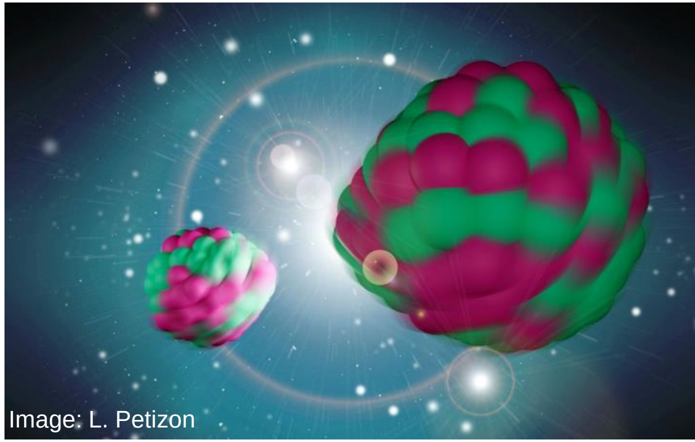
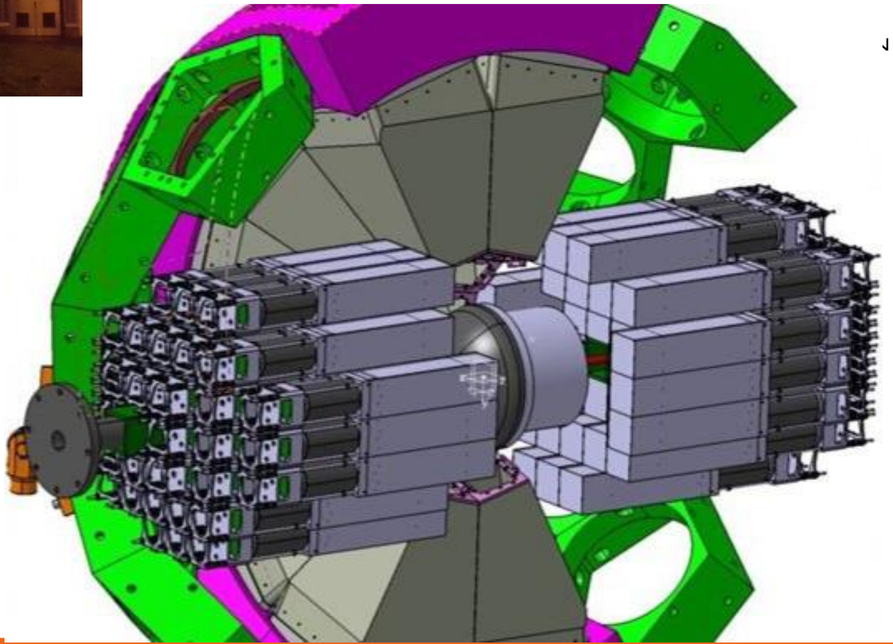
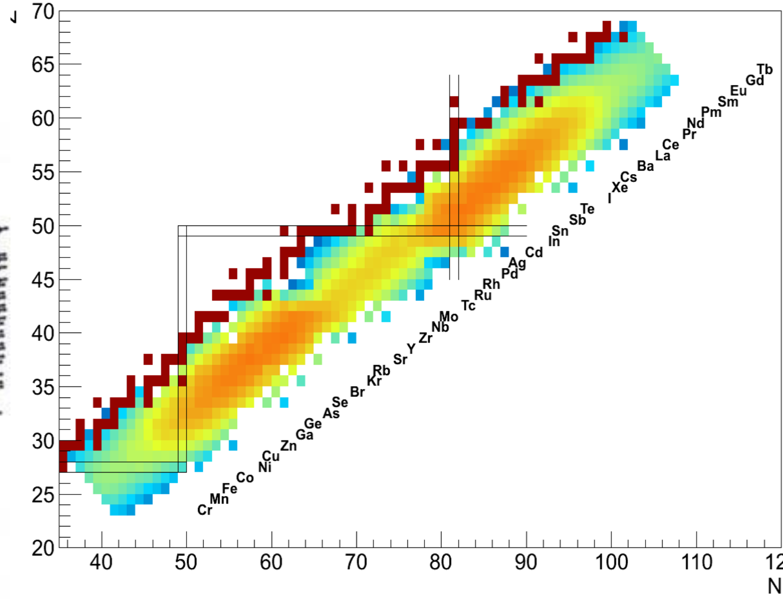
Future possibilities for γ-ray spectroscopy of fission in direct kinematics

J.N. Wilson, IJC Lab, Orsay

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis







NuBall 2

ALTO
Accélérateur Linéaire auprès du Tandem d'Orsay

Why do spectroscopy of fission?

Gamma-ray spectroscopy of fission fragments with state-of-the-art techniques
S. Leoni, C. Michelagnoli and J.N. Wilson, La Rivista del Nuovo Cimento 45, p 461–547, (2022)

Prompt gamma rays (and neutrons) carry information about the fission process and the nuclear structure of the fission fragments

Fission studies

- Mass/charge partition (fission yields) as a function of A,Z,E* and J
- Correlations in fission (multi-obsevable fission experiments, n/γ competion, etc.)
- Angular momentum generation (propagation, angular correlations, etc.)

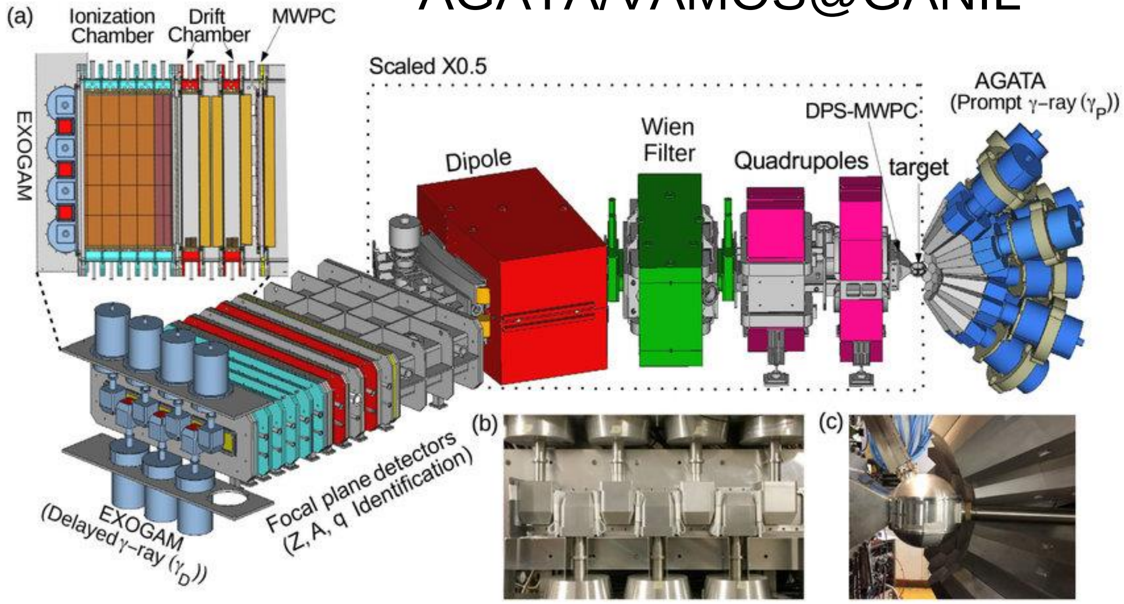
Studies of the nuclear structure of neutron-rich fragments

- Fast timing, nuclear moments
- Spectroscopy of more exotic fragments (very challenging!)

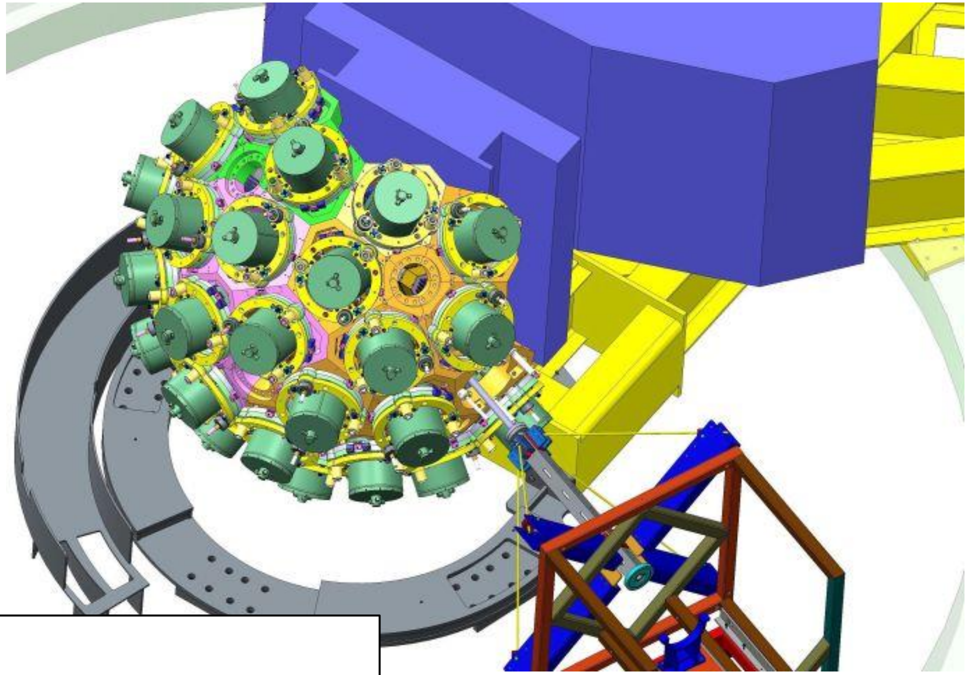
We need: (i) High statistics, (ii) the most neutron-rich reaction mechanisms,
(ii) High selectivity from both high-resolution gamma spectroscopy and other detection systems

Gamma Spectroscopy of fission in inverse kinematics

AGATA/VAMOS@GANIL



AGATA/PRISMA@Legnaro



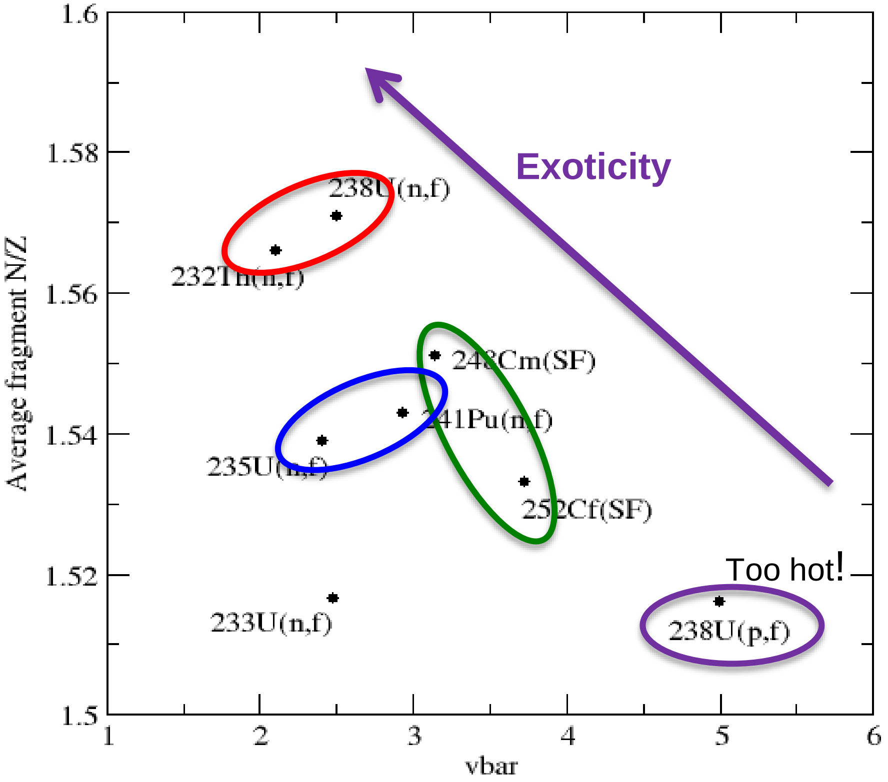
- ^{238}U and soon ^{232}Th beams at typically 6 MeV/u
- Fission induced after multinucleon transfer
- Control over E* with detection of outgoing particle (SPIDER)
- Full A/Z characterisation of fragments

