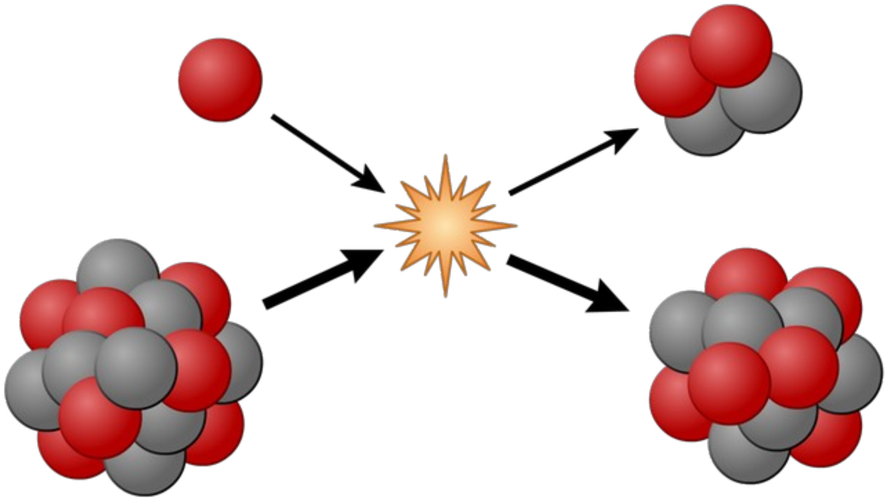
Nuclear chirality as a part of nuclear physics

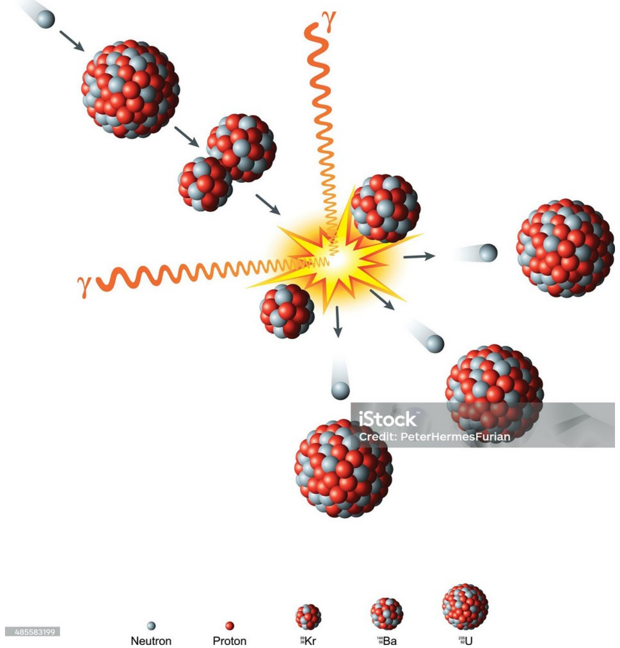
Adam Nałęcz-Jawecki

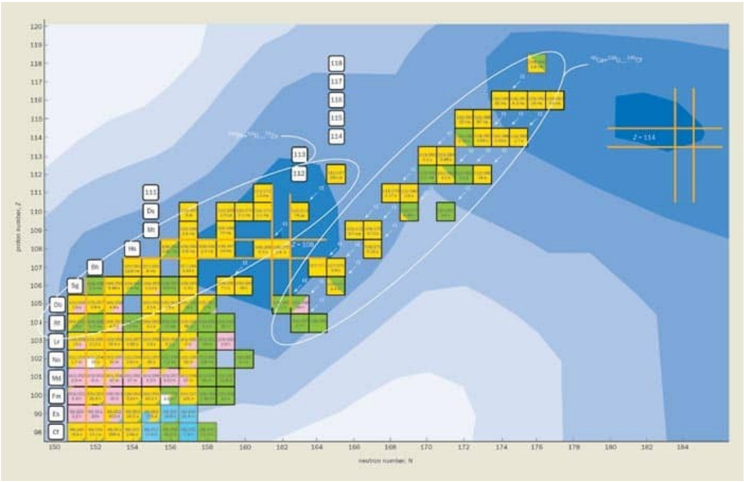
Part 1 – Gamma spectroscopy as a way of exploring excited levels in nuclei

Nuclear physics



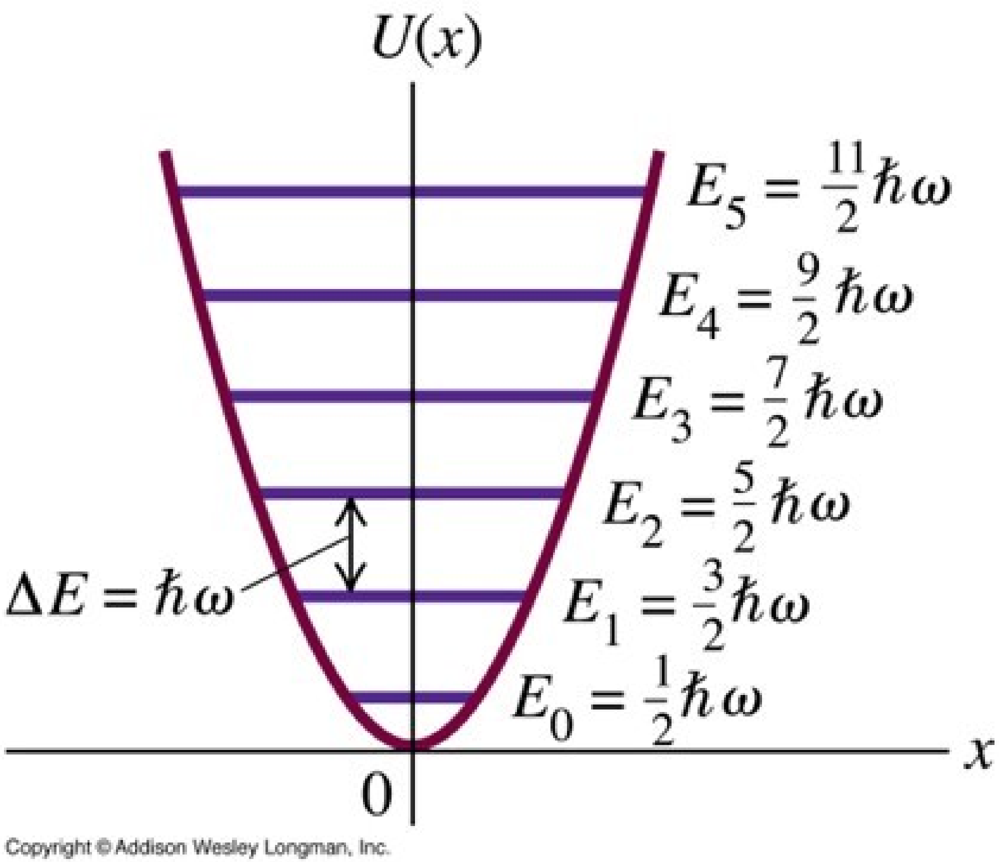
from Uppsala University website





from PhysicsWorld website

Excited levels



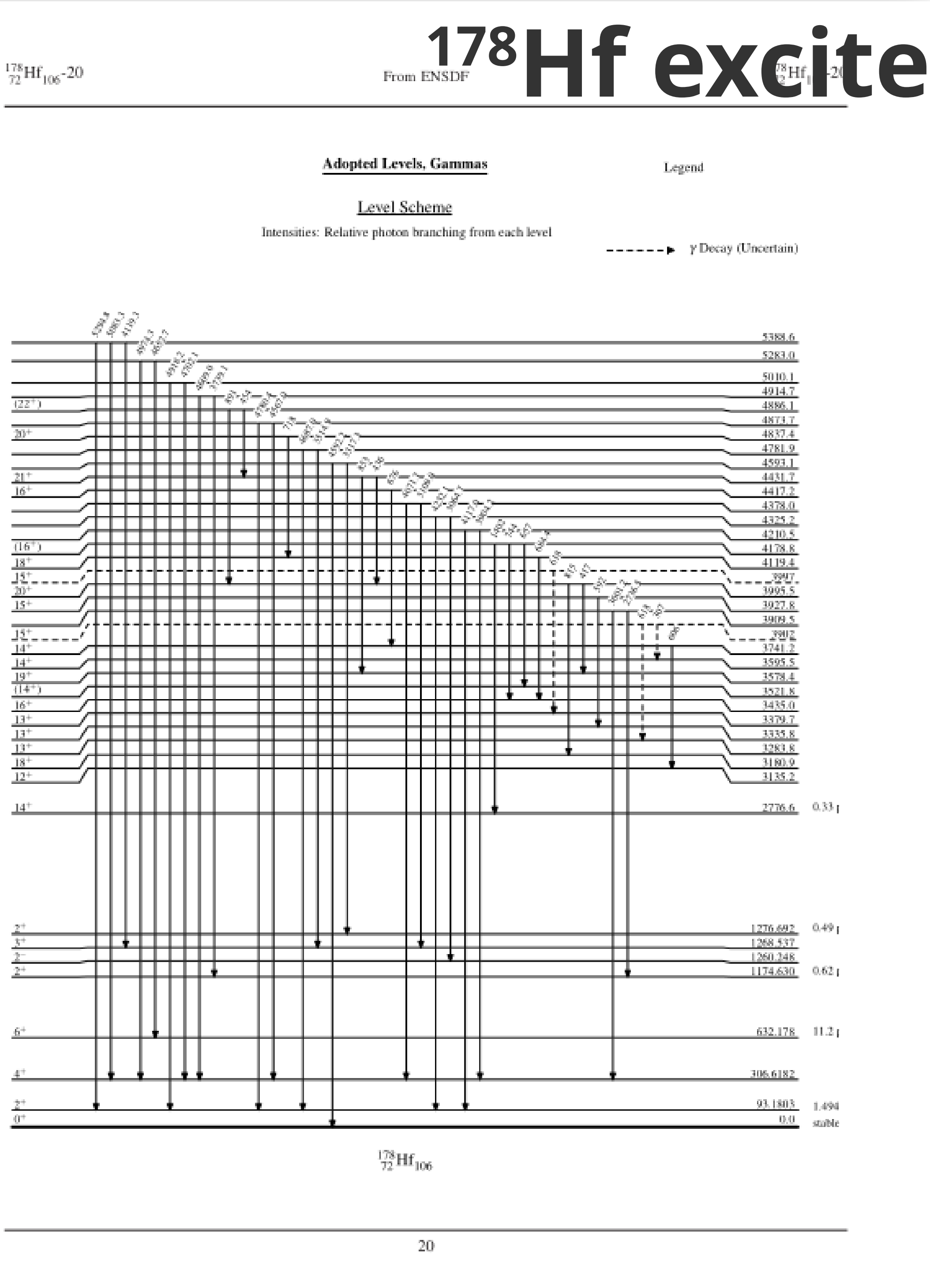
Quantum oscilator:

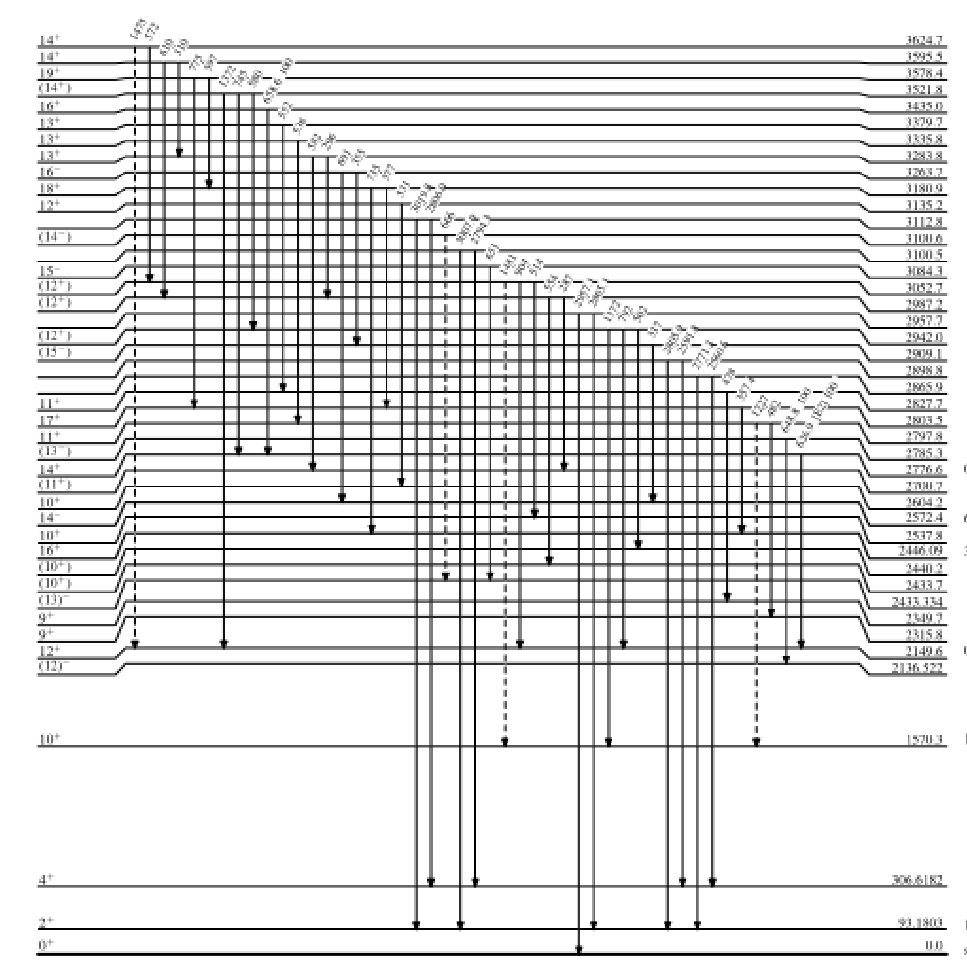
- Well known energy states
- Eigenvalues of easy, well known Hamiltonian
- Excitation/ deexcitation by gaining/emitting energy

Excited levels in nuclei

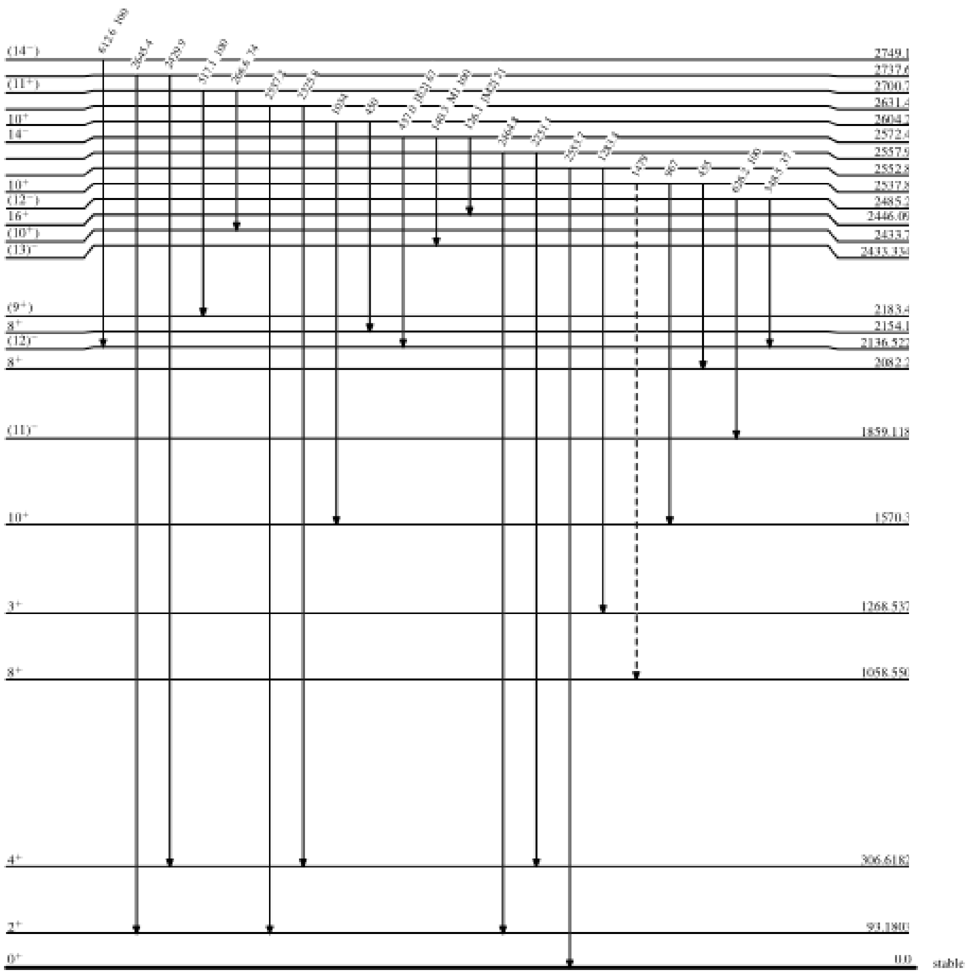
- Energies range from 100 keV to 10 MeV
- Excitation caused by nucleus nucleus collision or via decay
- Deexcitation by emitting photons

