Angular Momentum Generation in Nuclear Fission

RESANET Colloqium Seminar

J.N. Wilson, IJC Lab

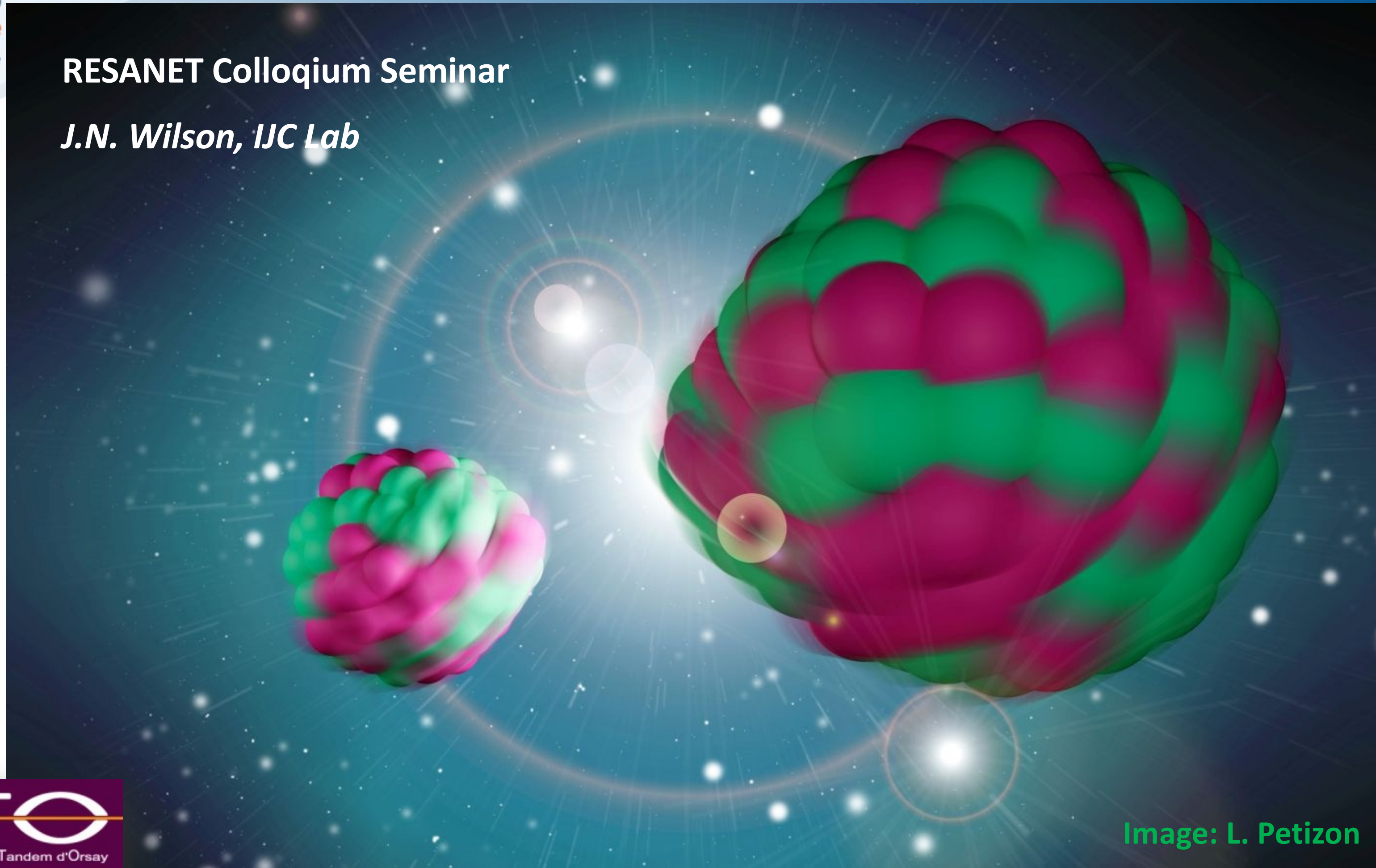
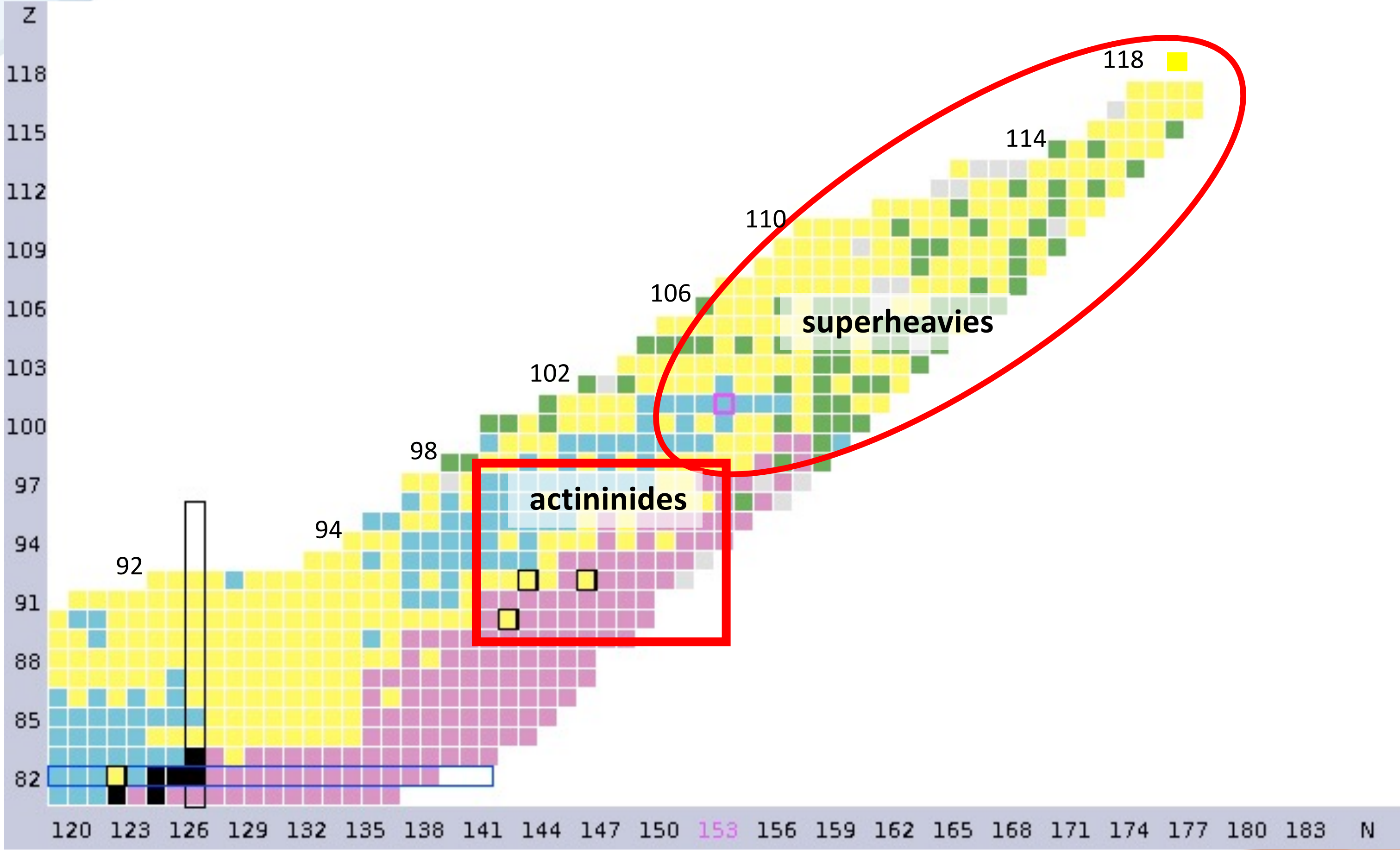


Image: L. Petizon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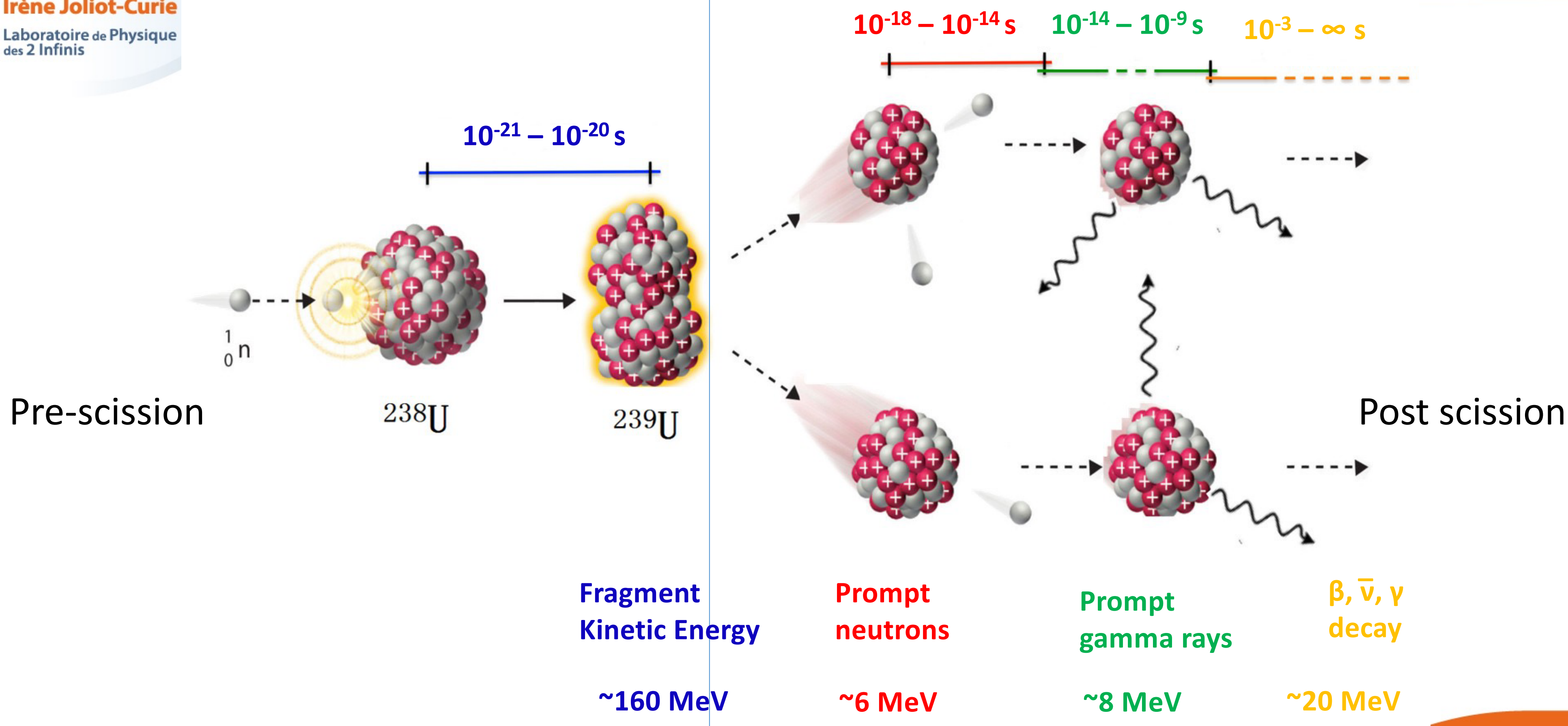
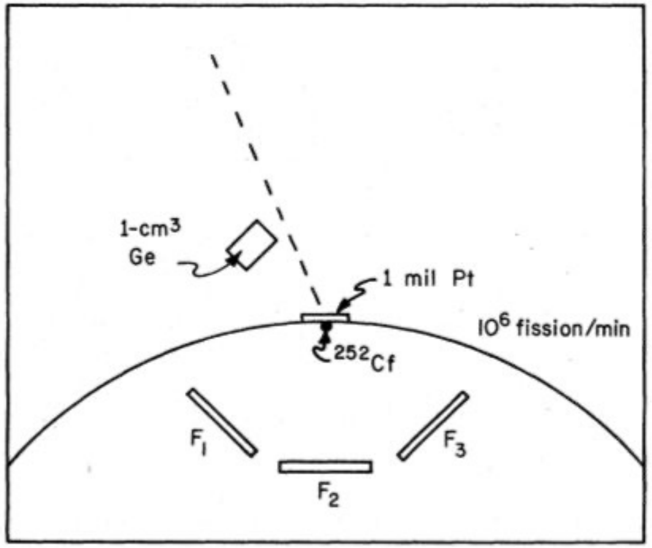
The de-excitation process in fission

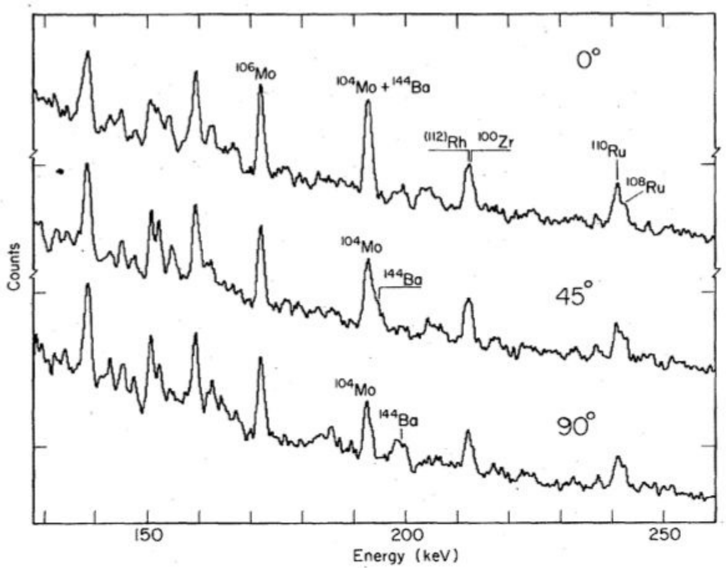


Fission fragments emerge spinning!

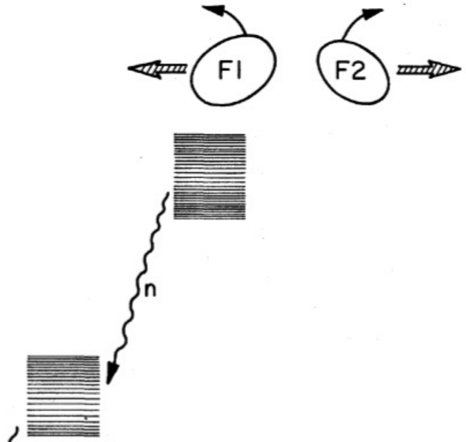
J.B. Wilhelmy et al.
Phys. Rev. C 5 2041 (1972)

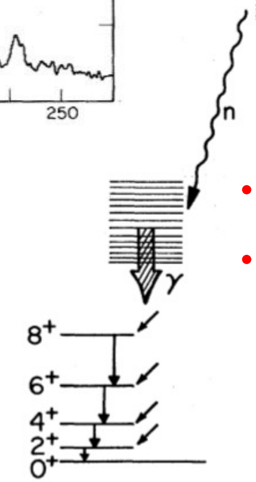
Experimental setup





Gamma-ray spectra





Conclusions

- Average spin is 7 ± 2 hbar
- Angular momentum must be oriented in a plane perpendicular to the fission axis

Theoretical explanations

Pre Scission Collective Vibration Theories

Rasmussen (1969) Bending. Di-nuclear system. Thermal excitations.
Moretto (1989) Bending, Wriggling, Twisting, Tilting. Semi-classical theory. Thermal excitations.
Misicu (1999) Bending, Coupled oscillators. Quantum fluctuations.
Shneidman (2002) Bending. Di-nuclear system. Quantum fluctuations.
Gönnenwein (2007) Bending, Wriggling. Quantum fluctuations.

Post Scission Theories

Hoffman (1964) Coulomb forces.
Mikhailov (1999) Orientation pumping, coupled deformed fragments. Equal spins.
Bonneau (2007) Coupled deformed fragments. Quantum fluctuations and thermal excitations.
Bertsch (2019) Microscopic theory: Energy density functionals (Gogny D1S).

Pre-scission modes theory: Bending

Rasmussen et al. (1969)

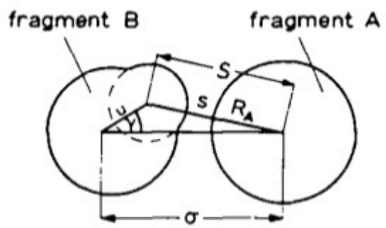


Fig. 3. Molecular model diagram of the compound nucleus.

Shneidman et al. (2002)

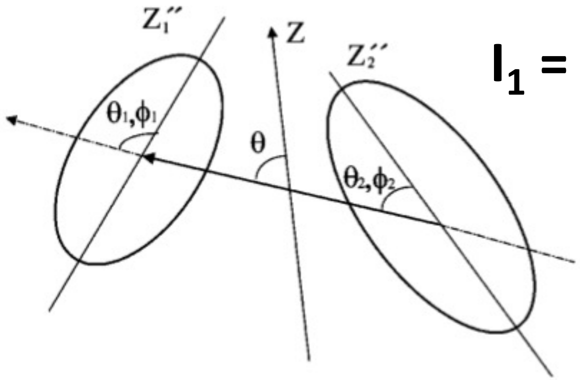


FIG. 1. Schematic picture and definitions of various coordinates of the DNS configuration.

