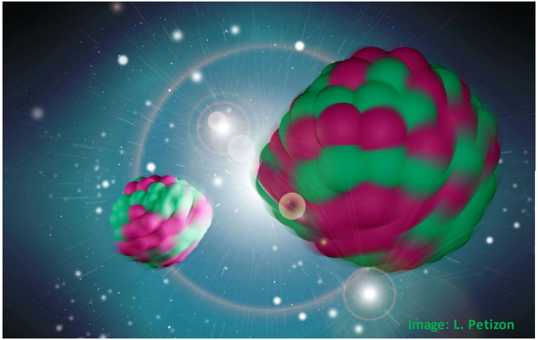
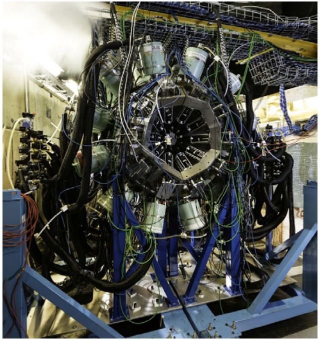
Experimental approaches to understand the generation of angular momentum in fission

J.N. Wilson, IJC Lab, Orsay





IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

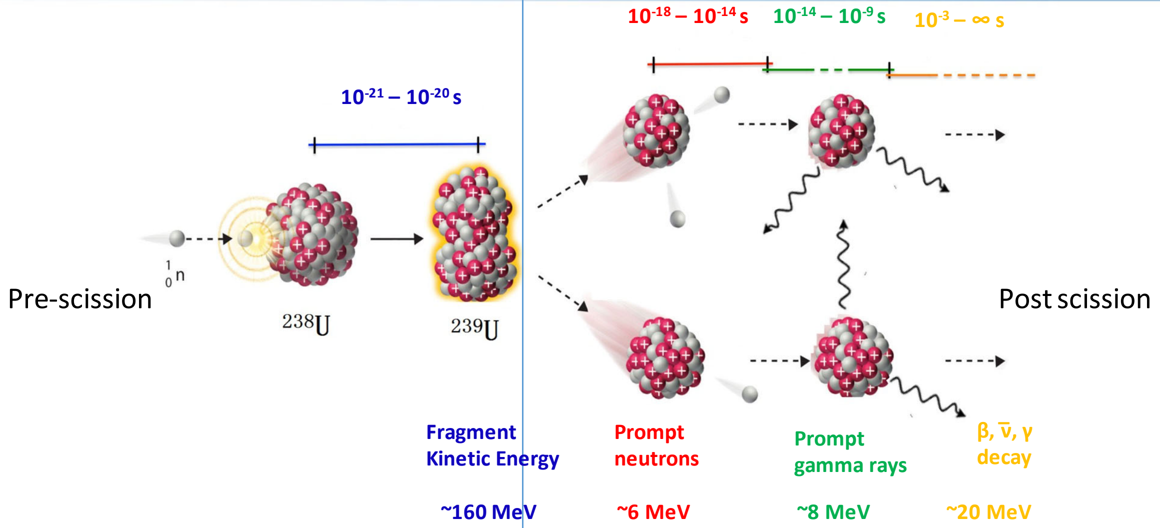
nu – ball

ALTO Accélérateur Linéaire auprès du Tandem d'Orsay

The spin sensitive observables

- **Prompt fission gamma gamma ray multiplicities**
- **Gamma ray spectroscopy of known excited states in the fragments**
- **Isomeric yield ratios**

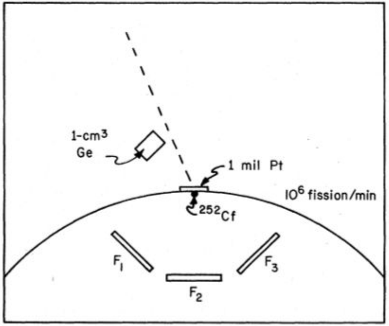
The de-excitation process in fission

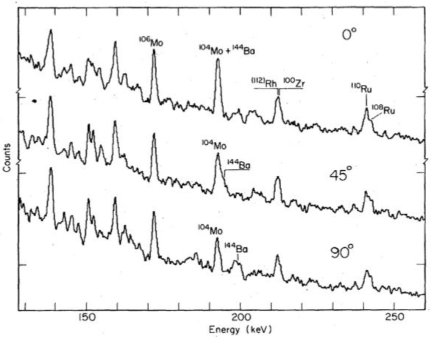


Fission fragments emerge spinning!

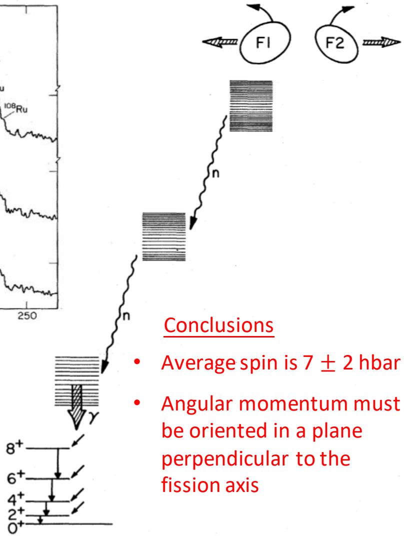
J.B. Wilhelmy et al.
Phys. Rev. C 5 2041 (1972)

Experimental setup





Gamma-ray spectra



Conclusions

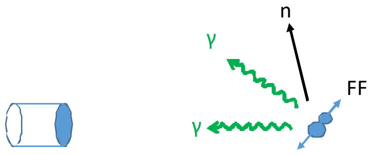
- Average spin is 7 $\pm$ 2 hbar
- Angular momentum must be oriented in a plane perpendicular to the fission axis

The spin sensitive observables

- **Prompt fission gamma gamma ray multiplicities**
- Gamma ray spectroscopy of known excited states in the fragments
- Isomeric yield ratios

Measurements of average prompt fission gamma ray multiplicities

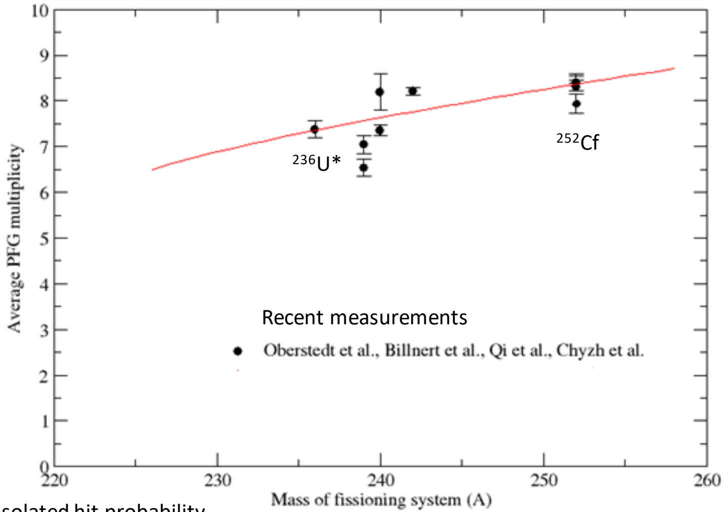
<u>One γ detector (low efficiency)</u>



Discrimination neutrons and gammas via TOF

Measure of average PFG multiplicity, $\langle M_\gamma \rangle$

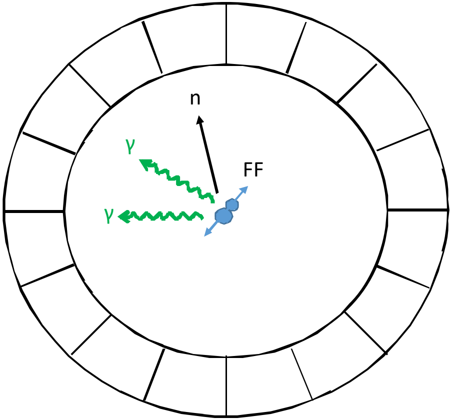
$$\langle M\gamma \rangle = \frac{N_{coinc}(FF-\gamma)}{\varepsilon_\gamma \, Nsing_{les}(FF)}$$