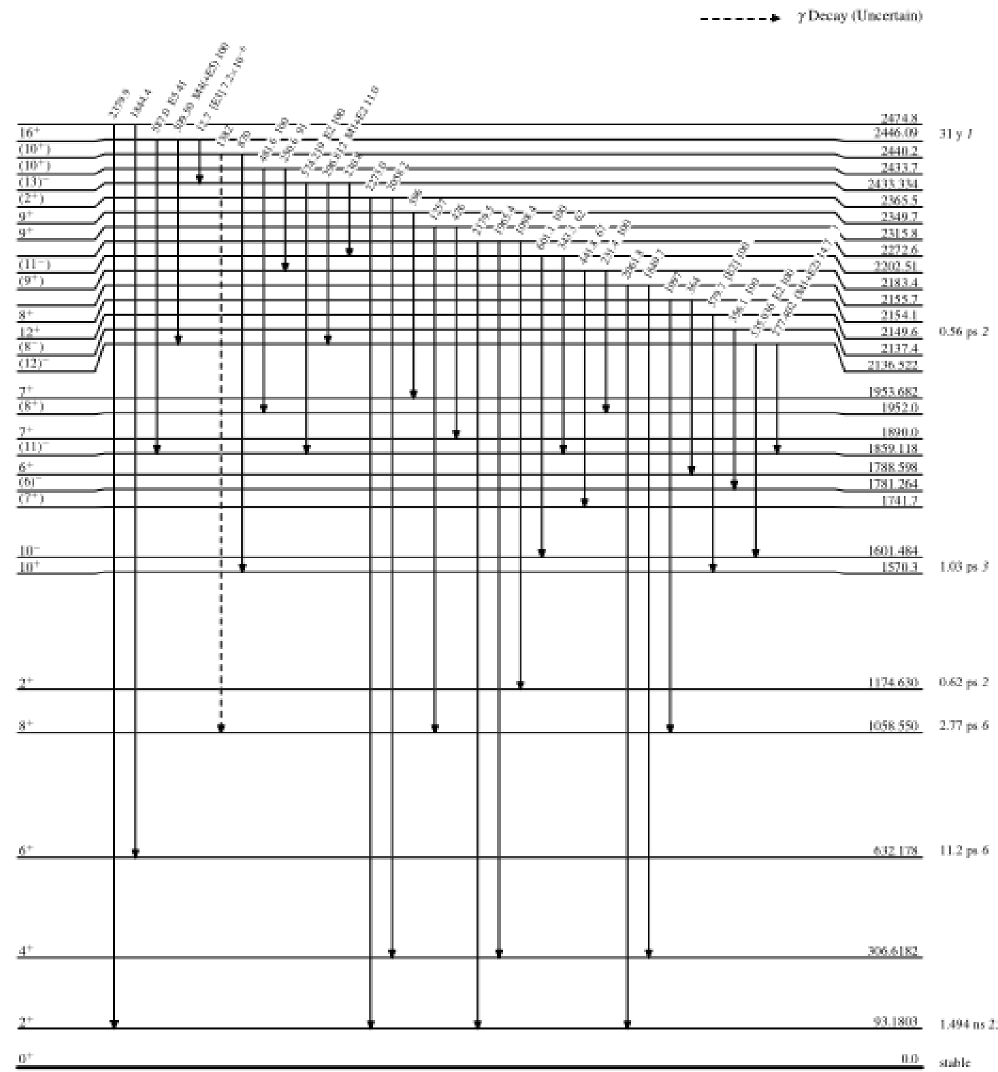
^{178}Hf excited states



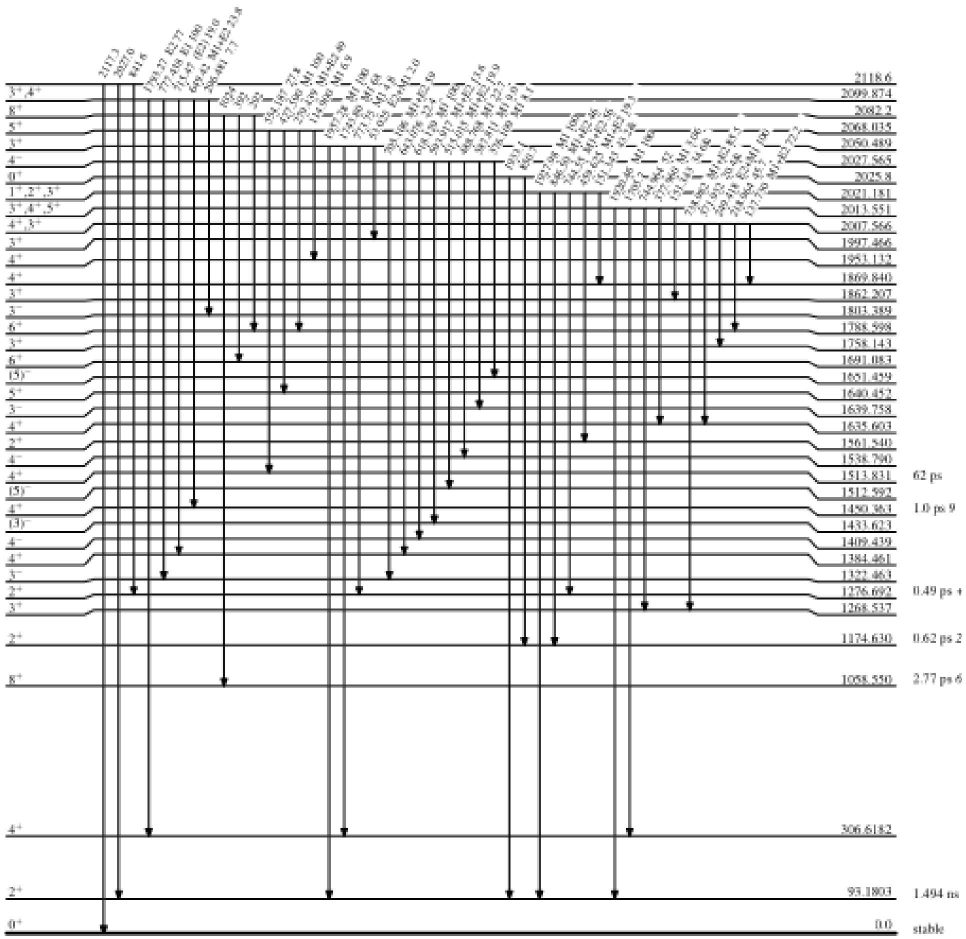


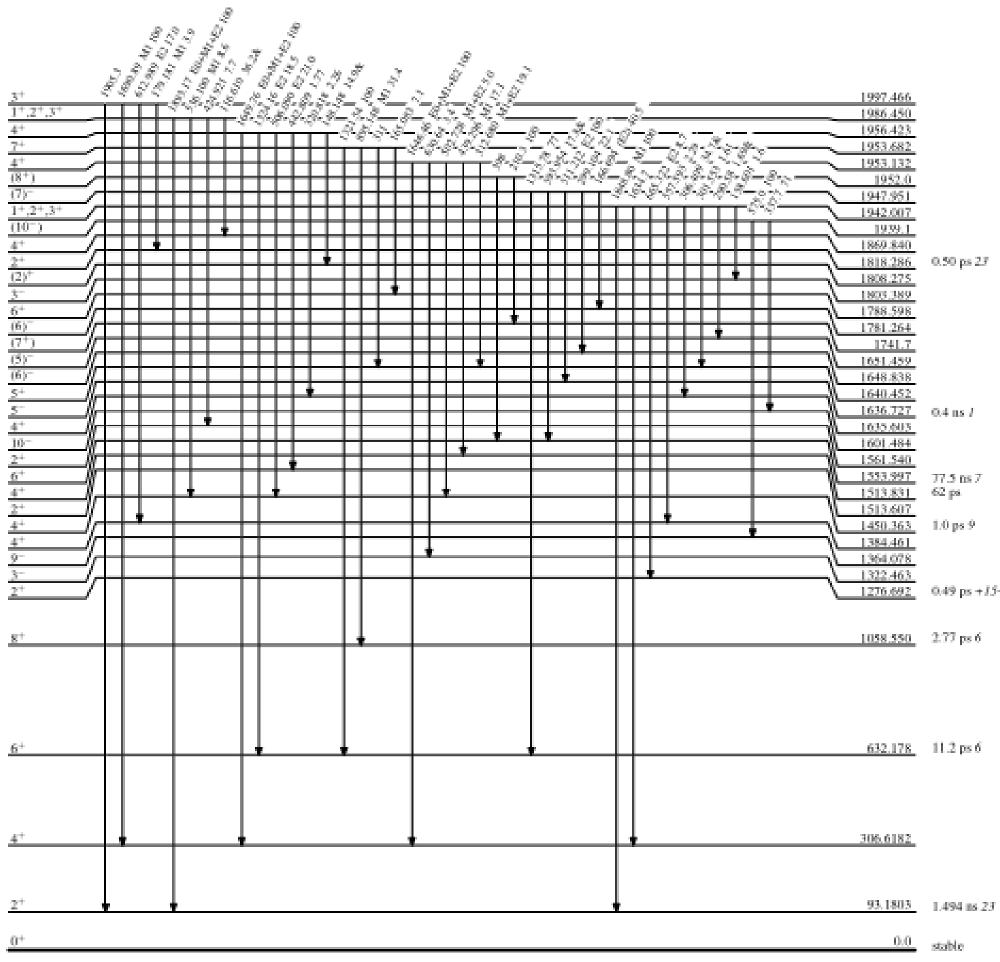
^{178}Hf excited states



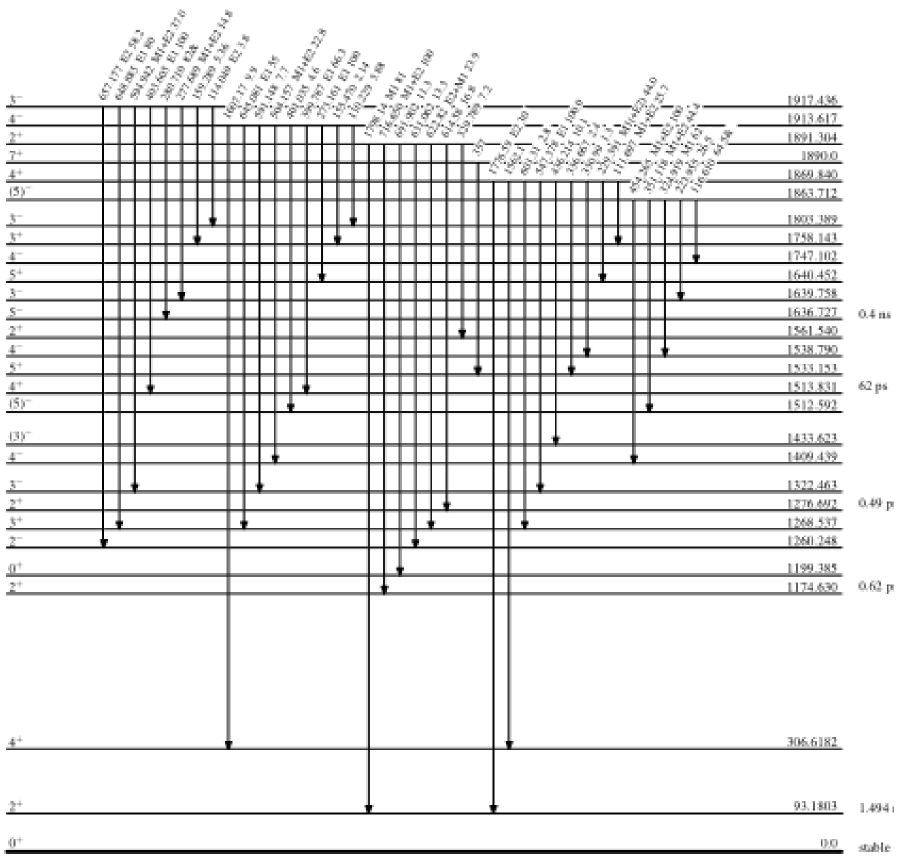


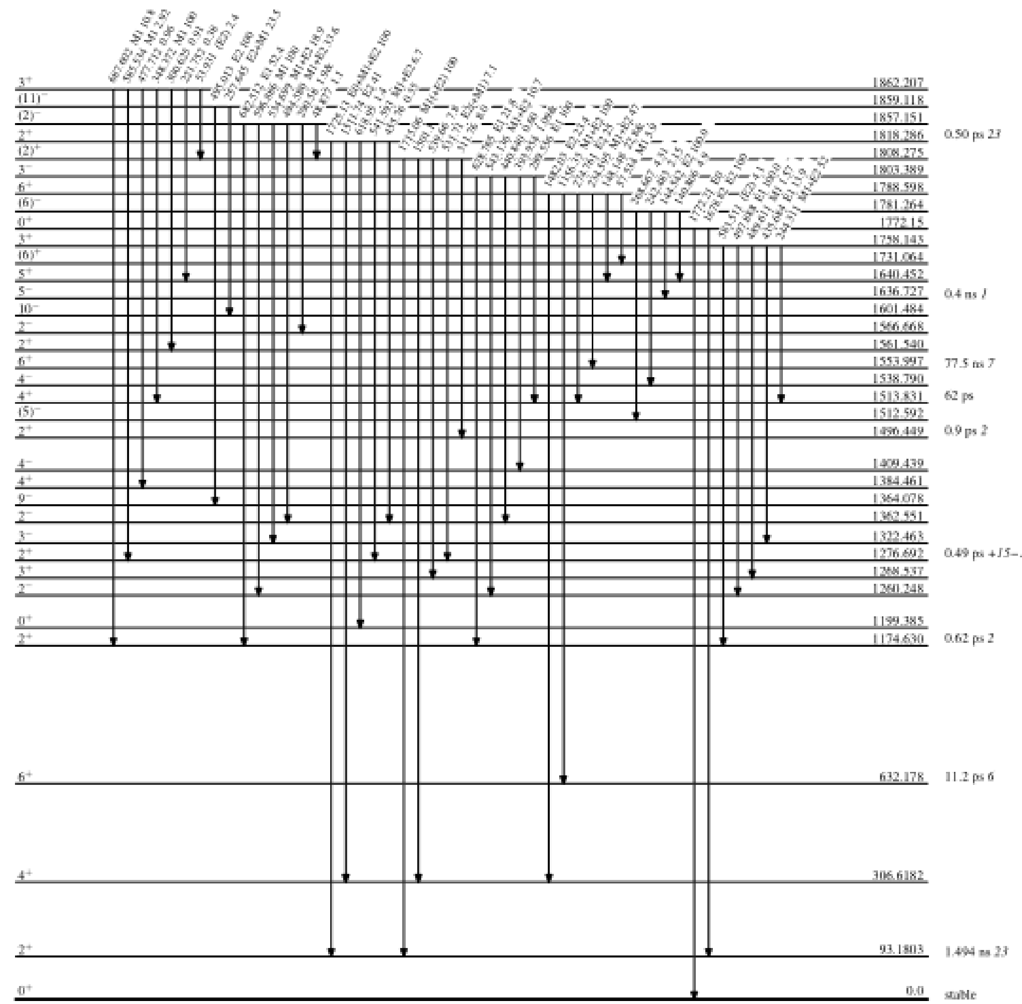
^{178}Hf excited states



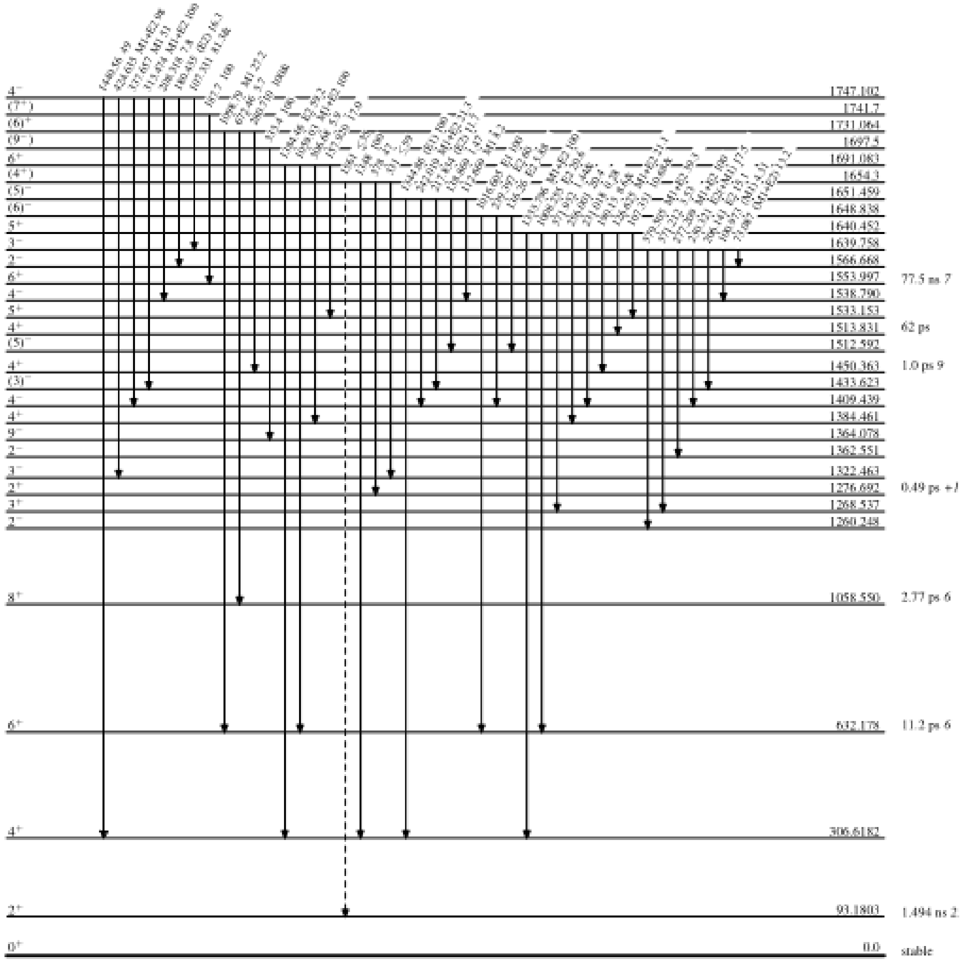


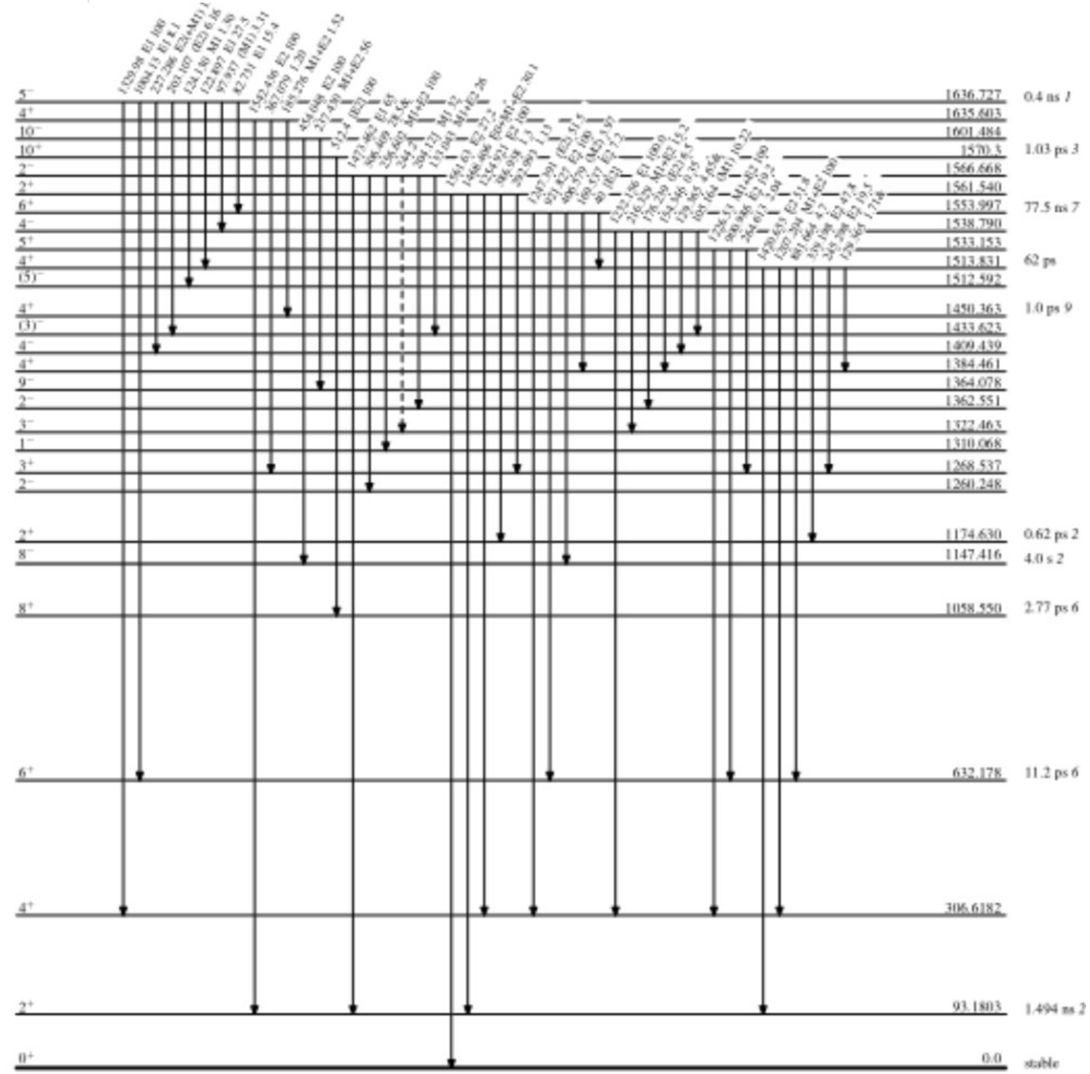
^{178}Hf excited states



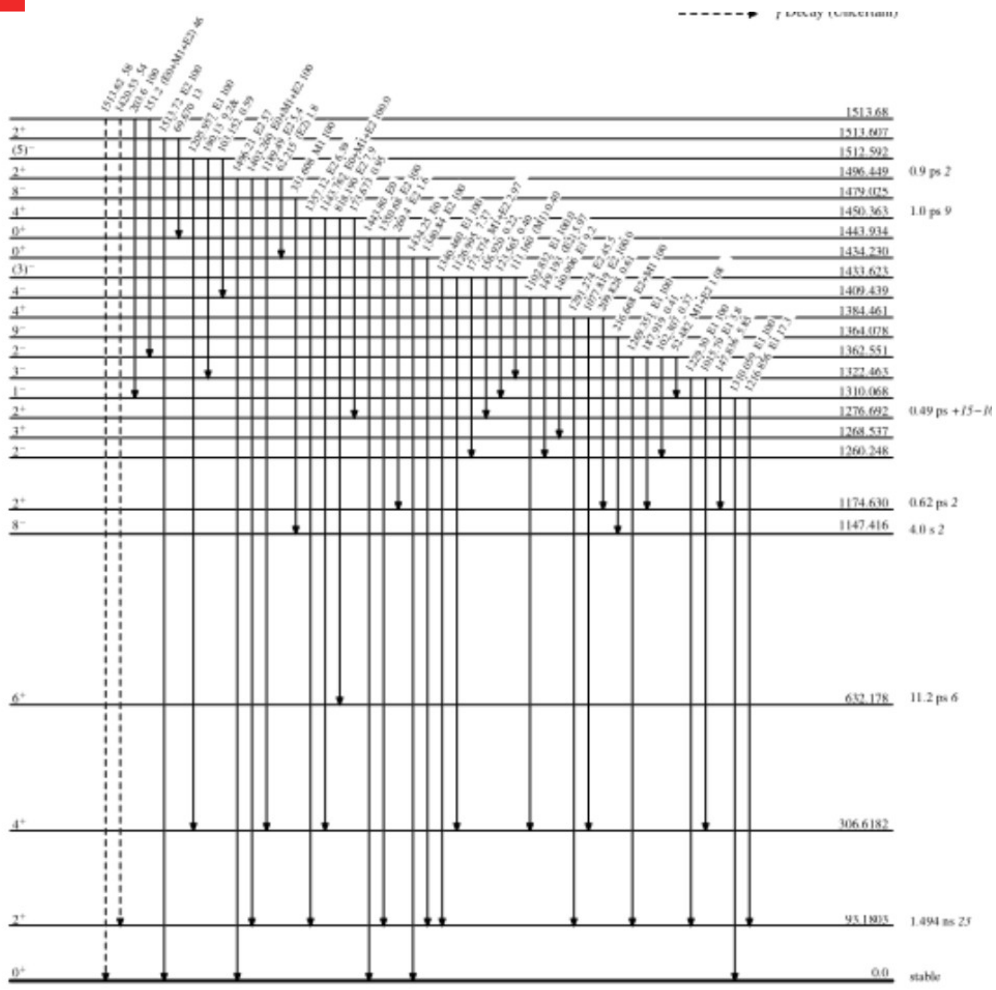


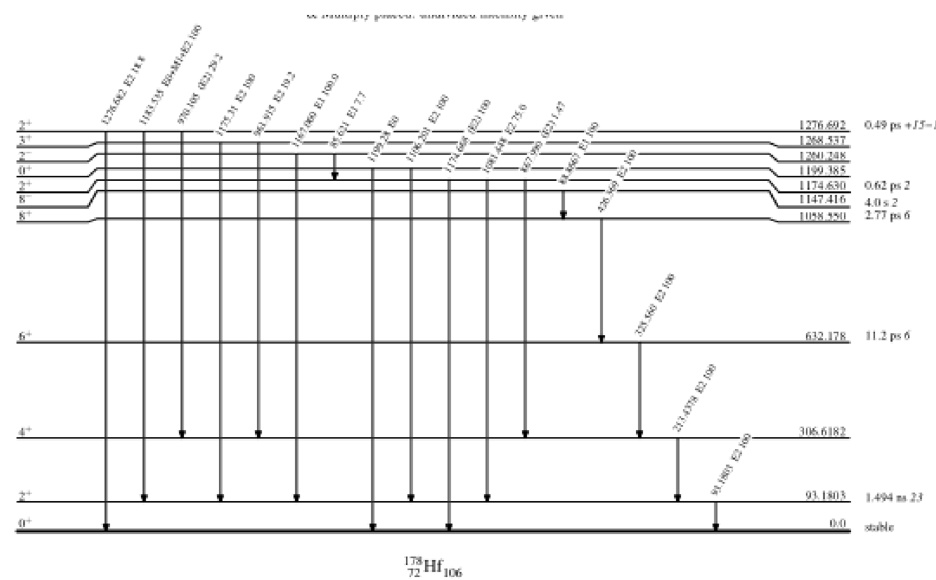
^{178}Hf excited states





^{178}Hf excited states



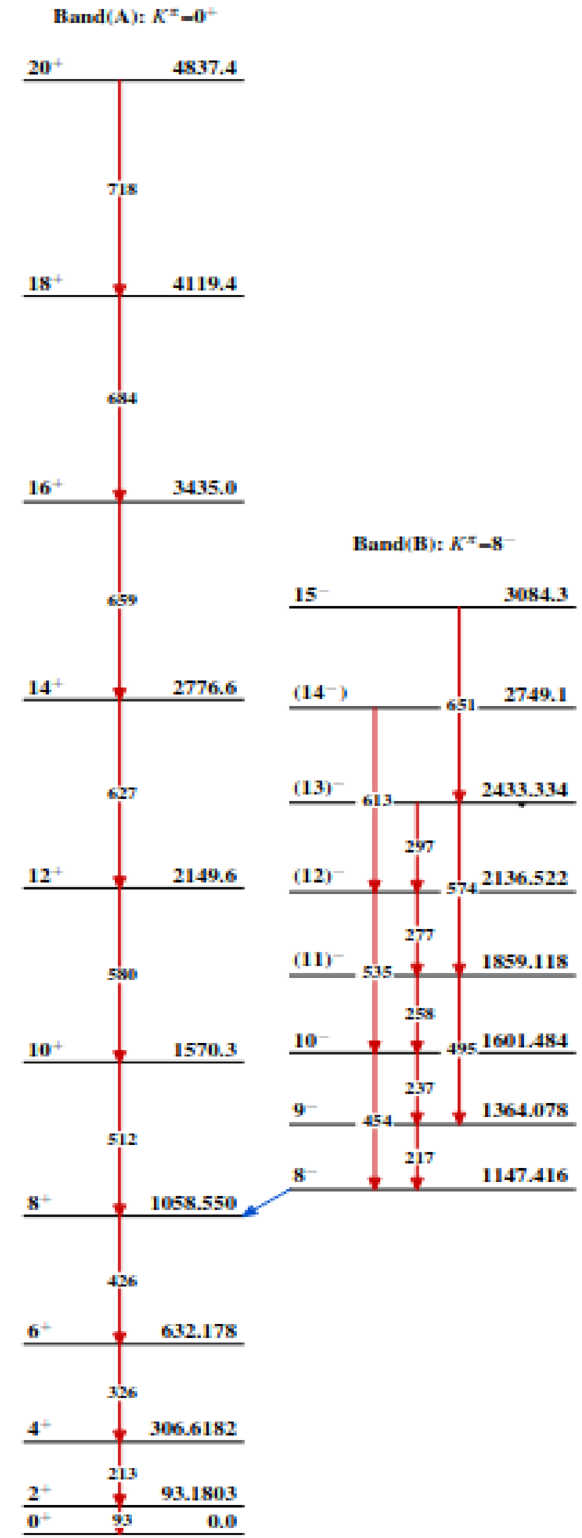


