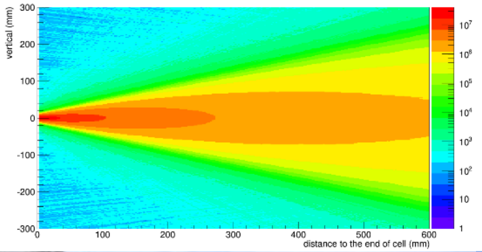
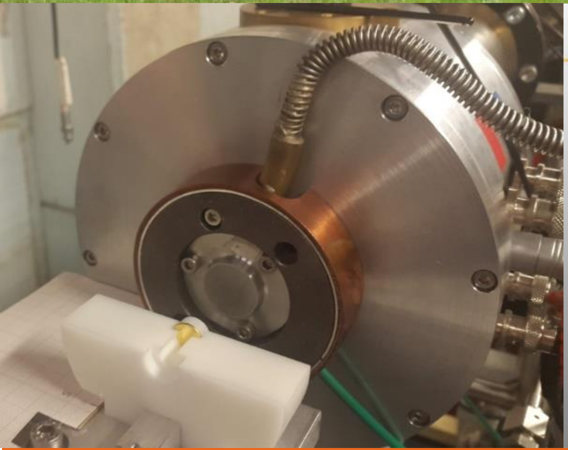
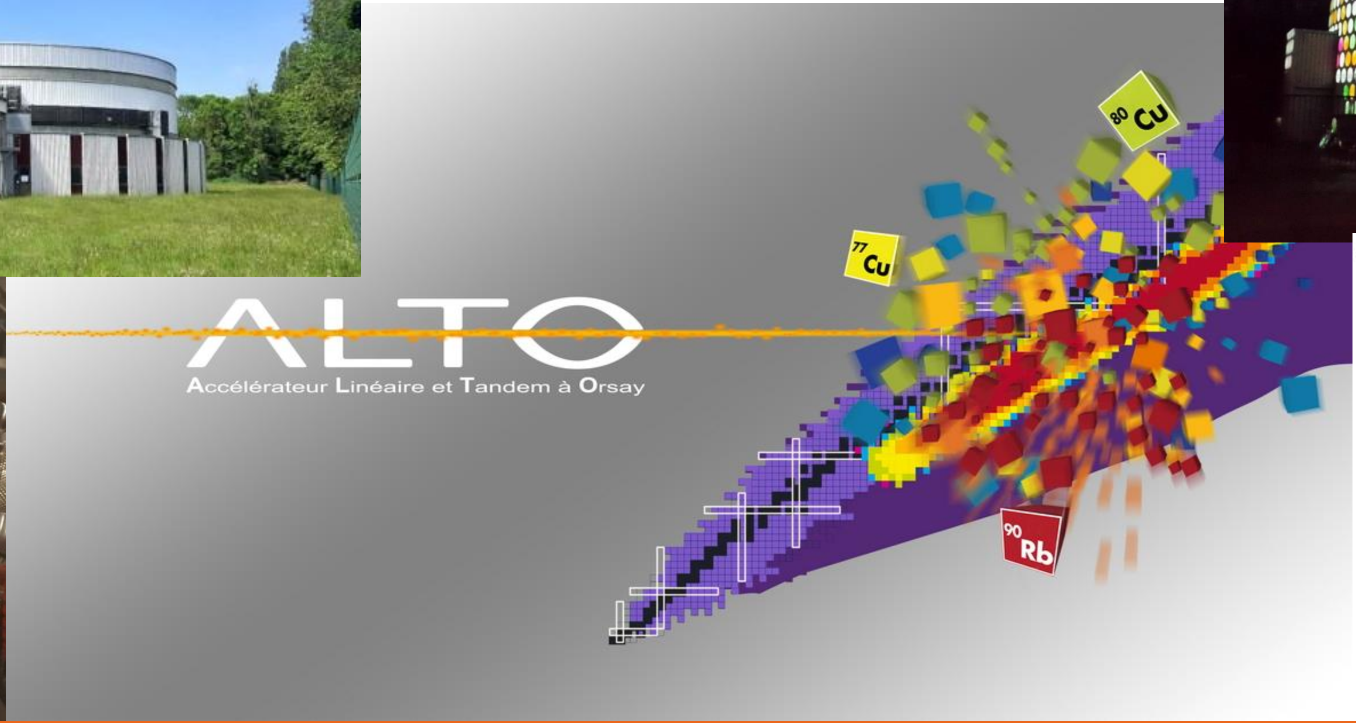
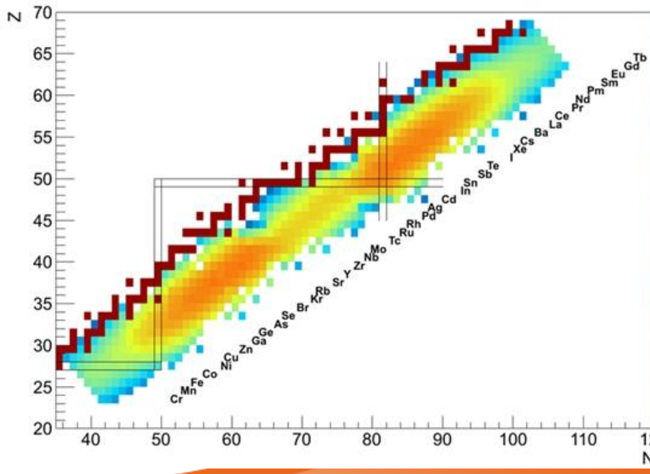
The use of naturally collimated neutron beams at the ALTO facility for applied research

J.N. Wilson, IJC Lab Orsay

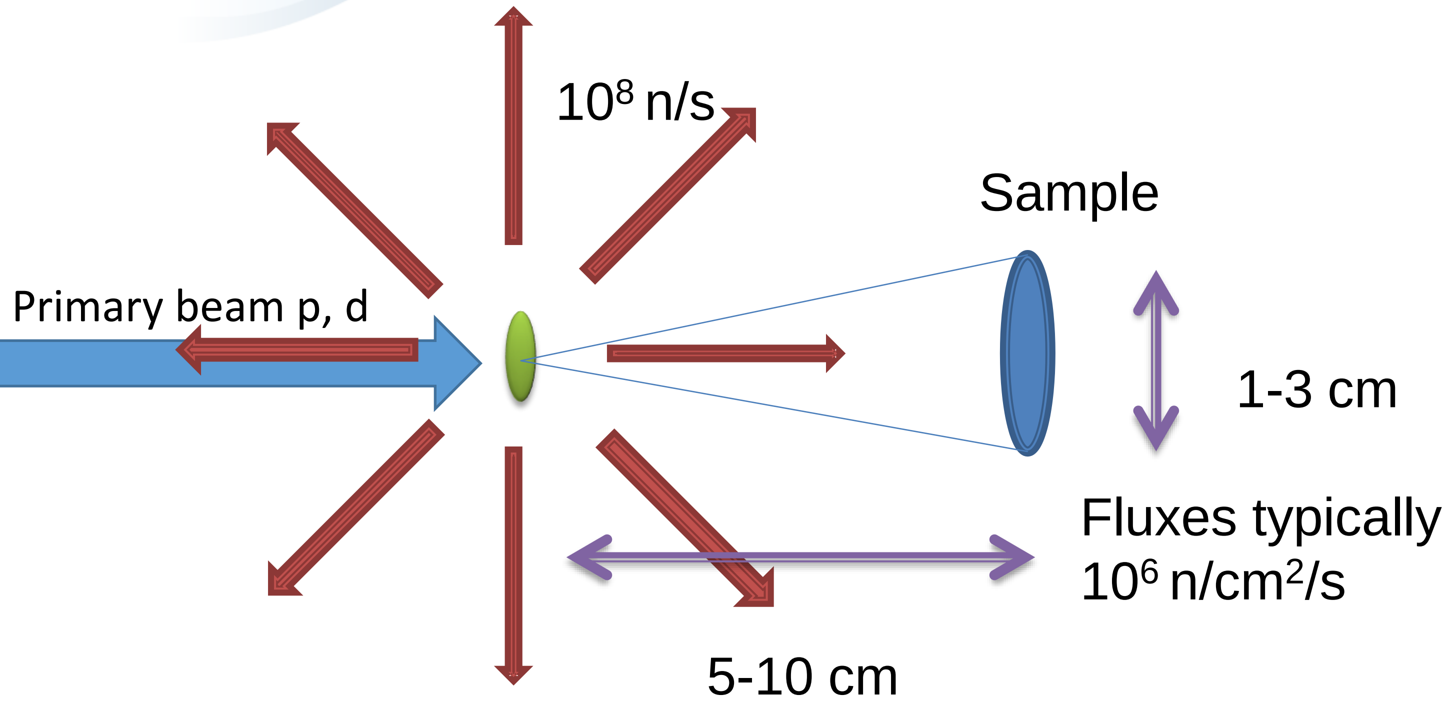




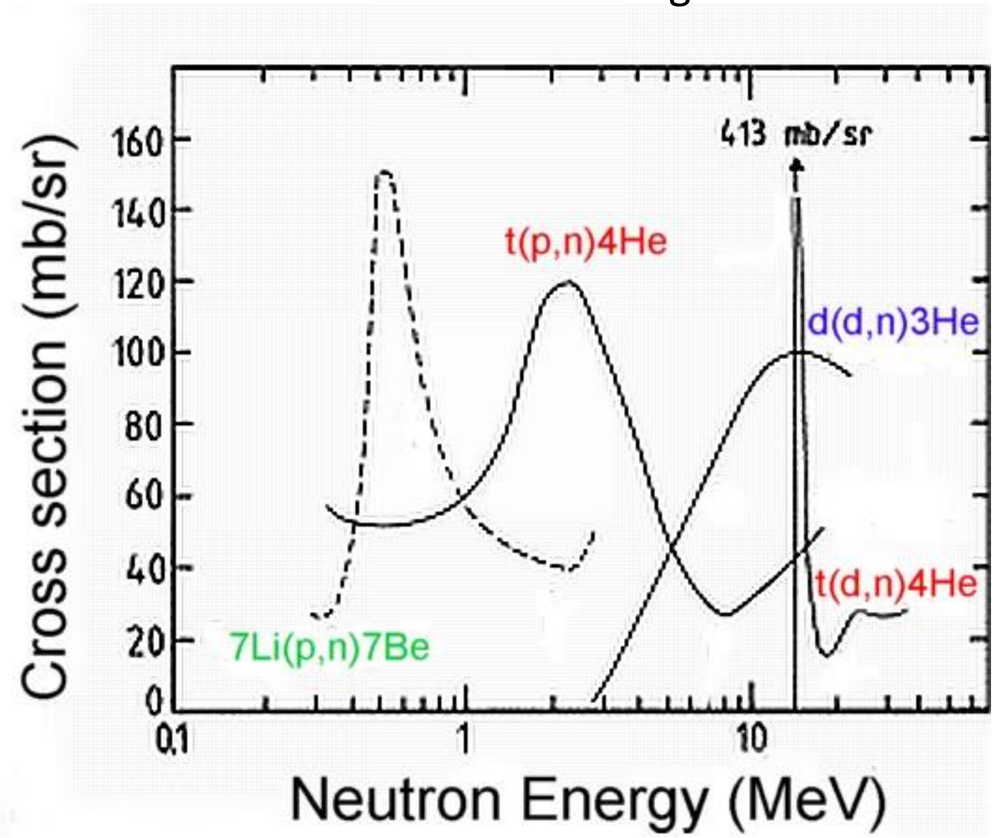




Accelerator based neutron sources (mono-energetic)

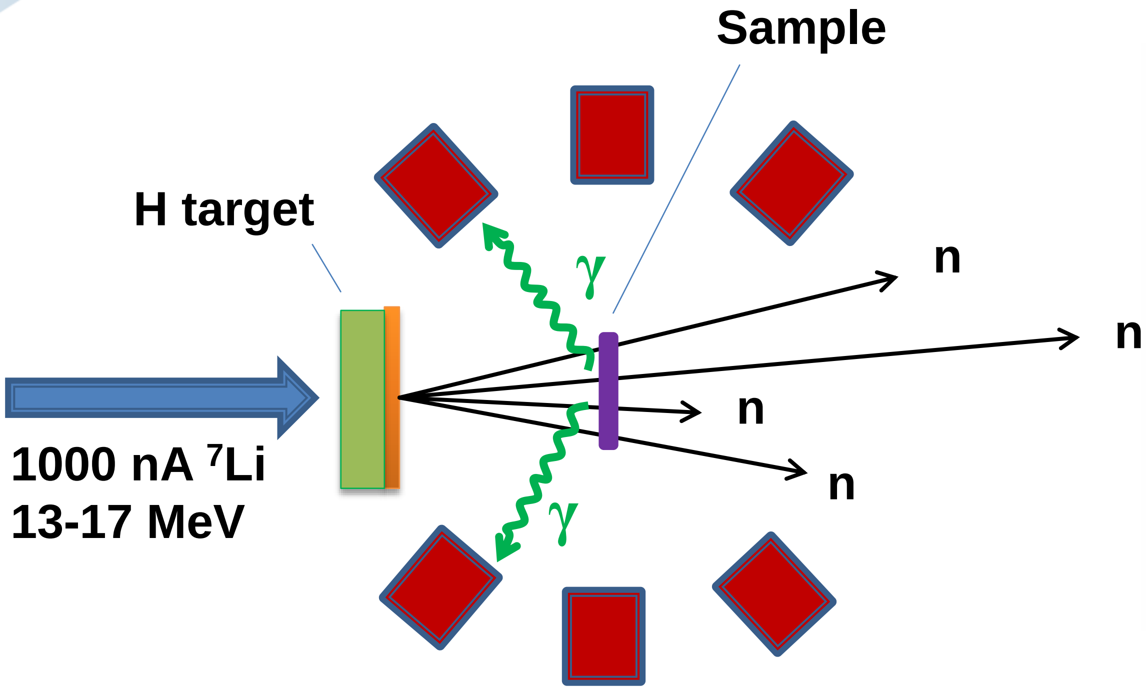


Direct reactions on light nuclei



- Typically over 99% of neutrons ''wasted''
- Wasted neutrons contribute to the room background
- Placement of sensitive detectors impossible without heavy shielding

Neutron production in inverse kinematics



ALTO 15 MV
Tandem accelertor

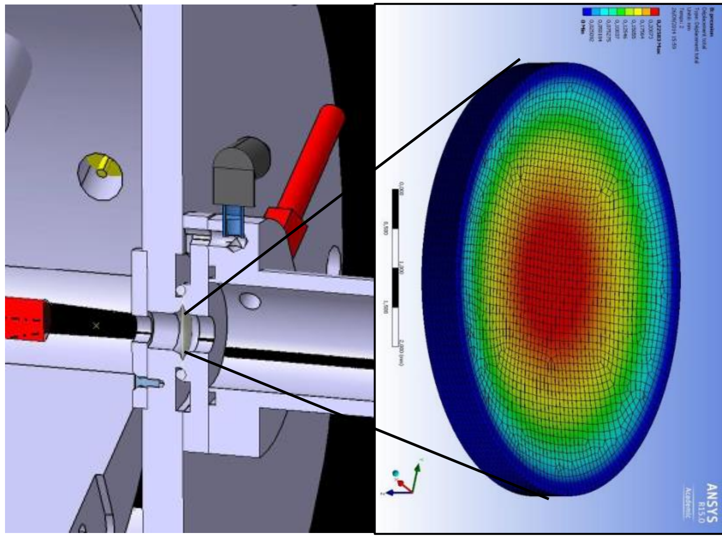
Lithium Inverse Cinematiques ORsay NEutron source

- p(^{7}Li,^{7}Be)n reaction in inverse kinematics
- Kinematic focusing increases flux by a factor of 10 - 30
- Low room background, since highly non-isotropic emission
- Quasi-monoenergetic fast neutrons between 0.5 and 4 MeV

Fluxes of up to 10^8 n/s/str

LICORNE (H_2 gas version)

H_2 pressure and flow control system + automatic shutdown



Thin Ta window

- Separates vacuum and up to 2 atm hydrogen
- Cooling circuit to maintain window temperate and avoid melting

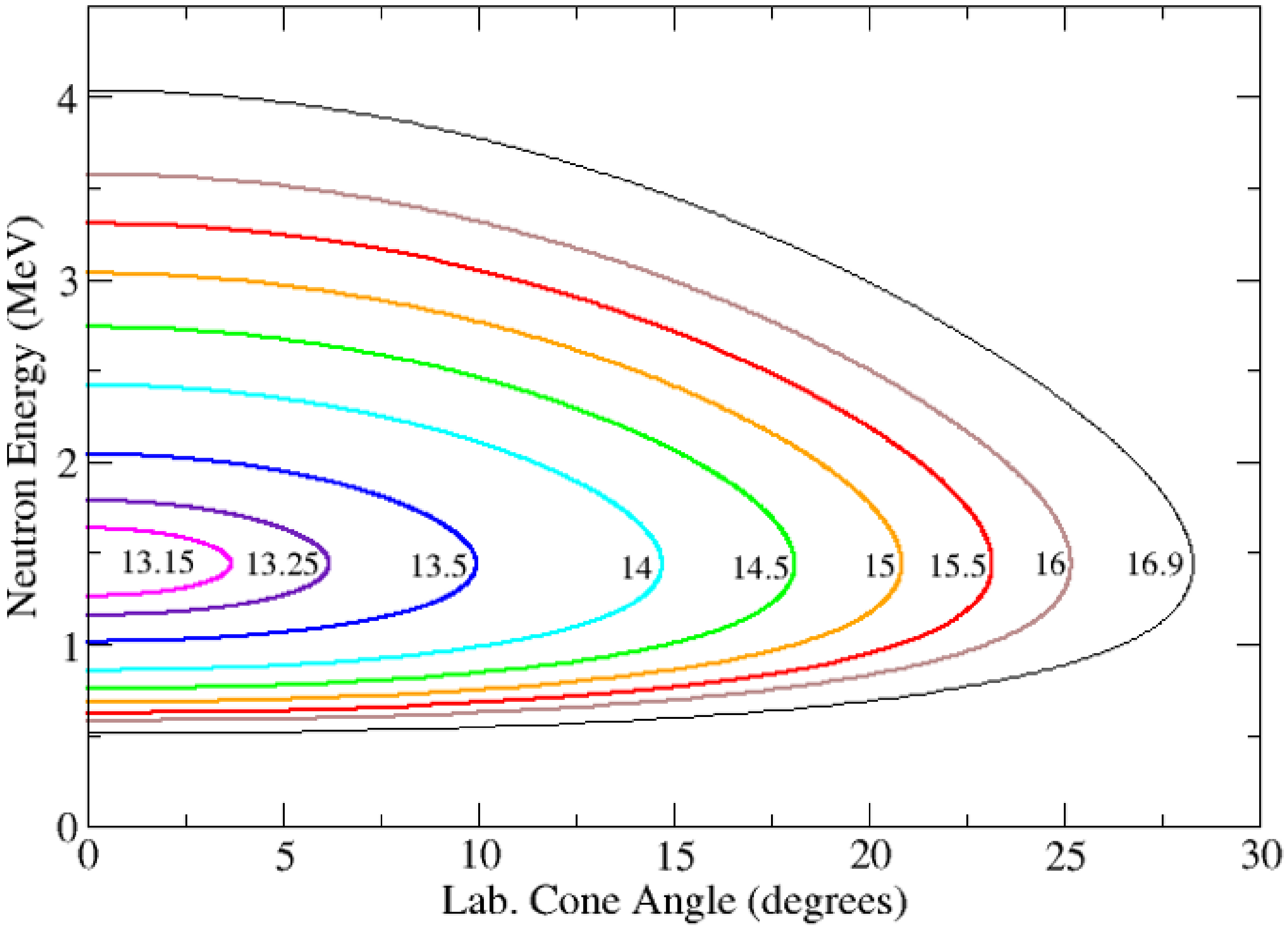
Hydrogen gas cells

Neutron spectrum is dependent on:

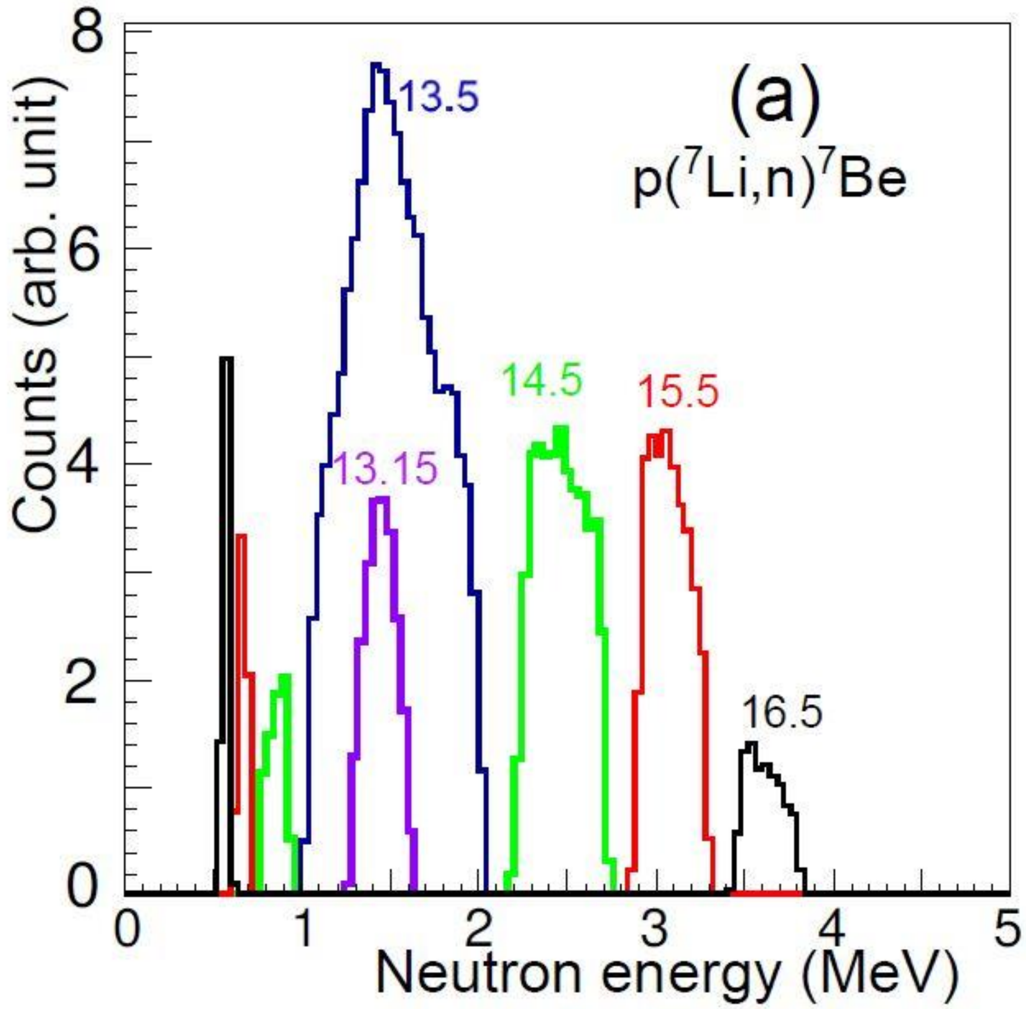
- Primary beam energy (13.5 – 17 MeV)
- Gas cell length (2 cm – 7.5 cm)
- Gas cell pressure (1.1 – 2 atm)
- Ta window thickness (2 – 4 um)
- Sample position and angle

LICORNE: Quasi-monoenergetic mode

2 cm gas cell, 1.1 atm pressure

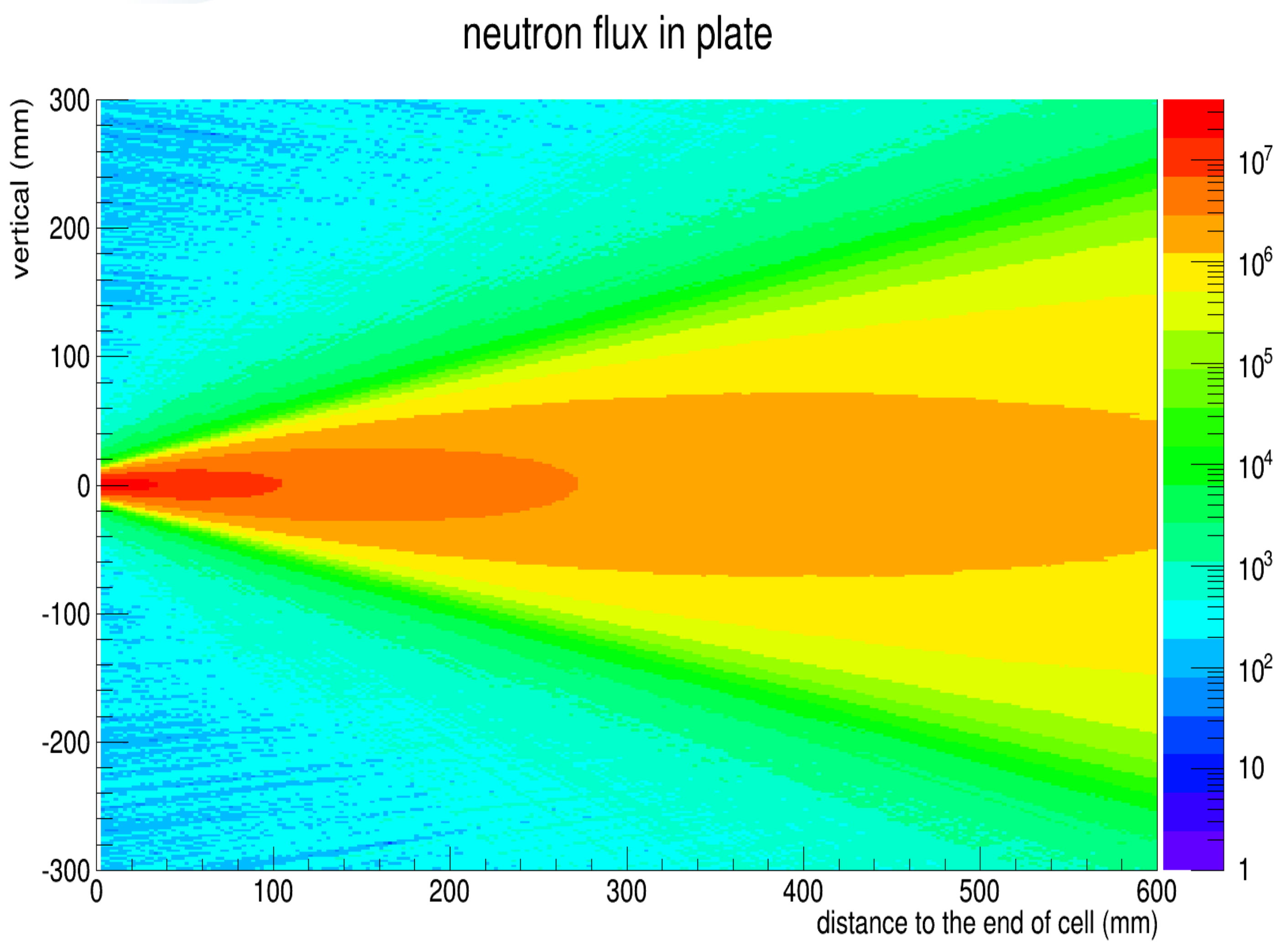


Neutron spectrum at zero degrees

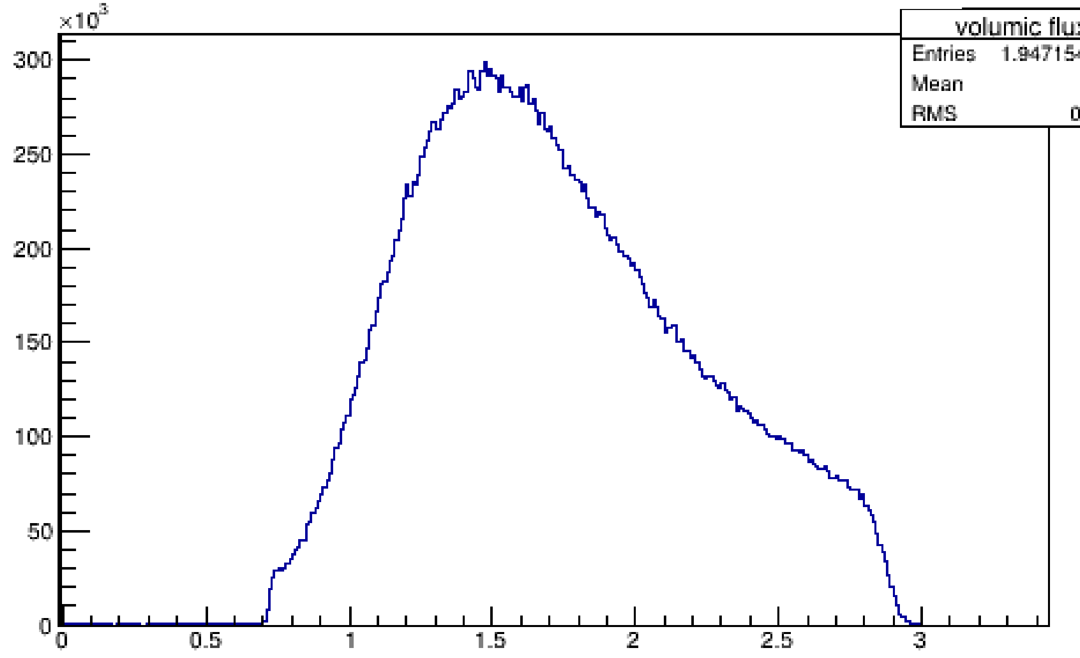


LICORNE: White source mode

3.5 cm gas cell, 1.6 atm pressure



Neutron spectrum at zero degrees



Neutron Energy (MeV)