Large detector distance -> low efficiency -> high isolated hit probability

Measurements of prompt fission gamma ray multiplicities

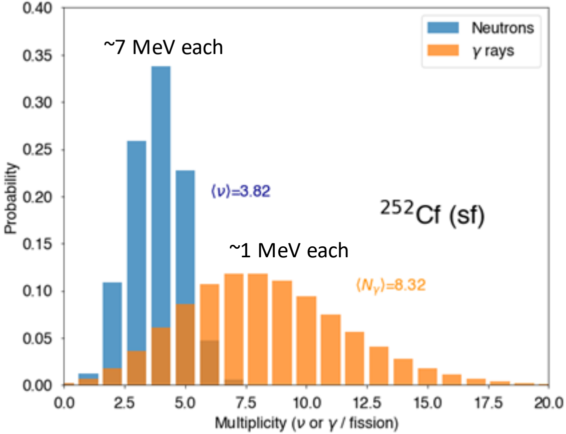
<u>4pi γ detector (high efficiency)</u>



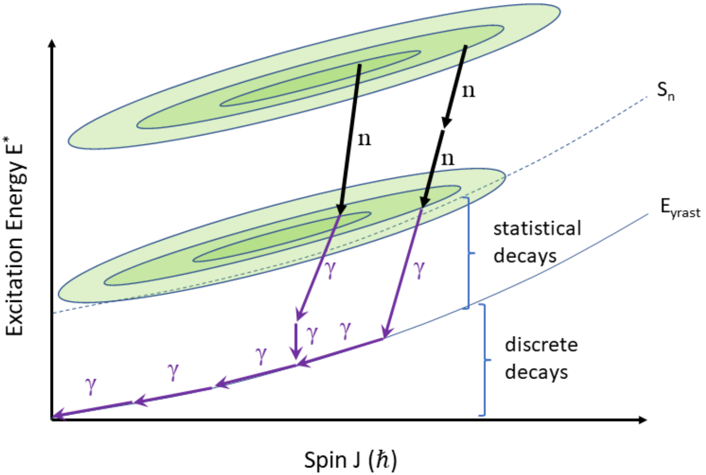
High efficiency + high granularity necessary
Unfolding of the detector response required

TXE: Energy available for prompt emission (25-30 MeV)

On average: ~21 MeV for neutrons, ~8 MeV for gammas



De-excitation of one fission fragment



Fragment entry distribution at scission

Fragment entry distribution after neutron emission

- ~75% of the excitation energy evacuated by neutrons
- ~80% of the angular momentum evacuated by discrete gamma decays

$\langle M_\gamma \rangle$ (one fragment) ~ 3.5 - 4 $\langle \nu \rangle$ (one fragment) ~ 1 - 2

How does gamma multiplicity vary with fragment mass? (Collimation)

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

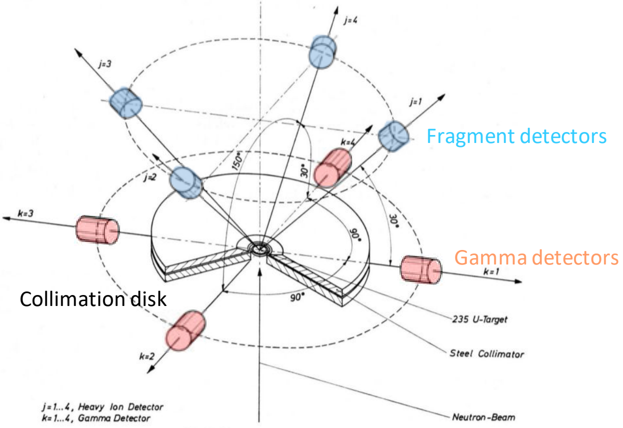
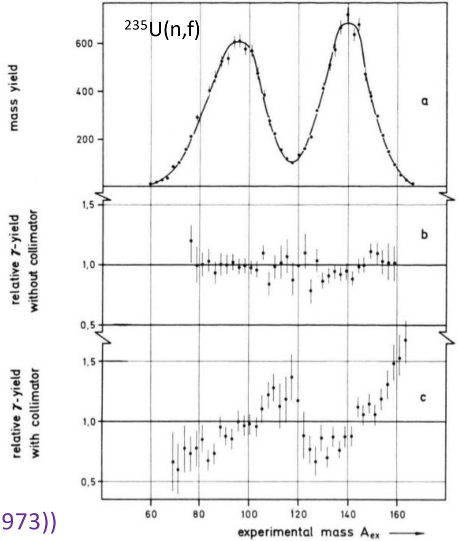


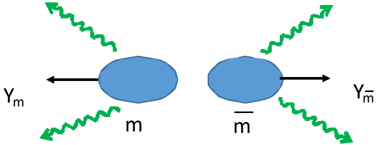
Fig. 1. Detector arrangement.



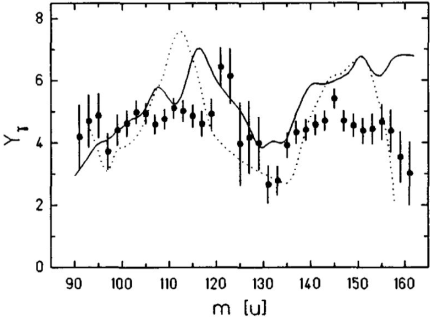
(Also F. Pleasonton, Nucl. Phys. A213 413 (1973))

How does gamma multiplicity vary with fragment mass? (Relativistic effect)

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

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

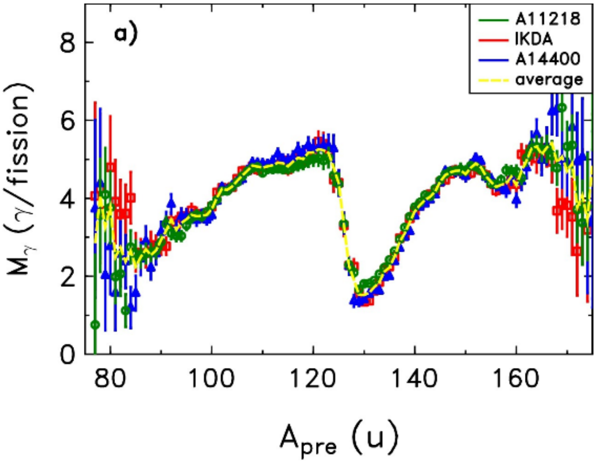
where m and $\overline{m}$ are corresponding fragments, Y_m and $Y_{\overline{m}}$ are the measured γ-yields in the narrow cone about the direction of the fragments, and $\beta_m, \beta_{\overline{m}}$ are the mean projections of the fragment velocity on the direction of the γ in that cone.