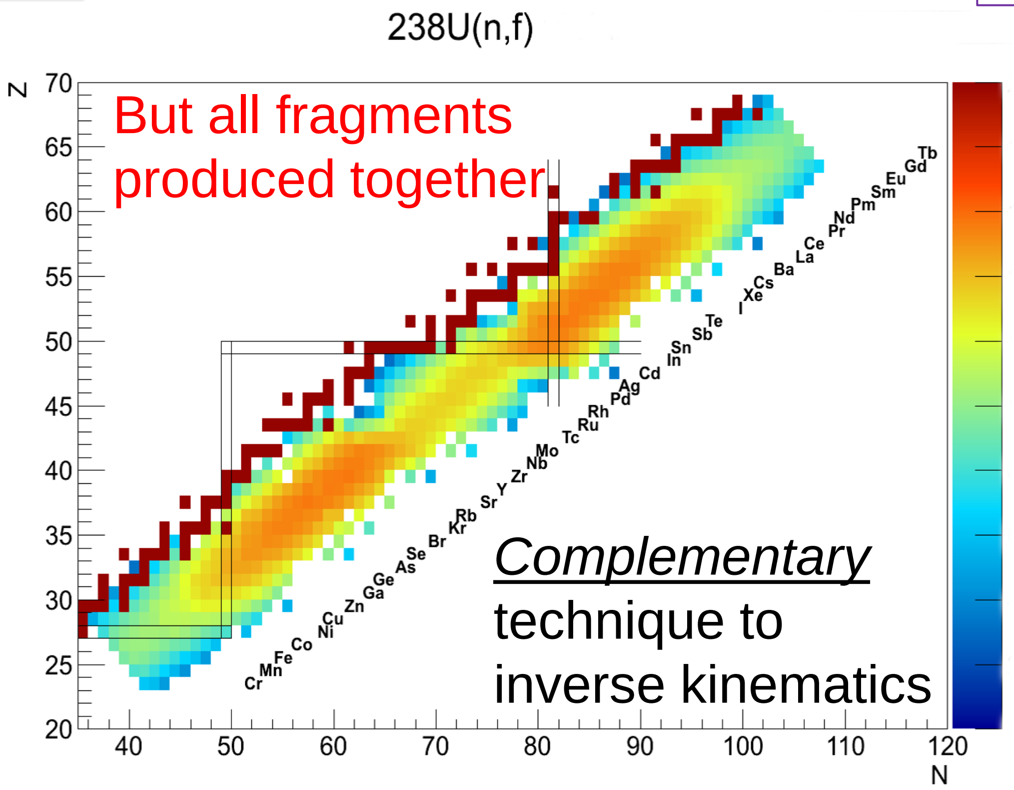
- These are surrogate reactions with potential large angular momentum transfer
- Only one fission fragment is detected in VAMOS (2nd branch under development)
- Doppler broadening due to high v/c, (but mitigated by high AGATA granularity)
- Count rate limited (2 kHz VAMOS?)

Why do spectroscopy of fission in direct kinematics?

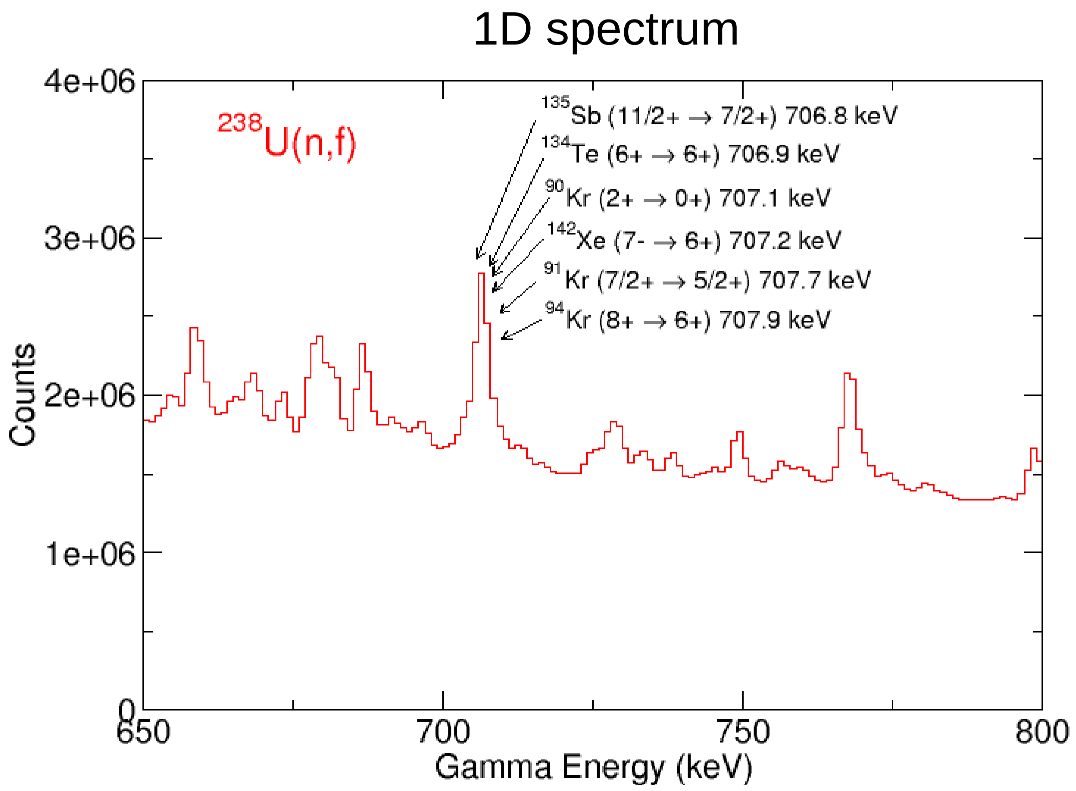
- It is useful for both the study of Nuclear Structure and the Nuclear Fission process
- We can access the most neutron rich production mechanisms available ^{232}Th(n,f) and ^{238}U(n,f)
- Since the fragments stop in 1-2 ps we can study with *direct kinematics* (v/c=0)
- v/c = 0 gives the ultra-high resolving power of Ge intrinsic resolution

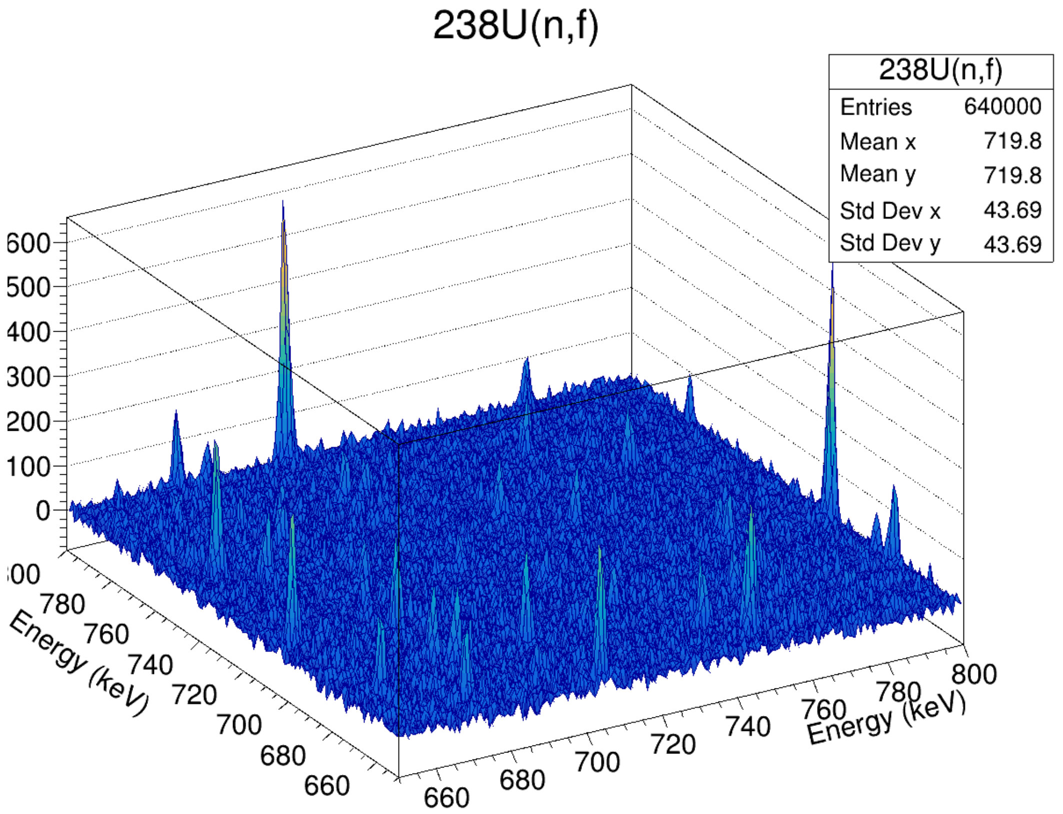
$$R \propto \frac{1}{(\Delta E)^3}$$





High resolution gamma-ray coincidence analysis



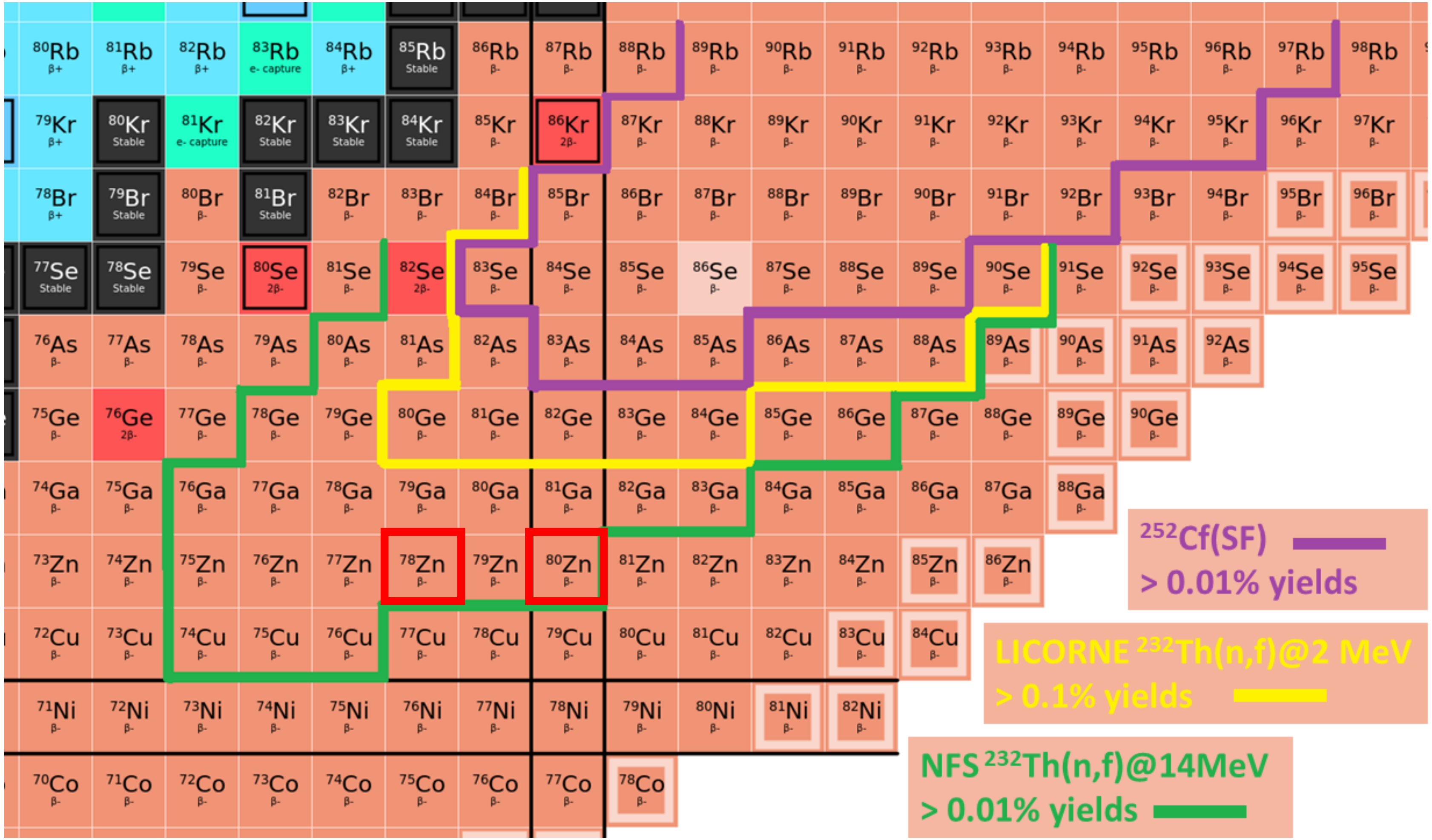


D.C. Radford, ESCL8R and LEVIT8R: software for interactive graphical analysis of HPGe coincidence data sets. Nucl. Instrum. Meth. Phys. Res. A 361, 297−305 (1995)