LICORNE physics program

Applications/Nuclear Data

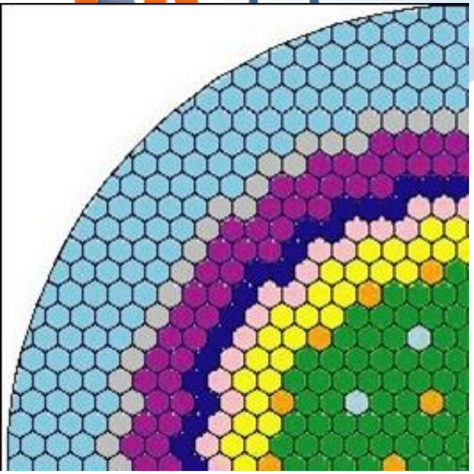
- Cross section measurements (limited potential)
- Prompt fission neutron spectra/multiplicities
- Fast neutron tomography
- Fission yield measurements
- Fast neutron inelastic scattering
- Prompt fission gamma ray emission characteristics

Fundamental Nuclear Physics

- Gamma spectroscopy of neutron rich isotopes
- Lifetimes/nuclear moments in neutron rich nuclei
- Angular momentum generation in fission

Couple LICORNE with high resolution, high efficiency gamma spectrometers

Gamma heating effects in reactor cores



- 10% of energy released in a reactor is in the form of gamma rays
- Gamma heating dominates in non-fissile components: (structural materials, reflectors, fertile blankets, instrumentation, etc.)
- In-core gamma heating effects underestimated by 30%
- Top of the OCDE/NEA high priority request list: ^{252}Cf, ^{235}U(n_{th},f), ^{239}Pu(n_{th},f)

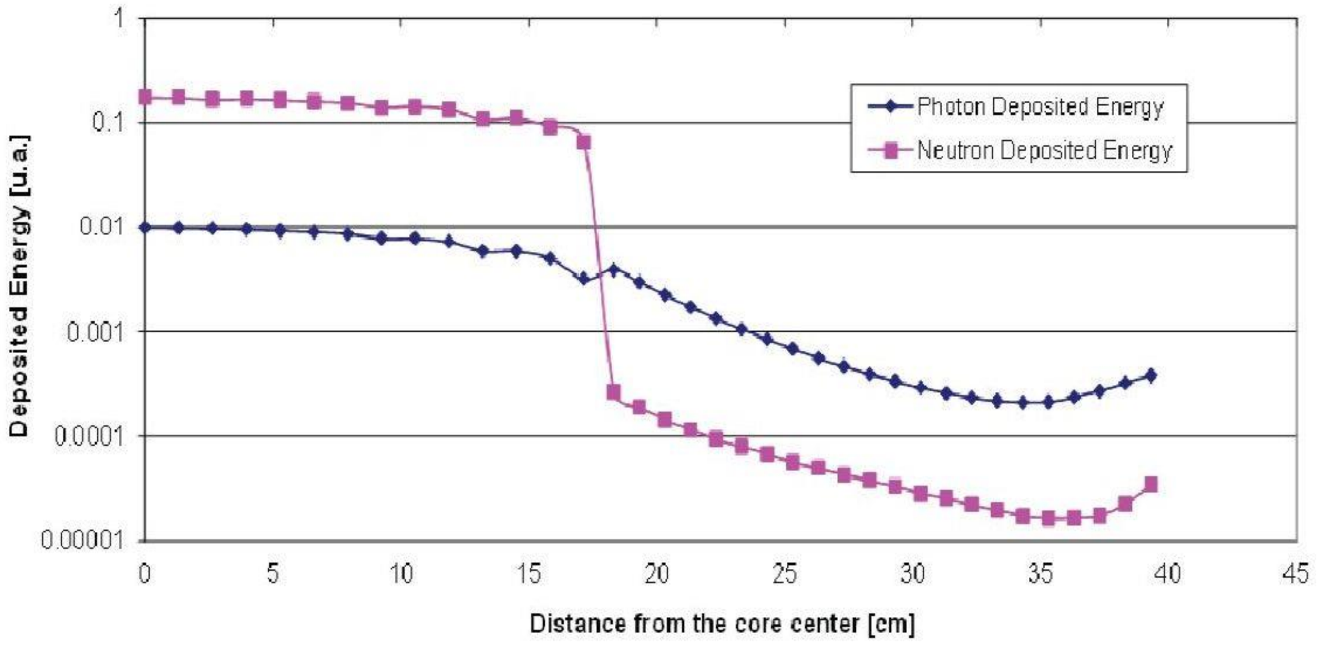
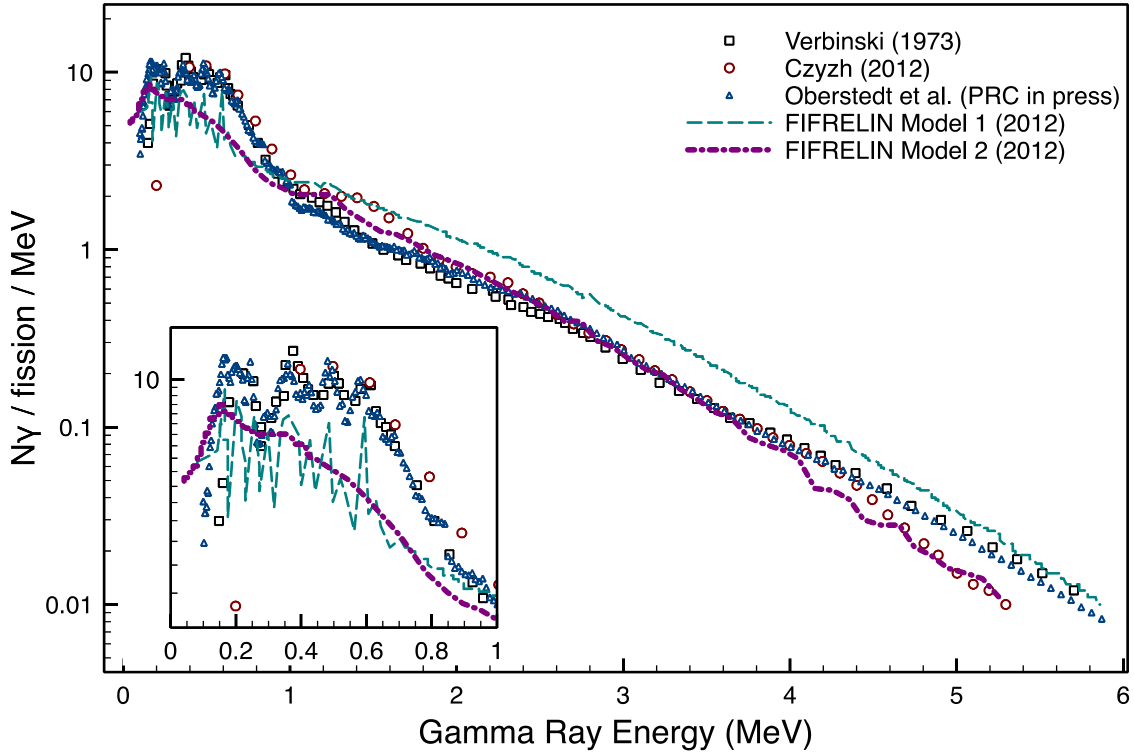


Figure 1: Deposited energy per neutrons and γ at different distances from the PWR core center



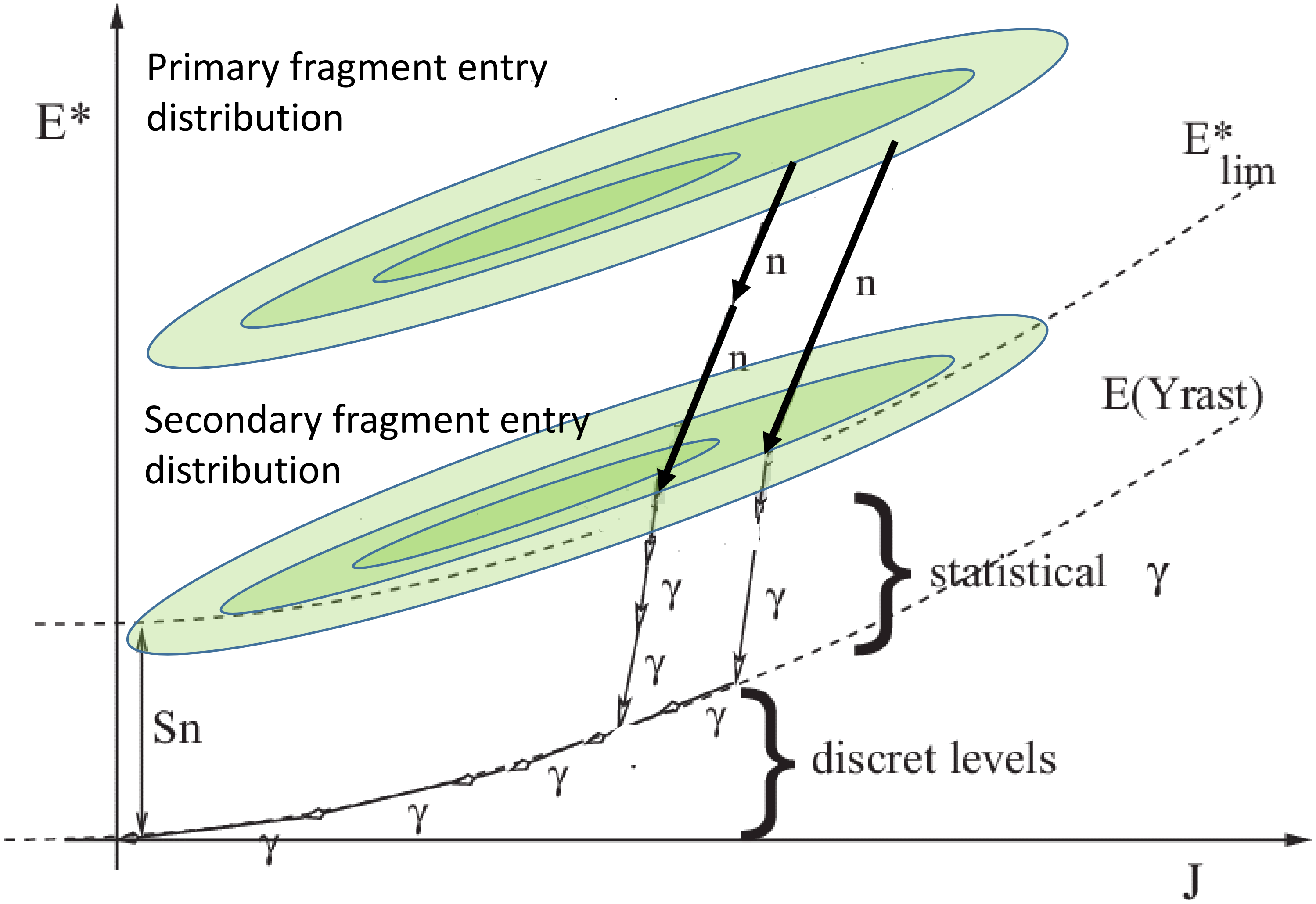
G. Rimpault et al., Phys. Proc. 31 p3 (2012)

Fission fragment decay

G. Rimpault et la., Phys. Proc. 31 p3 (2012)

“The main issue is to be able to predict the excitation-energy and spin distribution of the fission fragments.

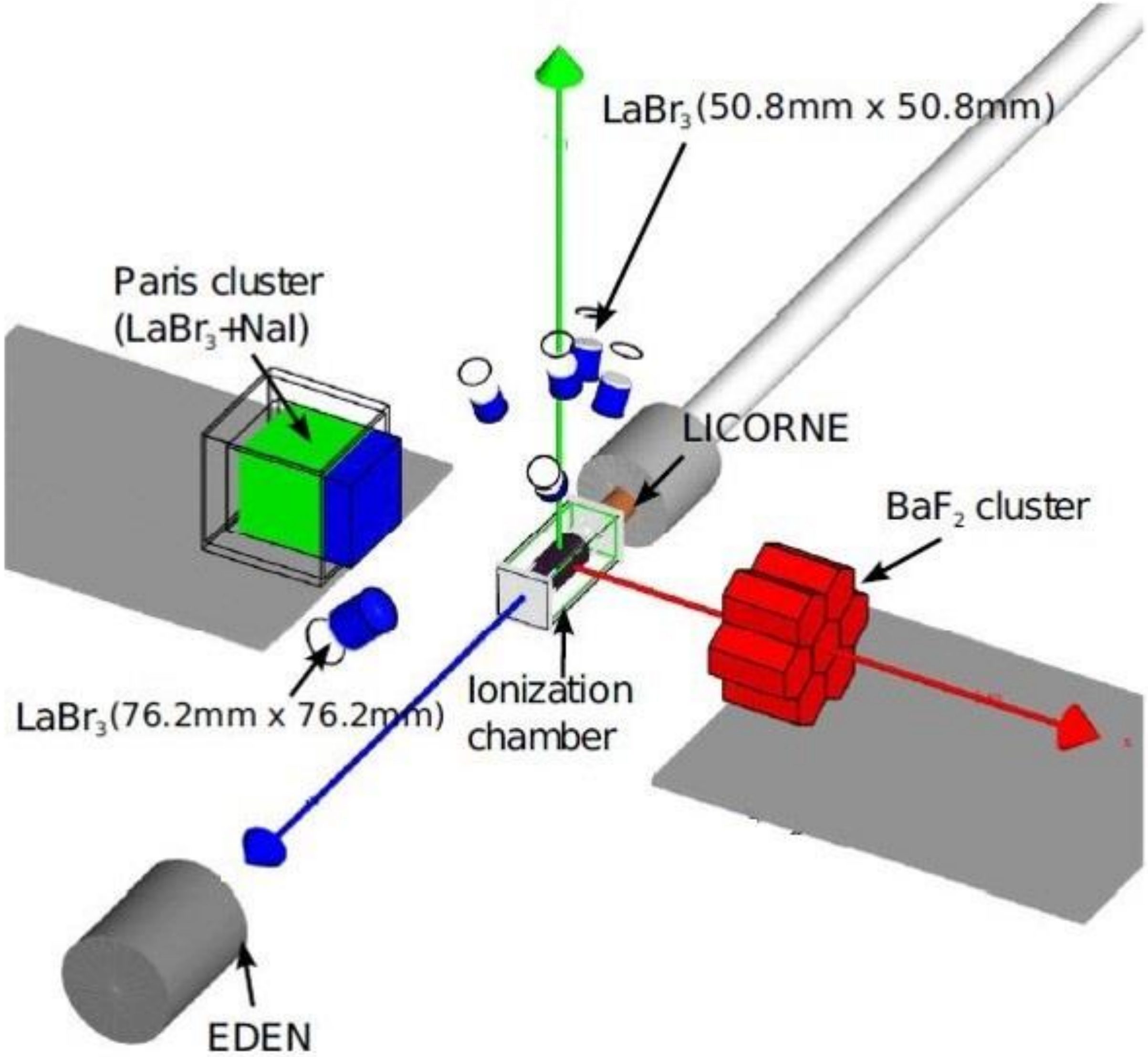
Even with the most sophisticated fission theories, these quantities are not accurately predicted as a function of fragment mass and charge.”



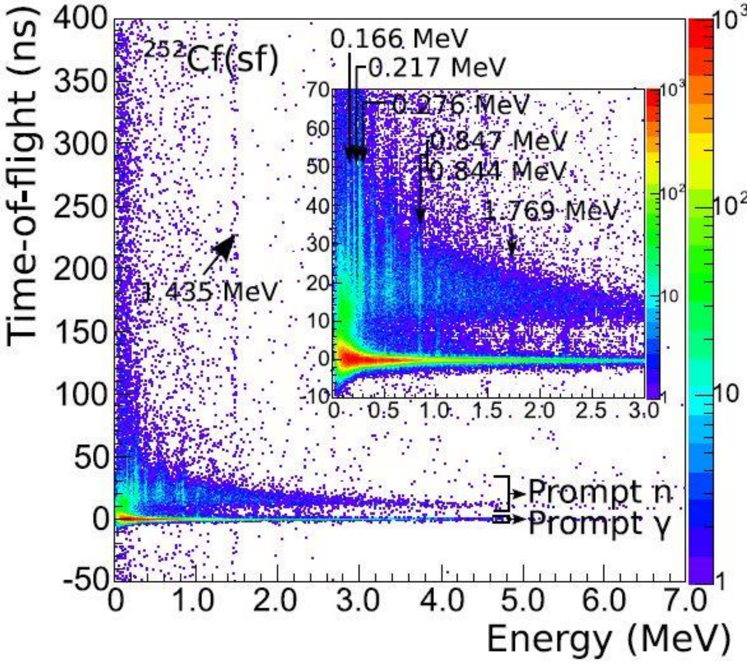
$\langle M_\gamma \rangle$ (one fragment) ~ 3.5 - 4

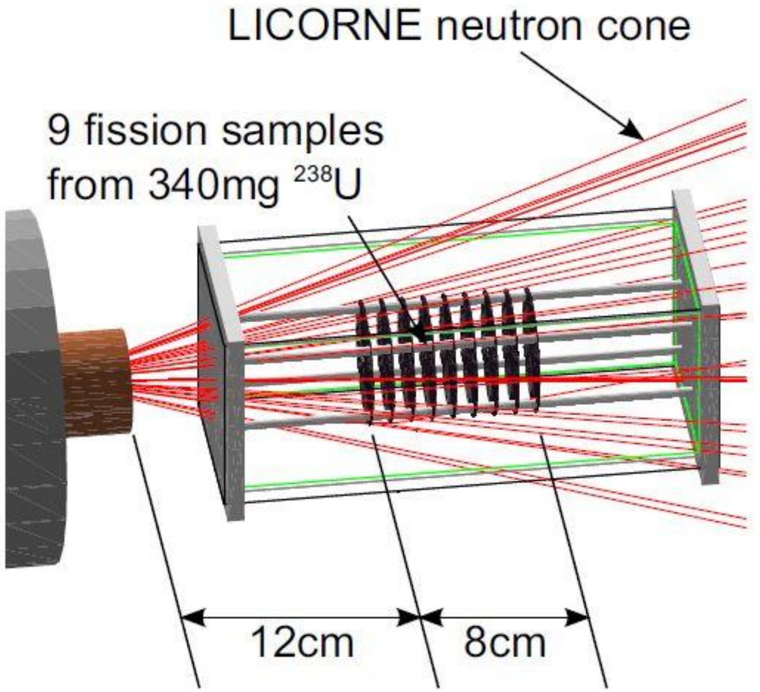
$\langle \nu \rangle$ (one fragment) ~ 1 - 2

PFG measurements setup



Neutron/gamma
Separation by TOF

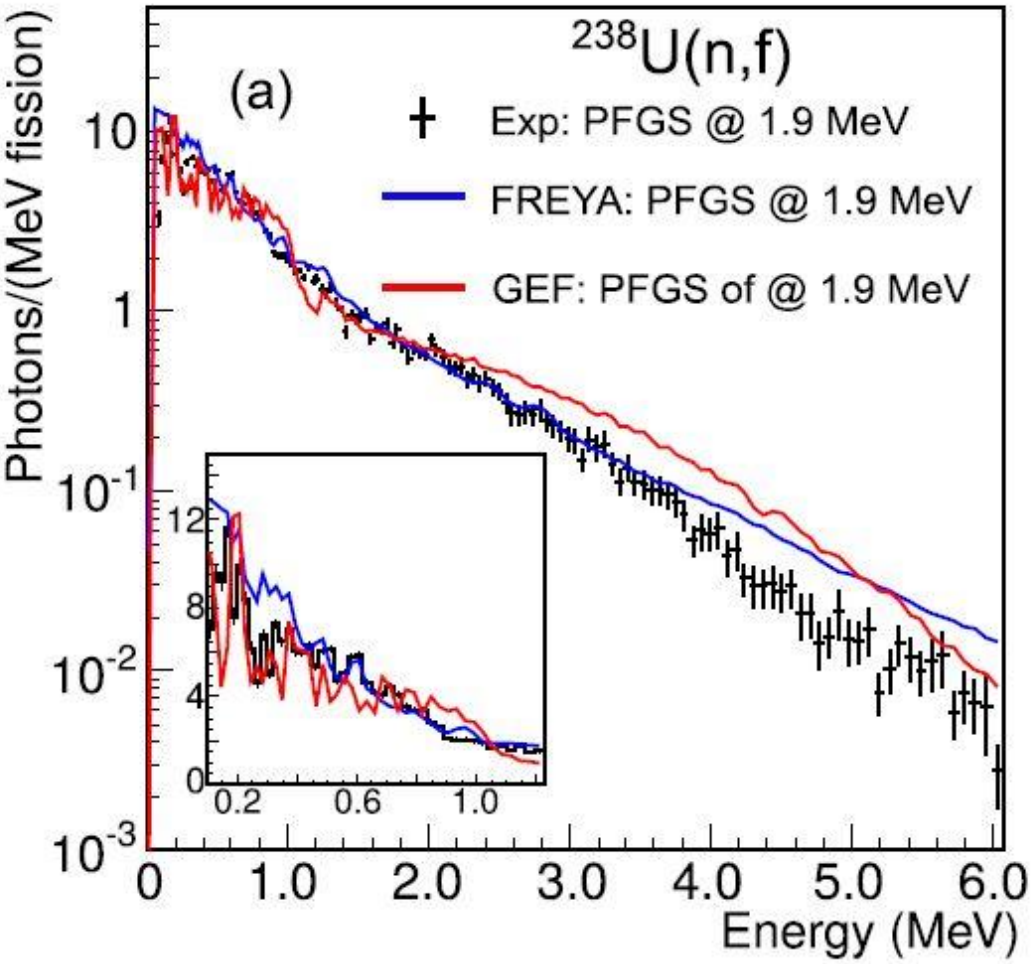


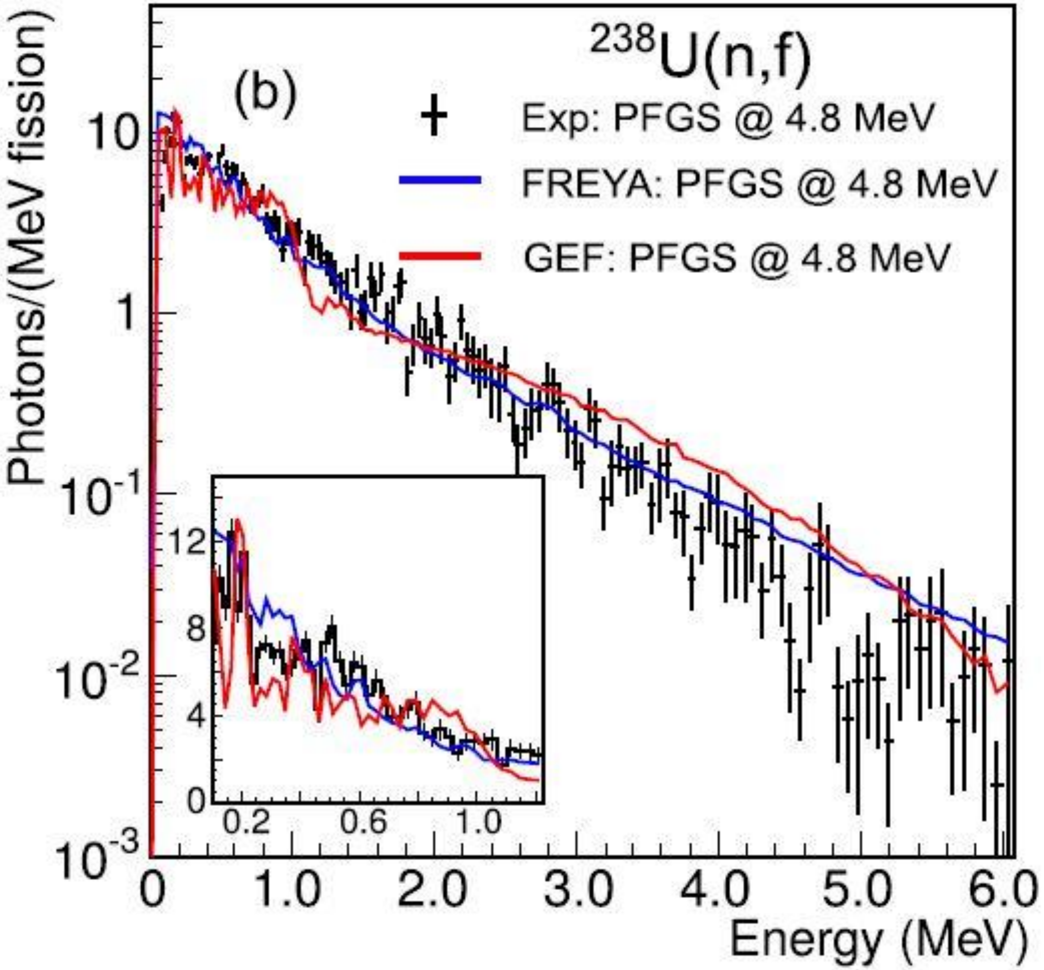


L. Qi et al., Phys. Rev. C 98, 014612 (2018)

PFG experiment: Results

En (MeV)	<Mγ>	Eγ,tot (MeV)	<Eγ> (MeV)
1.9	6.54 ± 0.19	5.25 ± 0.20	0.80 ± 0.04
4.8	7.31 ± 0.46	6.18 ± 0.65	0.84 ± 0.11