"Bending"

$$I_1 = J_1\omega_1 \qquad I_2 = J_2\omega_2$$

$$\boxed{J_1\omega_1 = -J_2\omega_2}$$

- Equal spins
- Symmetric spin distribution vs fragment mass

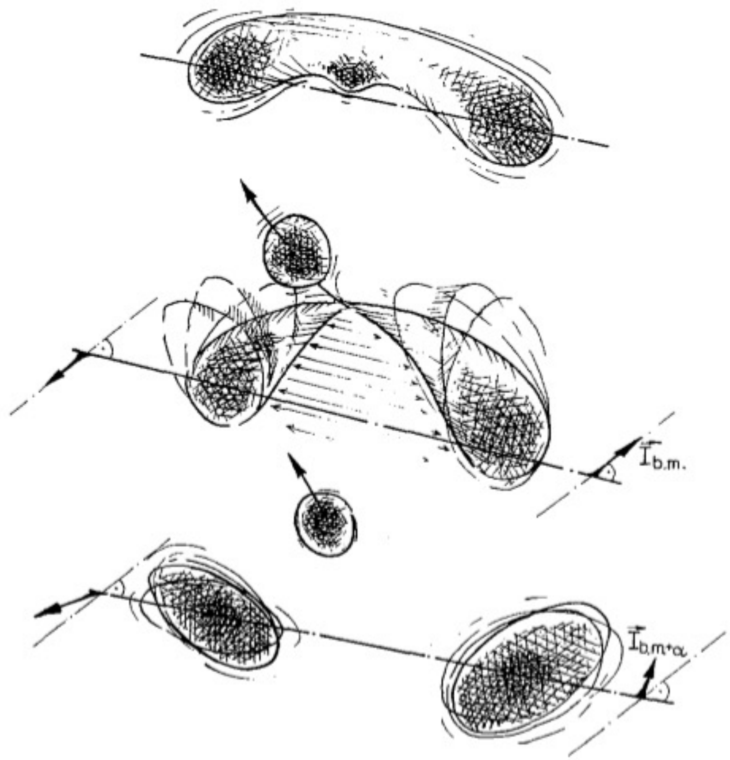


Fig. 11. Artists' view of evolution of spontaneous ternary fission

Pilz et al. (1991)

Previous experimental approaches

P. Armbruster et al. Zeitschrift für Naturforschung A26, 512 (1971)

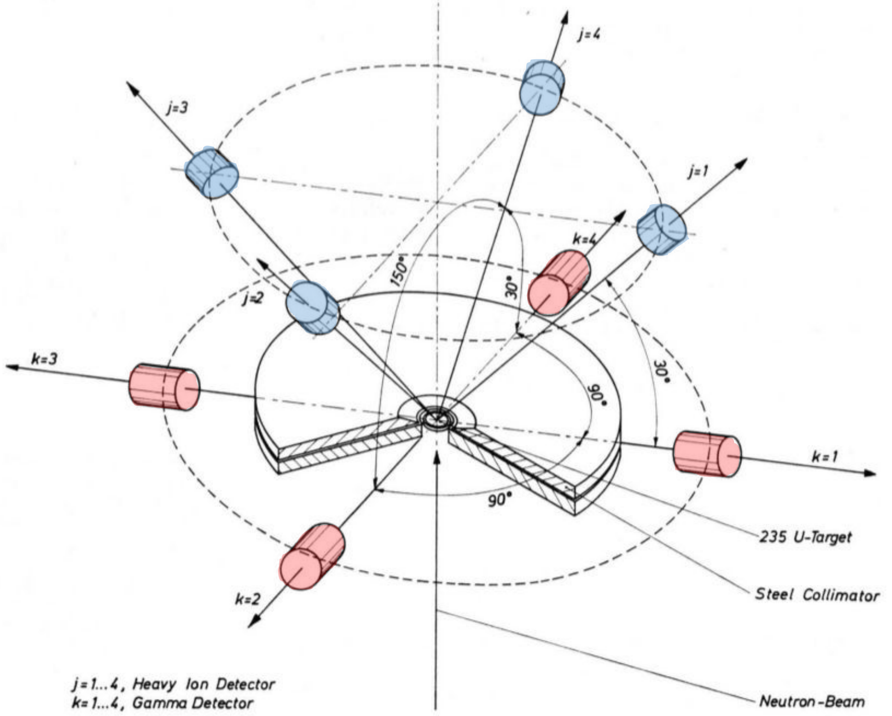
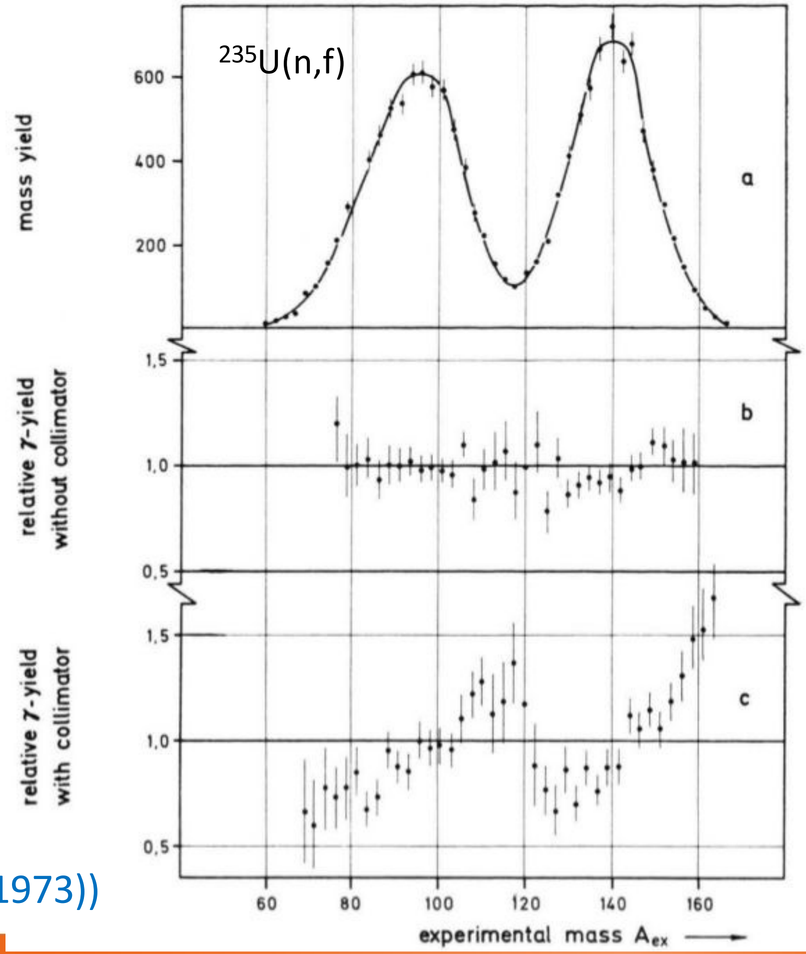


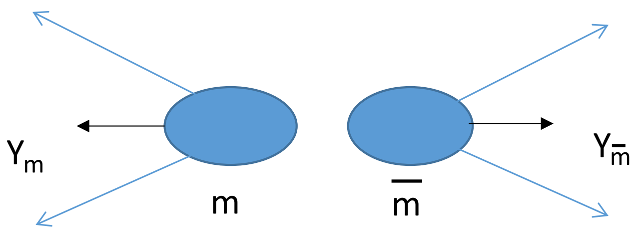
Fig. 1. Detector arrangement.

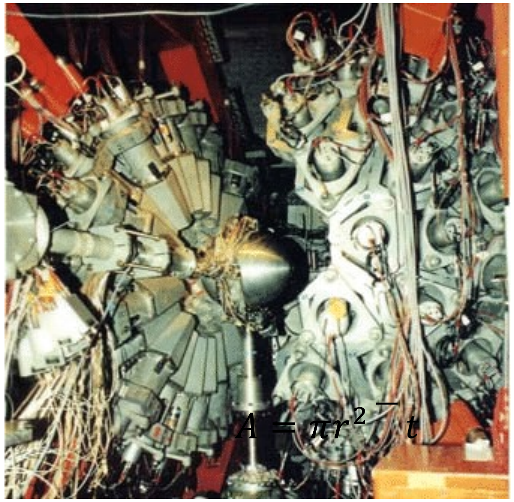


(Also F. Pleasonton, Nucl. Phys. A213 413 (1973))

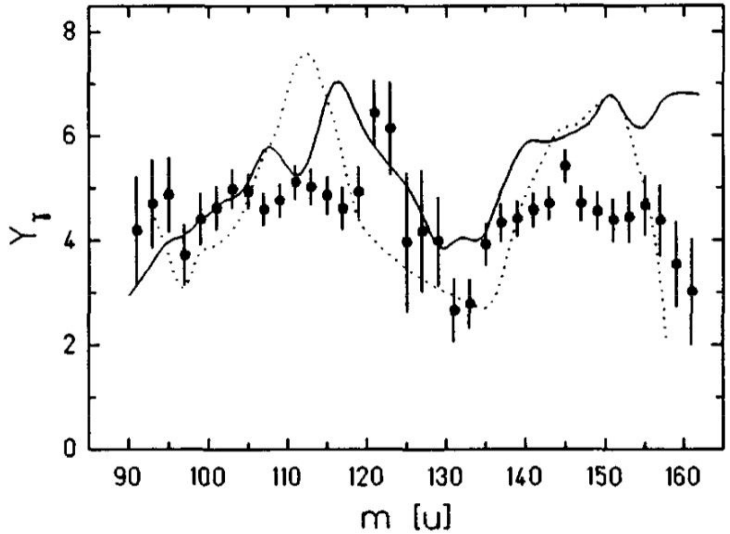
Gamma yield vs mass from exploiting Doppler shifts

P. Gassel et al. Nuc. Phys. A502 315 (1989)





Darmstadt-Heidelberg crystal ball
164 NaI + ^{252}Cf directional ionisation chamber



The γ-yield of the individual fragments is then calculated as

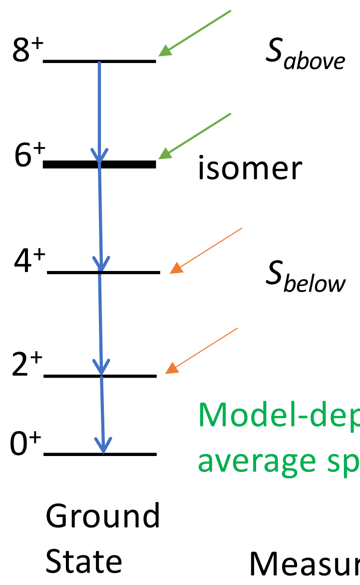
$$Y_\gamma(m) = \frac{Y_m(1+2\beta_{\overline{m}}) - Y_{\overline{m}}(1-2\beta_{\overline{m}})}{4(\beta_m + \beta_{\overline{m}})}$$

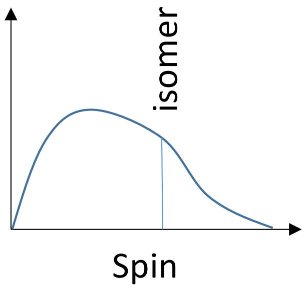
where m and $\overline{m}$ are corresponding fragments, Y_m and $Y_{\overline{m}}$ are the measured γ-yields in the narrow cone about the direction of the fragments, and $\beta_m, \beta_{\overline{m}}$ are the mean projections of the fragment velocity on the direction of the γ in that cone.

Conclusion
Previous saw-tooth patterns must be **wrong** because of time cuts

Estimation of <I> from isomeric yield ratios (IYR)

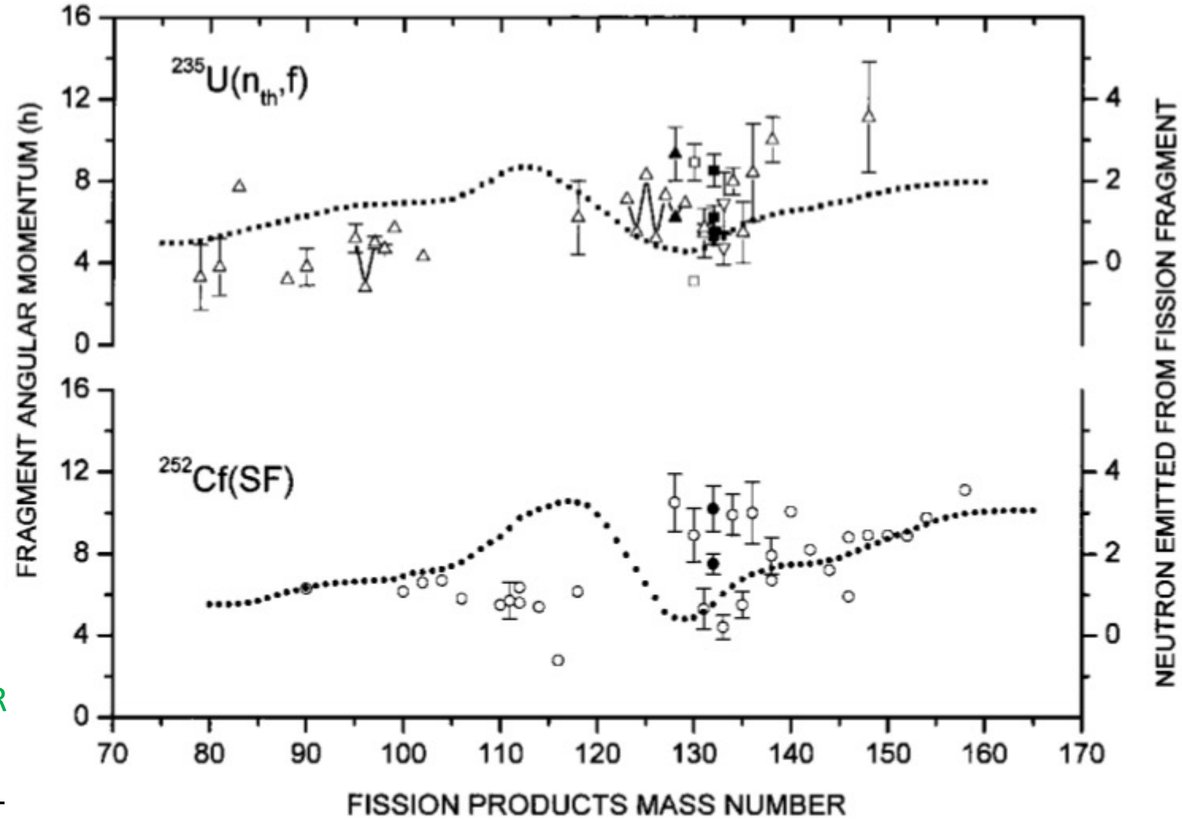
H. Naik et al. Phys. Rev. C71 014304 (2005)



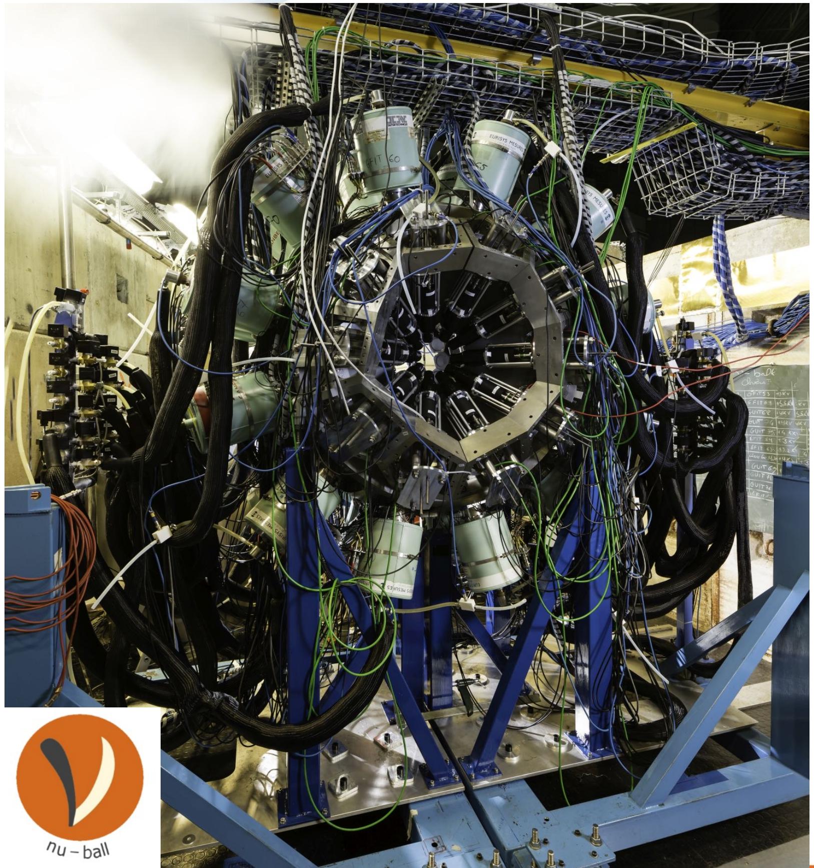


Model-dependent calculation of the average spin which reproduces the IYR

Measured $IYR = \frac{S_{above}}{S_{above} + S_{below}}$

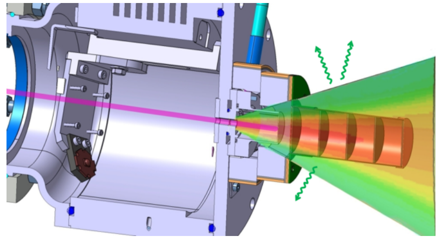


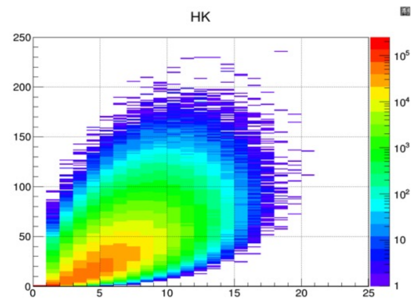
The ν-ball spectrometer @ ALTO



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

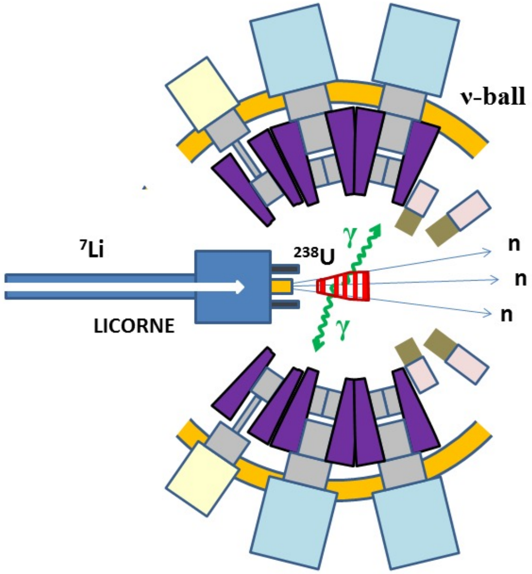
76 researchers from 16 countries
7 weeks of beam time in 2018

