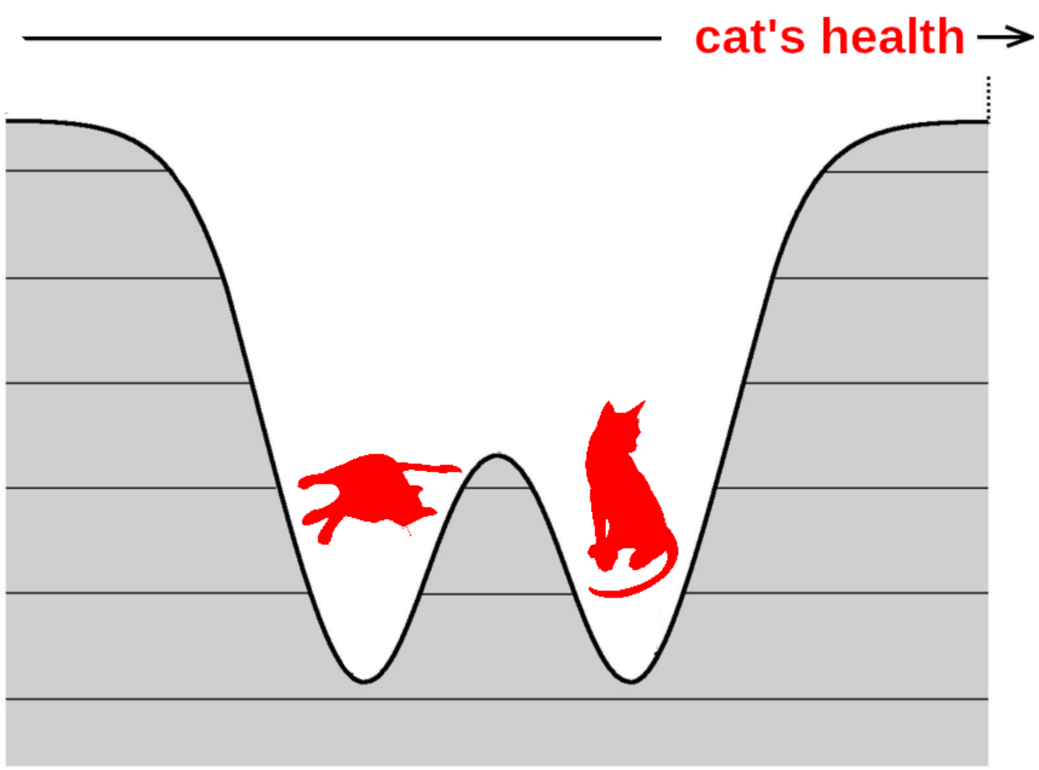


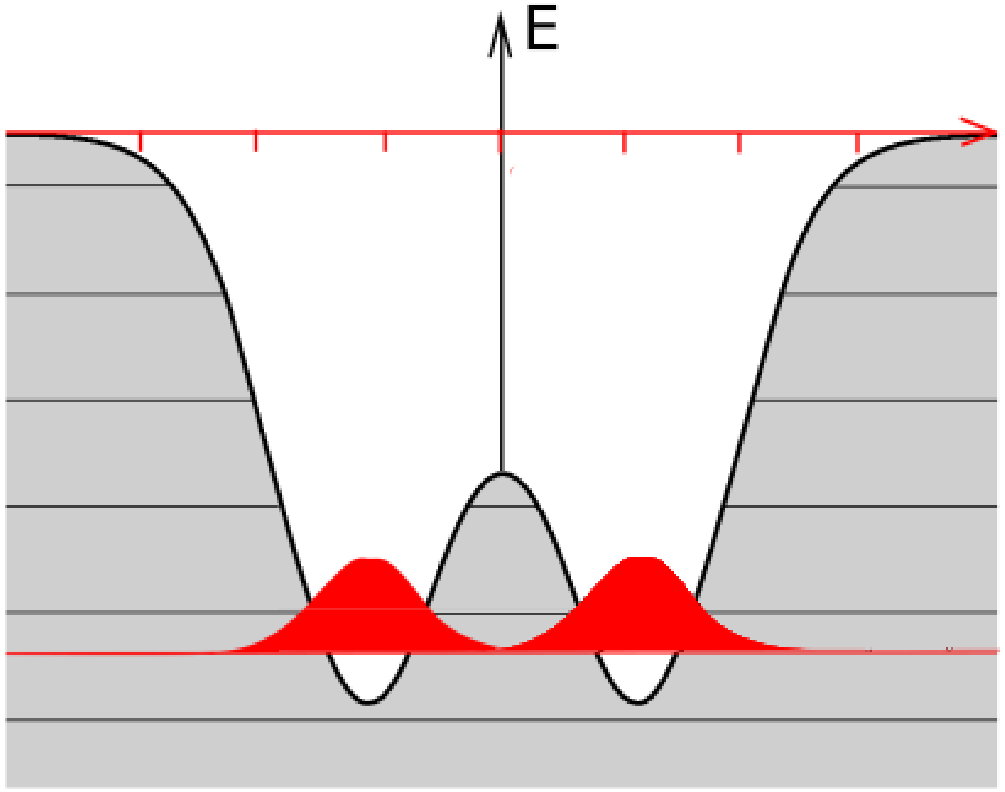


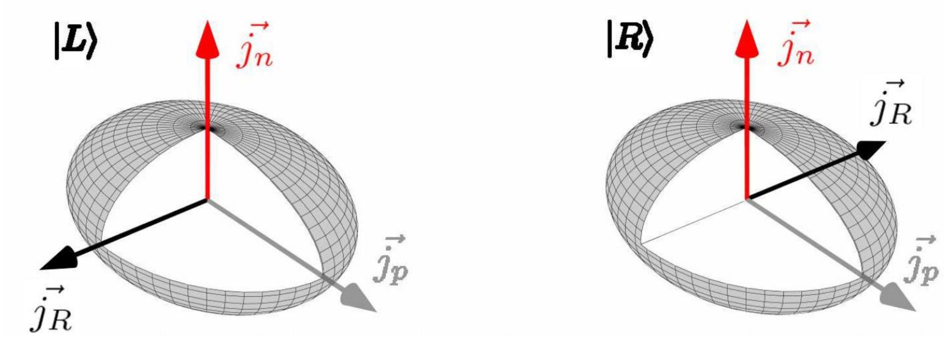


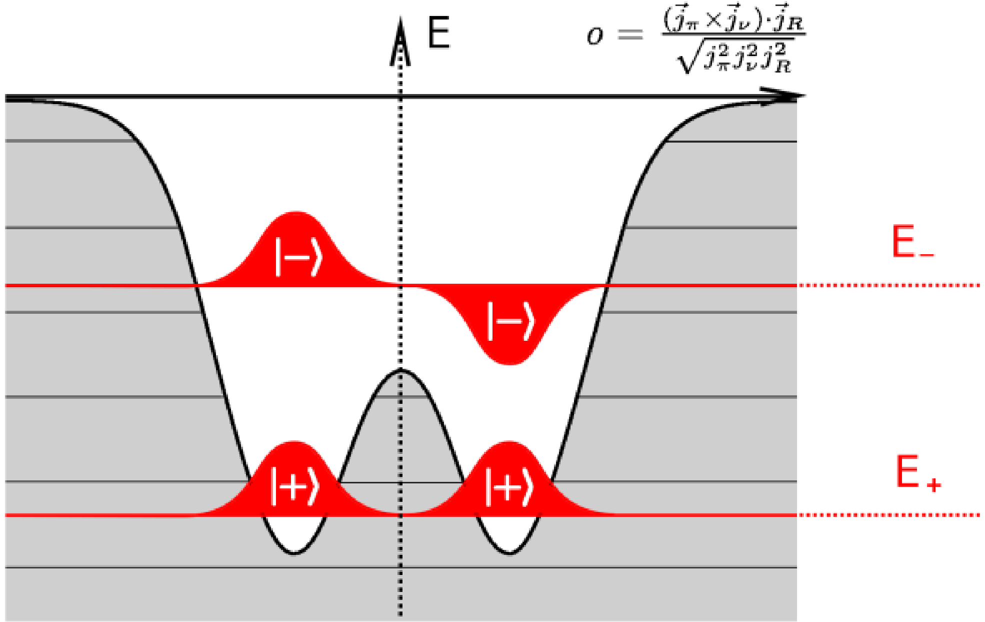
Taking a look into the cat's box forbidden.
We must deal with superimposed states



$$|+\rangle = \frac{1}{\sqrt{2}N_+}(|L\rangle + |R\rangle)$$
$$|-\rangle = \frac{i}{\sqrt{2}N_-}(|L\rangle - |R\rangle).$$

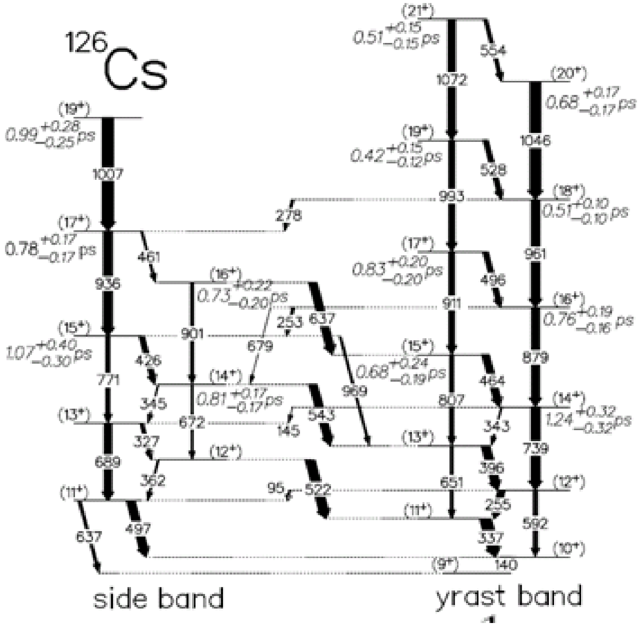


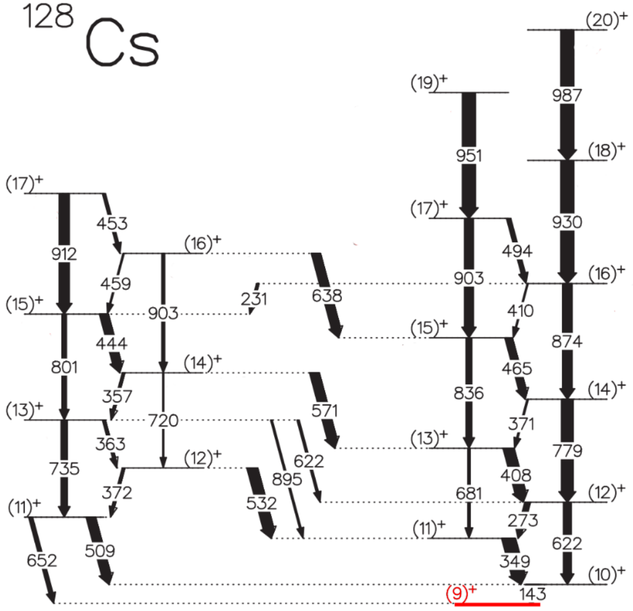




## chiral doublets

$$\langle -|H|-\rangle = \frac{Re\langle L|H|L\rangle - Re\langle L|H|R\rangle}{N_-^2}.$$

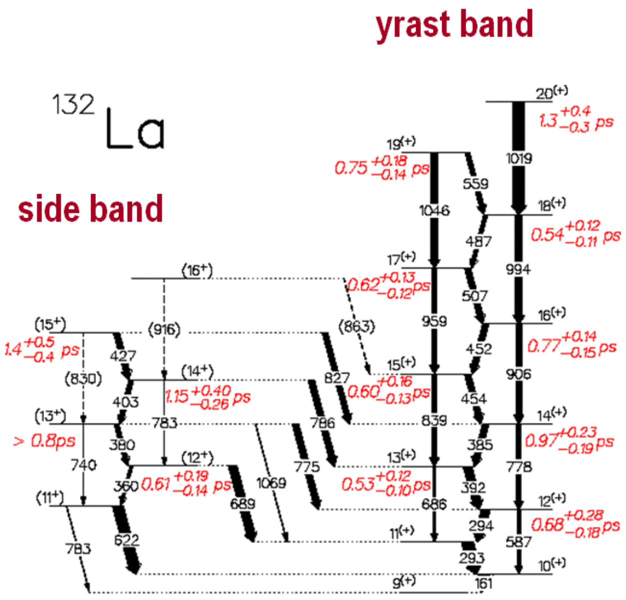
$$\langle +|H|+\rangle = \frac{Re\langle L|H|L\rangle + Re\langle L|H|R\rangle}{N_+^2}$$



