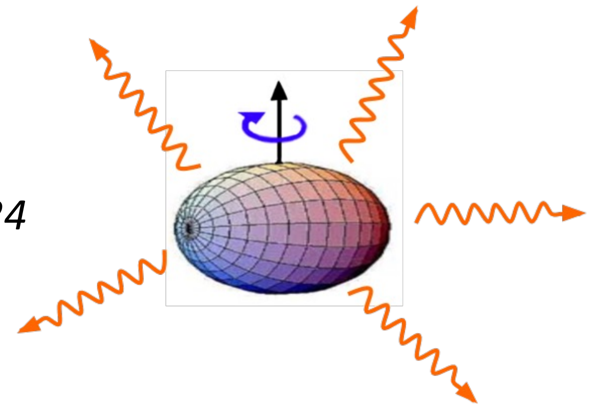
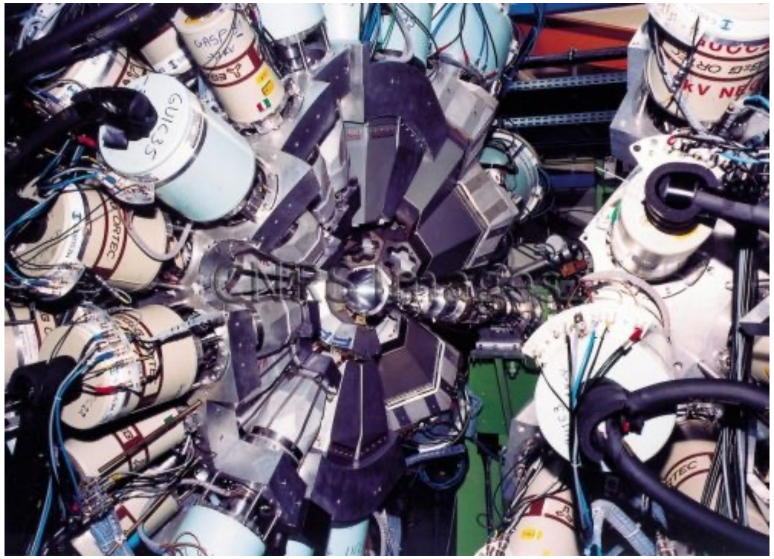
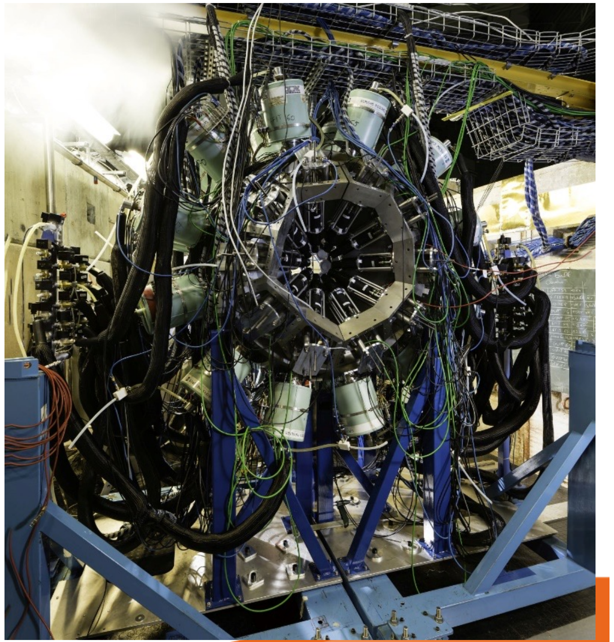
Exotic emergent phenomena in atomic nuclei

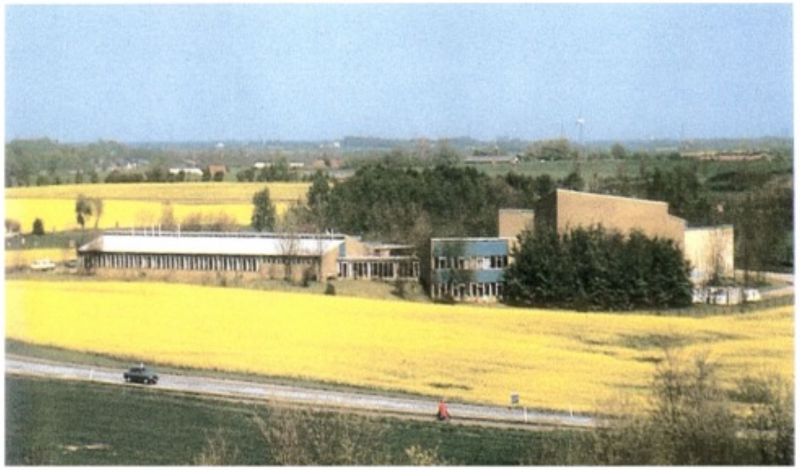
J.N. Wilson, IJC Lab
3x60 Workshop, Milano 2024







The group at the Niels Bohr Institute



Reflections on the science and impact of Bent Herskind

S. Leoni, A. Maj, M. A. Riley, J. Simpson, E. Vigezzi and J. N. Wilson
Eur. Phys. J. A 60: 206 (2024)

The group at the Niels Bohr Institute

Triaxial Wobbling

Hyperdeformation

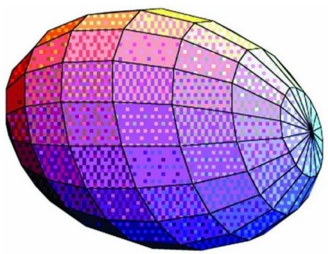
Nuclear Fission

The discovery of triaxial wobbling

VOLUME 86, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 2001

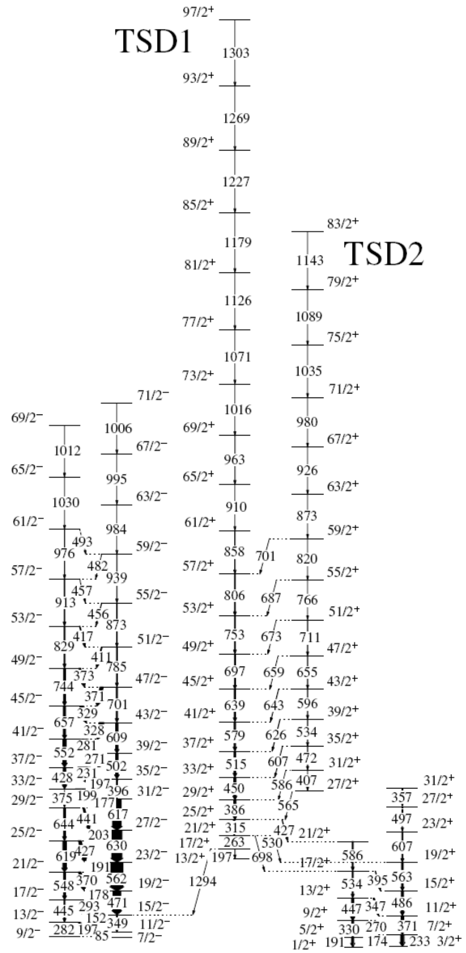
Evidence for the Wobbling Mode in Nuclei

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]



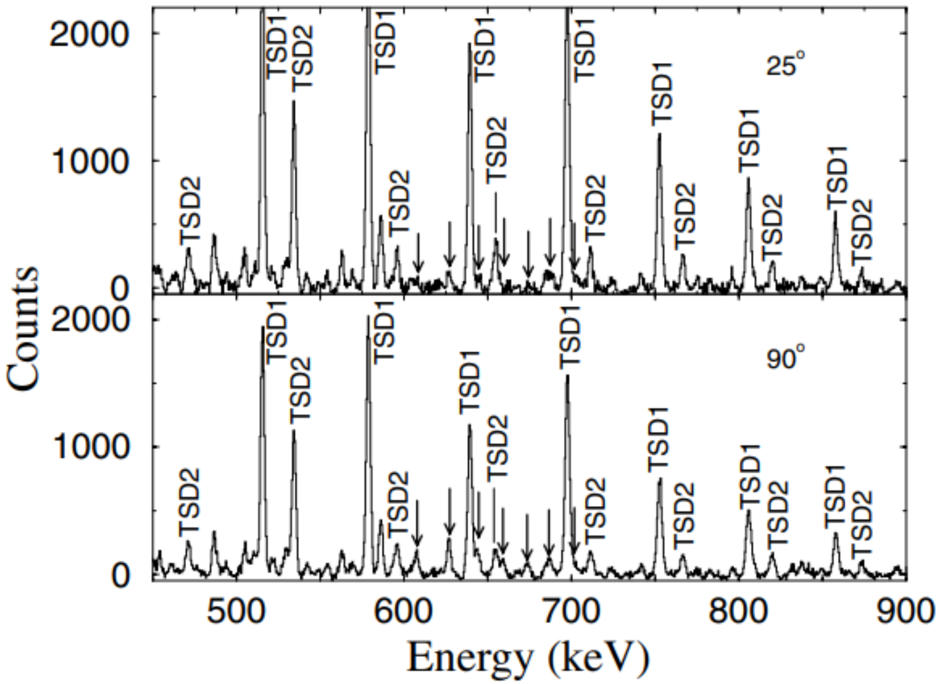
$$E(I,n_\omega) = I(I+1)\cdot\frac{\hbar^2}{2\Im_x} + \hbar\omega_\omega(n_\omega + \frac{1}{2})$$

$$\hbar\omega_\omega = \hbar\omega_{rot}\sqrt{(\Im_x - \Im_y)(\Im_x - \Im_z)/(\Im_y \Im_z)}$$