Problems with nuclear excitations

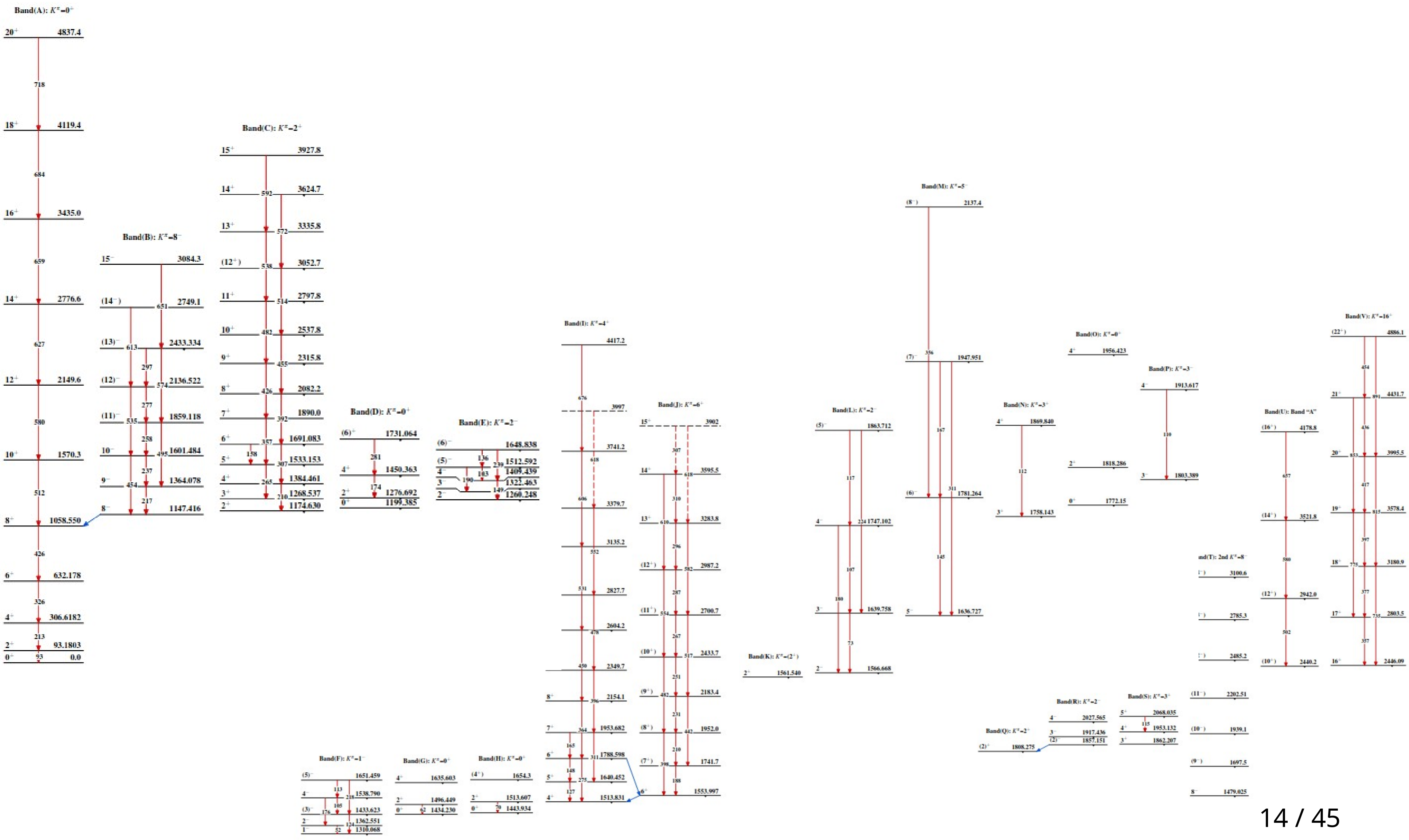
- Hamiltonian can’t be obtained from basic laws of physics
- Hamiltonian of precised number of nucleons – more than 20, but adding 1 or 2 nucleons change the Hamiltonian vastly
- Proton/neutron excitation levels
- Collective excitements (rotational, vibrational etc.)

Rotational bands

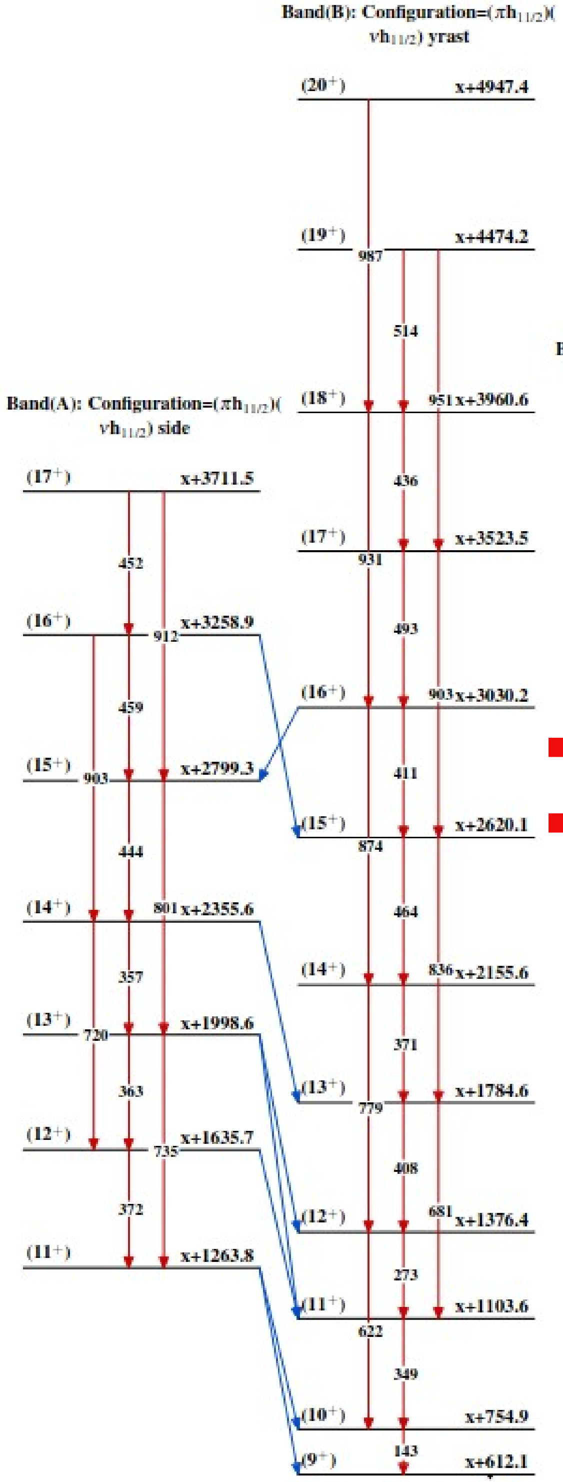
- Grouping excited stated into the rotational bands
- Similar structure inside a band
- Lowest state in a band called a bandhead

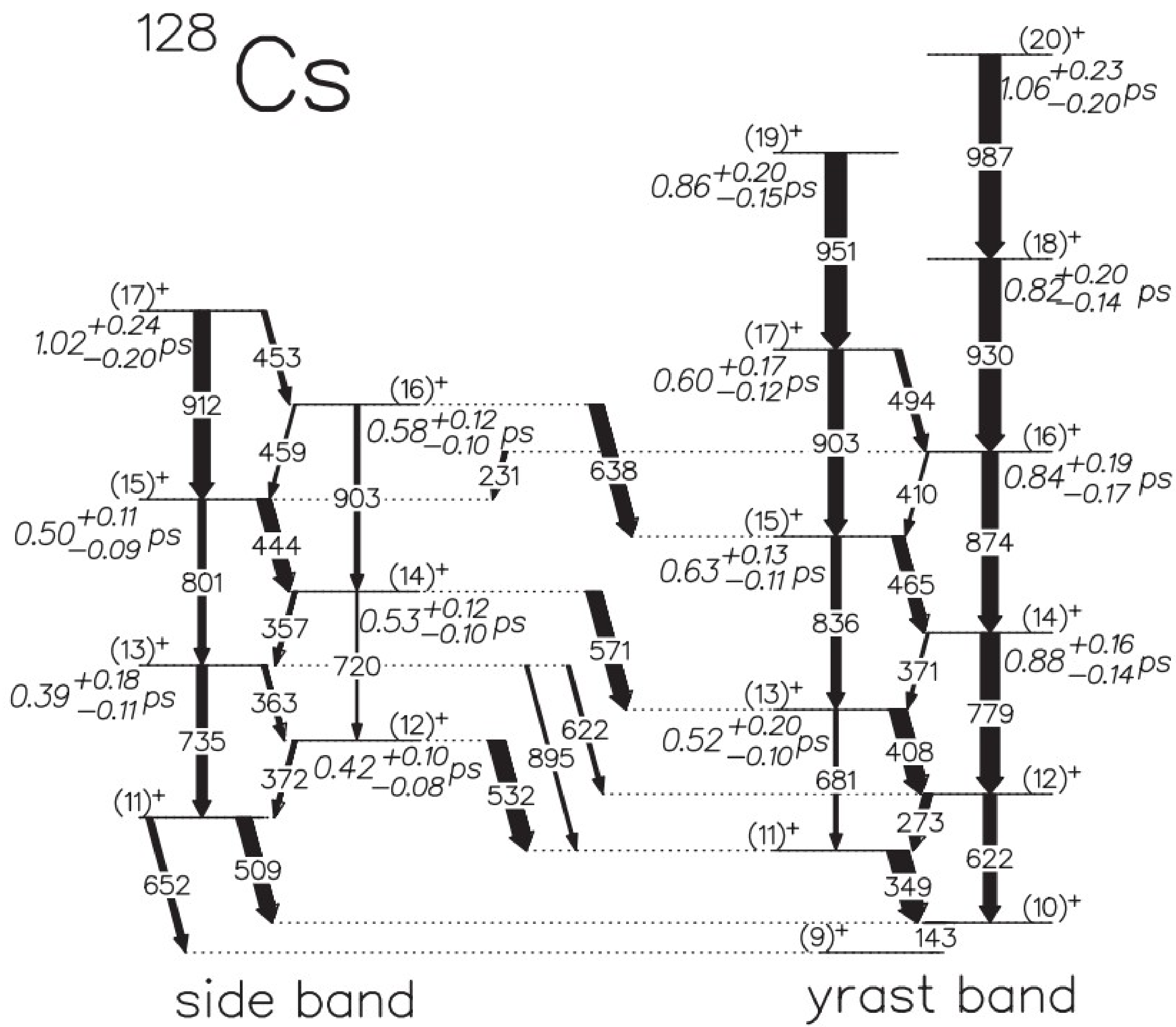


Multiple rotational bands (^{178}Hf)