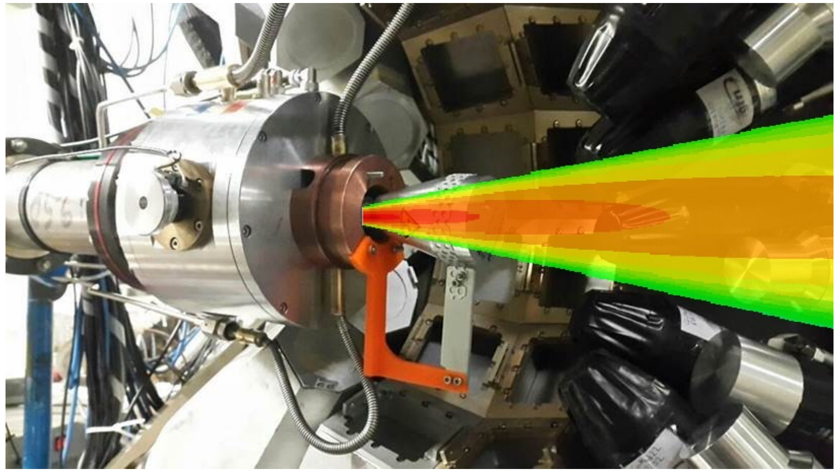
24 Clover Ge + BGO
10 Coaxial Ge + BGO
20 LaBr3
or 36 PARIS phoswich

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 x 10^{11} /s

^{7}Li (16 MeV)

100 nA

Gas target

H_2

3 x 10^{20} atoms/cm^2

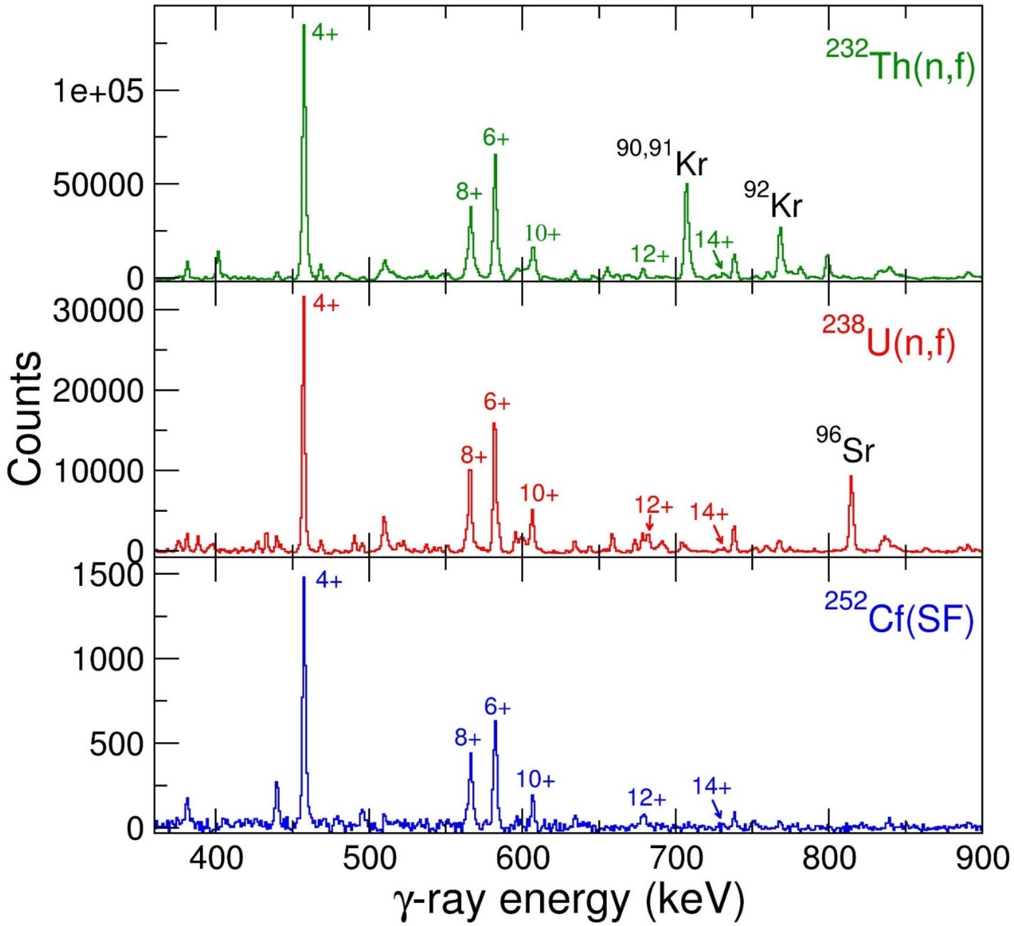
Secondary beam
2 x 10^{7} /s

1.5 MeV neutrons

Samples
up to 10^{5} fissions/s

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

Gate on the $2^+ \rightarrow 0^+$ transition in ^{140}Xe



Prompt decay only

Separation of prompt fission decay and beta feeding is essential

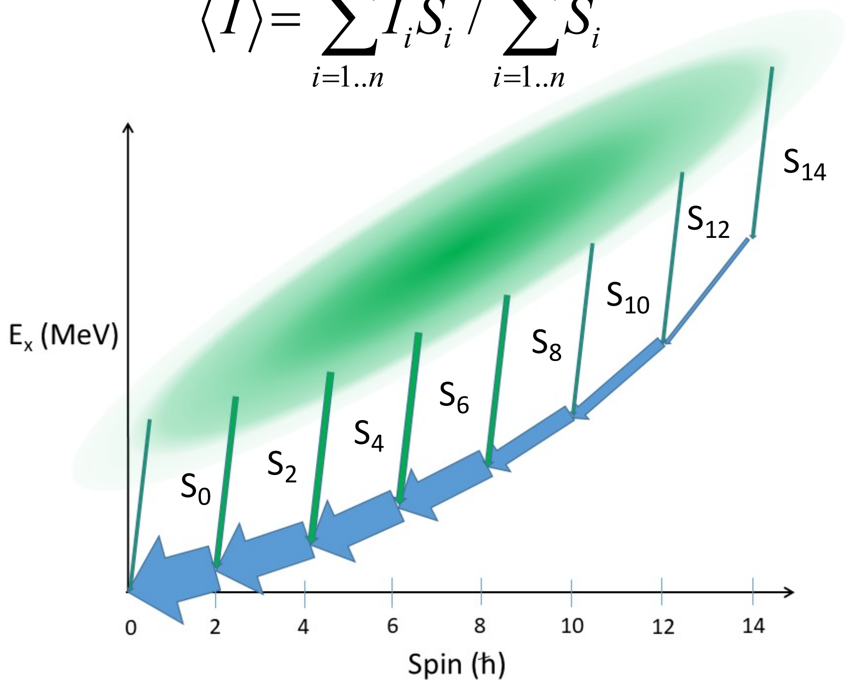
(with pulsed neutron beam)

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

The Manchester Spin Method (MSM)

Y. Abdelrahman et al.
Phys. Lett. B 199 4 504
(1987)

$$\langle I \rangle = \sum_{i=1..n} I_i S_i \Big/ \sum_{i=1..n} S_i$$



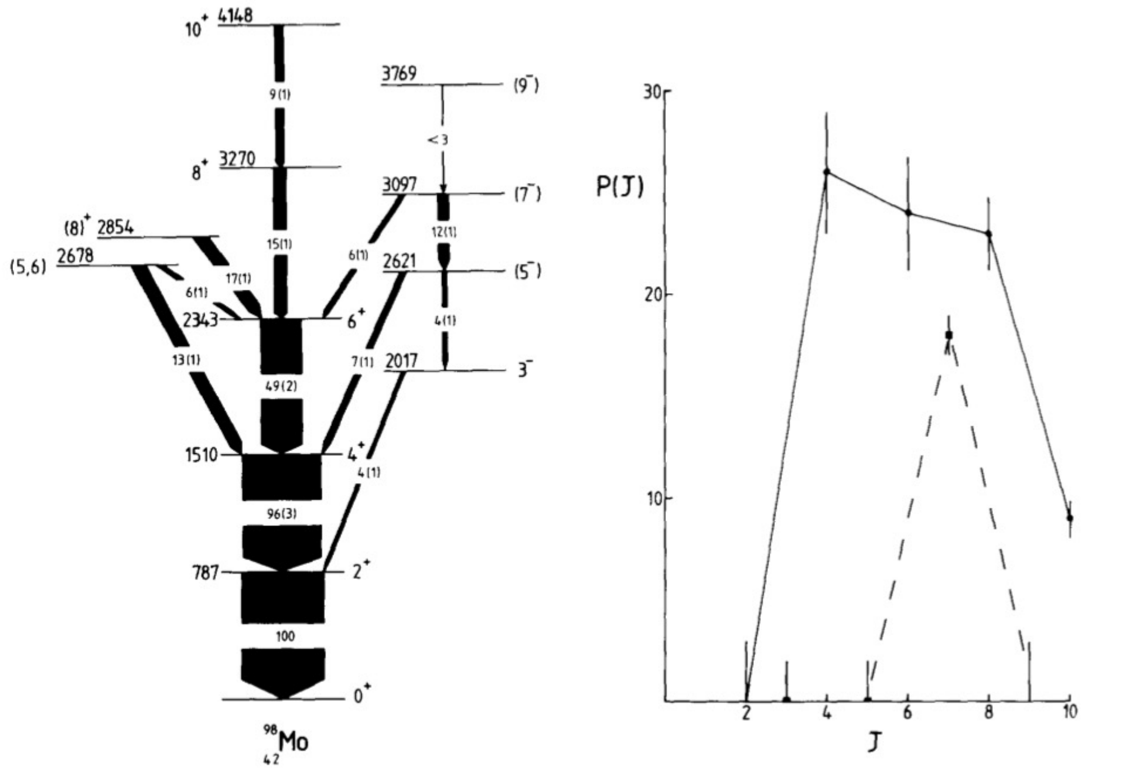
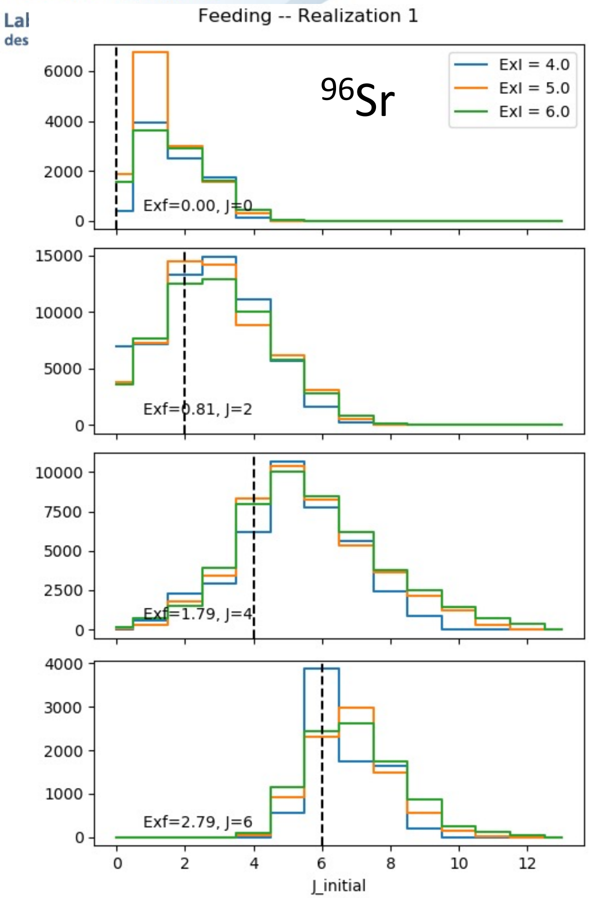
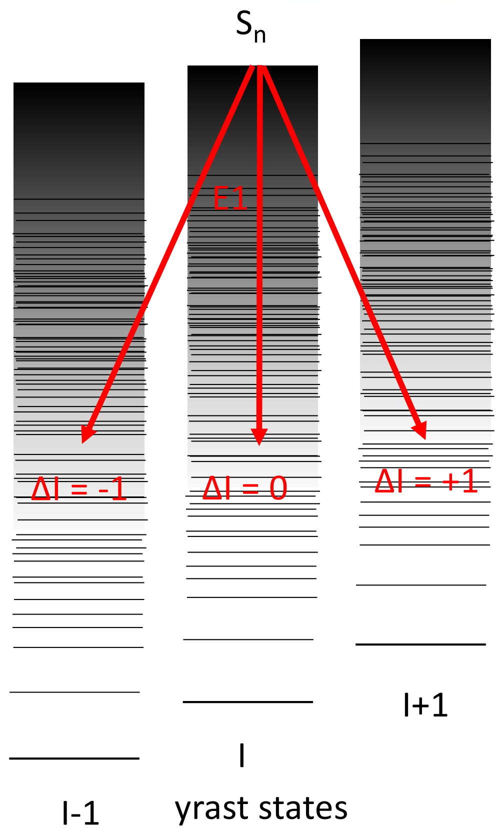
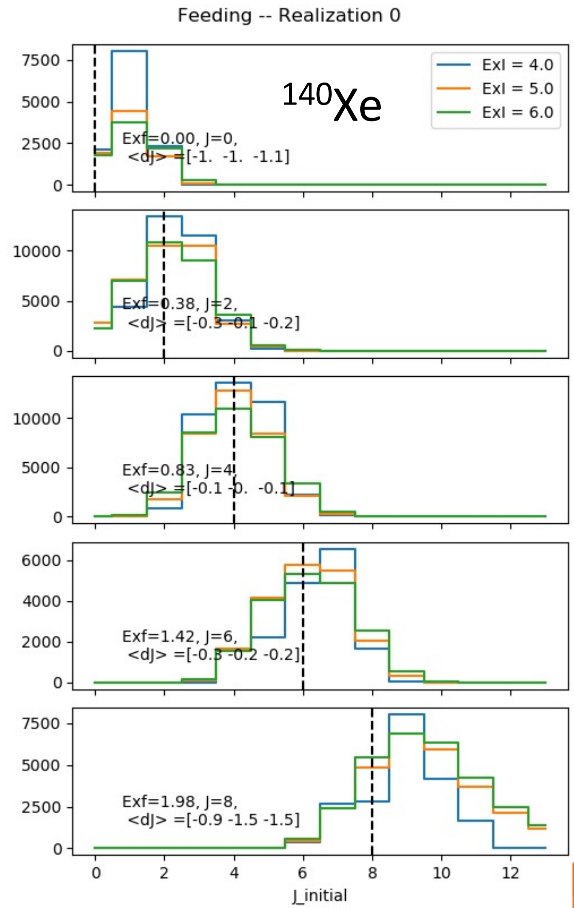


Fig. 1. An example of a partial decay scheme determined in the experiments, showing discrete line intensities observed following statistical population of entry points in ^{98}Mo final fragments. The populations $P(j)$ of states of spin j in ^{98}Mo fed directly by statistical γ-rays from the entry points are shown on the right.