386 Citations!

The discovery of triaxial wobbling



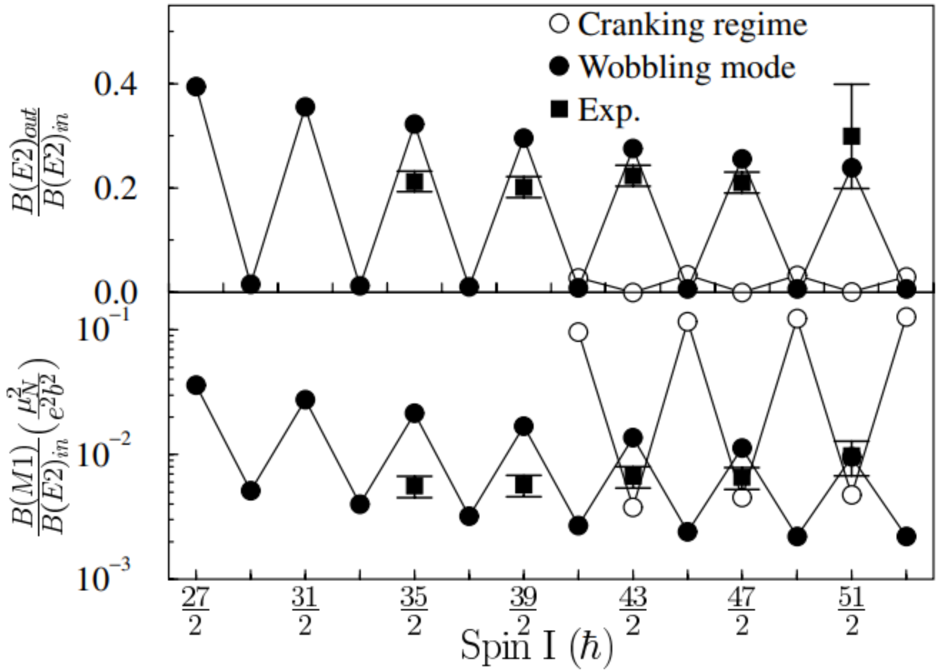
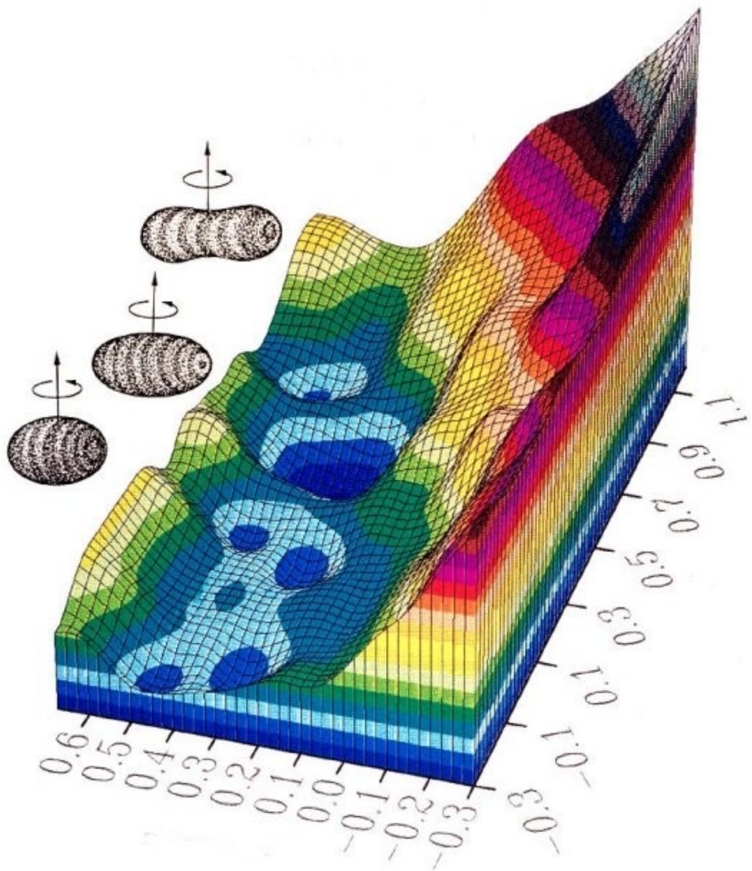


FIG. 5. Experimental and calculated electromagnetic properties of the connecting transitions.

*See Also:
Consequences of broken axial symmetry in heavy nuclei—an overview of the situation in the valley of stability
E. Grosse, A. Junghans and J.N. Wilson, Phys. Scr. 94 014008 (2019)

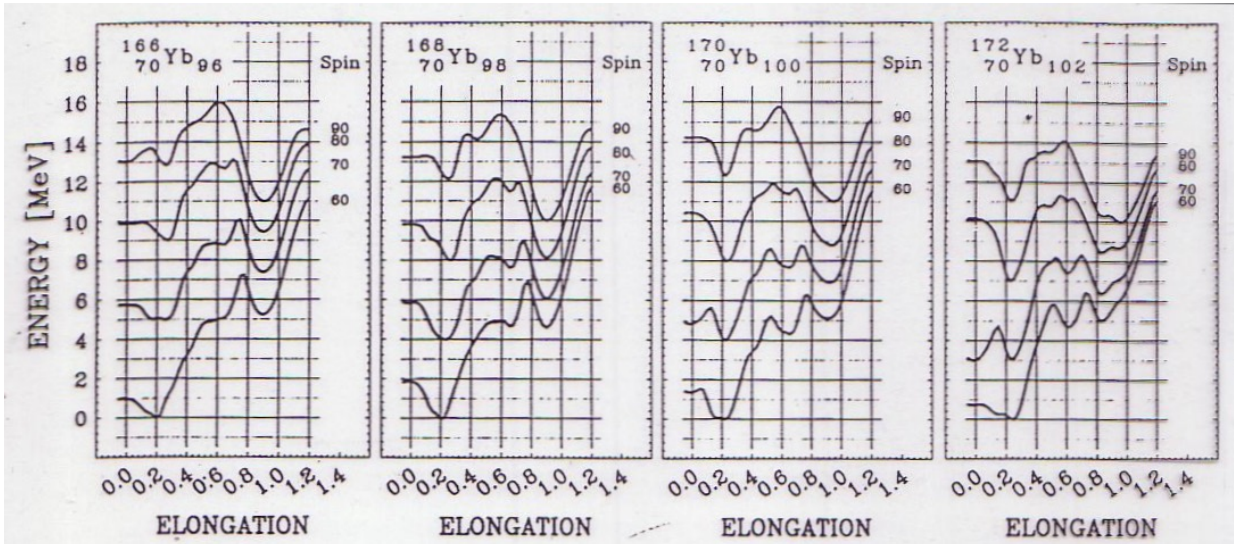
Hyperdeformation

Hyperdeformation: Tantilsing theoretical predictions!



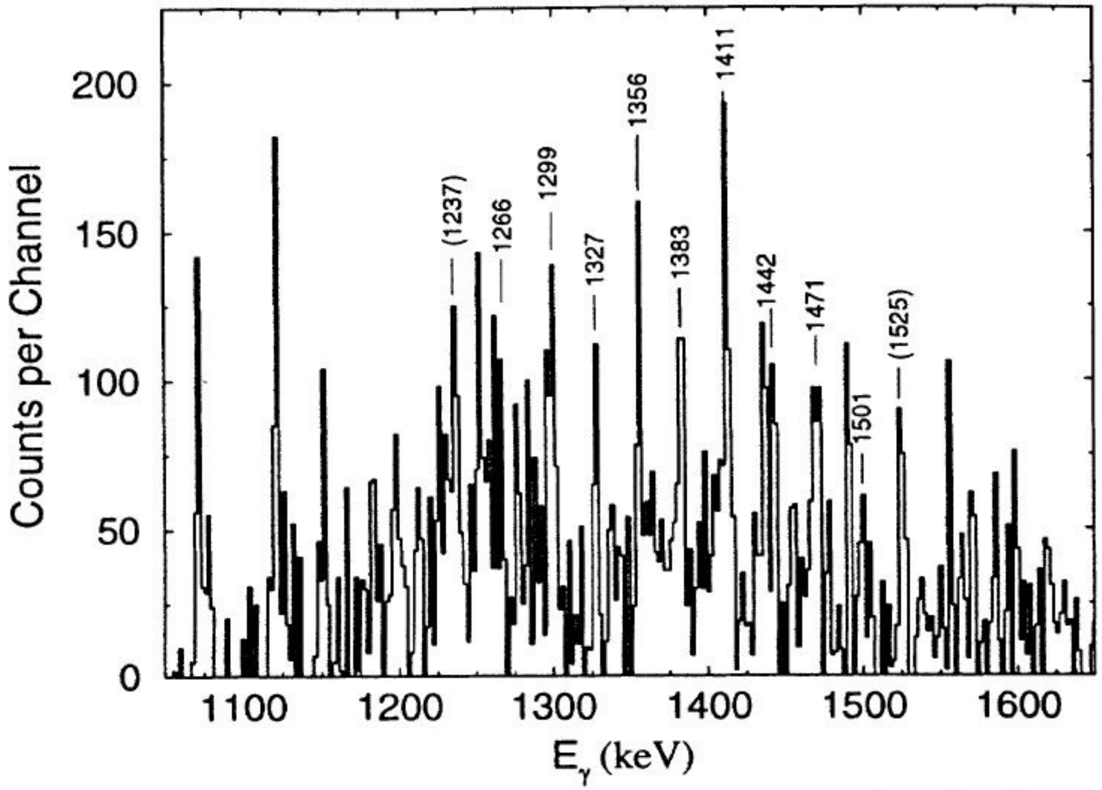
Prediction of hyperdeformed nuclear states at very high spins

J.Dudek, T.Werner, L.L.Riedinger, Phys Lett B 211 252 (1988)



"Discovery" of hyperdeformation (1)

First Evidence for the Hyperdeformed Nuclear Shape at High Angular Momentum, A. Galindo-Uribarri et al. Phys. Rev. Lett. 71 231 (1993)



Hopes for Hyperdeformation

W.R. Phillips, Nature News and Views (1994)

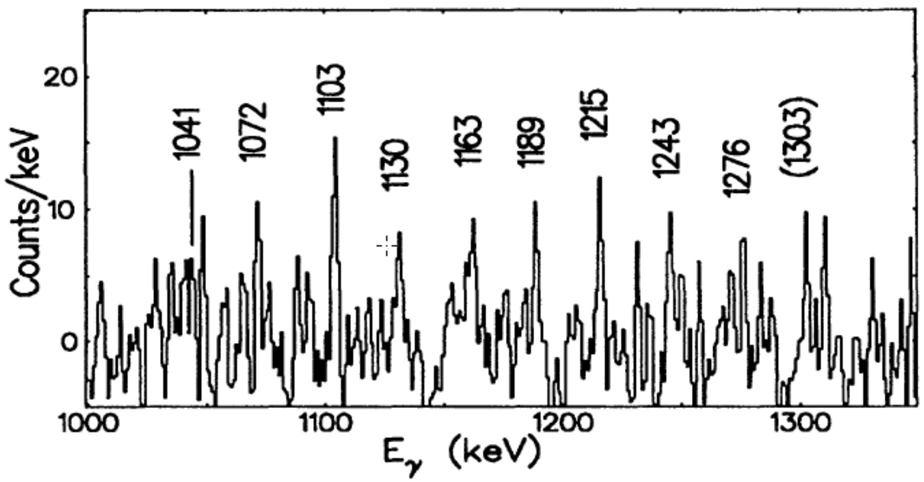
It is too early for the cautious to be sure that this interpretation is correct. The discrete transitions within the hyper-deformed band have not yet been clearly observed, and the pathway from the observation of ridge structures to the deduction of band deformations is strewn with pitfalls. Yet the first indications[7] of superdeformation, later substantiated[3], came from experiments much like this. Those designing further experiments to determine the shapes of nuclei under extreme conditions should be encouraged by the results. □