P. Glassel conclusion
Previous saw-tooth patterns must be ***wrong*** because of time cuts

Single fragment gamma multiplicity sawtooth confirmation

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

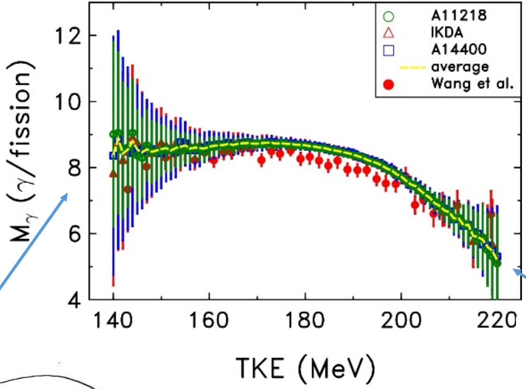
^{252}Cf(SF)



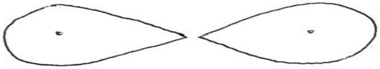
Gamma Multiplicity vs Total Kinetic Energy (TKE)

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

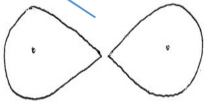
Fission Energy Release (Q) = Total Excitation Energy (TXE) + Total Kinetic Energy (TKE)



Suggests that fragment spins increase with E_x (but in a non-linear way)



Elongated rupture. Low TKE, High TXE, High M_γ



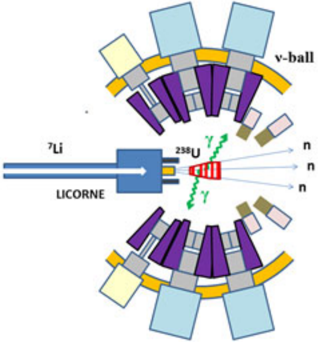
Compact rupture. High TKE, Low TXE, Low M_γ

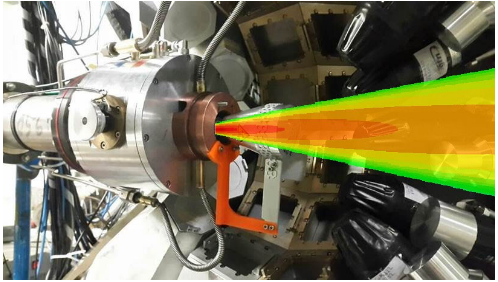
The spin sensitive observables

- Prompt fission gamma gamma ray multiplicities
- **Gamma ray spectroscopy of known excited states in the fragments**
- Isomeric yield ratios

LICORNE/ν-ball coupling principle

LICORNE: The 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

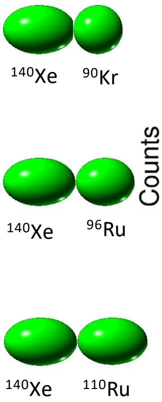
Secondary beam
2 x 10^7 /s

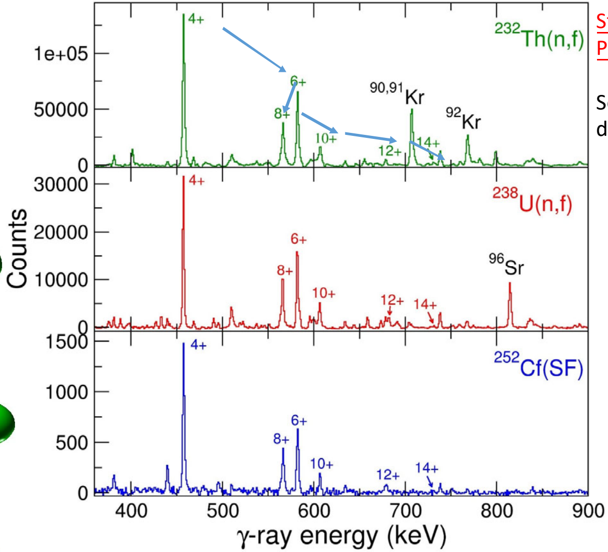
1.5 MeV neutrons

Samples
up to 10^5 fissions/s

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

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





Study of 3 different systems with the same device
Prompt decay only

Separation of prompt fission decay and beta-decay is essential (pulsed neutron beam)

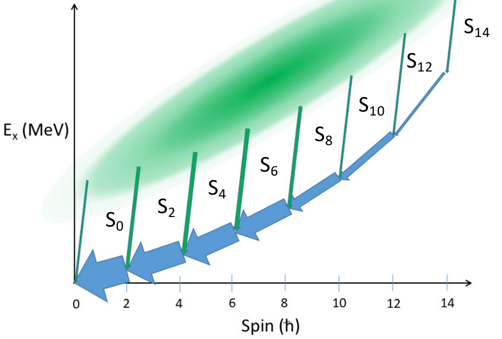
^{140}Xe shows invariant feeding pattern
Does the partner nucleus not matter?

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

Quantifiying the spin from the spectral data

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

$$\langle I \rangle \stackrel{?}{=} \sum_{i=1..n} I_i S_i \quad \sum_{i=1..n} S_i$$



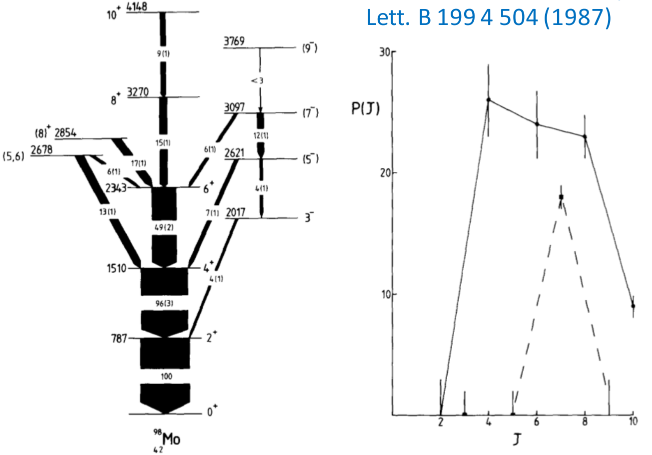
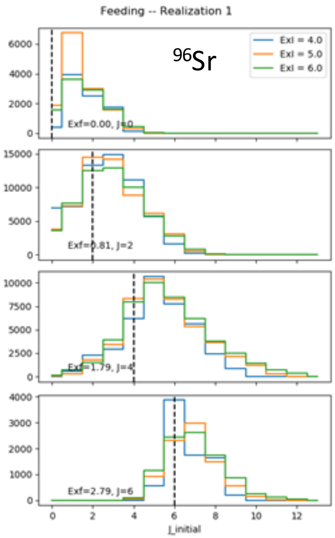
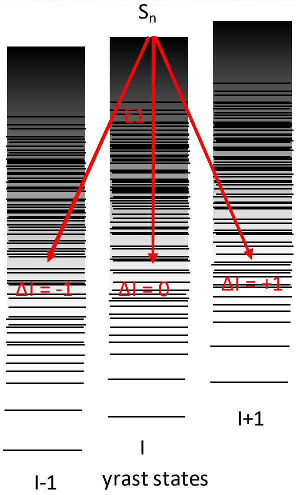
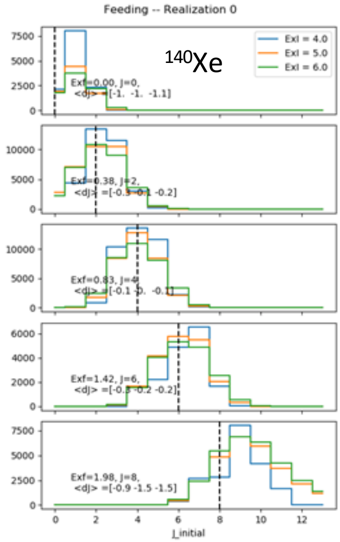


Fig. 1. An example of a partial decay scheme determined in the experiments, showing discrete line intensities observed following statistical population of entry points in ^{98}Mo final fragments. The populations $P(j)$ of states of spin j in ^{98}Mo fed directly by statistical γ-rays from the entry points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