The problems of reaching exotic isotopes

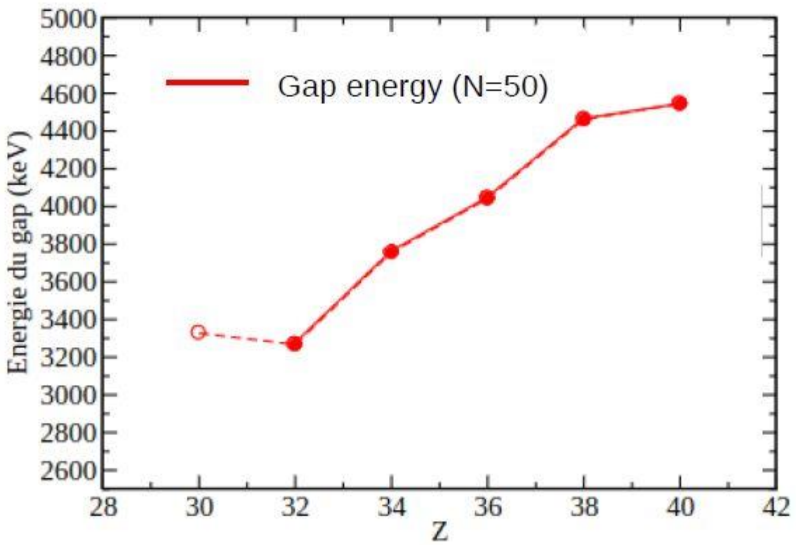
We need:
(i) High statistics
(ii) the most neutron-rich reaction mechanisms,
(iii) High selectivity from both high-resolution gamma spectroscopy and other detection systems

Nuclei accessible via gamma spectroscopy in direct kinematics

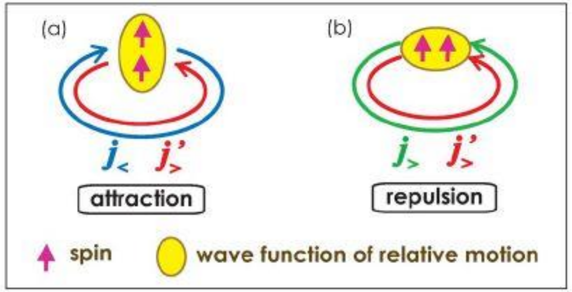


N=50 gap: $\Delta\varepsilon^{[N=50]} = \varepsilon(2d_{5/2}) - \varepsilon(1g_{9/2})$
Known to **reduce when approaching ^{78}Ni**

Central force + spin-orbit : not sufficient to describe nuclei far from stability
Tensor force mechanism added to explain the single particle orbits energy evolution
→ but limitations especially near ^{78}Ni

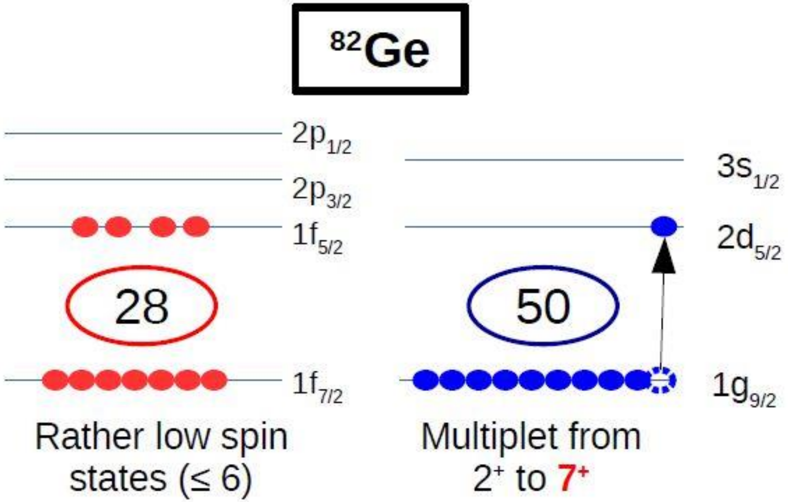


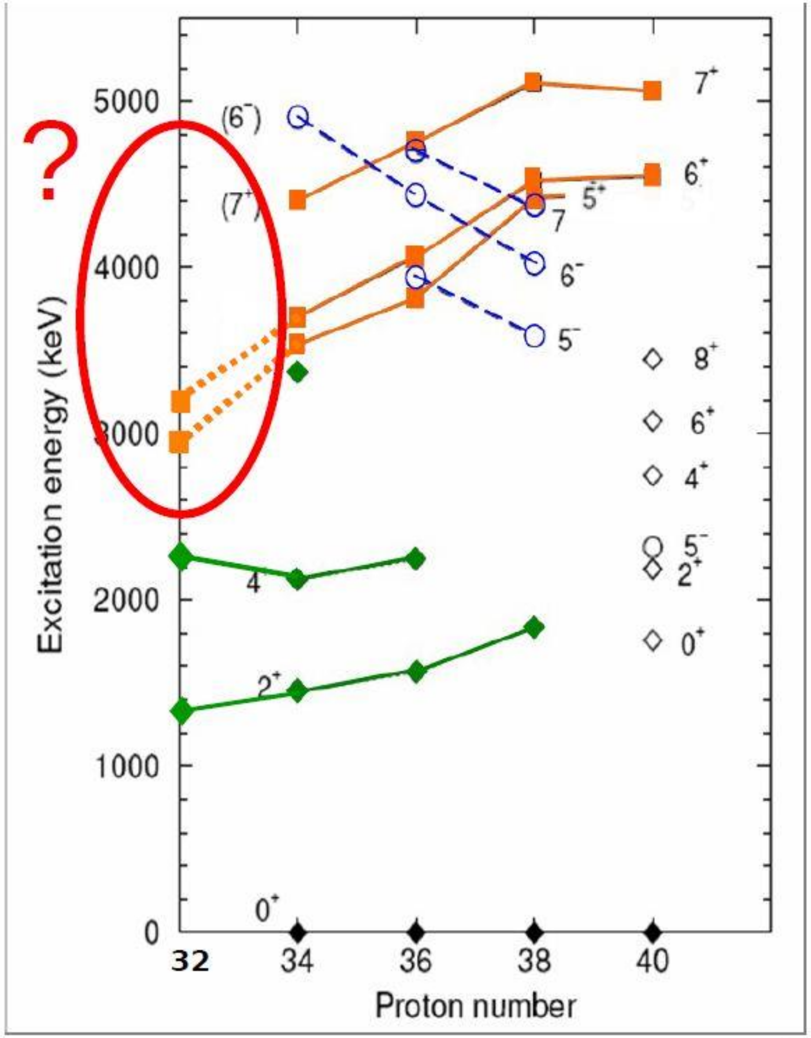
To access the gap size using spectroscopy :
Observation of states whose wave functions are **dominated by the 1p-1h configuration**



The tensor force to drive these evolutions

Study of ^{82}Ge (nu-Ball1) D. Thisse et al., Eur. Phys. J. A 59: 153 (2023)





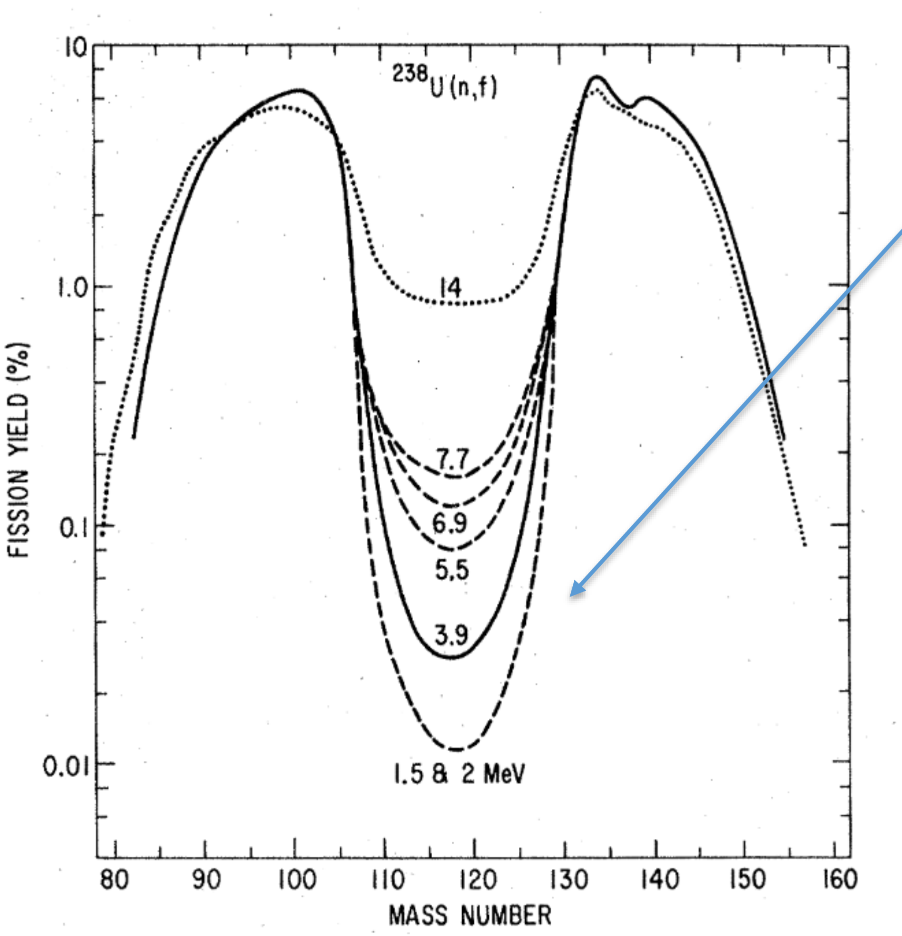
$(\nu 2d_{5/2})^1(\nu 1g_{9/2})^{-1}$ core-breaking configuration can be related to the N=50 gap properties

→ **Search for 7^+ <u>yrast*</u> state in ^{82}Ge**

→ Production of neutron-rich nuclei using fission reaction to populate **medium/high spin yrast states.**

*Other 7+ states (related to core coupling) are expected at higher energy (+1.5 MeV)

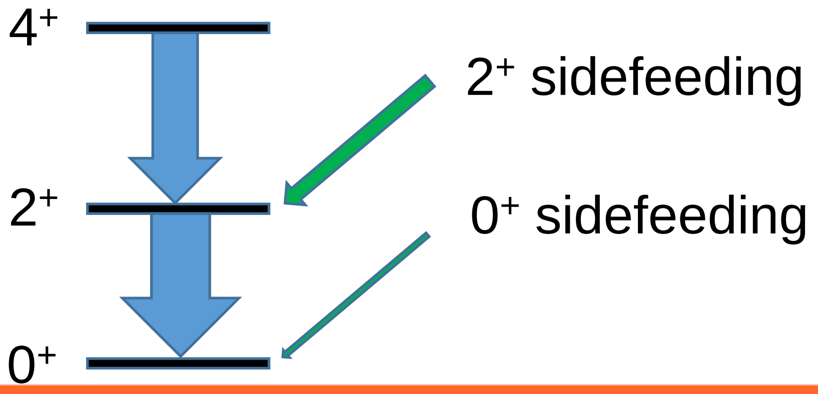
Fission studies: Evolution of fission yields with incident neutron energy



S. Nagy, Phys. Rev. C 17, 1 163 (1978)

Detailed study of the ingrowth of the symmetric fission mode with incident energy. Measure evolution of *A/Z distributions*.

- Yield measurements through determination of the total intensity of discrete gamma rays which feed the first excited states (even-even nuclei). Accuracy 20-30%.
- Benchmark γ–γ coincidence intensities with ^{252}Cf source measurement.