RAINIER Calculations for <ΔI> of statistical γ emissions





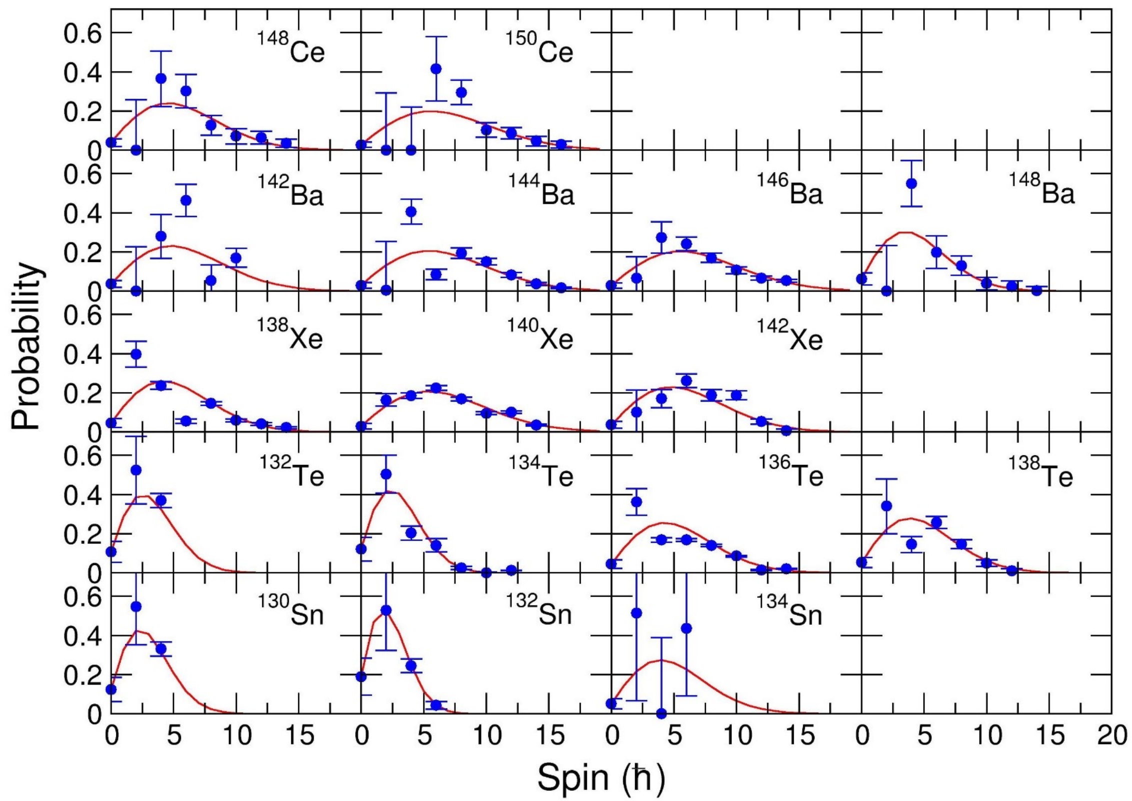


$\langle M_\gamma \rangle \sim 2 - 3$ $\langle \Delta I \rangle \sim 1$ hbar

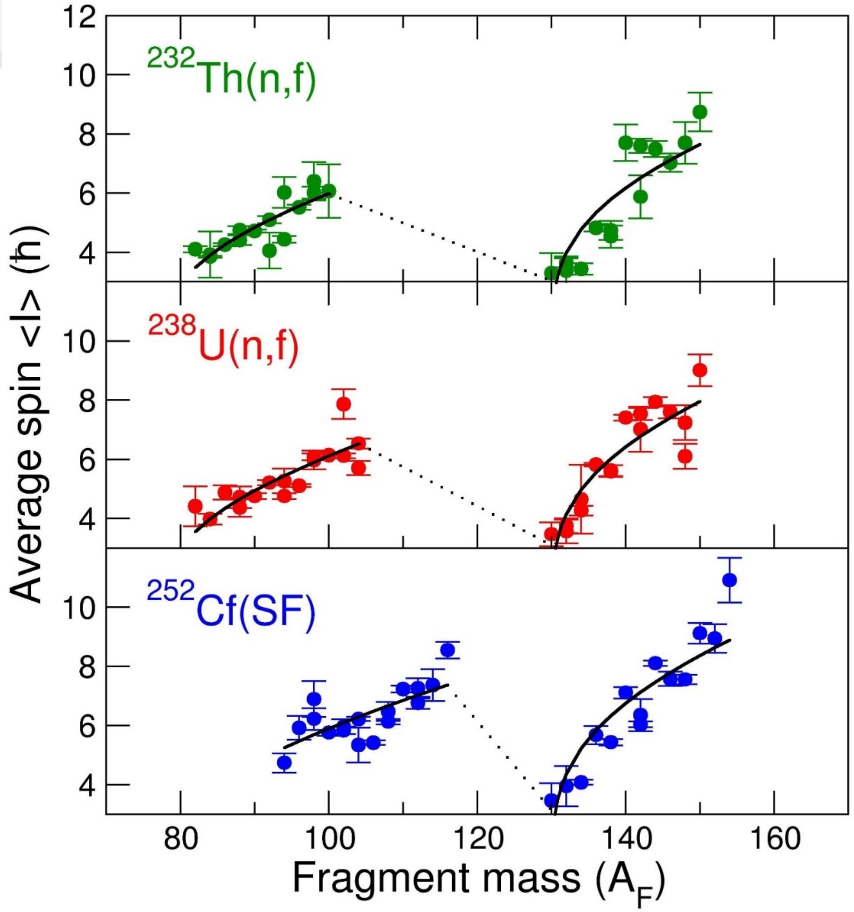
Courtesy of F. Zeiser

Example of measured side-feeding distributions

$^{238}U(n,f)$ heavy fragments



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

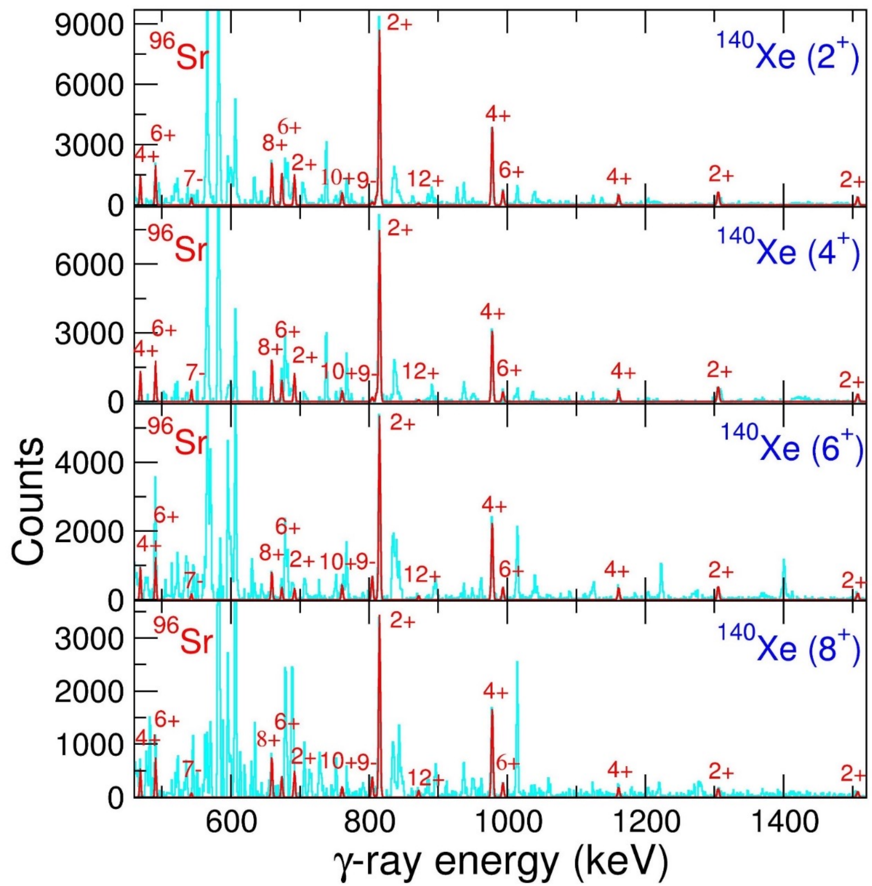
Each nucleus does not care who it emerged with!

- Certain partners have large asymmetries in <I>

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

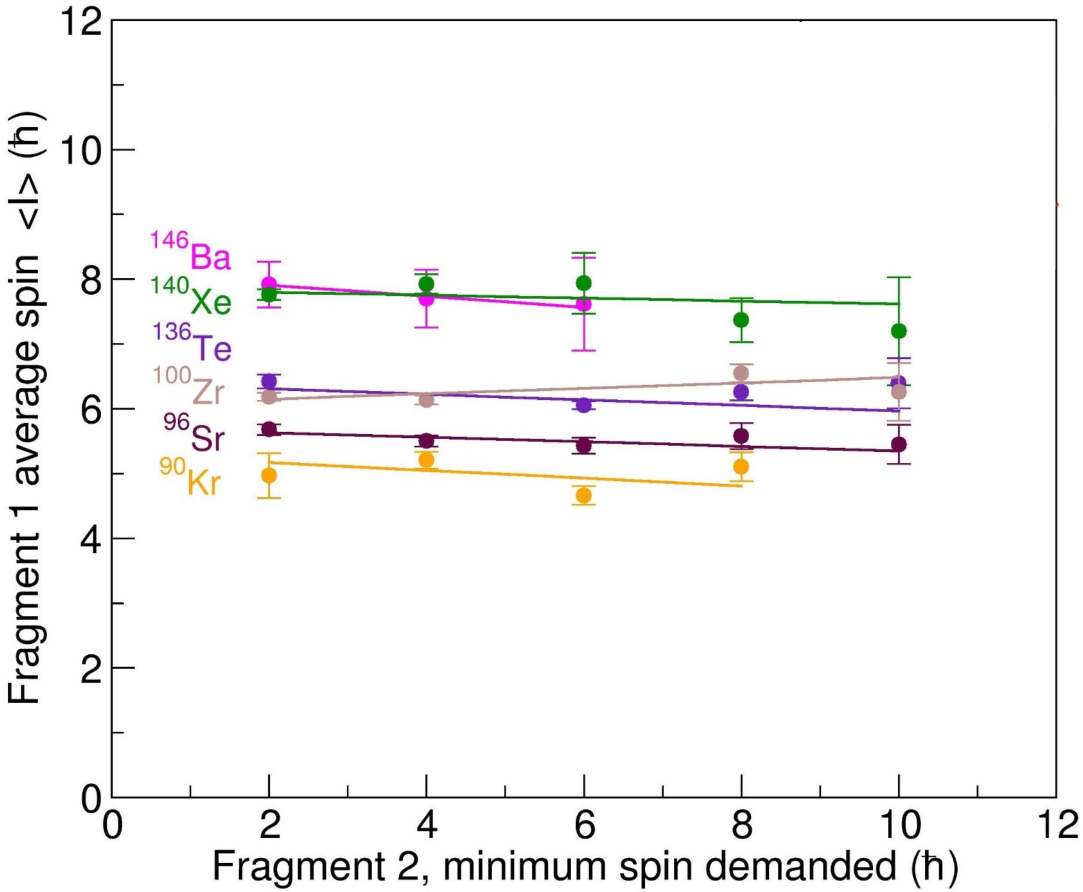
- Highly asymmetric distribution

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



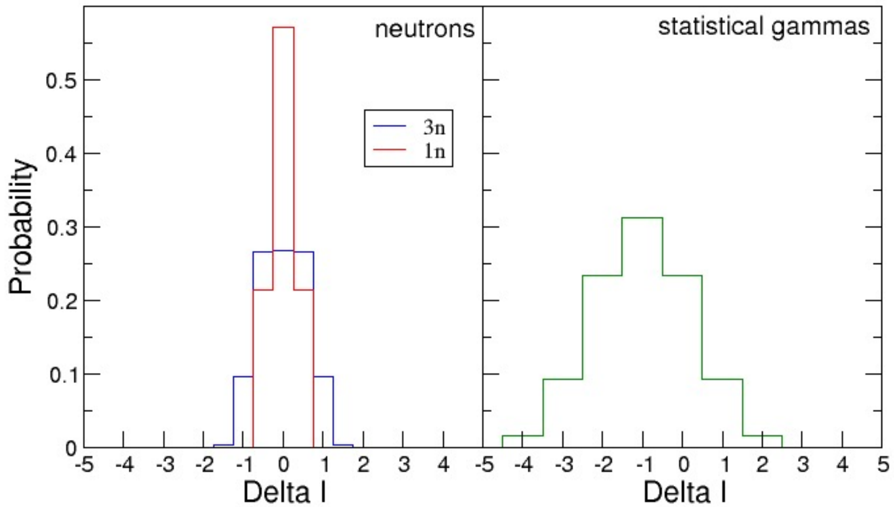
Increasing spin demanded in ^{140}Xe

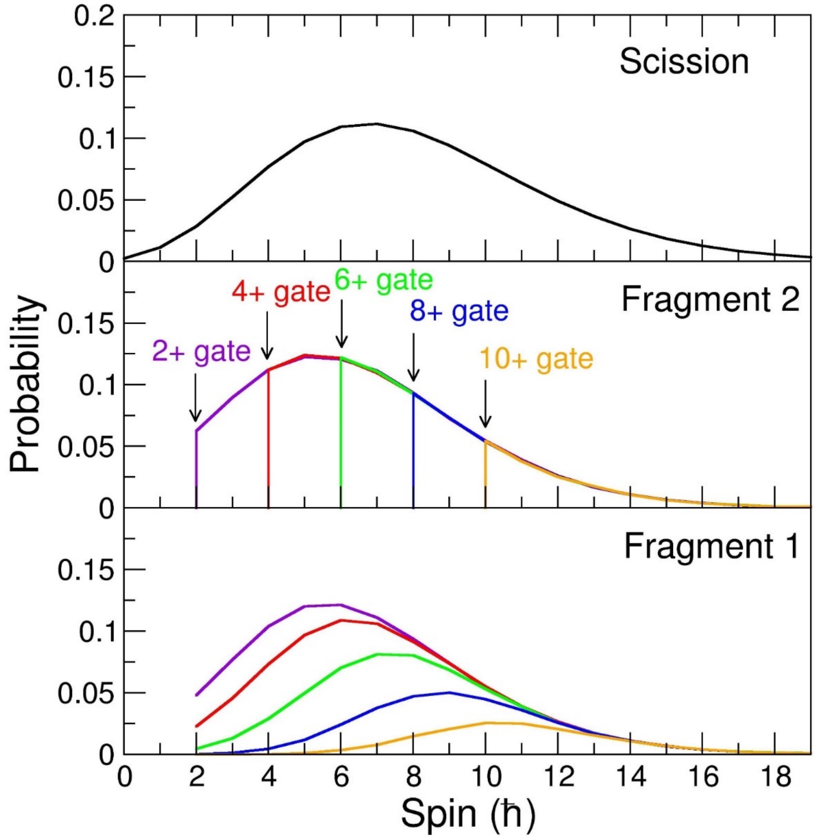
RESULTS: Correlation between fragment spins



Monte-Carlo code: scission to yrast spin propagation

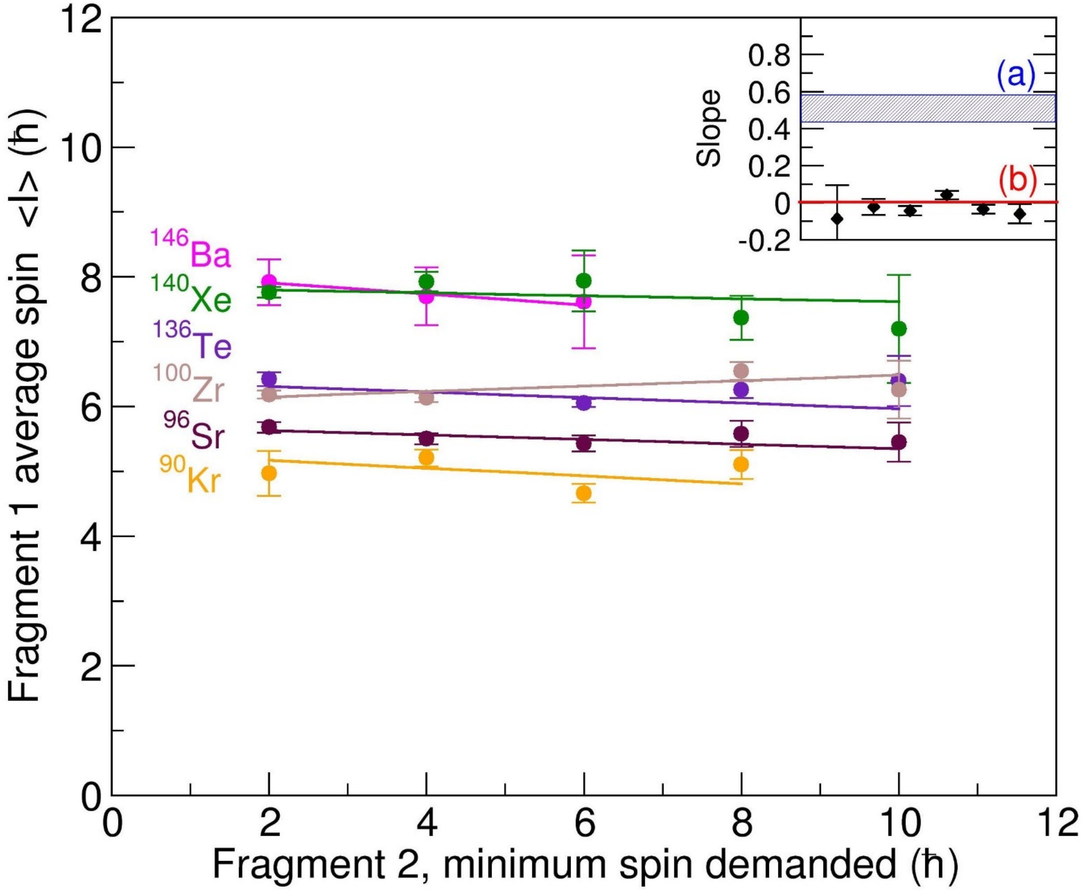
Spin dispersions from scission to yrast





Conclusion: dispersions weaken spin correlations at scission but do not destroy them

RESULTS: Correlation between fragment spins

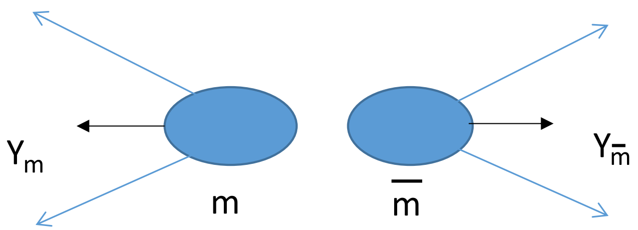


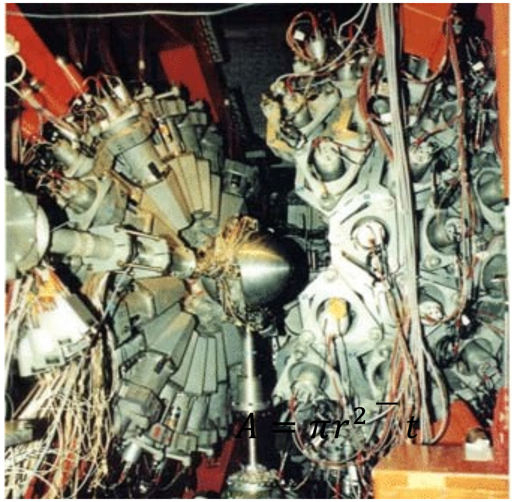
Correlated spins (pre-scission)

Uncorrelated spins (post scission)