RAINER Calculations for <ΔI> of statistical γ emissions





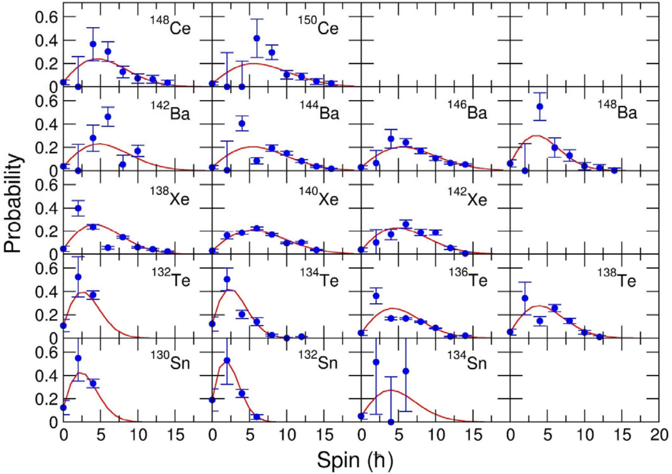


$\langle M_\gamma \rangle \sim 2 - 3$ $\langle \Delta I \rangle \sim 1$ hbar

Courtesy of F. Zeiser

Examples of measured side-feeding distributions

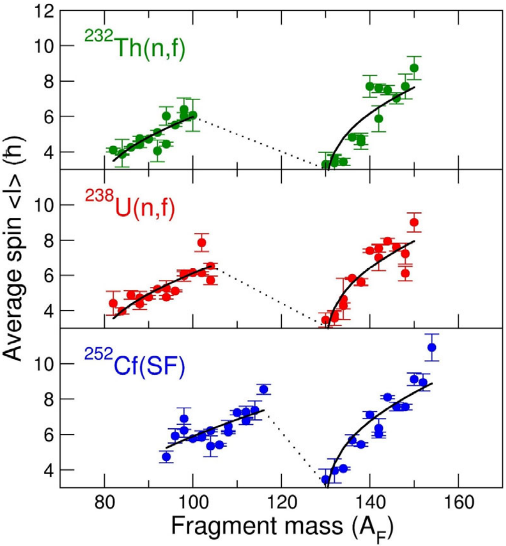
^{238}U(n,f) heavy fragments



Fit distributions with 1 parameter
Spin cutoff parameter σ^2

$$f(J) = \frac{2J+1}{2\sigma^2}\exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right]$$

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



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

Remarks

- Spin sawtooth complements M_γ sawtooth
- 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

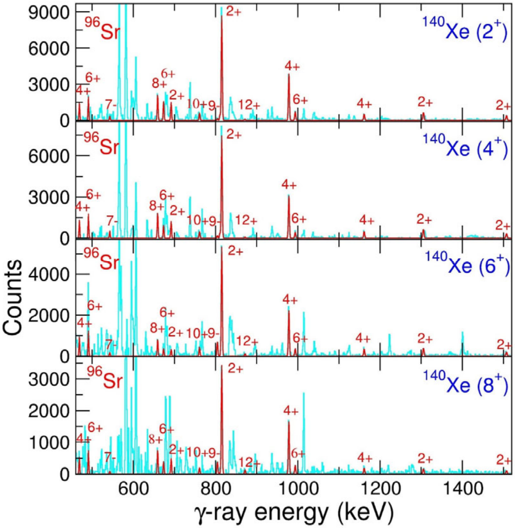
Each nucleus does not care who it emerged with!

- Certain partners have large asymmetries in <I>

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

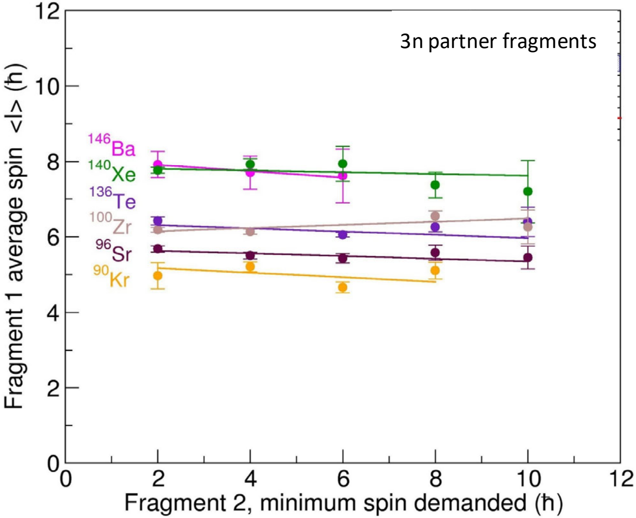
- Highly asymmetric distribution

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



Increasing spin demanded in ^{140}Xe

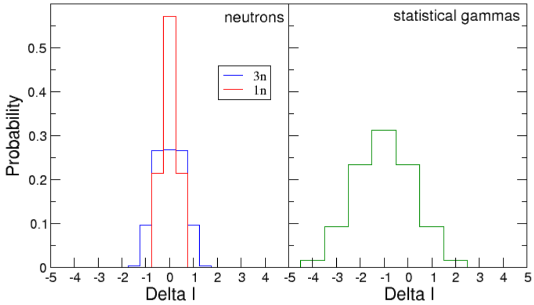
RESULTS: Correlation between fragment spins (3n partners)

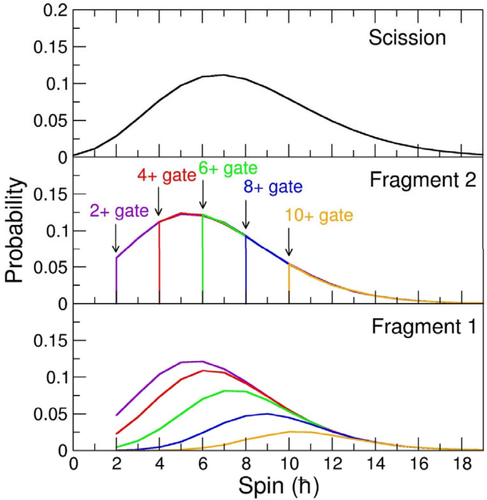


J.N. Wilson et al. Nature 590 566 (2021)

Monte-Carlo code: scission to yrast spin propagation

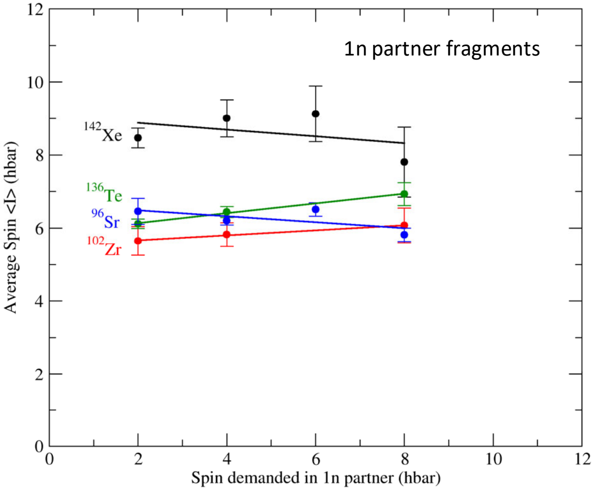
Spin dispersions from scission to yrast



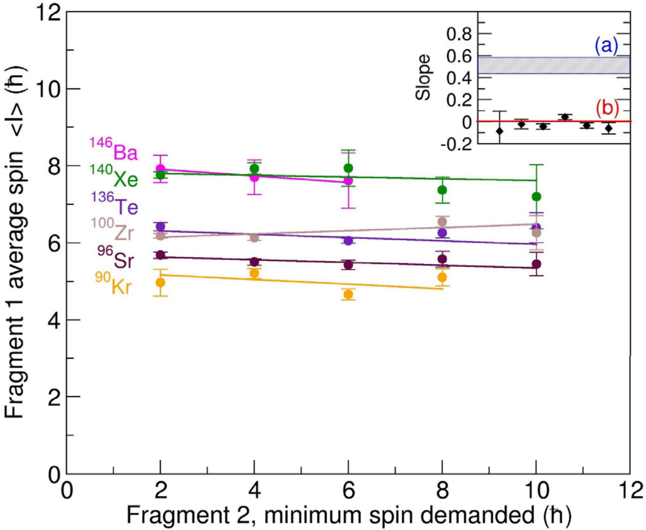


Conclusion: dispersions can slightly weaken spin correlations at scission but do not destroy them