W. R. Phillips is in the Department of Physics, Nuclear Group, Schuster Laboratory, University of Manchester, Manchester

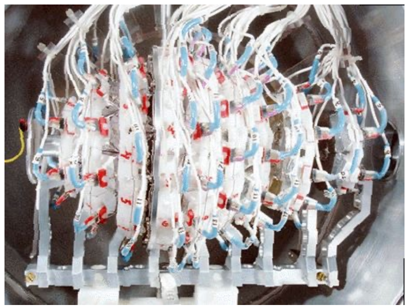
"Discovery" of hyperdeformation (2)

Evidence for hyperdeformation in ^{147}Gd

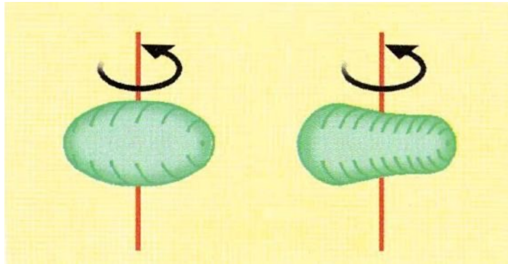
D. Lafosse et al., Phys. Rev. Lett., 74 5186 (1995)



Gammasphere +
Microball (proton-gated)



Gadolinium peanuts

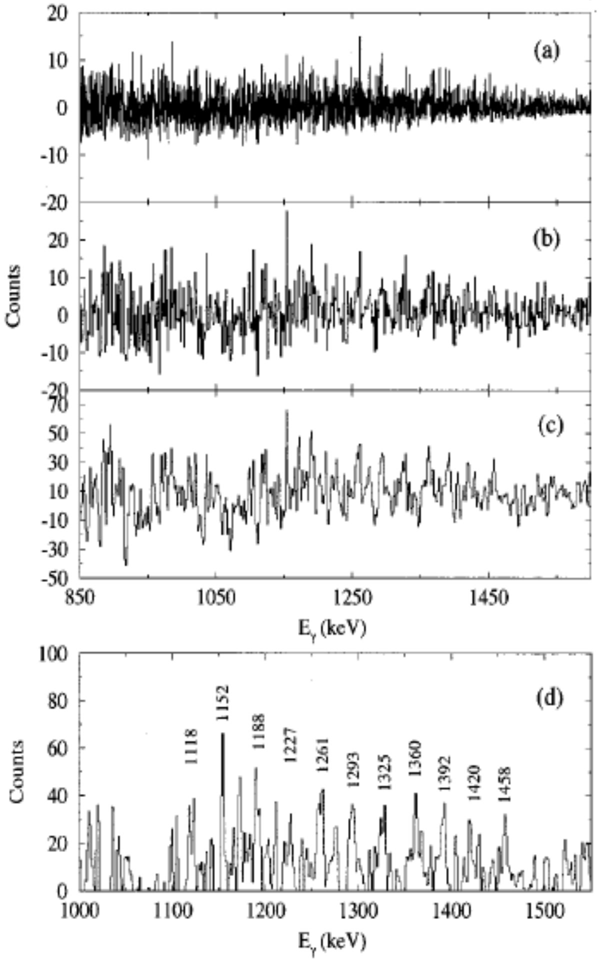


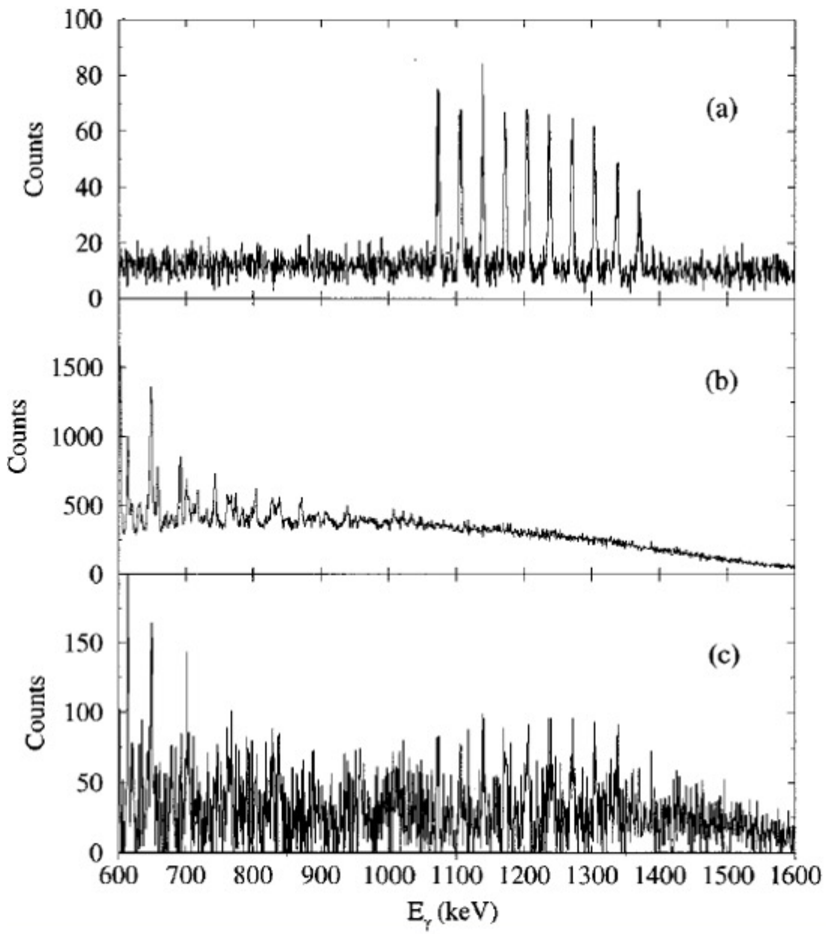
The next few months will see a flurry of activity, as groups in the United States and Europe attempt to answer these questions and show whether these sequences are indeed decays of hyperdeformed, peanut-shaped nuclei. Once again a new generation of powerful spectrometers is opening up new vistas in nuclear structure physics. □

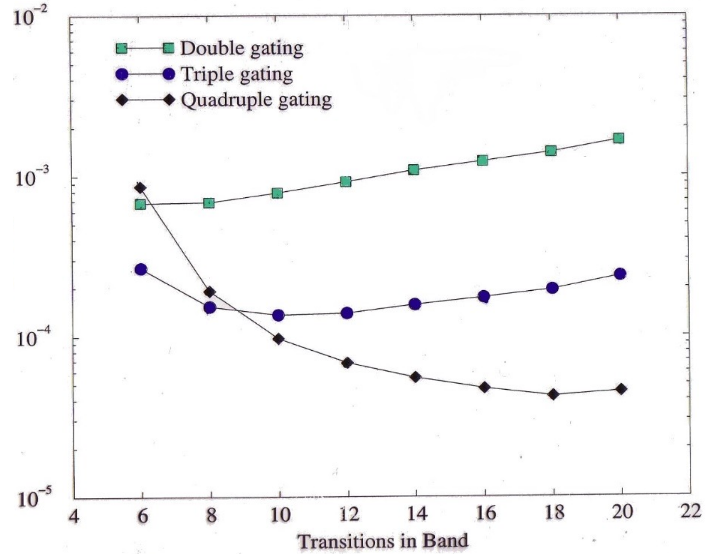
P.J. Twin, Nature News and Views (1995)

Search for hyperdeformation in ^{168}Yb

J.N. Wilson et al. Phys. Rev. C 56 2502 (1997)







It's disappeared ☹

PHYSICAL REVIEW C VOLUME 54, NUMBER 4 OCTOBER 1996

Search for hyperdeformation in ^{146,147}Gd

D. R. LaFosse,[1] D. G. Sarantites,[1] C. Baktash,[2] S. Asztalos,[3] M. J. Brinkman,[2] B. Cederwall,[4] R. M. Clark,[3] M. Devlin,[1] P. Fallon,[3] C. J. Gross,[2] H.-Q. Jin,[2] I. Y. Lee,[3] F. Lerma,[1] A. O. Macchiavelli,[3] R. MacLeod,[3] D. Rudolph,[2] D. W. Stracener,[2] and C.-H. Yu[2]

[1]*Department of Chemistry, Washington University, St. Louis, Missouri 63130*

[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[4]*Royal Institute of Technology, Stockholm, Sweden*

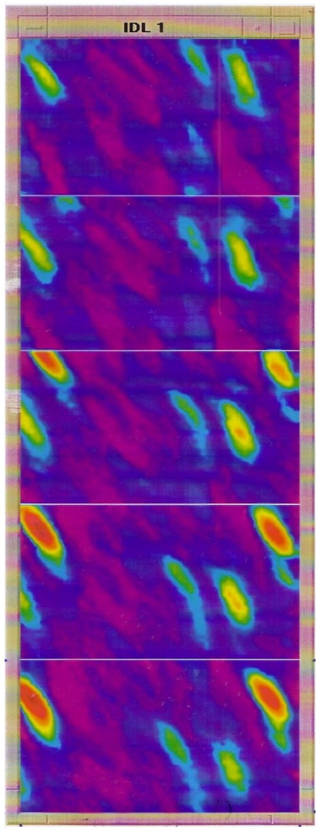
(Received 12 February 1996)

A search was undertaken to look for evidence of hyperdeformation in ^{146,147}Gd. Three experiments employing Gammasphere for gamma-ray detection coupled with the Microball for channel selection via charged particle detection were carried out with increasing detection sensitivity and statistics. No definitive evidence for band structures that could be assigned to hyperdeformation could be found. Candidates previously reported are shown not to have properties consistent with a band structure. [S0556-2813(96)00210-5]

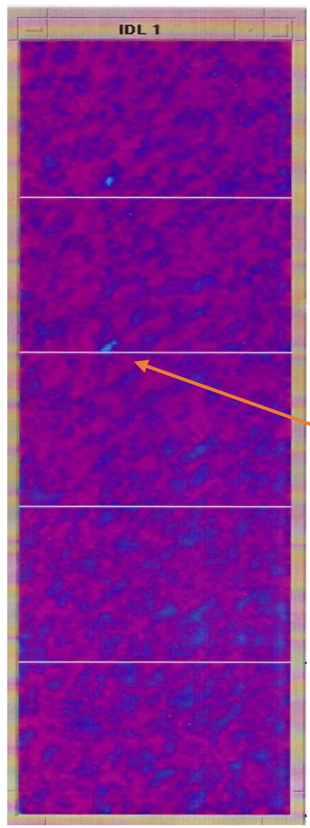
Hyperdeformation search tools

"Bandland" search parameter space visualisation

^{196}Pb (SD)