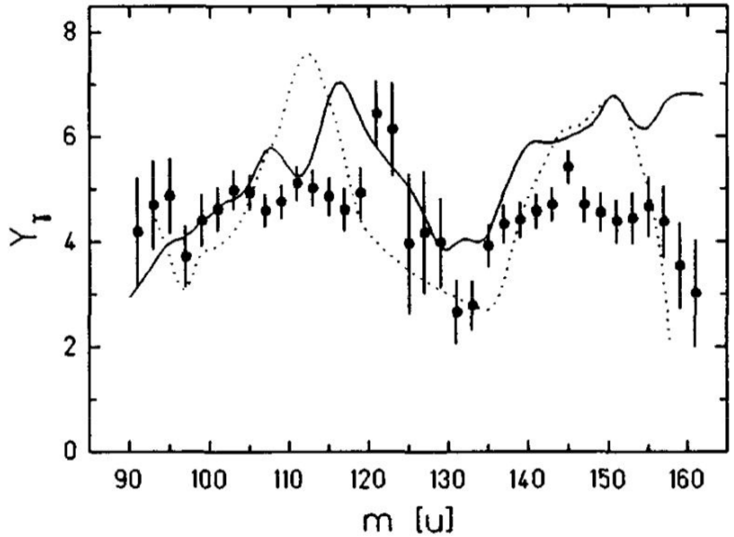
Gamma yield vs mass from exploiting Doppler shifts

P. Glassel et al. Nuc. Phys. A502 315 (1989)





Darmstadt-Heidelberg crystal ball
164 NaI + ^{252}Cf directional ionisation chamber



The γ-yield of the individual fragments is then calculated as

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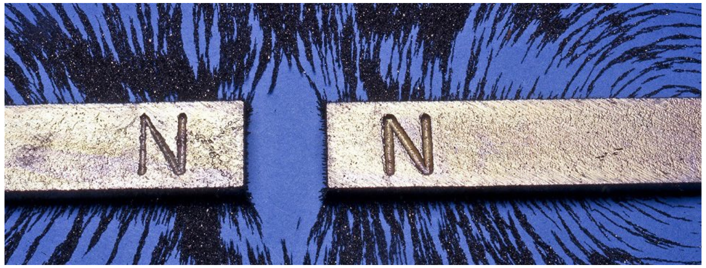
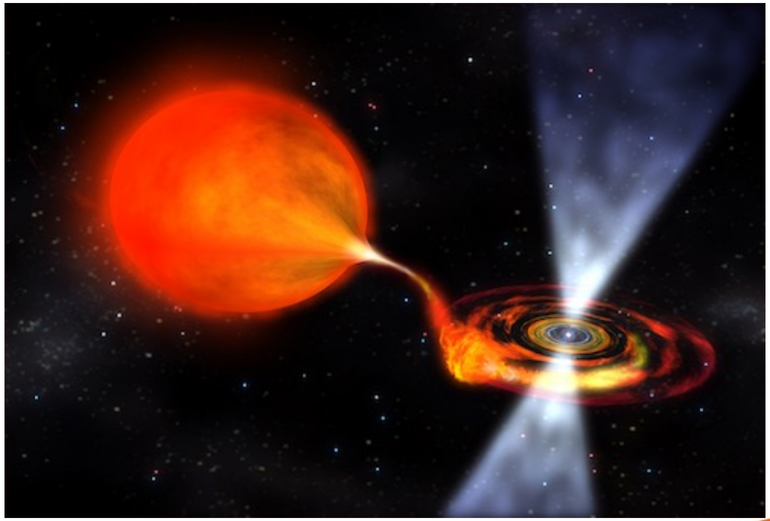
where m and $\overline{m}$ are corresponding fragments, Y_m and $Y_{\overline{m}}$ are the measured γ-yields in the narrow cone about the direction of the fragments, and $\beta_m, \beta_{\overline{m}}$ are the mean projections of the fragment velocity on the direction of the γ in that cone.

Spontaneous Axial Symmetry breaking in Nature

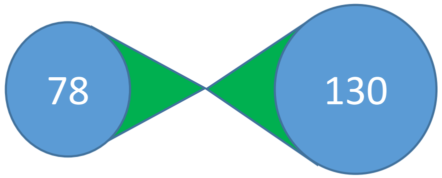




Macroscopic explanation (stretched elastic)

We suggest that: The slightly off-axis motion of the ruptured neck nucleons drives the angular momentum generation post scission.

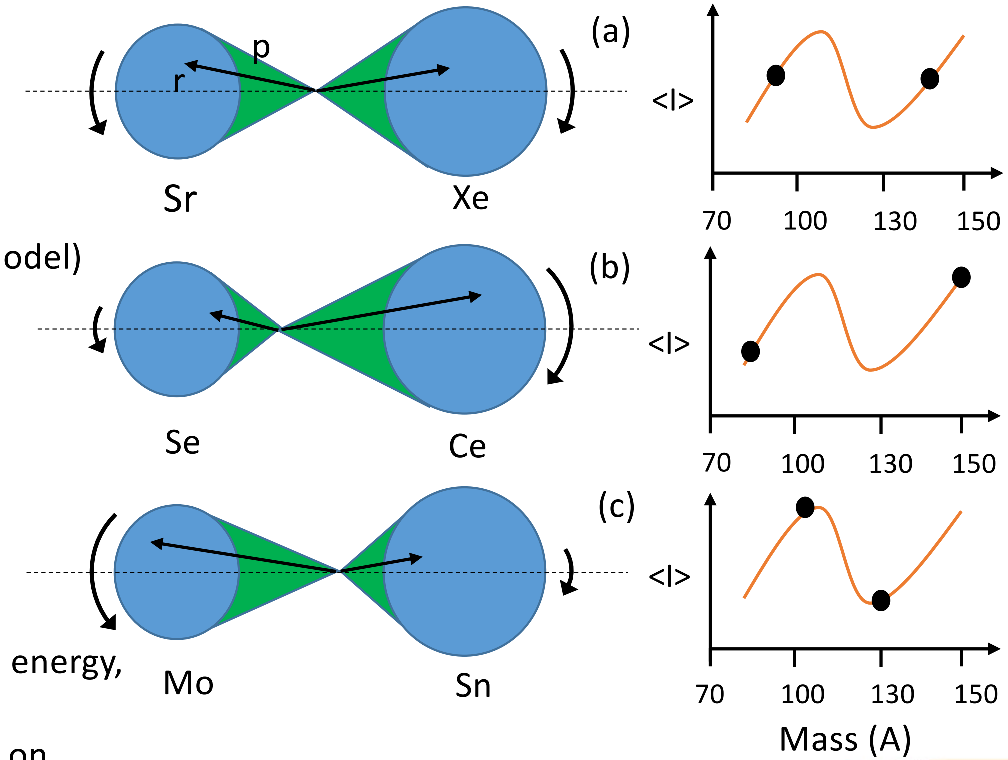
Macroscopically angular momentum is generated in each fragment by two torques: $\boldsymbol{I} = \boldsymbol{r} \times \boldsymbol{p}$
The size of each torque is related to the partition of neck nucleons involved, A_N



(Double cluster model)

$A_N = (A_F - 78)$
for light fragments

$A_N = (A_F - 130)$
for heavy fragments



What would be the expected functional form which describes the <I> vs A relationship?

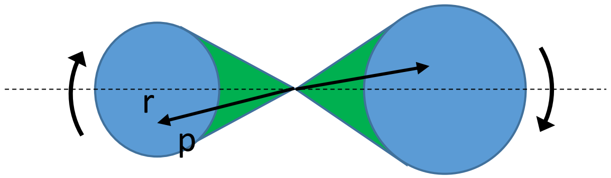
- Surface/Deformation energy converts to internal excitation energy, some of which is fragment rotational energy
- The energy partition between fragments is also dependent on location of neck rupture and hence A_N in each fragment

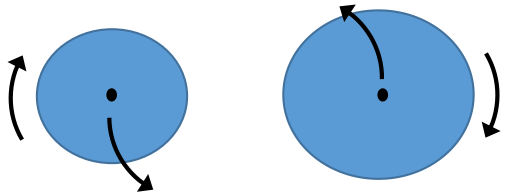
But some unresolved questions…

How is angular momentum conserved?

Why are the fragment spins in a particular event independent?

Conservation of angular momentum





- We suggest that small off-axis components, δp, in the linear momenta p, of the neck stubs as they are reabsorbed into the fragments
- Implied third torque generates the orbital angular momentum (large r, small δp)
- The resulting fragment angular momenta will lie in a plane perpendicular to the fission axis, but with no constraints on their relative directions
- Potential for significant orbital angular momentum $\vec{\boldsymbol{I}}_{\boldsymbol{o}}$ with accompanying orbital energy E_o

$$\boxed{\vec{\boldsymbol{I}}_1 + \vec{\boldsymbol{I}}_2 + \vec{\boldsymbol{I}}_{\boldsymbol{o}} = 0}$$

Hence:

Largest possible orbital angular momentum $|I_o| = |I_1 + I_2|$

Smallest possible orbital angular momentum $|I_o| = |I_1 - I_2|$

Parametrisation derived from statistical theory

(i) $$P\left(I|\sigma^2\right) = \frac{2I+1}{2\sigma^2}\exp\left(-\frac{\left(I+½\right)^2}{2\sigma^2}\right)$$

"An Attempt to Calculate the Number of Energy Levels of a Heavy Nucleus"

H. A. Bethe, Phys. Rev. 50, 332 (1936)

(ii) $$T = \sqrt{\frac{E_x}{a}}$$

where σ is known as a spin-cutoff parameter describing the breadth of this distribution. In the Fermi gas model, the spin cut-off parameter depends directly on the nuclear temperature, T, and is related to the excitation energy E_x and the level density parameter, a.

(iii) $$\sigma^2 = \mathrm{I}_{\mathrm{rigid}} T$$

In this model, the spin cut-off parameter is then usually defined as the product of the rigid body moment of inertia and the temperature

(v) $$\mathrm{I}_{\mathrm{rigid}} \propto A_F^{5/3}$$

From expressing the nuclear radius, R, as proportional to the cubed root of A_F

Excitation energy depends where the neck is cut (i.e. like stretched elastic). This **links** spin and neutron multiplicity sawtooths.

(vi) $$\sigma^2 \propto \sqrt{E_x}\, A_F^{7/6}$$

Using a level density parameter a that is proportional to A_F, the variation in the spin cut-off parameter with fragment mass can then be defined. (combining (ii), (iii) and (v))

(vii) $$E_x \propto A_N$$

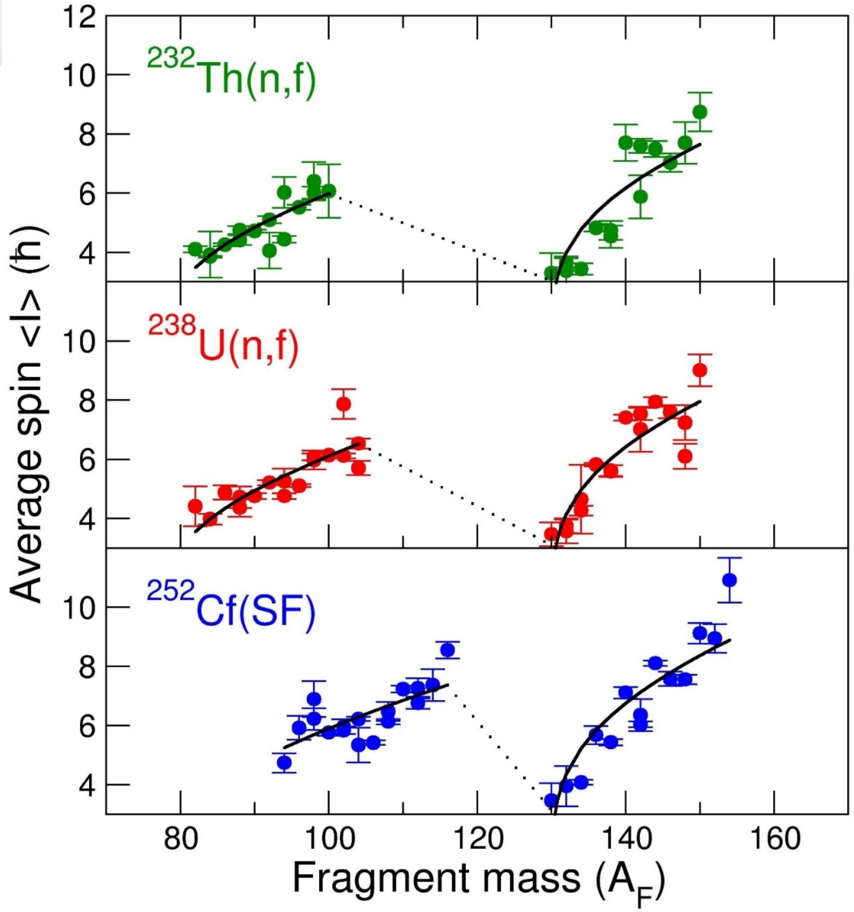
If we assume that the excitation energy of the fragment is proportional to the mass of the nucleons from the ruptured neck

Thanks to S. Aberg and O. Serot for their help

(viii) $$\boxed{I = cA_N^{1/4} A_F^{7/12}}$$

Expected spin-mass relationship using a (basic) statistical/single particle theory

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



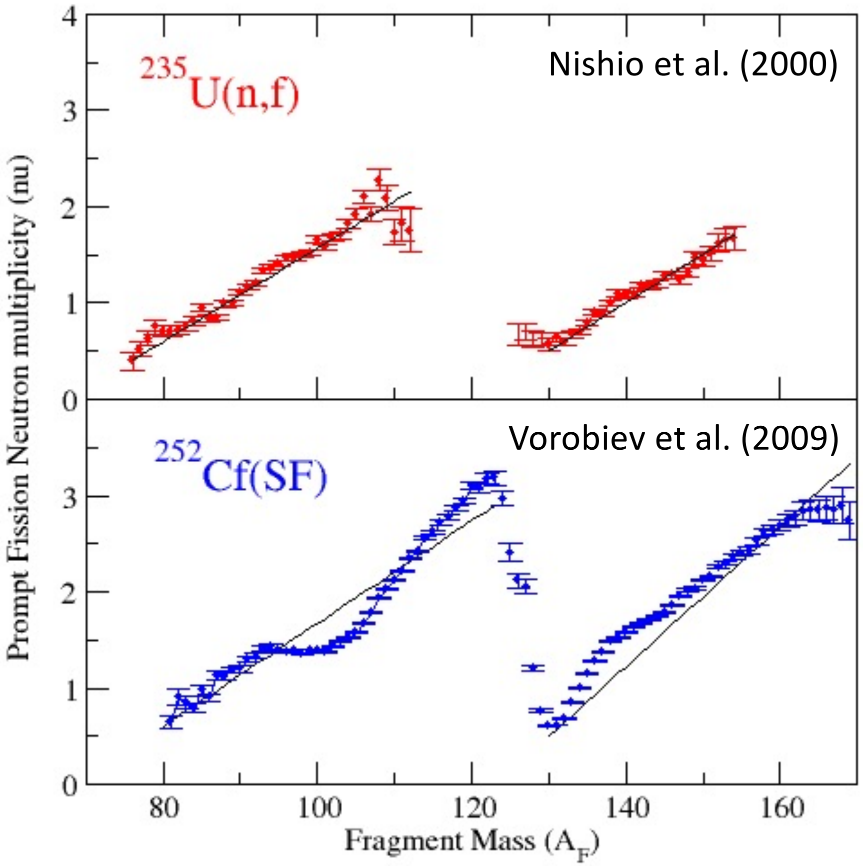
Fitting function from statistical theory

$$\boxed{I = cA_{\mathrm{N}}^{1/4} A_{\mathrm{F}}^{7/12}}$$

System	Mass peak	Fitted constant c	Correlation coefficient R^2
^{232}Th(n,f)	light	0.189	0.837
^{238}U(n,f)	light	0.192	0.806
^{252}Cf(SF)	light	0.186	0.803
^{232}Th(n,f)	heavy	0.195	0.848
^{238}U(n,f)	heavy	0.202	0.854
^{252}Cf(SF)	heavy	0.213	0.884

- The data points fall on a universal curve to within ~ 4%!
- The simple statistical theory explains the main ingredients of the spin-mass relationship
- Other second order physics terms possible (e.g. Coulomb effects)

Simultaneous neutron sawtooth parametrisation

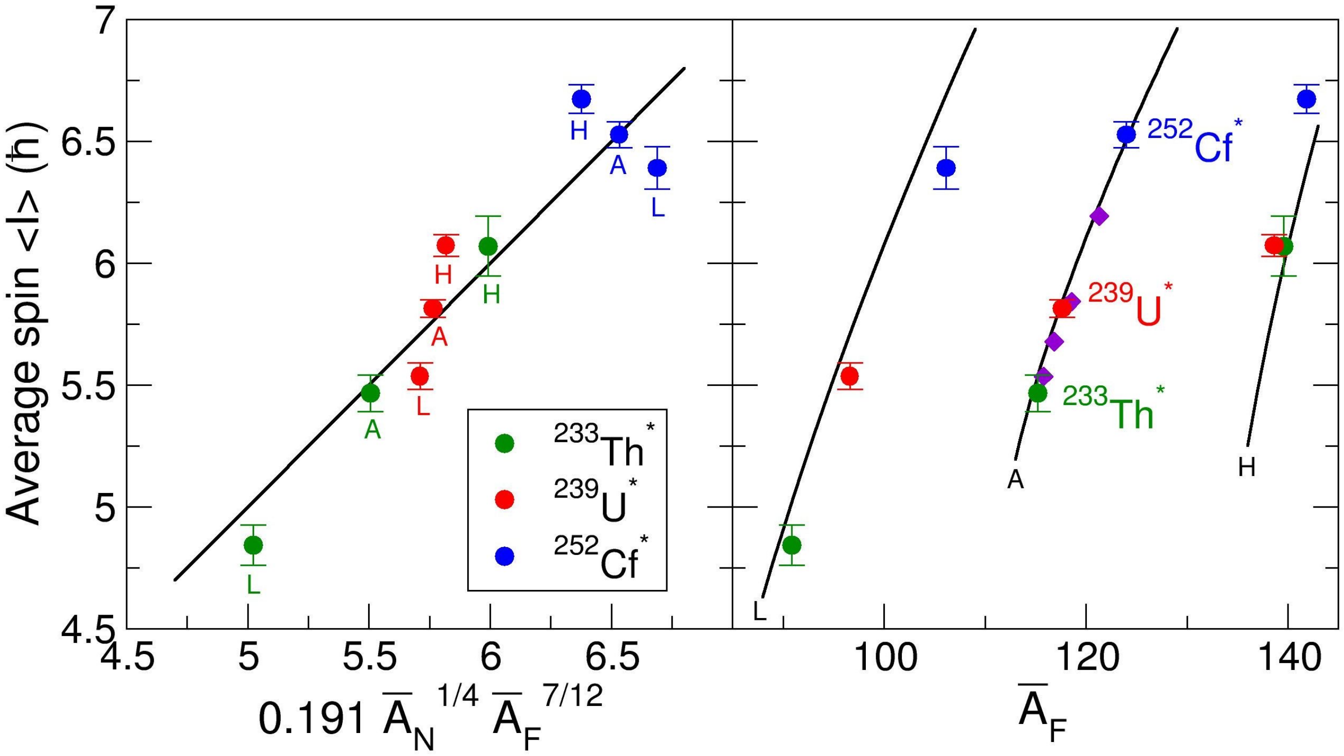


Sawtooths patterns in the prompt neutron multiplicities well-known for a long time (Terrell et al. 1964)

- The data points fall on a universal *line* to within ~ 9%!
- The simple statistical theory also explains the main ingredients of the prompt fission neutron-mass relationship
- PFN is also governed by the energy partition between fragments

Consequences: Predictions for other systems

Combined fission yield and spin data to relate two fission observables for the first time <A> and <I>



Consequences for:

- Reactor gamma heating problem
- Nuclear structure: e.g. which states are accessible?
- Fission (no access to pre-scission information from gammas)
- Fission: new mass regions

e.g. "A New Type of Asymmetric Fission in Proton-Rich Nuclei", A. Andreyev, Phys. Rev. Lett. 105, 252502 (2010)

Subsequent articles! …

A. Bulgac, I. Abdurrahman, S. Jin, K. Godbey,N. Schunck, and I. Stetcu,
"Fission fragment intrinsic spins and their correlations," Phys. Rev. Lett.126,142502 (2021).