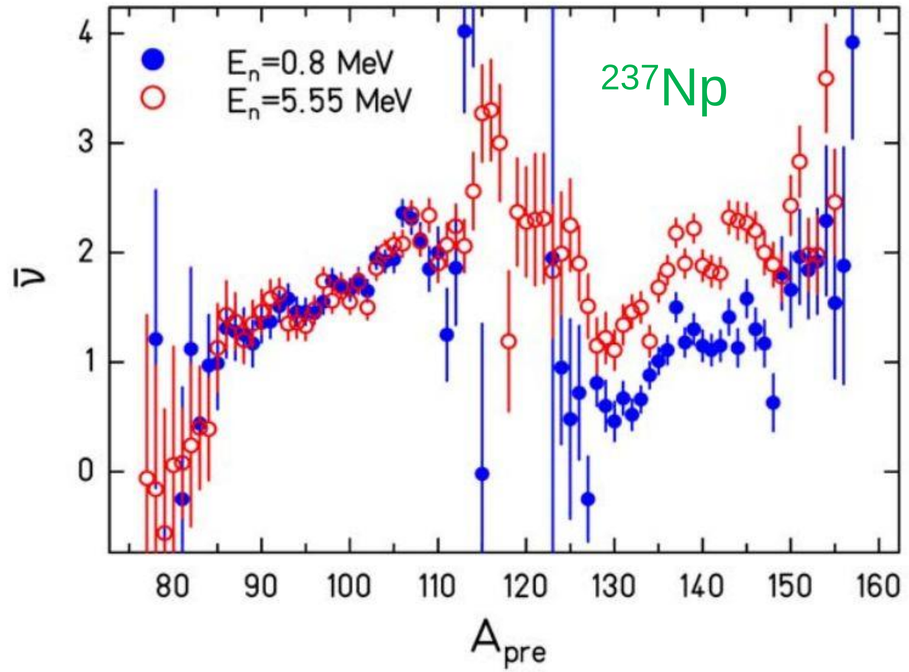


Fission studies: Test of the fission energy sorting mechanism

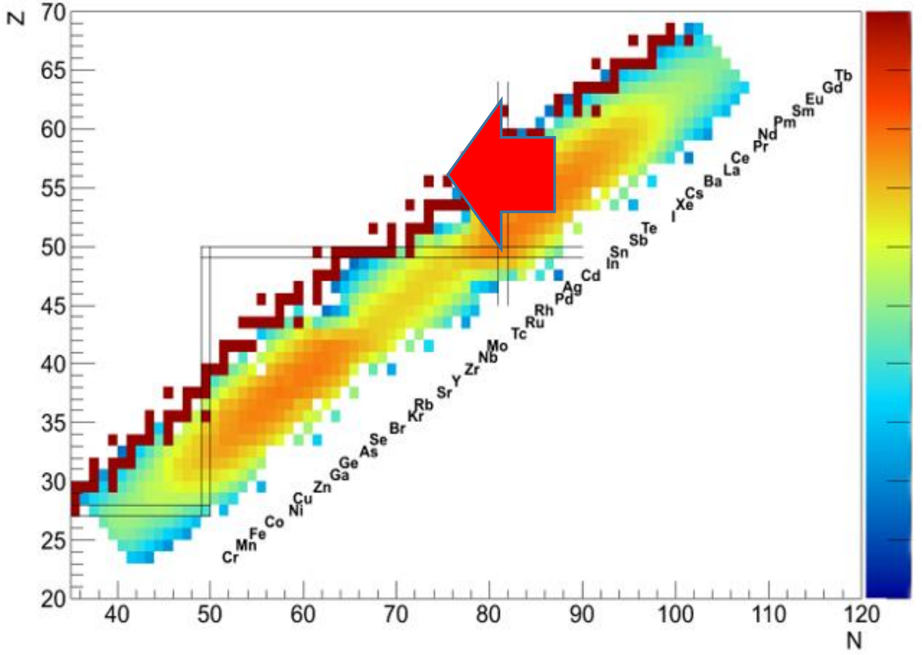
K-H. Scmidt and B. Jurado, Phys. Rev. Lett. 104 212501 (2010)

Extra excitation energy is expected to flow from light to heavy fragment due to differences in level densities

A. A. Naqvi et al., Phys. Rev. C 34 1 218 (1986)

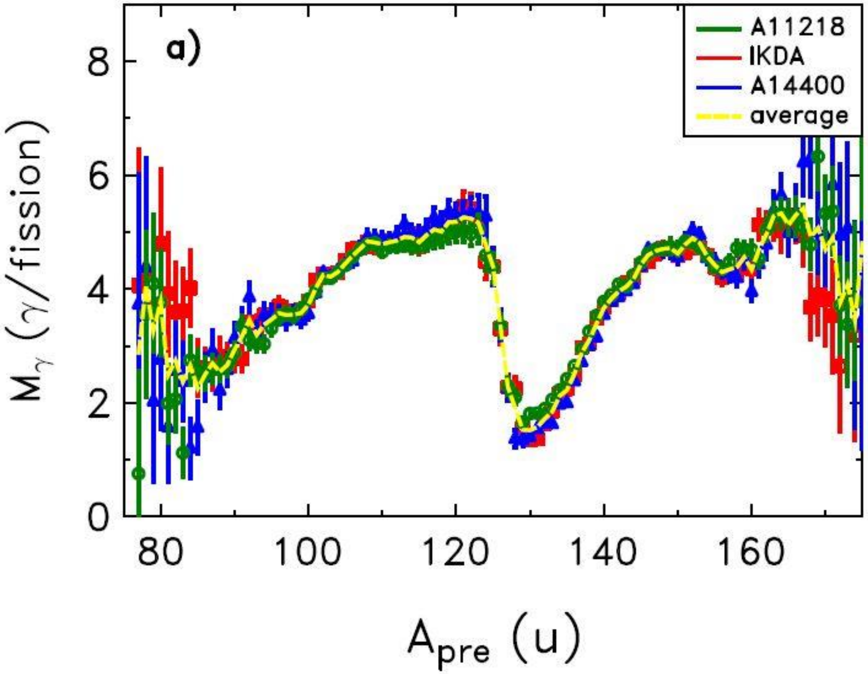


In our proposed experiment, heavy fragment yields would be expected to move towards stability with increasing E_n

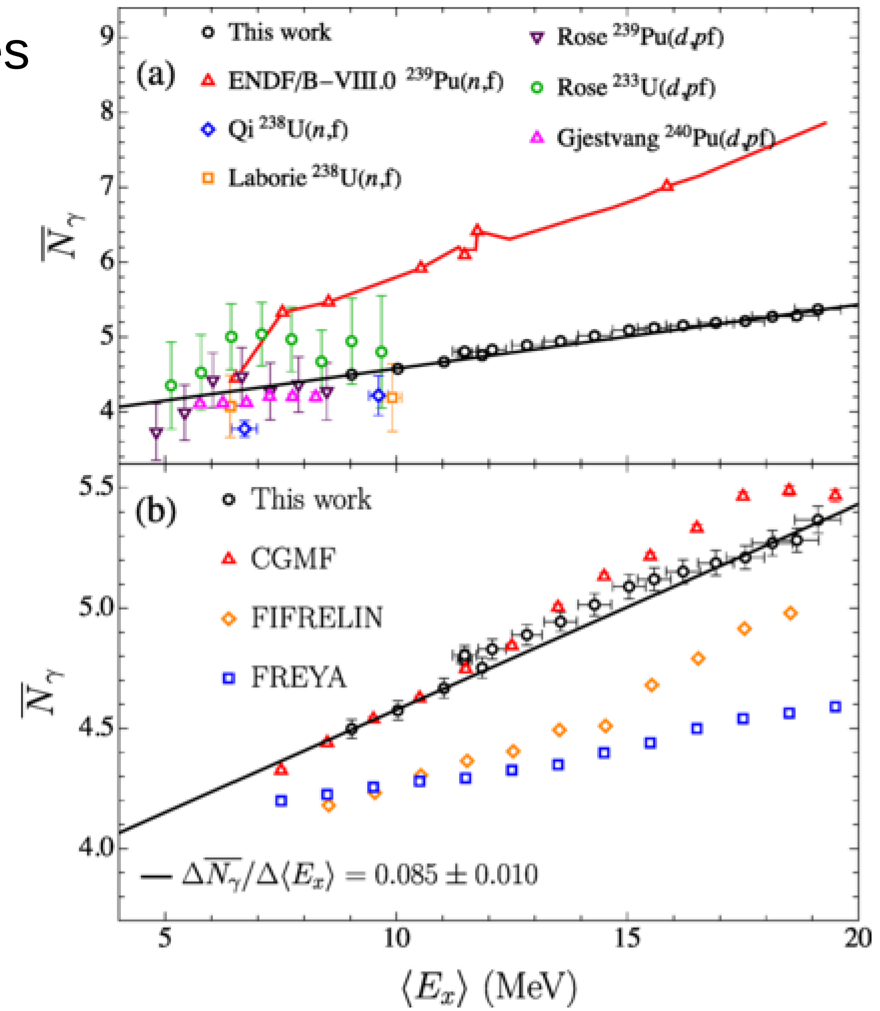


Evolution of gamma multiplicities with energy: angular momentum effects

For cold fission single fragment gamma multiplicities and <I>, sawtooth patterns recently observed



M. Travar et al., Phys. Lett. B817 136293 (2021)
J.N. Wilson et al., Nature 590, 566–570 (2021)



N.Ghia Phys. Rev. C 107, 014612

Open questions on angular momentum effects we hope to address

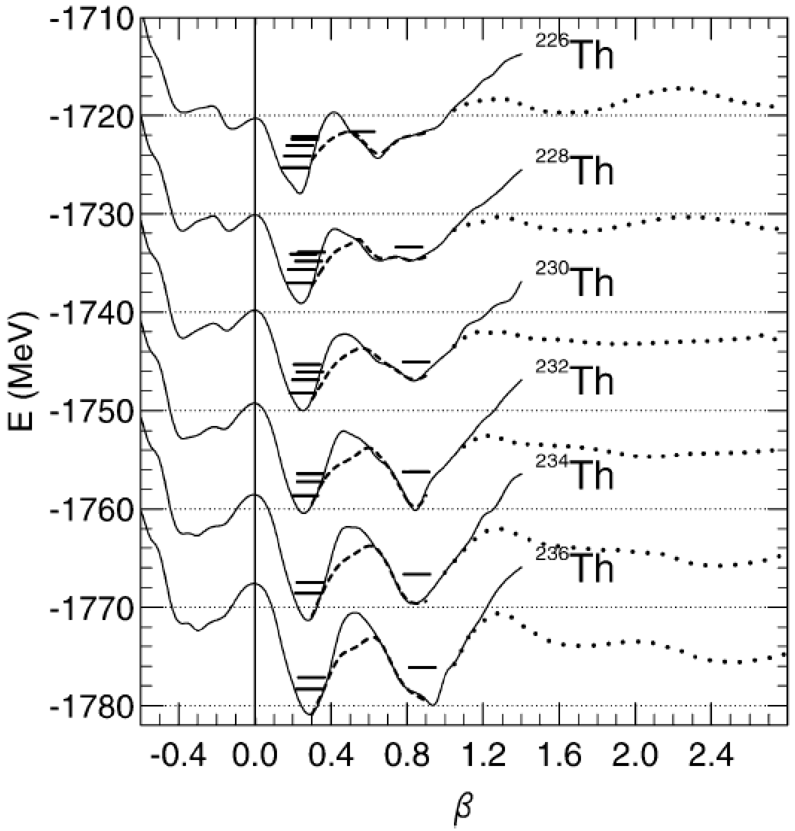
- How does the spin sawtooth pattern change with increasing excitation energy as the symmetric fission mode begins to dominate?
- Is the intrinsic angular momentum generation mechanism for the symmetric fission mode the same as for the asymmetric?
- Does some pre-scission spin feed through to the final fragments or does it go into the 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?