RESULTS: Correlation between fragment spins (1n partners)



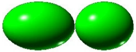
Correlation between fission fragment spin magnitudes



Correlated spins

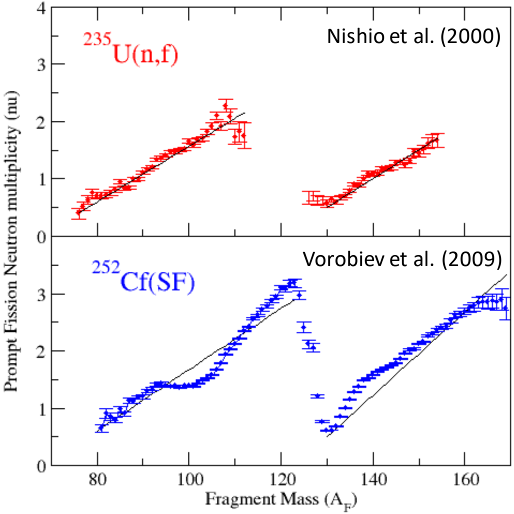
Uncorrelated spins

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



$$E_r = \hbar^2 \frac{I(I+1)}{2\mathcal{J}}$$

Simultaneous *neutron* and *gamma* sawtooth parametrisation



Suppose a linear relation between in fragment excitation energy, E_x with the number of nucleons outside the closed shell, A_N

$$E_x \propto A_N$$

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

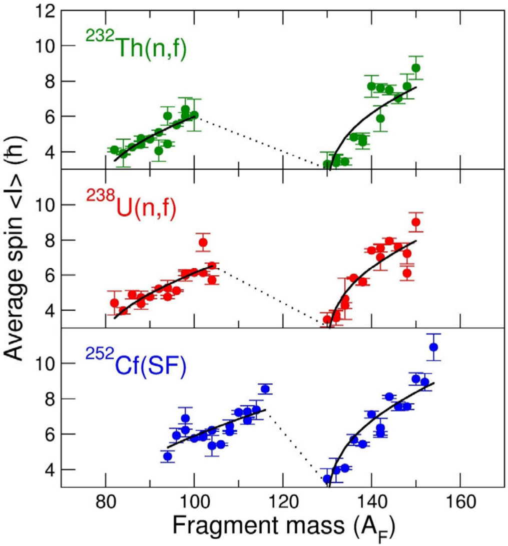
$$\sigma^2 \propto \sqrt{E_x}\, A_F^{7/6}$$ (From statistical theory)

Therefore, then spin sawtooth would vary as follows

$$I = cA_N^{1/4} A_F^{7/12}$$

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

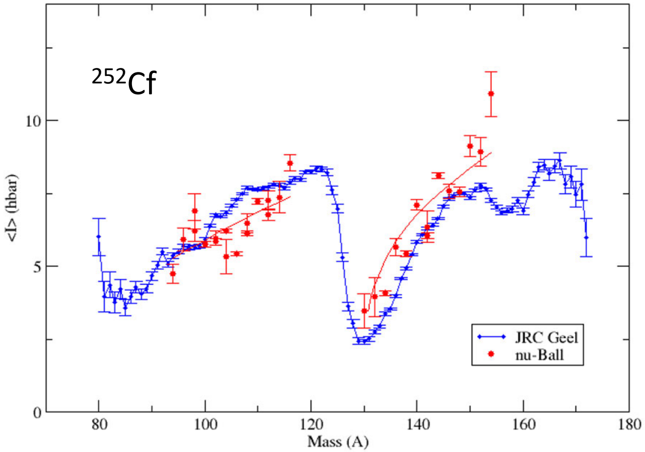
RESULTS: Average spin <I> vs fragment mass (A)



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

- The data points fall on this 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)

Comparison of spectroscopic and multiplicity data



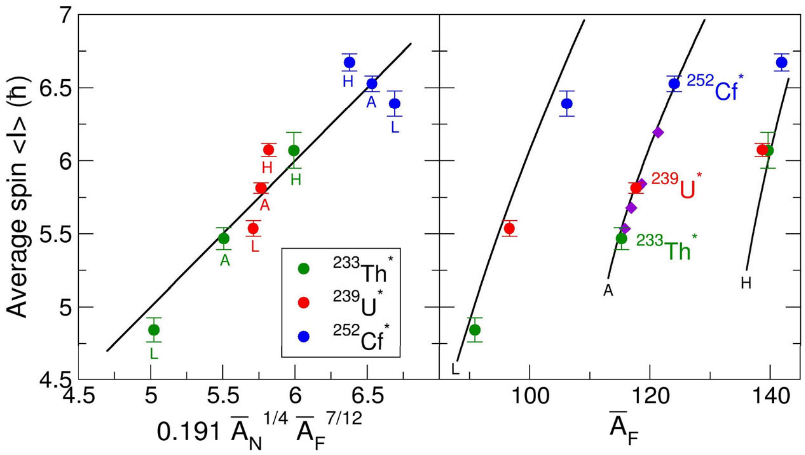
Normalization of multiplicity data:

$\langle I \rangle = 1.6 \langle M_\gamma \rangle$

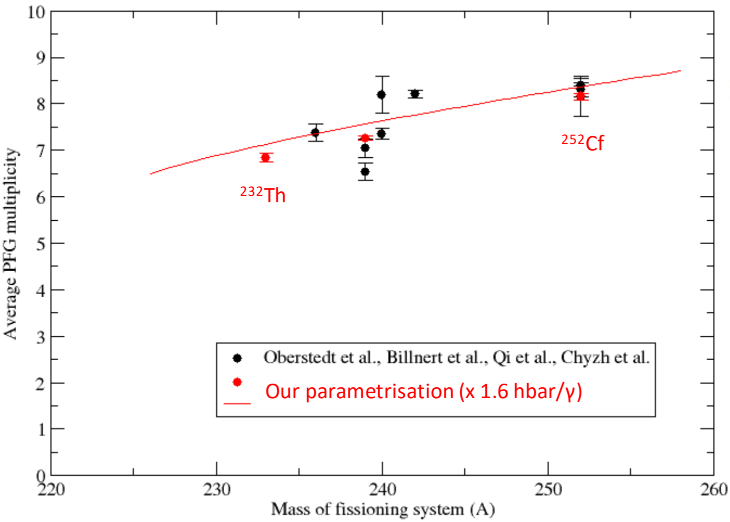
M. Travar et al. Phys. Lett. B 817 136293 (2021)
J.N. Wilson et al., Nature 590 566 (2021)

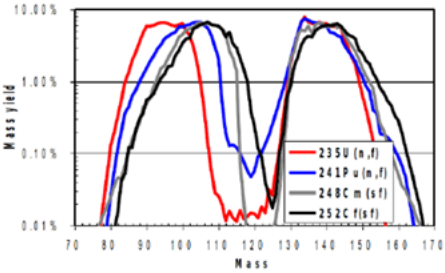
Predictions for other fissioning systems

Combining fission yield and spin data to calculate the <I> of the fissioning system



Cross check with PFG multiplicity (both fragments)



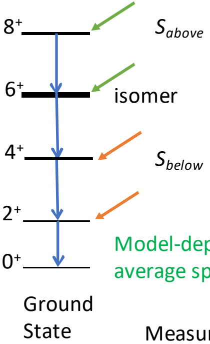


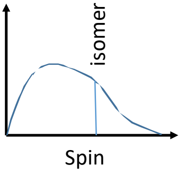
Total gamma multiplicity decreases with mass because the light peak moves closer to the ^{78}Ni closed shell and hence lower average spins occur in the light fragment