^{126}Xe (HD)

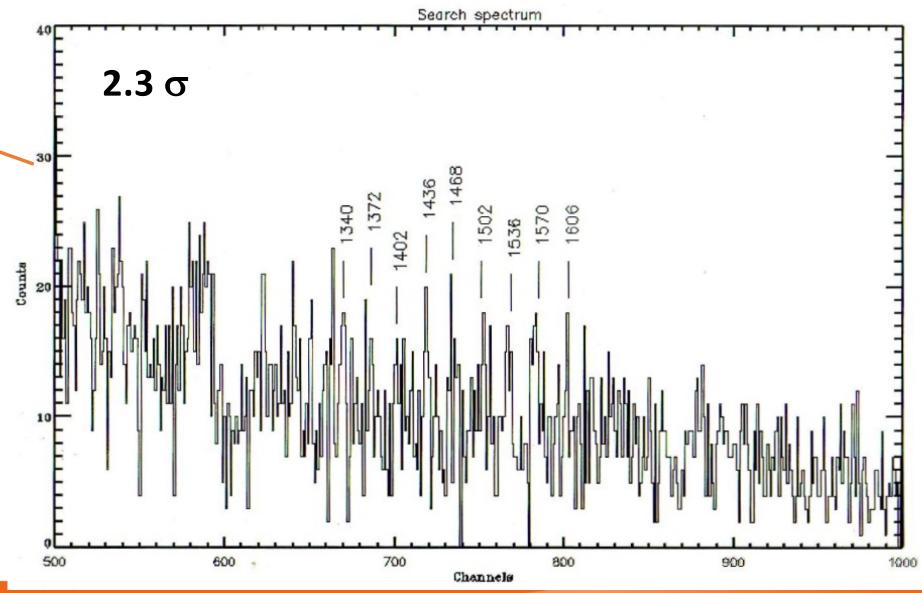


Δ(ΔE)

ΔE

E_0

- ^{48}Ca+^{124}Sn → ^{172}Yb* - Gammasphere (1996)
- ^{64}Ni +^{64}Ni → ^{128}Ba* - Gammasphere (2001)
- ^{48}Ca +^{82}Se → ^{130}Xe* - Euroball (2001)
- ^{50}Ti+^{124}Sn → ^{174}Hf* - Euroball (2001)
- ^{48}Ca+^{68}Zn ^{116}Sn* - Gammasphere (2001)

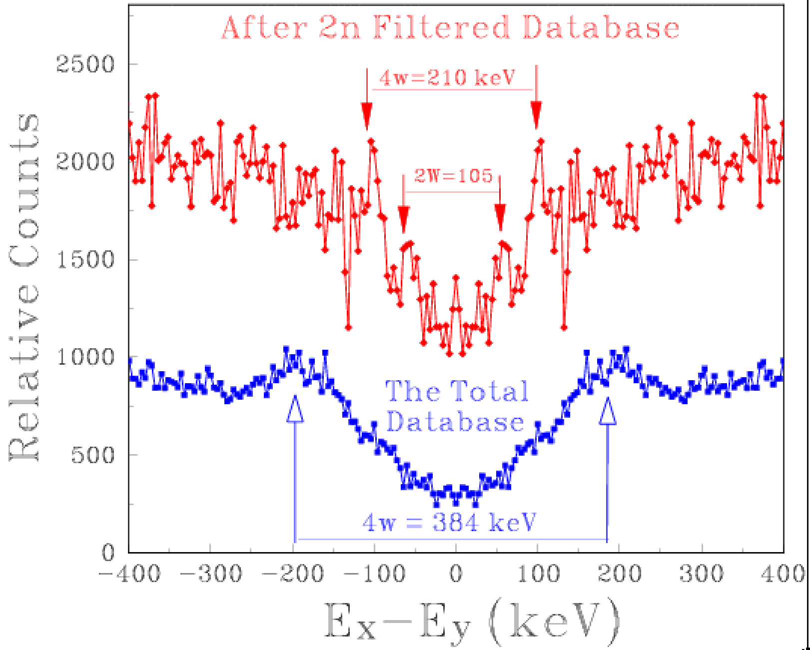


Results of the First Experiment

at Gammasphere in Berkeley

using $^{64}Ni + ^{64}Ni \Rightarrow ^{128}Ba^*$ - 2n

$J^{(2)} \sim 77\ \hbar^2/$ MeV => SD

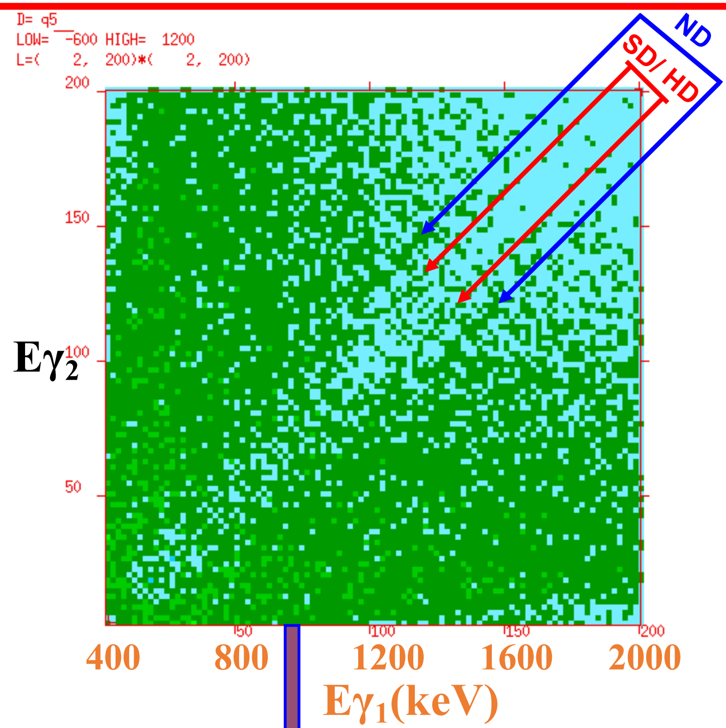


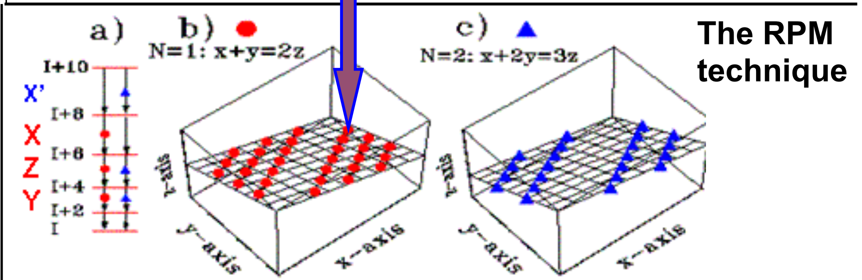
Extracted by Filtering and Rotational Plane Mapping

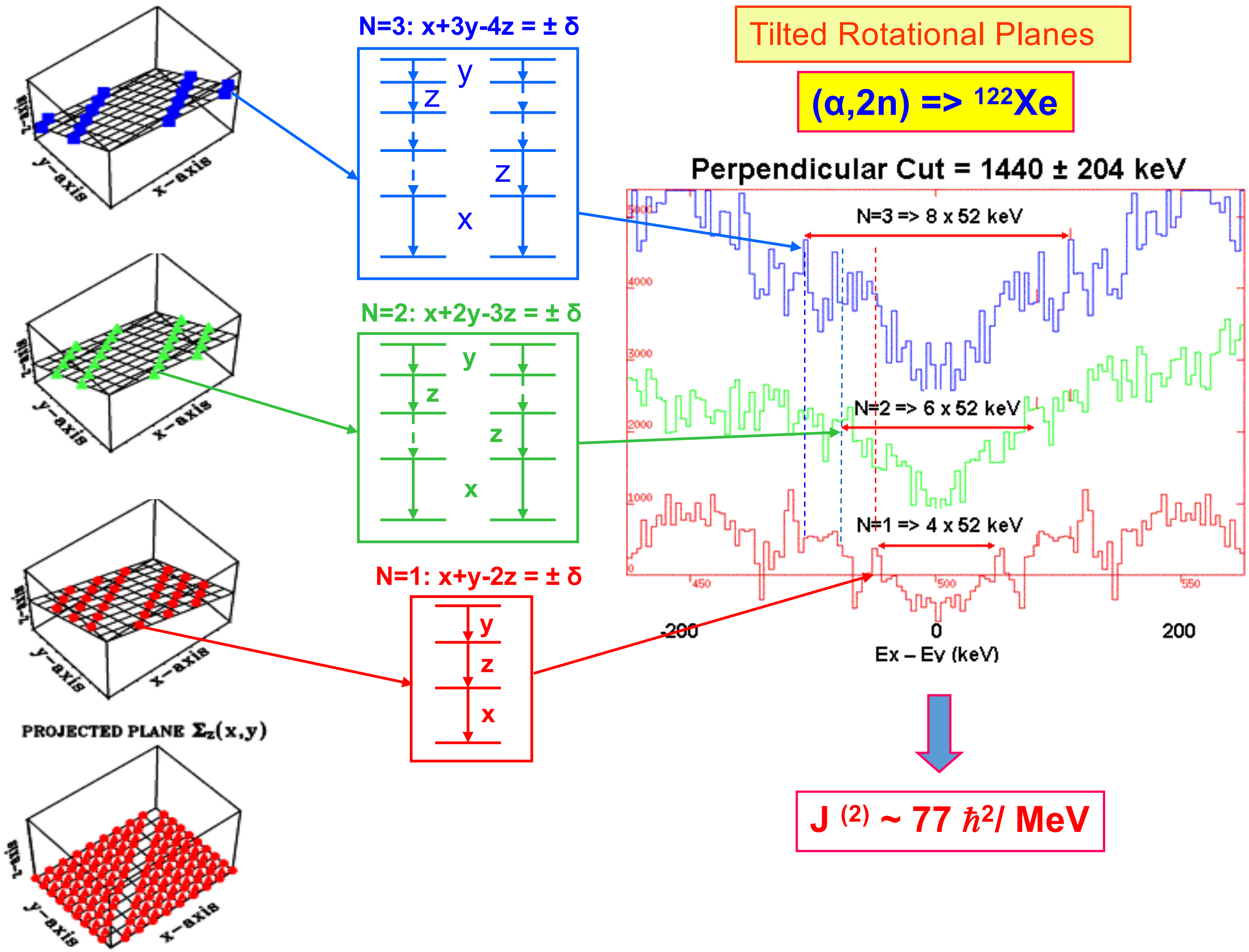
Rotational Plane Mapping (RPM)