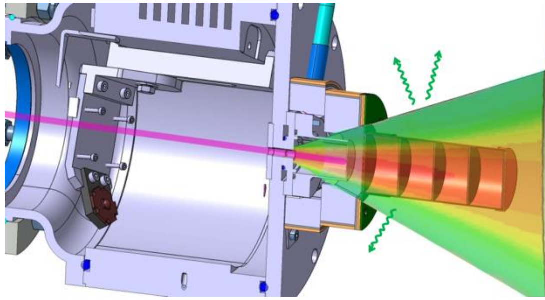
Coupling LICORNE with high resolution, high efficiency gamma spectrometers

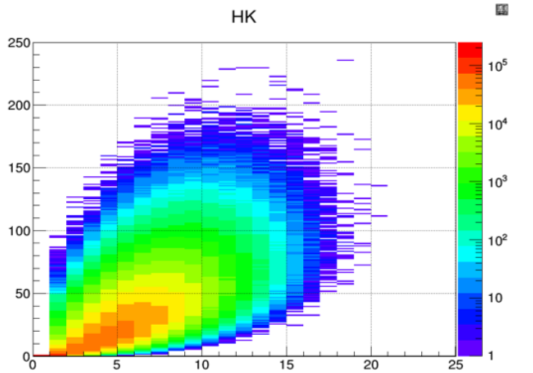
→ Gamma ray coincidence spectroscopy of fast neutron induced reactions

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

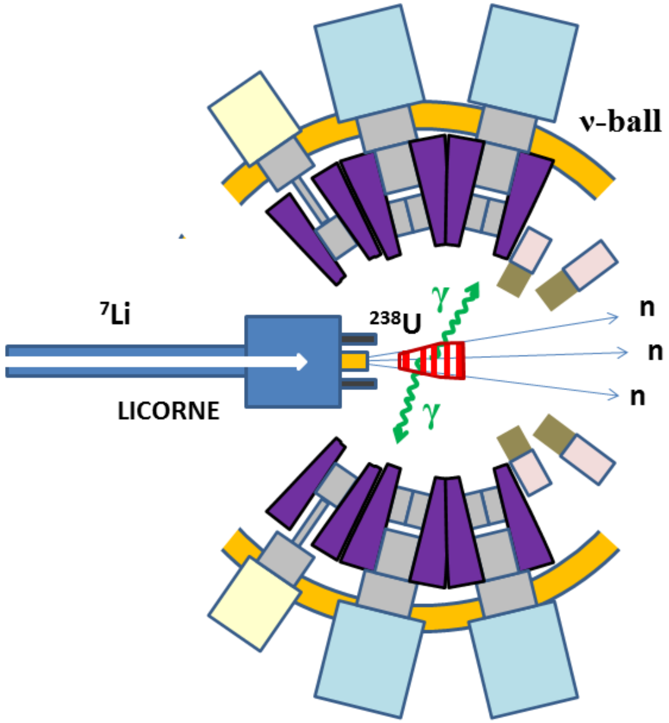
76 researchers from 16 countries
7 weeks of beam time in 2018

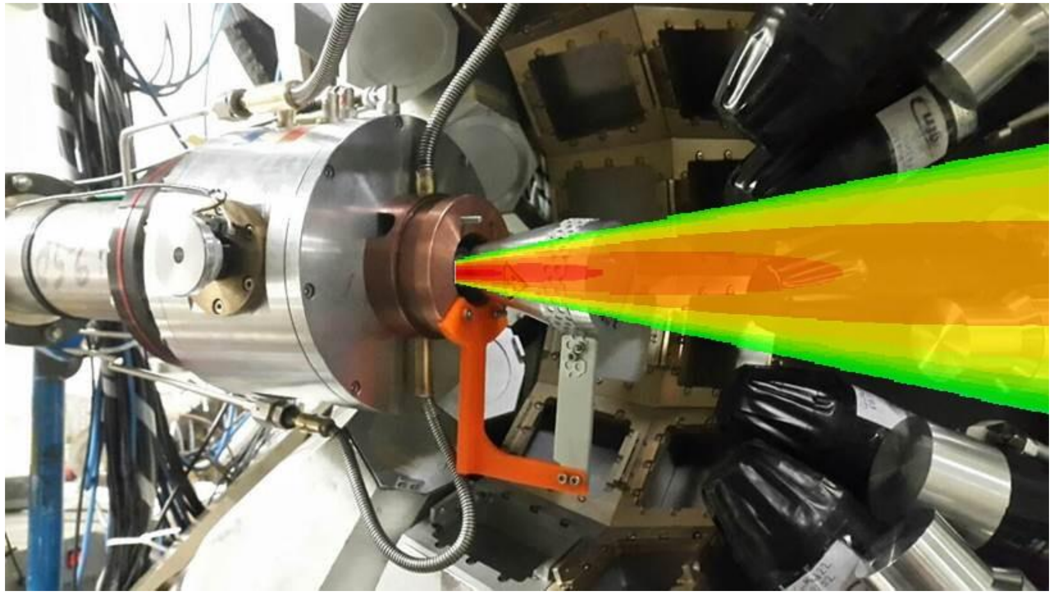
24 Clover Ge + BGO
10 Coaxial Ge + BGO
20 LaBr3
or 36 PARIS phoswich

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

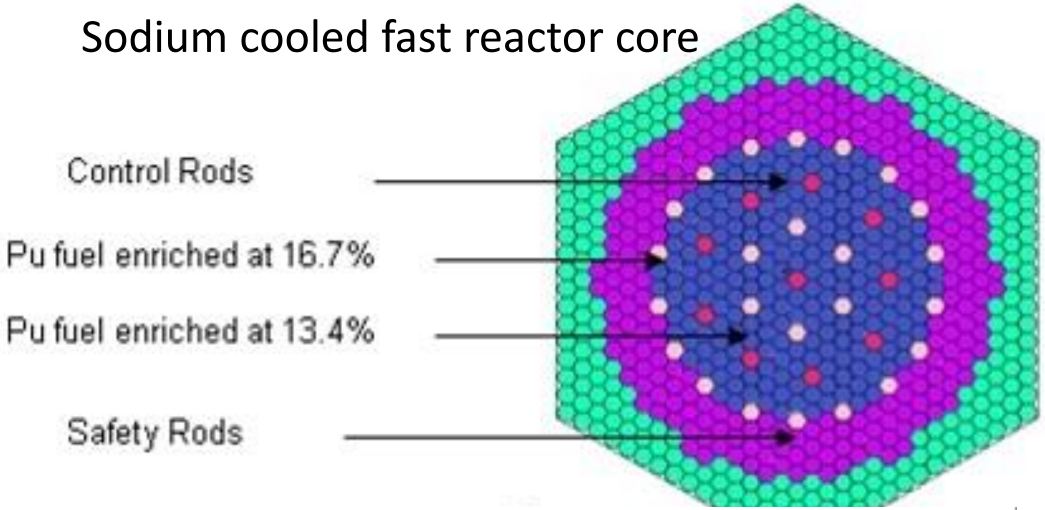
Inelastic neutron scattering in reactors

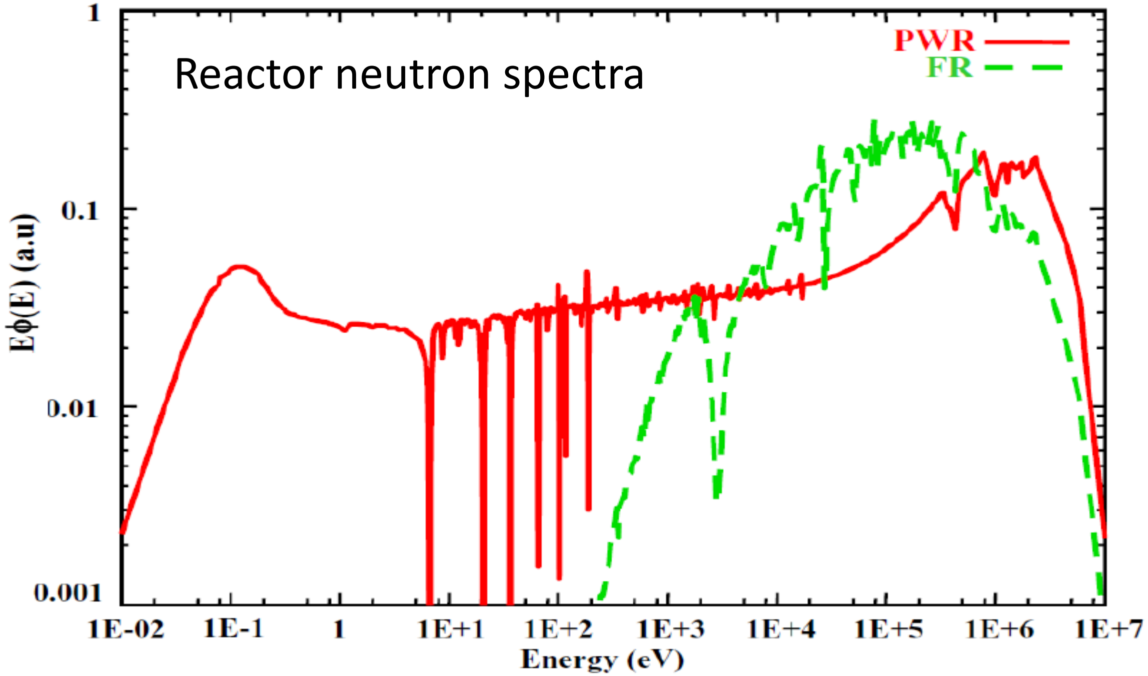
Project of Carole Chatel, IPHC Strasbourg

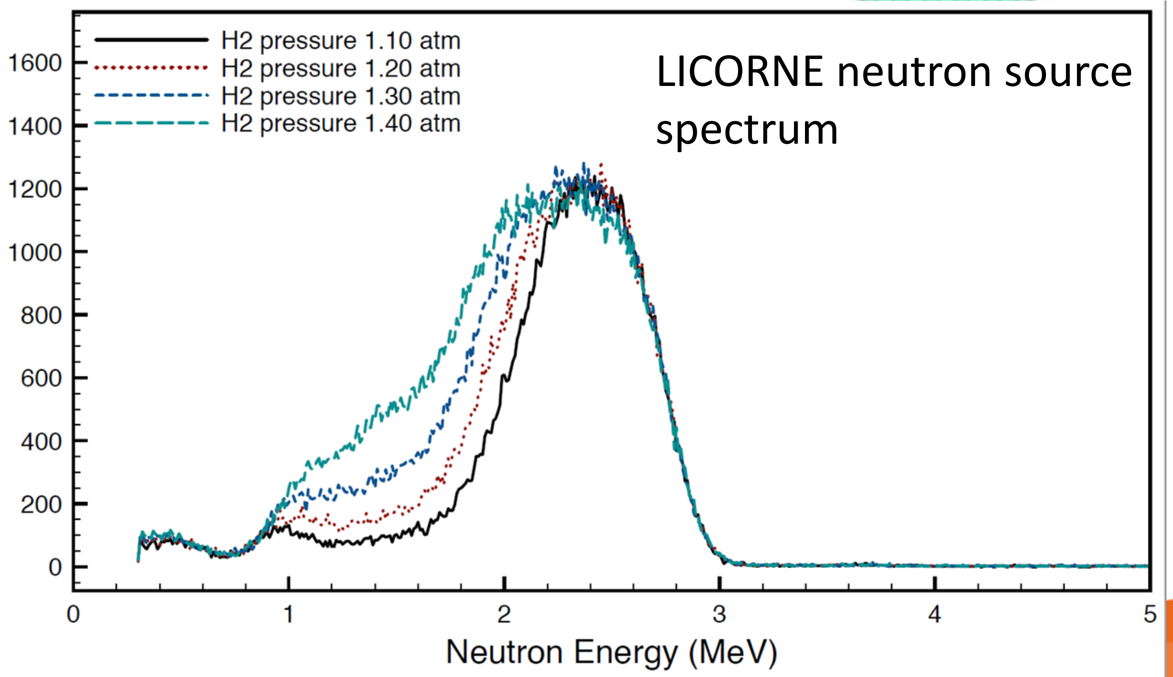
Existing reactor fuel contain > 95% ^{238}U
Advanced reactor fuels contain > 85% ^{238}U

Inelastic scattering affects neutron moderation

Sodium cooled fast reactor core

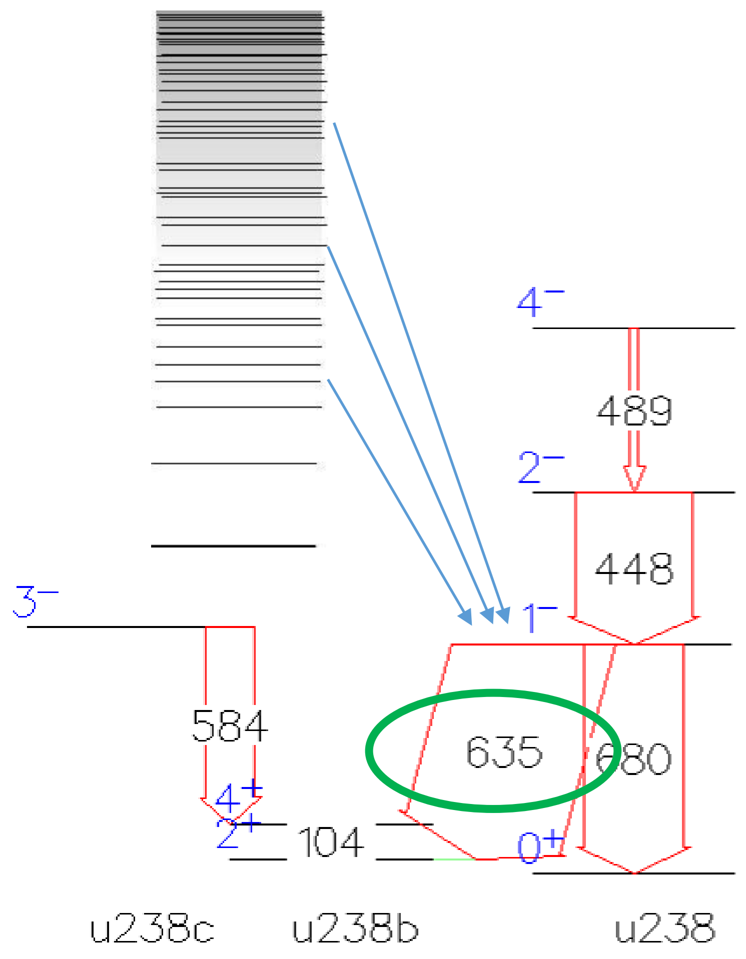


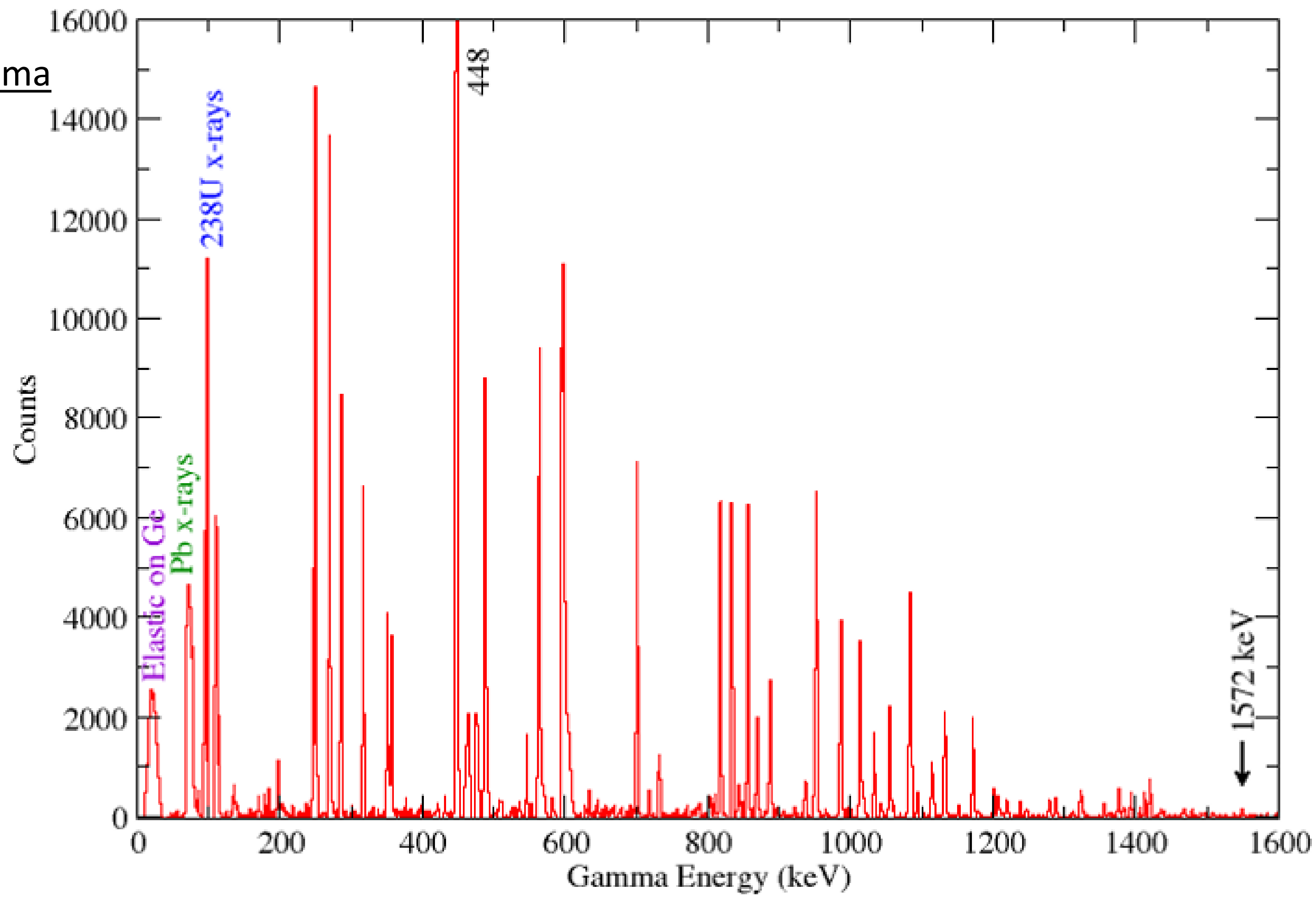




Inelastic neutron scattering on ^{238}U

First measurements with gamma-gamma coincidence data





Inelastic neutron scattering on ^{238}U

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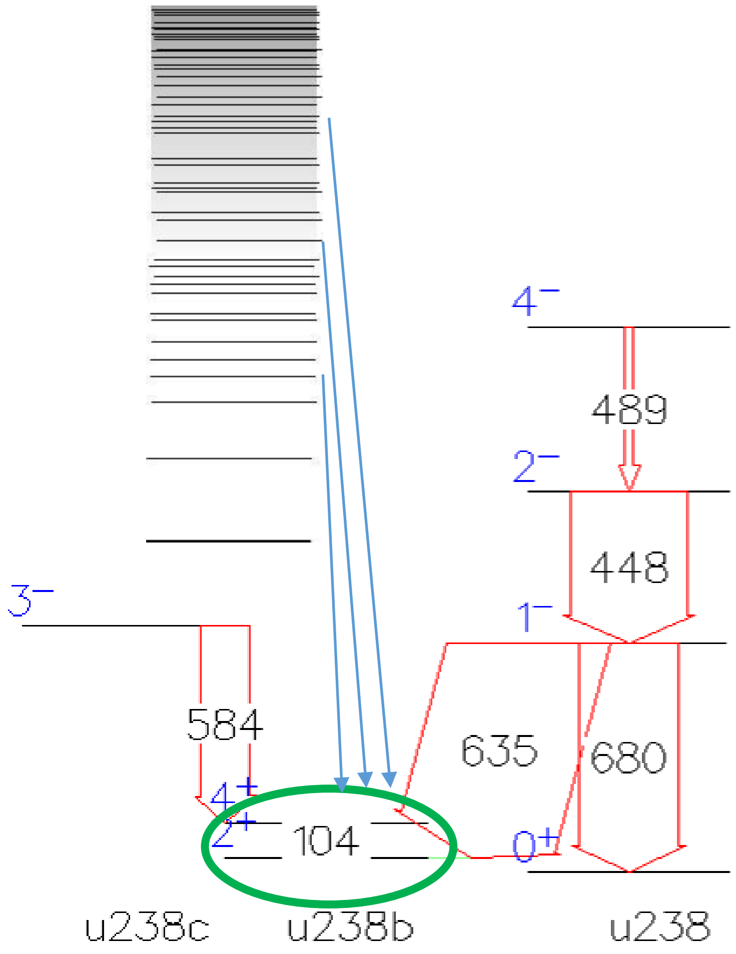
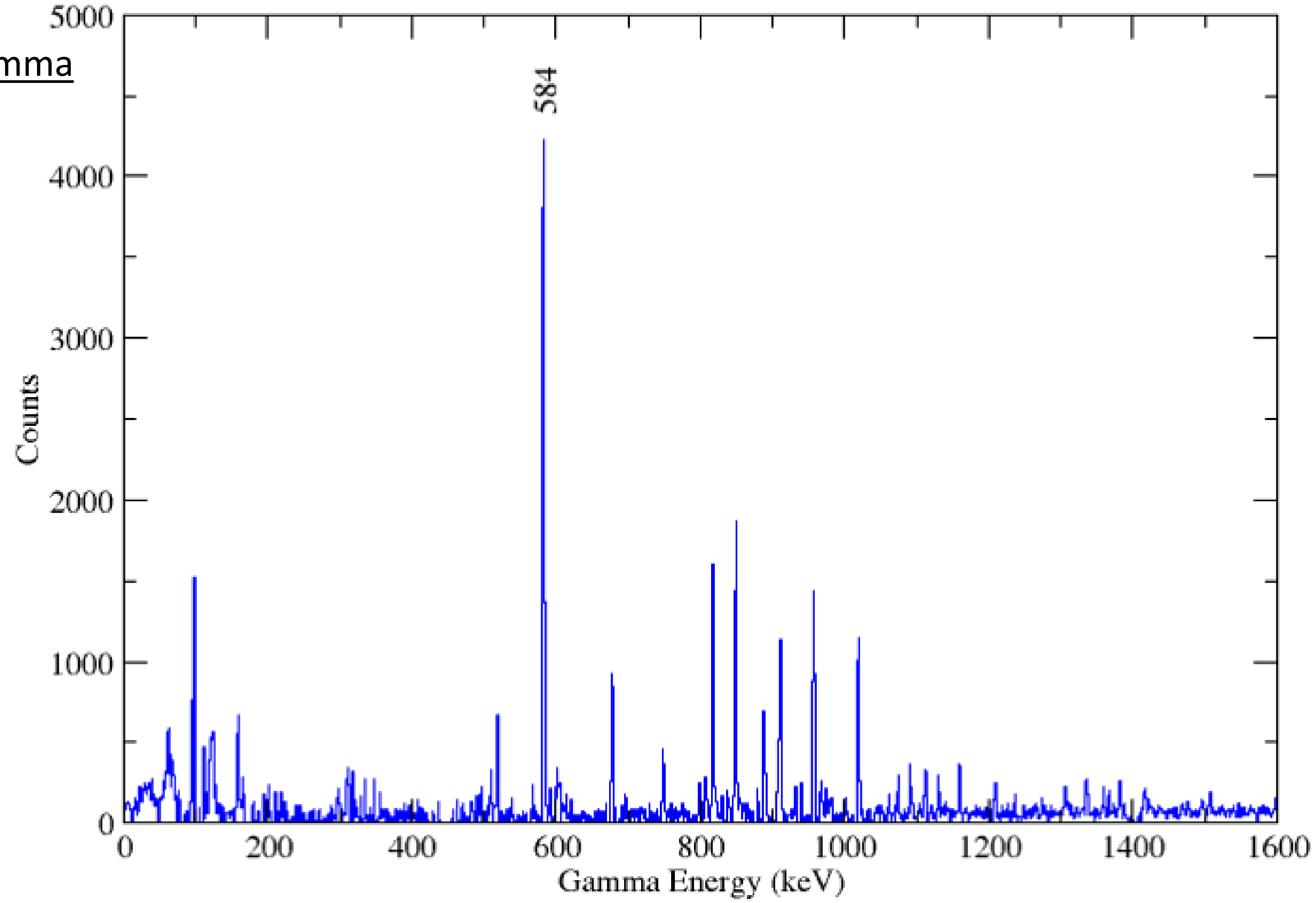
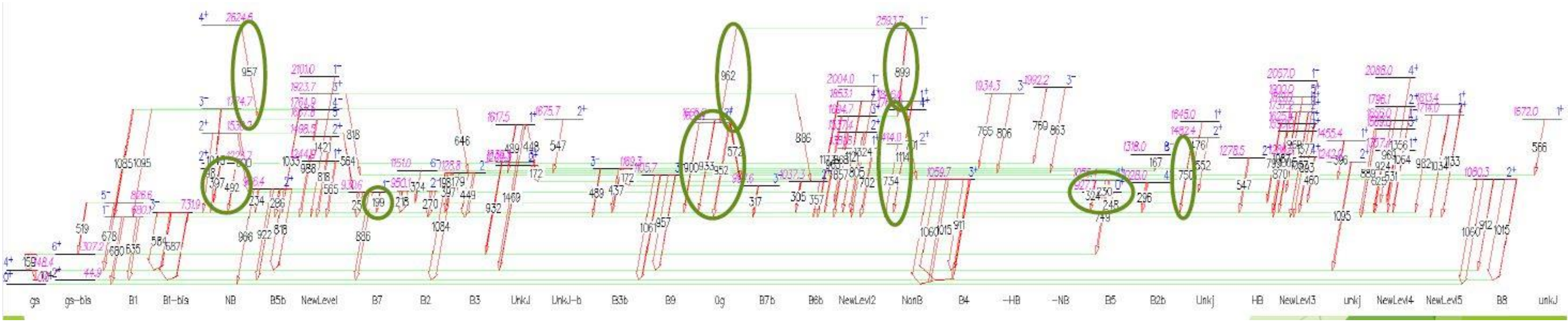