The spin sensitive observables

- Prompt fission gamma gamma ray multiplicities
- Gamma ray spectroscopy of known excited states in the fragments
- **Isomeric yield ratios**

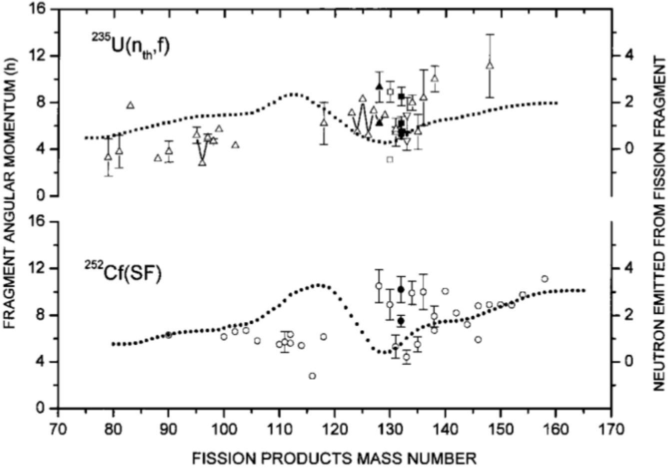
Estimation of <I> from isomeric yield ratios (IYR)





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

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

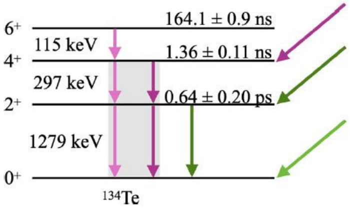


H. Naik et al. Phys. Rev. C71 014304 (2005)

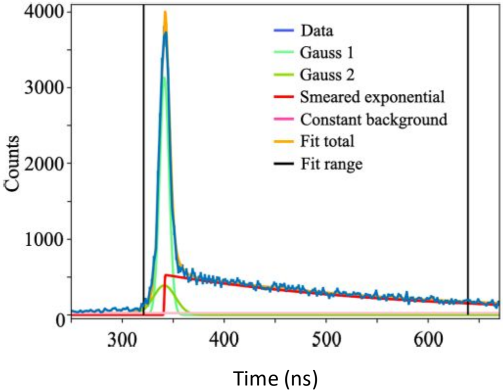
Variation of ^{134}Te Isomeric Yield Ratio (IYR) with other observables

Using the IYR of ^{134}Te as a highly sensitive probe to *small changes* in fragment angular momentum

D. Gjestvang, J. N. Wilson, et al. Phys. Rev. C 108, 064602 (2023)



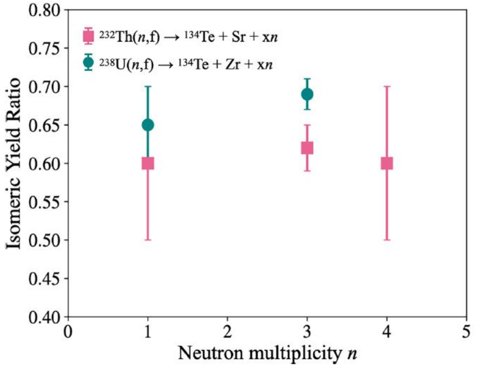
- IYR is defined as isomer feeding/total feeding
- Measured by fits to the time distribution (prompt and delayed componnents)
- IYR is sensitive to small changes in spin



Time distribution of 1279 keV/297 keV coincidence in nu-Ball

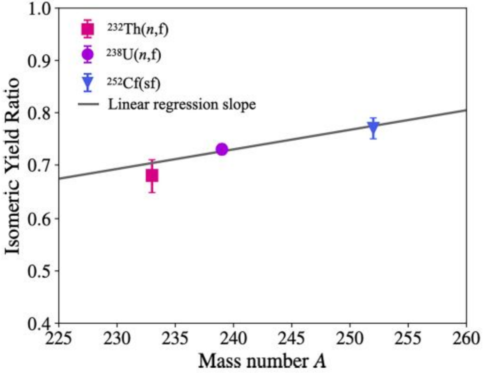
Results

Dependence of IYR on neutron multiplicity



No significant dependence on number of emitted neutrons

Dependence of IYR on mass of fissioning system



Weak dependence on fissioning A_{system} (~2σ significance)

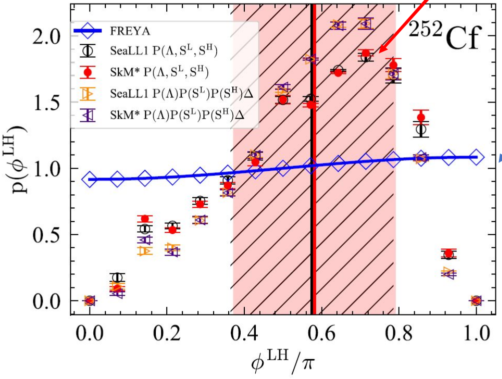
Remaining puzzles and open questions

Correlation between the fragment spin *directions?*

Theoretical predictions strongly disagree!

TDDFT, A. Bulgac et al., Phys. Rev. Lett. 128, 022501 (2022)

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



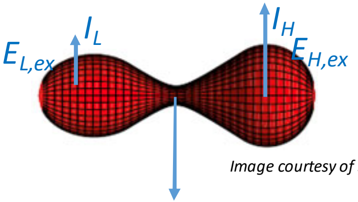
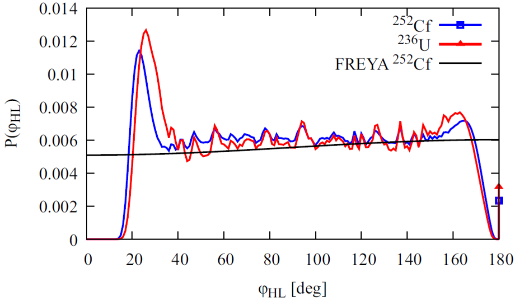


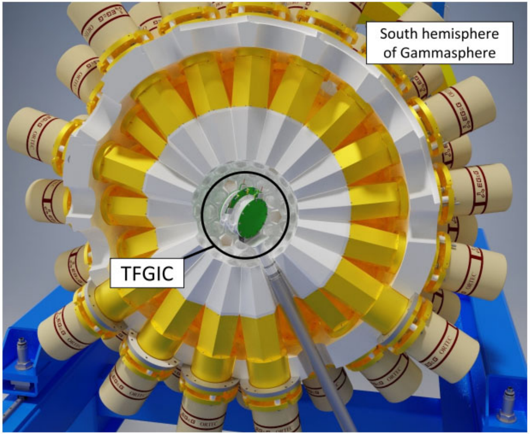
Image courtesy of S. Aberg

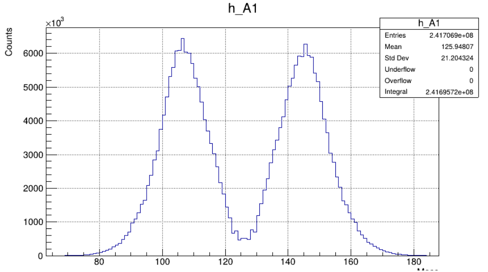


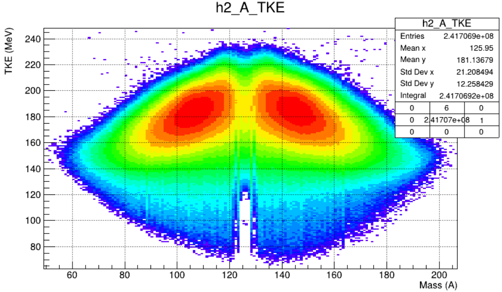
G. Scamps et al., Phys. Rev. C 108, L061602 (2023)