N=1, and after 2n filtering and

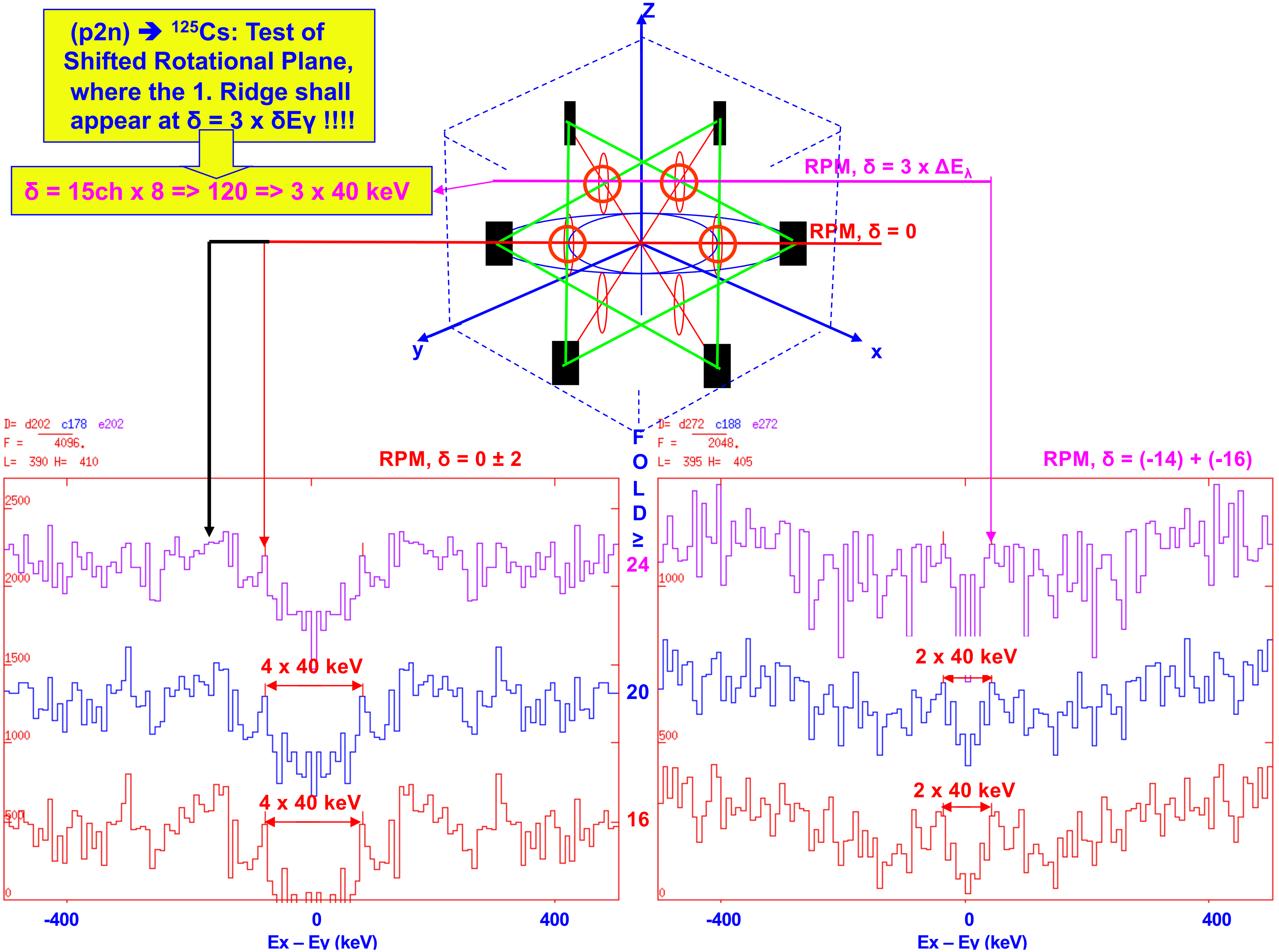
note: => 265 MeV ^{64}Ni beam







Tilted Rotational Planes
(α,2n) => 122Xe
Perpendicular Cut = 1440 ± 204 keV
N=3: x+3y-4z = ± δ
N=2: x+2y-3z = ± δ
N=1: x+y-2z = ± δ
y
z
x
N=3 => 8 x 52 keV
N=2 => 6 x 52 keV
N=1 => 4 x 52 keV
-200
0
200
Ex – Ev (keV)
y-axis
x-axis
PROJECTED PLANE Σz(x,y)
J (2) ~ 77 ℏ2/ MeV

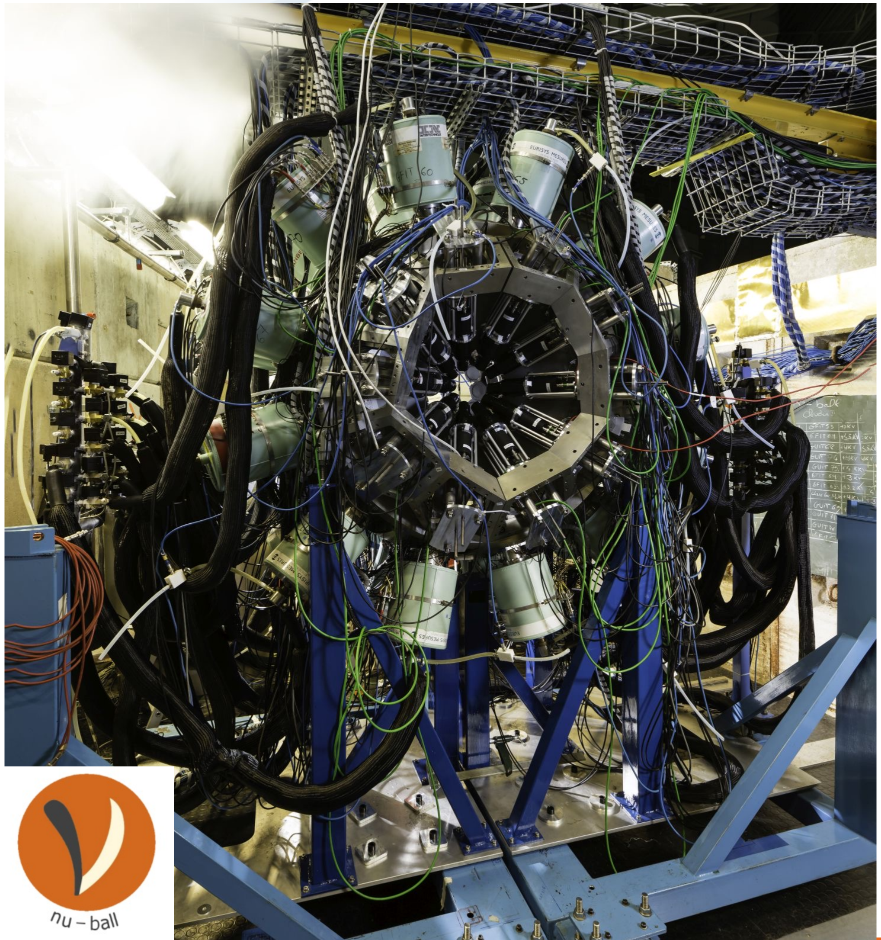

(p2n) ➔ ¹²⁵Cs: Test of Shifted Rotational Plane, where the 1. Ridge shall appear at δ = 3 x δEγ !!!!
δ = 15ch x 8 => 120 => 3 x 40 keV
RPM, δ = 3 x ΔEλ
RPM, δ = 0
z
y
x
RPM, δ = 0 ± 2
RPM, δ = (-14) + (-16)
FOLD ≥
24
20
16
4 x 40 keV
4 x 40 keV
2 x 40 keV
2 x 40 keV
-400
0
400
Ex – Ey (keV)
-400
0
400
Ex – Ey (keV)

Nuclear Fission

Gamma-ray spectroscopy of fission fragments with state-of-the-art techniques
S. Leoni, C. Michelagnoli, J.N. Wilson
Riv. Nuovo Cimento Soc. Ital. Fis. 45, 461 (2022)

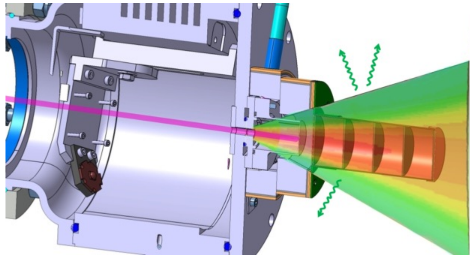
Angular Momentum Generation in Nuclear Fission
J.N. Wilson + the nu-Ball collaboration, Nature 590 566 (2021)

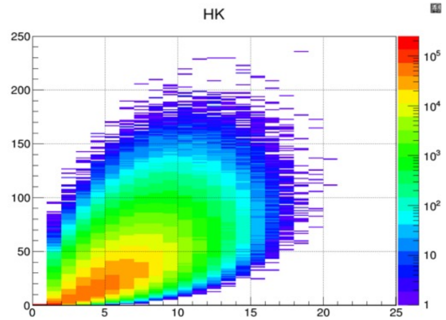
The ν-ball spectrometer @ ALTO



Innovations

- ✓ Hybrid Spectrometer (Ge/BGO/LaBr3) high resolution, high efficiency
- ✓ Coupling with the LICORNE directional neutron source
- ✓ Calorimetry for reaction studies/selection
- ✓ Fully digital, 200 channels, including BGO
- ✓ Modes Triggered or Triggerlesss





ν-ball fission experiments

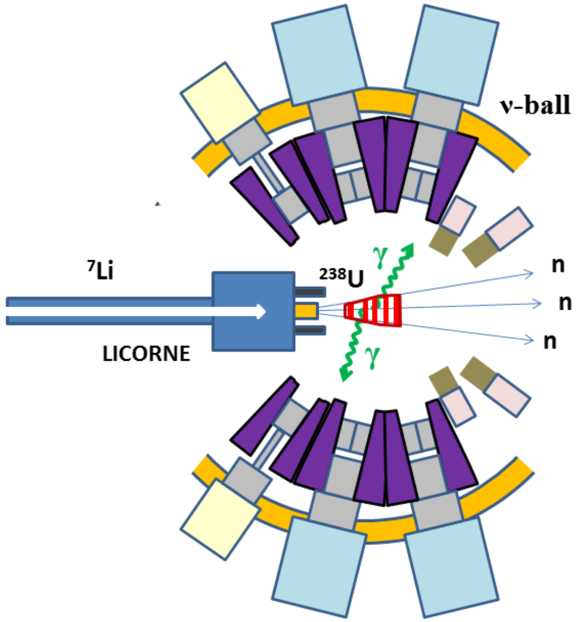
76 researchers from 16 countries
7 weeks of beam time in 2018