^{128}Cs $(\pi h_{11/2})(\nu^{-1} h_{11/2})$





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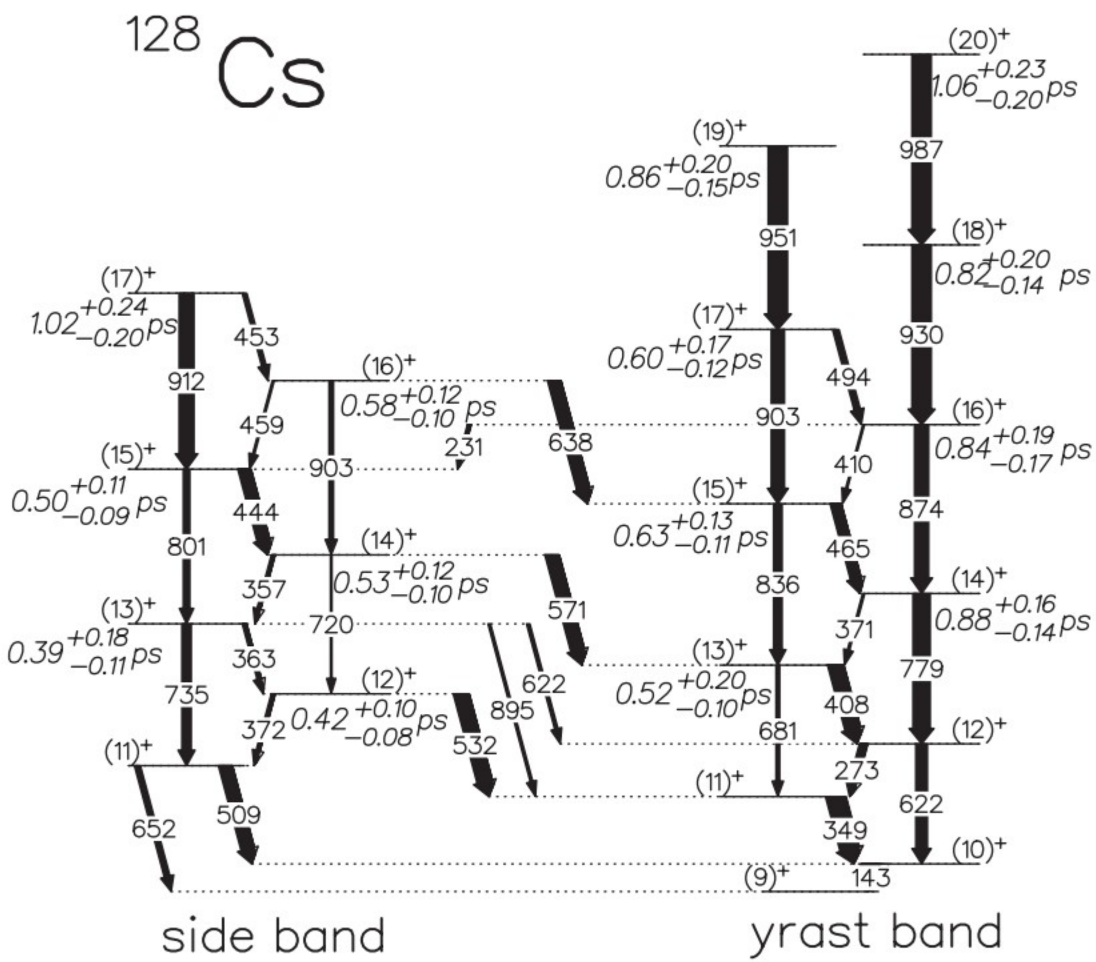
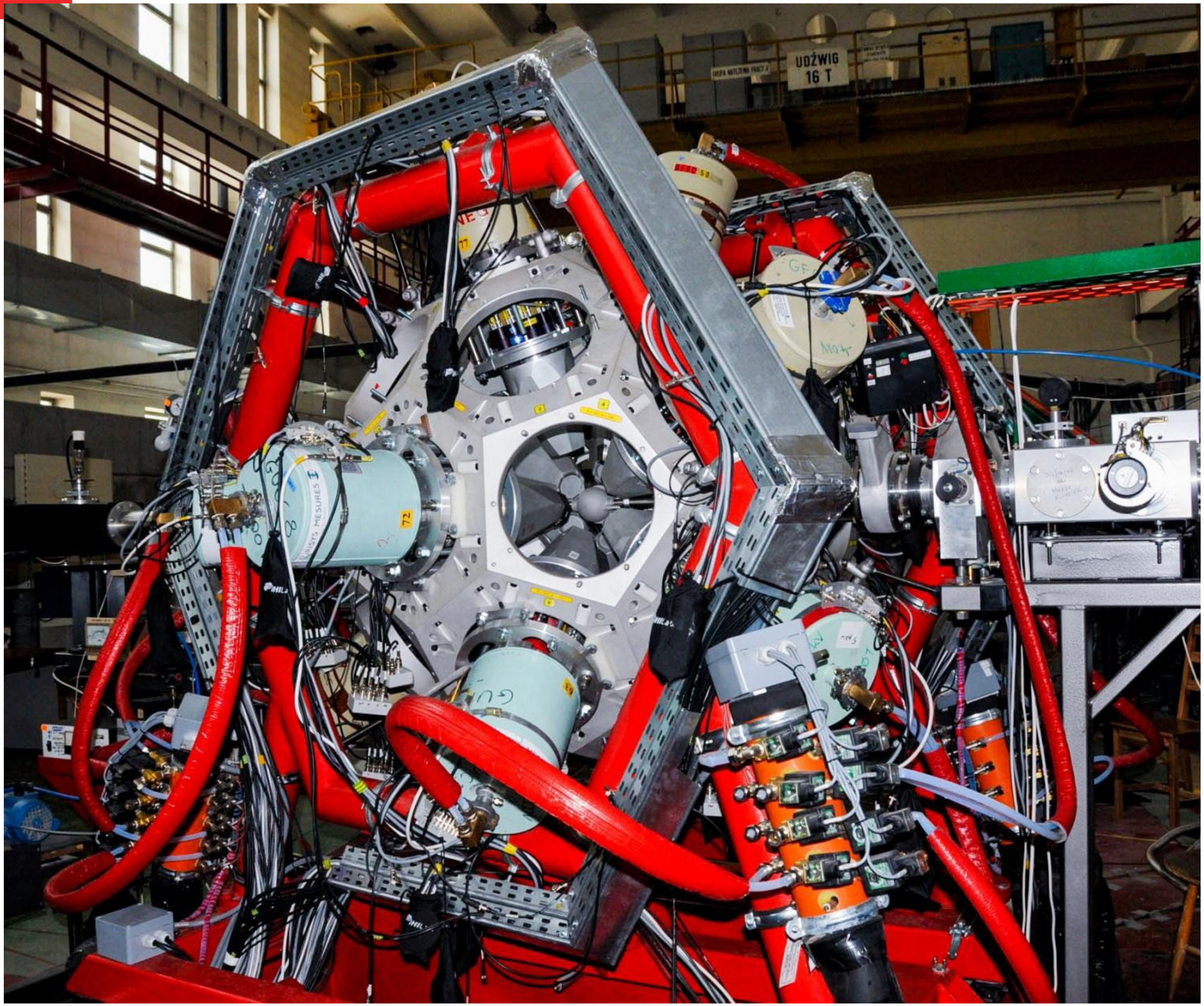


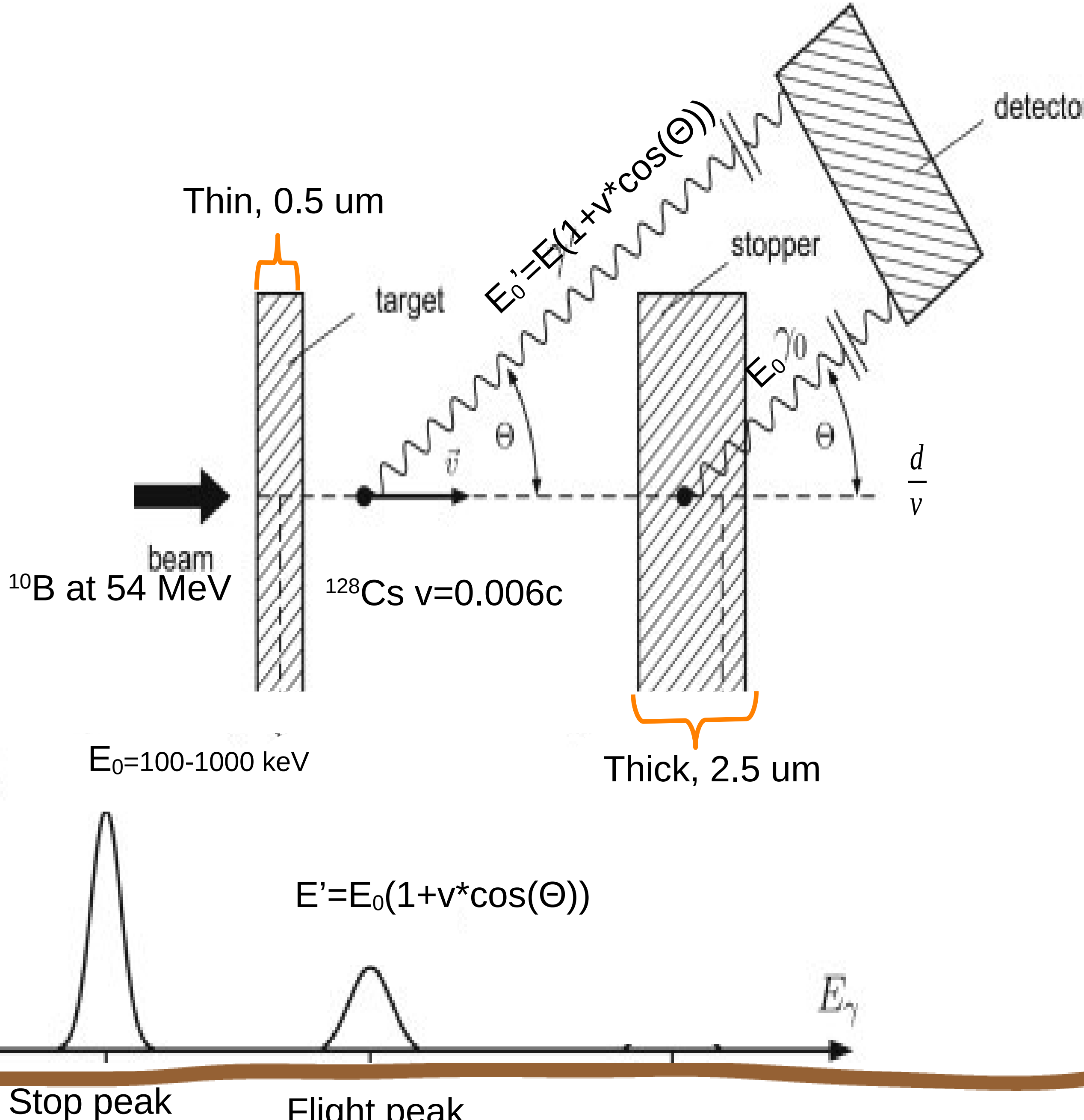
- Probable structure known (excitation of a proton and a neutron hole both to $h_{11/2}$ shell)
- Lifetimes and transition probabilities
- Chirality
- Magnetic g-factor measurement of the 9+ bandhead

Detection setup



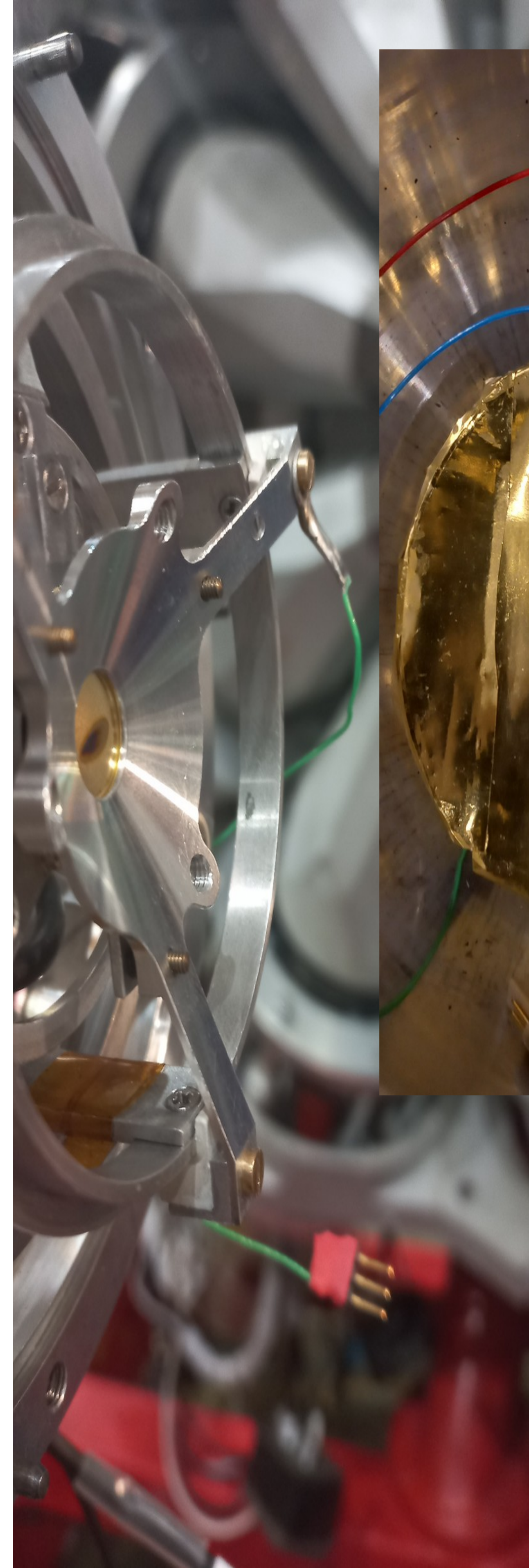
- EAGLE (3m high)
- 15 Ge detectors
- 20 ns time resolution for gamma-gamma coincidences

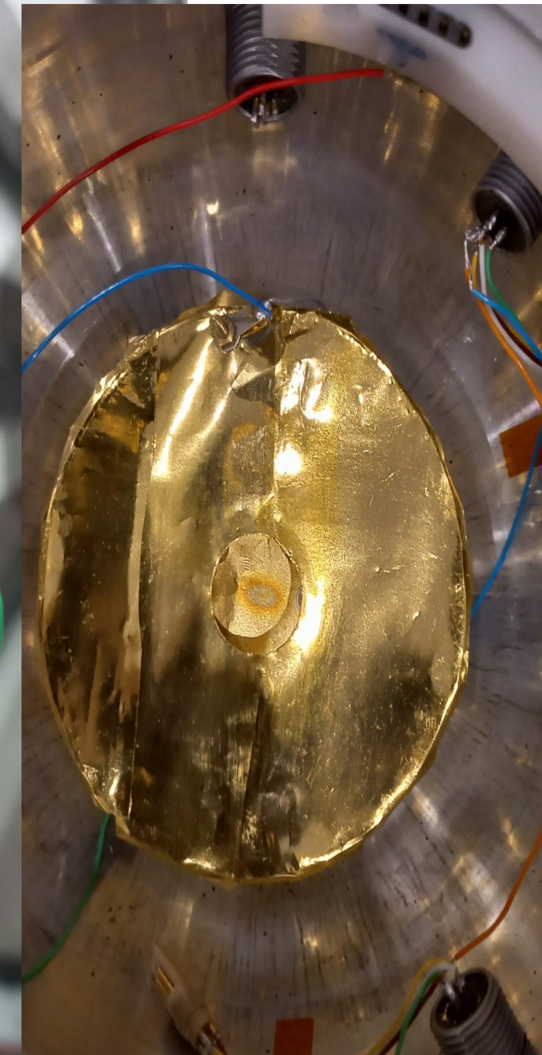
Recoil Distance Doppler Shift – lifetime measurement



- Flight time $t=\frac{d}{v}$
- Probability of de-excitation during flight $e^{\frac{-t}{\tau}}$
- Minimal distance 15 um
- $v=0.006c=1.8*10^6$ m/s
- Minimal time 8 ps

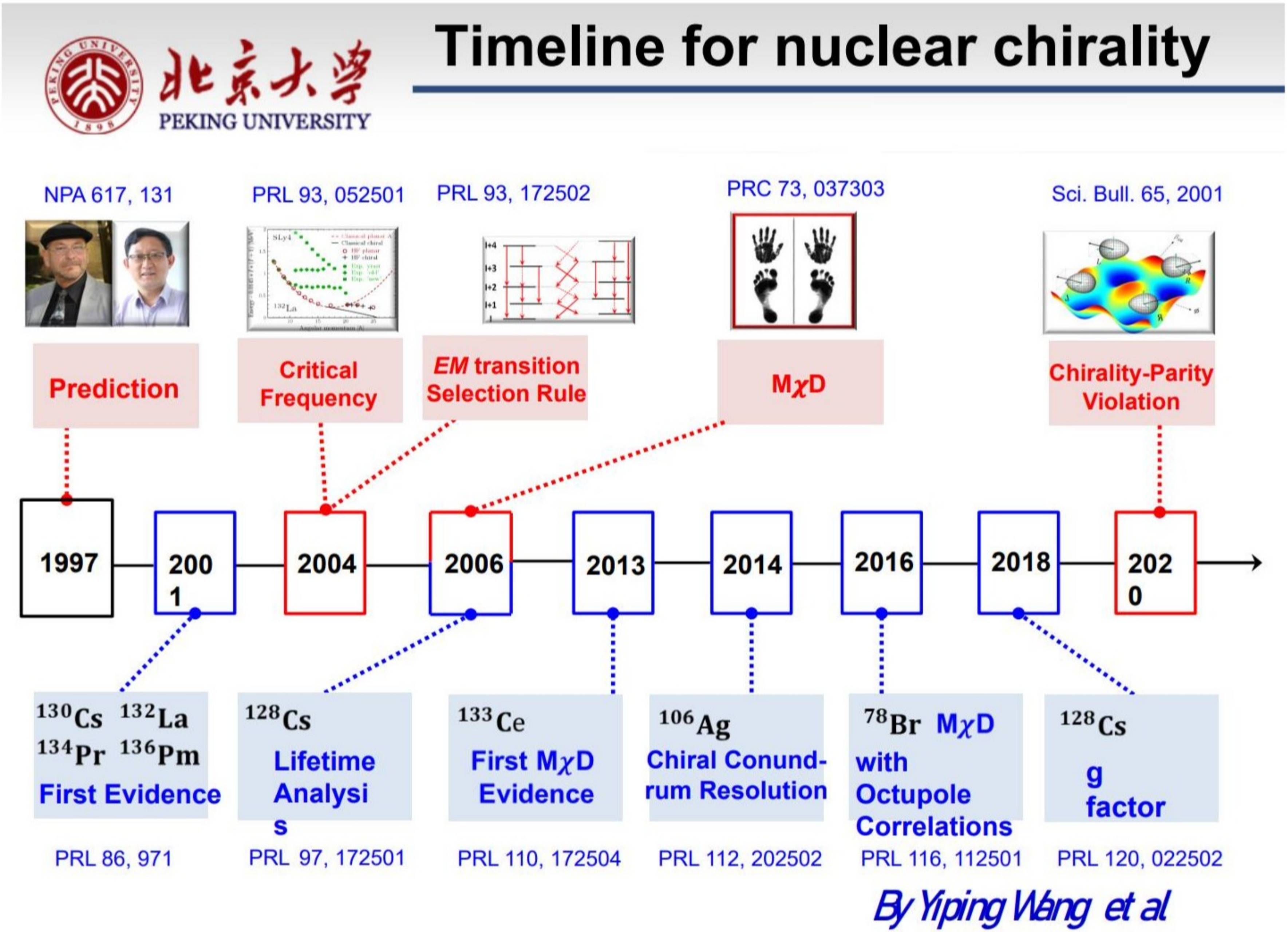
RDDM setup





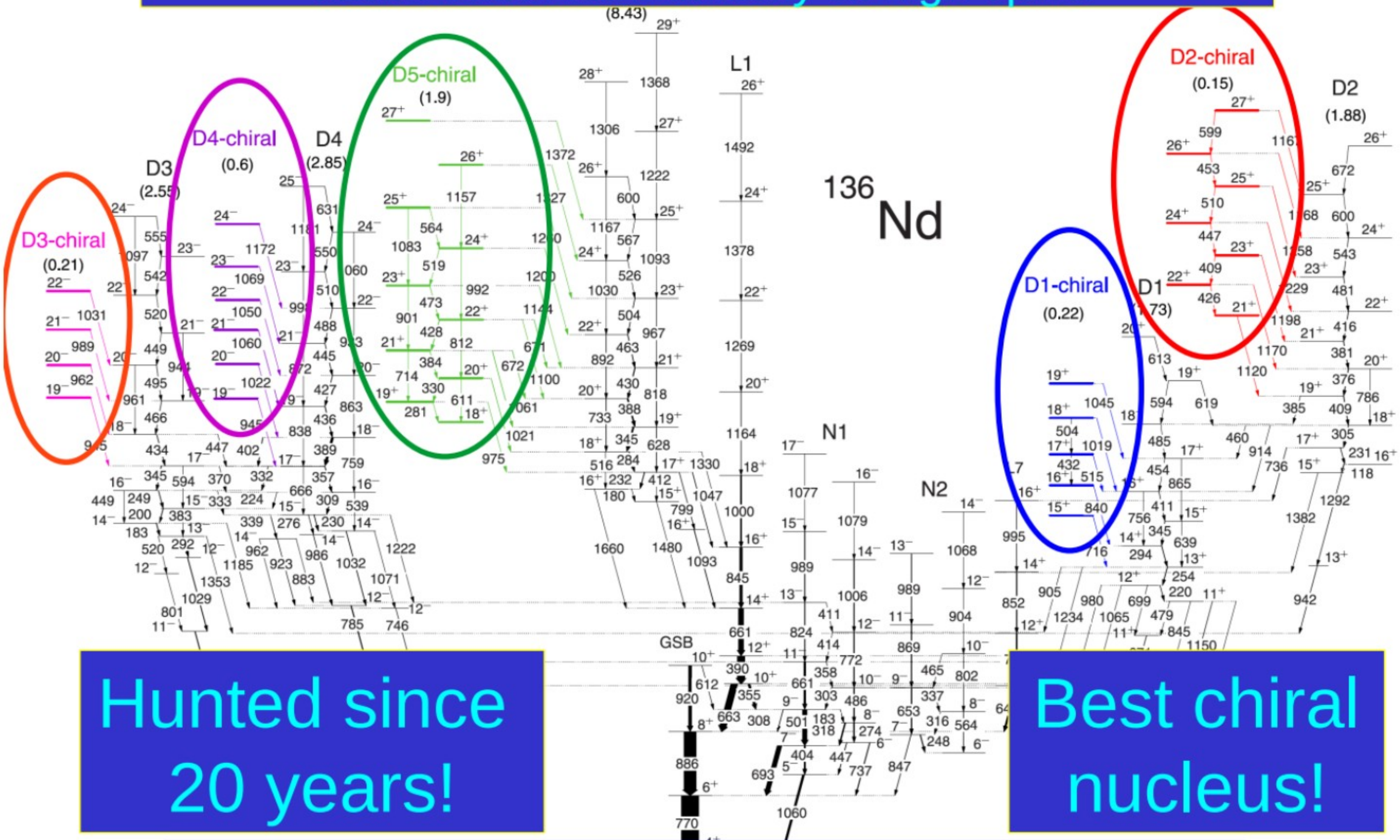
Part 2 – why chirality is examined and what it really is