Ionisation chamber + ^{252}Cf + Gammasphere

- Expt: 4 kBq fission, 10 days
- Only theta, no phi

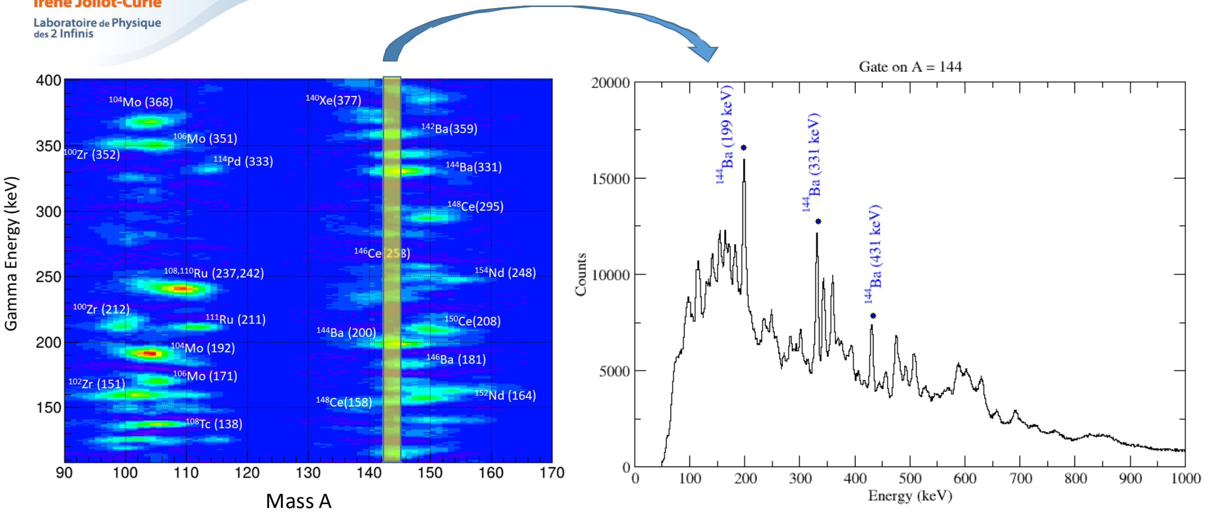






Courtesy of S. Marin and N. Giha, University of Michigan

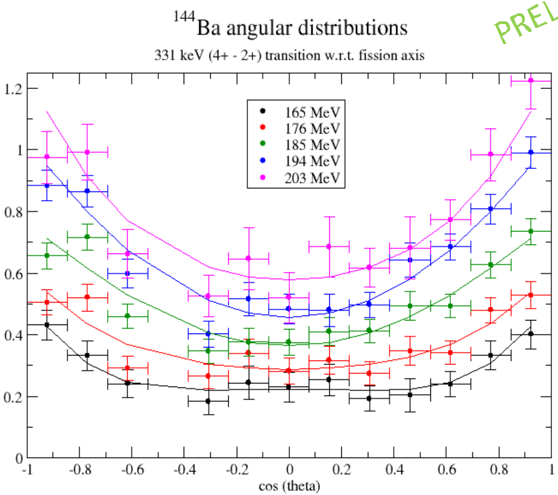
Mass – E_γ correlations



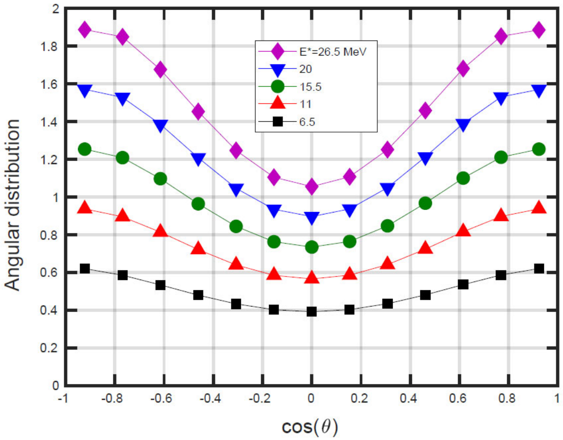
TKE dependence of the gamma ray angular distributions

Measurements

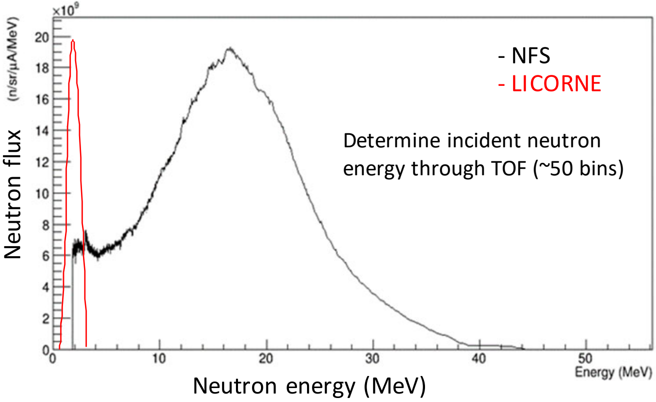
PRELIMINARY

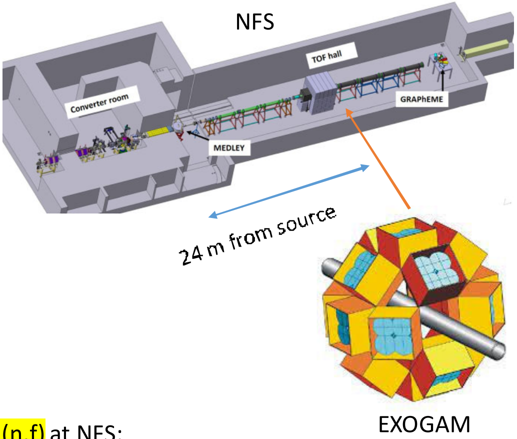


Theoretical calculations
T. Dossing and J. Randrup



Gamma ray spectroscopy of fast neutron-induced fission with EXOGAM at NFS

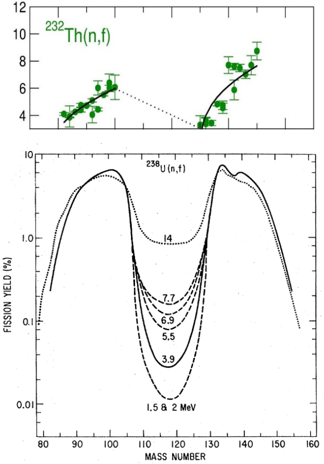




- July 2026 experiment to perform spectroscopy of ^{232}Th(n,f) at NFS:
- 50µA, 880 kHz primary beam and EXOGAM@24m with 20g thorium target
- Incident neutrons give both initial compound nucleus E* and angular momentum (r x p)

Open questions on angular momentum effects we hope to address

- How does the spin sawtooth pattern change with increasing excitation energy as the symmetric fission mode begins to dominate?
- Is the intrinsic angular momentum generation mechanism for the symmetric fission mode the same as for the asymmetric? ($\langle I \rangle \sim E_x^{1/4}$?)
- How much does pre-scission spin feeds through to the final fragments? How much goes into relative motion (orbital angular momentum)?
- What happens to the correlation between partner fragment spins when there is a significant source of pre-scission angular momentum?