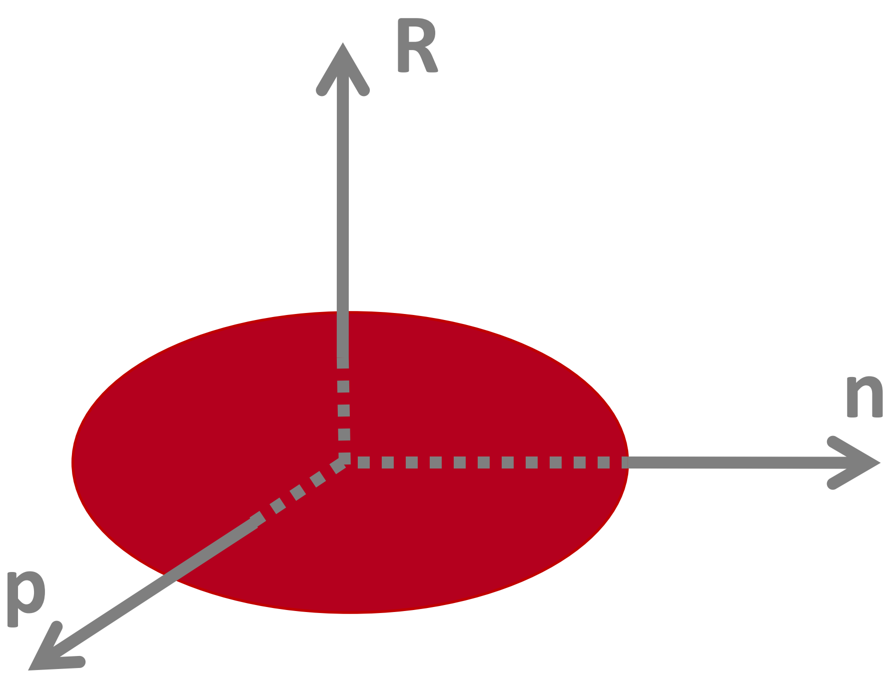

E. G. et al..

**Int. Jour. Of Mod. Phys. E13, 243, (2004)**



# Patterns – signature staggering





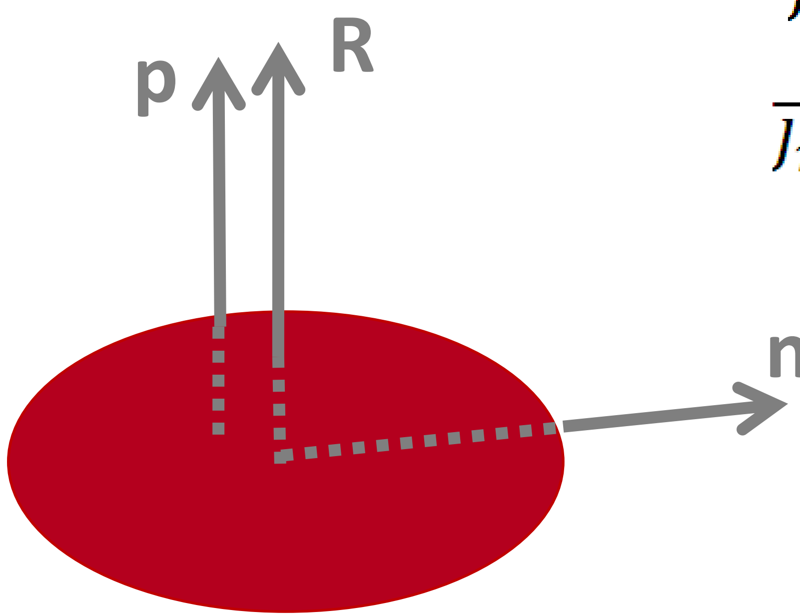

$$\vec{J_p} \cdot \vec{J_R} = 0$$

$$\vec{J_n} \cdot \vec{J_R} = 0$$

$$\vec{I} \cdot \vec{\omega} = 0$$

# Patterns – signature staggering



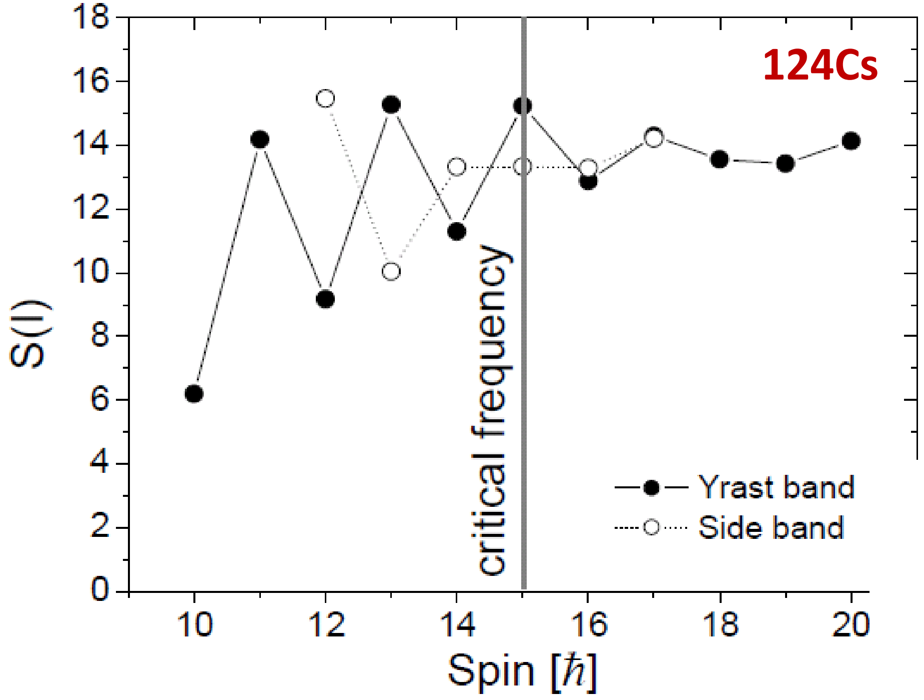


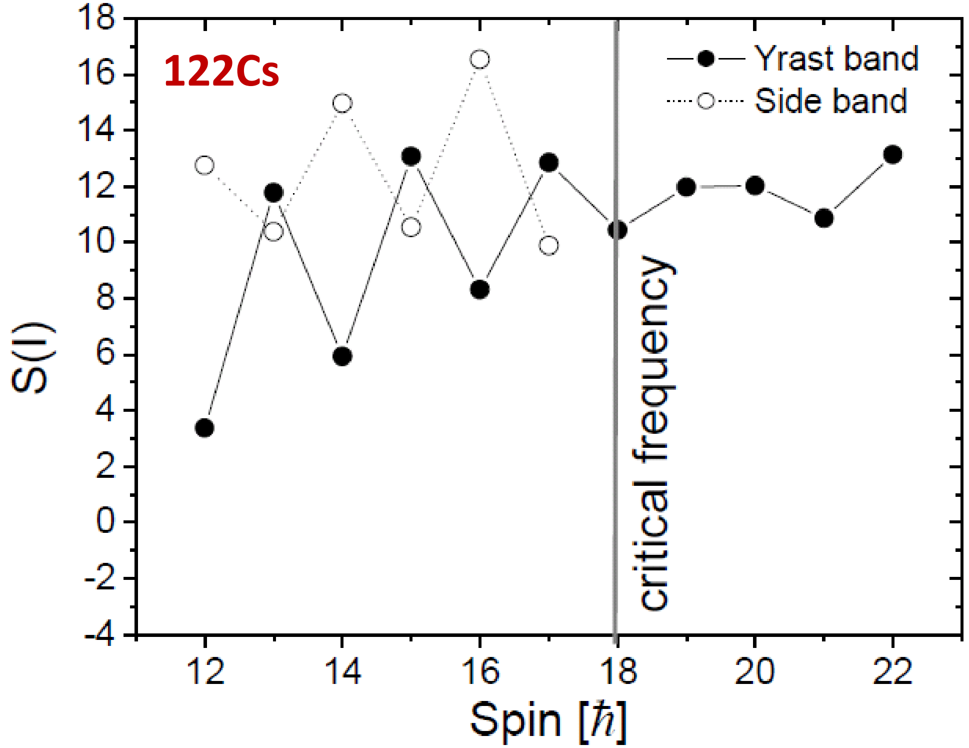

$\overrightarrow{J_p} \cdot \overrightarrow{J_R} \neq 0$ Large energy splitting for |I,M> and |I,-M> substates

$\overrightarrow{J_n} \cdot \overrightarrow{J_R} \neq 0$ Small energy splitting

# Patterns – signature staggering





# First electromagnetic transition probabilities measurement $^{132}La$ (2002)

$$[R_Y T, H] = 0$$

$$|+\rangle = \frac{1}{\sqrt{2}} \frac{|L\rangle + |R\rangle}{\sqrt{1+\varepsilon}} \qquad \langle + | H | + \rangle = \frac{E_0 + \Delta E}{1+\varepsilon}$$

$$|-\rangle = \frac{i}{\sqrt{2}} \frac{|L\rangle - |R\rangle}{\sqrt{1-\varepsilon}} \qquad \langle - | H | - \rangle = \frac{E_0 - \Delta E}{1-\varepsilon}$$

Doubling of the energy for LAB states

**Parameters**

Overlap $\varepsilon = \mathrm{Re}\langle L | R \rangle$

Tunneling effect $\Delta E = \mathrm{Re}\langle L | H | R \rangle$

Diagonal mat. element $E_0 = \mathrm{Re}\langle L | H | L \rangle$

$$[R_Y T, B(\sigma\lambda)] = 0 \qquad \sigma\lambda = M1, E2, M3, E4, \ldots$$

$$\langle + | B(\sigma\lambda) | + \rangle = \frac{B_0 + \Delta B}{1+\varepsilon}$$

$$\langle - | B(\sigma\lambda) | - \rangle = \frac{B_0 - \Delta B}{1-\varepsilon}$$

Doubling of the transition probabilities

**Parameters**

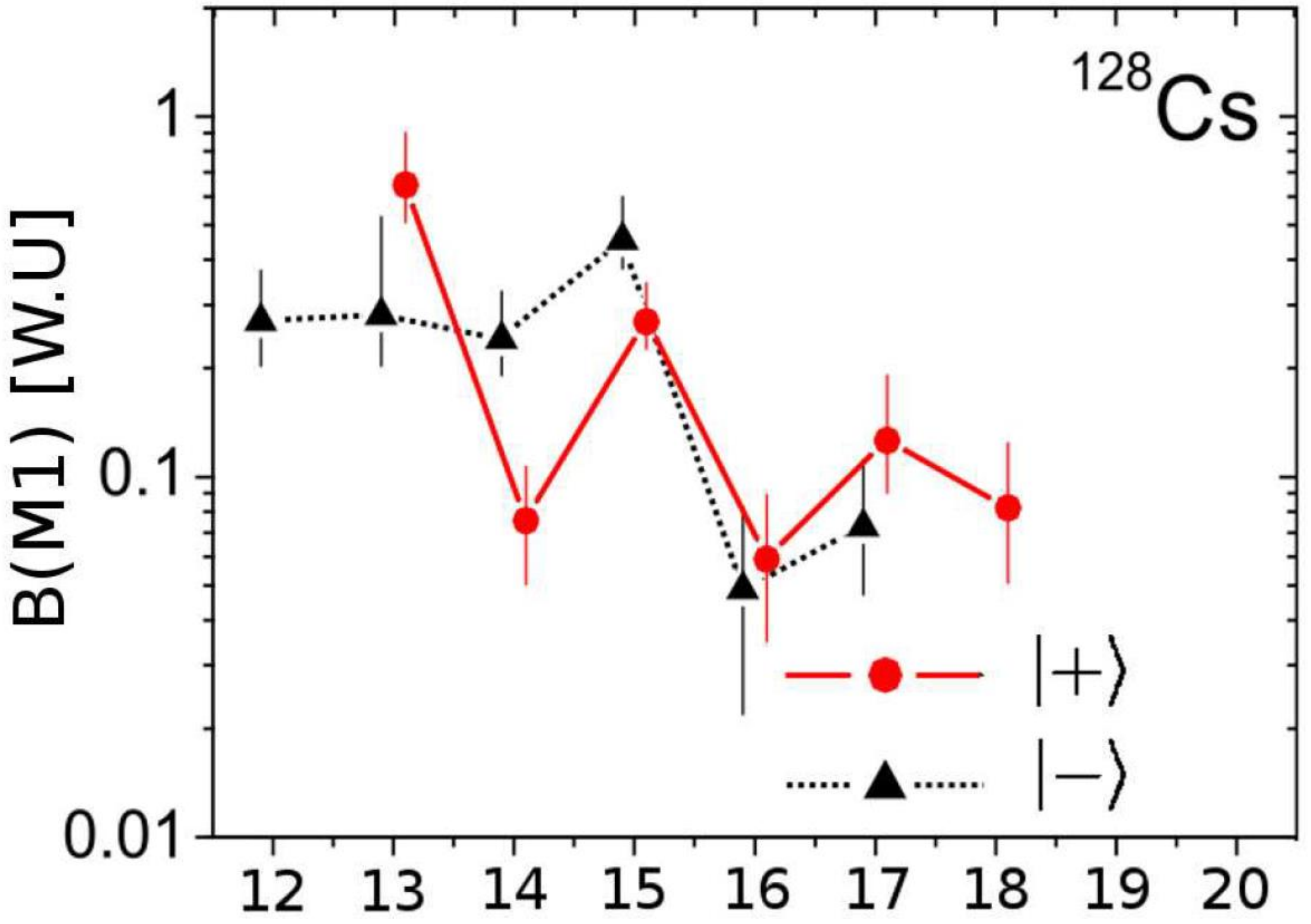
Overlap $\varepsilon = \mathrm{Re}\langle L | R \rangle$