^{238}U(n,n') results

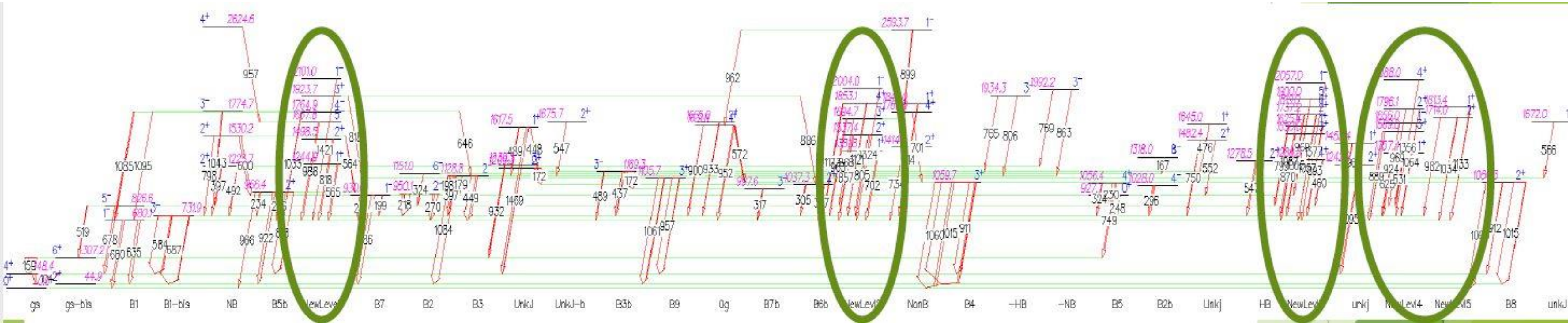
Courtesy of Carole Chatel, IPHC Strasbourg



- 18 new gammas depopulating levels already known in ENSDF

^{238}U(n,n') results

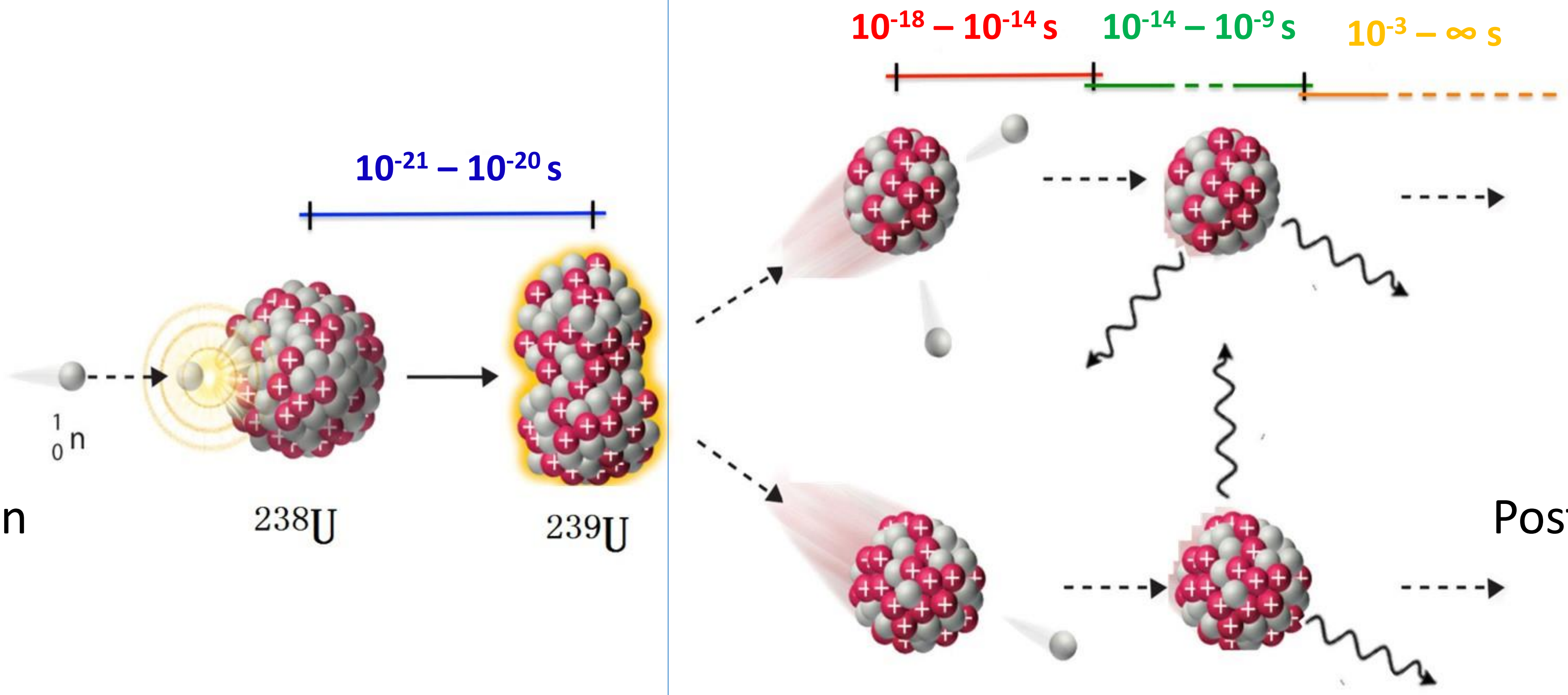
Courtesy of Carole Chatel, IPHC Strasbourg



- 26 new levels (not known in ENSDF)
- 36 new gammas (de)populating these levels

10% uncertainty in branching ratios leads to 4% uncertainty in the (n,n') cross section
Branching ratios to be measured precisely

The de-excitation process in fission



Pre-scission

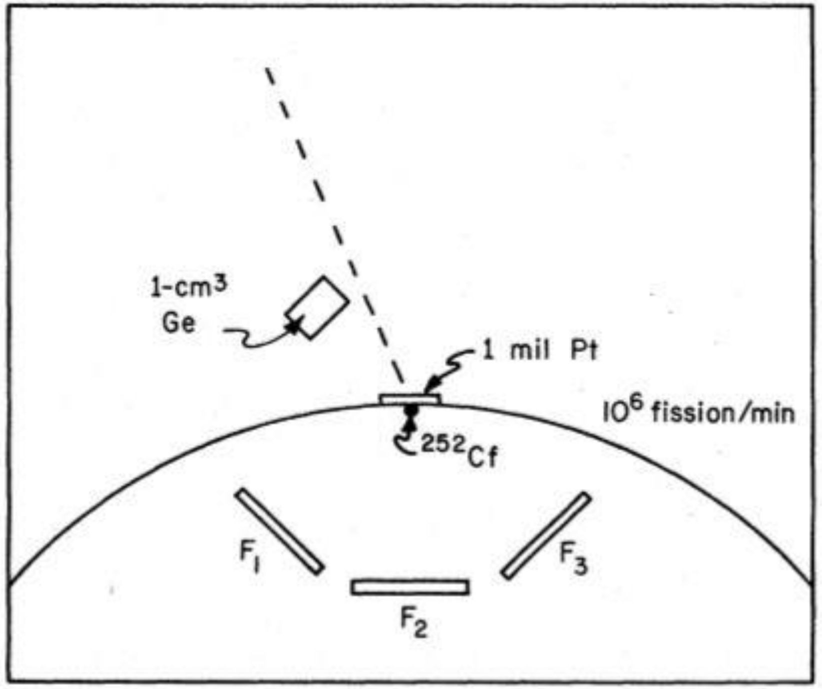
Post scission

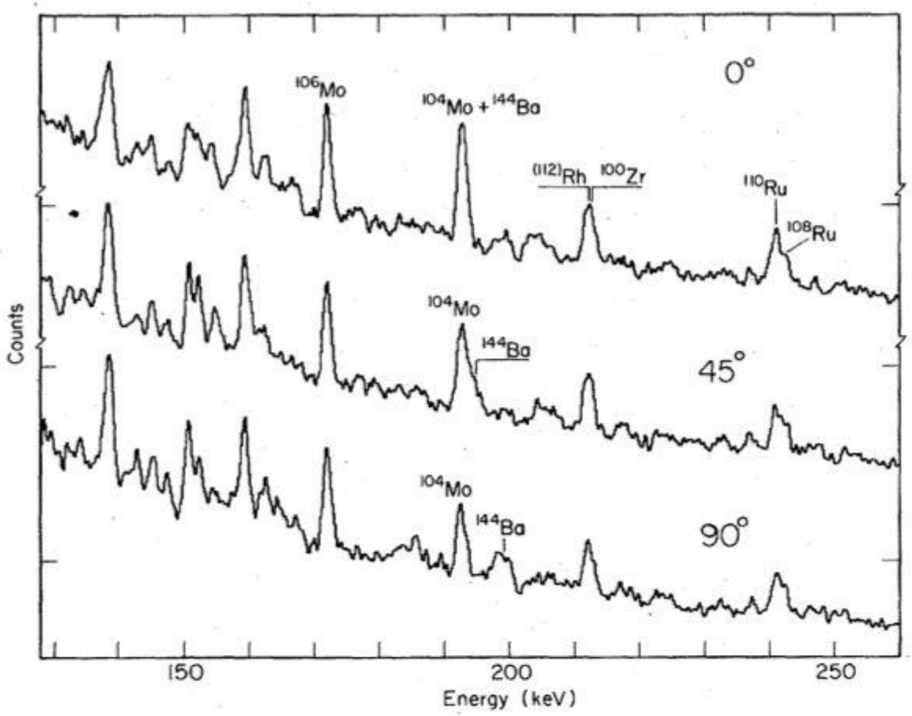
Fragment Kinetic Energy	Prompt neutrons	Prompt gamma rays	β, $\bar{\nu}$, γ decay
~160 MeV	~6 MeV	~8 MeV	~20 MeV

Fission fragments emerge spinning!

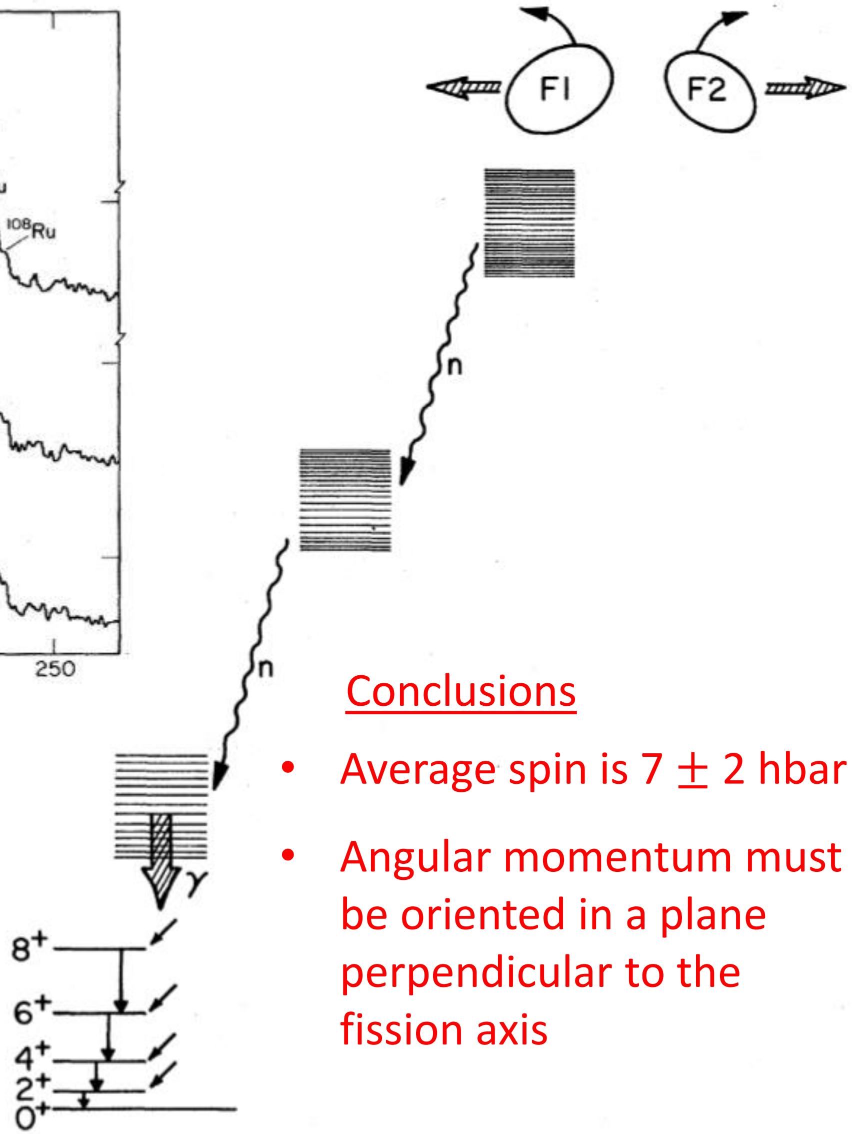
J.B. Wilhelmy et al.
Phys. Rev. C 5 2041 (1972)

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 of angular momentum in fission

Pre Scission Collective Vibration Theories

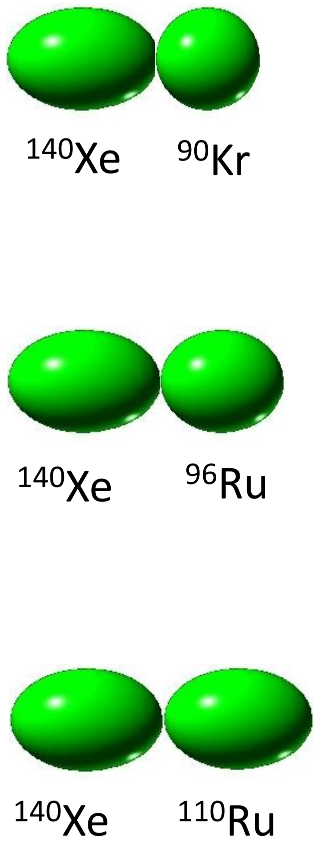
Rasmussen (1969) Bending. Di-nuclear system. Thermal excitations.
Moretto (1989) Bending, Wriggling, Twisting, Tilting. Semi-classical theory. Thermal excitations.
Misicu (1999) Bending, Coupled oscillators. Quantum fluctuations.
Shneidman (2002) Bending. Di-nuclear system. Quantum fluctuations.
Gönnenwein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

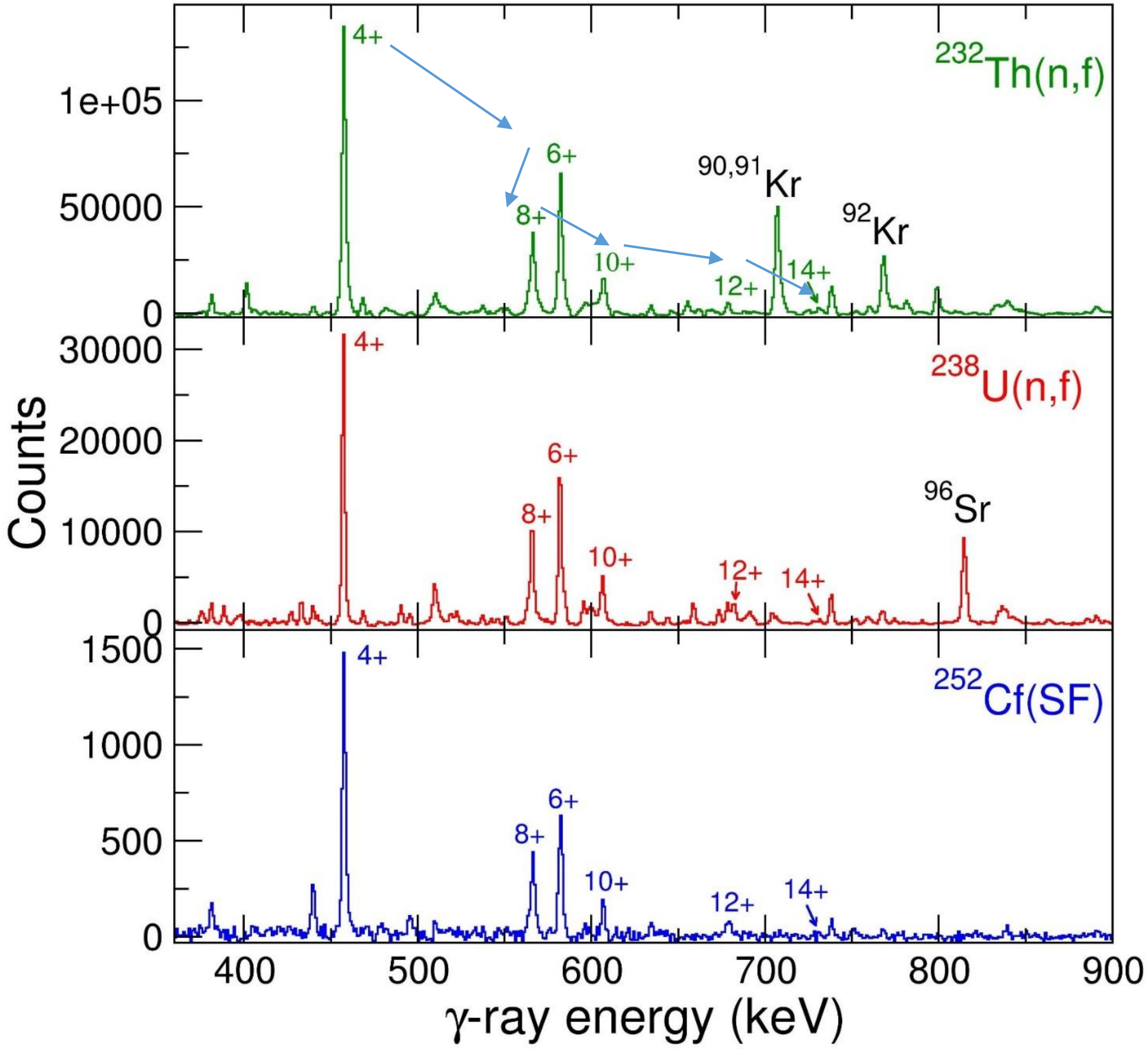
Post Scission Theories

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).

Nu-Ball1 fission spectroscopy results

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





Prompt decay only

Separation of prompt fission decay and beta feeding is essential

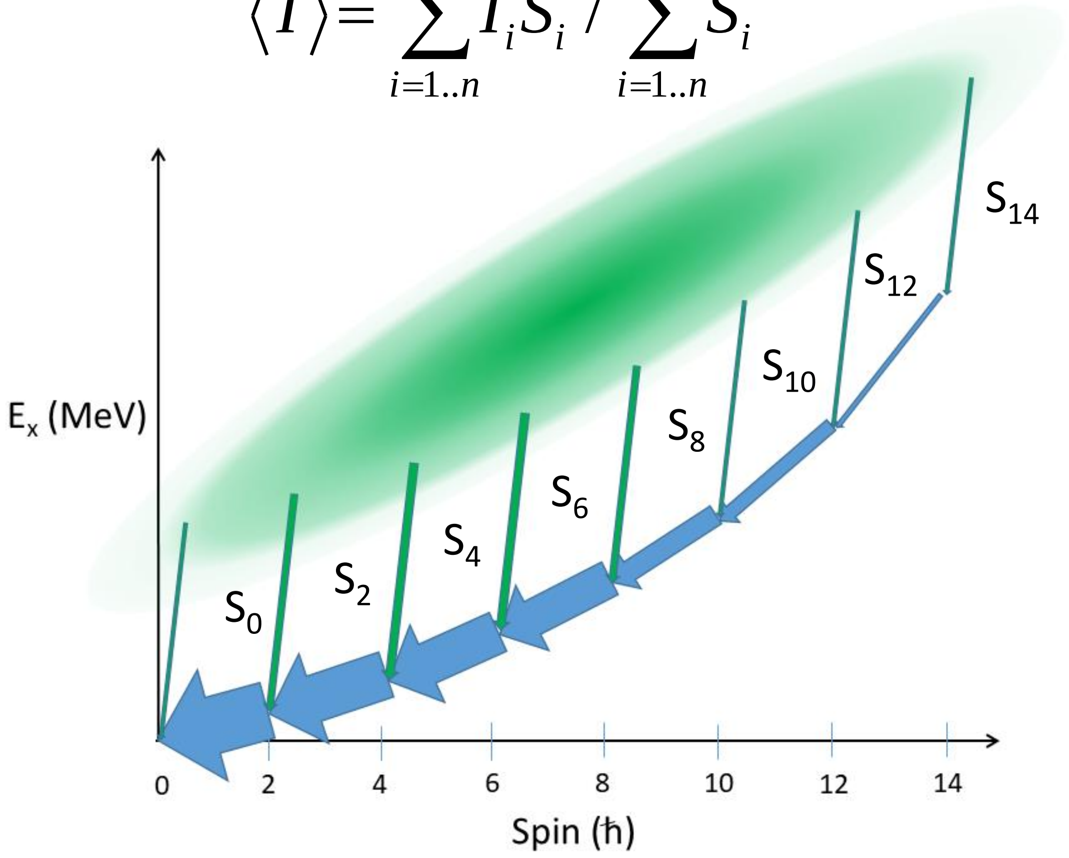
(with pulsed neutron beam)

(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)

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



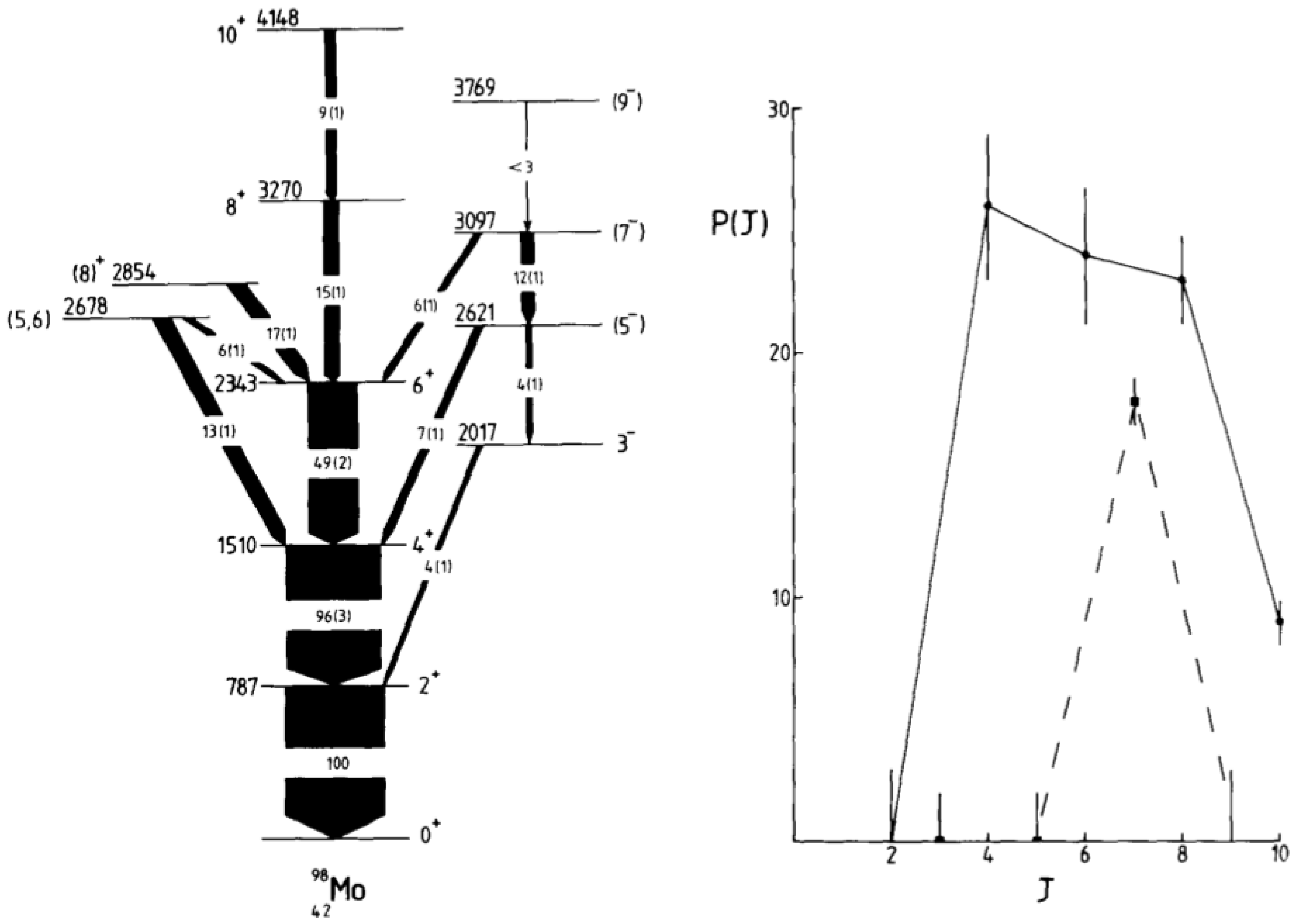
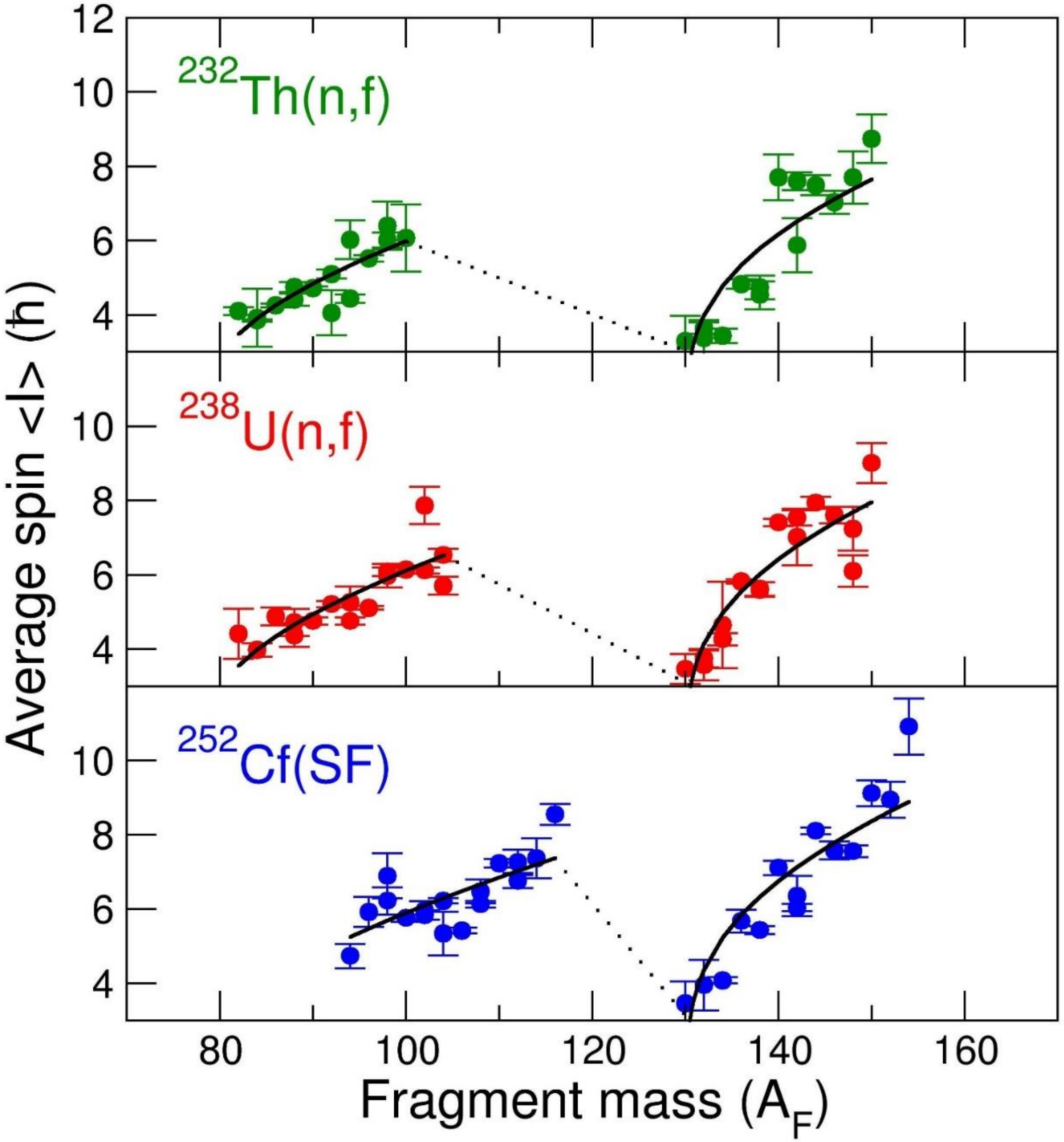


Fig. 1. An example of a partial decay scheme determined in the experiments, showing discrete line intensities observed following statistical population of entry points in ^{98}Mo final fragments. The populations $P(j)$ of states of spin j in ^{98}Mo fed directly by statistical γ-rays from the entry points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

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

- 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!