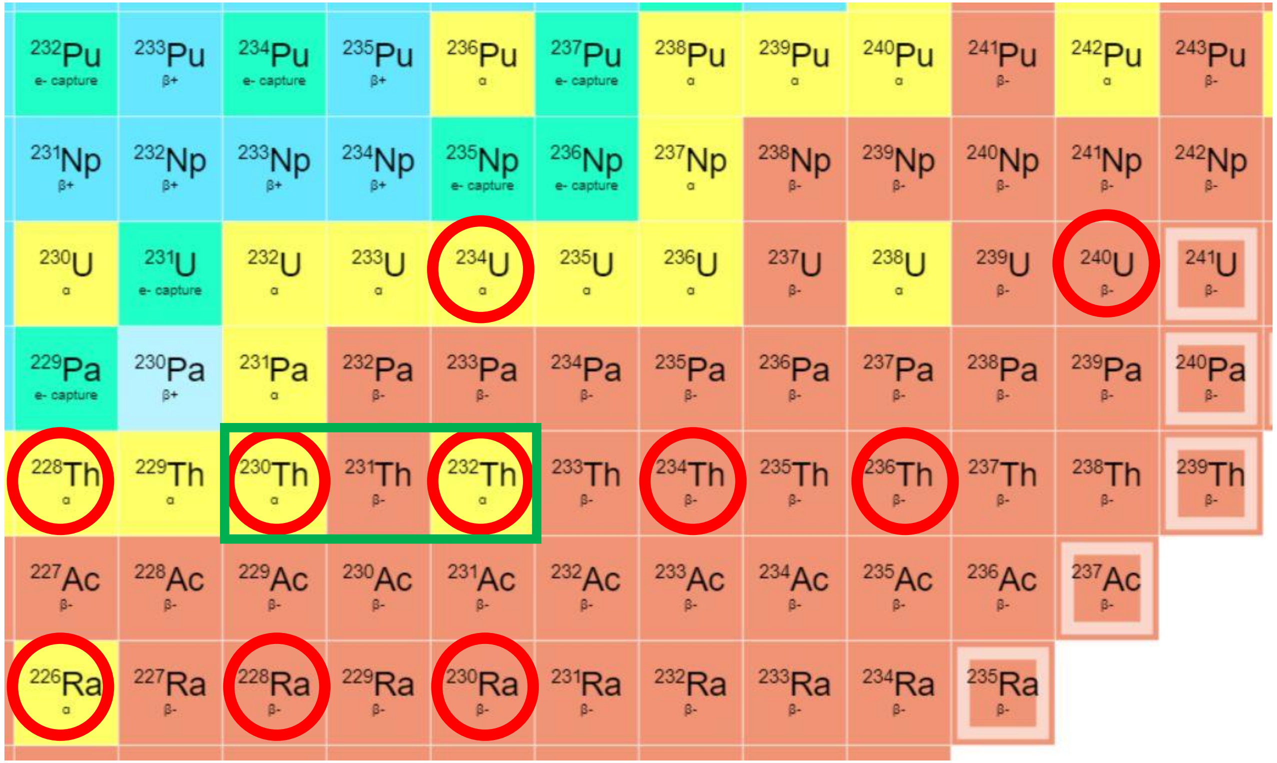
(n,xn) reactions: Predicted fission shape isomers in the light actinides

S. J.-P. Delaroche, M. Girod, H. Goutte, J. Libert., Nuclear Physics A 771 103–168 (2006)
P. Jachimowicz, M. Kowal and J. Skalski, Phys. Rev. C 85, 034305 (2012)
B. Nerlo-Pomorska, K. Pomorski, J. Bartel, and C. Schmitt, Eur. Phys. J. A 53:67 (2017)

Population in this experiment of

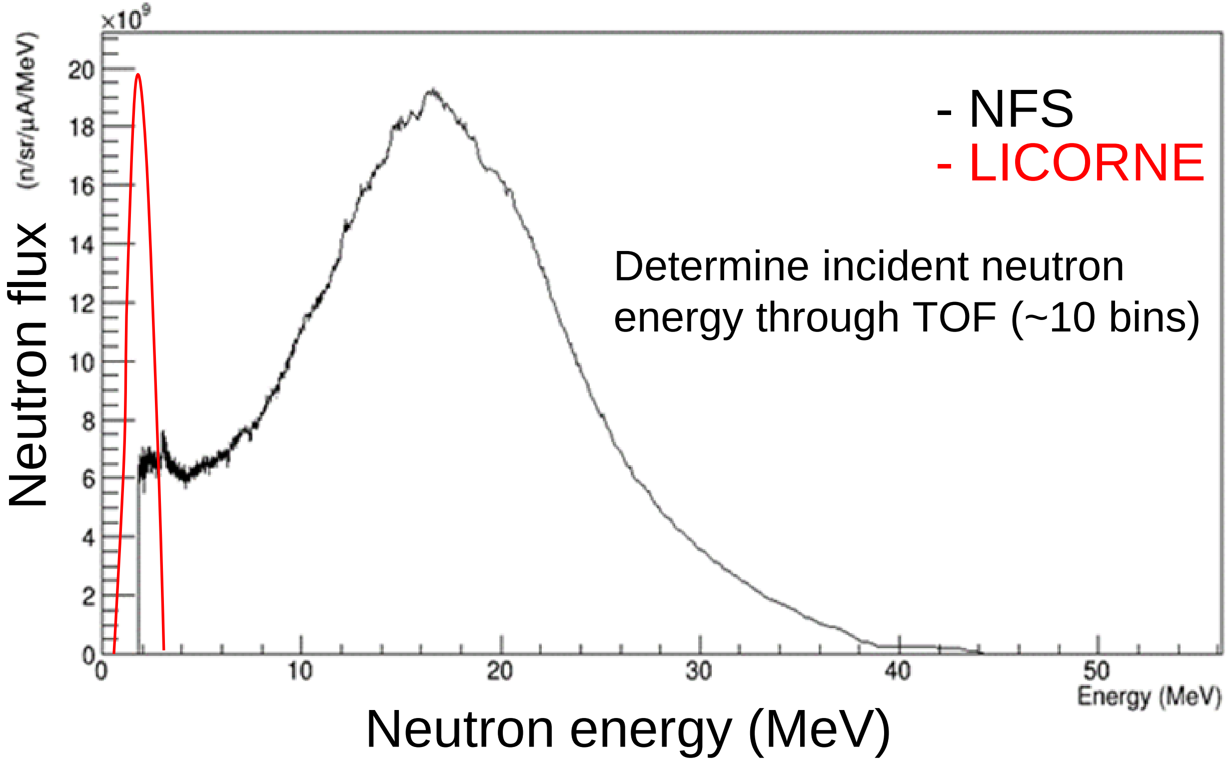
$^{232}Th(n,n')^{232}Th^*$
$^{232}Th(n,2n)^{231}Th^*$
$^{232}Th(n,3n)^{230}Th^*$

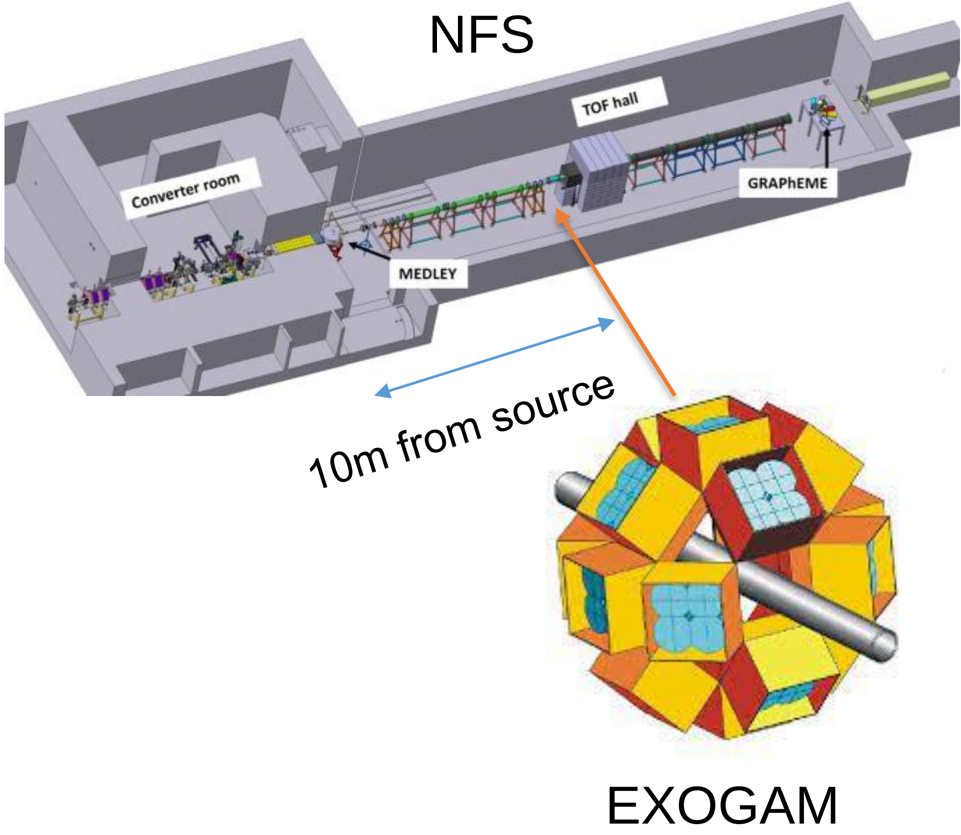




γ ray spectroscopy of fast neutron-induced fission with EXOGAM at NFS

$^{232}Th(n,f)$ Experimental details





Proposal to perform $^{232}Th(n,f)$ at NFS:

- Requires 8µA, 880 kHz primary beam and EXOGAM@10m with 8.3 g thorium target

LICORNE/NFS comparaison for ^{232}Th(n,f)

	nu-ball/LICORNE@ALTO 1.9 MeV	EXOGAM/NFS@GANIL 14 MeV
Primary Beam Frequency	2.5 MHz	800 kHz
Primary beam current	100 nA	8 uA
Beam period	400 ns	1200 ns
Sample distance	8 cm	1040 cm
Integrated flux at sample position	1e6 n/s/cm²	2e6 n/s/cm²
^{232}Th Fission cross section	0.11 barns	0.467 barns
^{232}Th Inelastic Scattering	3.3 barns	0.59 barns
^{232}Th n,2n	-	1.15 barns
Sample mass	131 g	8.3 g
Sample fission rate	25 kHz	25 kHz
γ multiplicity per fission	7	10
Fission γ rate	175 kHz	250 kHz
Parasitic reactions γ rate	656 kHz	91 kHz
Sample intrinsic γ rate	1048 kHz	66 kHz
Number of Ge crystals	106	48
Efficiency at 1 MeV (%)	4	12
Solid angle of 1 Ge crystal (% 4pi)	0.25	1.65
Fission γ rate/Ge crystal	0.43 kHz	4.1 kHz
Background γ rate/Ge crystal	4.3 kHz	2.6 kHz

Expected count rates for ^{232}Th(n,f) fission products with EXOGAM@NFS

Nuclide	Yield % (JENDL) @14 MeV	Yield % (GEF) @14 MeV	γ-γ coinc rate (Hz)	γ-γ-γ coinc rate (Hz)	γ-γ total coinc counts	γ-γ-γ total coinc counts
^{140}Xe	3.23	2.93	178	0.62	10.8 M	377 k
^{82}Ge	0.63	0.80	49	0.17	295 k	103 k
^{78}Zn	0.06	0.179	11	0.04	66 k	23 k
^{80}Zn	0.015	0.038	2	0.008	140 k	4.8 k

(Assuming GEF yields)

*Counts divided over 10 TOF bins for spectroscopy as a function of incident E_n

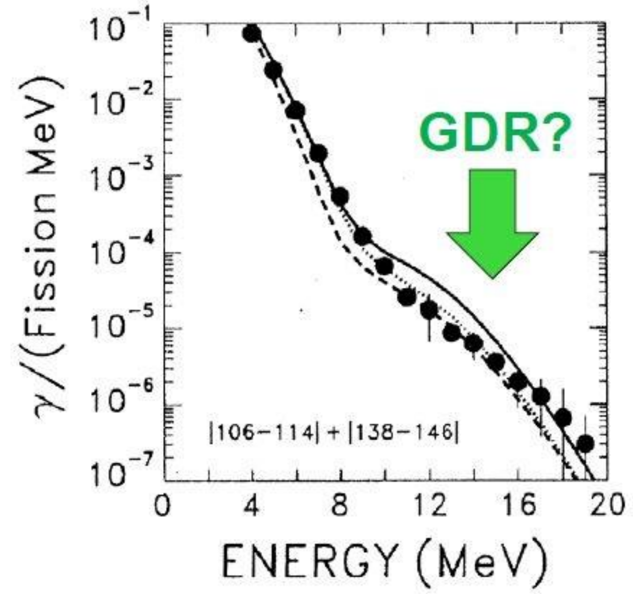
Our approved experiment with EXOGAM@NFS-GANIL likely to be scheduled in October 2025