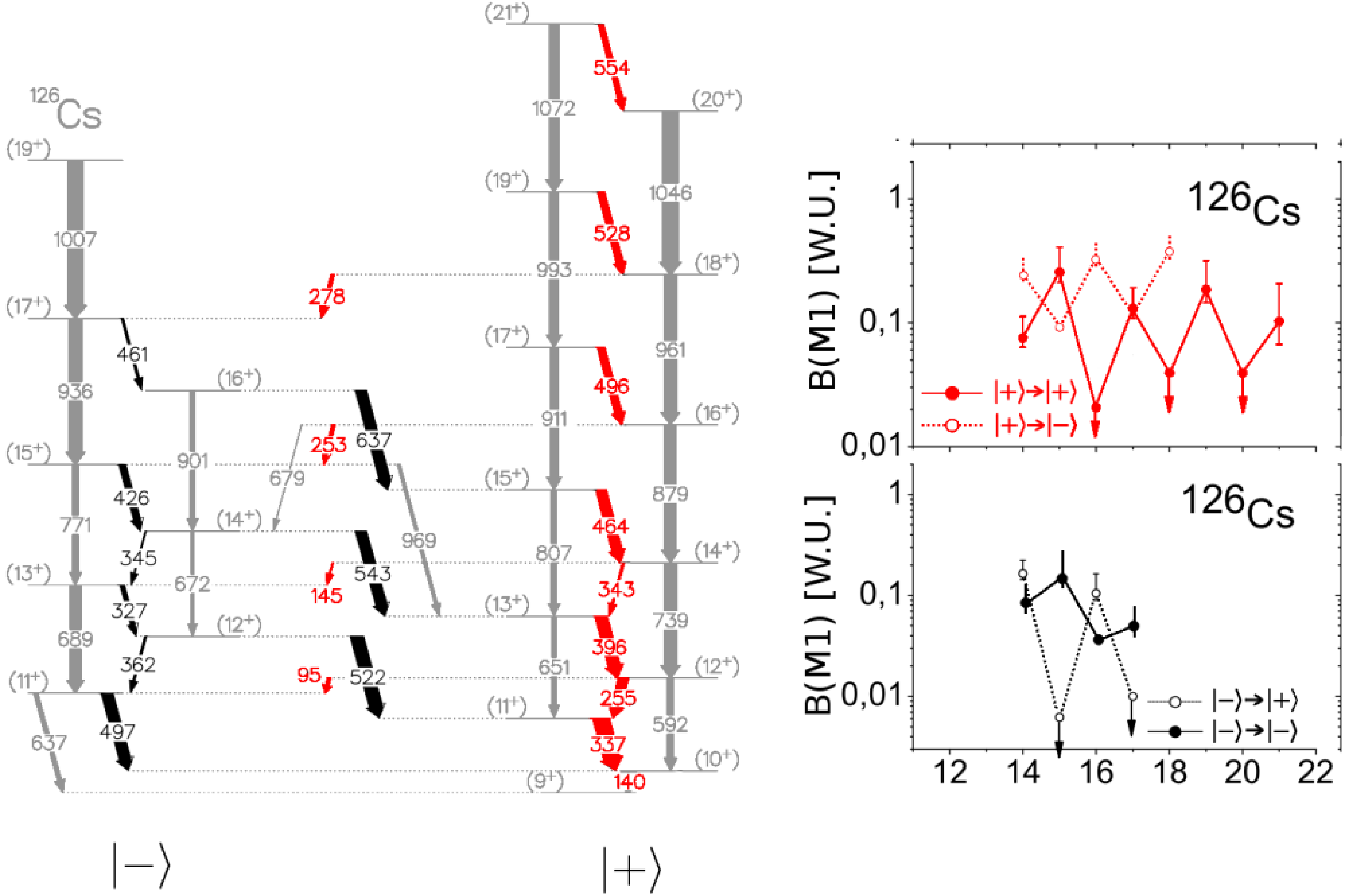
non-diagonal element $\Delta B = \mathrm{Re}\langle L | B | R \rangle$

diagonal mat. element $B_0 = \mathrm{Re}\langle L | B | L \rangle$

**Above spin 14 the B(E2) and B(M1) values are close to each other.**
**Similar electromagnetic behaviour of both rotational bands.**
**Good candidate for chiral partner bands, however….**

**What is that zig-zag pattern in B(M1) values ? (staggering)**

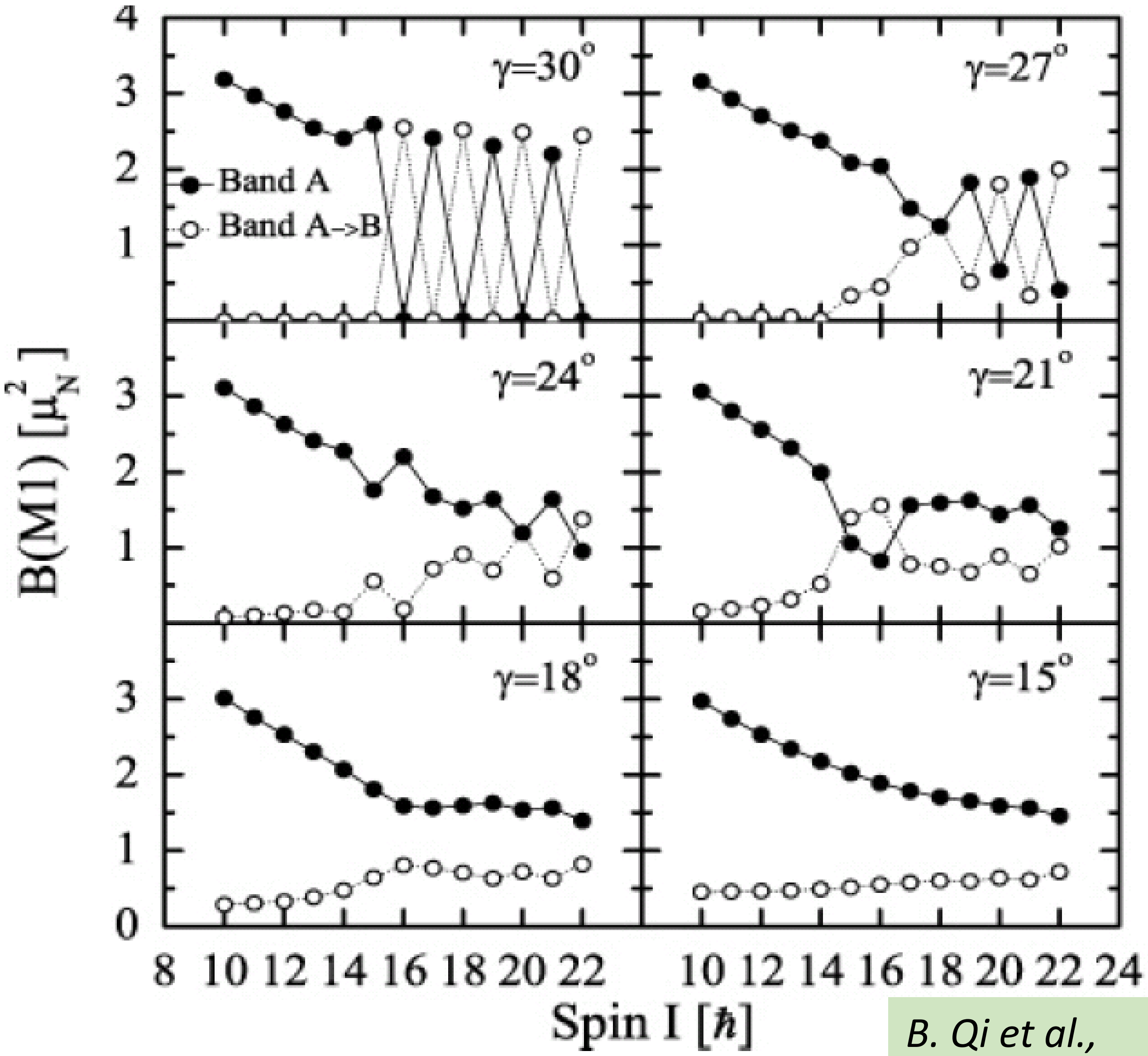




126Cs
(19+)
1007
(17+)
461
936
(16+)
(15+)
901
426
771
(14+)
345
(13+)
672
327
689
(12+)
362
(11+)
637
497
278
253
637
679
969
145
543
95
522
(21+)
554
1072
(20+)
(19+)
528
1046
993
(18+)
(17+)
496
961
911
(16+)
(15+)
464
879
807
(14+)
343
(13+)
396
739
651
(12+)
255
(11+)
337
592
(10+)
(9+)
140
|−⟩
|+⟩
B(M1) [W.U.]
126Cs
|+⟩→|+⟩
|+⟩→|−⟩
B(M1) [W.U.]
126Cs
|−⟩→|+⟩
|−⟩→|−⟩
1
0,1
0,01
12
14
16
18
20
22

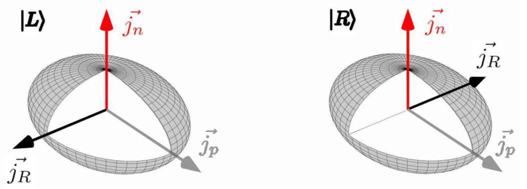
# Chiral bands talk opposite values

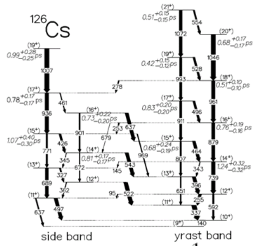




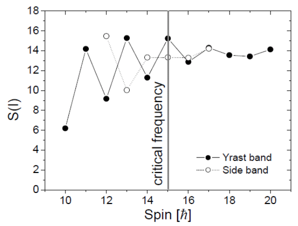

*B. Qi et al.,*
**PHYSICAL REVIEW C 79, 041302(R) (2009)**

# Indirect signatures of chirality

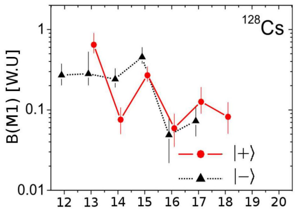


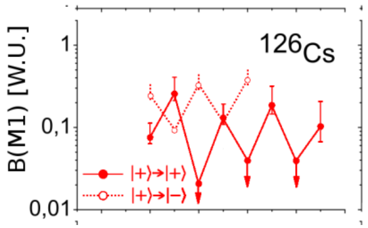

- 1. two nearly degenerated rotational bands with same I and parities



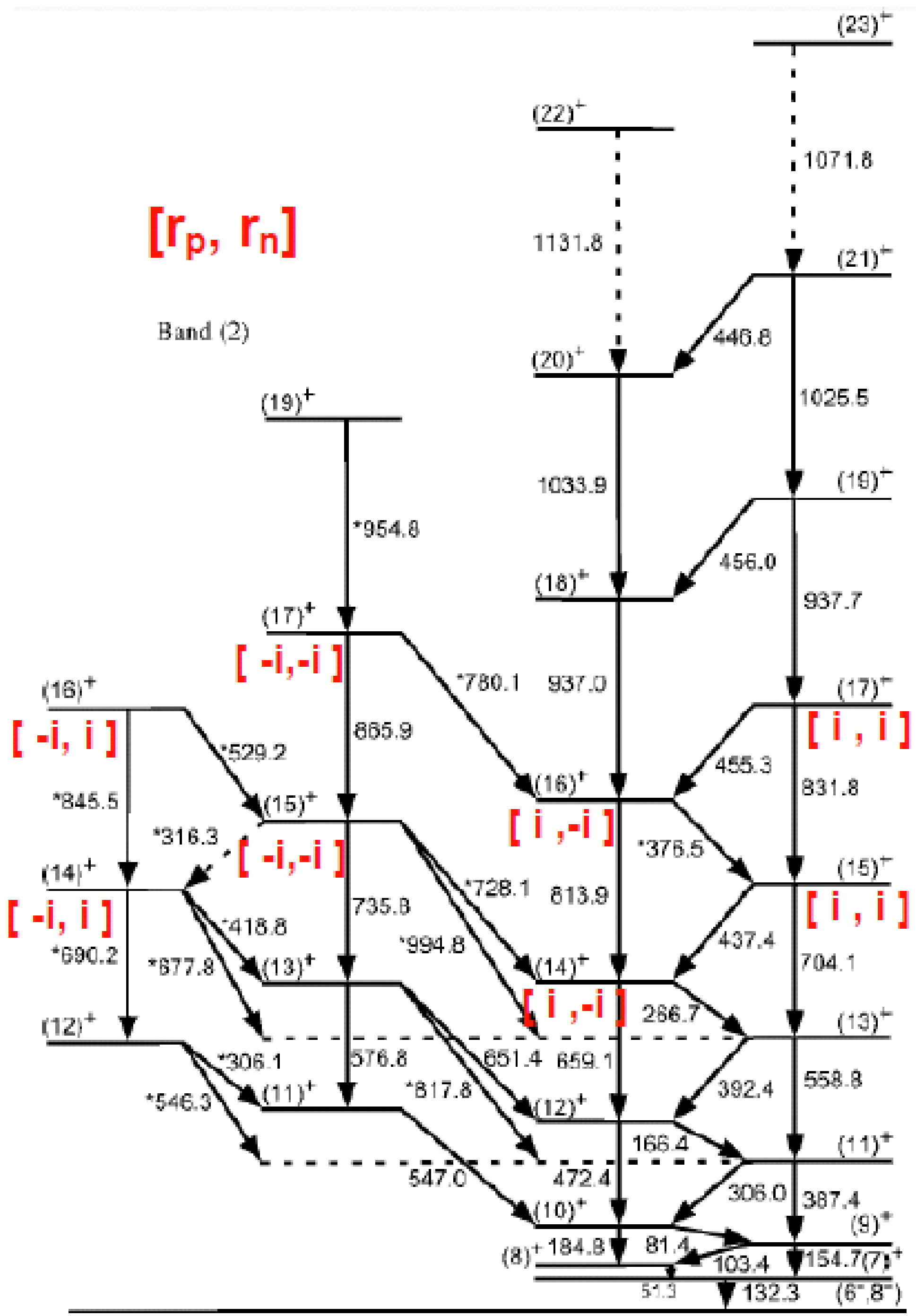

- 2. No energy staggerings




- 3. Nearly the same EM transition probabilities in both bands
- 4. B(M1) staggerings (in some isotopes only)