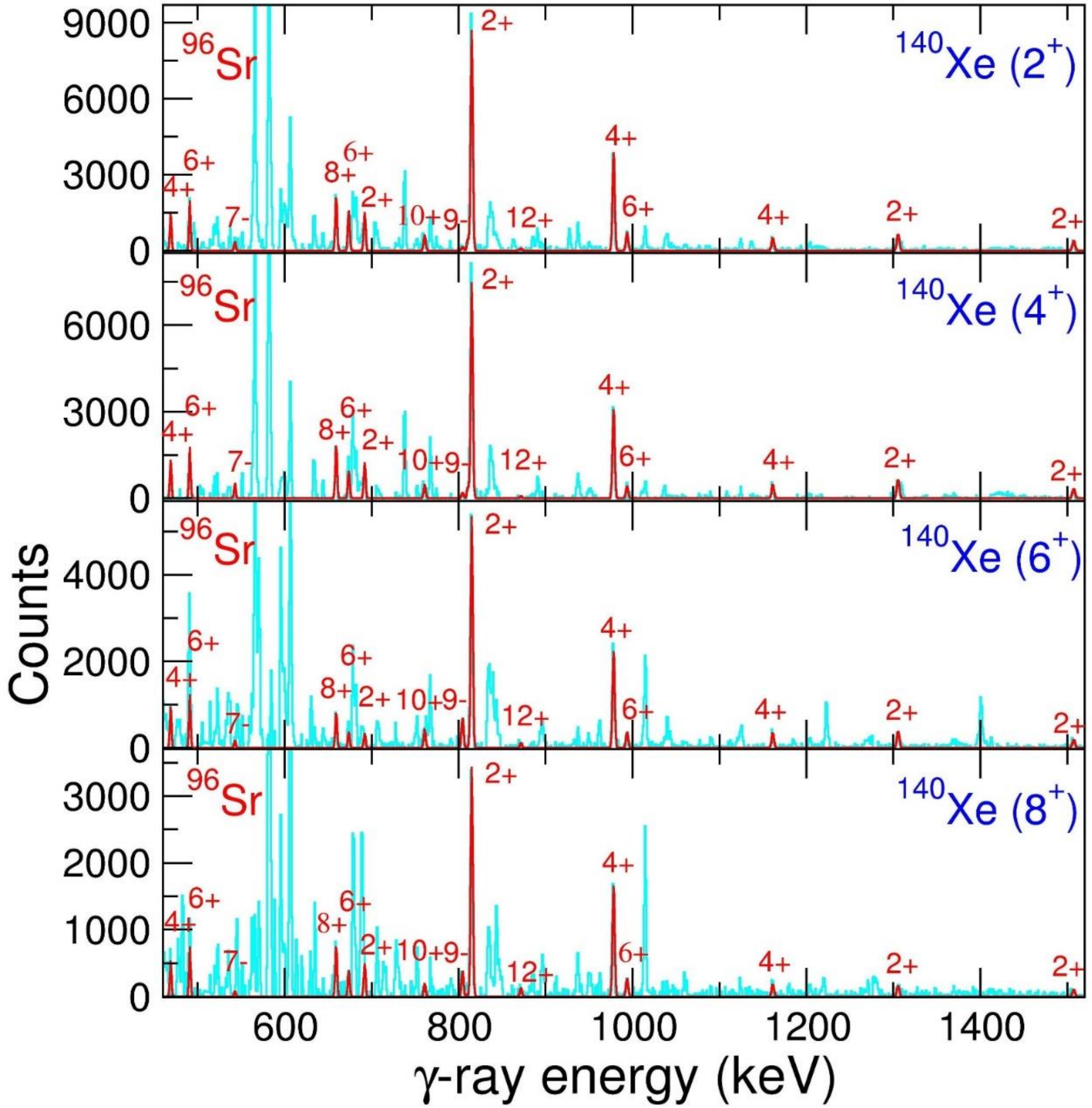
- Certain partners have large asymmetries in <I>

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

- Highly asymmetric distribution

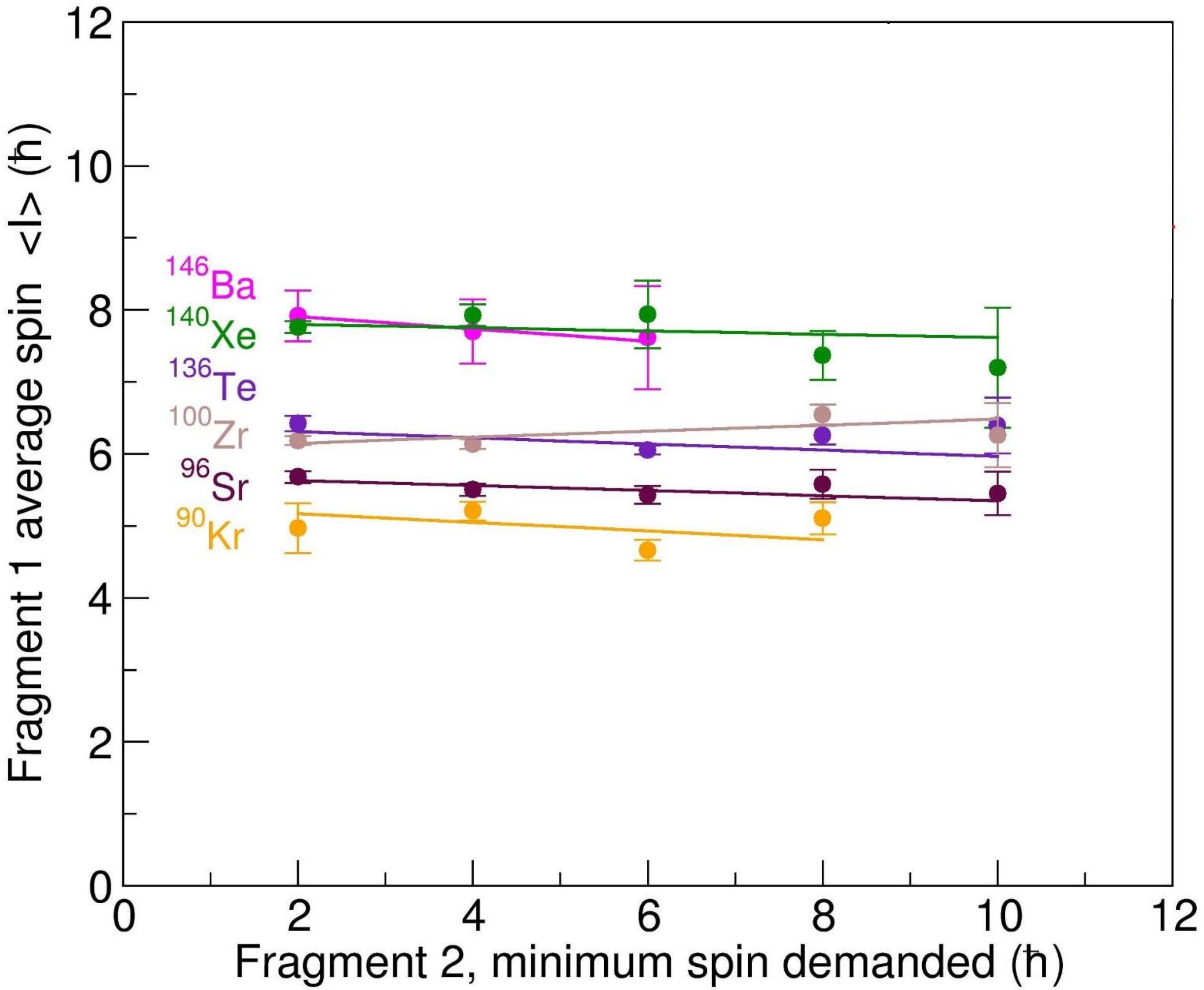
J.N. Wilson et al. Nature 590 566 (2021)

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



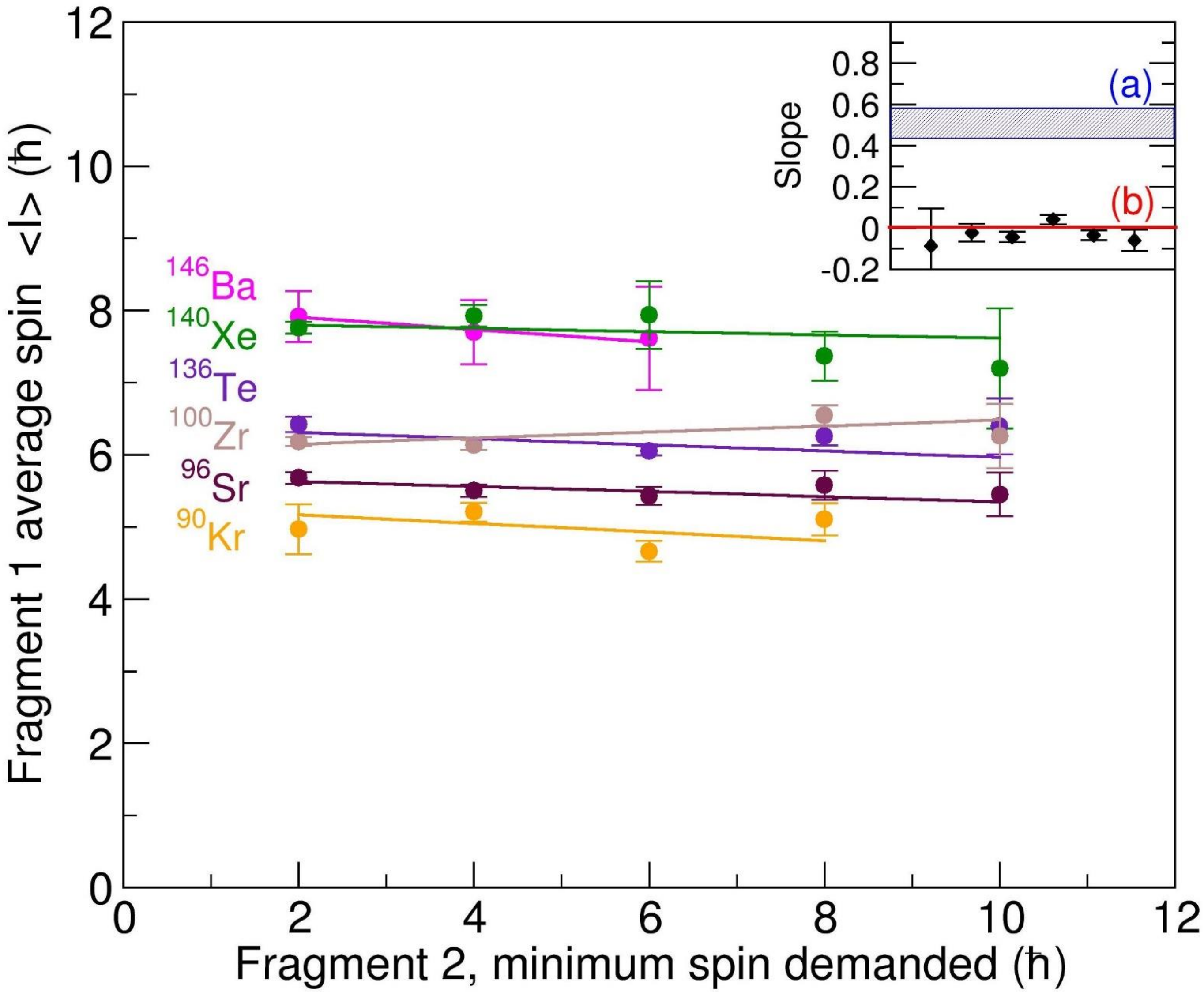
Increasing spin demanded in ^{140}Xe

RESULTS: Correlation between fragment spins



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

RESULTS: Correlation between fragment spins



Correlated spins (pre-scission)

Uncorrelated spins (post scission)

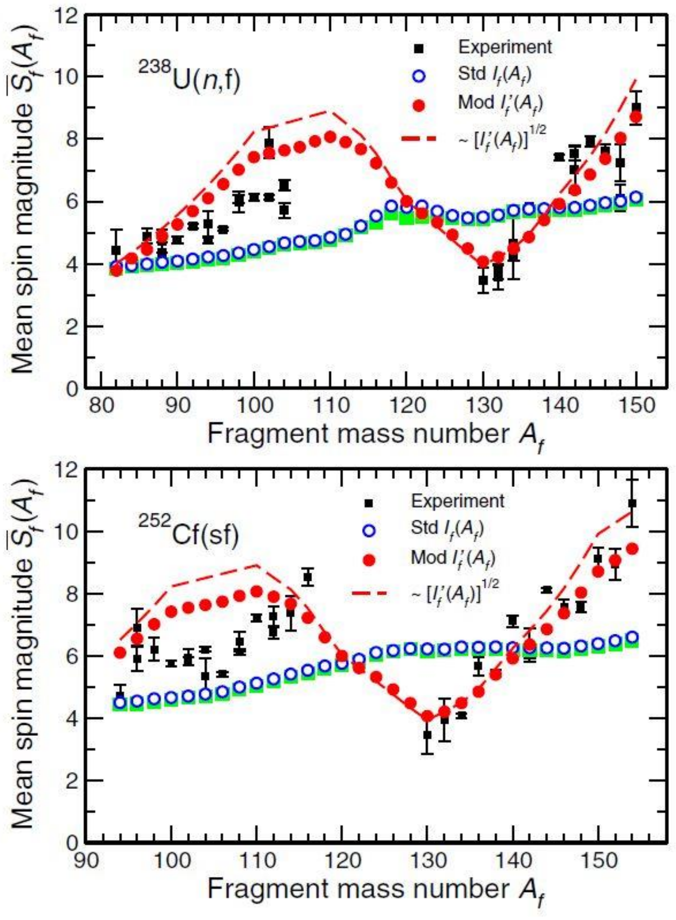
$$\vec{I}_1 + \vec{I}_2 + \vec{I}_o = 0$$

$|I_o| = |I_1 + I_2|$

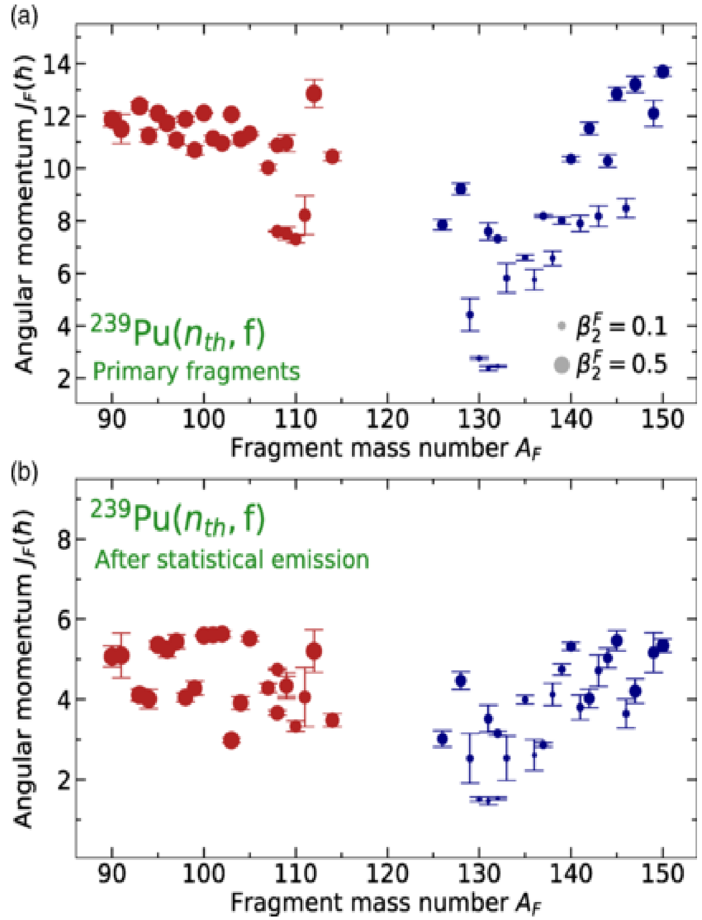
$|I_o| = |I_1 - I_2|$

Subsequent articles! …

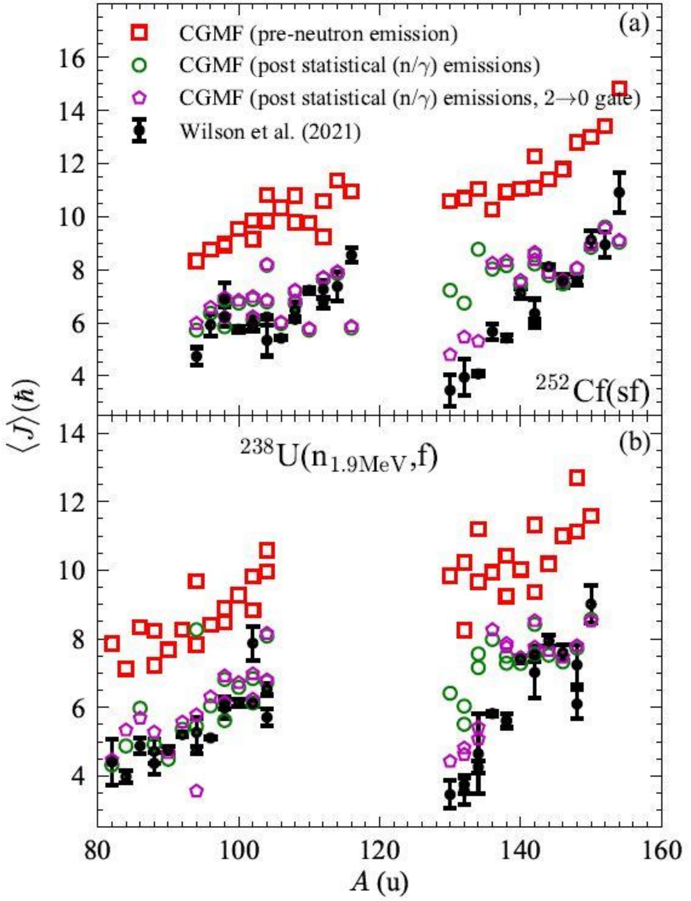
J. Randrup and R. Vogt, (Berkeley)
Phys. Rev. Lett.127, 062502(2021)
FREYA, Monte-Carlo de-excitation code



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



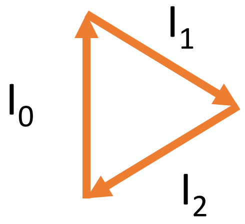
I. Stetcu et al. (Los Alamos)
Phys. Rev. Lett. 127, 222502 (2021)
CGMF, Monte-Carlo Hauser Feshbach



Coupled fission fragment angular momenta

J. Randrup, Phys. Rev. C 106, L051601 (2022)

“The relative motion, due to the large size of the associated moment of inertia in comparison with those of the individual fragments, effectively acts as a reservoir of angular momentum”



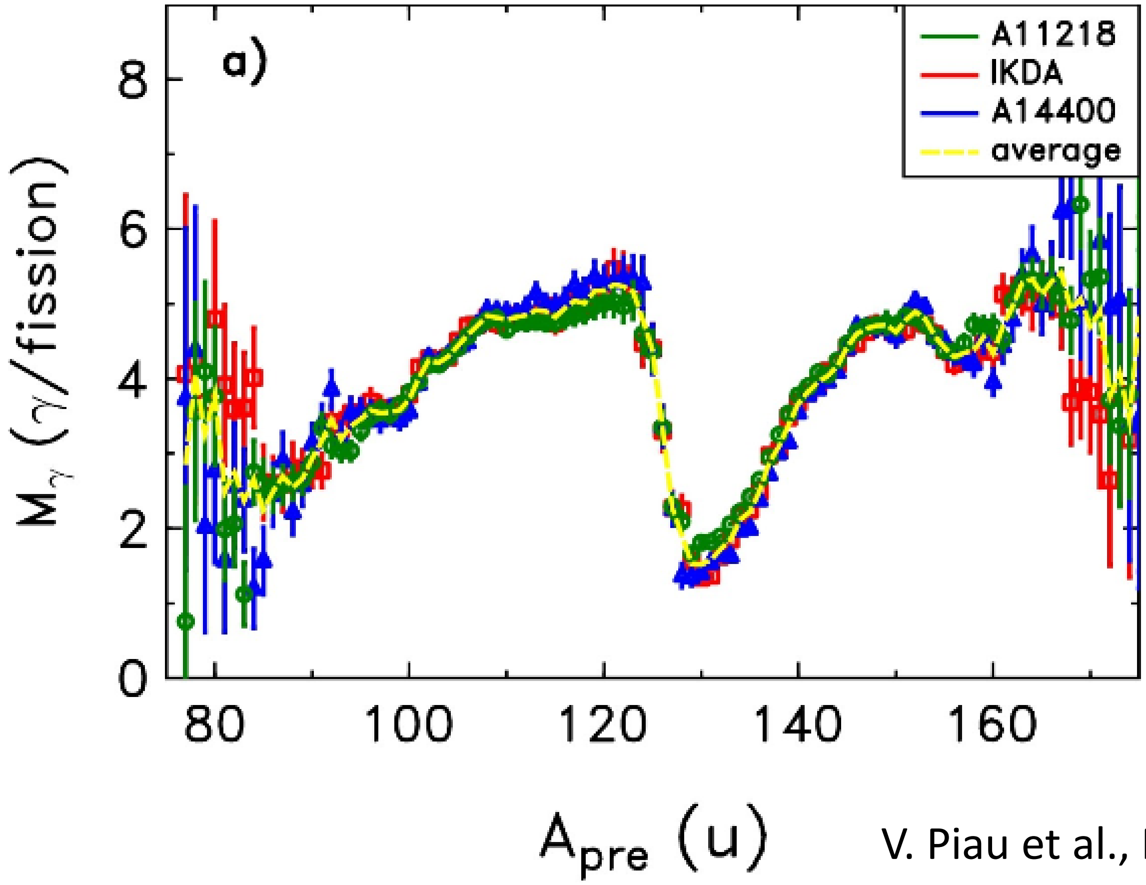
$$\vec{I}_1 + \vec{I}_2 + \vec{I}_o = 0$$

Scission Configuration		Ratios of moments of inertia $J_1:J_2:J_0$	Correlation in spin magnitudes fragment 1 and 2
Compact		1:1:2	33%
Touching spheres		1:1:5	17%
Elongated		1:1:17	5.5%

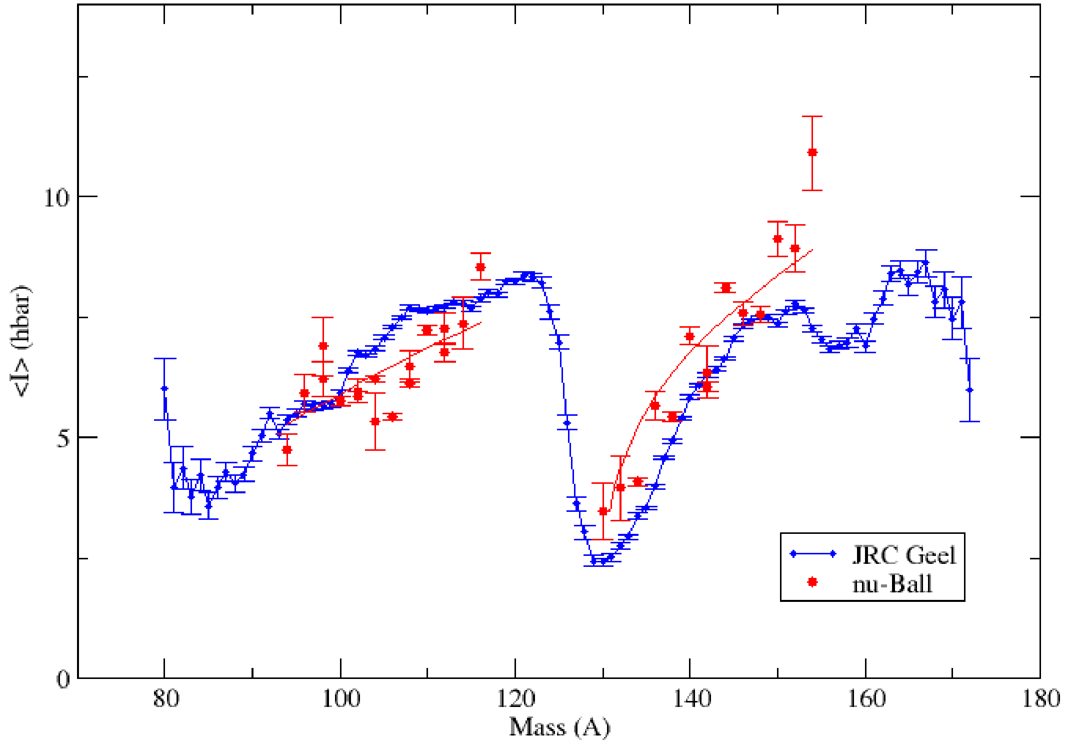
Independent sawtooth confirmation

^{252}Cf

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



Normalization: Literature value of 1.6 hbar per emitted gamma



V. Piau et al., Phys. Lett. B837 137648 (2023)

ν-ball2 @ALTO Fission experiments 2022/2023

<u>1) Propagation of angular momentum in fission</u>

Gradually increase initial angular momentum input

Transfer reactions ^{235}U(d,xf), heavy ion reactions ^{18}O+^{197}Au

What happens to fragment spins?