E877_23

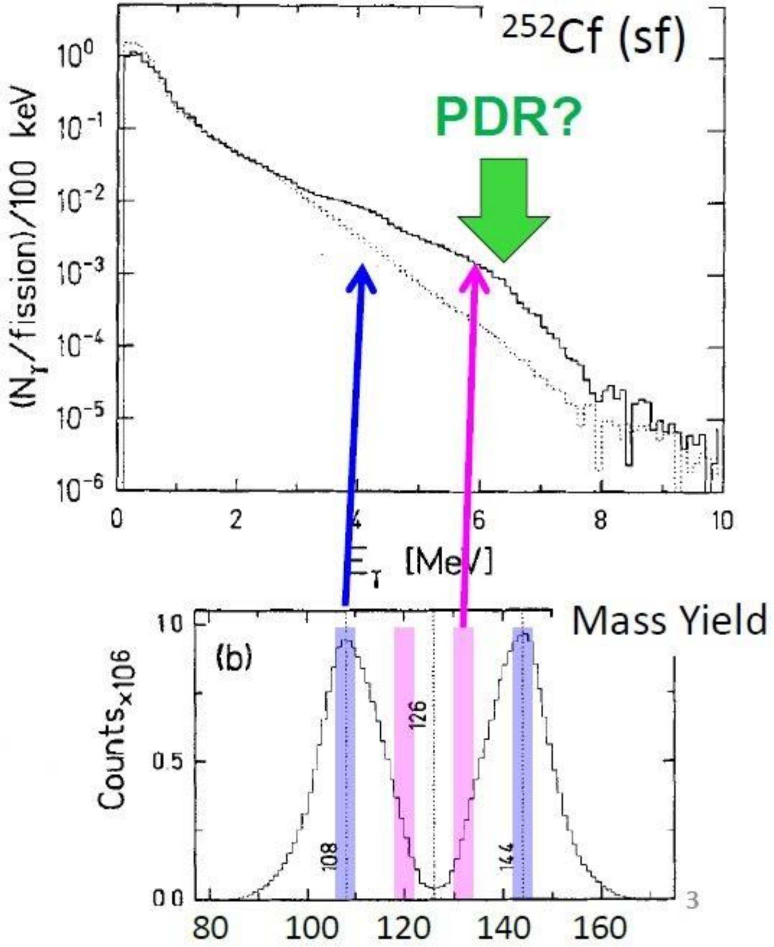
High Energy gamma-rays emitted in fission

High Energy gamma-rays emitted in fission

H. van der Ploeg *et al.*,
Phys. Rev. C, **52**, 1915 (1995).



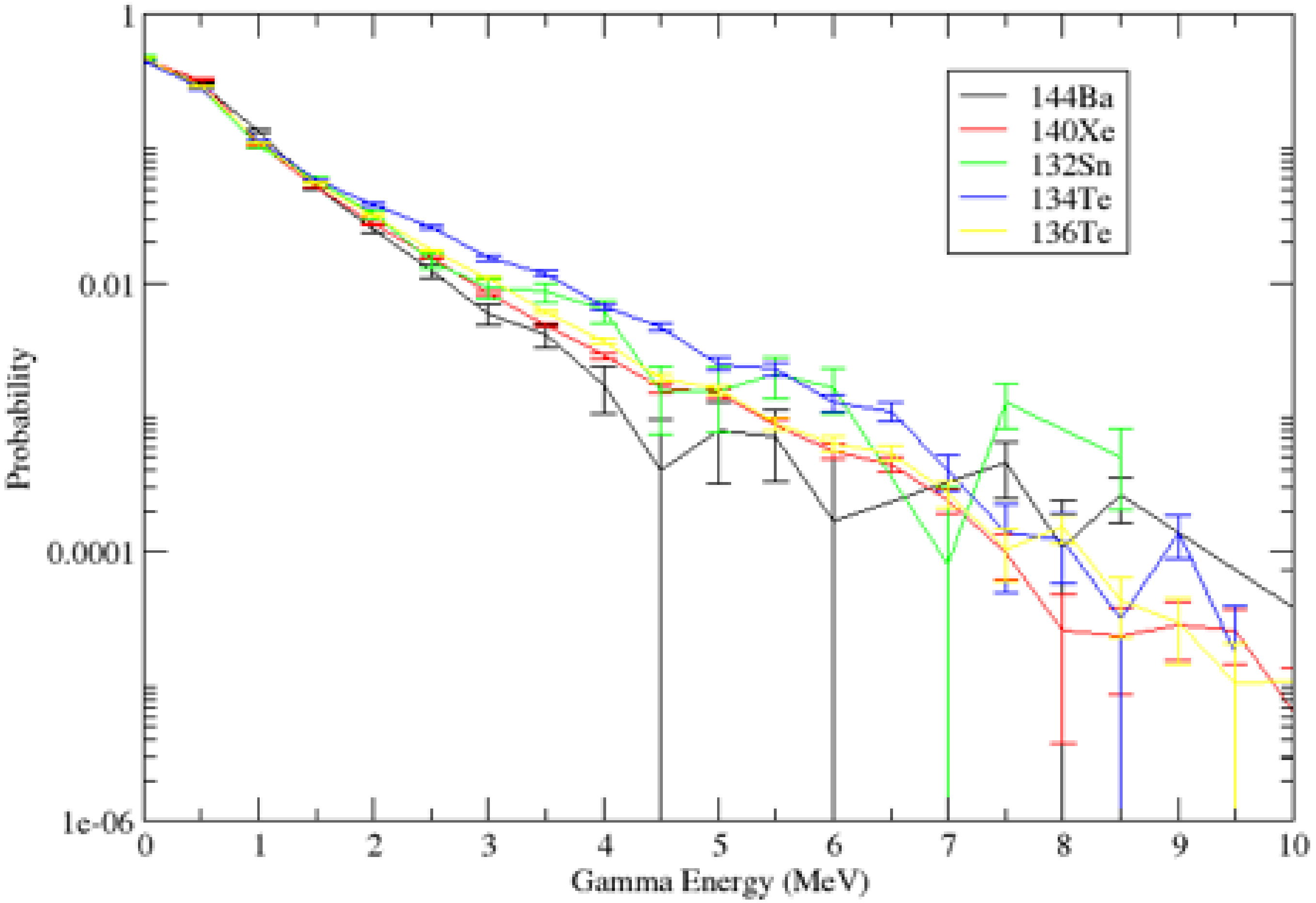
A. Hotzel et al., Z. Phys. A336 (1996) 299.



High Energy Gamma Spectra (BGO) correlated with A/Z (and partners)

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

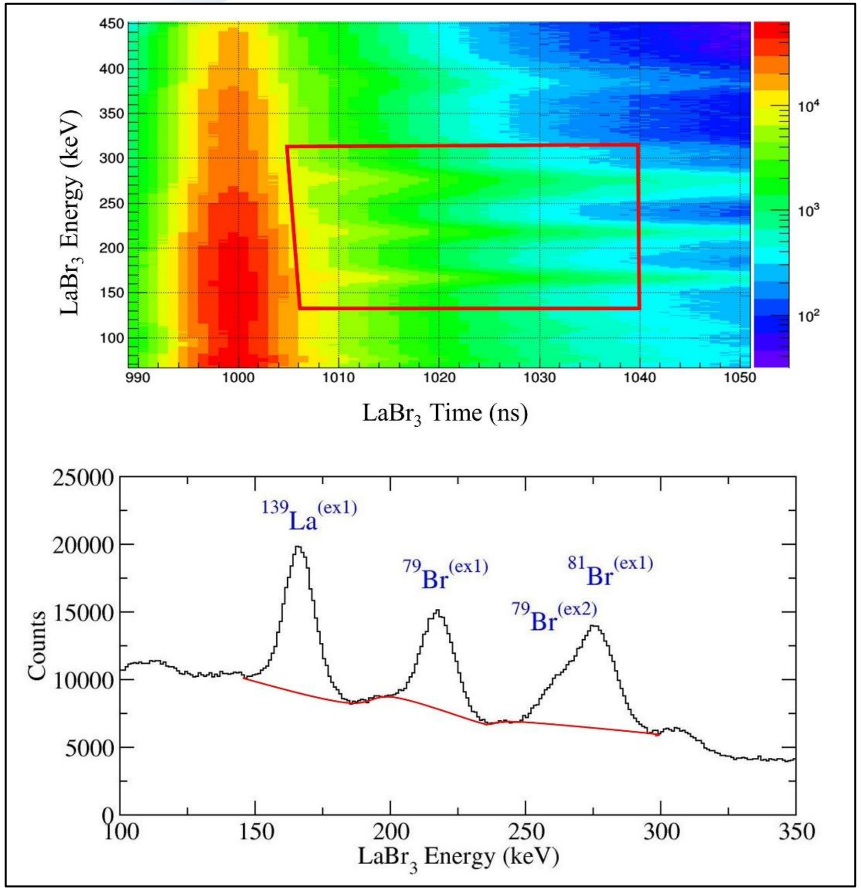
BGO spectra
nu-Ball1



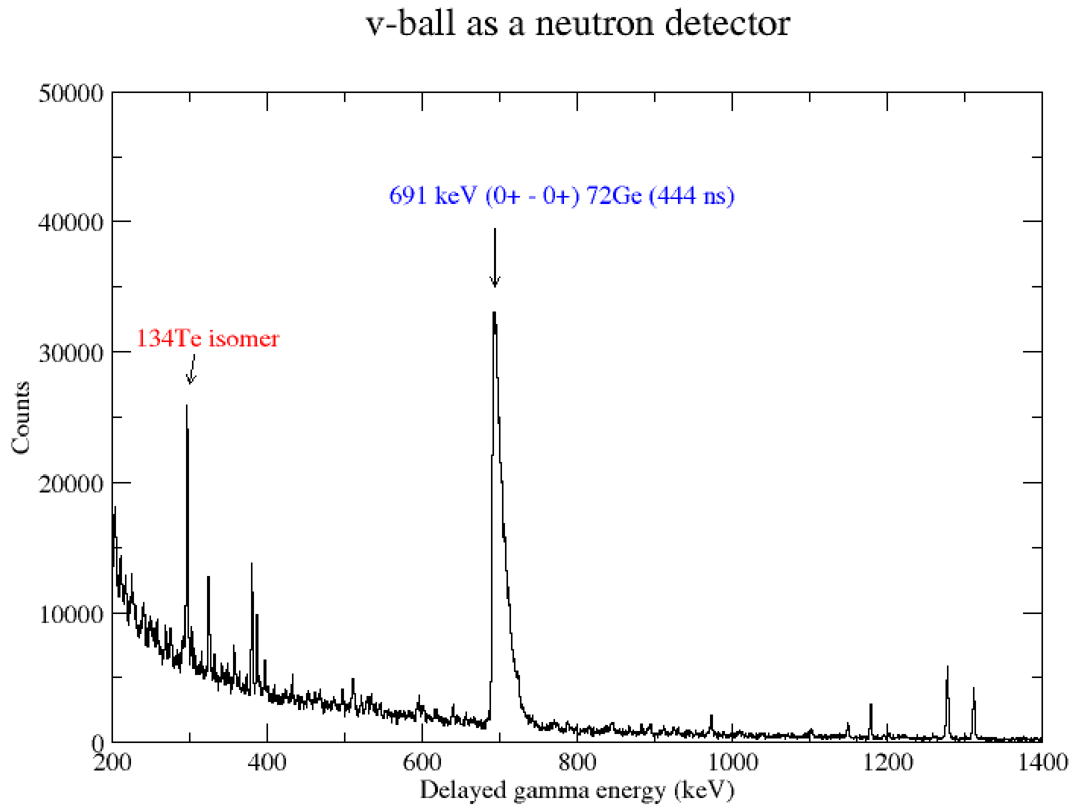
More experiments needed!!