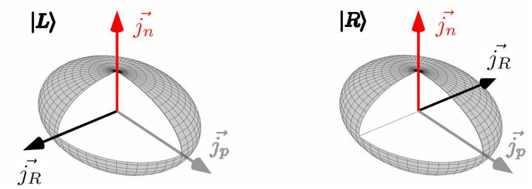



- 5. Opposite B(M1) staggering for inband and intraband transitions




| total signature | $r_p$ | $r_n$ | $r_c$ | spin sequence |
|---|---|---|---|---|
| -1 | i | i | 1 | 1, 3, 5, 7, ... |
| 1 | i | -i | 1 | 0, 2, 4, 6, ... |
| -1 | -i | -i | 1 | 1, 3, 5, 7, ... |
| 1 | -i | i | 1 | 0, 2, 4, 6, ... |

Urgent need for direct
Spin geometry measurement

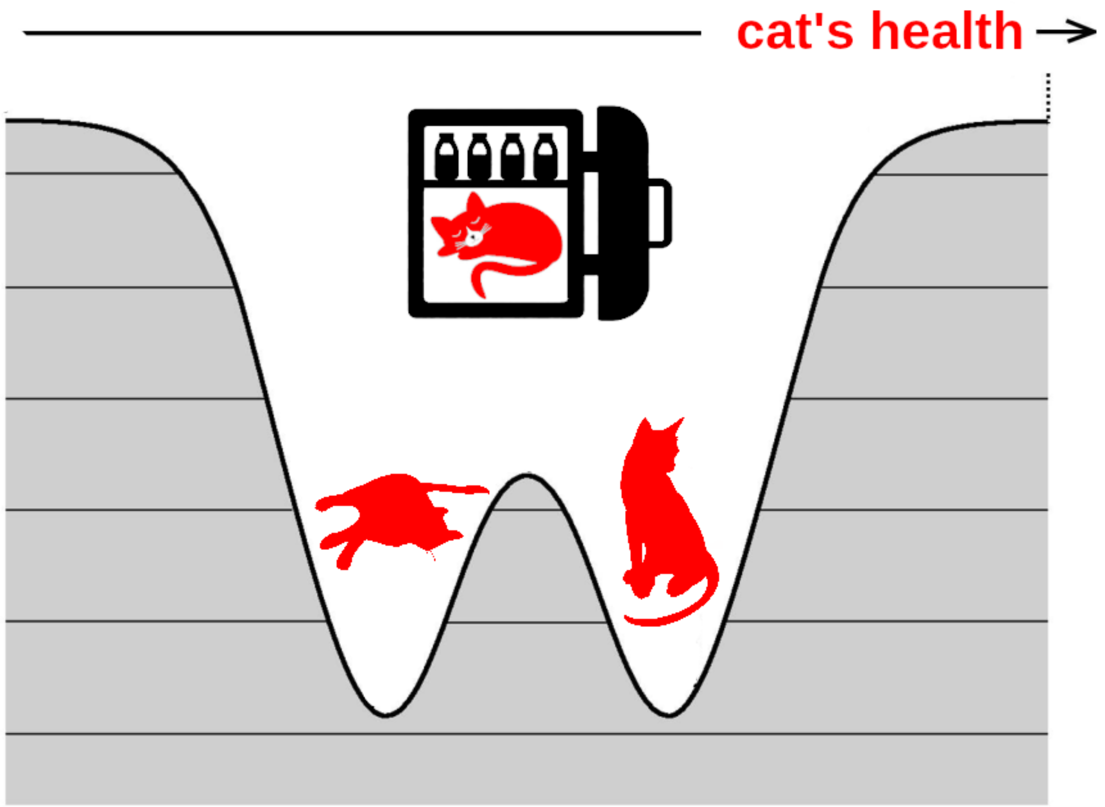


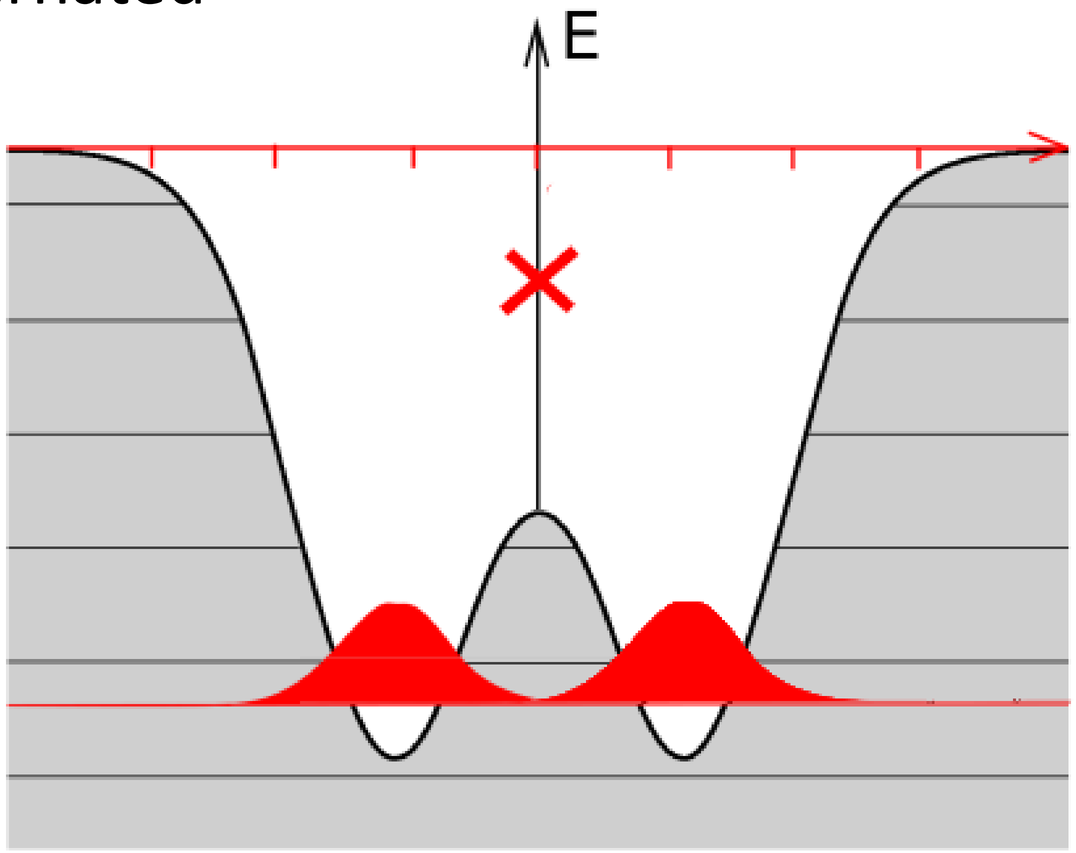

Direct chirality measurement

Let’s return to the Schroedinger’s cat

Cat’s health expectation value on superimposed states?

Neither alive nor dead , rather = hibernated

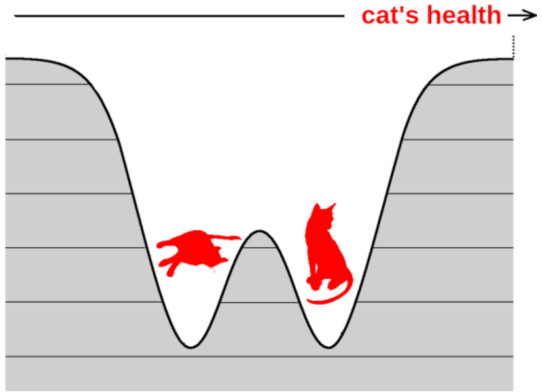


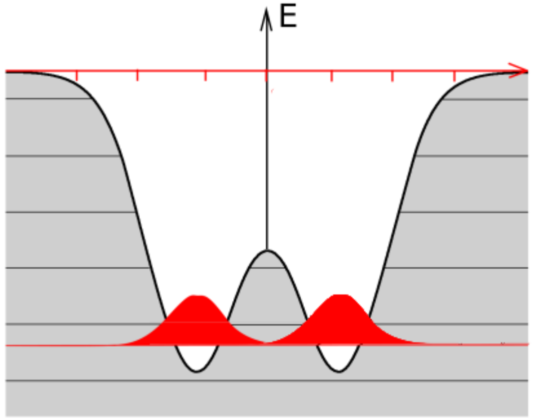



Attention!
Now the clue for experimenters

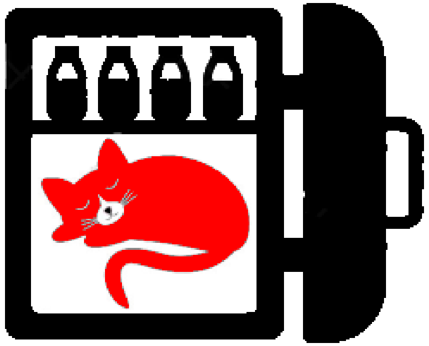
Superimposed states of a cat in the box

Symmetry braking cat inside



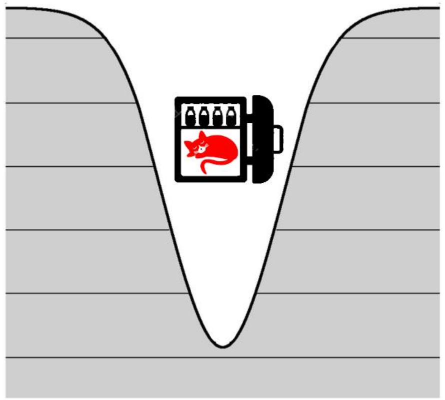



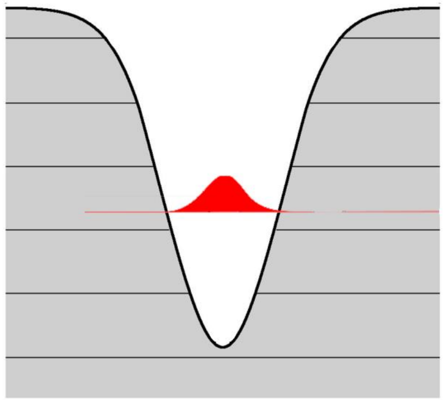

Measured cat's health:
hibernated



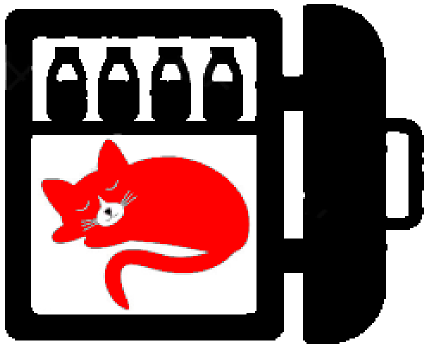
But what if we put a hibernated cat in the box in a first place?

Symmetry conserving cat inside



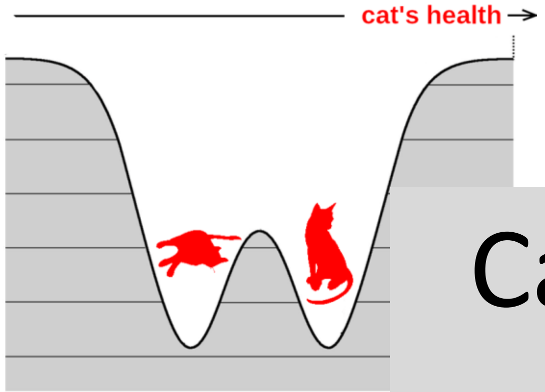


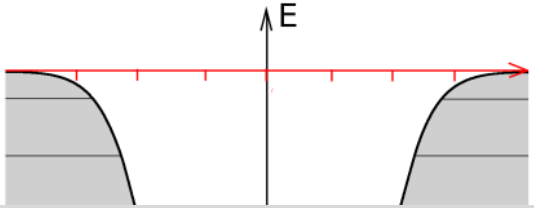
Measured cat's health:
hibernated



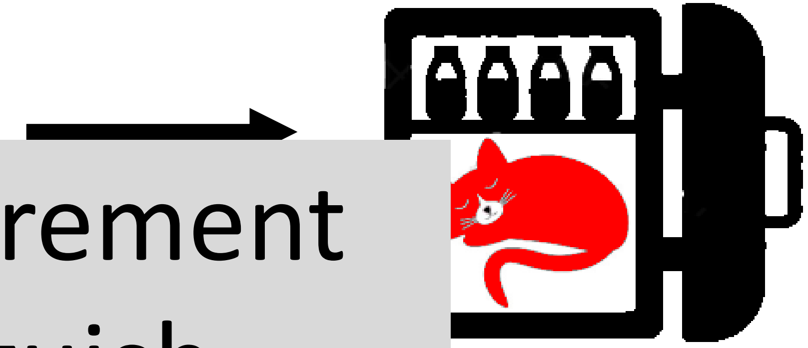
Superimposed states of a cat in the box

Symmetry braking cat inside



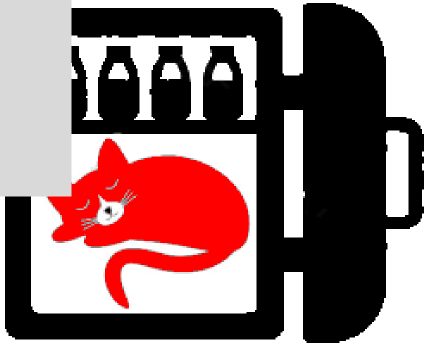

Measured cat's health:
hibernated

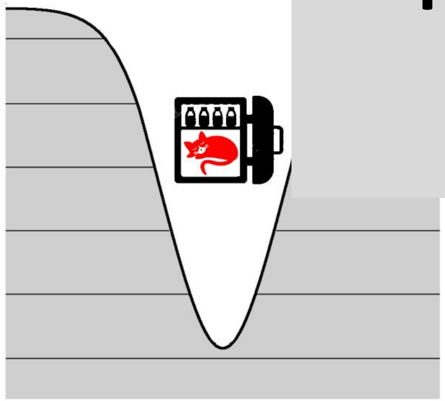


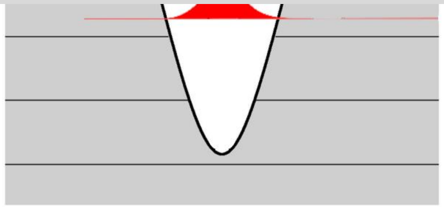
Cat's health measurement
unable to distinguish
the symmetry breaking from
The symmetry conserving
cat in the box.