How does the saw-tooth pattern evolve?

<u>2) Emission of high energy gammas in fission</u>

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?)

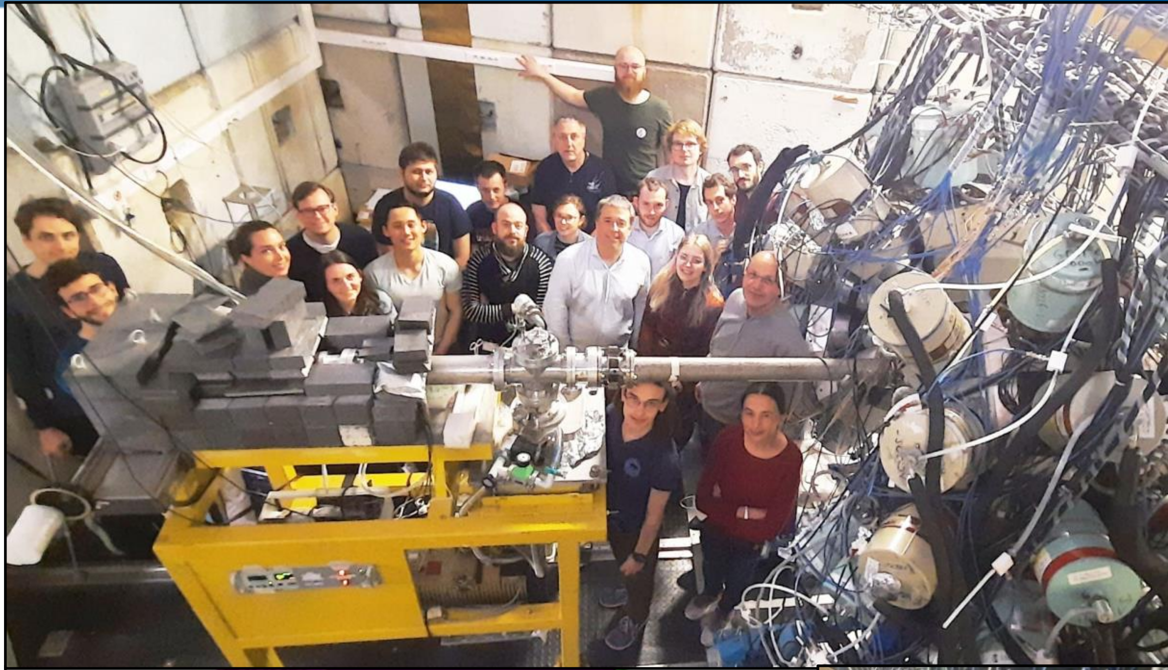
<u>3) Spectroscopy in the 2nd minimum of fission shape isomers</u>

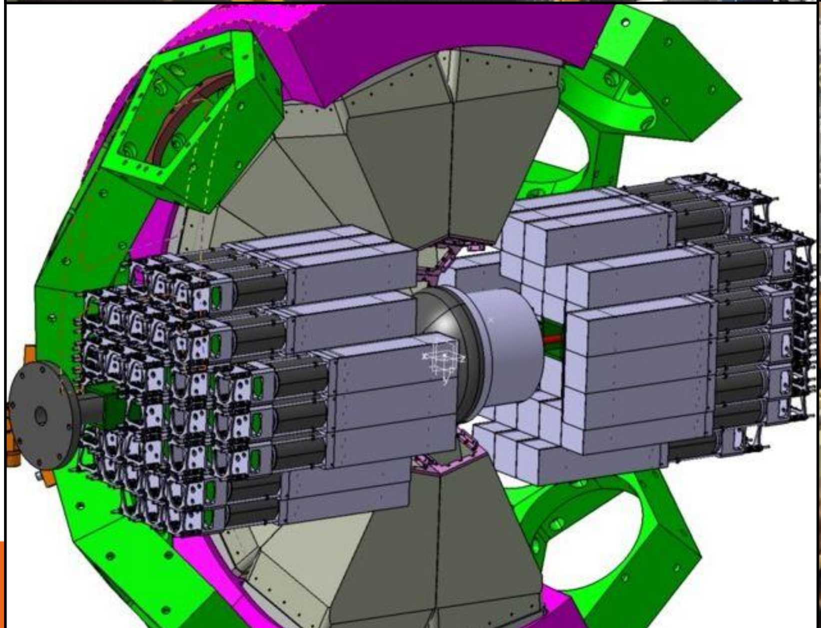
Gamma decay's branches to first minimum and characterisation of states in the 2^{nd} minimum

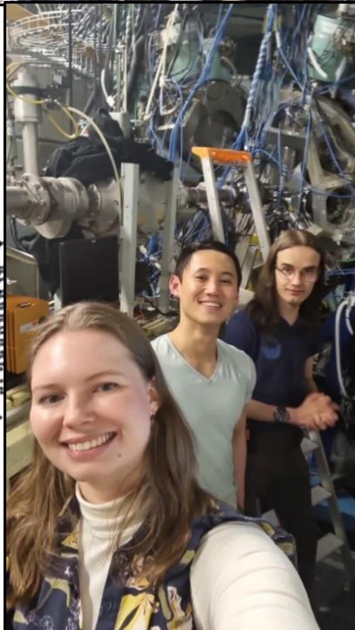
<u>4) Coupling with Ionization chamber + ^{248}Cm(SF) source</u>

Multi-fission observables: Each fragment's Mass (ΔM ~ 3)

K.E., theta, phi, gamma emission, neutron emission

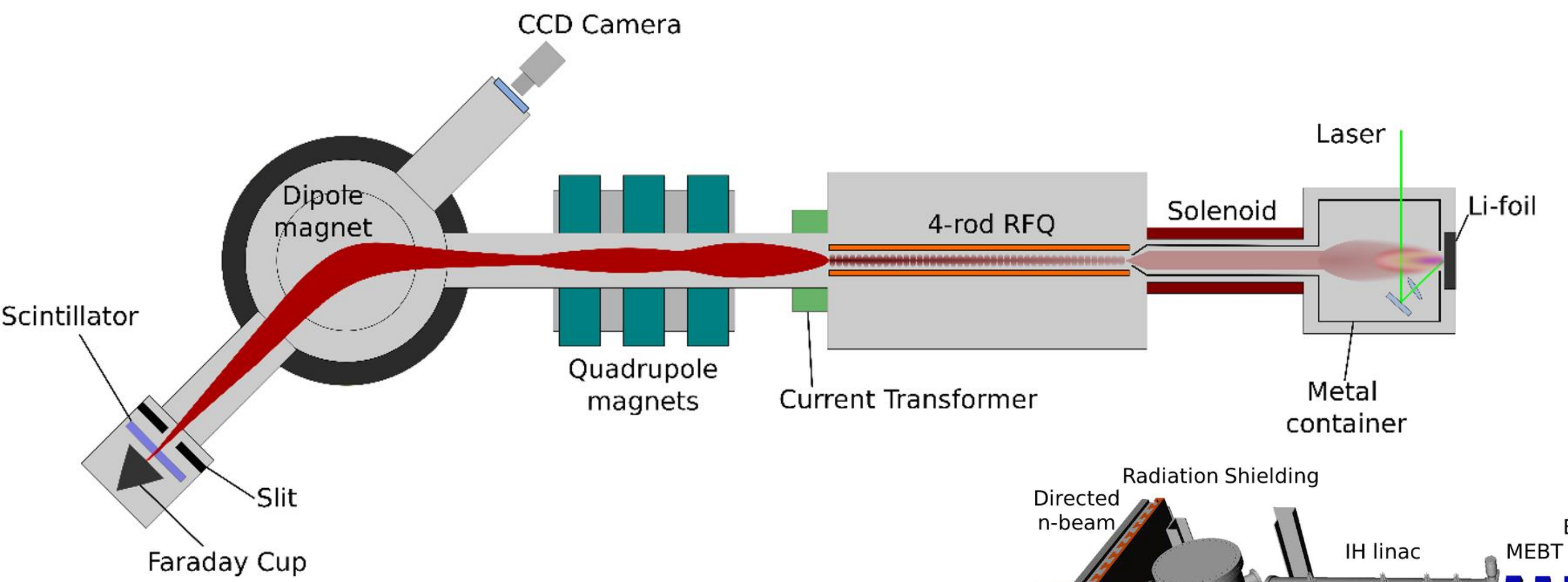


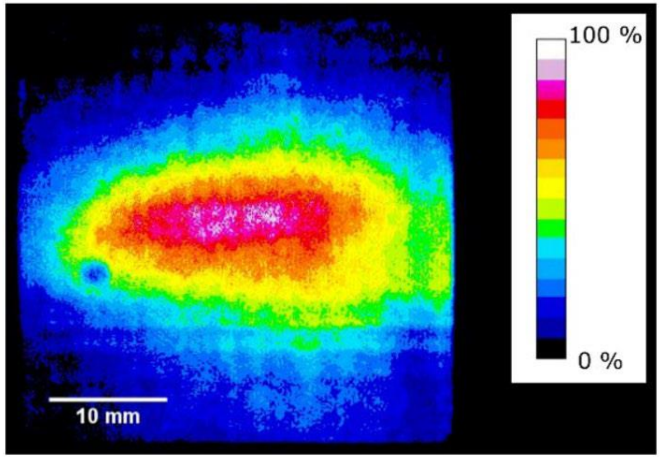




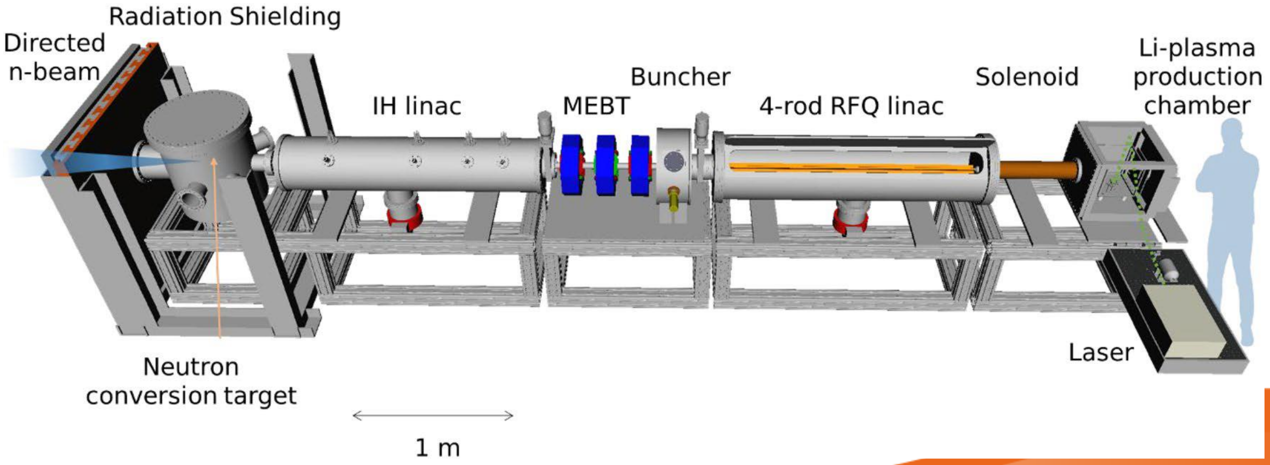
Super-LICORNE??

Demonstration of an intense lithium beam for forward-directed pulsed neutron generation
M. Okamura et al. Nature Scientific Reports 12 14016 (2022)





Li beam, 35 mA !!!



Neutron converter is still in the design phase

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

LICORNE publications (2013 – 2017)

14) Studies of fission fragment yields via high-resolution γ-ray spectroscopy
J.N. Wilson, M. Lebois, L. Qi, et al., Proceedings of the Theory-4 international workshop, Varna, Bulgaria (2017)
13) Neutron-rich isotopes from 238U(n,f) and 232Th(n,f) studied with the nu-ball spectrometer coupled to the LICORNE neutron source
J.N. Wilson, M. Lebois , and L. Qi, Proceedings of the FISSION-2017 international conference, Chamrousse (2017)
12) Anomalies in the charge yields of fission fragments from the 238U(n,f) reaction
J.N. Wilson, M. Lebois, L. Qi et al.,, Phys. Rev. Lett. 118, 222501 (2017)
11) Production and study of neutron-rich nuclei using the LICORNE directional neutron source
J.N. Wilson, M. Lebois, L. Qi et al., Proceedings of the Zakopane international conference, Acta Physica Polonica B Vol.48 395 (2017)
10) Studies of γ-ray emission in the fission process with LICORNE
M. Lebois, J.N. Wilson, et. al , Proceedings of the CNR*15 international conference , EPJ Web of Conferences 122, 01010 (2016)
9) Comparative measurement of prompt fission gamma-ray emission from fast neutron induced fission of 235U and 238U
M. Lebois, J.N. Wilson, et al, Phys. Rev. C 92 034 618 (2015)
8) Prompt Emission in Fission Induced with Fast Neutrons
J.N. Wilson, M. Lebois, P. Halipré, S. Oberstedt, A. Oberstedt, Physics Procedia, Volume 64, Pages 107–113 (2015)
7) Future research program on prompt gamma-ray emission in nuclear fission
S. Oberstedt, R. Billnert, F. -J. Hambsch, M. Lebois, A. Oberstedt and J. N. Wilson , Eur. Phys. J. A, 51 12 (2015) 178
6) Development of a kinematically focused neutron source with the p(7Li,n)7Be inverse reaction
M. Lebois, J.N. Wilson, P. Halipre, B. Leniau, I. Matea, A. Oberstedt, S. Oberstedt, D. Verney, Nucl. Instrum. Meth. A 735 46 (2014)
5) The LICORNE neutron source and measurements of prompt gamma rays emitted in fission
J.N. Wilson, M. Lebois, et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
4) Prompt fission gamma-rays from fast neutron-induced fission of 238U, 232Th and 235U with LICORNE
M. Lebois, J.N. Wilson et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
3) Measurements of prompt gamma-rays from fast-neutron induced fission with the LICORNE directional neutron source
J.N. Wilson, M. Lebois, P. Halipre, A. Oberstedt, S. Oberstedt, Proceedings of the final ERINDA meeting, CERN, Geneva (2013)
2) The LICORNE neutron source
J.N. Wilson, M. Lebois et al., Proceedings of the International Conference, FISSION2013, Caen, France (2013)
1) Nuclear Research with Quasi Mono-Energetic Neutrons at the IPNO LICORNE Facility
S. Oberstedt, J.N. Wilson, R. Billnert, G. Georgiev, P. Halipre, M. Lebois, B. Leniau, J. Ljungvall, I. Matea, A. Oberstedt, D. Verney, International Atomic Energy Agency (IAEA), Proceedings technical meeting IAEA-F1-TM-42752 (2013)

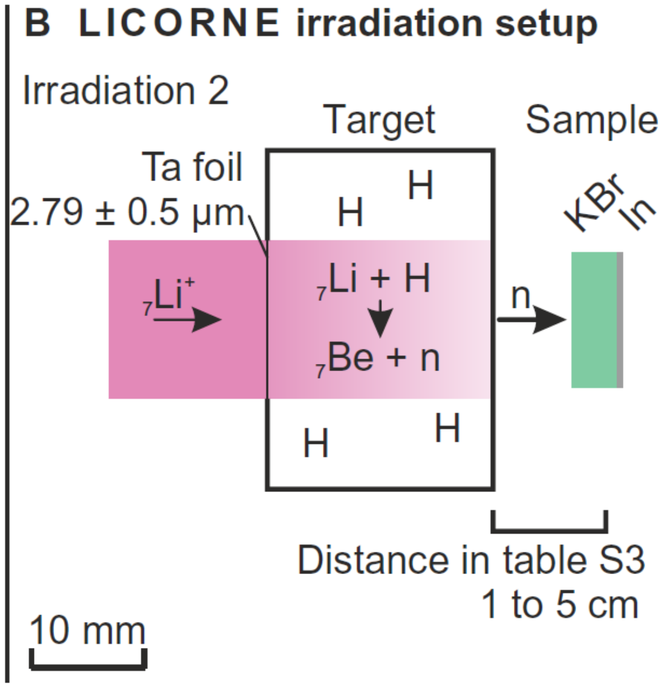
95 users from 34 different institutions in 13 different countries

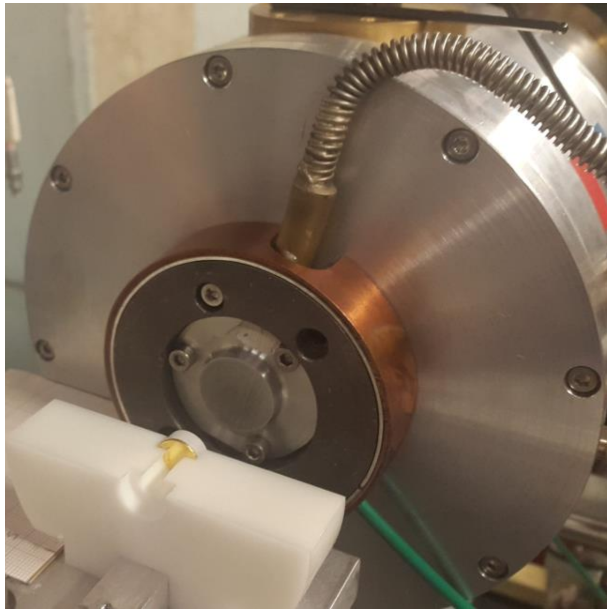
Geochronology: Measurement of $^{39}K(n,p)^{39}Ar$ cross section

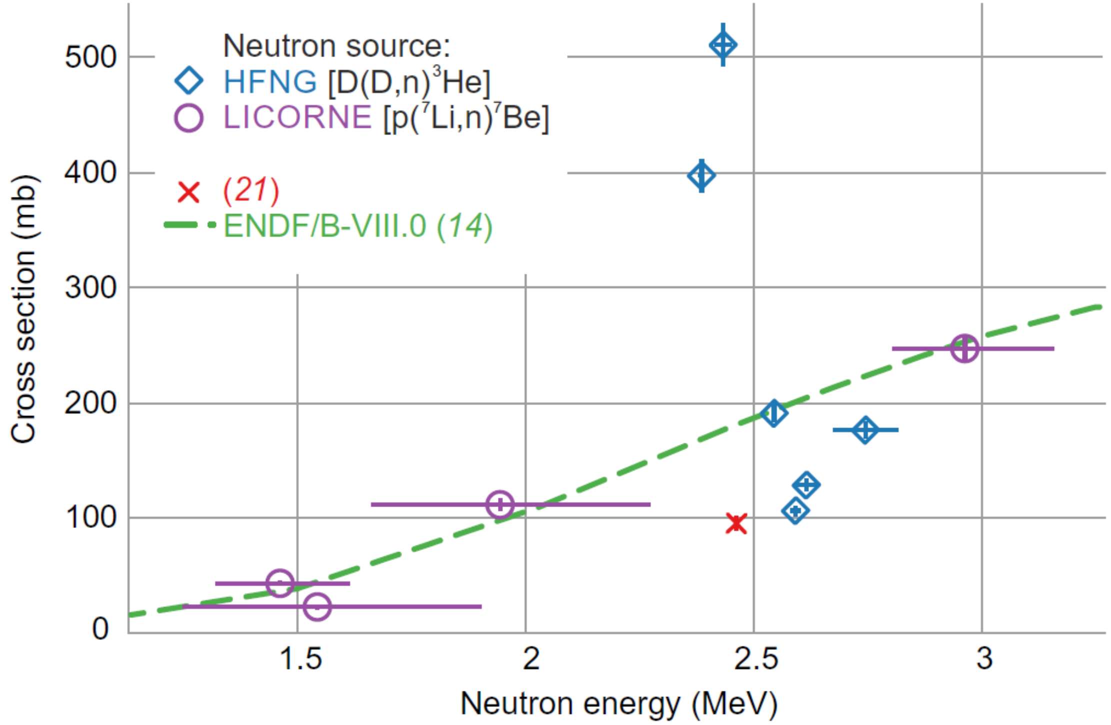
Boutique neutrons advance 40Ar/39Ar geochronology D. Rutte et al. Science Advances, Vol5. No.9 (2019)

$T_{1/2}$ (^{40}K) = 1.25 x 10^9 years   Geochronological dating method for old rocks -> build up of ^{40}Ar daughter

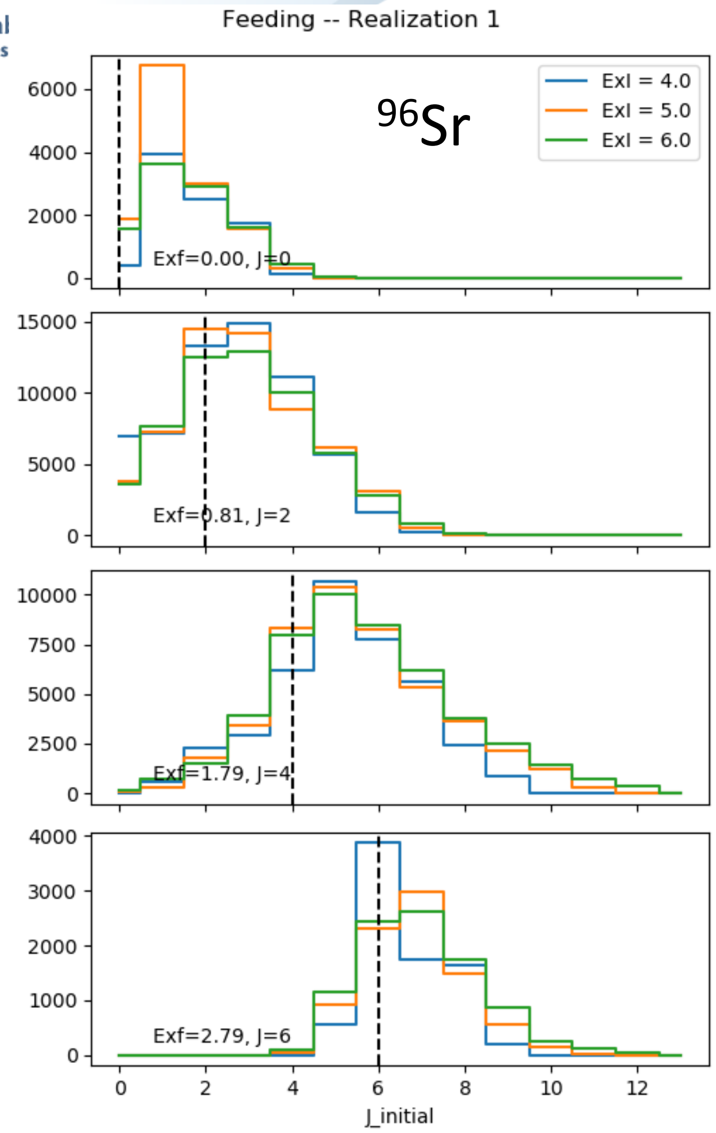
Accelerator based neutron irradiations broaden the applicability of the dating method to fine-grained materials