R. Vogt and J. Randrup, "Angular momentum effects in fission," Phys. Rev. C103, 014610 (2021)

J. Randrup and R. Vogt, "Generation of Fragment Angular Momentum in Fission," Phys. Rev. Lett.127, 062502(2021).

P. Marevic, N. Schunck, J. Randrup, and R. Vogt, "Angular momentum of fission fragments from microscopic theory," Phys. Rev. C104, L021601 (2021).

A. Bulgac, I. Abdurrahman, K. Godbey, and I. Stetcu, "Fragment Intrinsic Spins and Fragments' Relative Orbital Angular Momentum in Nuclear Fission," arXiv:2108.03763.

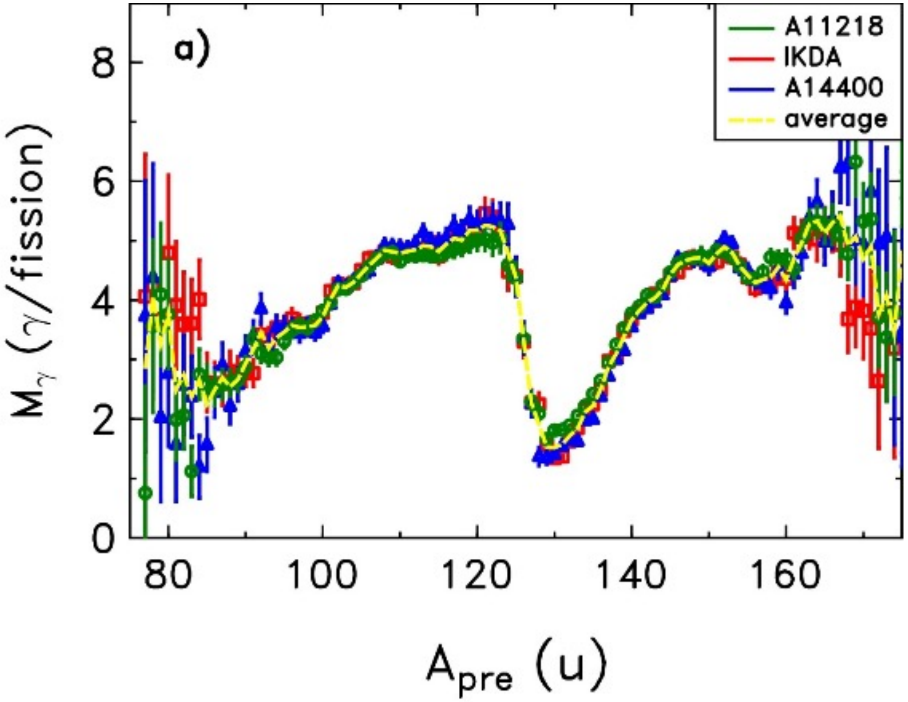
I. Stetcu, A.E. Lovell, P. Talou, T. Kawano, S. Marin, S.A. Pozzi, and A. Bulgac, "Angular momentum removal by neutron and γ-ray emissions during fission fragment decay," Phys. Rev. Lett. 127, 222502 (2021)

A. Bulgac, "The angular correlation between the fission fragment intrinsic spins," , Phys. Rev. Lett. 126, 142502 (2021)

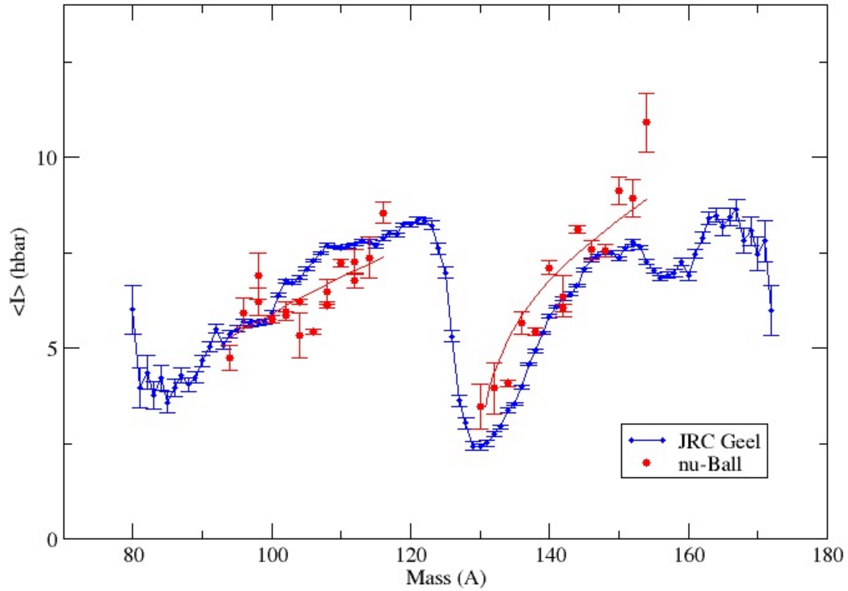
Independent sawtooth confirmation

^{252}Cf

M. Travar et al. Phys. Lett. B 817 136293 (2021)

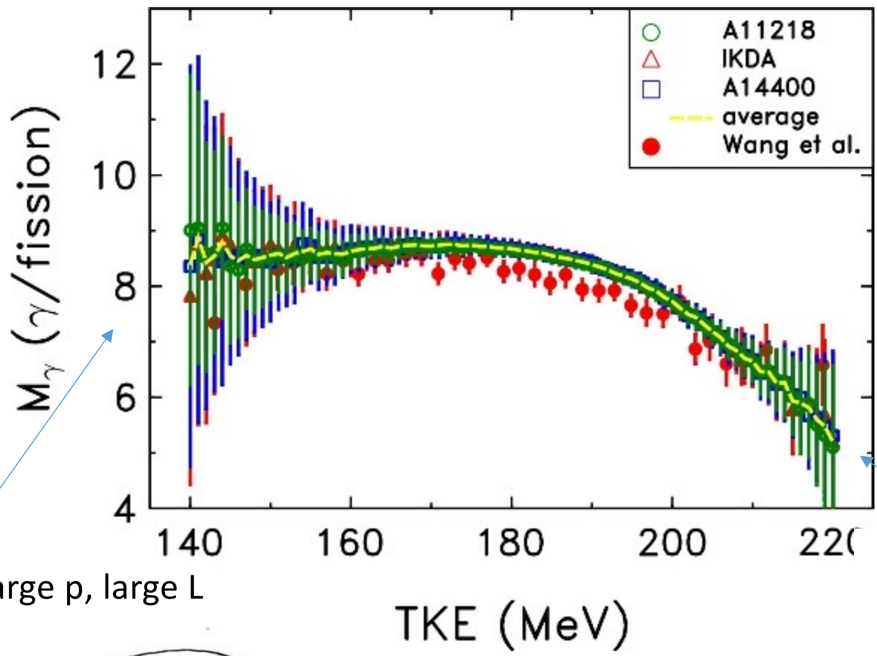


Normalization: Literature value of 1.6 hbar per emitted gamma



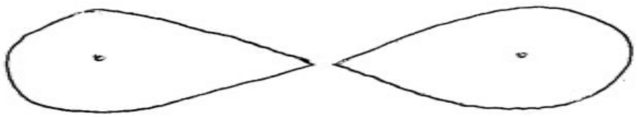
Gamma Multiplicity vs TKE

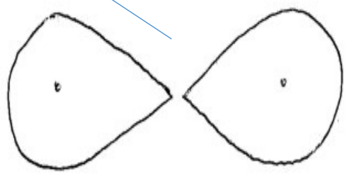
M. Travar et al. Phys. Lett. B 817 136293 (2021)



Large p, large L

Small p, small L



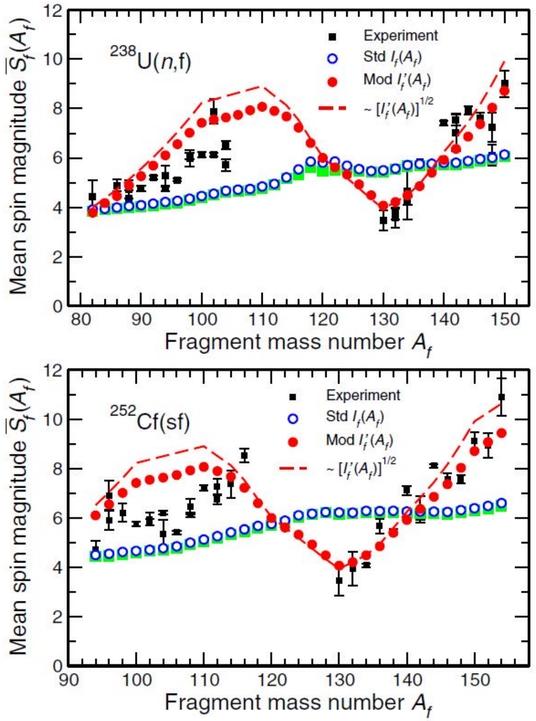


Elongated rupture. Low TKE

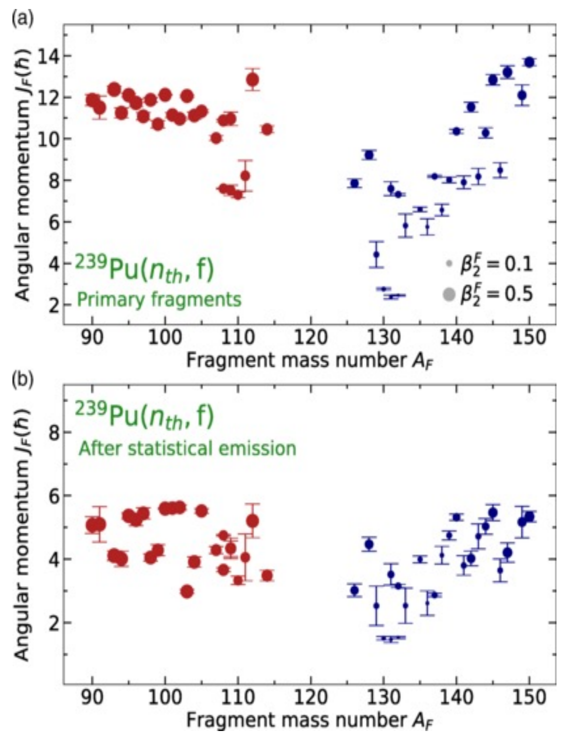
Compact rupture. High TKE

Subsequent articles! …

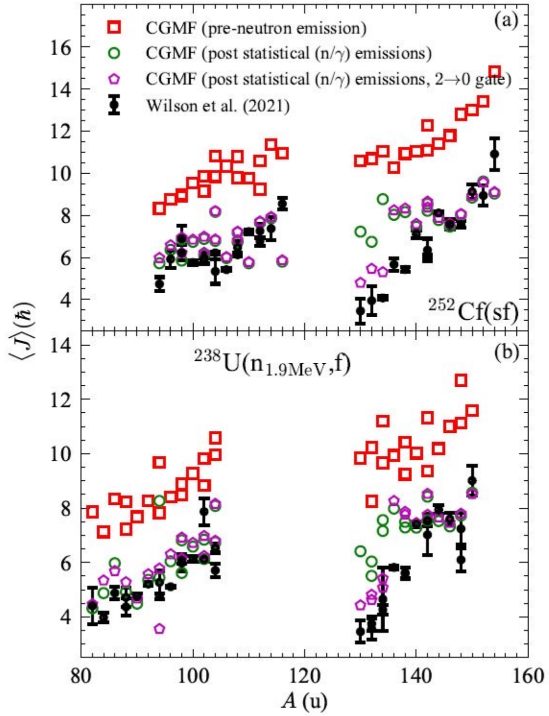
J. Randrup and R. Vogt, (Berkeley)
Phys. Rev. Lett.127, 062502(2021)
FREYA, Monte-Carlo de-excitation code



P. Marevic et al. (Livermore)
Phys. Rev. C104, L021601 (2021)
Microscopic DFT



I. Stetcu et al. (Los Alamos)
Phys. Rev. Lett. 127, 222502 (2021)
CGMF, Monte-Carlo Hauser Feshbach



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

(1) "Using the fission model FREYA [2], we demonstrate here that a fission treatment based on correlated rotational modes in the dinuclear complex prior to scission may in fact endow the fragments with spins that are nevertheless approximately independent. This fact invalidates the above assumption and hence casts doubt on the conclusion in Ref. [1]"

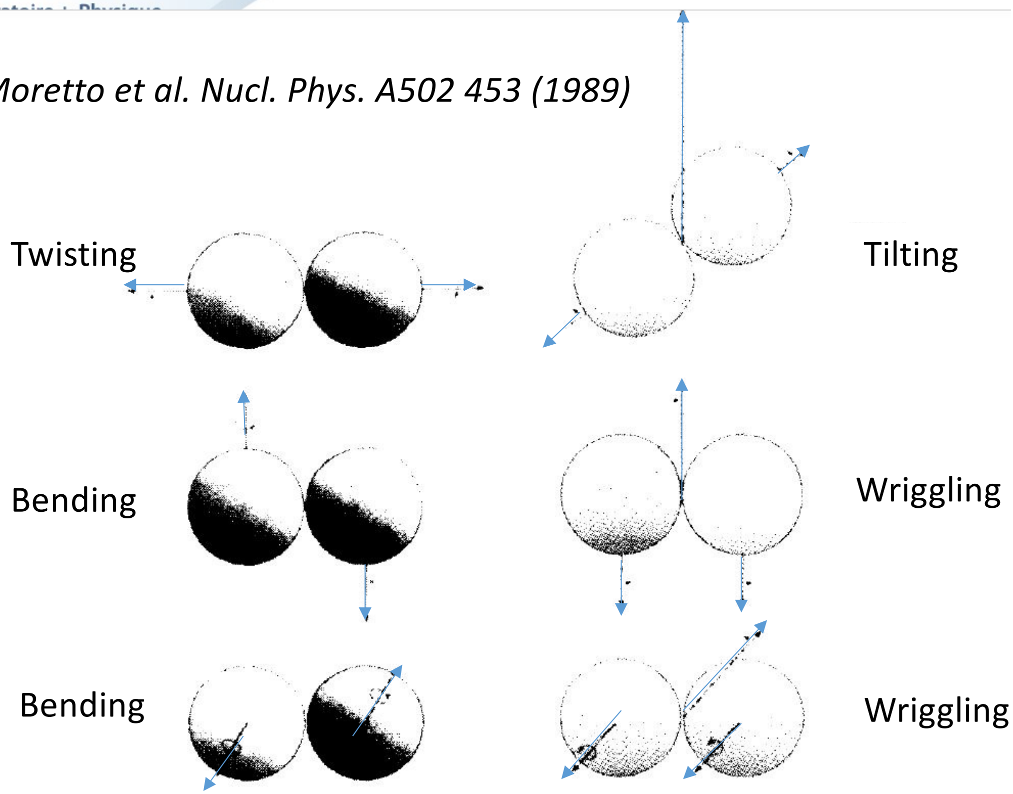
(2) "…the independent population of rotational states in the fragments after their separation seems hard to reconcile with the principle of angular momentum conservation for isolated systems."