But what if v
in a first plac
Symmetry co

…d cat's health:
…bernated







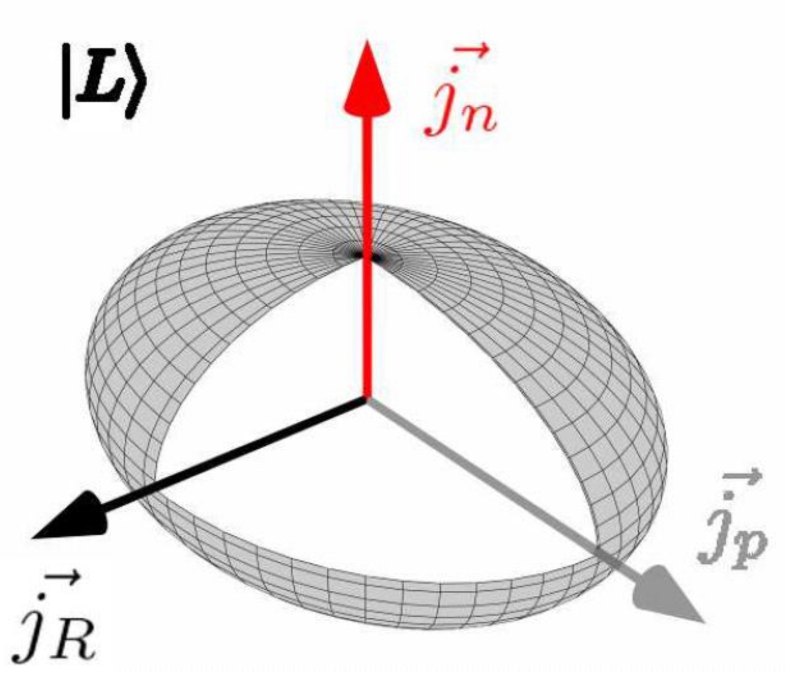
## Nuclear chirality

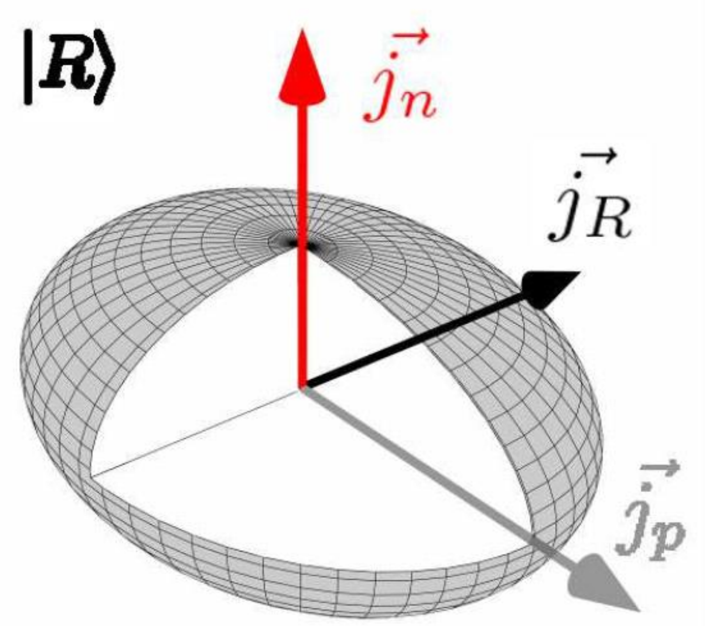
Handedness instead
of cat’s health parameter

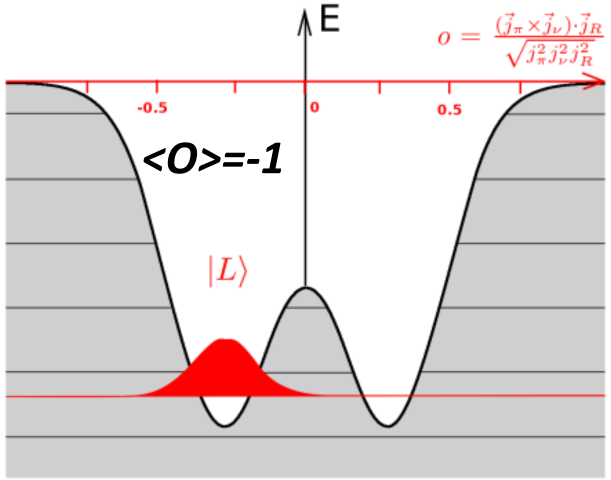
$$O = \frac{(\vec{j}_\pi \times \vec{j}_\nu)\cdot\vec{j}_R}{\sqrt{j_\pi^2 j_\nu^2 j_R^2}}$$

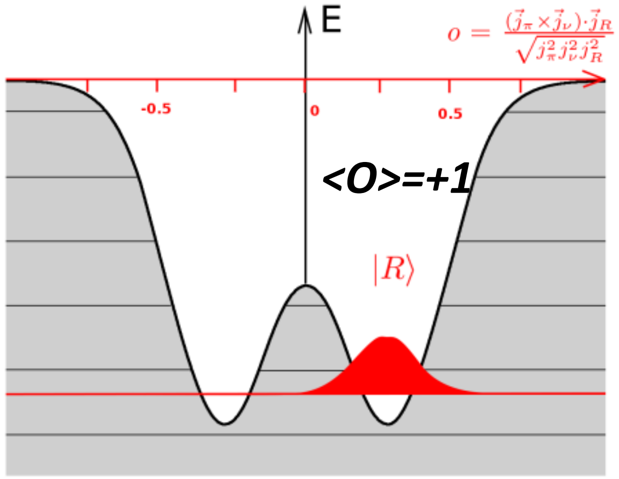
<O>=-1

<O>=+1






**Fusion-evaporation reactions used to produce highly excited odd-odd isotopes at HIL (U200p cyclotron).**

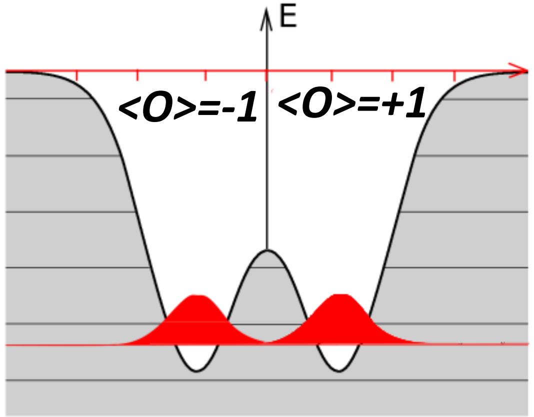
**A nucleus cools-down emitting particles and gamma quanta.**

**At some point is must chose spontaneously the handedness.**

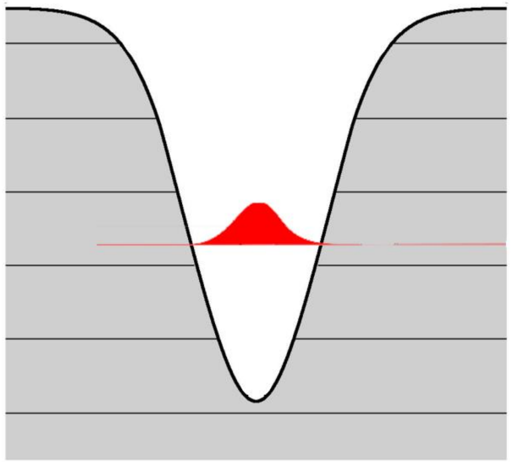
**Spontaneous chiral symmetry breaking in nuclear physics.**

Stefan Frauendorf ”*Spontaneous symmetry breaking in rotating nuclei*”, Reviews of Modern Physics **73**, 463 (2001)

Broken symmetry




Conserved symmetry



In both cases the same measured handedness value =0.0
(a hibernated cat again)

$$\langle O \rangle = \frac{(\vec{j}_\pi \times \vec{j}_\nu)\cdot\vec{j}_R}{\sqrt{j_\pi^2 j_\nu^2 j_R^2}} = 0.0$$

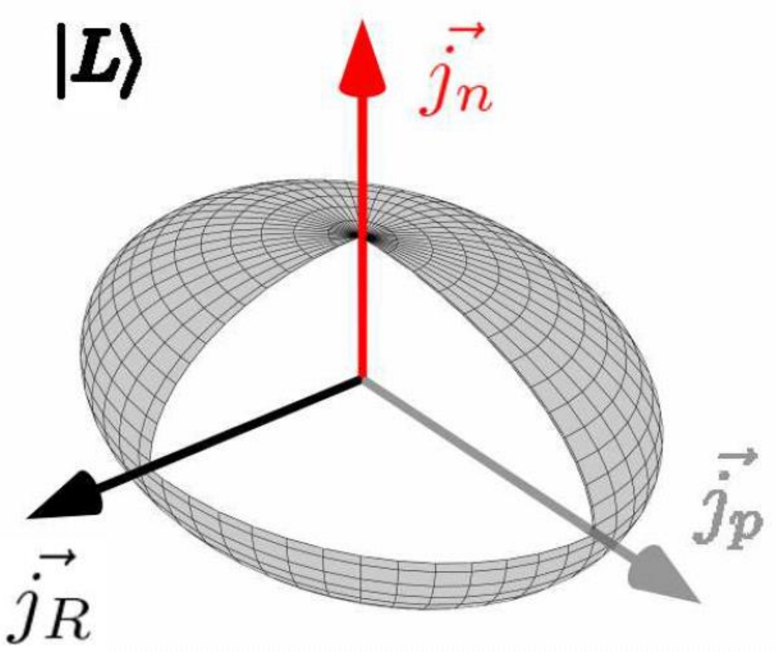
Expectation value of handedness
does not distinguish the symmetry breaking
from the symmetry conserving nucleus.

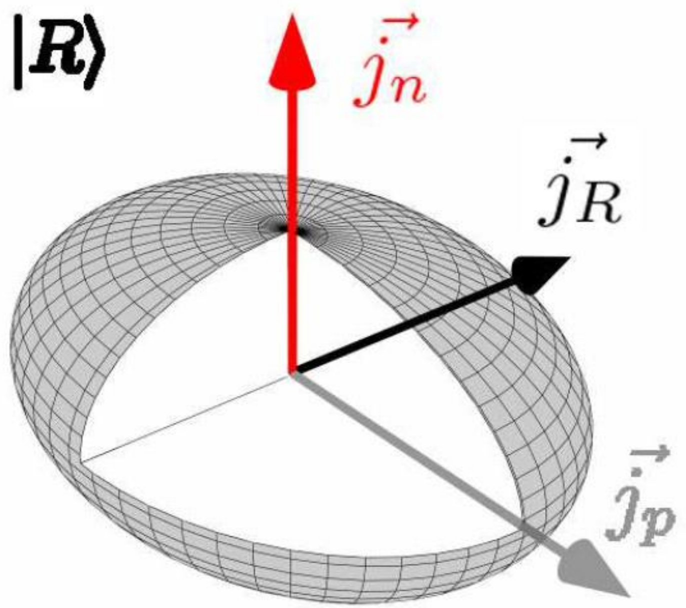
Measuring unsigned observable like volume may distinguish symmetry broken from symmetry conserved state.