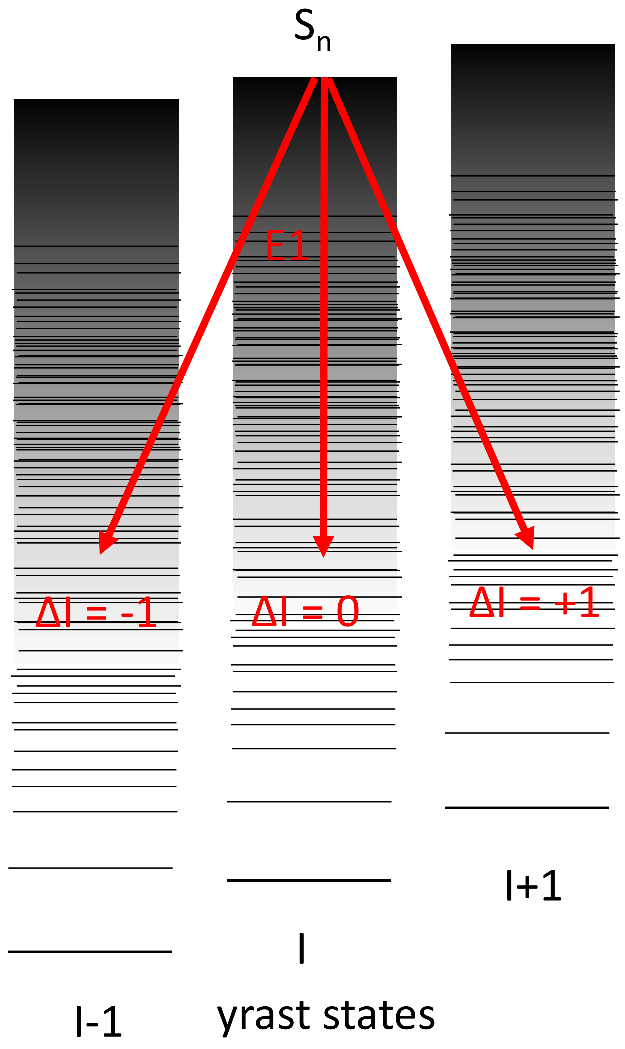


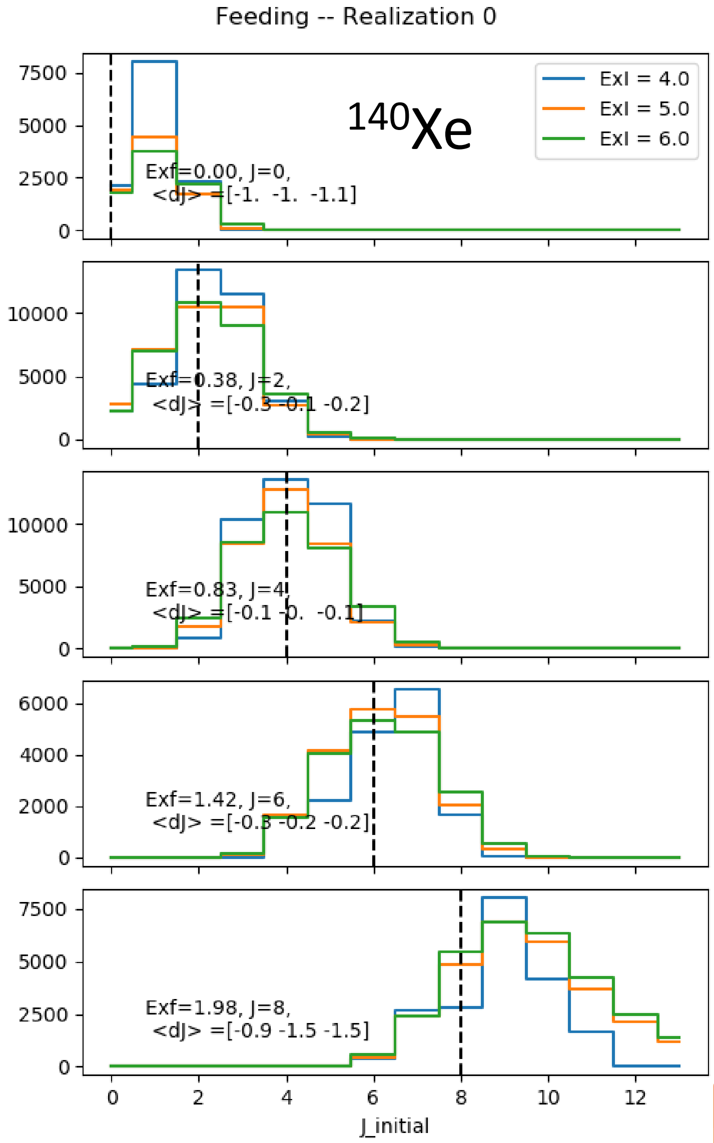




RAINIER Calculations for $\langle \Delta I \rangle$ of statistical γ emissions



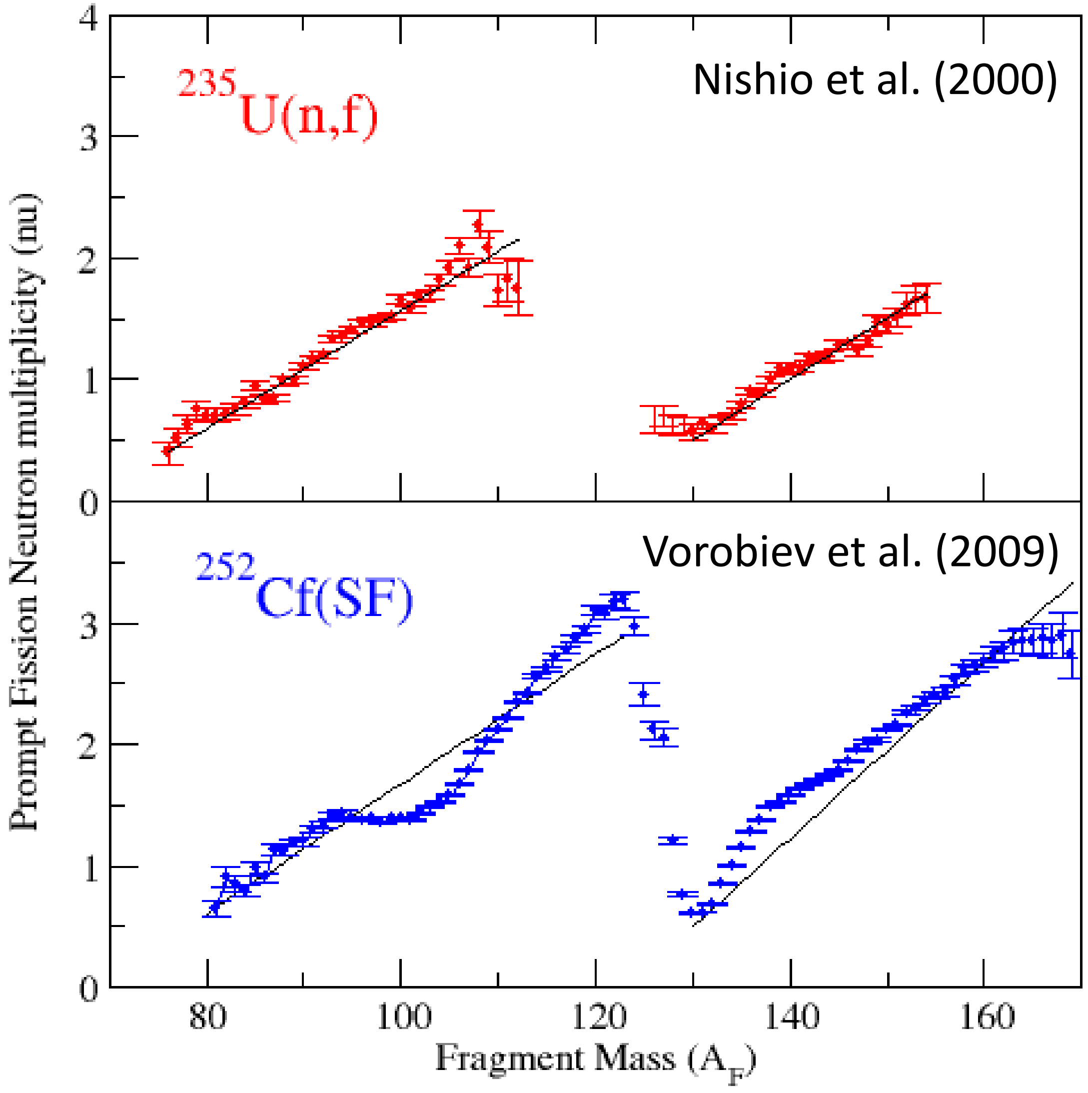




$\langle M_\gamma \rangle \sim 2 - 3$ $\langle \Delta I \rangle \sim 1$ hbar

Courtesy of F. Zeiser

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

- Introduction to neutron production
- Neutrons in inverse kinematics with LICORNE@ALTO

Applications

- Detector calibrations for Direct Dark Matter Search (DS50)
- Fast neutron tomography
- Inelastic neutron scattering in reactors

Fundamental physics

- Nuclear structure of exotic fission fragments
- Angular momentum generation in nuclear fission

DarkSide-50

The Dual-Phase TPC

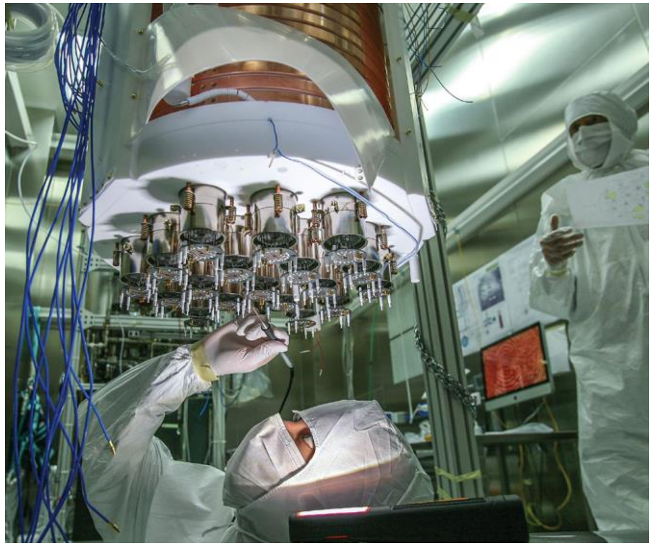
- 50 kg active mass of UAr
- 19 top + 19 bottom R11065 HQE 3’’ PMTs
- 36 cm height, 36 cm diameter
- Low field of 0.2 kV/cm drift

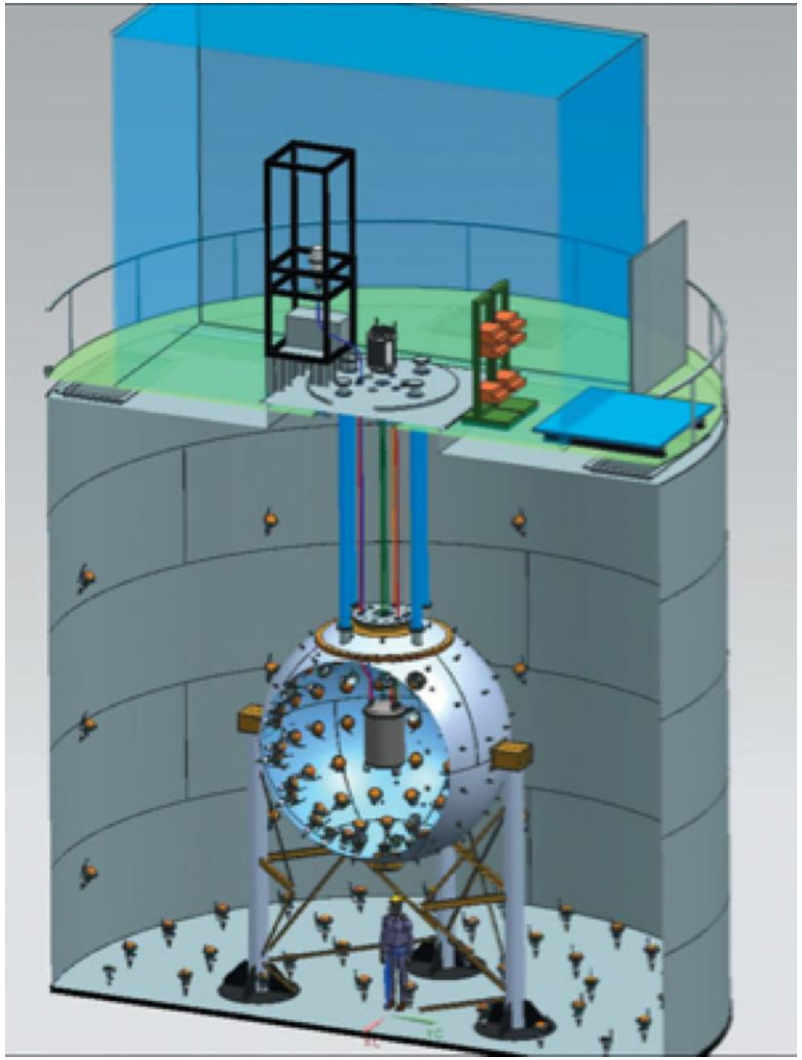
Liquid Scintillator Veto against neutrons

- 4 m diameter sphere
- Boron-loaded: 1:1 PC and TMB
- 110 8” PMTs
- LY ~ 500 pe/MeV

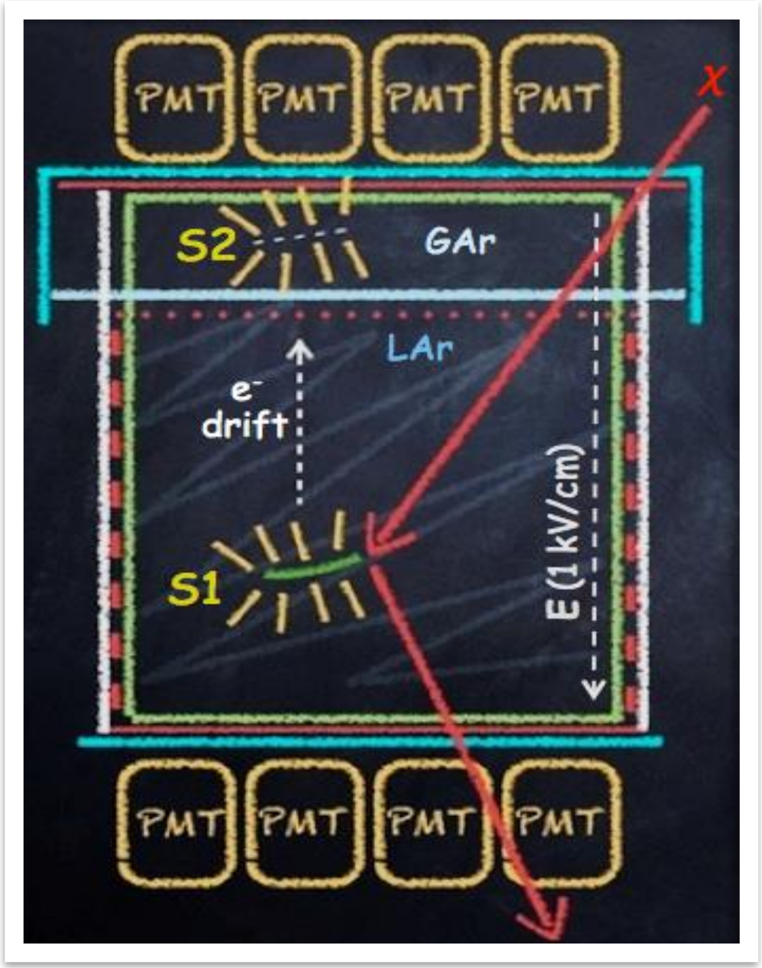
Cherenkov Water Detector

- 11 m diam. x 10 m
- 80 PMTs



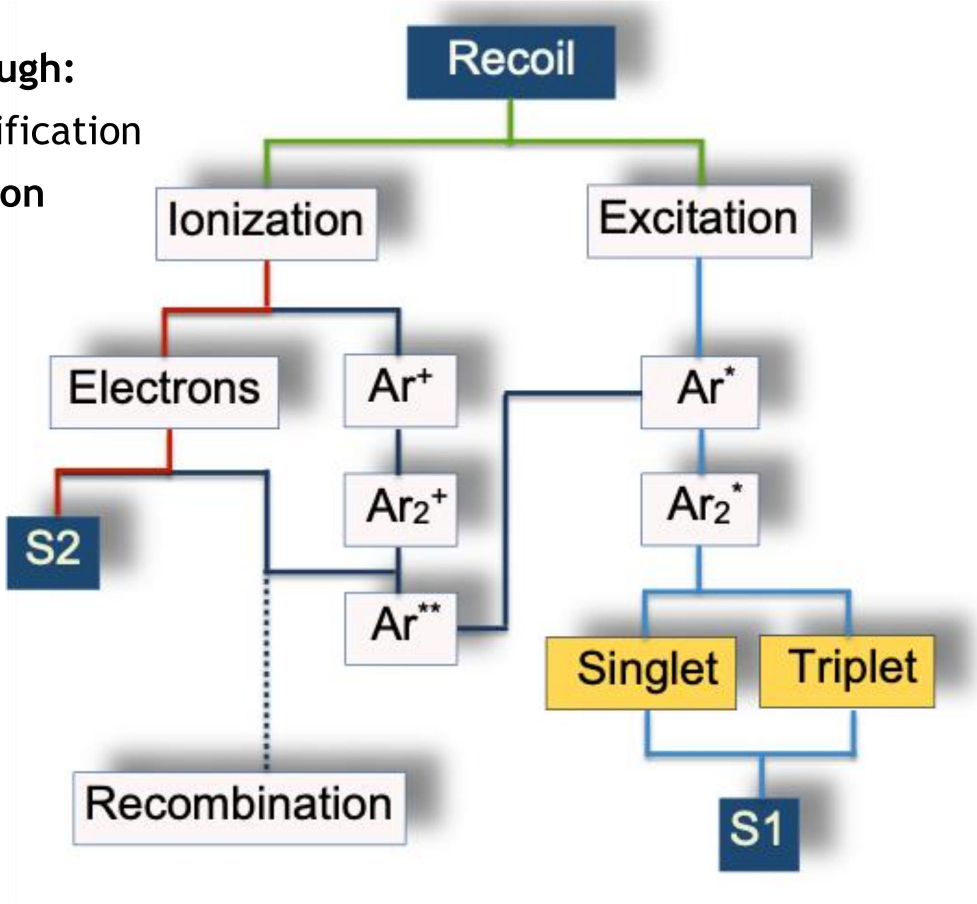


DarkSide-50



Particle discrimination through:

- Accurate 3D **position** identification
- **Multiple-scattering rejection**
- **S2/S1 ratio**
- S1 **PSD** (if available)



The DS-50 high-mass search

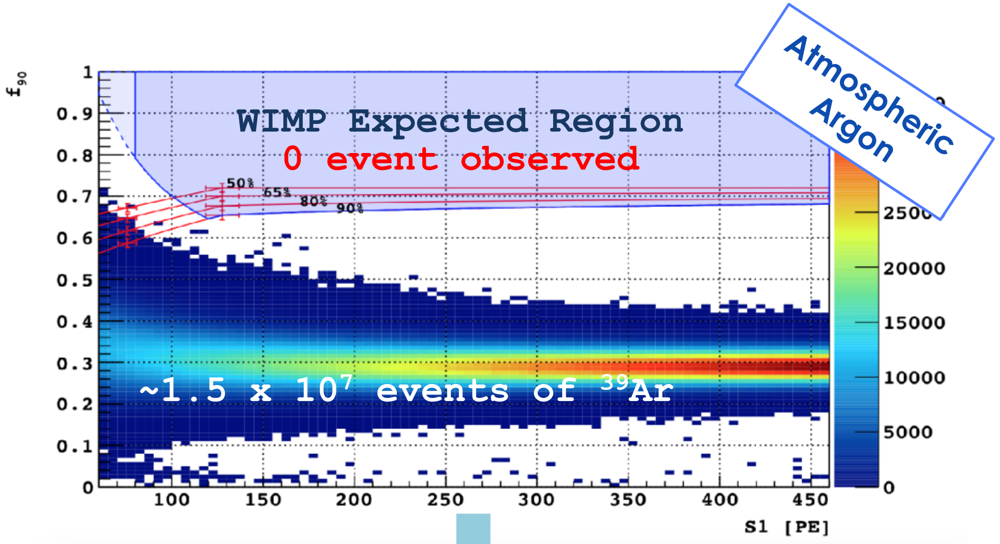
LAr scintillation times:

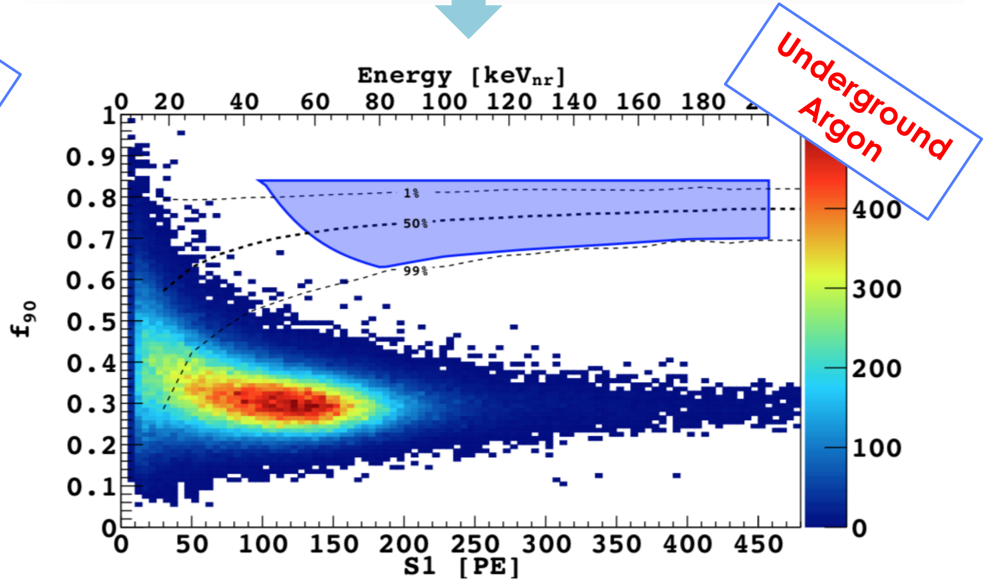
- singlet ~ 6 ns
- Triplet ~ 1600 ns

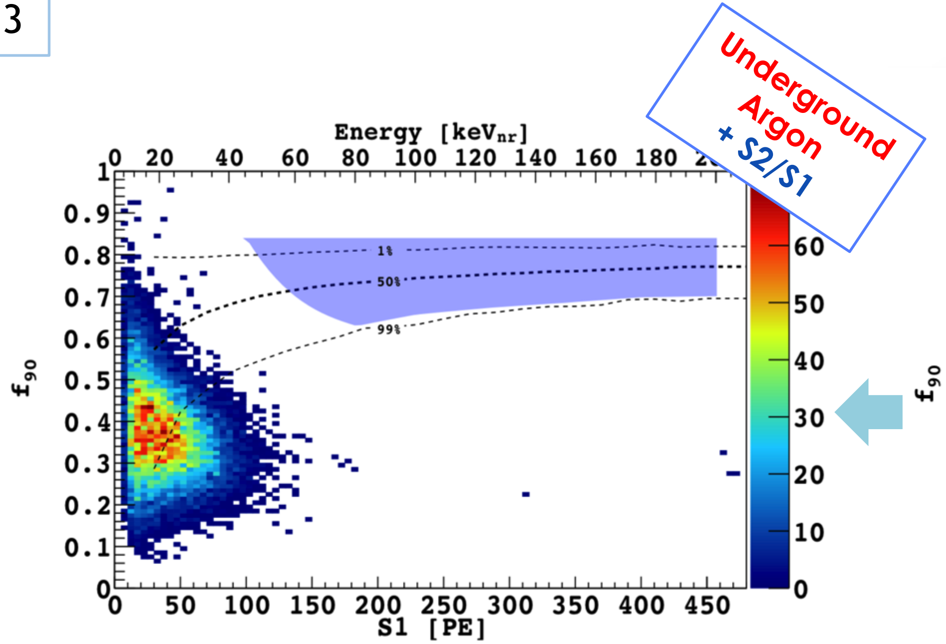
Singlet-to-triplet ratios:

- Nuclear recoils ~ 0.7
- Electron recoils ~ 0.3

Very distinctive (and unique) signatures to separate electron recoils from nuclear recoils







Background-free over more than 530 days!

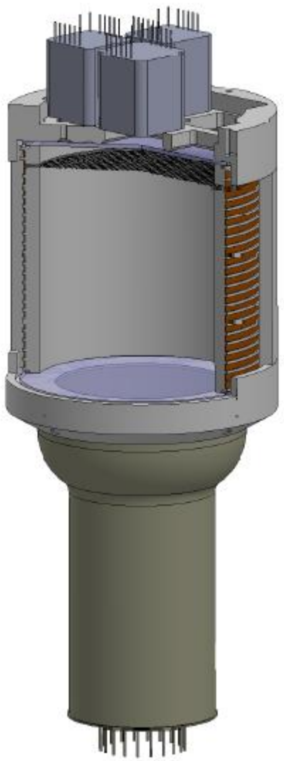
ARIS: Dark Matter Search, Liquid Argon TPC irradiation

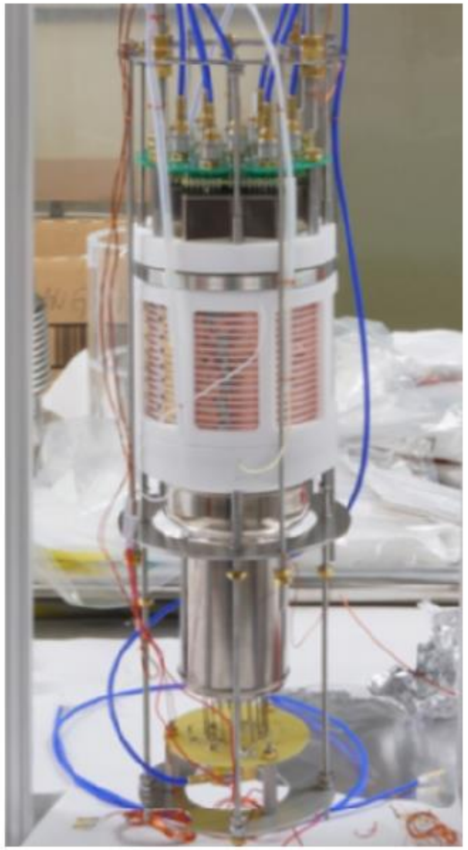
Measurement of the liquid argon energy response to nuclear and electronic recoils

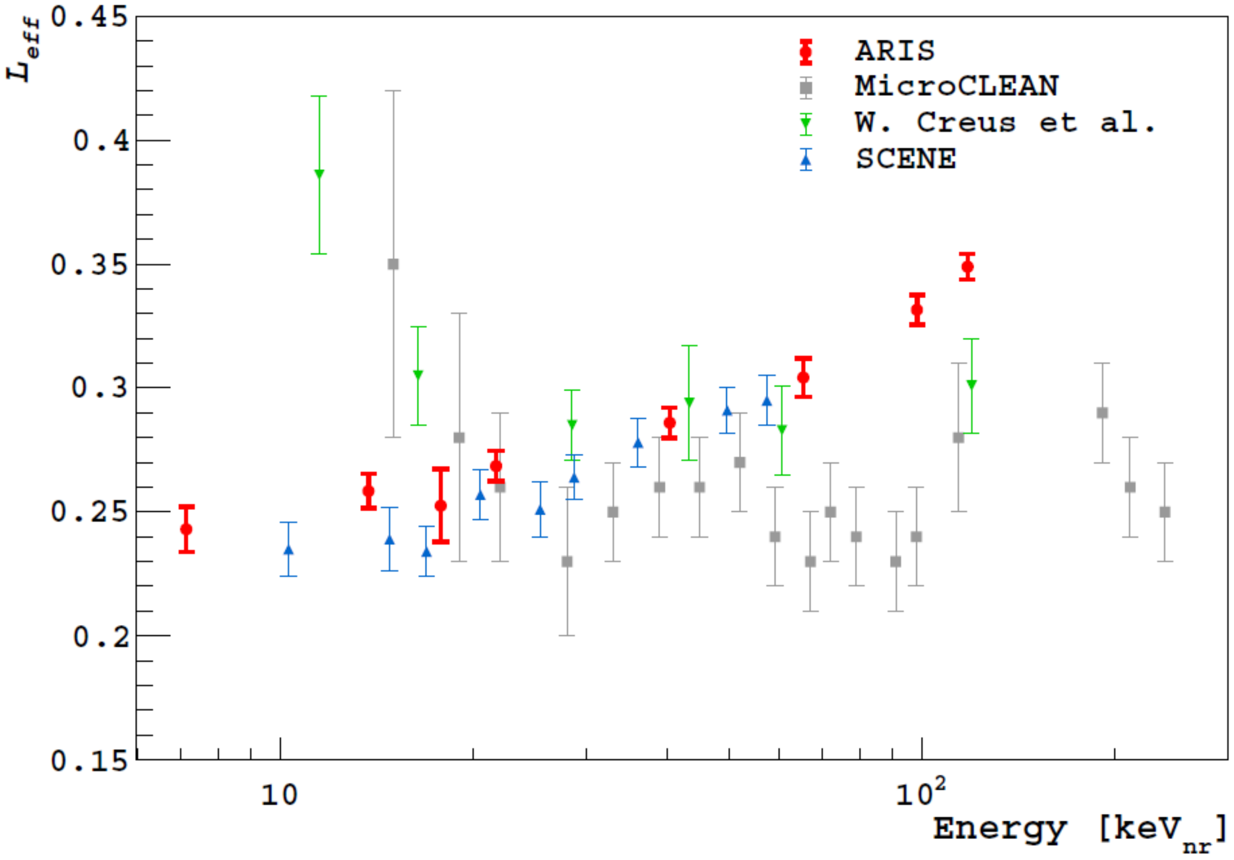
P. Agnes, et al. Phys. Rev. D 97, 112005 (2018)