Using gamma detectors as neutron detectors

LaBr3



Ge – delayed time gate

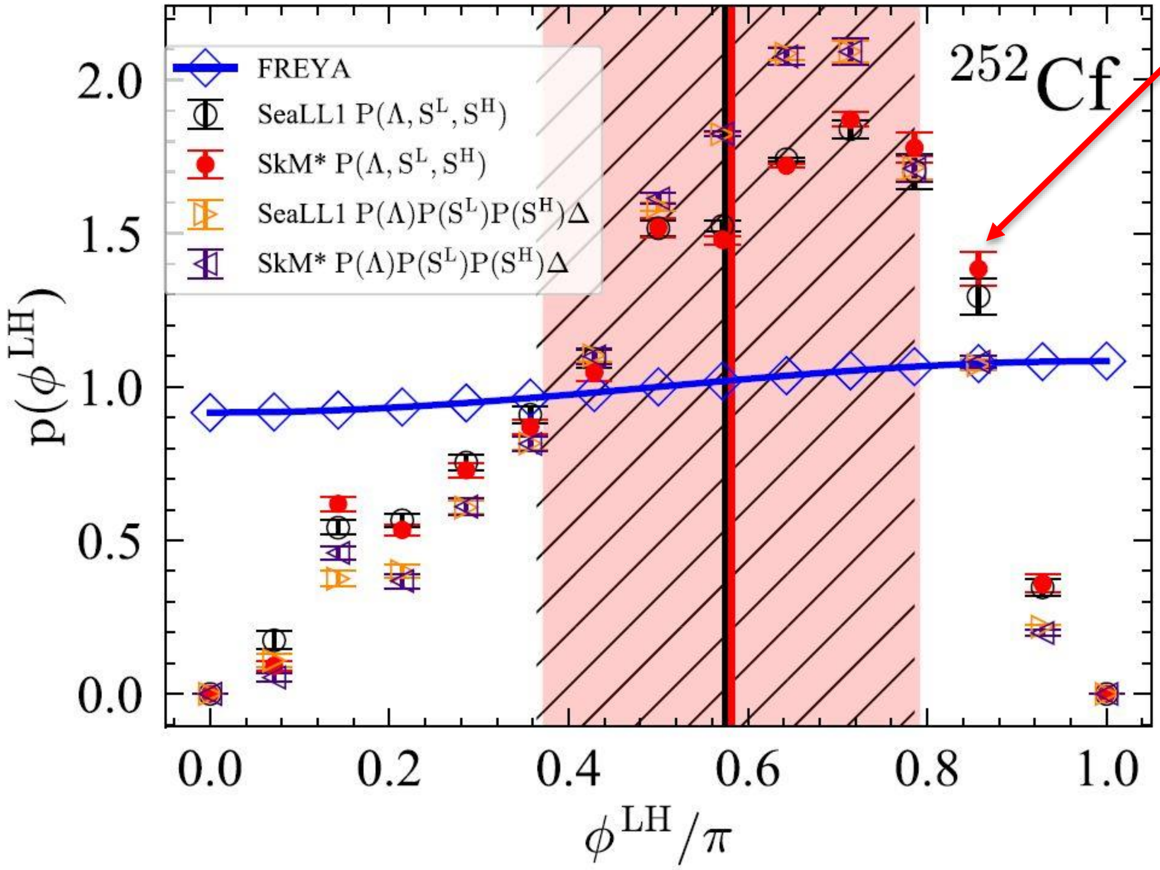


Permits study of neutron/gamma correlations

Coupling large spectromters with Ionization chambers

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)

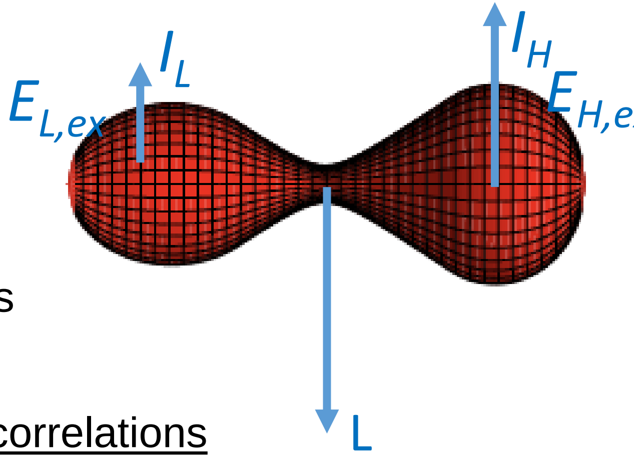
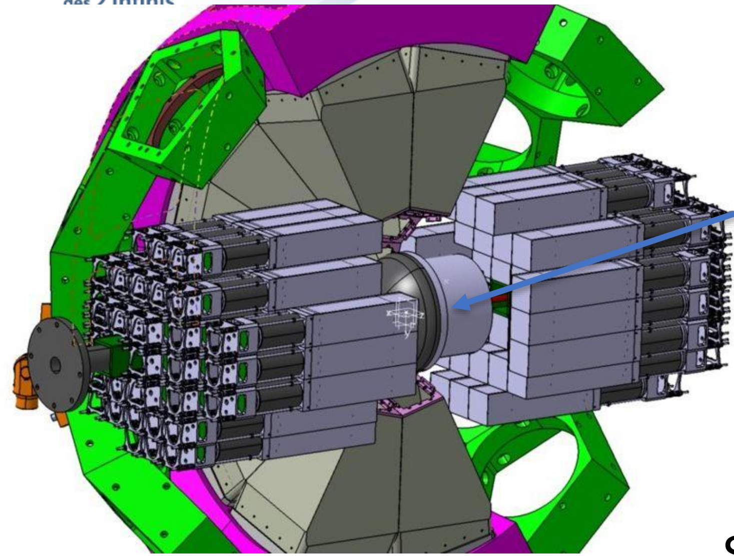


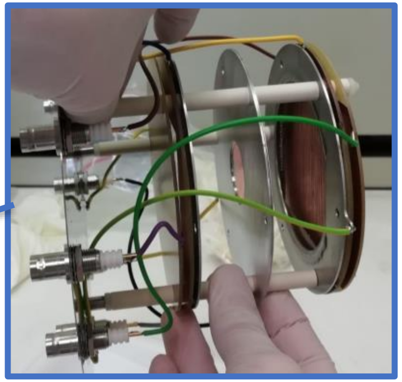
Image courtesy of S. Aberg

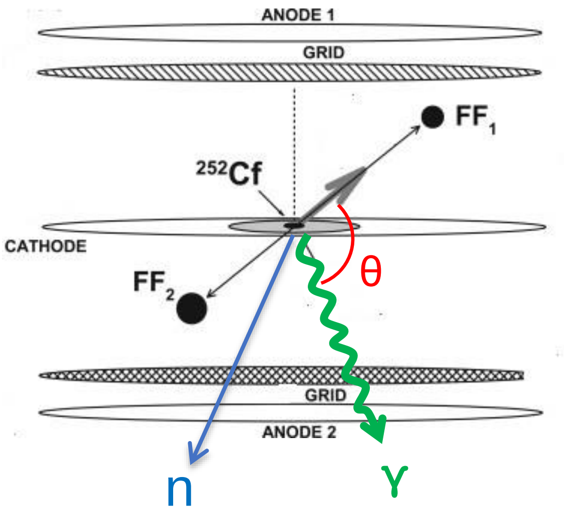
Theoretical predictions strongly disagree

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

ν-ball2 + 4π ^{252}Cf source + Segmented Ionisation chamber







FROZEN project
M. Lebois

A. Göök et al.
JRC-Geel

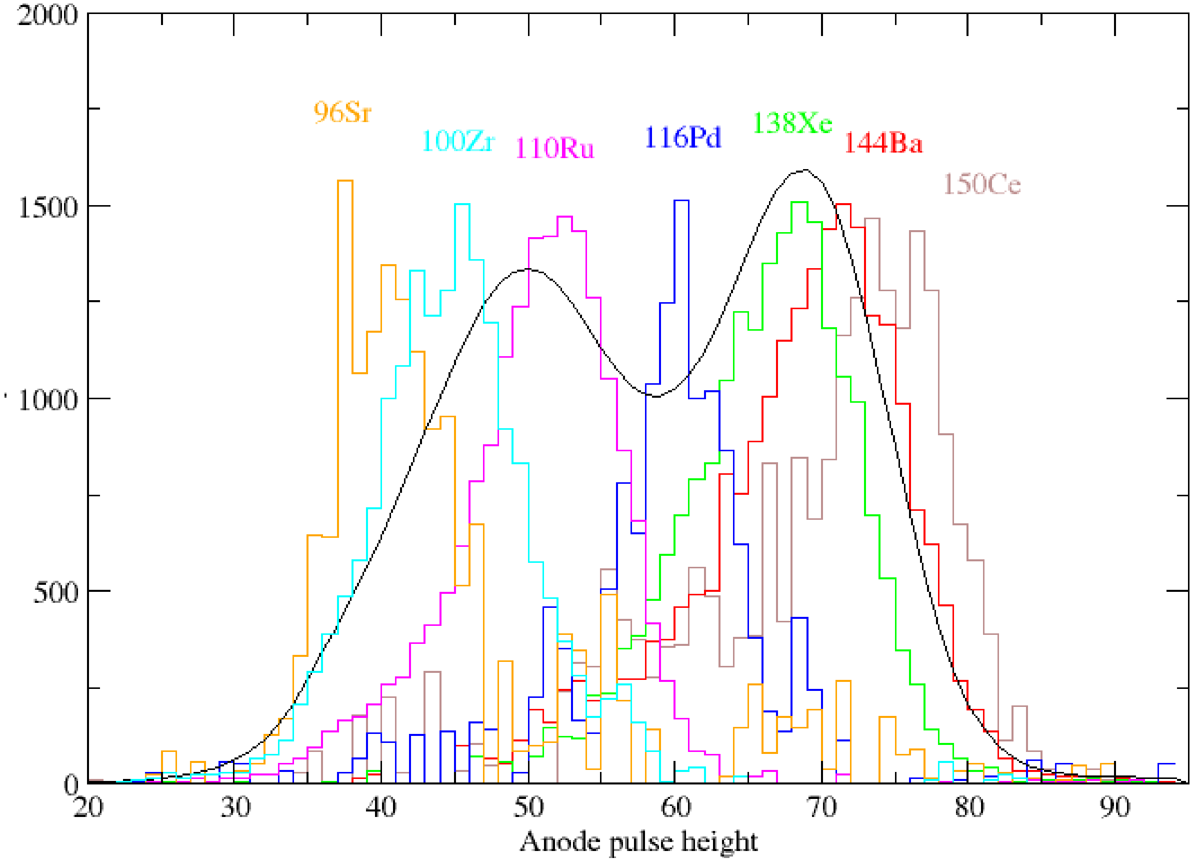
Measurment of correlations between multiple fission observables are key to obtaining interesting new results (in our opinion)

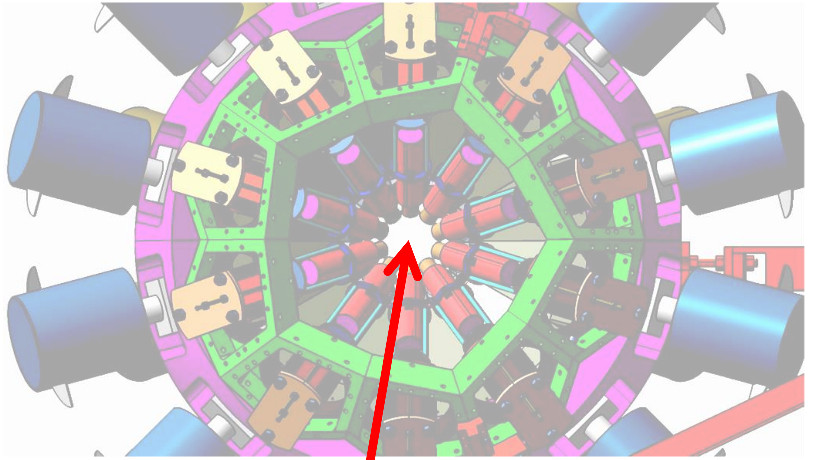
Simultaneous event-by-event measurement of:

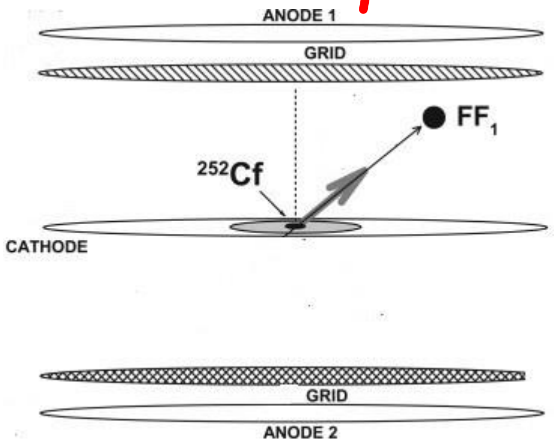
- Prompt/delayed fission gamma rays and neutron(s) (via TOF)
- Fragment Kinetic Energies, Fragment A/Z and partner A/Z
- Fission axis direction and all directional correlations
- Prompt/Delayed gamma sum energy and multiplicity