*<V>=+1*
Left handed

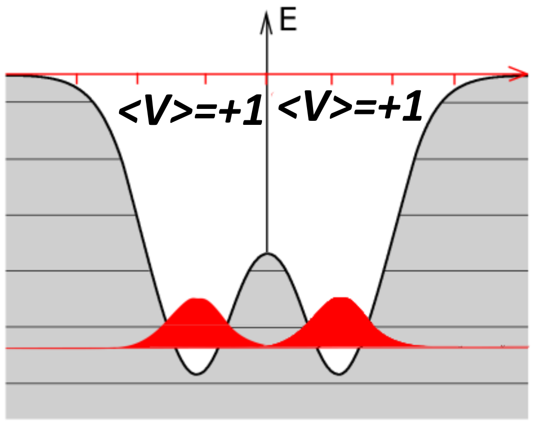
*<V>=0*
planar

*<V>=+1*
Right handed



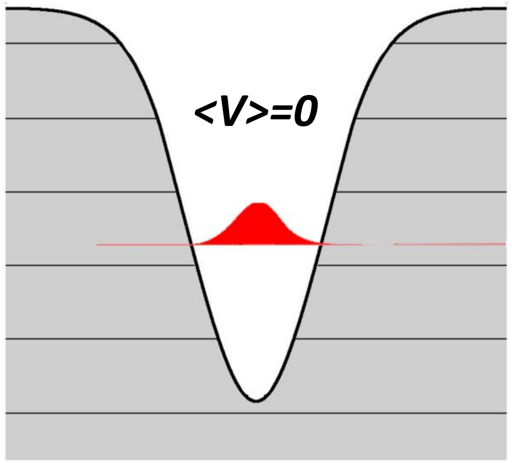



Broken symmetry




Volume <V> close to +1
for symmetry breaking nucleus

Conserved symmetry




Volume <V> close to +0
for symmetry conserving nucleus

# G-factors – volume measurement



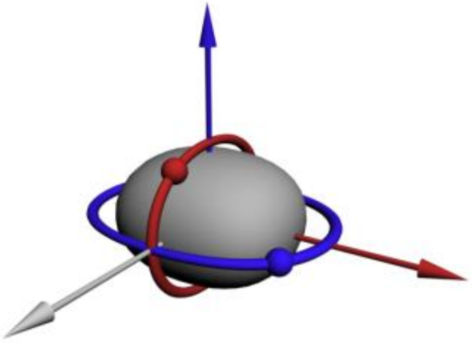
$$g = \frac{1}{2}(g_p + g_n + g_R)$$

$$+ \frac{1}{J(J+1)}\frac{1}{2} j_p(j_p+1)(g_p - g_n - g_R)$$

$$+ \frac{1}{J(J+1)}\frac{1}{2} j_n(j_n+1)(g_n - g_p - g_R)$$

$$+ \frac{1}{J(J+1)}\frac{1}{2} j_R(j_R+1)(g_R - g_p - g_n)$$

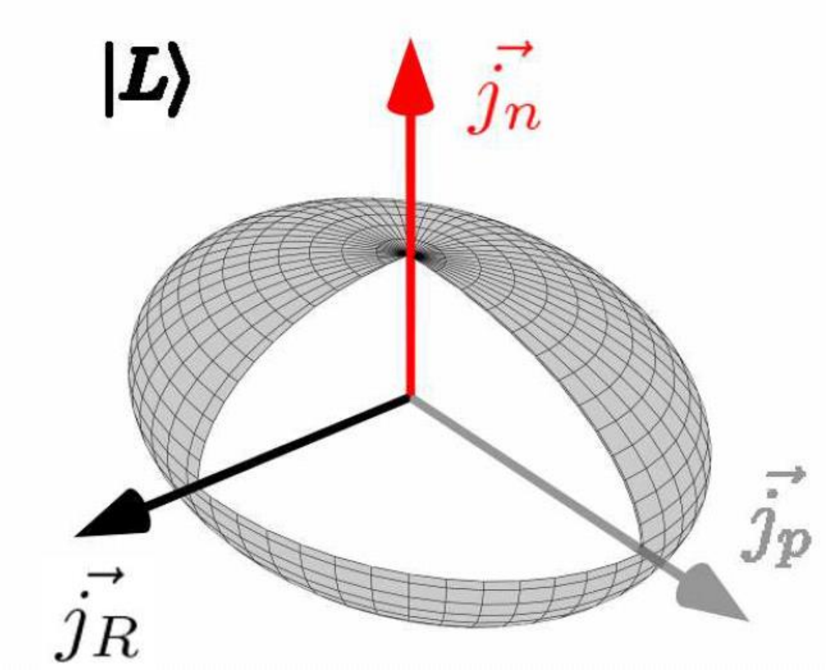
$$- \frac{1}{J(J+1)}(g_p \vec{J}_n \cdot \vec{J}_R + g_n \vec{J}_p \cdot \vec{J}_R + g_R \vec{J}_p \cdot \vec{J}_n)$$

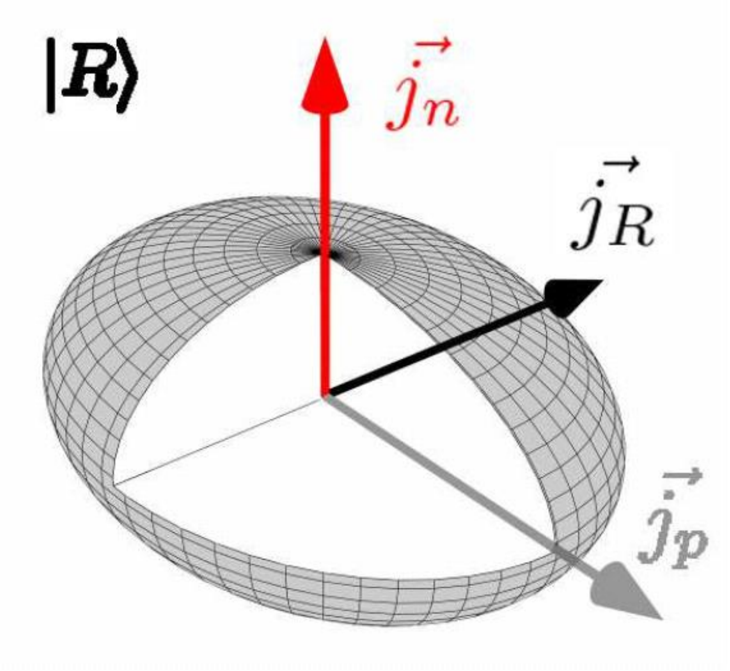


# Magnetic dipole moment is a hit! Measured value: the g-factor

$$\frac{1}{\langle J^2 \rangle}\left(g_p\langle \vec{j}_n \cdot \vec{j}_R\rangle + g_n\langle \vec{j}_p \cdot \vec{j}_R\rangle + g_R\langle \vec{j}_p \cdot \vec{j}_n\rangle\right)$$

| | | |
|---|---|---|
| *<g>=0* | *<g>=+0.1* | *<g>=0* |
| Left handed | planar | Right handed |



# First Measurement of the *g* Factor in the Chiral Band: The Case of the $^{128}$Cs Isomeric State

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PHYSICAL REVIEW C
*covering nuclear physics*



# Examination of nuclear chirality with a magnetic moment measurement of the $I = 9$ isomeric state in $^{128}$Cs

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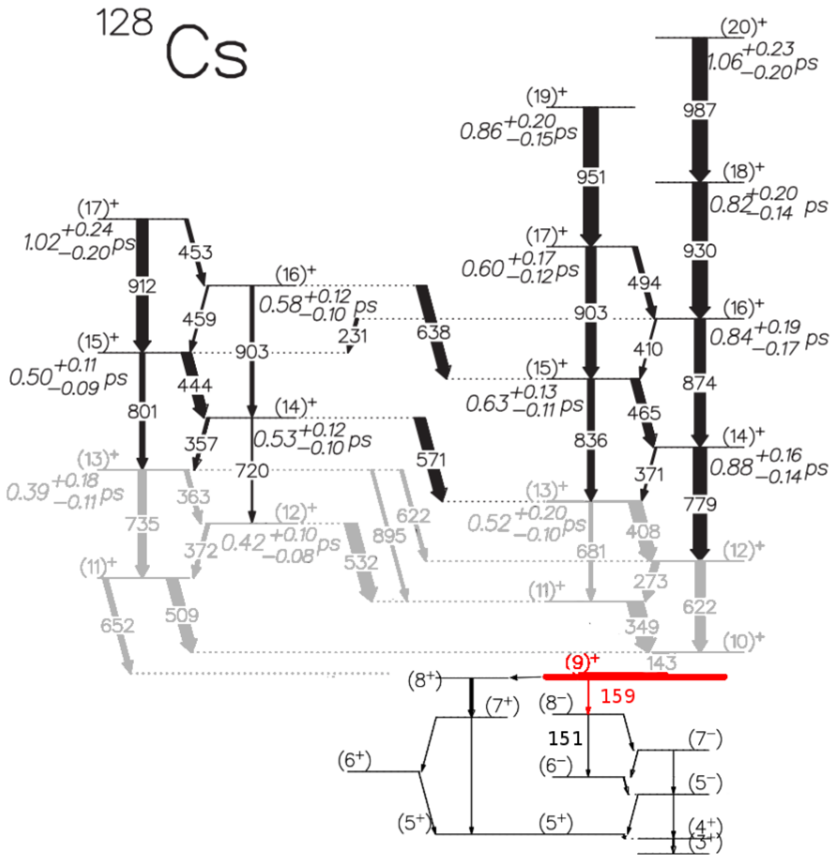
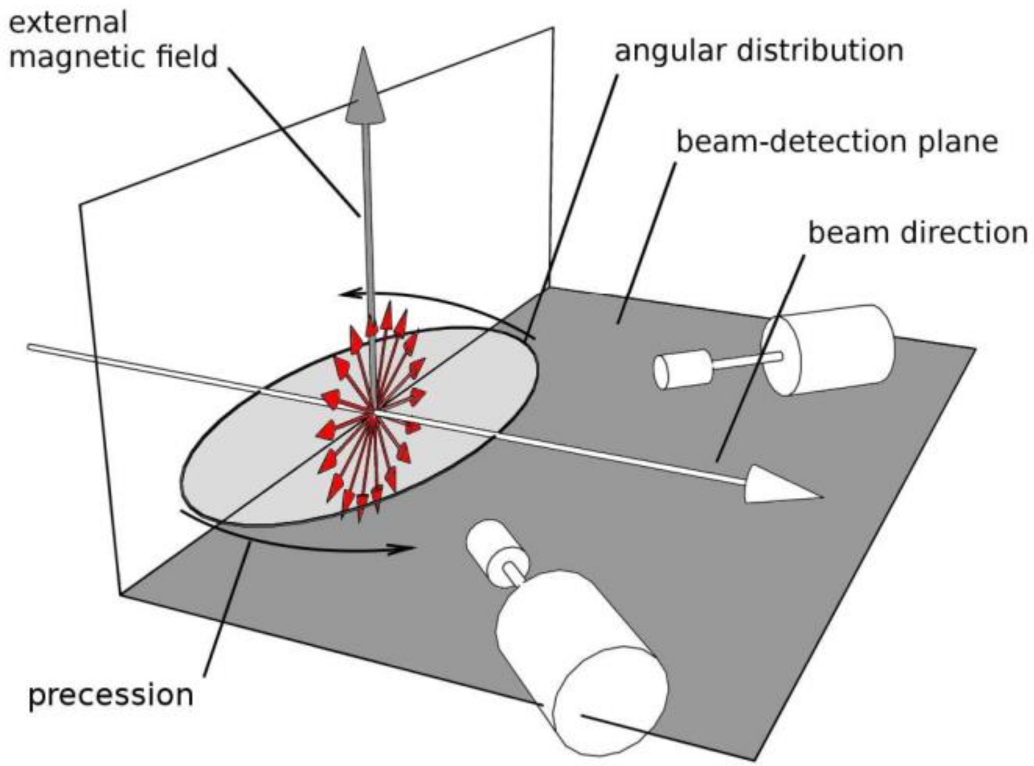
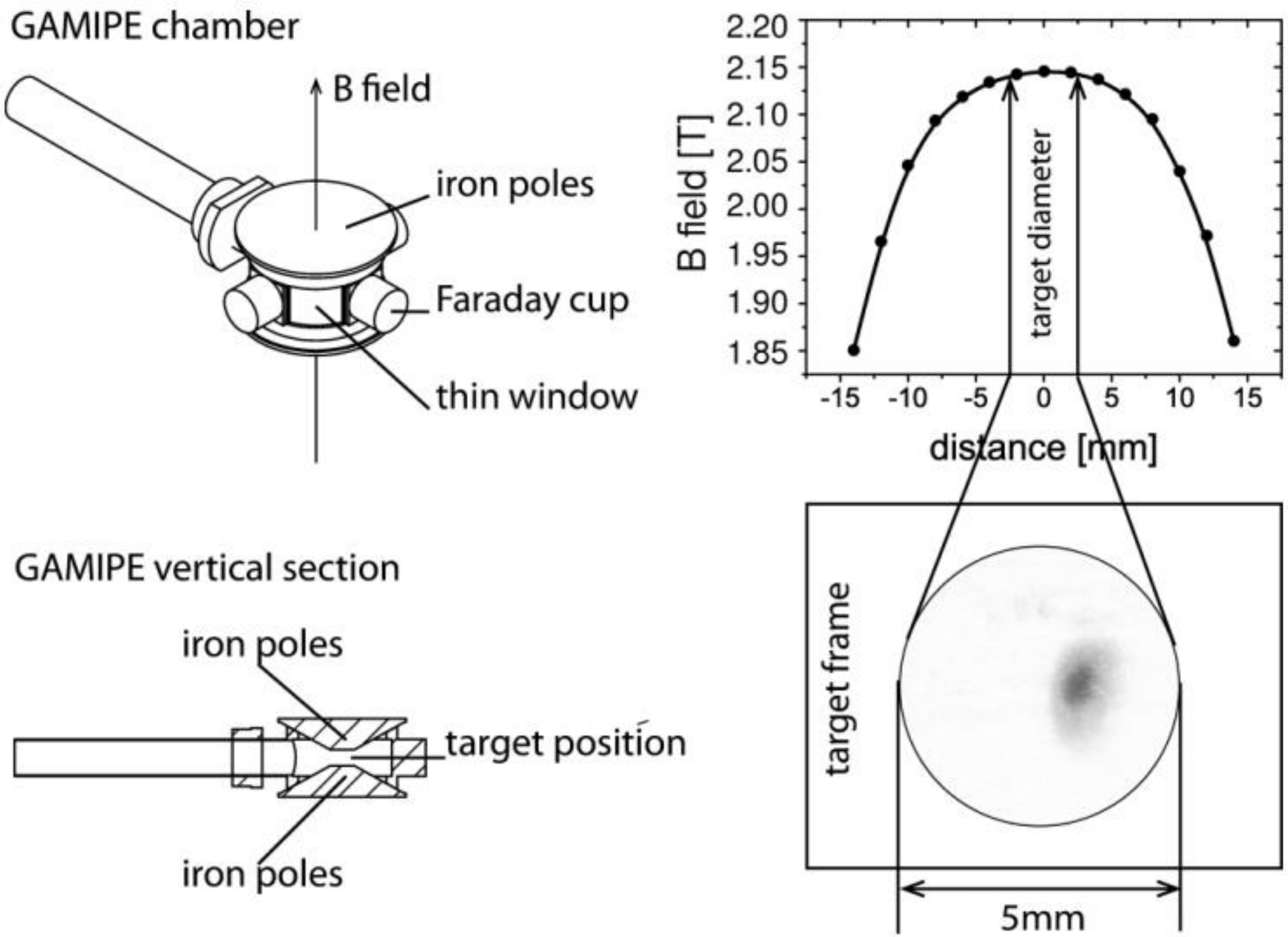
## ABSTRACT

The $g$ factor of the isomeric $I = 9^+$ bandhead of the yrast states in $^{128}$Cs is obtained from the time differential perturbed angular distribution measurement performed with the electromagnet at IPN Orsay. An external magnetic field of 2.146 T at the target position was attained with GAMIPE reaction chamber surrounded by four high-purity germanium detectors, of which two were low-energy photon spectrometer type. The results are in accordance with $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$ $I = 9^+$ bandhead assignment and are discussed in the context of chiral interpretation of the $^{128}$Cs nucleus as a composition of the odd proton, odd neutron, and even-even core with their angular momentum vectors. The obtained $g$ -factor value was compared with predictions of the particle-rotor model. The experimental $g$ factor corresponds to the nonchiral geometry of the isomeric bandhead. This observation indicates the existence of the chiral critical frequency in $^{128}$Cs and may explain the absence of the chiral doublet members for $I < 13\hbar$.