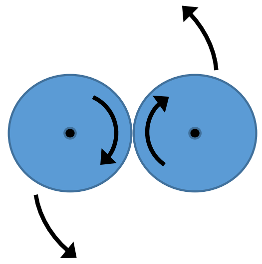
(3) "…measurements of $S_f(A_f)$, such as those reported in Ref. [1], may provide unique experimental information on the fissioning system at the time of scission, which in turn would be very helpful for the further development of fission theory." –

- Multiple exchange of nucleons during neck formation.
- Strongly damped, dissipative (and therefore relatively slow) process.
- Stochastic excitation of two of the 6 dinuclear pre-scission modes (bending and wriggling)
- Leads to (almost) independent spins at scission

Six di-nuclear pre-scission modes

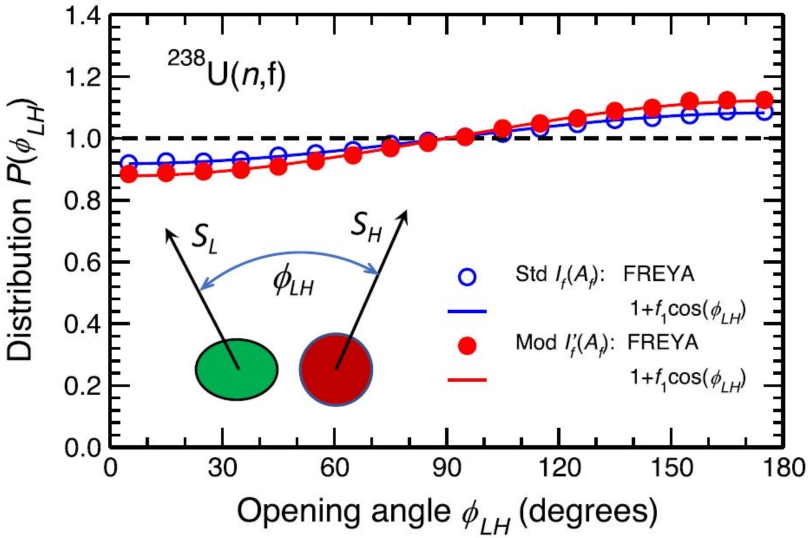
L. Moretto et al. Nucl. Phys. A502 453 (1989)

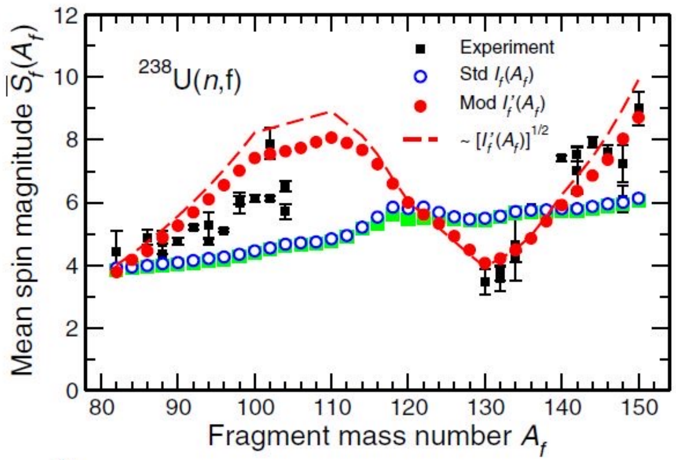


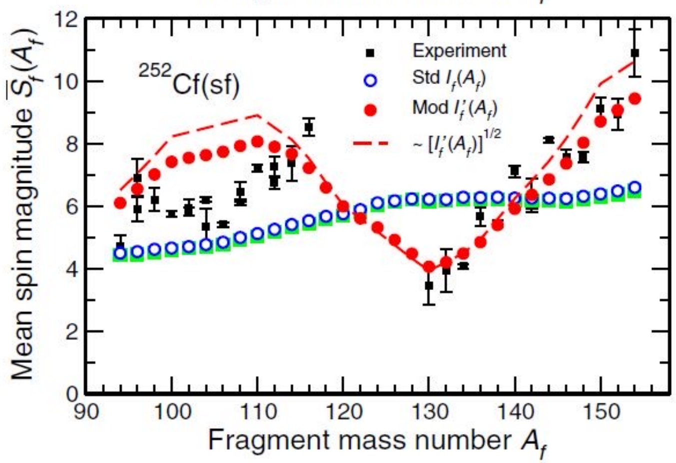


- Comment on wriggling mode: It is not clear in practice how two pre-fragments can rotate in opposite directions when locked together pre-scission
- Lack of <I> dependence on the fragment partner mass not currently addressed by theory (universality of observed sawtooth)

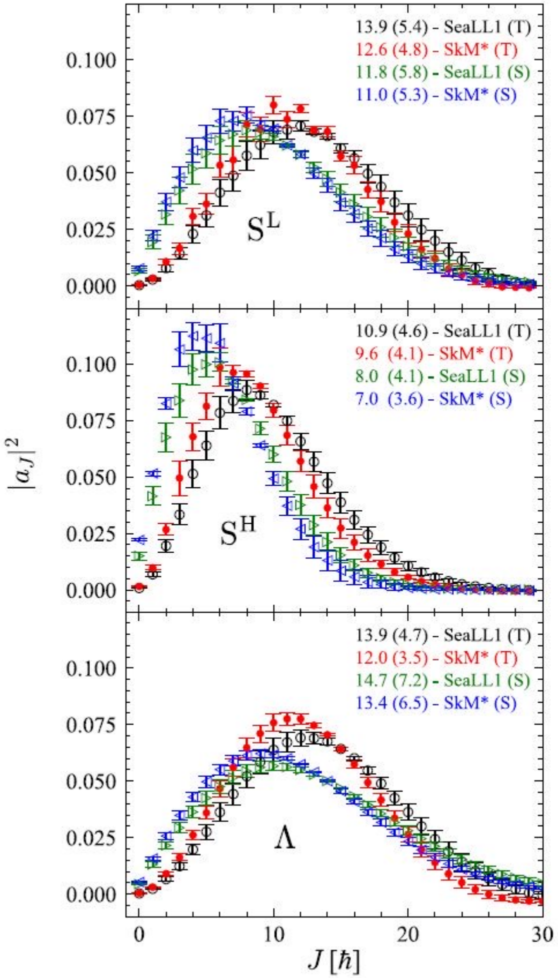
J. Randrup and R. Vogt. Phys. Rev. Lett.127, 062502(2021)



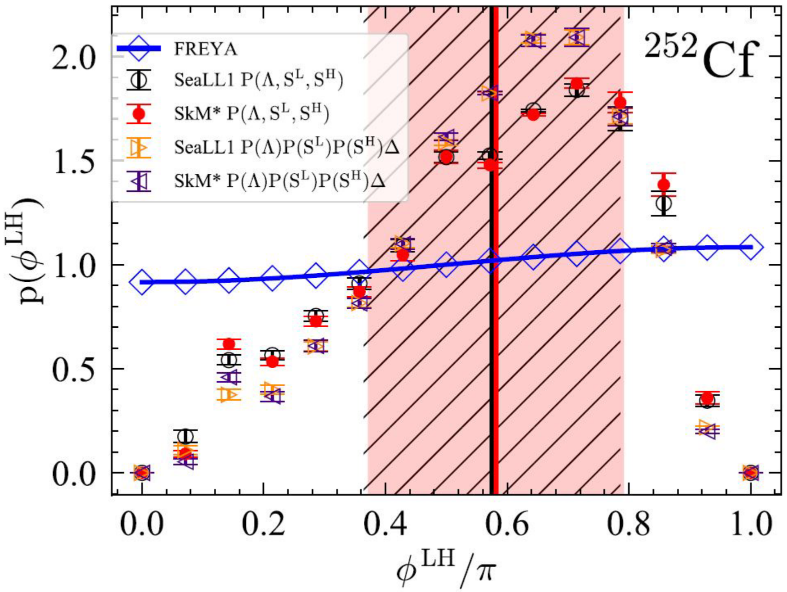




“Angular momenta in both fragments will point in a plane perpendicular to the fission axis, consistent with previous experiments, although there will be no correlation or constraint on their relative orientations.” – Wilson et al. Nature 590 566 (2021)



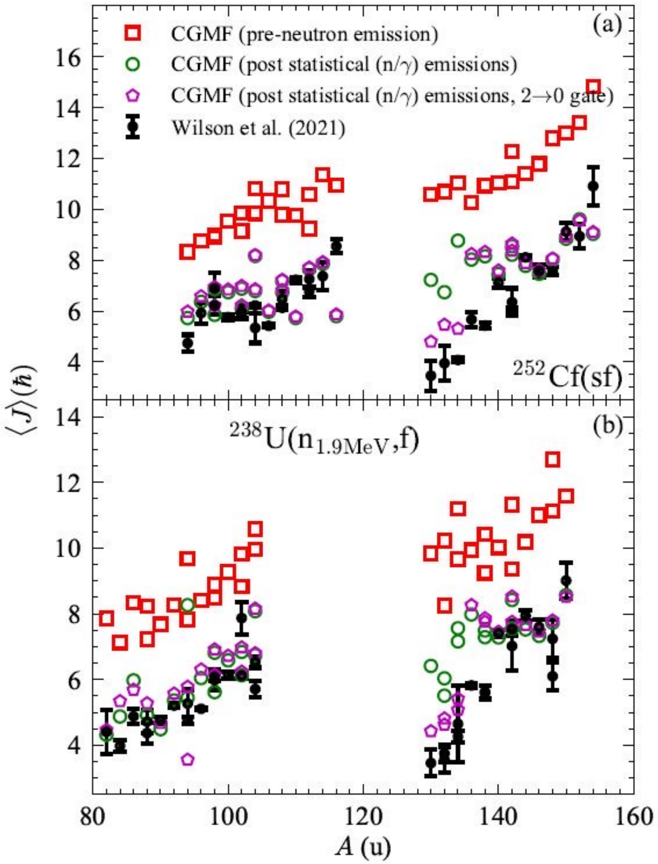
A. Bulgac et al. Phys. Rev. Lett. 127, 222502 (2021)

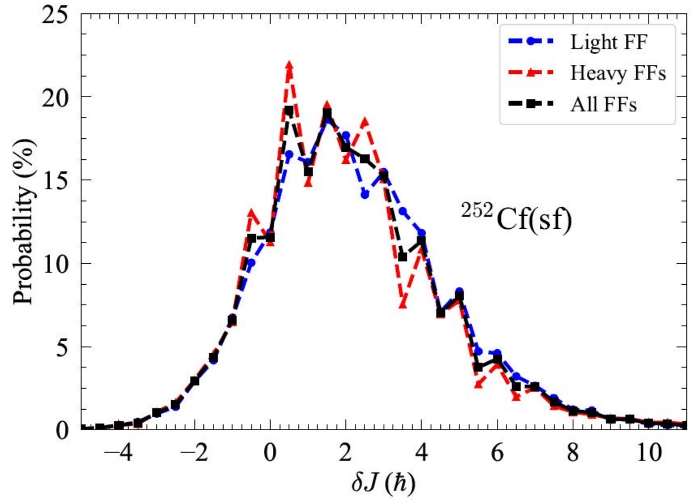


- Large orbital angular momenta are predicted
- But some correlation in the directions of the angular momenta
- Disagreement with J. Randrup et al.

I. Stetcu et al. Phys. Rev. Lett. 127, 222502 (2021)

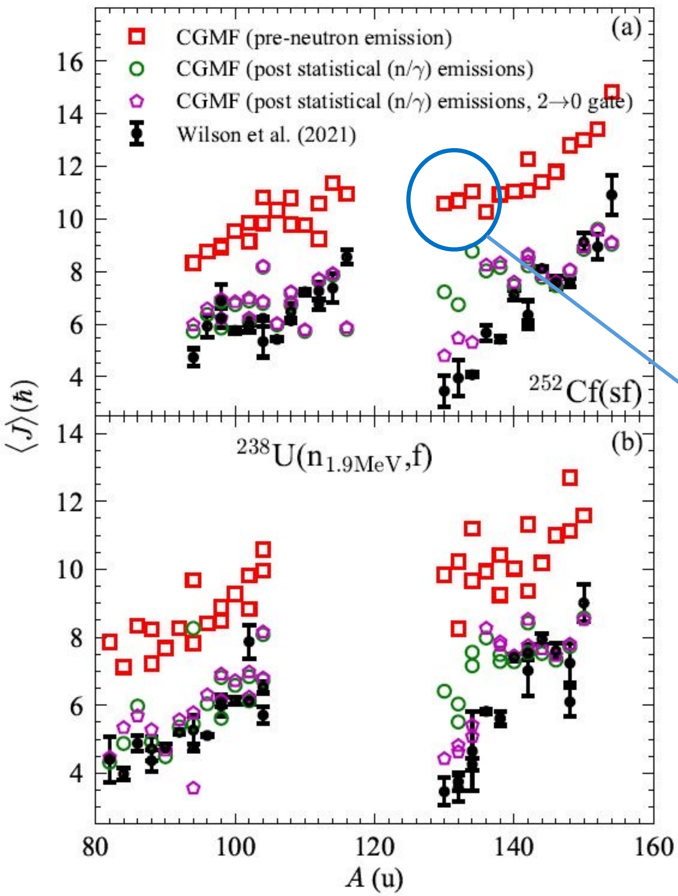
Angular momentum removal by neutron and γ-ray emissions during fission fragment decays





- New calculations show that angular momentum carried away by neutron is considerably larger than currently thought ΔI = 1.13 +/- 1.71 per neutron
- Contradicts the available literature which supposes neutron emissions is s-wave, carrying very little angular momentum on average.

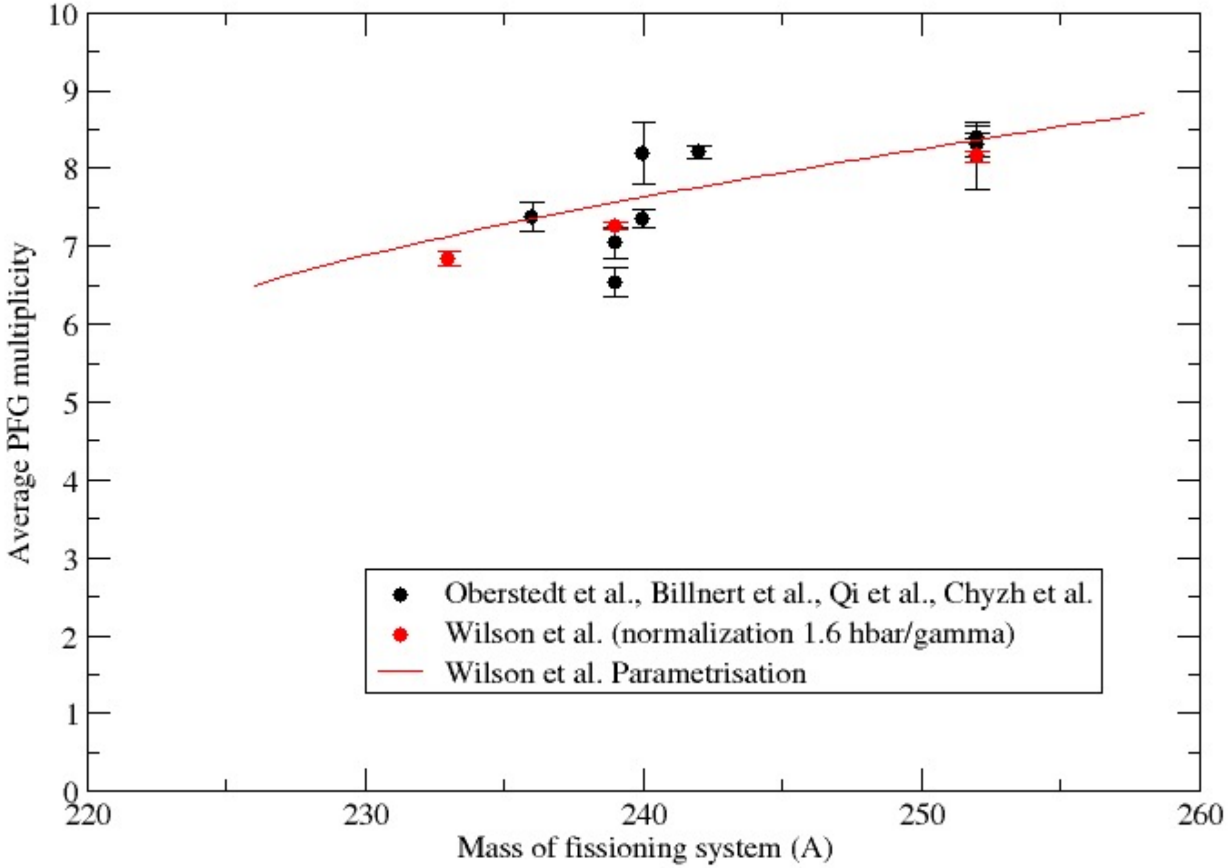
I. Stetcu et al. Phys. Rev. Lett. 127, 222502 (2021)



- Average spin data alone are insufficient to fully constrain theory. They provide only a lower limit, since statistical gammas and neutrons cannot be measured

- Both average spin and gamma multiplicity data are needed to fully constrain theory
- Prediction of $10\hbar$ of spin, but only 0.5 neutrons and 2 gammas available on average to evacuate it.
- Hence inconsistent with Travar et al. gamma multiplicity data by approx a factor of 2!

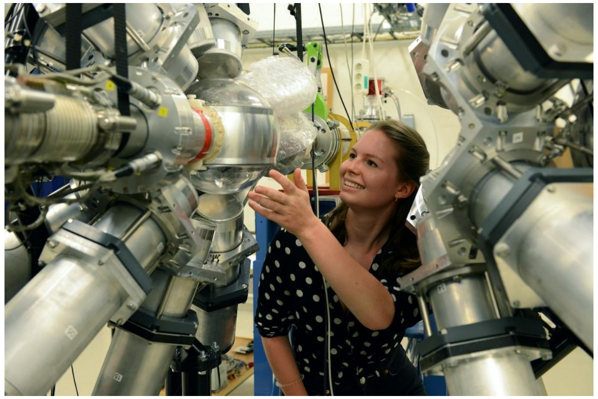
Cross check with known integral PFG multiplicity data



<u>Conclusion:</u> Cross checks needed for THEORY with integral PFG multiplicity data to ensure number of statistical gammas emitted is in accordance with the data.