Chirality timetable



^{136}Nd – 5 doublets of chiral bands

Ultimate chirality under best conditions:
stable maximal triaxiality at high spins



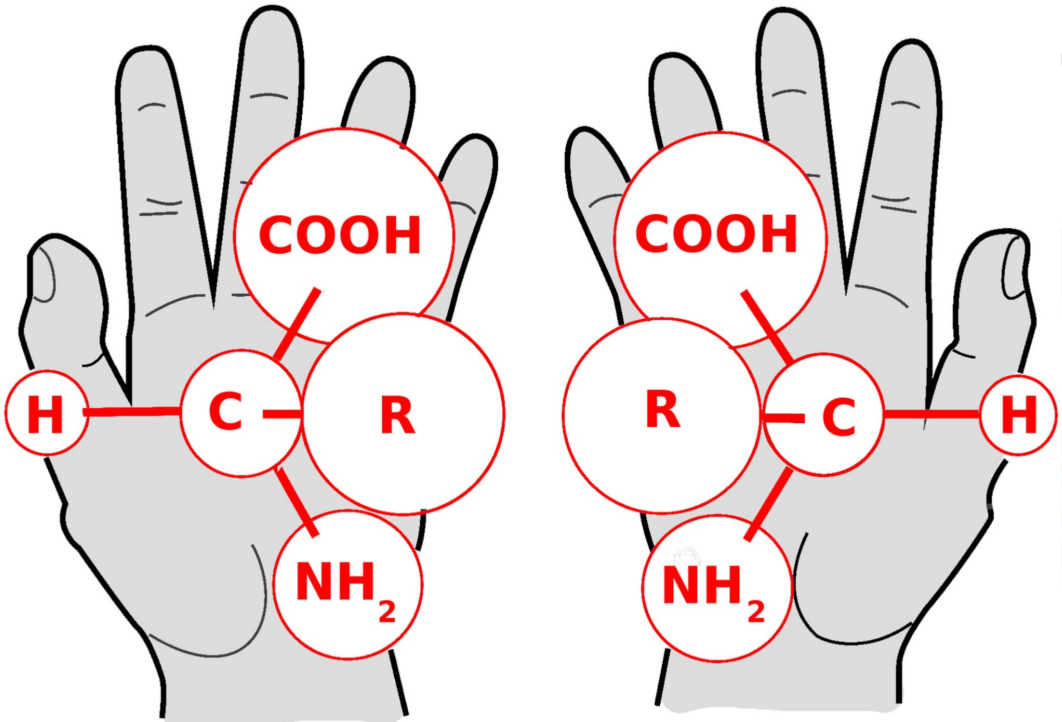
Hunted since 20 years!

Best chiral nucleus!

Credit: C. Petrache

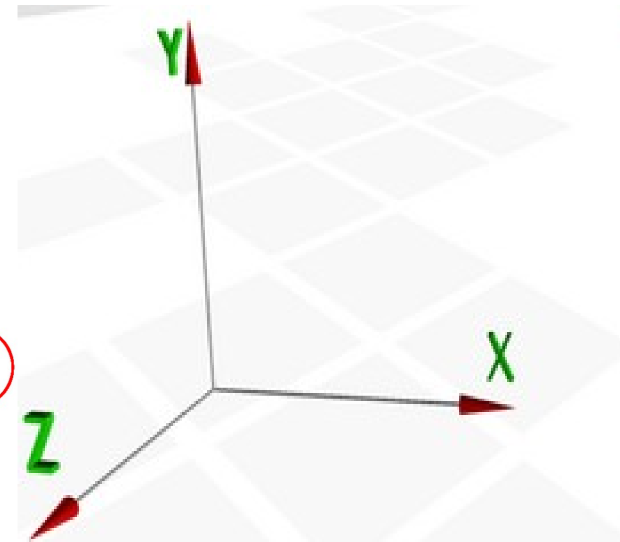
CP, B.F. Lv et al, PRC 97 (2018) 041304 (R)

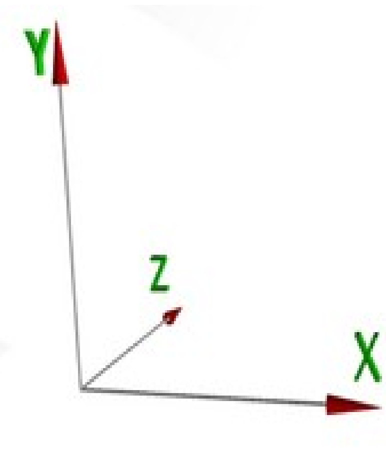
Chirality – mirror reflection



Credit:
E. Grodner

Left (L) **Right (R)**

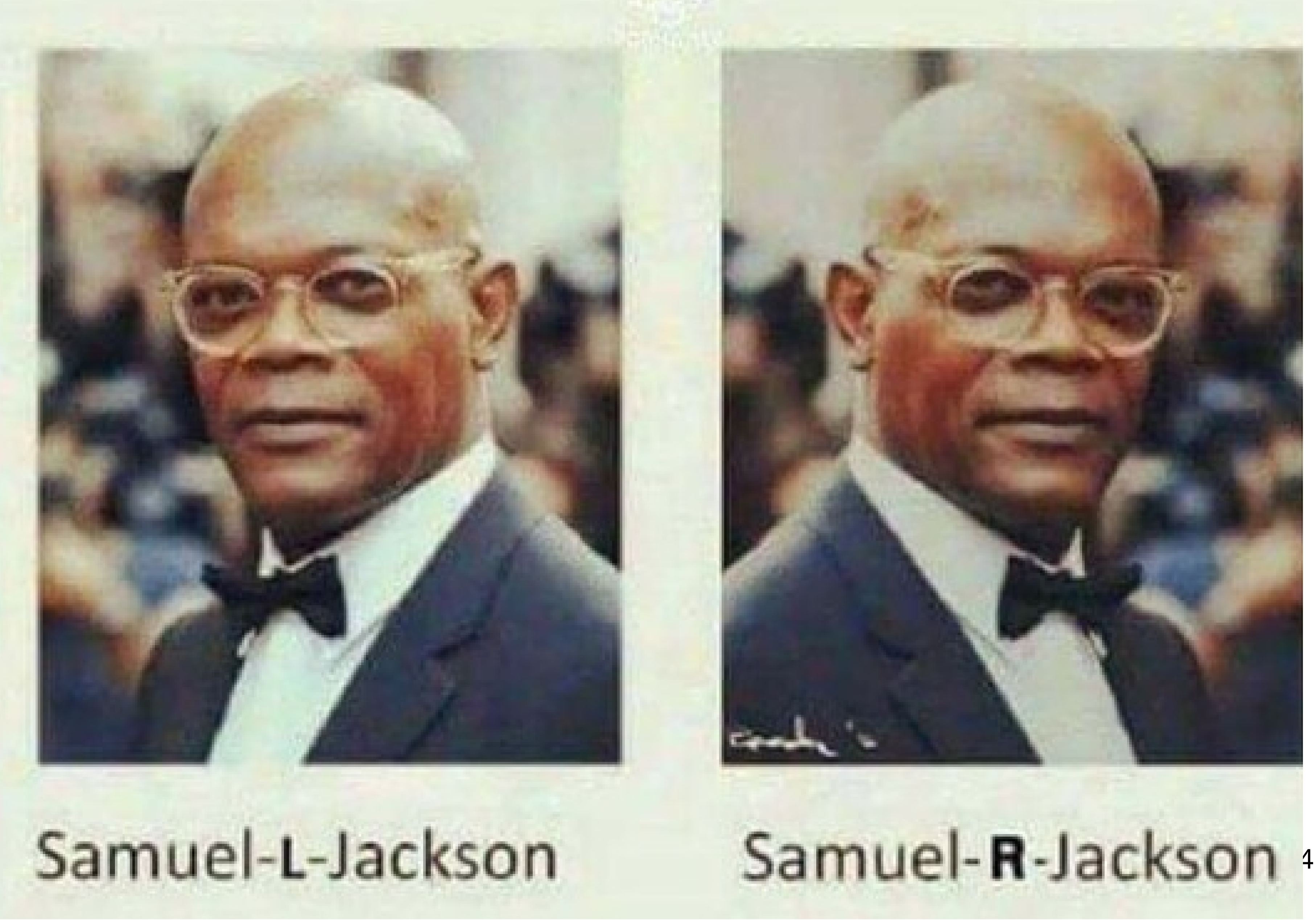




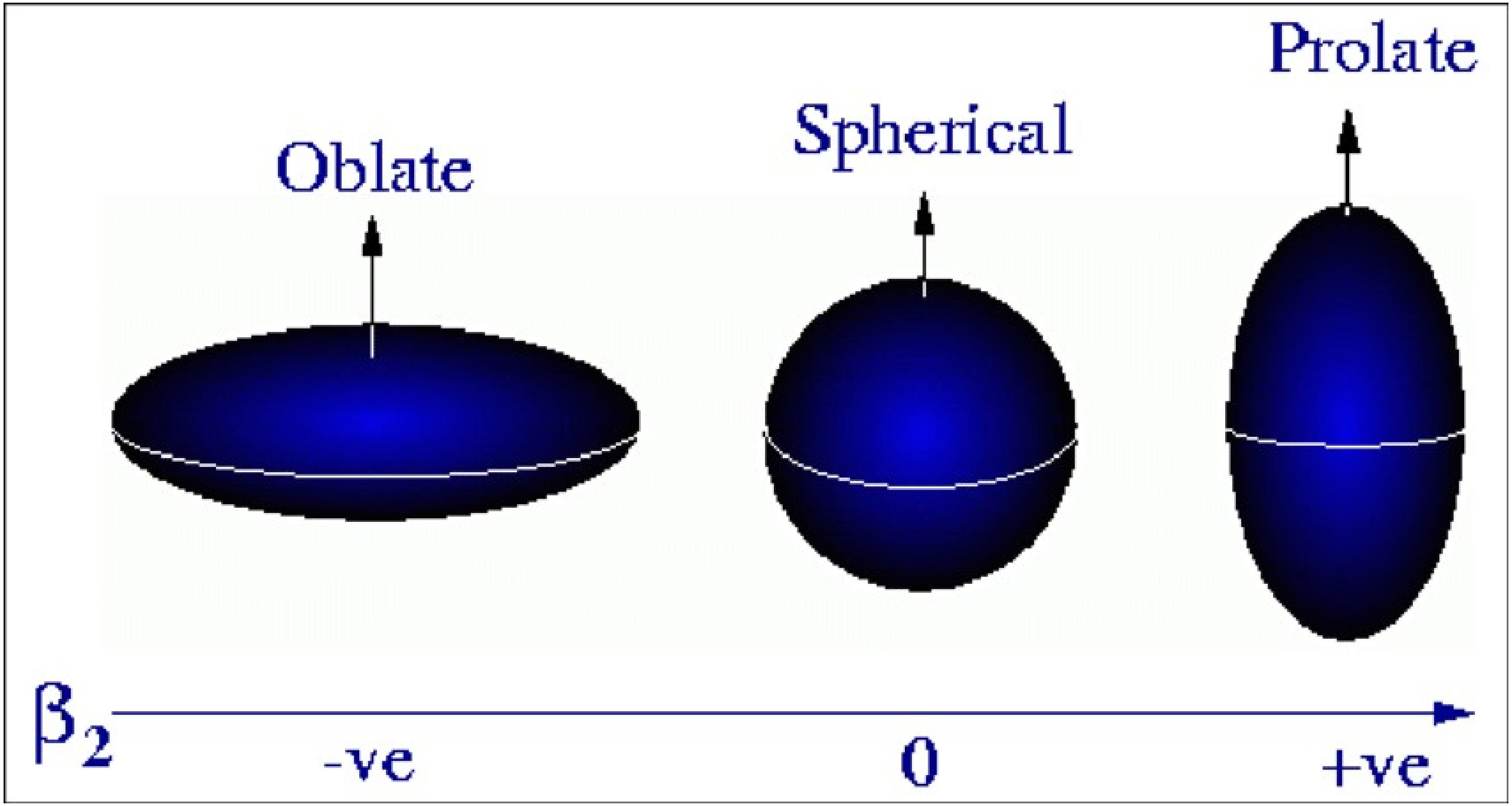
Source: mimuw.pl

Right (R) **Left (L)**

Chirality – mirror reflection



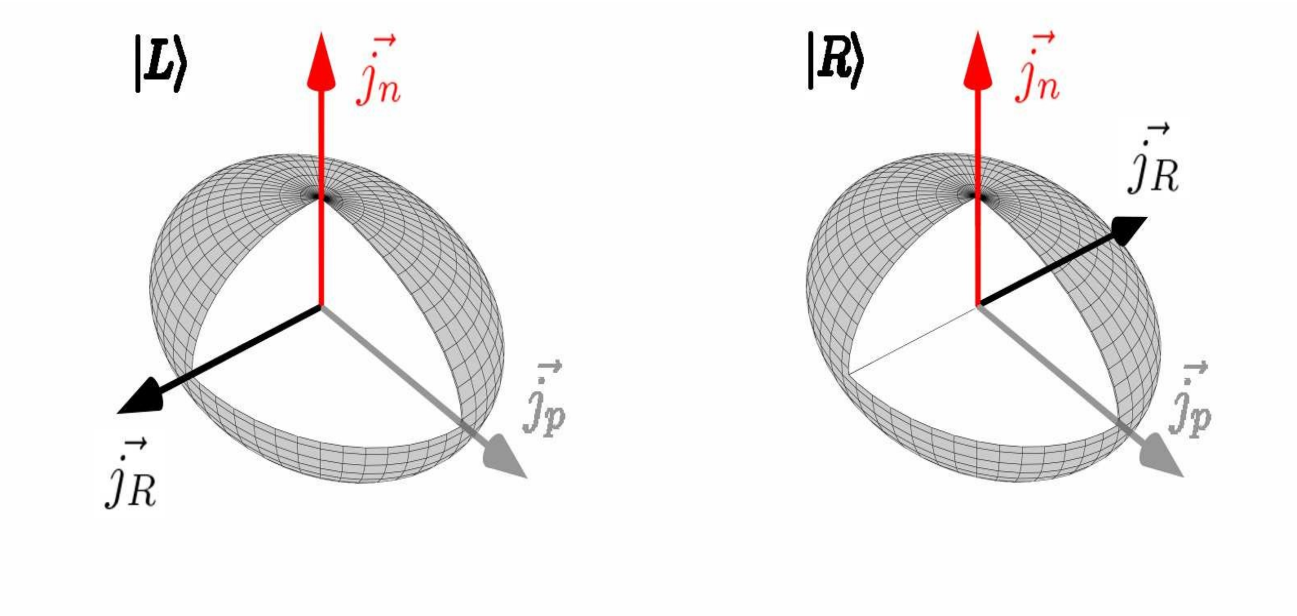
Core deformation



Ridha, Ali. (2009). Deformation parameters and nuclear radius of Zirconium (Zr) isotopes using the Deformed Shell Model. Wasiit Journall for Sciience & Mediiciine. 2. 115-125.

Chirality: nucleus

- Odd-odd nuclei
- 3 spins: core, proton and neutron
- 3 non-planar angular momentum pseudo-vectors leads to 2 arrangements



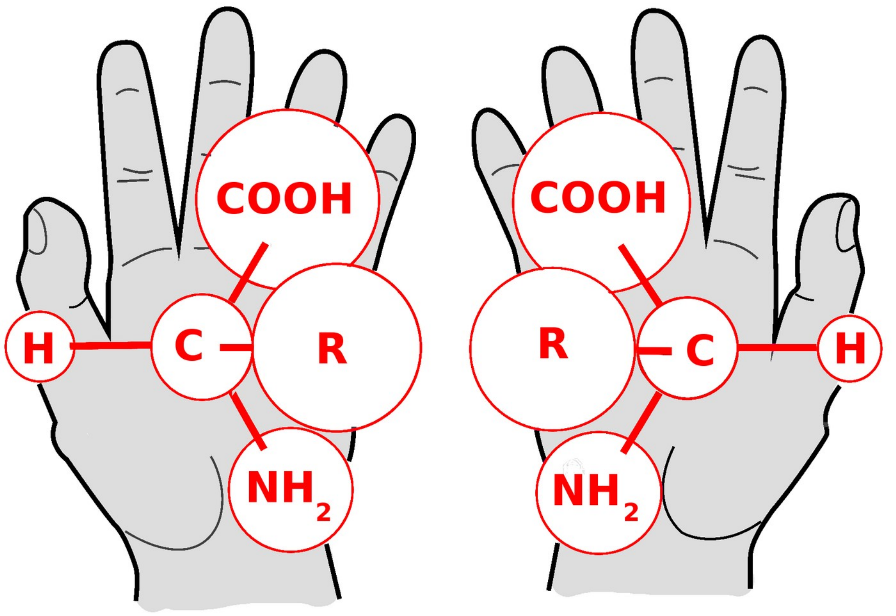
|L> state

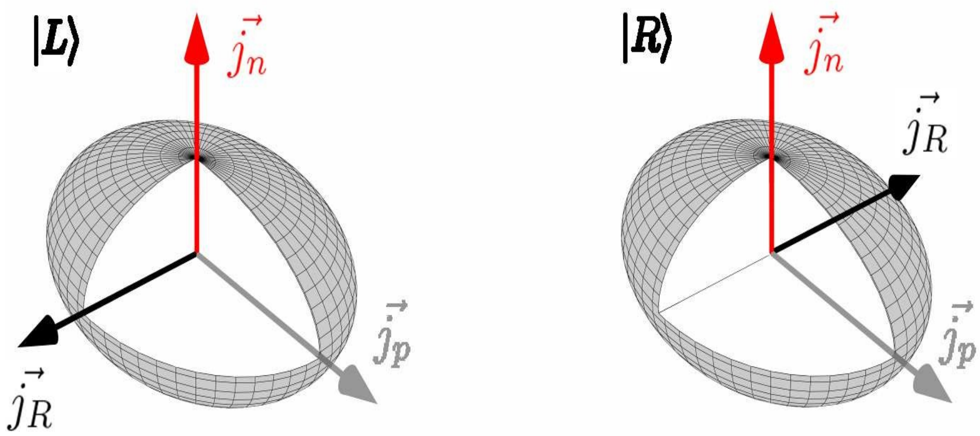
|R> state

Credit:
E. Grodner

Chirality: standard & nuclear

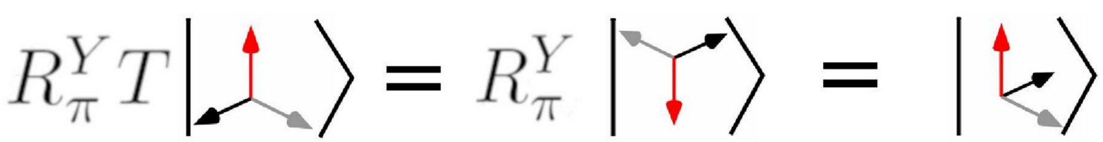
Credit: E. Grodner



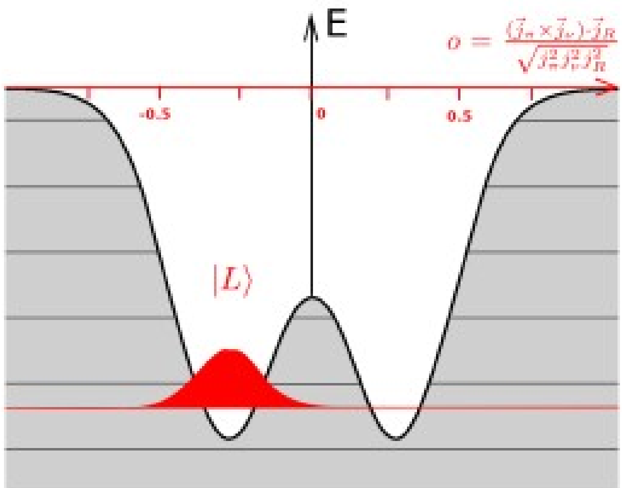


- 3 or more different vectors
- Their order determine its L or R handed
- 2 identical states, transformed by space reflection + rotation