# Just two detectors with magnet on a table. The cheapest experiment with an expensive idea.

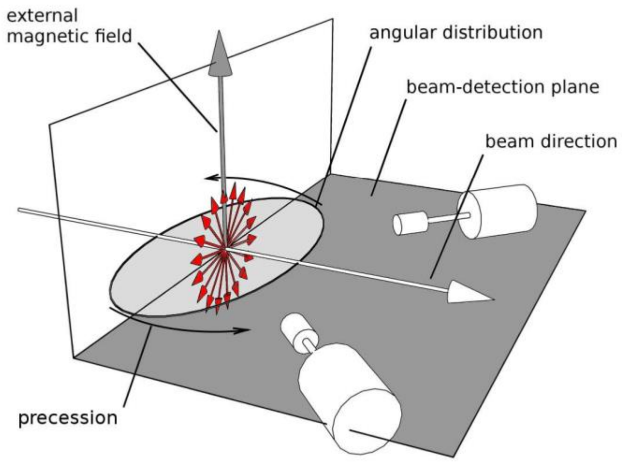


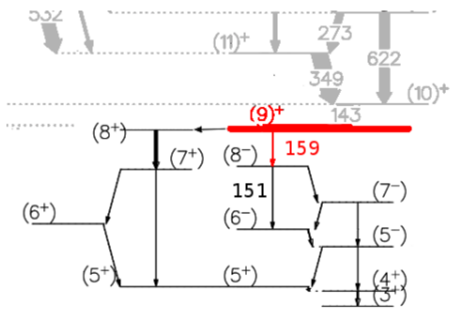



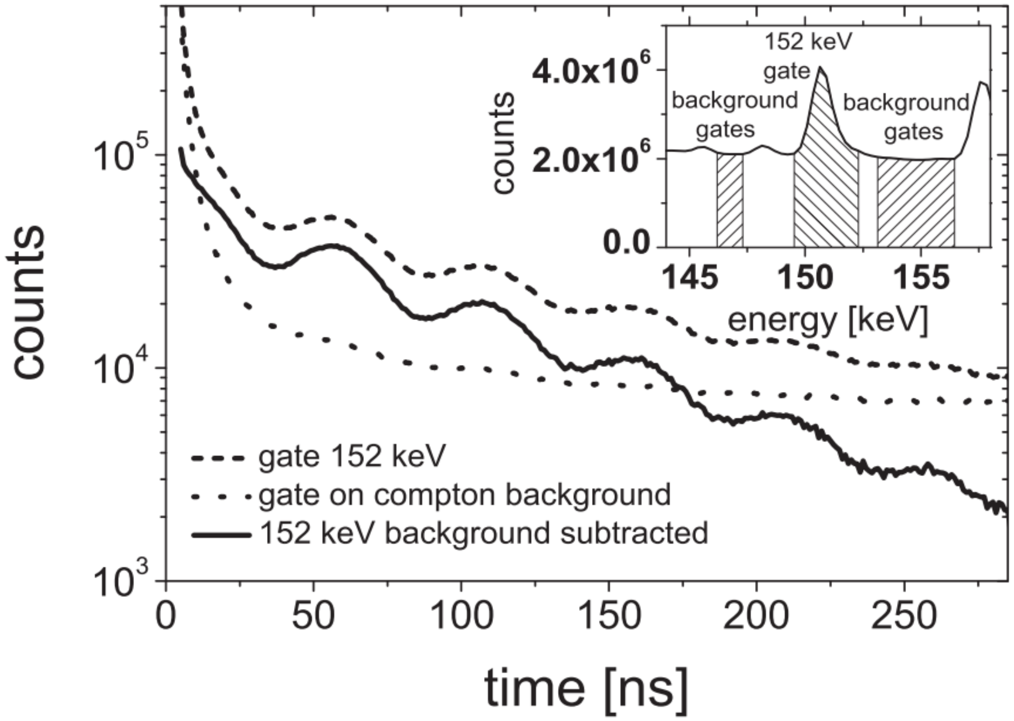


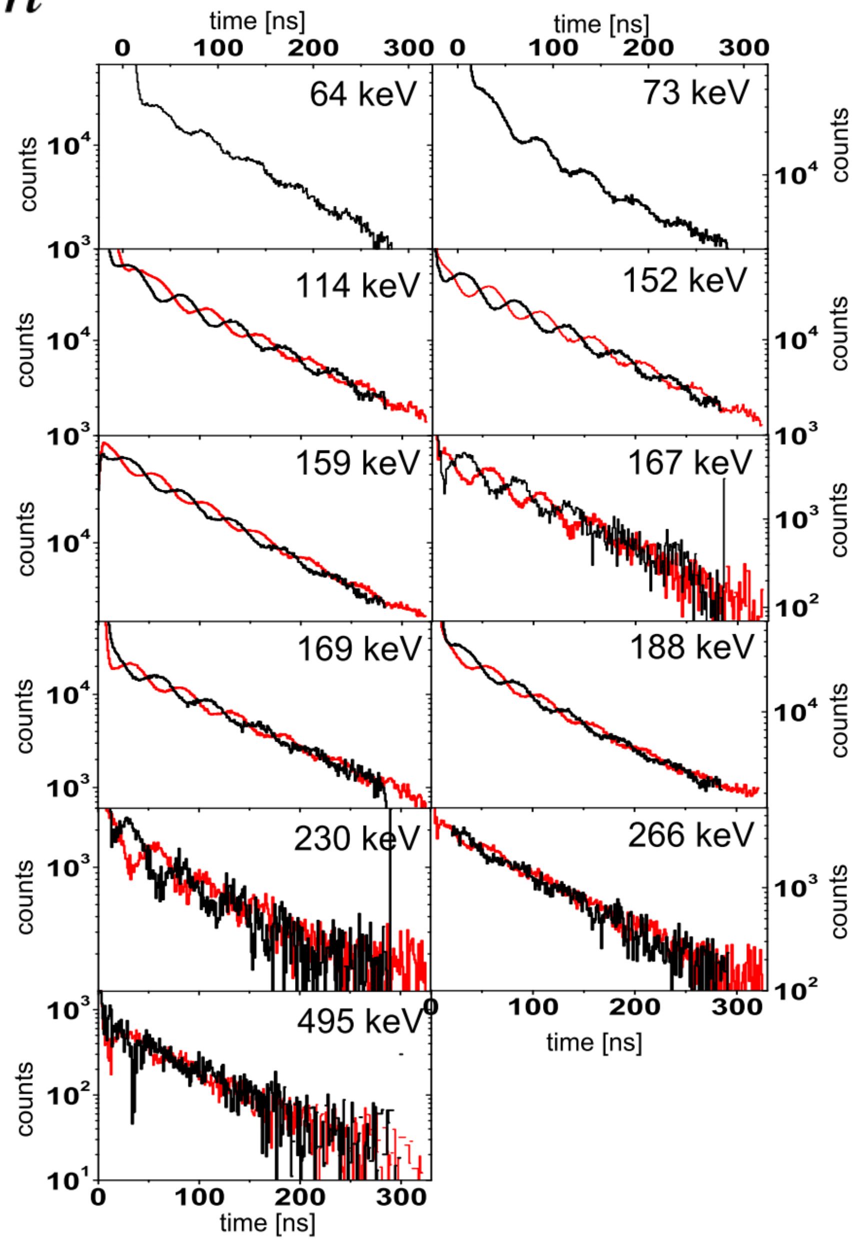
GAMIPE chamber
B field
iron poles
Faraday cup
thin window
GAMIPE vertical section
iron poles
target position
iron poles
2.20
2.15
2.10
2.05
2.00
1.95
1.90
1.85
B field [T]
target diameter
-15
-10
-5
0
5
10
15
distance [mm]
target frame
5mm

$$\omega_L = -g\mathbf{B}\mu_N/\hbar$$



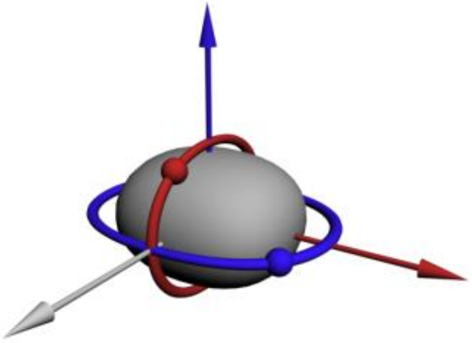



# G-factors – volume measurement



$$g = \frac{1}{2}(g_p + g_n + g_R)$$
$$+ \frac{1}{J(J+1)}\frac{1}{2} j_p(j_p+1)(g_p - g_n - g_R)$$
$$+ \frac{1}{J(J+1)}\frac{1}{2} j_n(j_n+1)(g_n - g_p - g_R)$$
$$+ \frac{1}{J(J+1)}\frac{1}{2} j_R(j_R+1)(g_R - g_p - g_n)$$

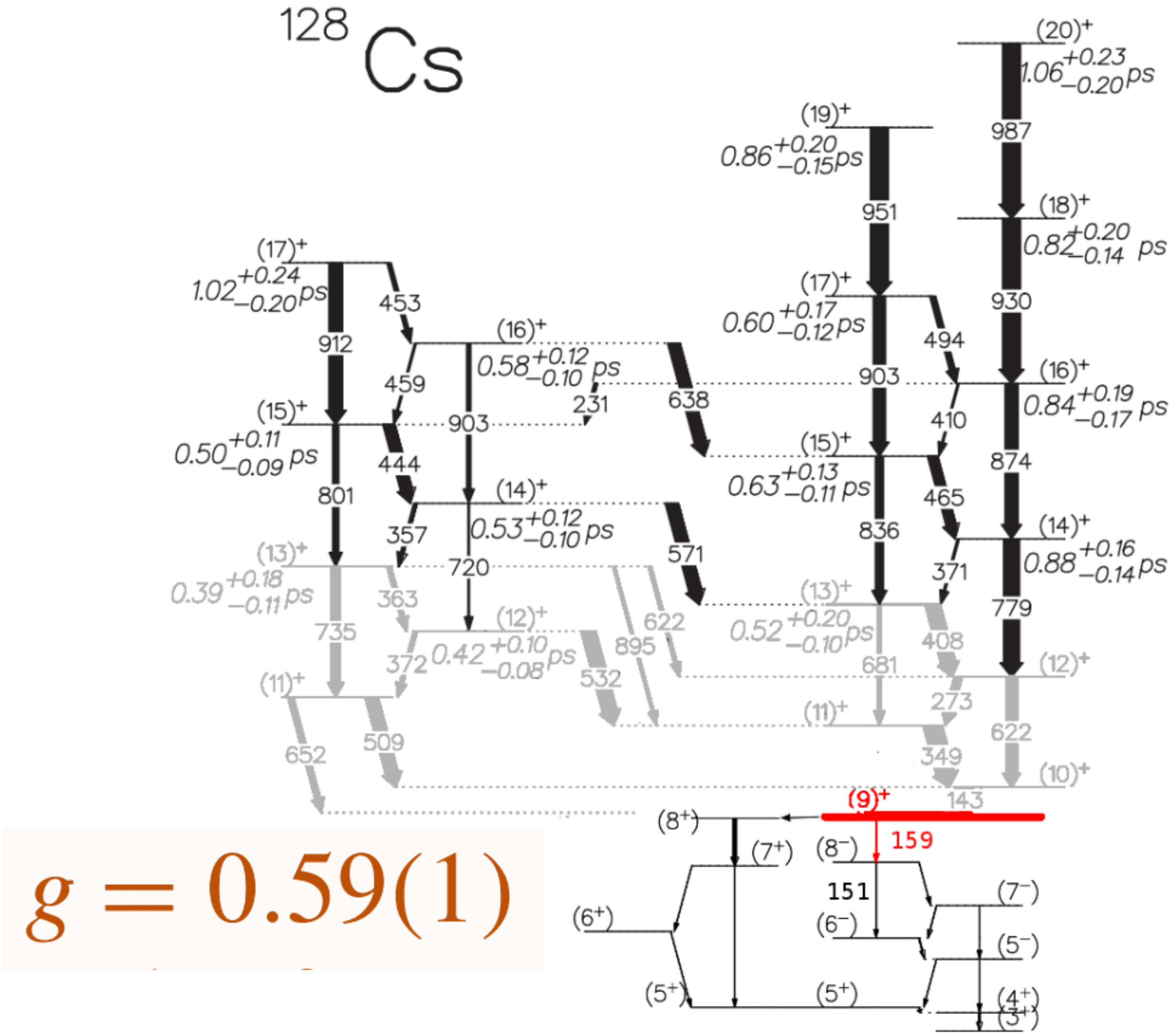


g-chiral = 0.5

$$- \frac{1}{J(J+1)}(g_p \vec{J}_n \cdot \vec{J}_R + g_n \vec{J}_p \cdot \vec{J}_R + g_R \vec{J}_p \cdot \vec{J}_n)$$