What next? Nu-Ball2 Fission experiments

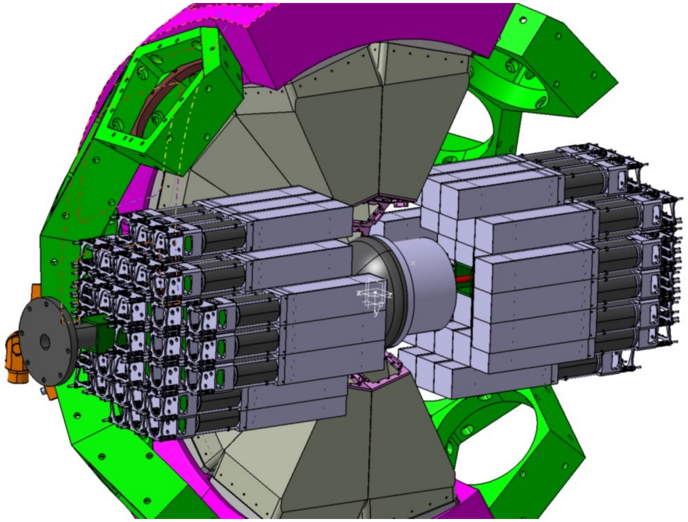
1) Propagation of angular momentum in fission
Gradually increase initial angular momentum input
Transfer reactions (d,pf) (^{3}He,pf) (α, α'f) for example
What happens to fragment spins?
How does the saw-tooth pattern evolve?



Thesis project
D. Gjestvang

OSCAR at the Oslo Cyclotron Laboratory (Apr 2021)

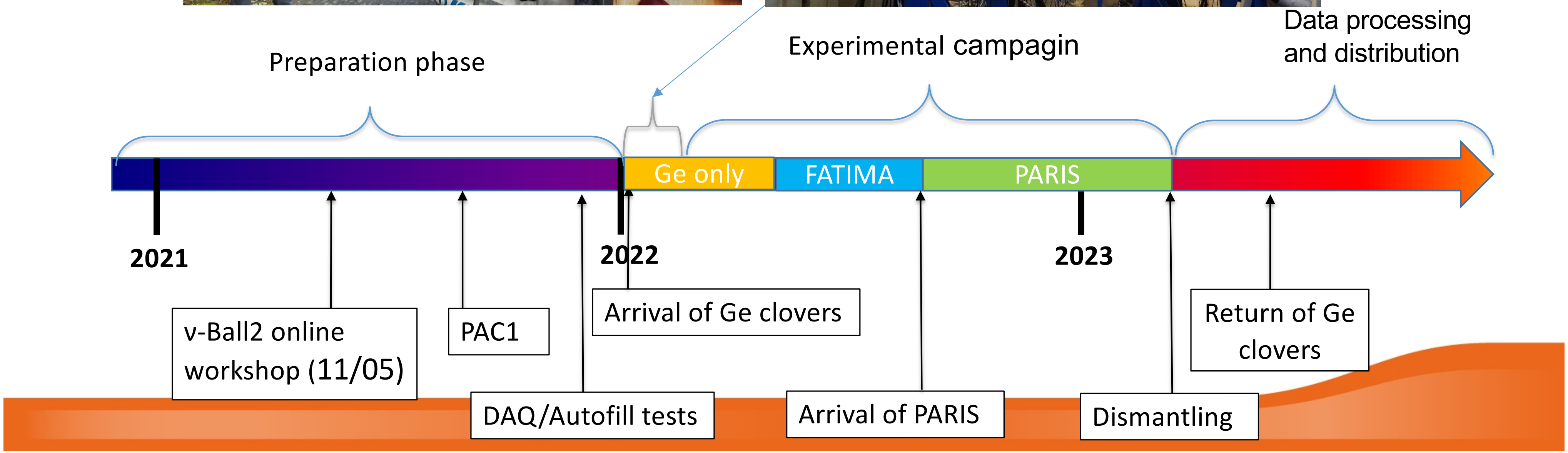
ν-ball2 at ALTO in 2022



2) Emission of high energy gammas in fission
PFG spectra extend way beyond S_n (E = 6 – 10 MeV)
Study of competition between neutron and gamma emission in fission. Population of collective resonances in certain neutron-rich fission fragments? (pygmy, even GDR?). C. Schmitt et al.

3) Spectroscopy in the second minimum of the fission shape isomers
Gamma decay's branches to first minimum and characterisation of states in the 2nd minimum: Ph.D. Thesis C. Hiver

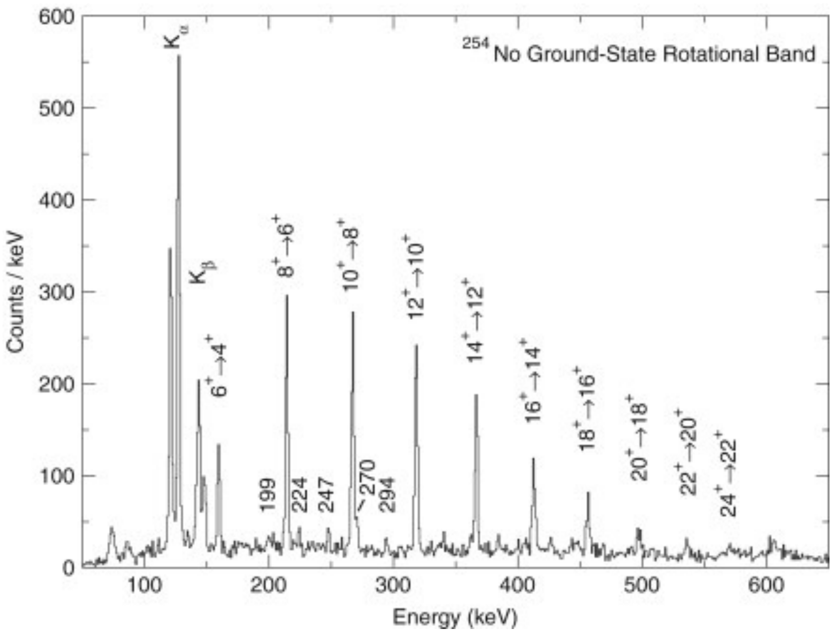
Nu-Ball2: Currently under construction at ALTO



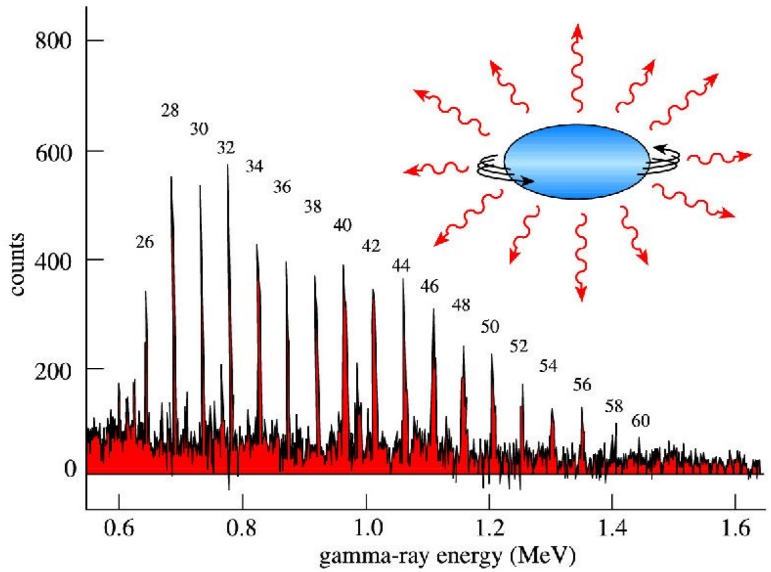
General Perspectives

- The MSM is a <u>very much underused</u> technique
- Can be used to obtain average spin for <u>any nucleus</u> populated by <u>any reaction</u>
- Sensitive to small changes in experimental conditions (bombarding energy, reaction type, etc.)

e.g. Studies of the reaction mechanisms which populate superheavy nuclei?

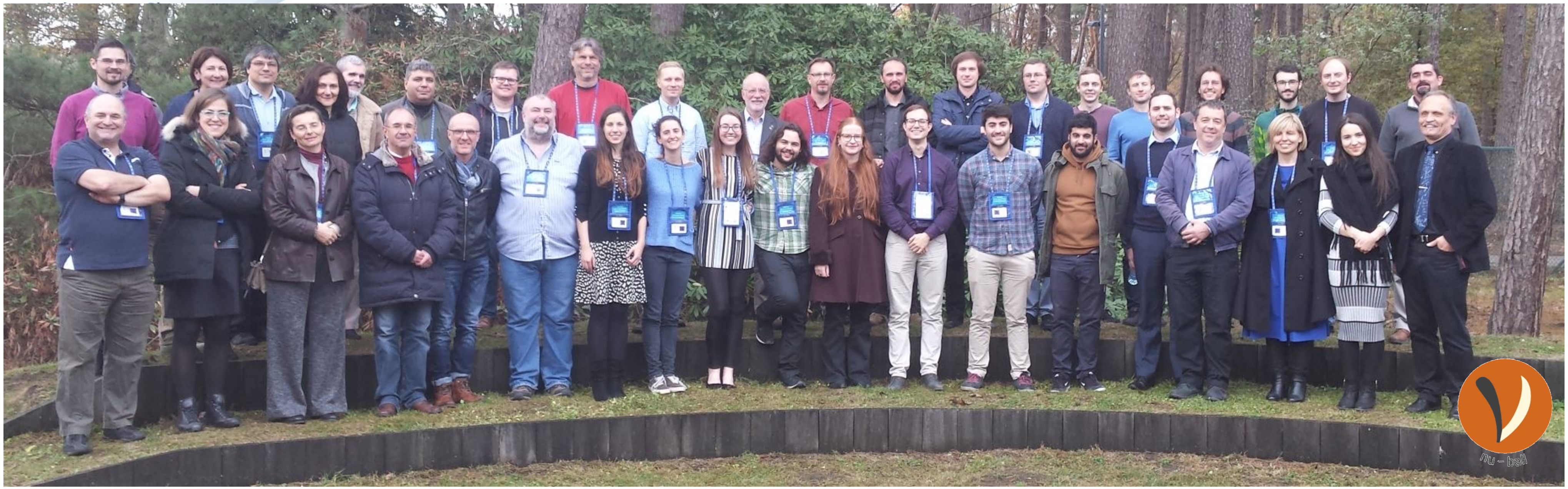


e.g. Population mechanisms of the very highest angular momentum states in nuclei?



γ - rays from a superdeformed band in ^{152}Dy

The ν-Ball collaboration



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

University of Surrey, NPL
University of Manchester

IFJ-PAN Krakow
University of Warsaw

University of Novi Sad

University of Oslo

TU Darmstadt
IFK- Koln

University of Milano
INFN Legnaro

JRC-Geel
Leuven

University of Madrid
IFIC Valencia

ELI-NP, Bucharest

University of Sofia

Riken

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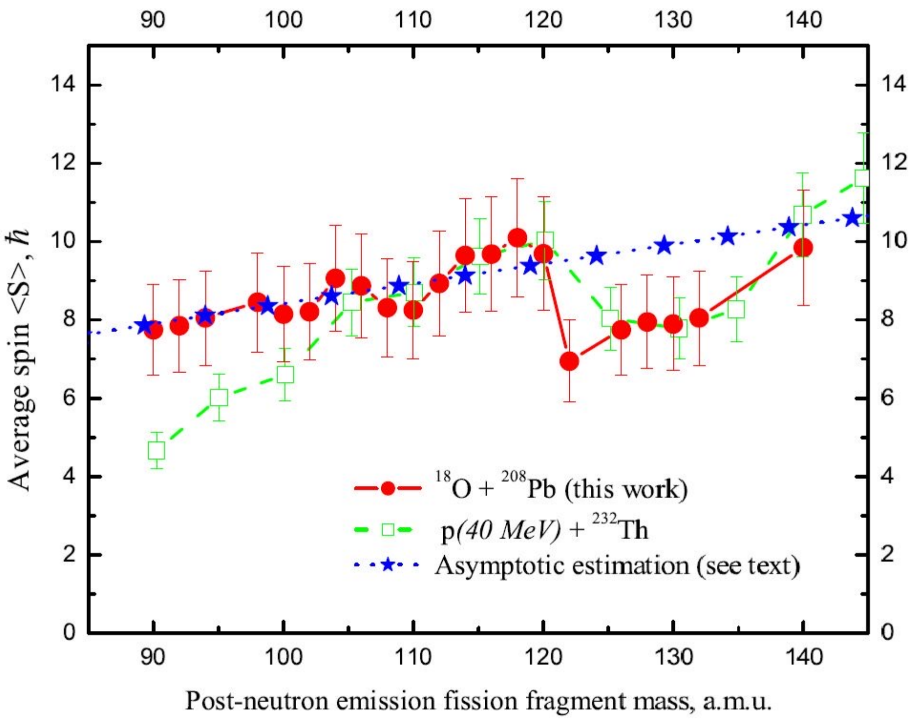
Backup Slides

Average spin measured in heavy-ion induced fission

A. Bogachev Eur. Phys. J. A **34**: 23-28 (2007)

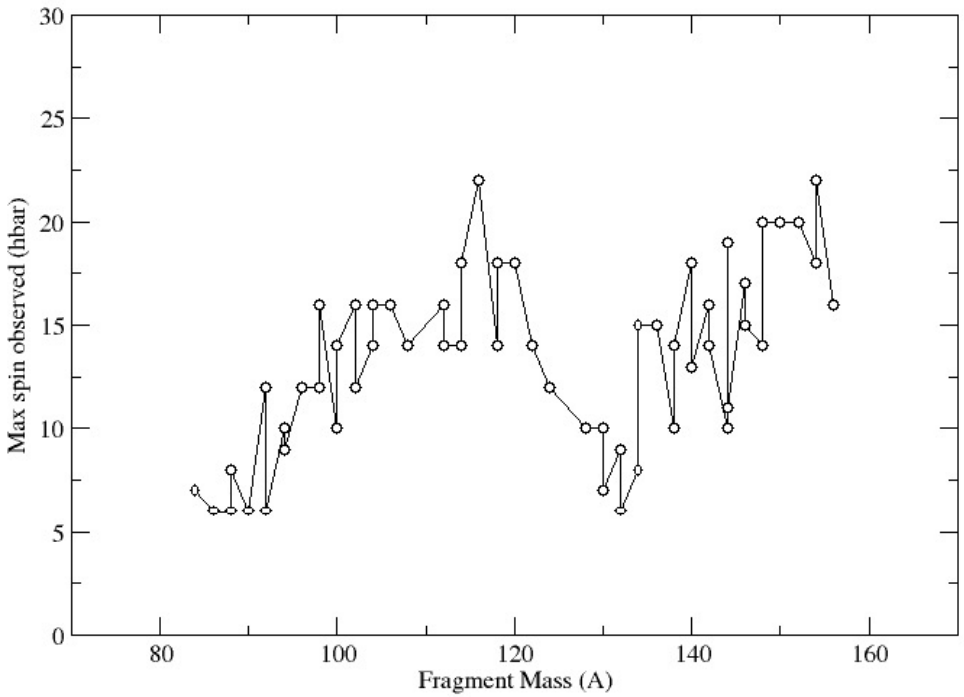
$^{18}O+^{208}Pb$



Why has this sawtooth not been seen before in SF?

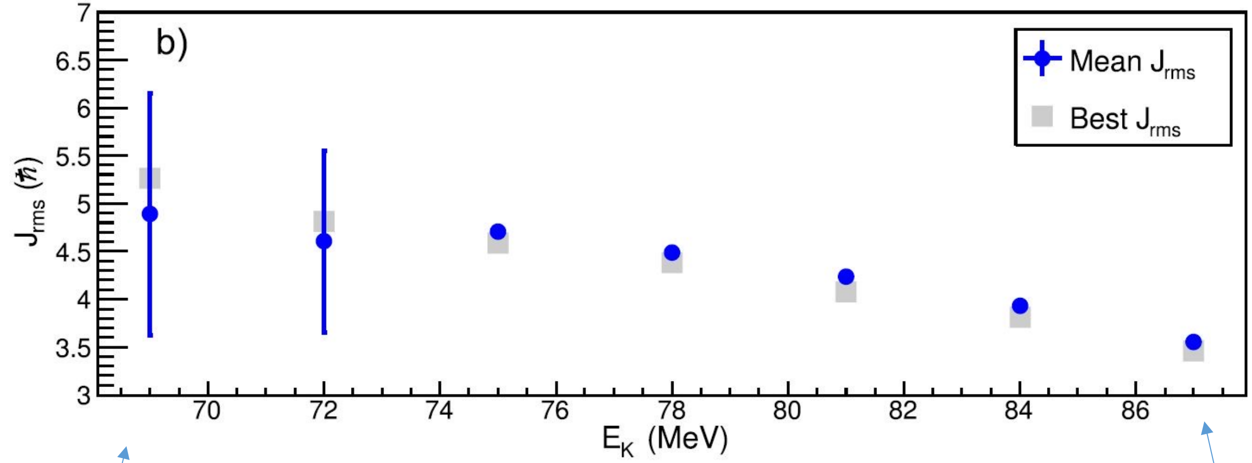
Spin sawtooth already exists in the existing literature

Max spin of even-even fragments populated with 252Cf(SF)



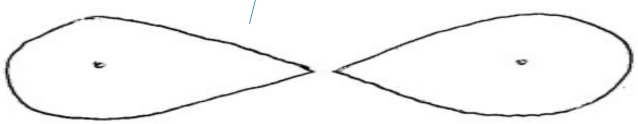
- Previous focus on fragment nuclear structure studies
- Previous experiments had population by both beta decay *and* fission. No technique was used to separate the two processes.
- Previous experiments had high multiplicity trigger conditions which biased results?

Relationship between spin and fragment kinetic energy



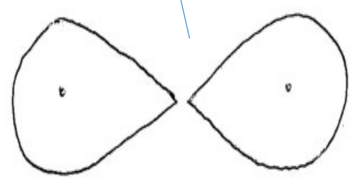
Kinetic energy dependence of fission fragment isomeric ratios for spherical nuclei 132Sn. Chebboubi et al. Phys. Lett. B775 190–195 (2017)

Large p, large L



Elongated rupture. Low TKE

Small p, small L



Compact rupture. High TKE

Correlations between 1n partner spins