- 3 different pseudo-vectors
- 2 identical states, transformed by time reflection + rotation

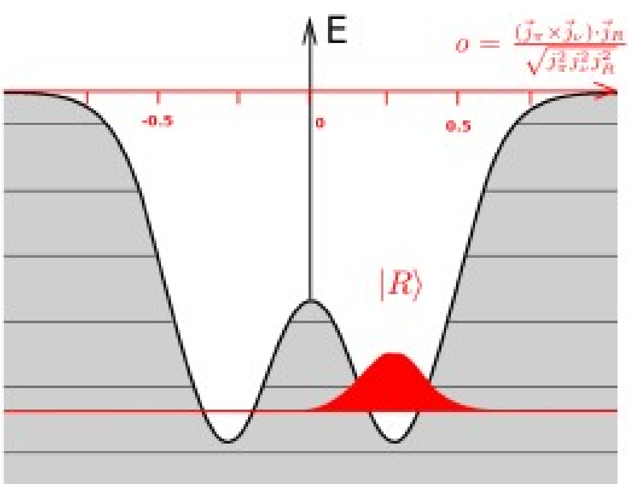


Chirality: value



Knowing spins of a core, odd proton and odd neutron we can calculate how chiral the nucleus is:

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

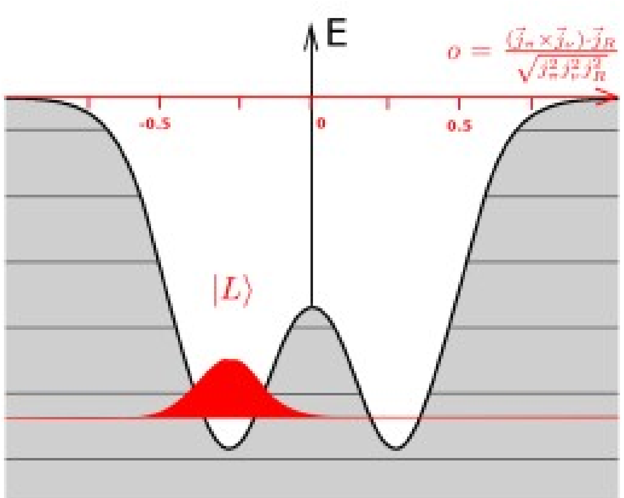


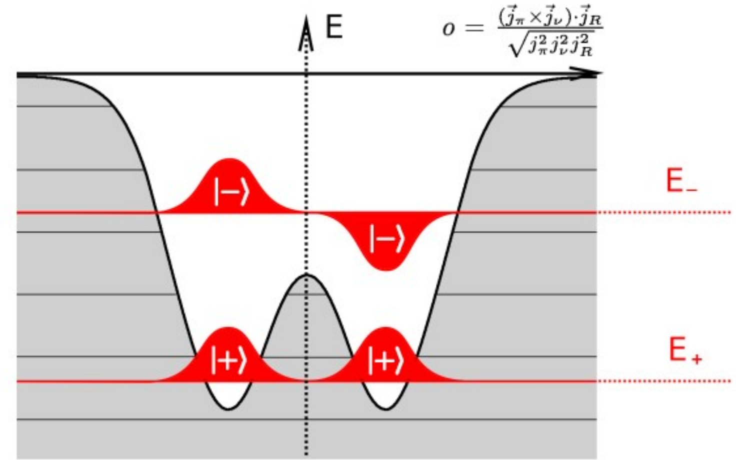
nucleus is:

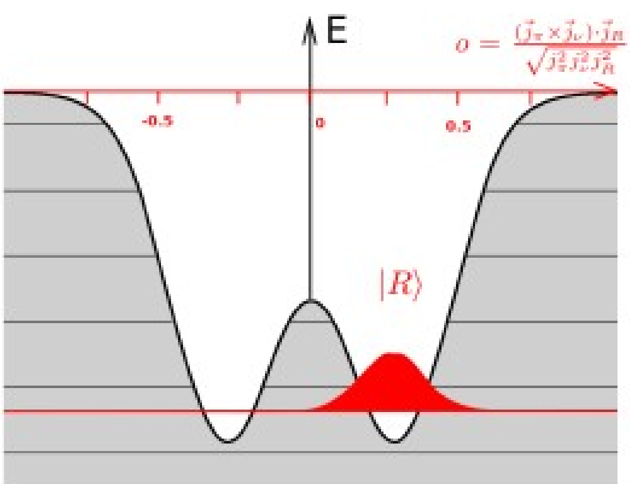
- o=0 ↔️ spins are planar, no chirality
- o<0 ↔️ |L> state
- o>0 ↔️ |R> state

Credit: E. Grodner

Chirality: tunneling



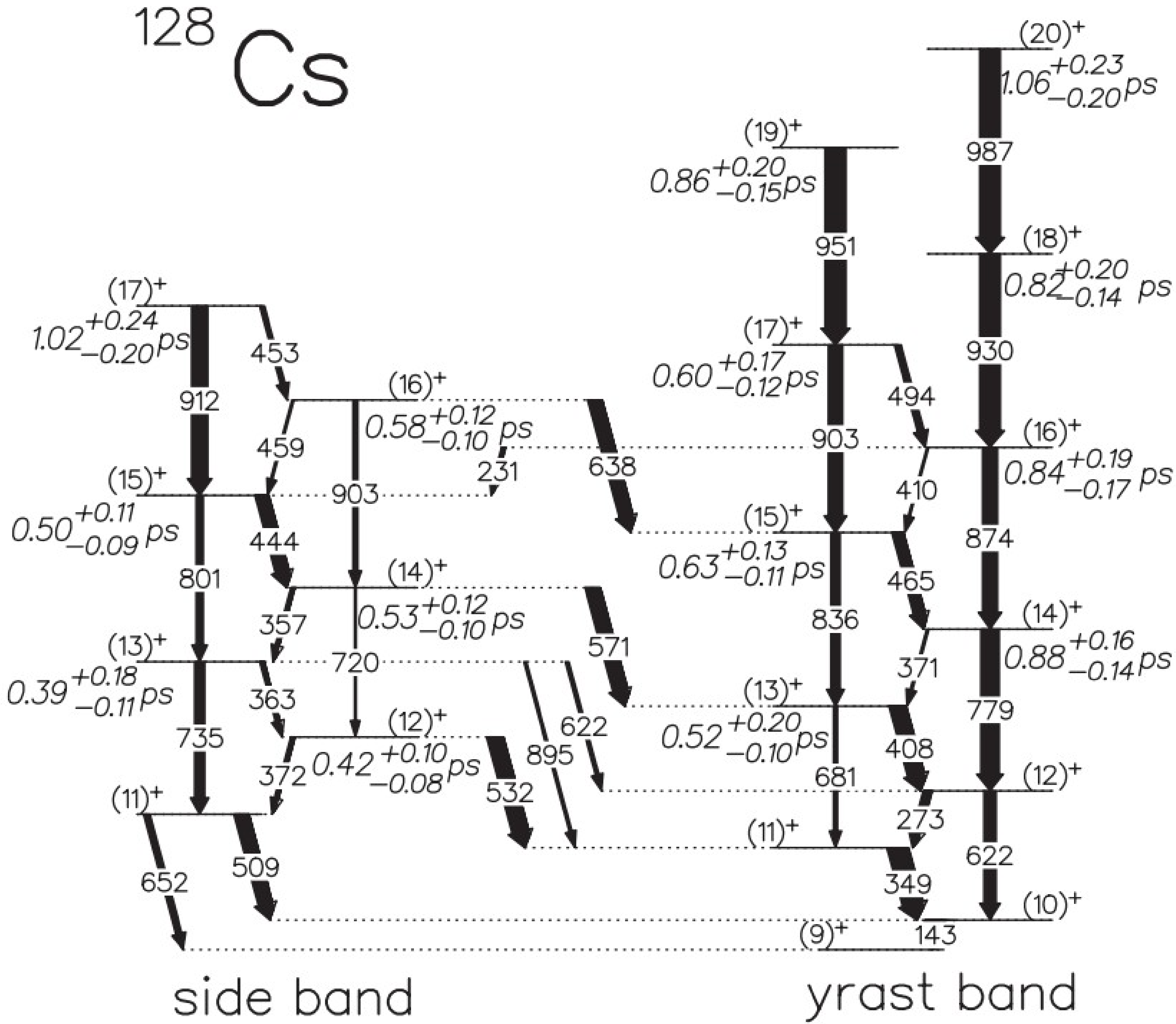




|L> and |R> states are not eigenstates of Hamiltonian ==> unstable, tunneling to |+> and |-> states

|+> and |-> states differ slightly by their energies and have very similar properties

Credit: E. Grodner


128 Cs
(20)+
1.06 +0.23 −0.20 ps
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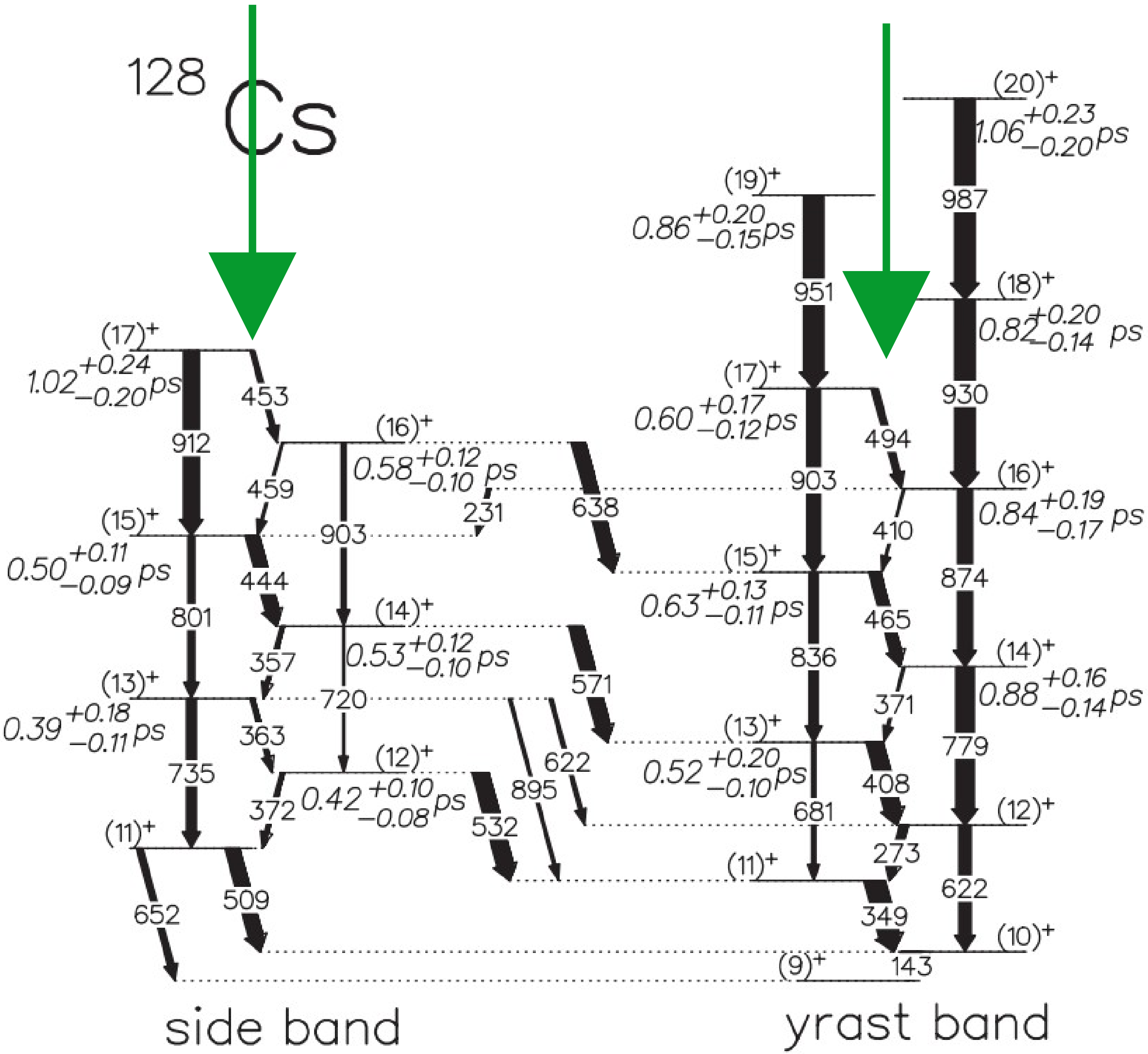
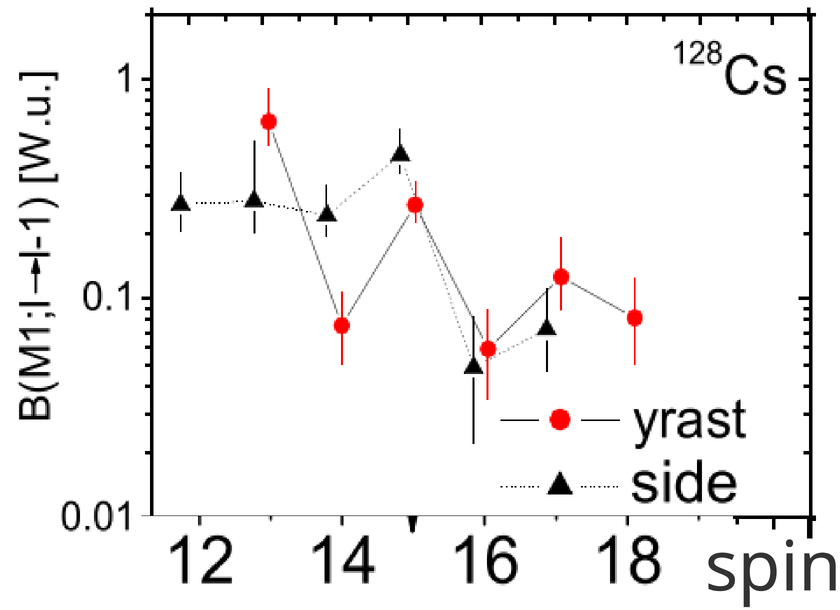
410
874
(15)+
0.50 +0.11 −0.09 ps
444
801
(14)+
0.53 +0.12 −0.10 ps
357
571
(15)+
0.63 +0.13 −0.11 ps
465
836
(14)+
0.88 +0.16 −0.14 ps
371
779
(13)+
0.39 +0.18 −0.11 ps
720
363
735
(12)+
0.42 +0.10 −0.08 ps
372
532
895
622
(13)+
0.52 +0.20 −0.10 ps
408
681
(12)+
273
622
(11)+
652
509
(11)+
349
(10)+
(9)+
143
side band
yrast band

Part 3 – How chirality is examined?

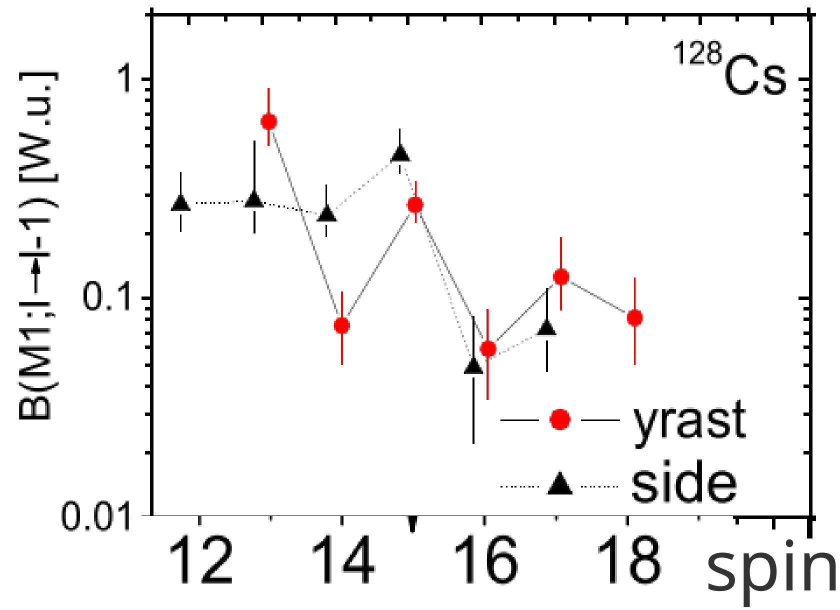
Transition probabilities B(M1)





Transition probabilities B(M1)

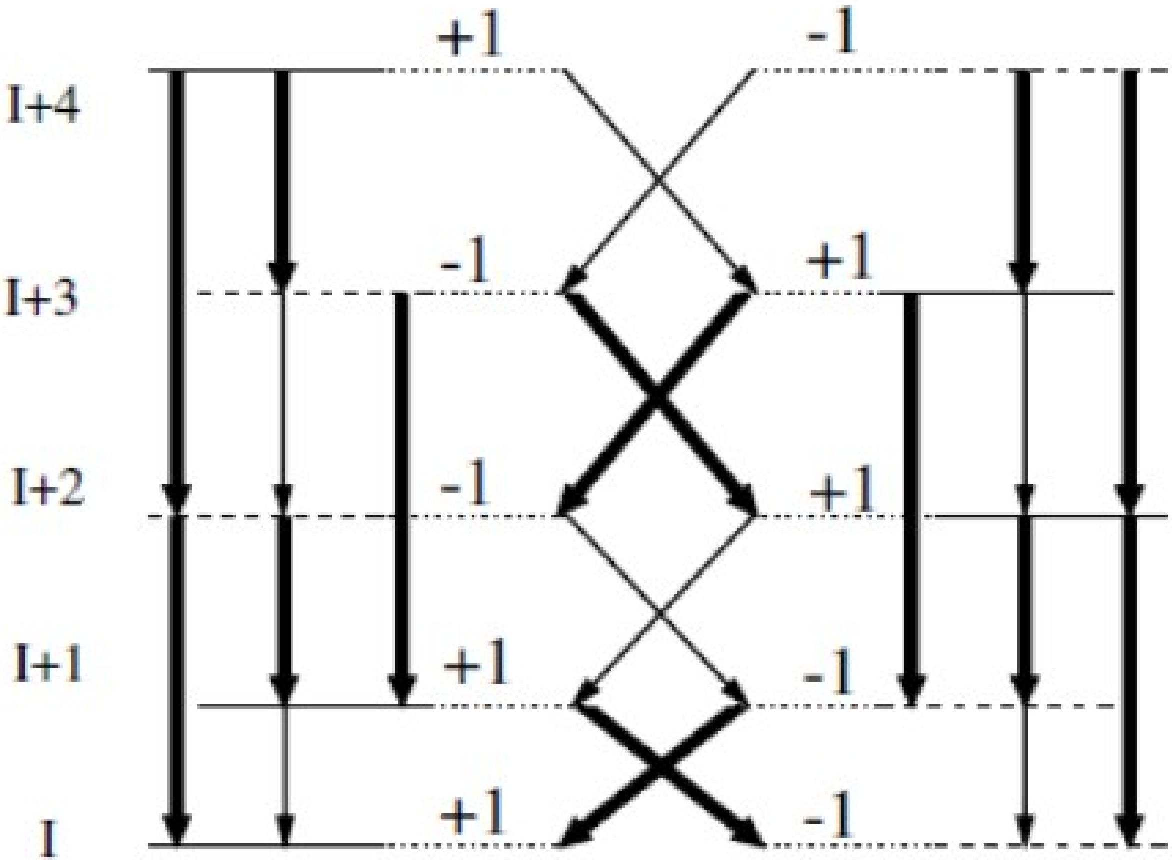
- Calculated by lifetimes
- Gives some information about the internal structure of the band
- Experimentally measured just for few % of states



$$T(E1) = 1.59 \times 10^{15} (E)^3 B(E1)$$
$$T(E2) = 1.22 \times 10^{9} (E)^5 B(E2)$$
$$T(E3) = 5.67 \times 10^{2} (E)^7 B(E3)$$
$$T(E4) = 1.69 \times 10^{-4} (E)^9 B(E4)$$

$$T(M1) = 1.76 \times 10^{13} (E)^3 B(M1)$$
$$T(M2) = 1.35 \times 10^{7} (E)^5 B(M2)$$
$$T(M3) = 6.28 \times 10^{0} (E)^7 B(M3)$$
$$T(M4) = 1.87 \times 10^{-6} (E)^9 B(M4)$$