g = 0 chiral

g= 0.1 nonchiral

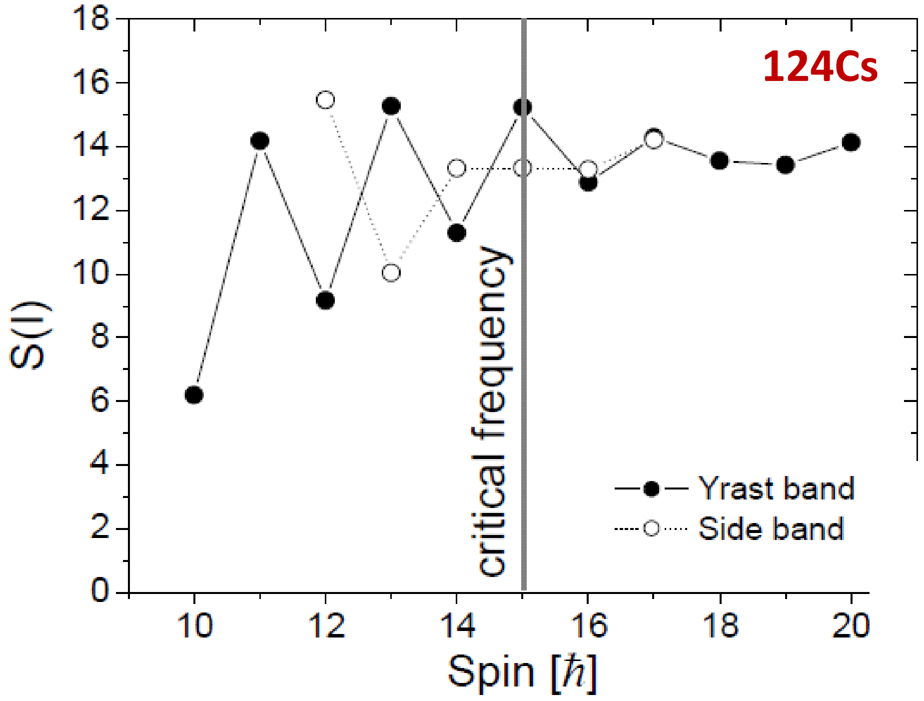


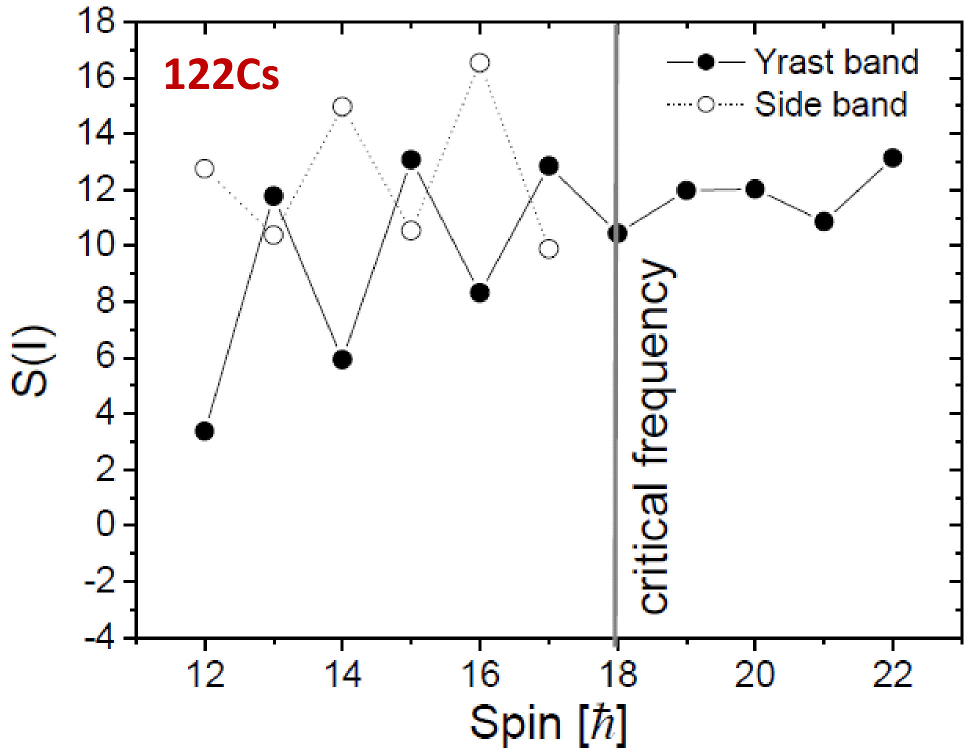

Chiral
based on indirect observables

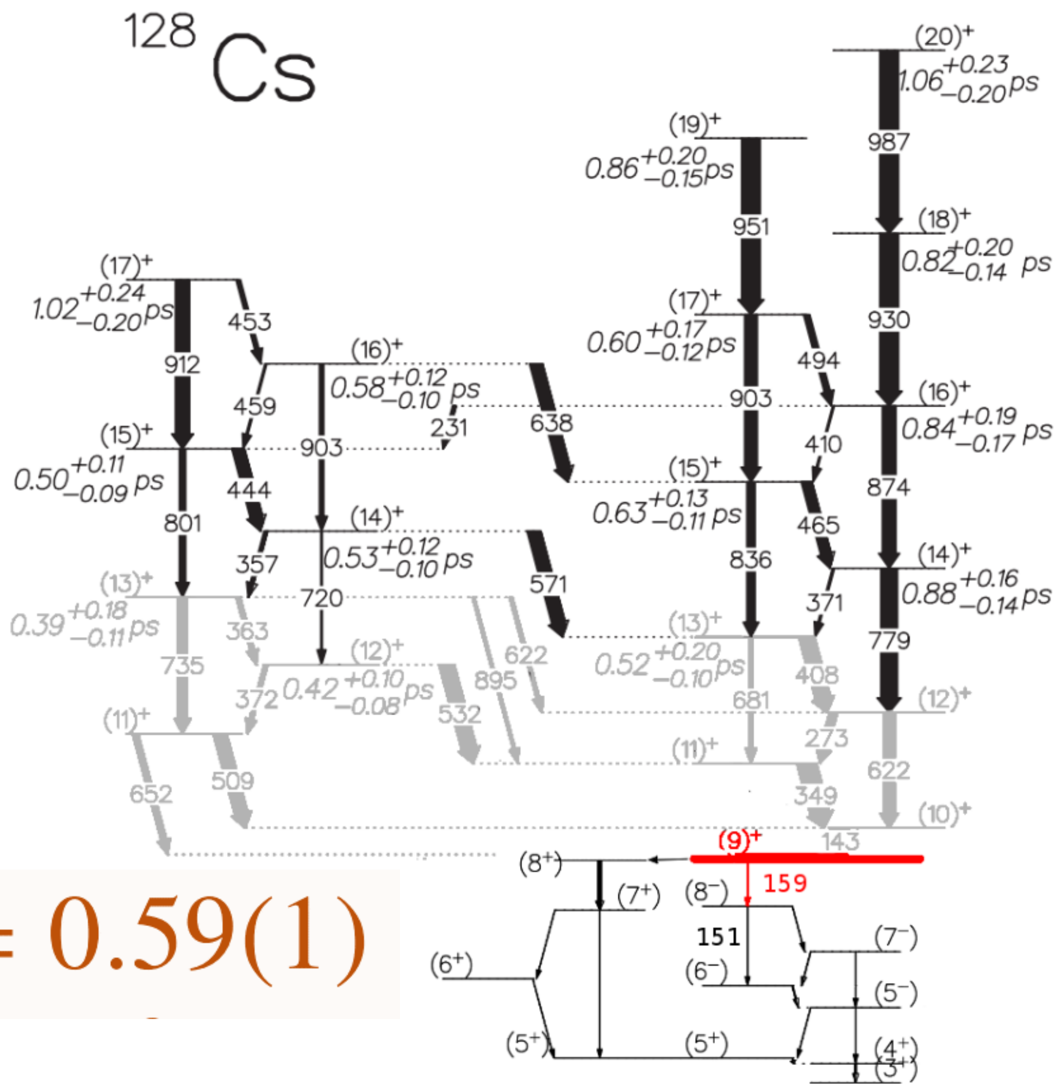
Non-chiral
based on direct mesurement

# Patterns – signature staggering





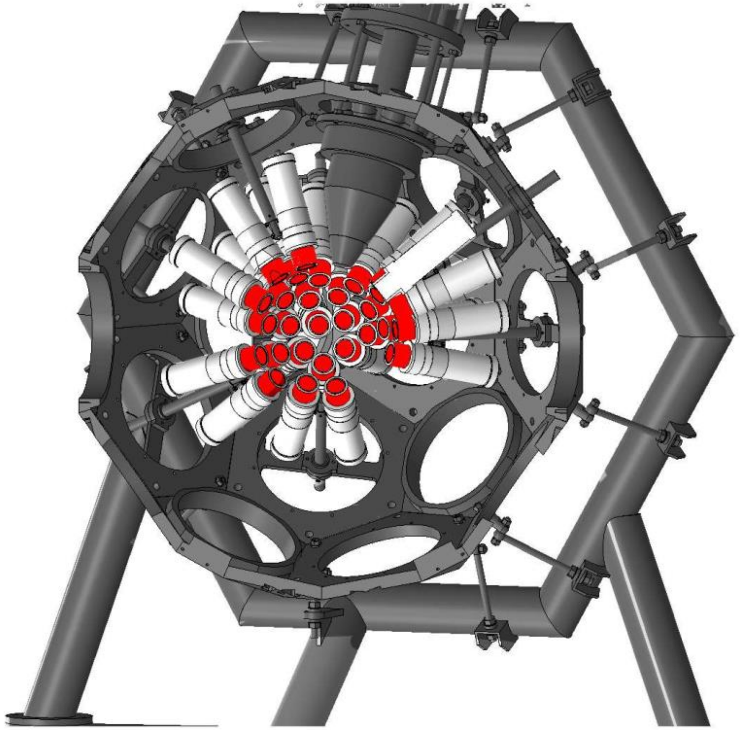



$$g = 0.59(1)$$

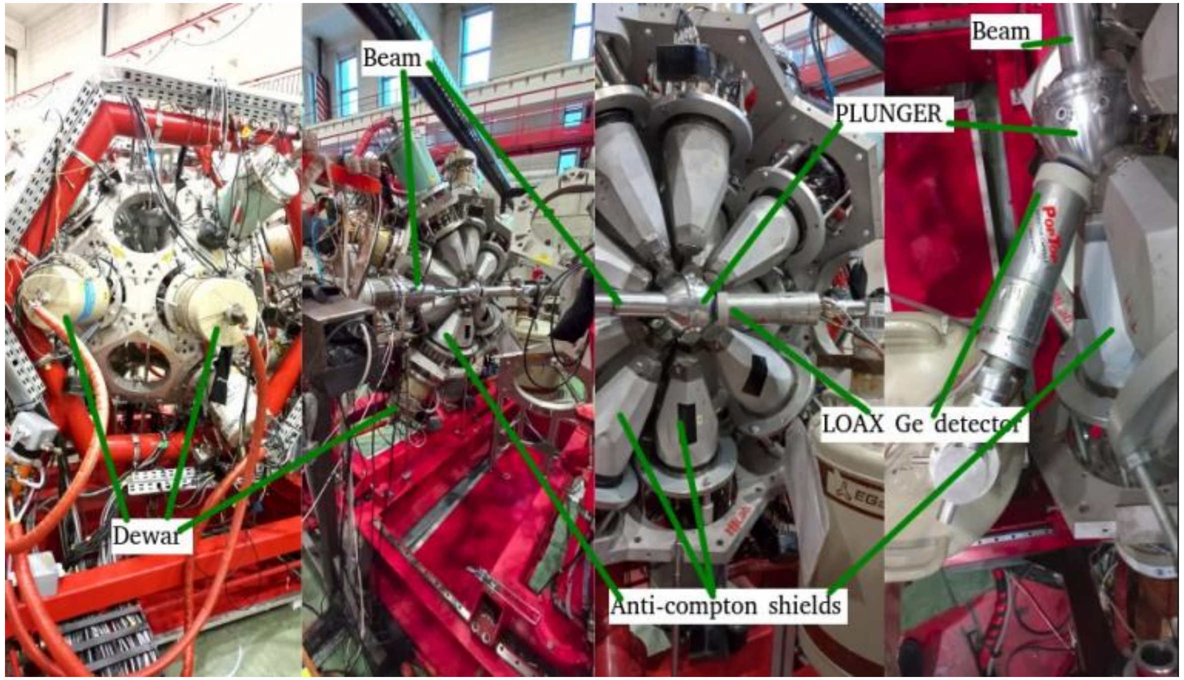
Chiral
based on indirect observables

Non-chiral
based on direct mesurement

Future: preparations for similar measurements in other excited states. Fast-Timing and Plunger lifetime measurements.
PHD thesis of Adam Nałęcz-Jawecki (NCNR).



EAGLE-EYE




EAGLE-PLUNGER

PHYSICAL REVIEW C **106**, 014318 (2022)

# Examination of nuclear chirality with a magnetic moment measurement of the $I = 9$ isomeric state in $^{128}$Cs

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