→ Analysis is ongoing

ν-ball1 + 2π ^{252}Cf source + Ionisation chamber

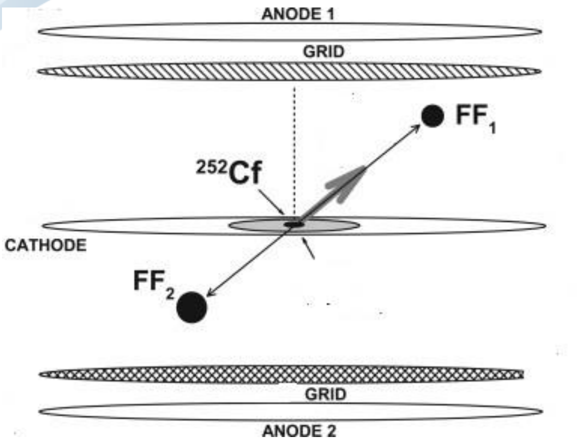


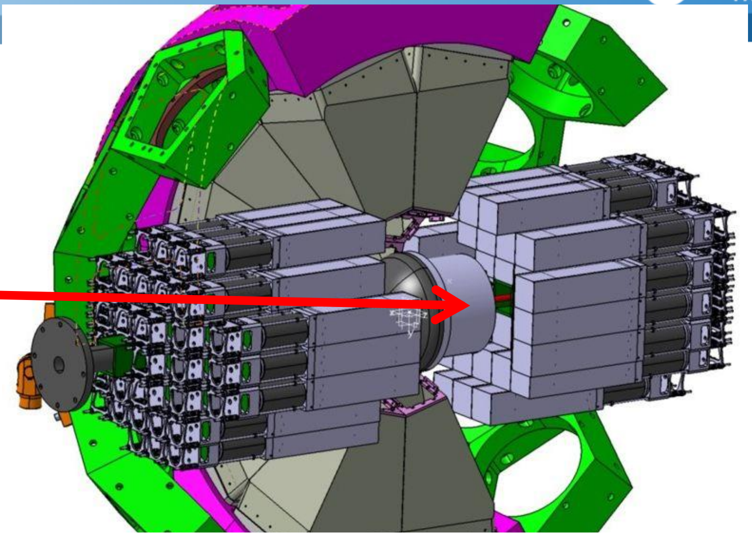




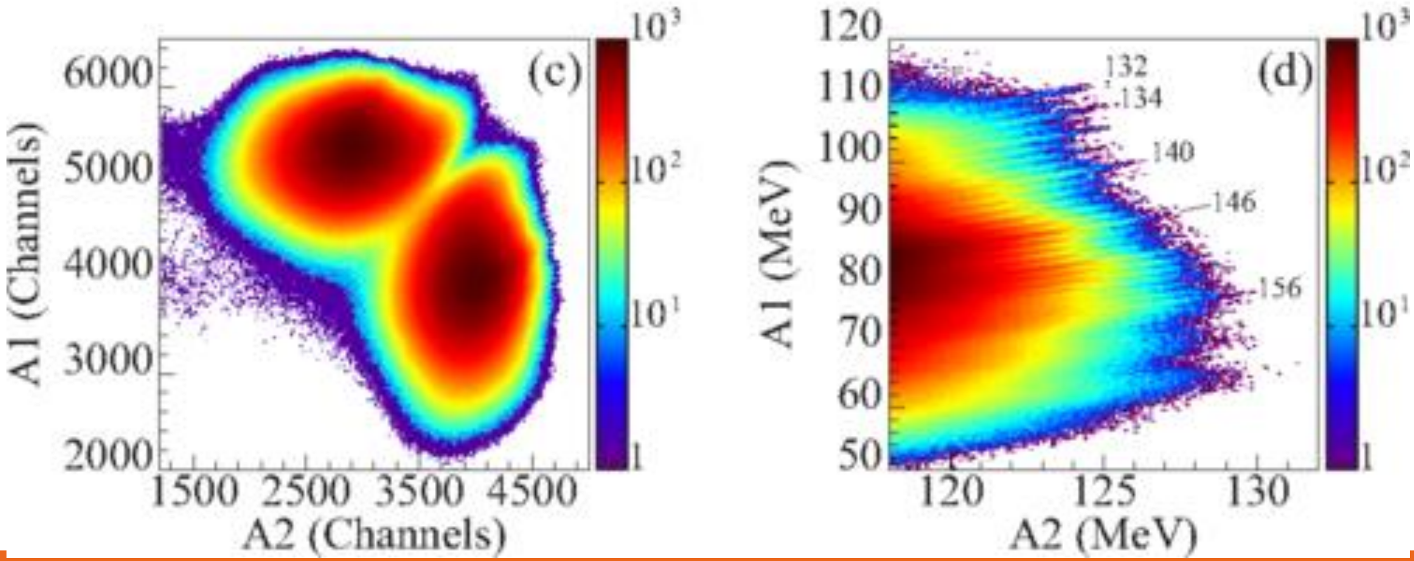
ν-ball2 + 4π ^{252}Cf source + Segmented Ionisation chamber

A. Gook et al.



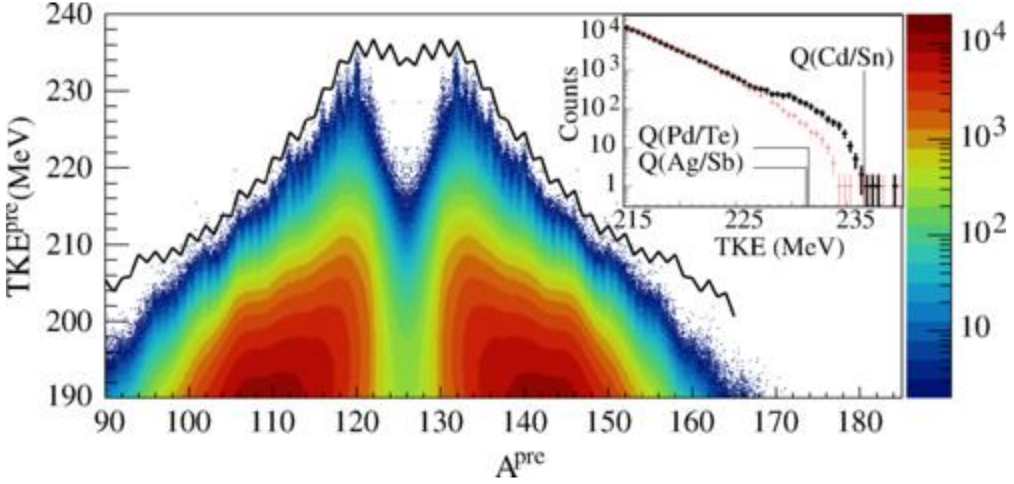


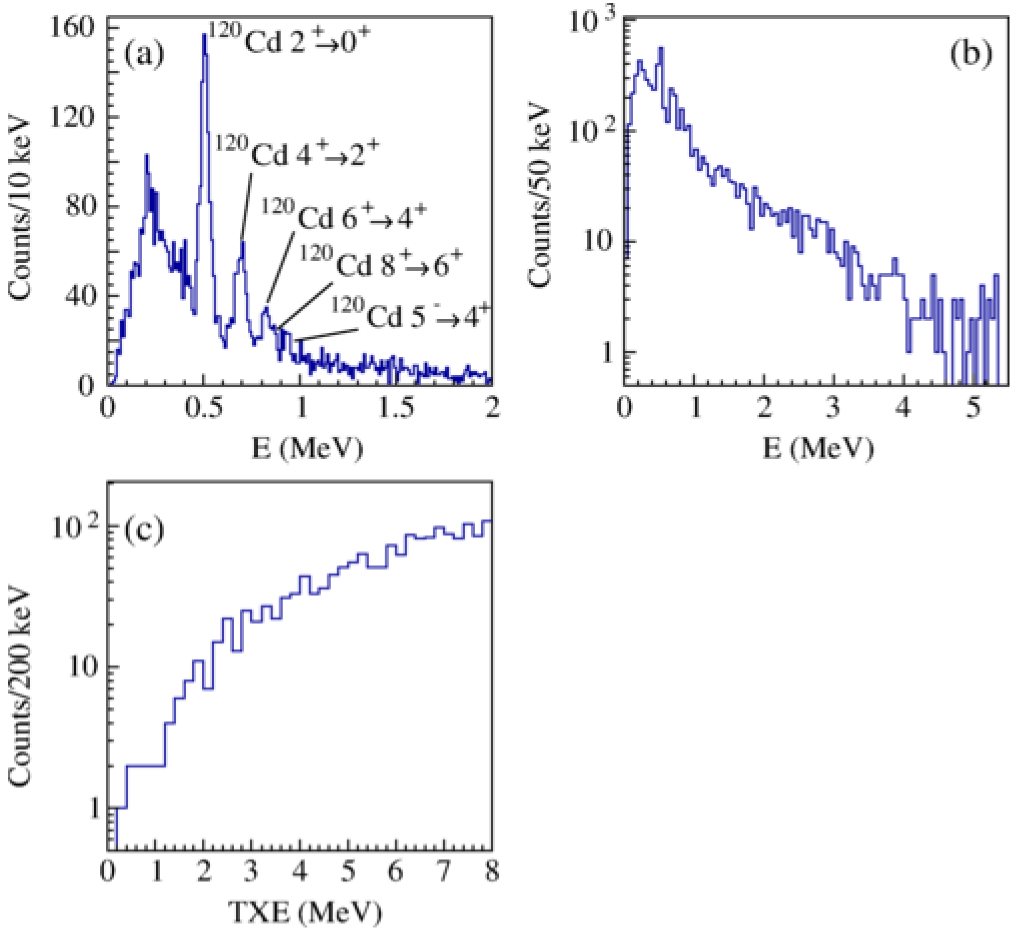
FROZEN project
M. Lebois



L. Gaudefroy et al.

Scission Deformation of the ^{120}Cd /^{132}Sn Neutronless Fragmentation in ^{252}Cf (SF)





A. Francheteau et al. Phys. Rev. Lett. 132, 142501 (2024)

Prospectives for the next decade

1) Propagation of angular momentum in fission

Gradually increase initial angular momentum input

Transfer reactions, e.g. $^{235}U(d,xf)$, heavy ion reactions $^{12}C+^{197}Au$. Or $^{232}Th(n,f)$ at NFS. How does angular momentum propagate in the reaction? What happens to fragment spins? How do the saw-tooth patterns evolve?

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?) Deconvolution of fragment spectra?

3) Gamma spectroscopy to gain information on fission mass/charge yields

Lighter systems with HI-induced fission (K. Miernik et al.). Evolution of mass/charge yields with incident neutron energy.

4) Directional correlations in fission

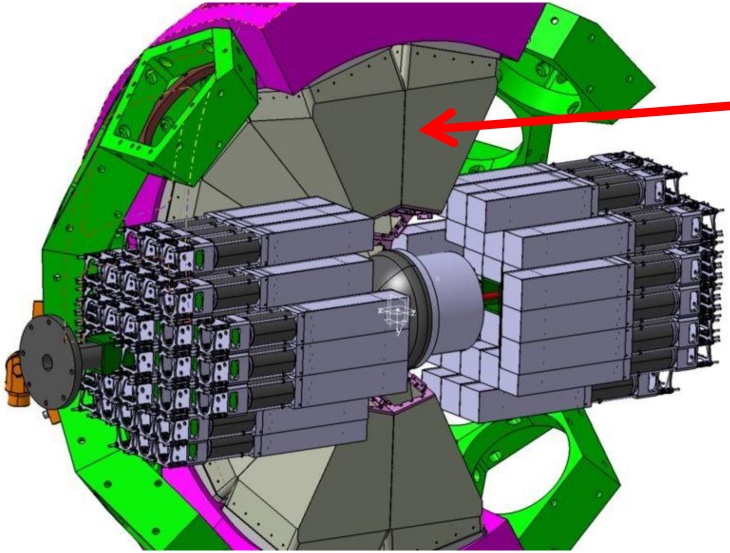
Coupling with Ionization chamber + spontaneous fission sources. Multi fission-observable experiments: Each fragment's Mass (ΔM ~ 3) K.E., theta, phi, gamma emission, neutron emission.

5) Study of higher energy neutron-induced fission at NFS

$^{78,80}Zn$ accessible in inverse kinematics for nuclear structure studies. Mass/charge yields + angular momentum effects.

The COFFEE project

Near term future:
COFFEE project – Cracow-Orsay Fission Fragment Exclusive Experiments



At ALTO, Orsay
- PARIS clusters + DSSD
- Replace clovers with 20 Loan Pool phase I detectors, using part of the Orgam Frame

→ Possibility to run for many months coupled to ionization chambers (SF sources)

Longer term future: **nu-Ball3**?

At CCB, Krakow
- Experiments at CCB Krakow to study fission induced by 200 MeV protons (^{232}Th, ^{208}Pb, ^{178}W, etc.)
- Control of E* via detection of outgoing protons (Kratta)
- Fragment and gamma coincident detection (PARIS)

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

30