B(M1) staggering

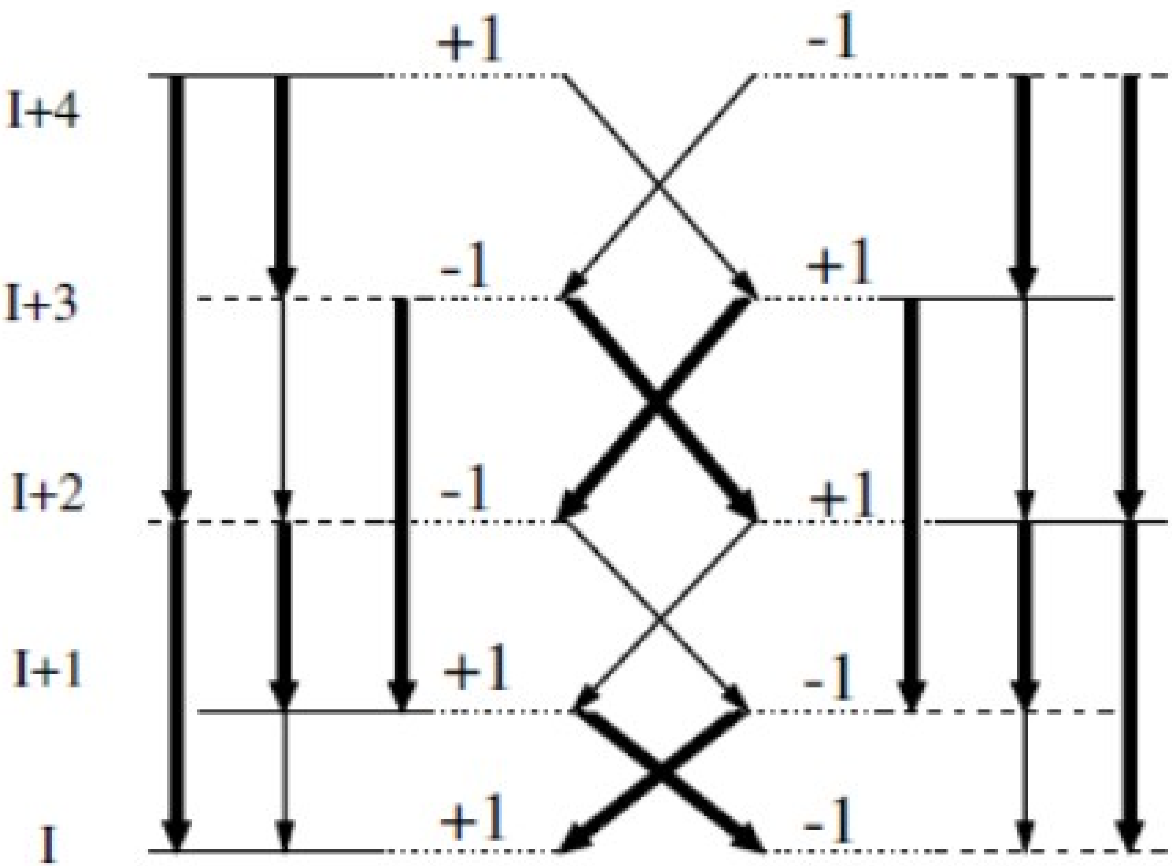


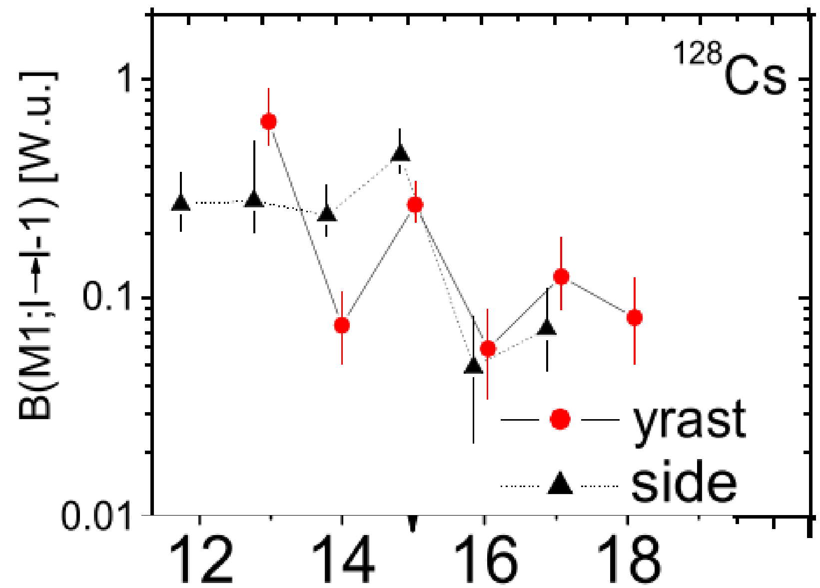
VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Chiral Bands, Dynamical Spontaneous Symmetry Breaking, and the Selection Rule for Electromagnetic Transitions in the Chiral Geometry

T. Koike,[1] K. Starosta,[1,2] and I. Hamamoto[3,4]

B(M1) staggering





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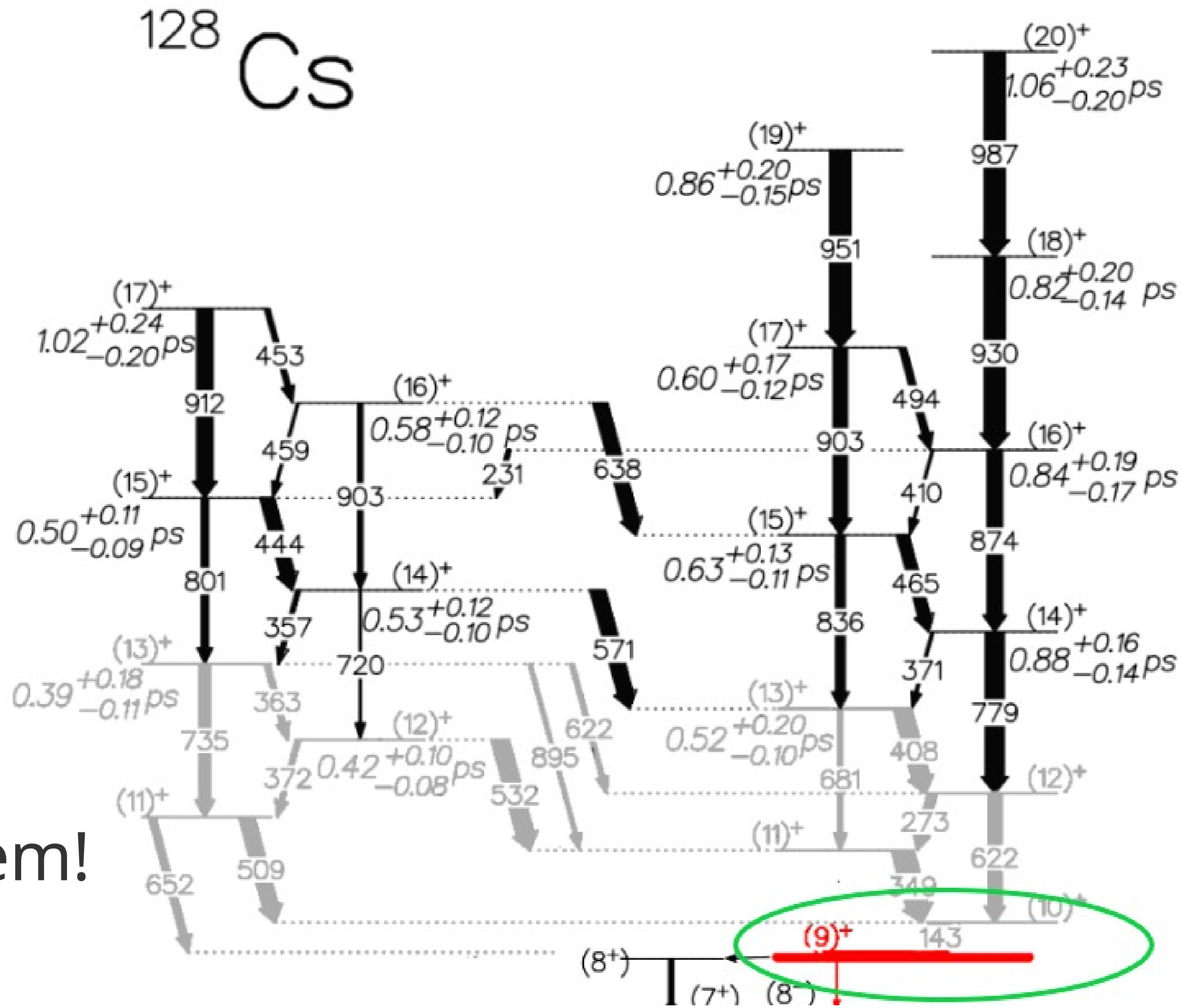
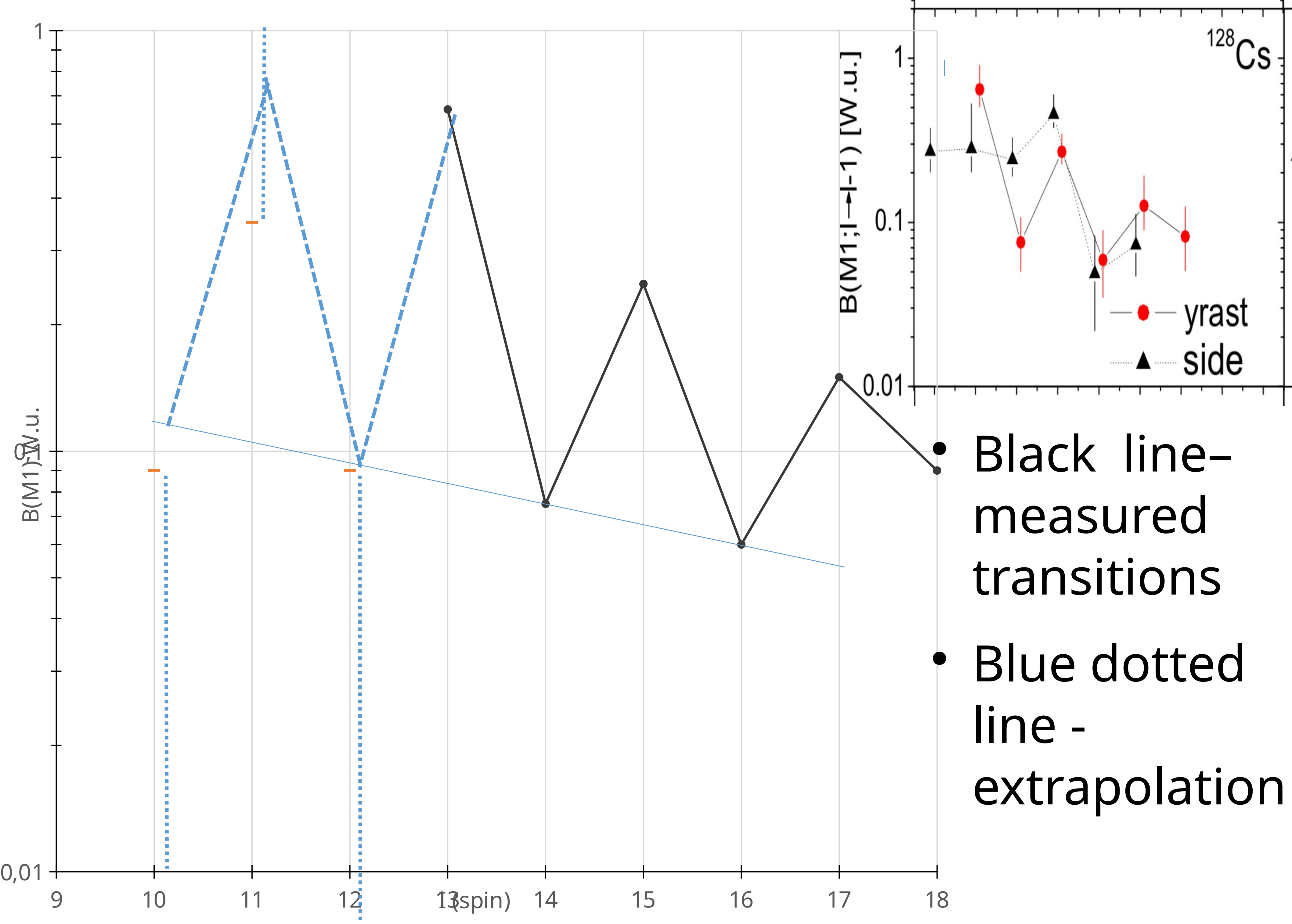
My work

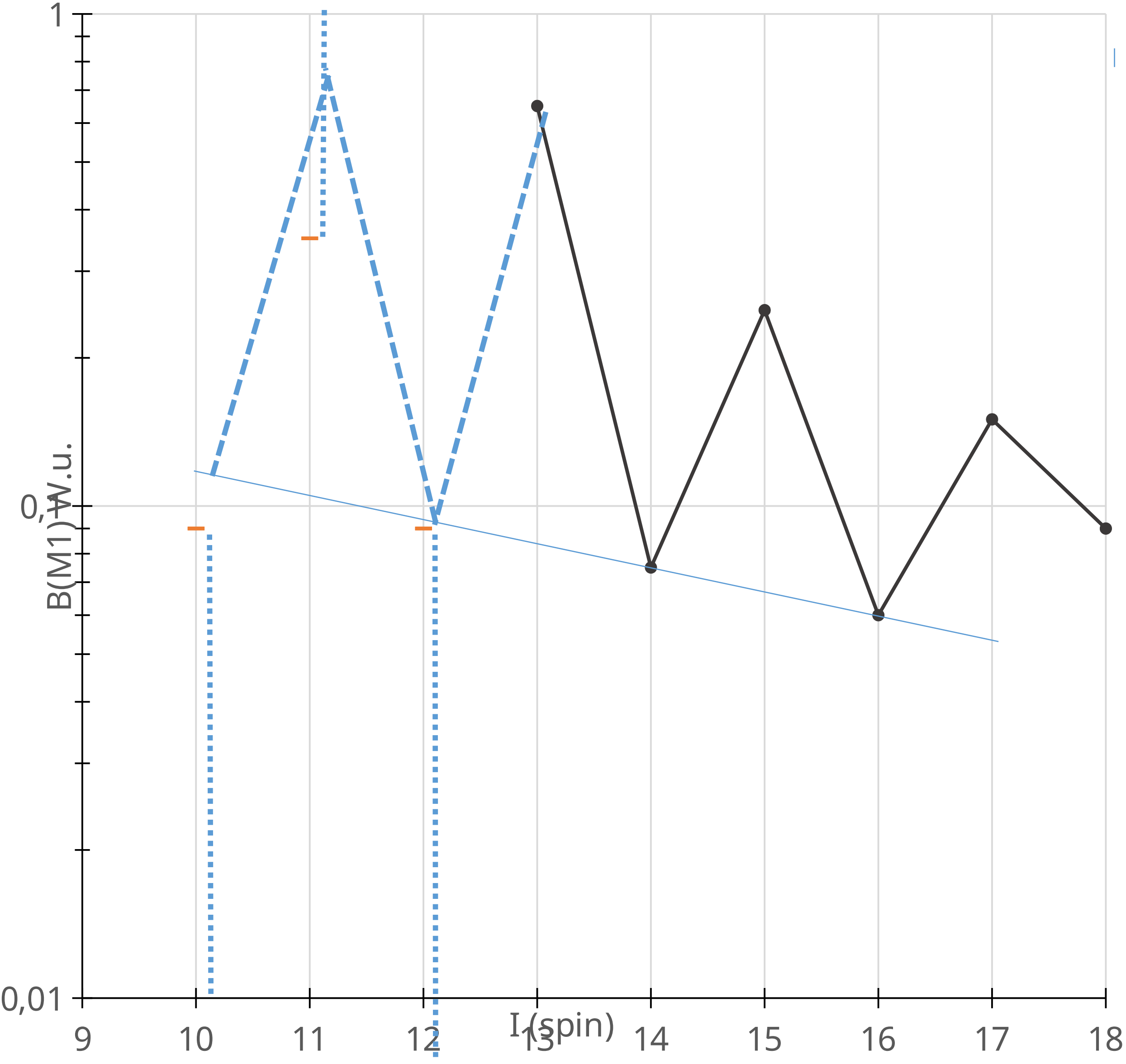
- Black states are chiral
- Red state is not chiral
- What about gray states?
- Let's measure them!