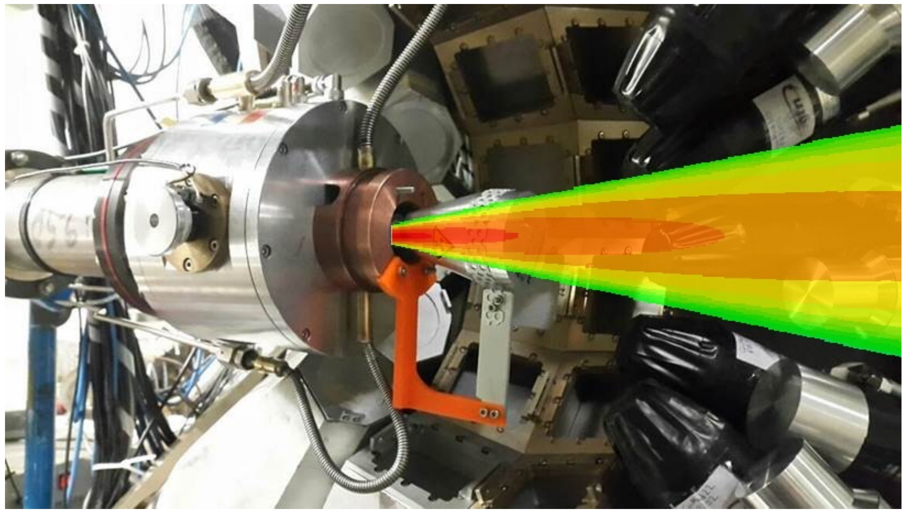
24 Clover Ge + BGO
10 Coaxial Ge + BGO
20 LaBr3
or 36 PARIS phoswich

Radioactive ^{232}Th + ^{238}U targets made at IJC Lab

LICORNE/ν-ball coupling principle

LICORNE: The unique inverse kinematics neutron source of the ALTO facility





Primary beam
(400ns – pulsed)
2×10^{11} /s

^{7}Li (16 MeV)

100 nA

Gas target

H_2

3×10^{20} atoms/cm^2

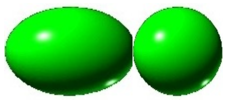
Secondary beam
2×10^{7} /s

1.5 MeV neutrons

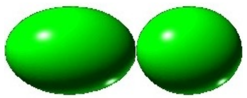
Samples
up to 10^5 fissions/s

^{238}U
^{232}Th ~100 g

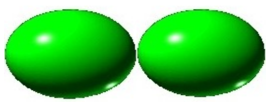
nu-Ball1 results: Gates on the $2^+ \rightarrow 0^+$ transition in ^{140}Xe



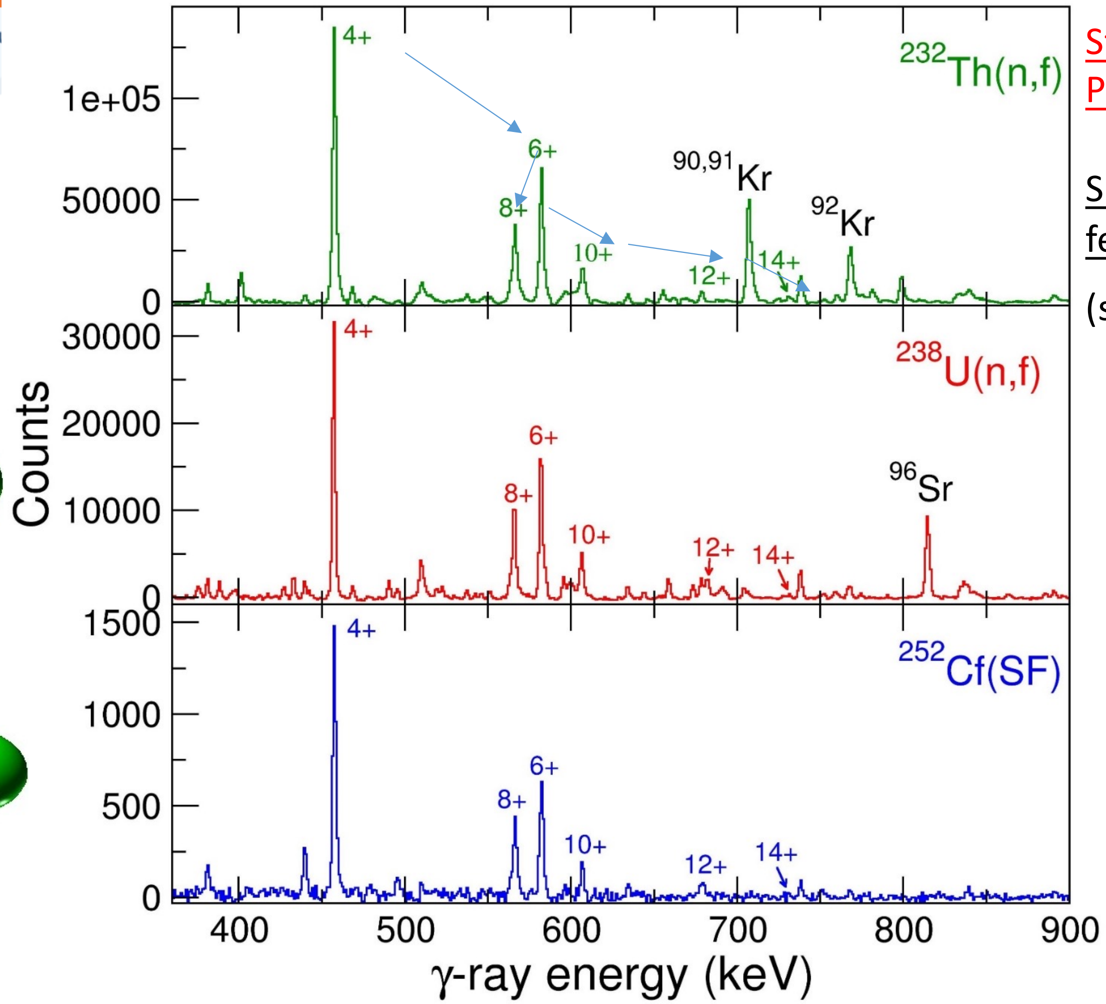
^{140}Xe ^{90}Kr



^{140}Xe ^{96}Ru



^{140}Xe ^{110}Ru



Study of 3 different systems with the same device

Prompt decay only

Separation of prompt fission decay and beta feeding is essential

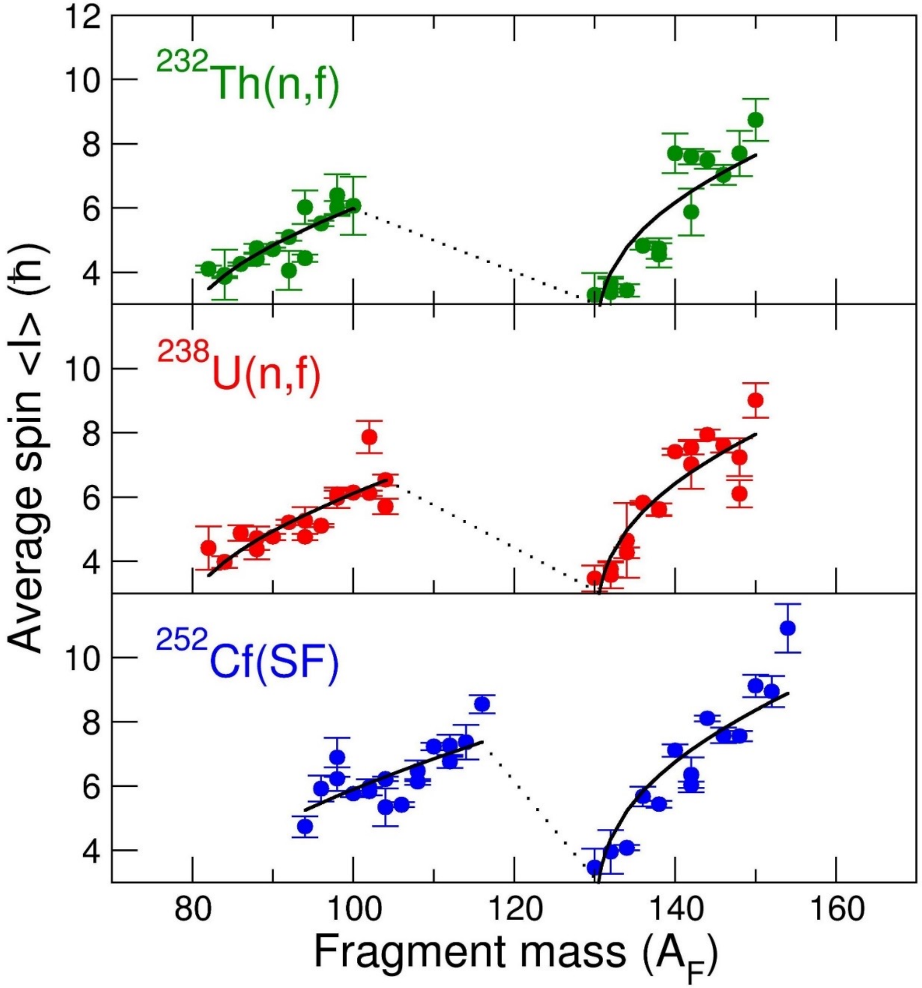
(separation with pulsed neutron beam)

^{140}Xe shows invariant intensity pattern

Does the partner nucleus not matter?

(With ionisation chamber tagging one Fragment in flight and stopping the other)

RESULTS: Average spin <I> vs fragment mass (A)



- 30 even-even nuclei measured for each system
- Definitive saw-tooth patterns
- Slope <u>and</u> curvature. Heavy peak has higher spins

<u>Remarks</u>

- Armbruster, Pleasonton, were **not** wrong!
- No notable dependence on the partner nucleus

e.g.