<u>Also</u>: More spin sensitive observable measurements outside the actinide region are needed

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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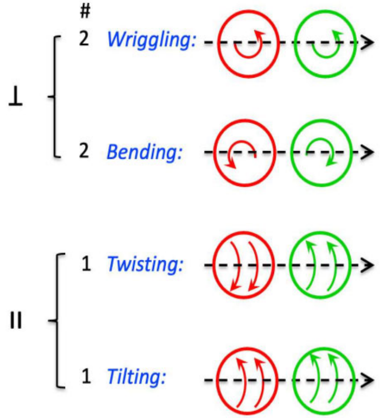
Backup Slides

Angular momentum "modes"



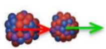
Beware of overuse of the word « mode »!!

1) Spontaneous fission: a ***mode of decay***

2) Description of ***the shell effects*** governing the mass partition (e.g. S1 mode, S2 mode, Super-long mode, etc.)

3) A ***zoology*** of fragment spin directions after scission (bending mode, wobbling mode, etc.)

4) A kind of vibrational ***mechanism*** via which fragment spin is generated

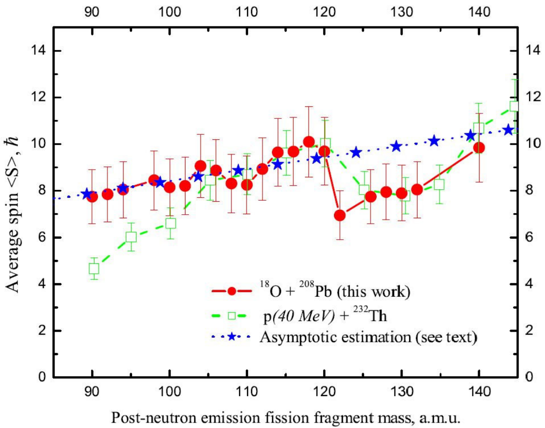


mutually parallel,
parallel to axis

Average spin measured in heavy-ion induced fission

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

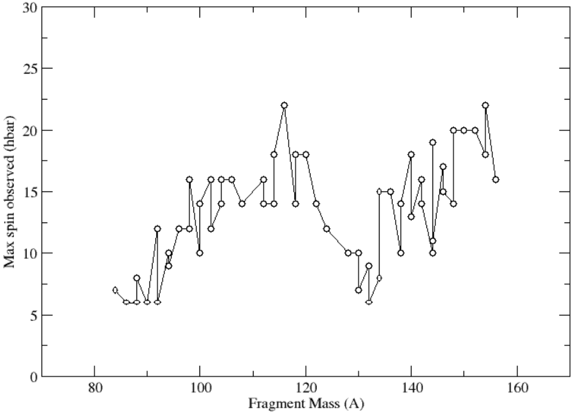
$^{18}O+^{208}Pb$



Why has this sawtooth not been seen before in SF?

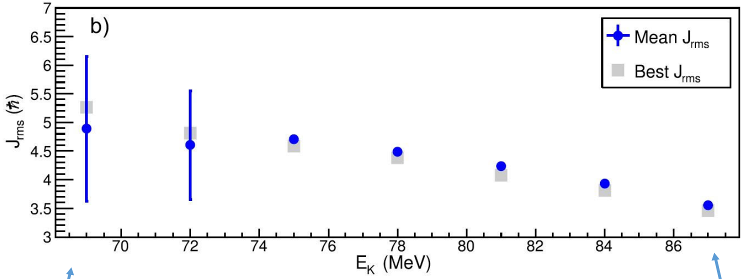
Spin sawtooth already exists in the existing literature

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



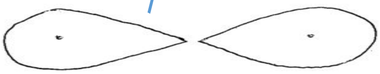
- Previous focus on fragment nuclear structure studies
- Previous experiments had population by both beta decay *and* fission. No technique was used to separate the two processes.
- Previous experiments had high multiplicity trigger conditions which biased results?

Relationship between spin and fragment kinetic energy



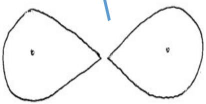
Kinetic energy dependence of fission fragment isomeric ratios for spherical nuclei 132Sn. Chebboubi et al. Phys. Lett. B775 190–195 (2017)

Large p, large L



Elongated rupture. Low TKE

Small p, small L



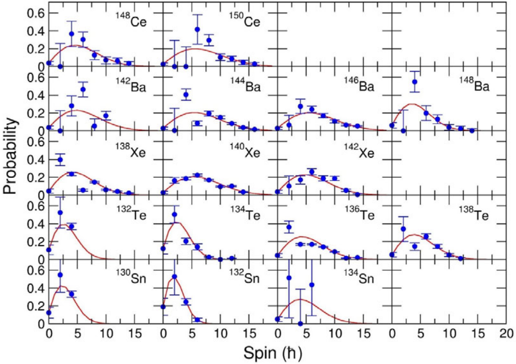
Compact rupture. High TKE

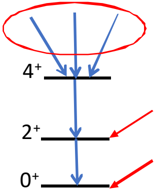
Corrections of fission yields for 2+ side-feeding

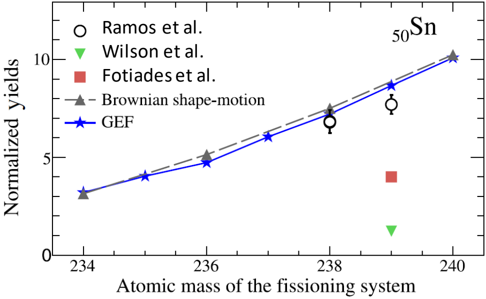
238U(n,f) yields

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

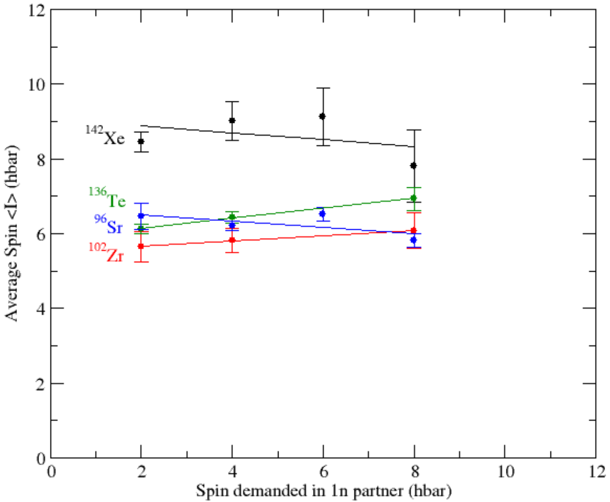
J. N. Wilson et al., Phys. Rev. Lett. 118, 222501 (2017)
D. Ramos et al. Phys. Rev. Lett. 123, 092503 (2019)
N. Fotiades et al., Phys. Rev. C 99, 024606 (2019)



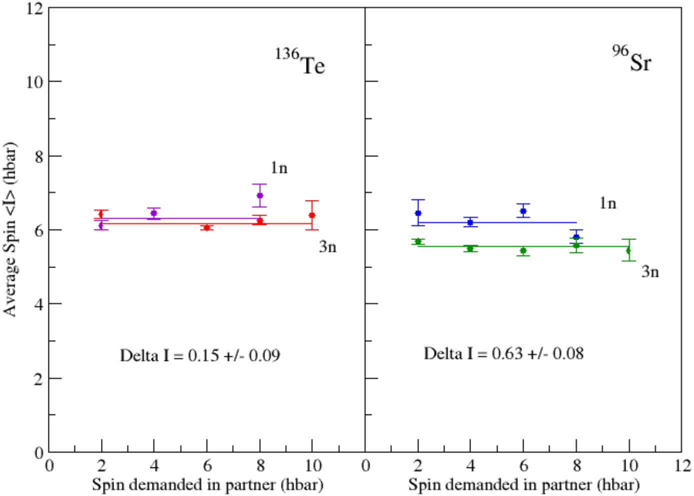




Correlations between 1n partner spins



Measurement of Delta I vs neutrons?



Preliminary