- Black line– measured transitions
- Blue dotted line - extrapolation

Lifetime prediction



- 10+ over 65 ps
- 11+ under 1.5 ps
- 12+ over 5 ps

Expected results vs measured results

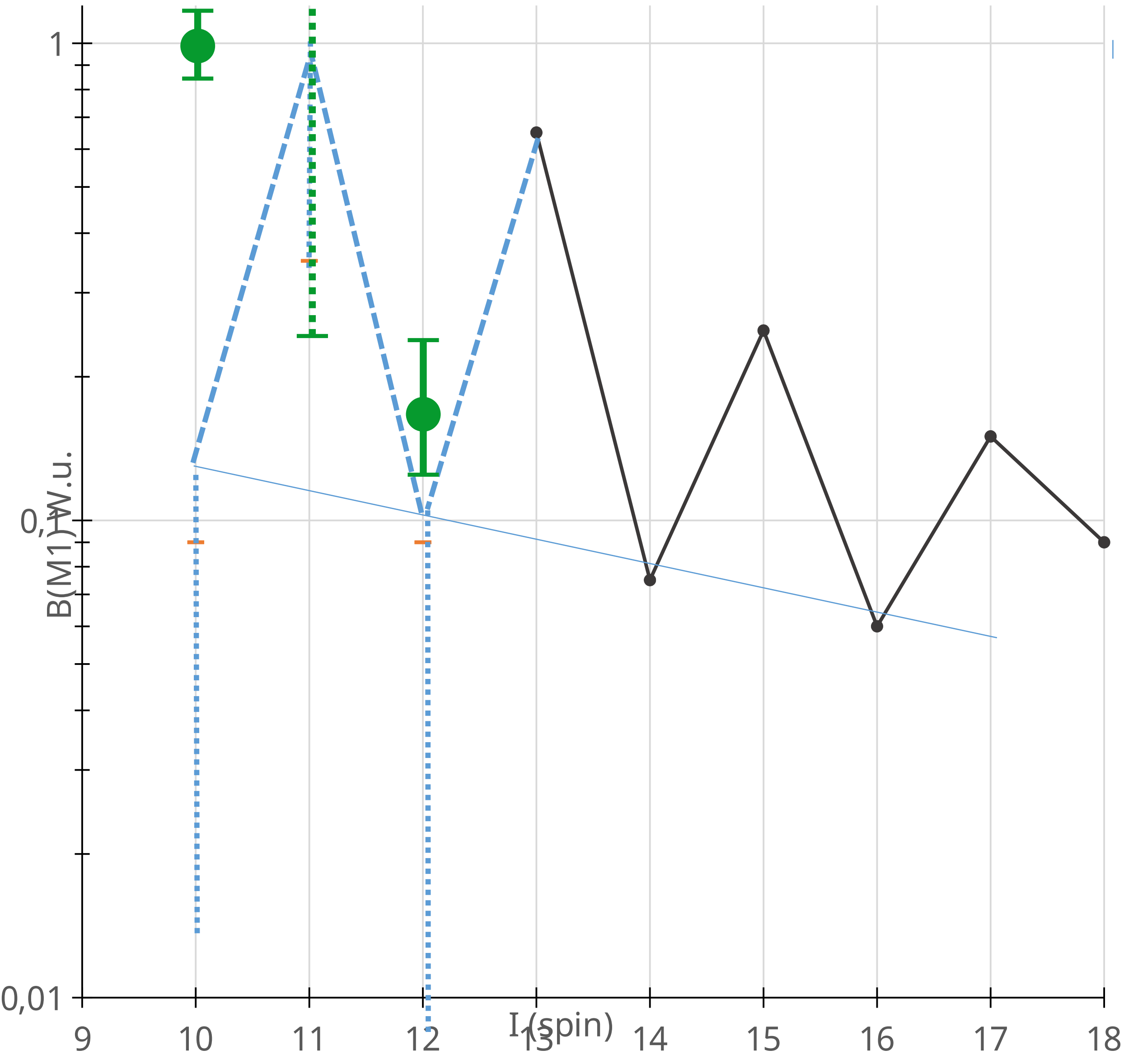
Expected results:

- 10+ over 65 ps
- 11+ under 1.5 ps
- 12+ over 5 ps

Measured results:

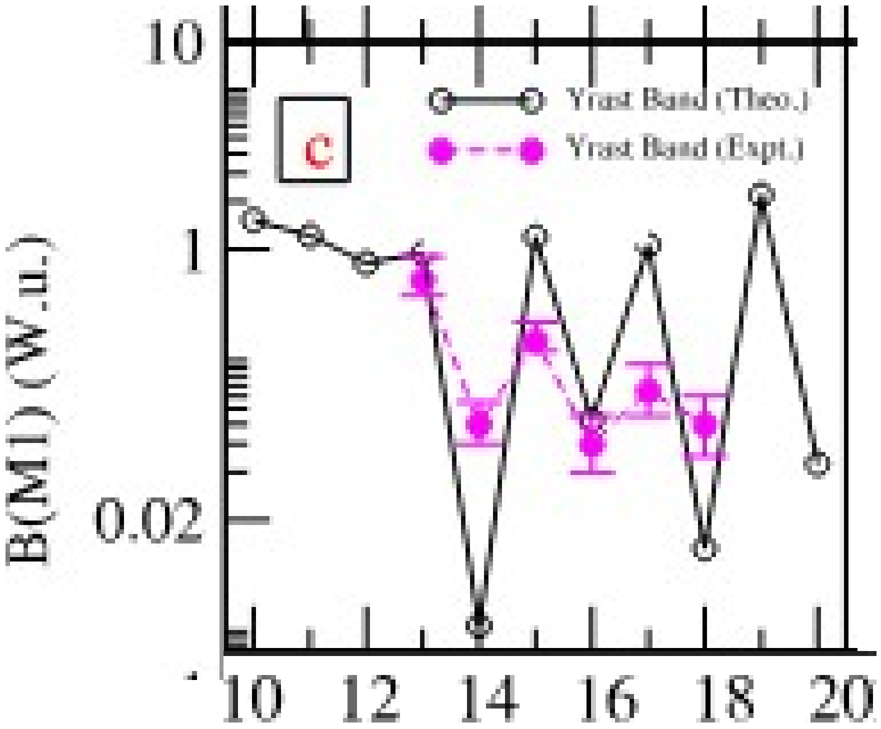
- 10+ 8.5 +- 1.0 ps
- 11+ under 3 ps
- 12+ 3.5 +- 1.5 ps

B(M1) results



- 10+ $0.96^{+0.13}_{-0.10}$ W.u.
- 11+ >0.24 W.u.
- 12+ $0.17^{+0.07}_{-0.05}$ W.u.

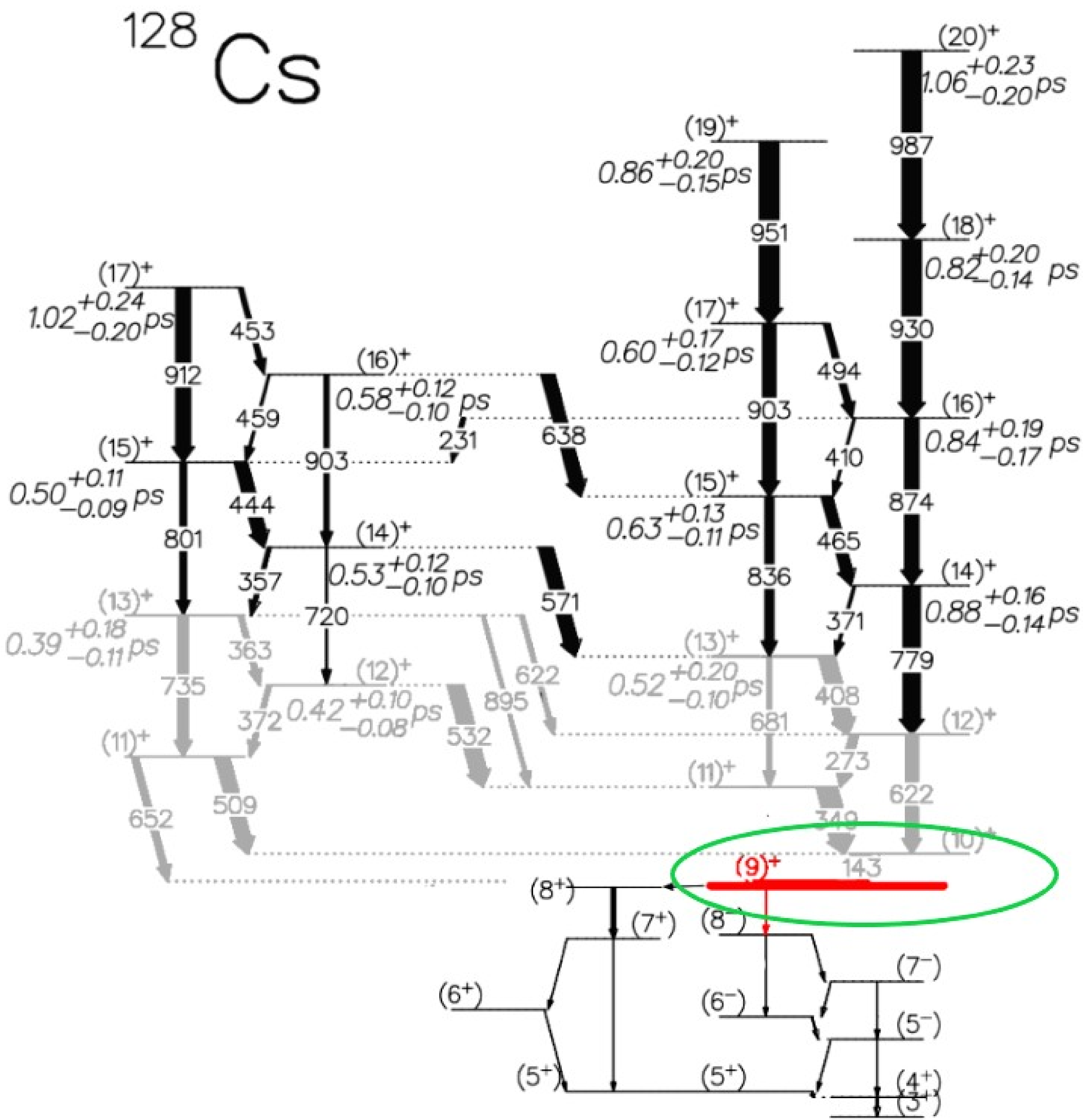
Another explanation



- Another model of those bands
- Predicts that staggering stops at spin 13
- Problems with side band

Summary

- Gamma spectroscopy is a part of nuclear physics that examine excited levels in nuclei
- Excitation of a nuclei is caused by nucleus nucleus collision and observed by measuring energies of gammas
- Chirality is a phenomenon of left and right “hand”
- Measuring lifetime of states can identify a rotational band as chiral



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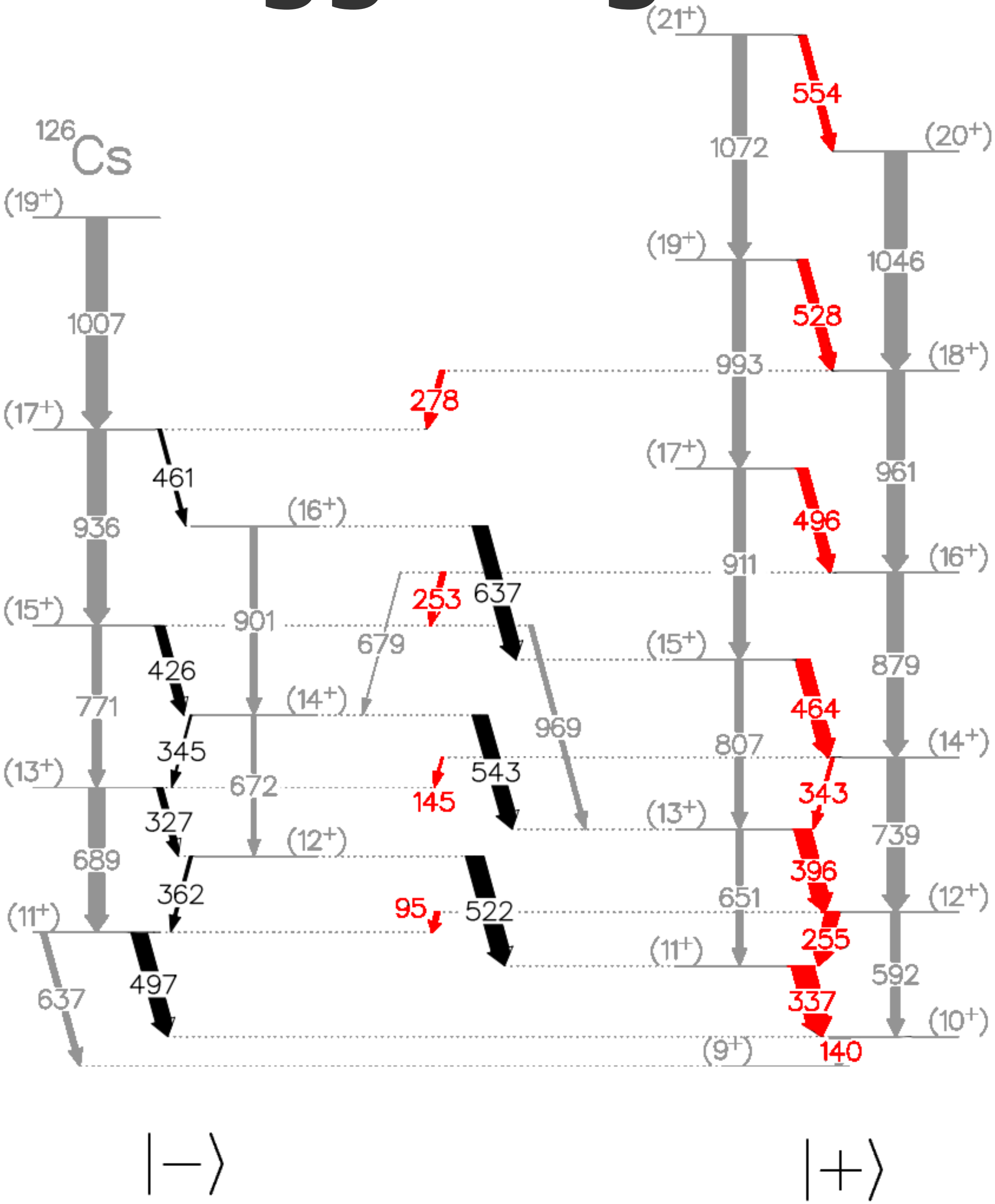
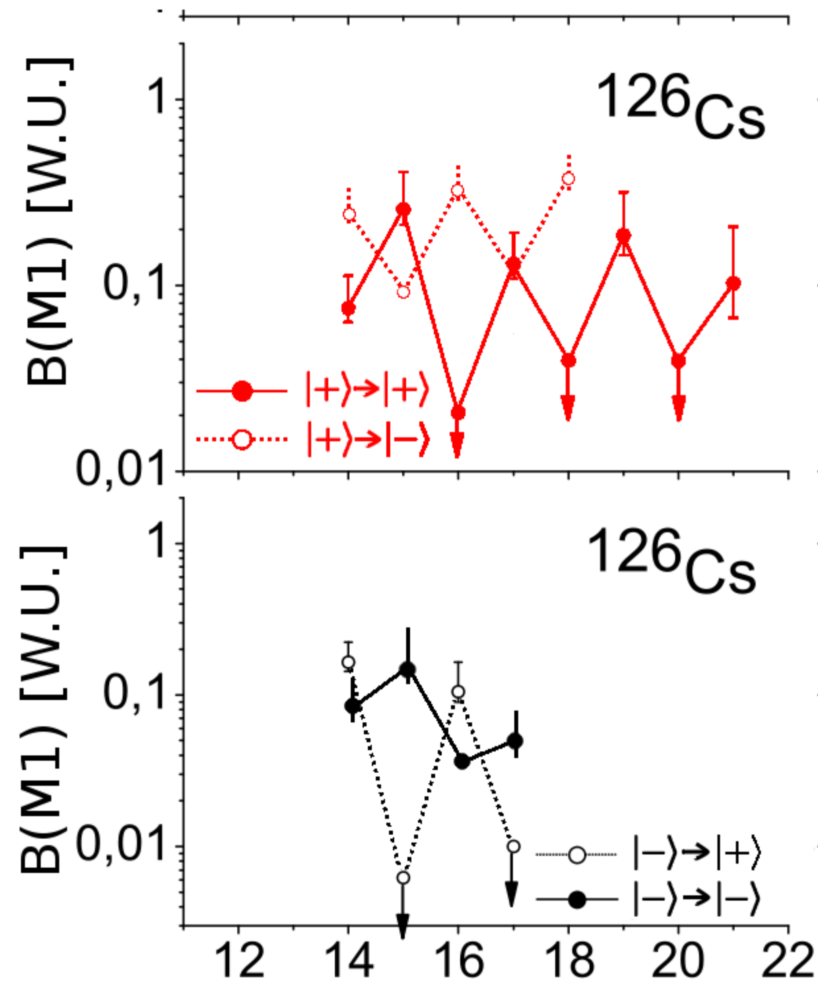
0.88 +0.16 −0.14 ps
357
571
371
(13)+
0.39 +0.18 −0.11 ps
720
363
735
622
895
(12)+
0.42 +0.10 −0.08 ps
372
532
(13)+
0.52 +0.20 −0.10 ps
408
779
681
(12)+
(11)+
273
622
(11)+
652
509
349
(10)+
(9)+
143
(8+)
(7+)
(8−)
(7−)
(6+)
(6−)
(5−)
(5+)
(5+)
(4+)
(3+)

Staggering



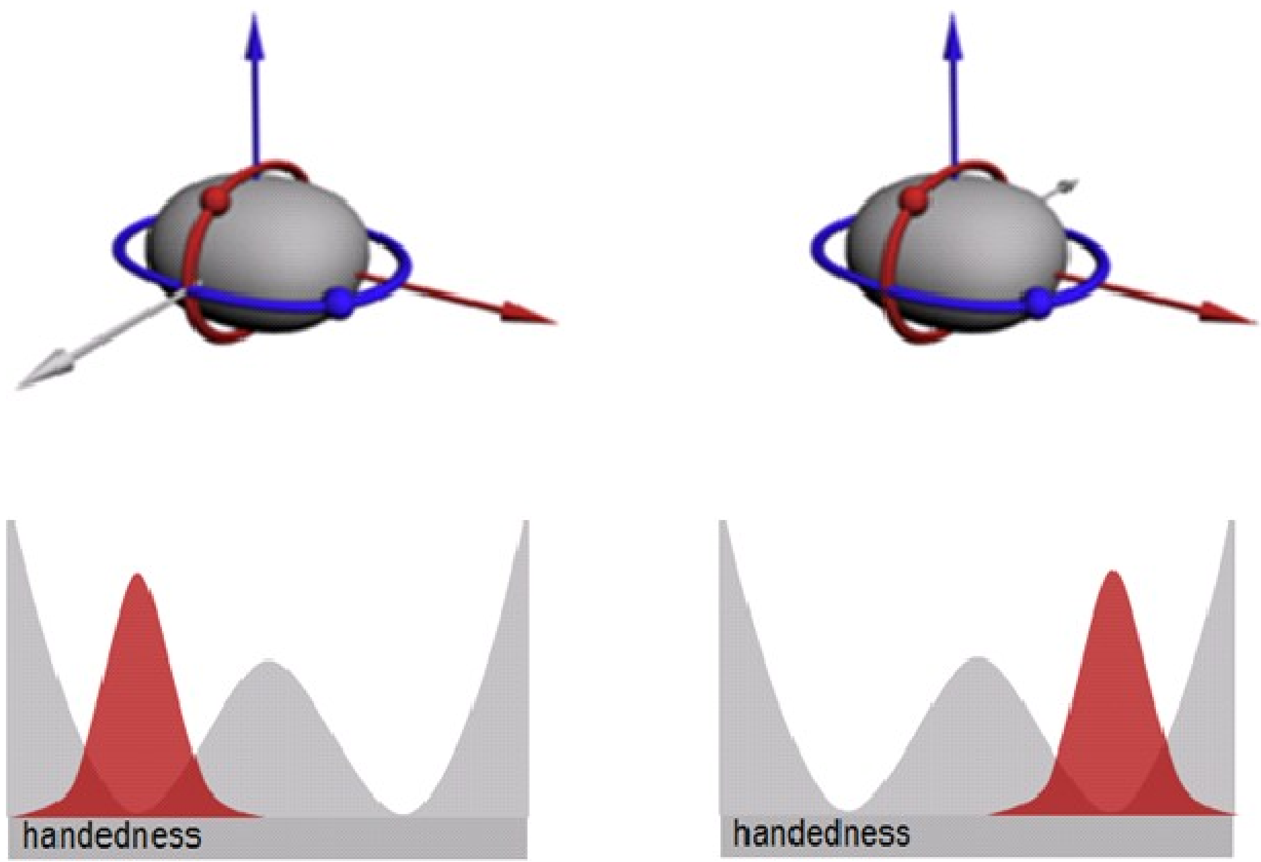
126Cs
(19+)
(17+)
(15+)
(13+)
(11+)
(16+)
(14+)
(12+)
(21+)
(20+)
(19+)
(18+)
(17+)
(16+)
(15+)
(14+)
(13+)
(12+)
(11+)
(10+)
(9+)
1007
936
771
689
637
461
426
345
327
362
497
901
672
679
278
253
145
95
637
543
522
969
1072
993
911
807
651
554
528
496
464
343
396
255
337
140
1046
961
879
739
592
|−⟩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



B(M1) [W.U.]
126Cs
1
0,1
0,01
|+⟩→|+⟩
|+⟩→|−⟩
|−⟩→|+⟩
|−⟩→|−⟩
12
14
16
18
20
22

Chirality: nuclea

- Odd-odd triaxial nuclei
- 3 spins: core, proton and neutron
- 3 perpendicular angular momentum pseudovectors leads to 2 arrangements



|L> state |R> state

Credit:
E. Grodner