^{140}Xe + ^{90}Kr
^{140}Xe + ^{96}Sr
^{140}Xe + ^{112}Ru

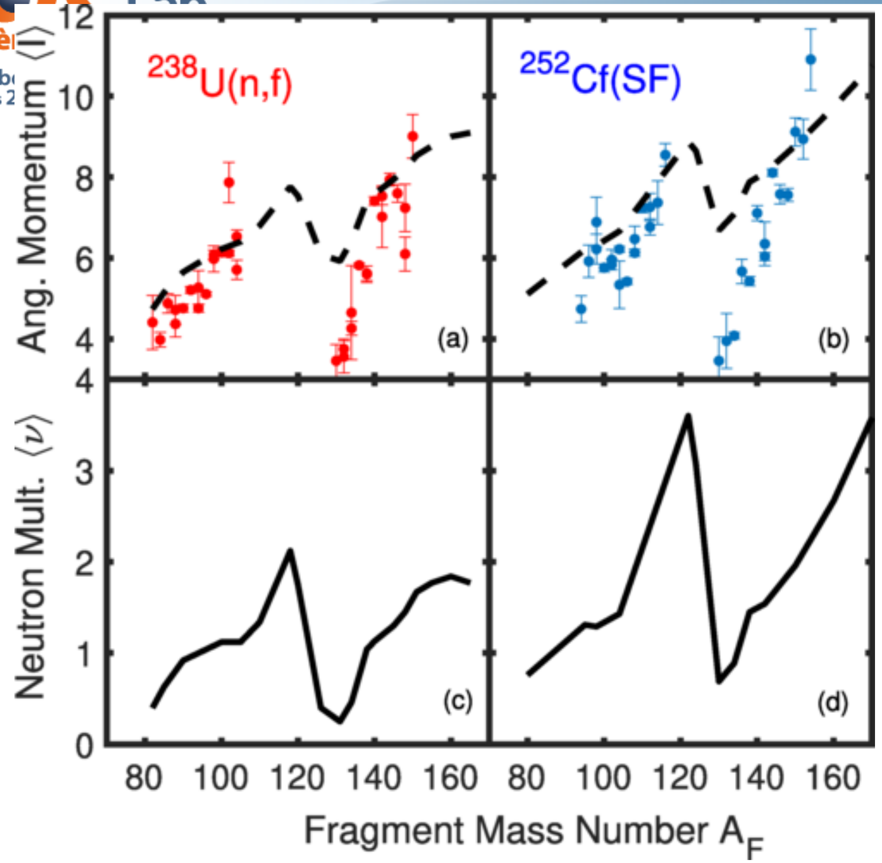
} 25% difference in mass

Each nucleus does not care who it emerged with!

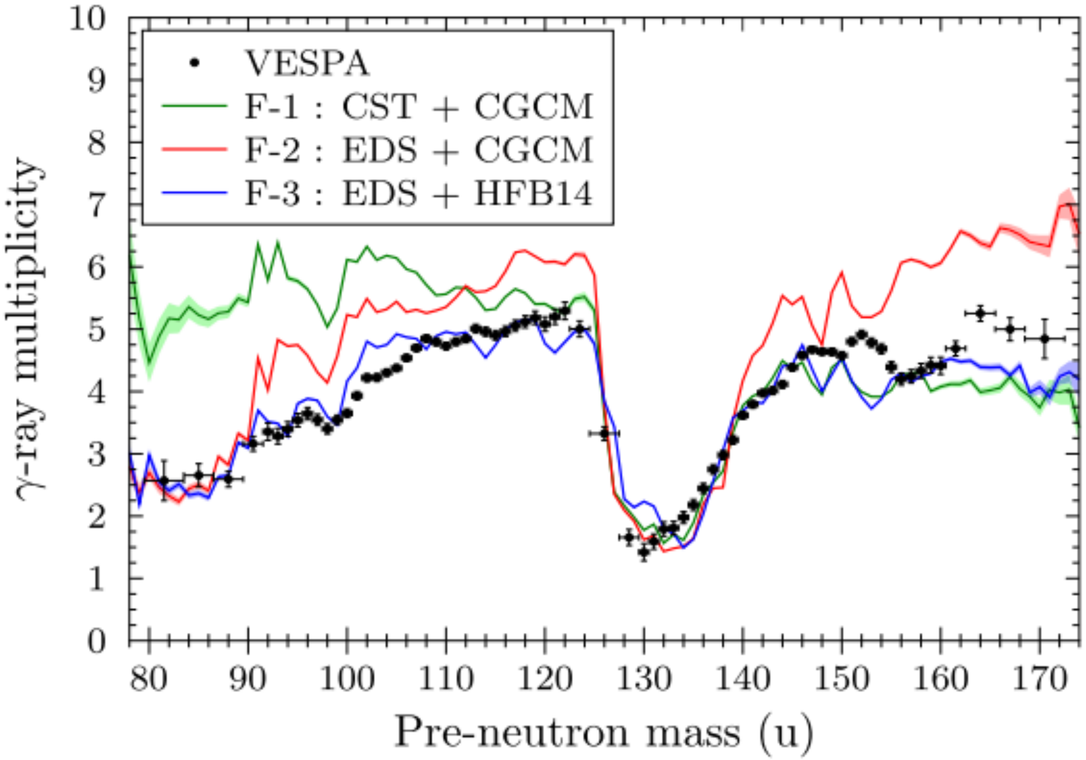
- Certain partners have large asymmetries in <I>

e.g. ^{150}Ce has double the <I> of ^{86}Se

- Highly asymmetric distribution

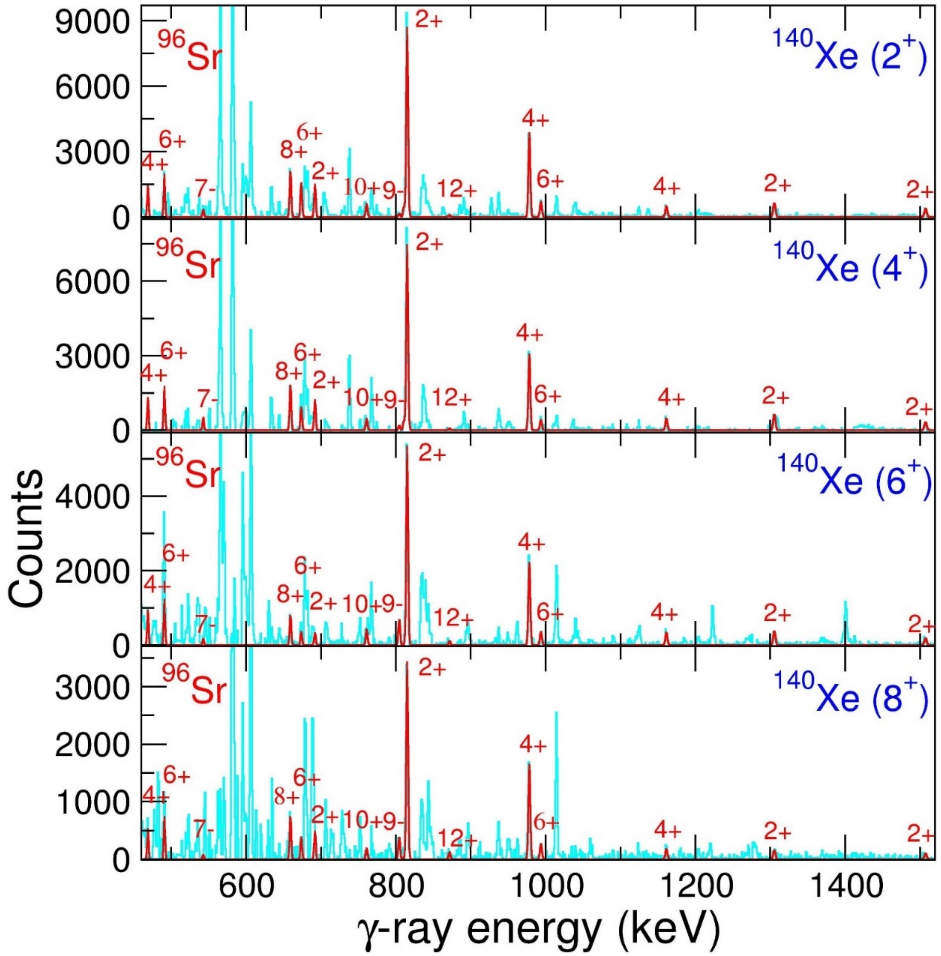


T. Døssing, S. Åberg, M. Albertsson, B. G. Carlsson, and J. Randrup
Phys. Rev. C 109, 034615 (2024)



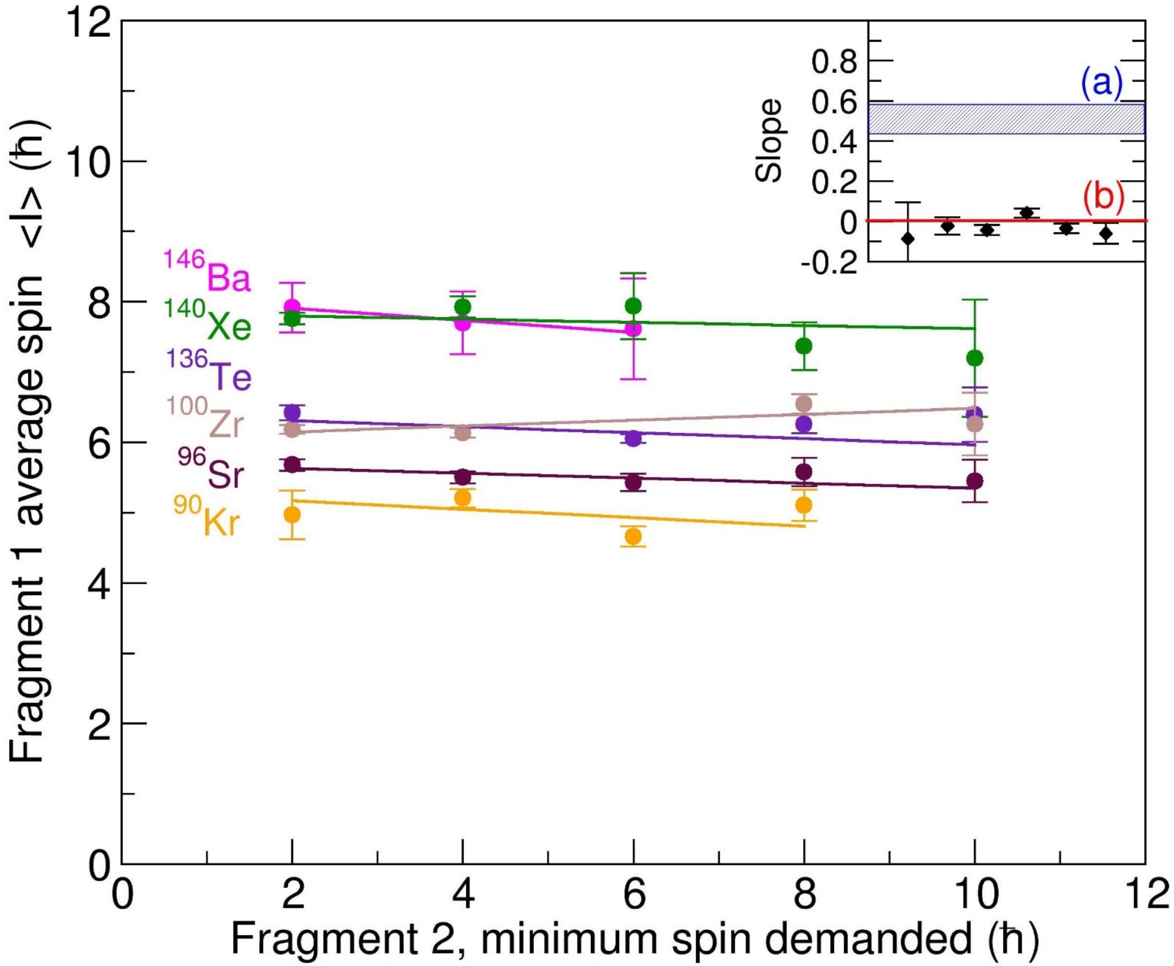
V. Piau et al. Phys. Lett. B 837 137648 February (2023)

^{96}Sr partner γ's with increasing ^{140}Xe spin conditions



Increasing spin demanded in ^{140}Xe

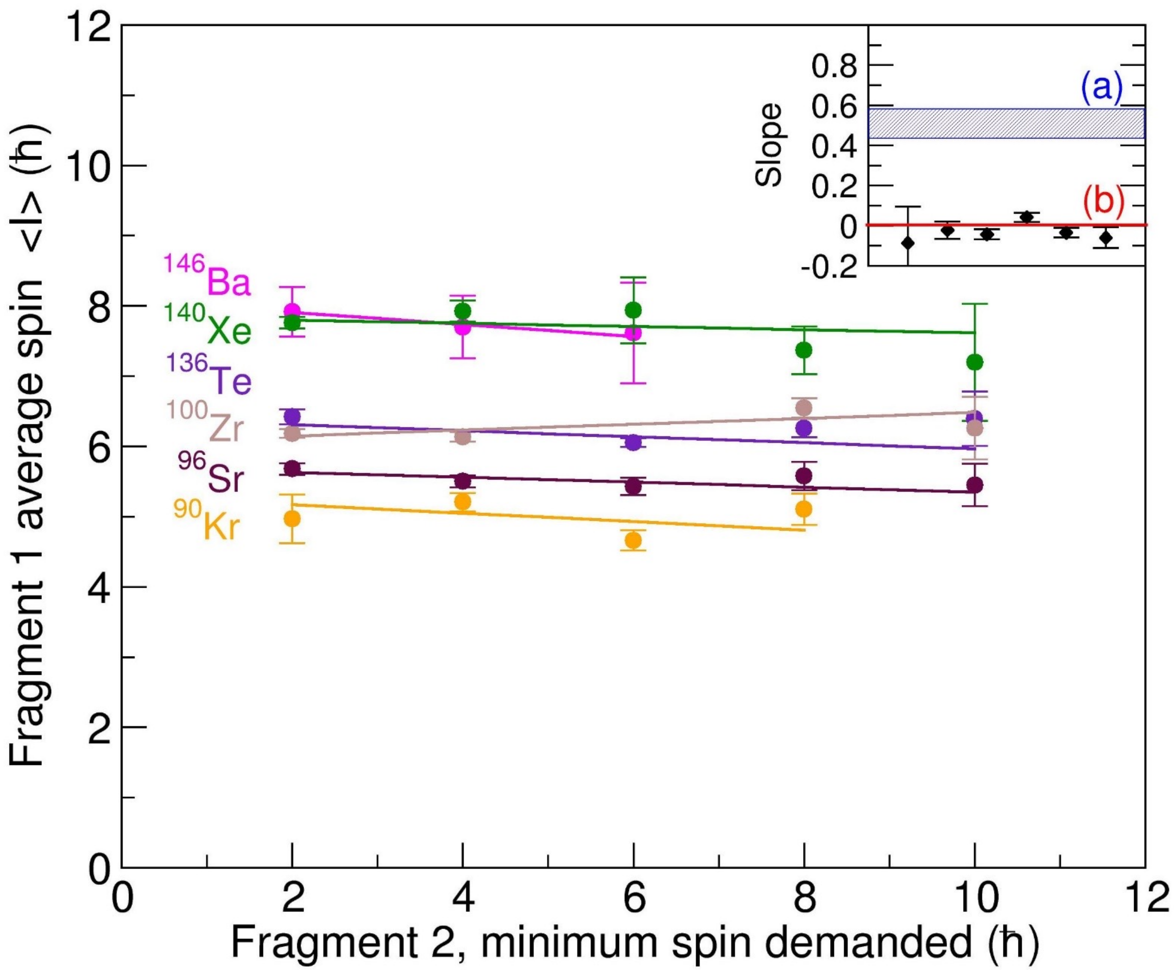
RESULTS: Correlation between fragment spins



Correlated spins (Pre-scission)

Uncorrelated spins

Correlation between fission fragment spin magnitudes



Correlated spins (Pre-scission)

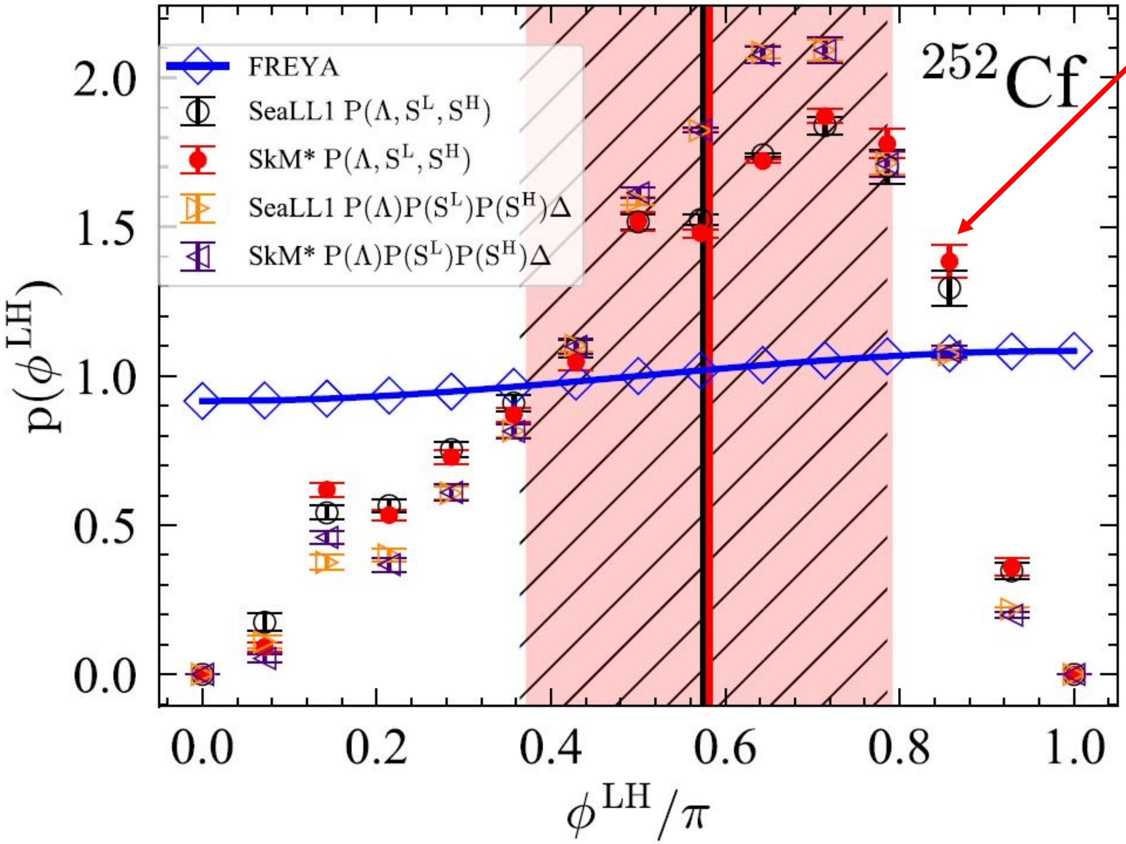
Uncorrelated spins

$$\vec{S}_1 + \vec{S}_2 + \vec{S}_o = 0$$

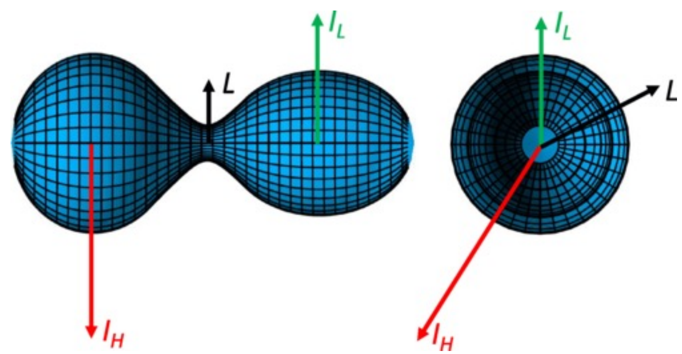
J.N. Wilson et al. Nature 590 566 (2021)

Correlation between the fragment spin *directions?*

TDDFT, A. Bulgac, I. Abdurrahman, K. Godbey, and I. Stetcu, Phys. Rev. Lett. 128, 022501 (2022)



J. Randrup and R. Vogt, Phys. Rev. Lett.127, 062502(2021)



Theoretical predictions strongly disagree

<u>However, directional correlations can be determined by experiment!</u>

The nu-Ball2 workshop, Milano, July (2024)

IJC Lab, CEA DAM
Subatech, CENBG, IPHC,
GANIL, LPC Caen

University of Milano
INFN Legnaro

IFJ-PAN Krakow
University of Warsaw

University of Oslo

JRC-Geel
Leuven

University of Surrey, NPL
University of Manchester

TU Darmstadt
IFK- Koln

University of Novi Sad

University of Madrid
IFIC Valencia

ELI-NP, Bucharest

University of Sofia

Riken

Silvia Gianluca Franco