- Dark matter search liquid Argon detector prototype
- Neutrons used as a proxy for WIMPS

Characterisation of the detection properties via nuclear recoils and sensitivity limits

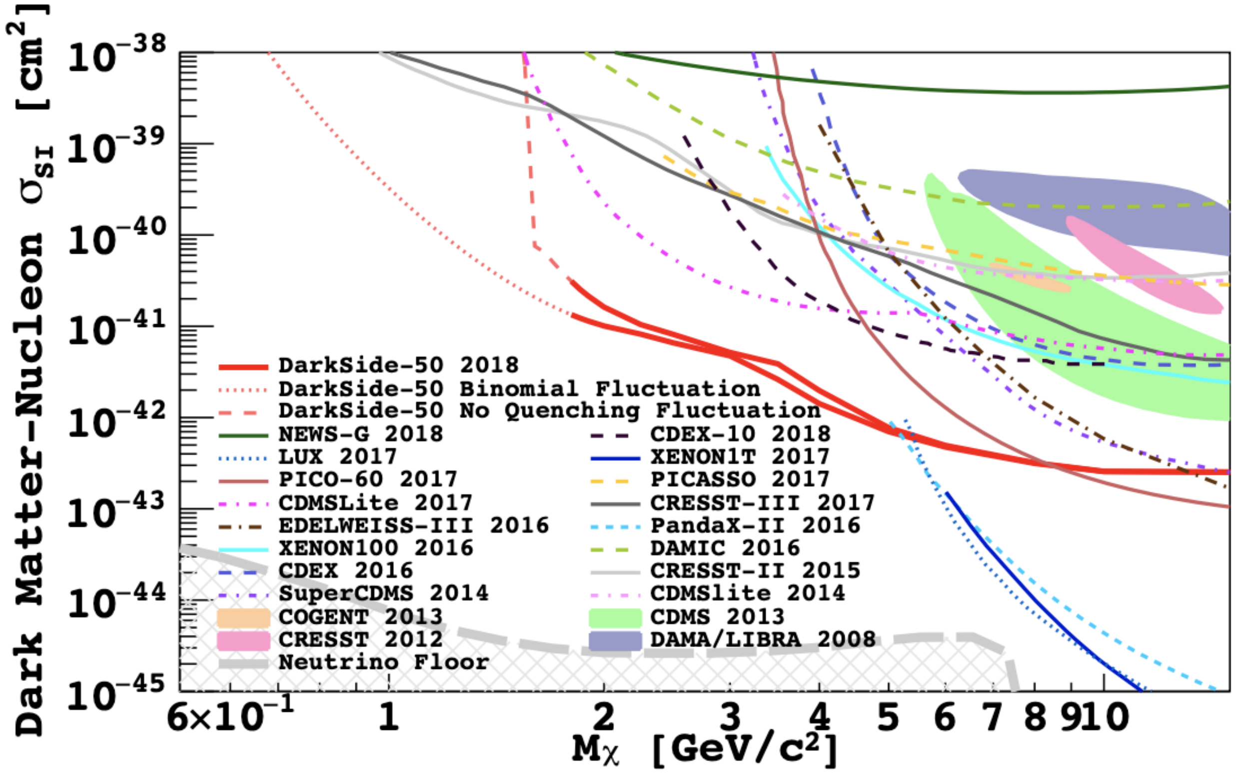






The DS-50 low-mass search in brief

- **2018** First results on light dark matter candidates with liquid argon using the ionization channel:
  - DarkSide-50, Phys. Rev. Lett. 121 (2018) 081307
  - DarkSide-50, Phys. Rev. Lett. 121, 111303 (2018)
- **2019** End of the DarkSide-50 data taking
- **2021** Measurement of the LAr ionization response down to the sub-keV with DarkSide-50
  - DarkSide-50, Phys.Rev.D 104 (2021) 8, 082005
- **2022** Re-analysis of the DarkSide-50 dataset
  - DarkSide-50, arxiv:2207.11966 (2022)
  - DarkSide-50, arxiv:2207.11967 (2022)
  - DarkSide-50, arxiv:2207.11968 (2022)



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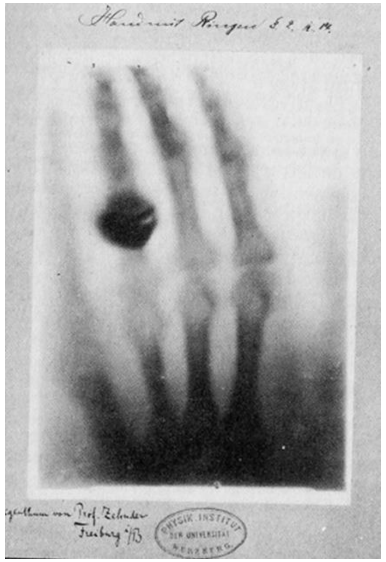
X-rays for imaging applications

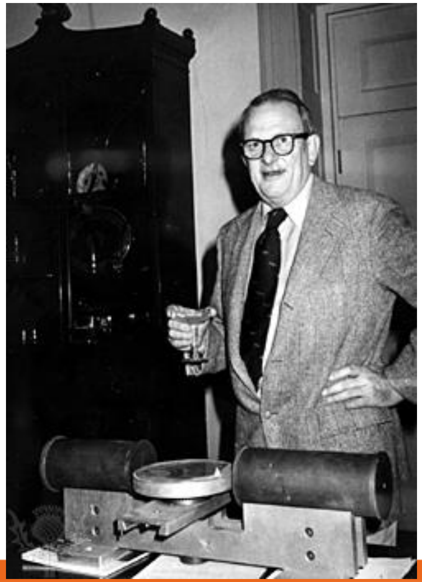
First x-ray Images

Willhelm Röntgen (1895)
1st ever Nobel Prize (1901)



First x-ray Computed Tomographic Images

Allan M. Cormack &
Godfrey N. Hounsfield
Nobel Prize in Medicine (1979)



Why fast neutron tomography?

X-ray tomography is a mature technology and currently a multi-billion dollar industry

Complimentarity between x-rays and neutrons

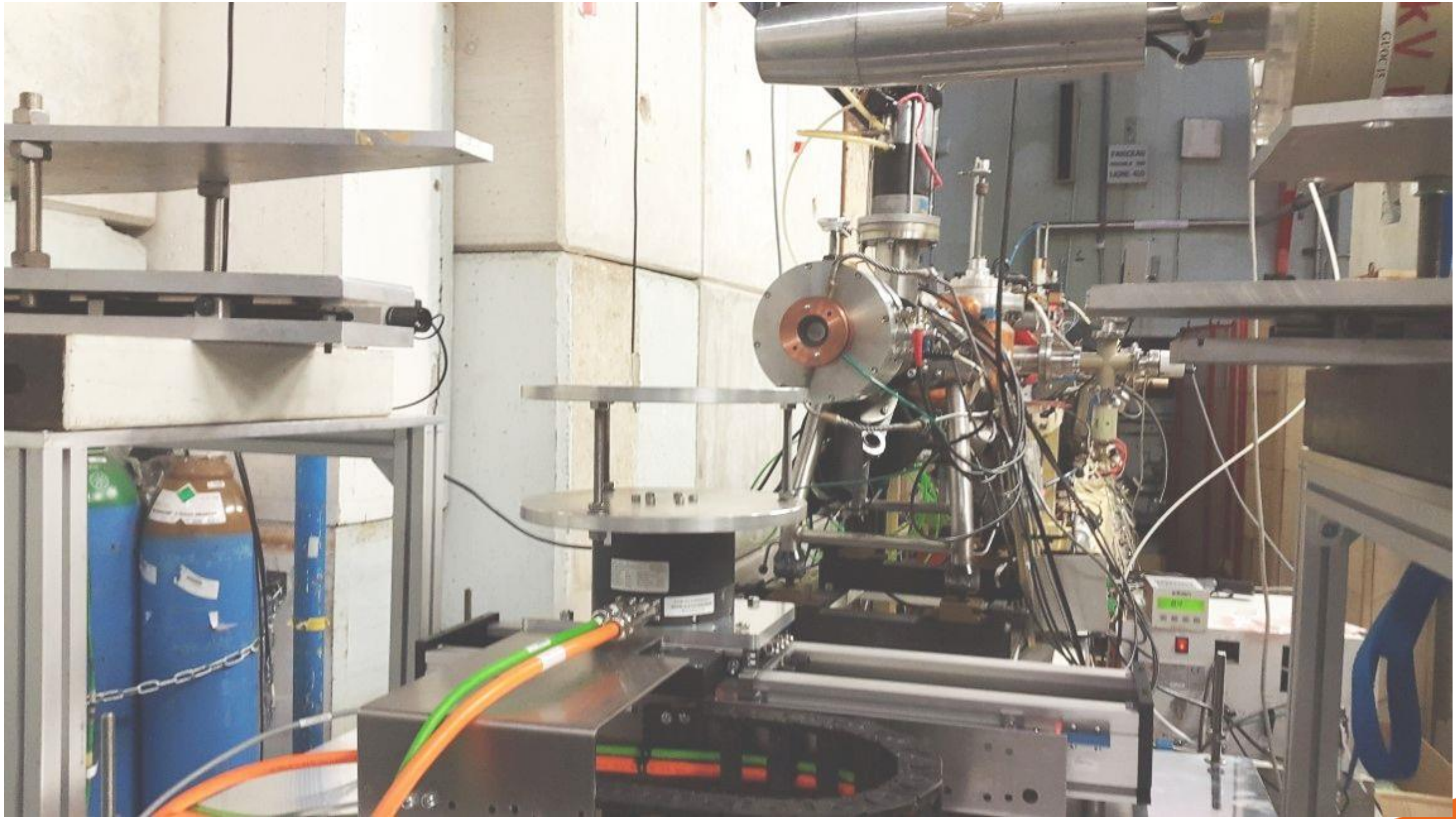
X-rays are strongly absorbed by high-Z materials but pass easily through low-Z materials
Fast neutrons penetrate high-Z materials but are easily scattered by low-Z materials

Potential Applications

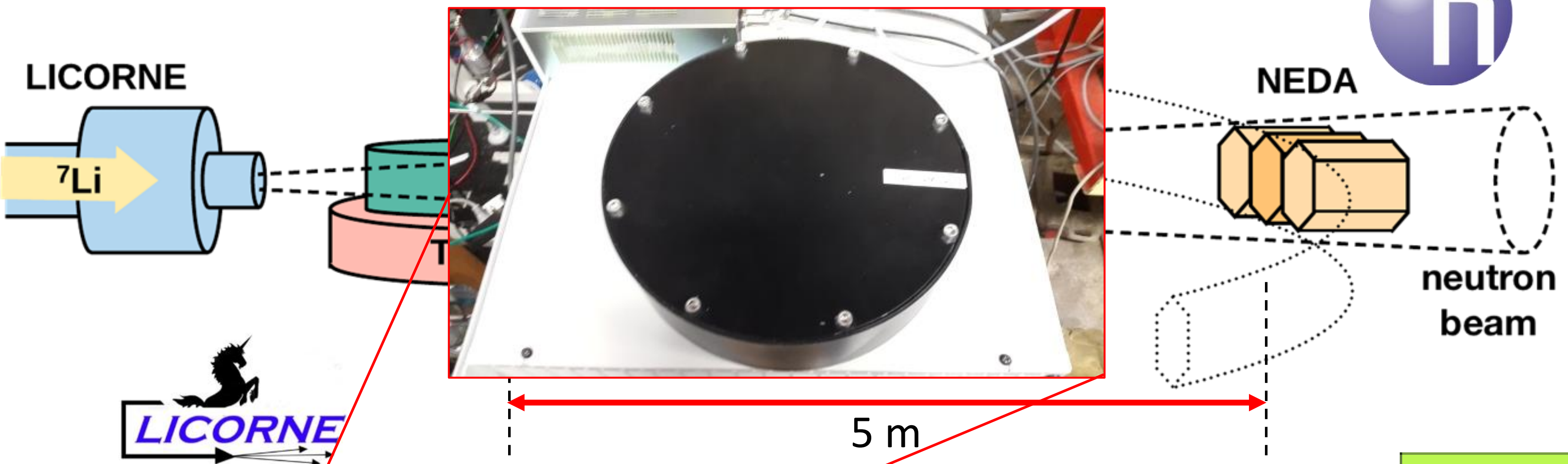
- Border/airport security (e.g. detection of explosives in suitcases)
- Nuclear Industry: Characterisation of nuclear waste packages
- Cultural Heritage: Imaging inside precious artifacts and objects
- Precision quality control for industry
- Non destructive characterization of geological samples (e.g. Metorites)

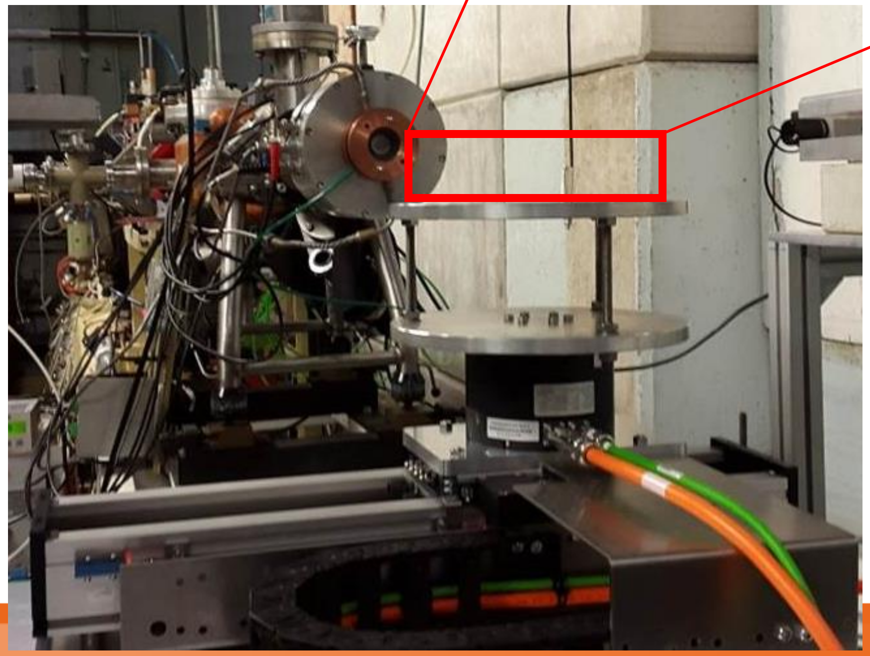
Courtesy of BAM, Berlin

Fast neutron tomography with LICORNE @ ALTO

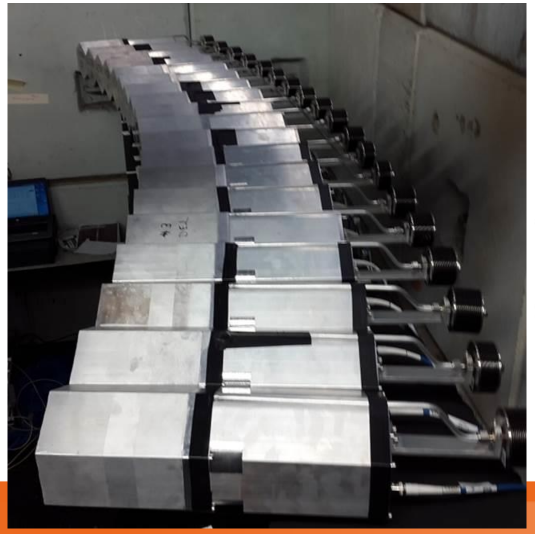


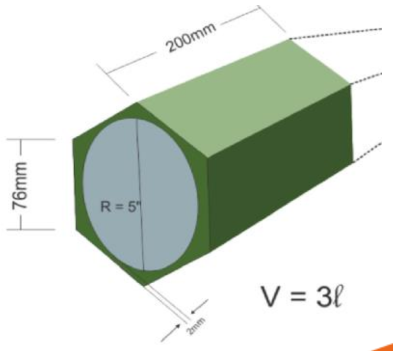
Fast neutron tomography with LICORNE @ ALTO





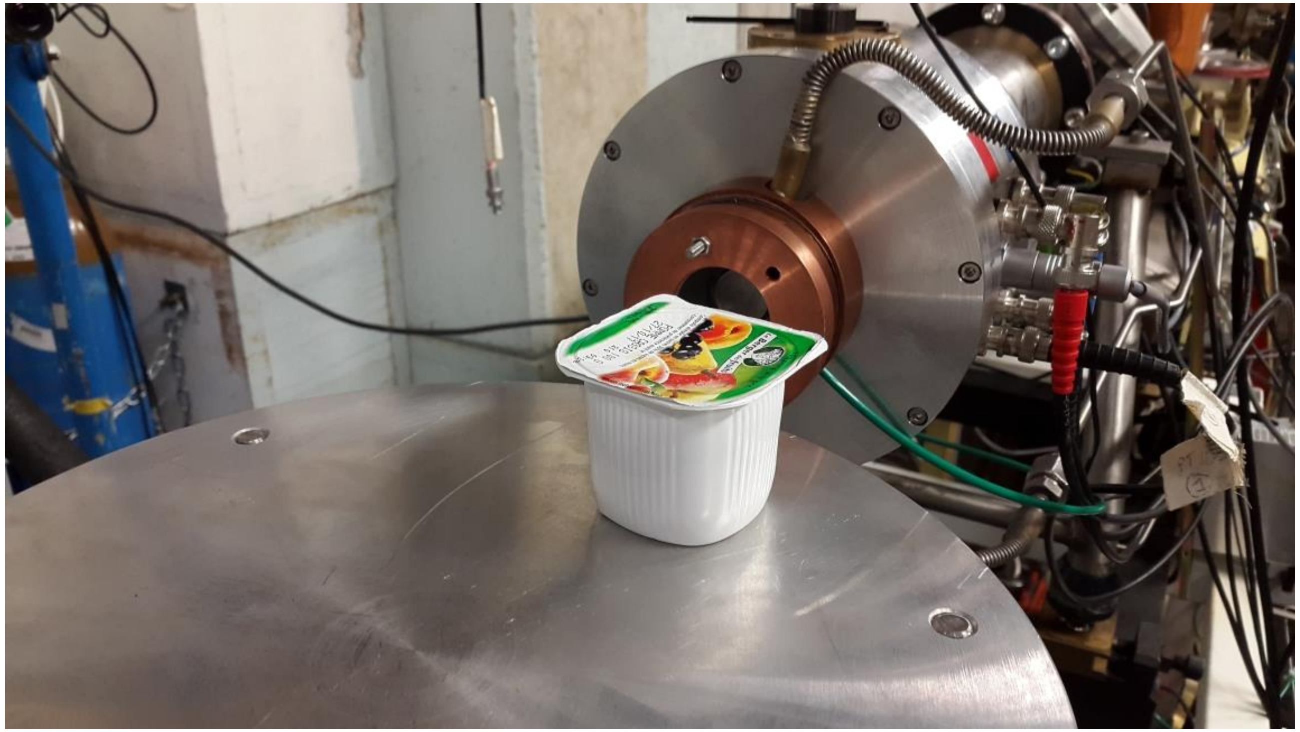
First Use of **NEDA** with FASTER

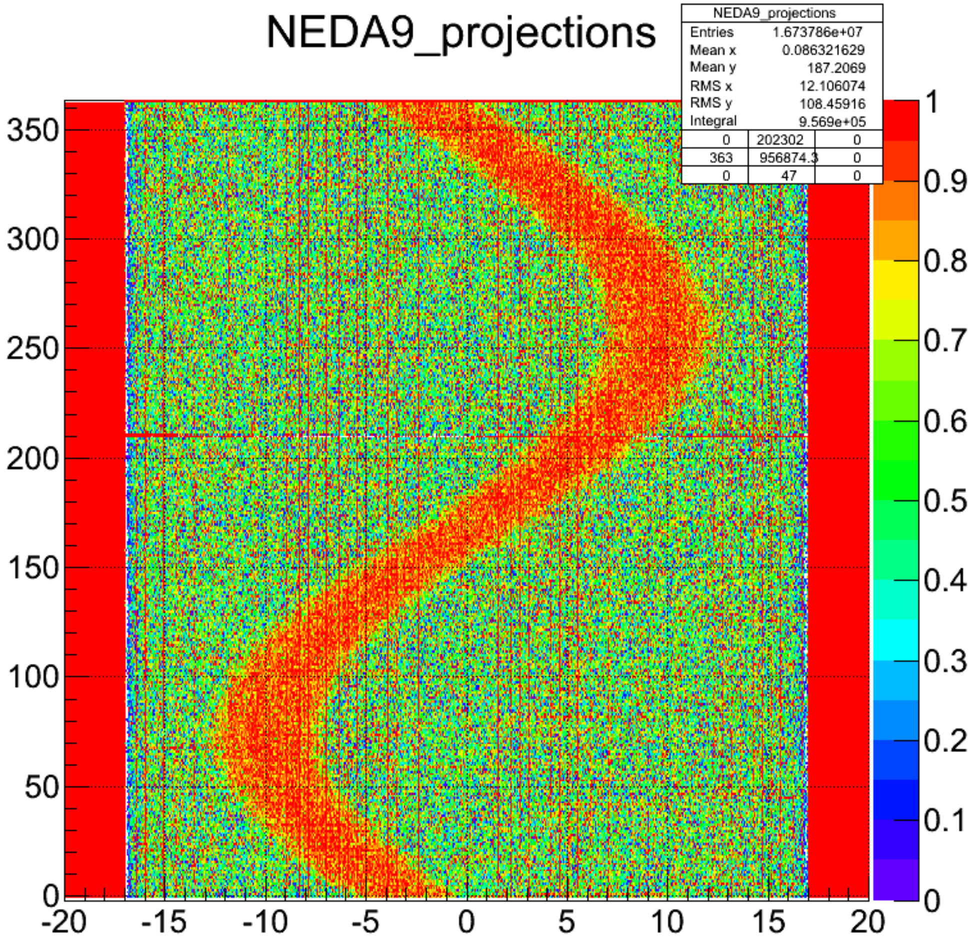




BC501A

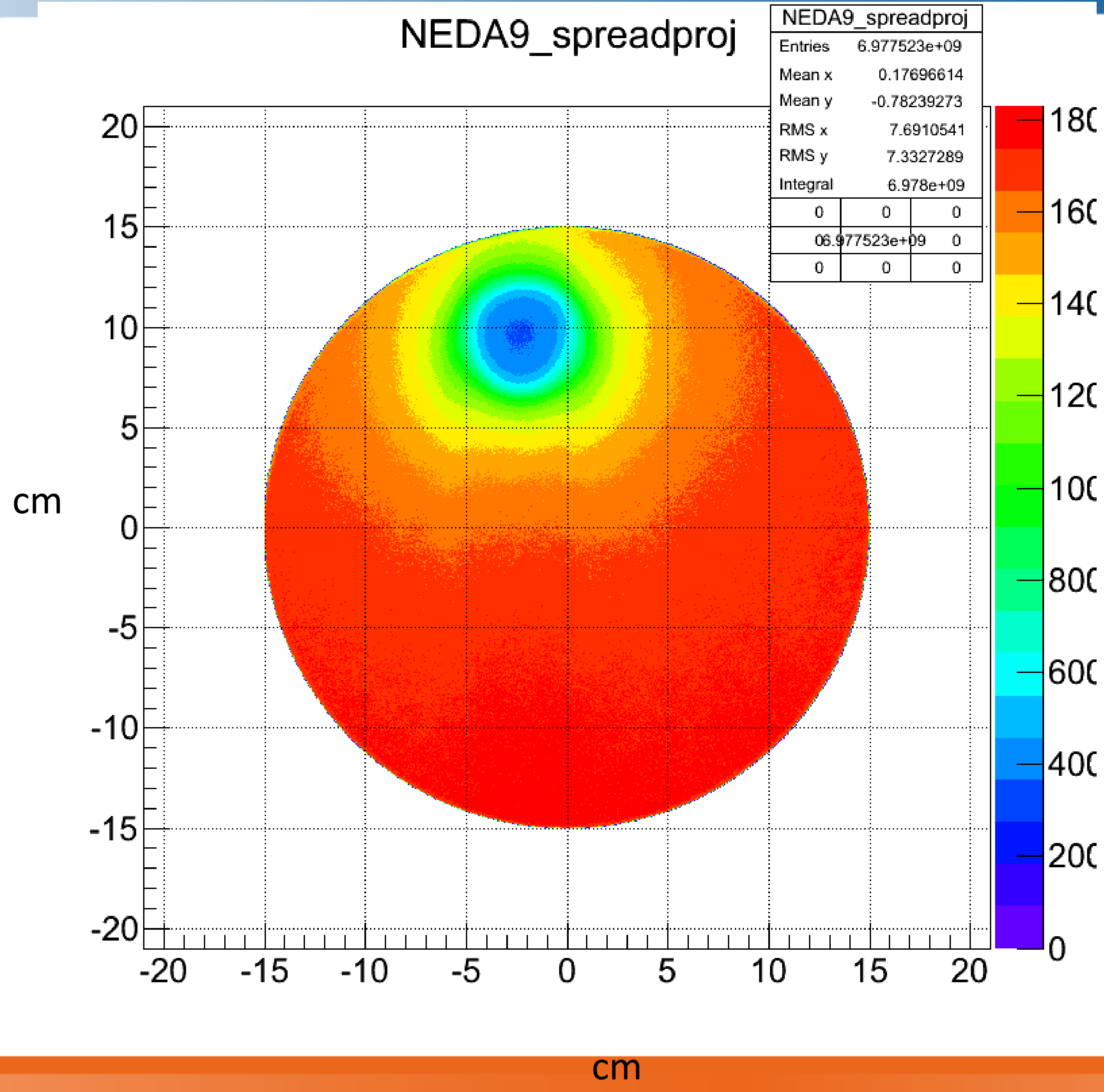
Fast neutron tomography: Simple objects





Courtesty of B. Wasilewska

Fast neutron tomography: Reconstruction simple objects



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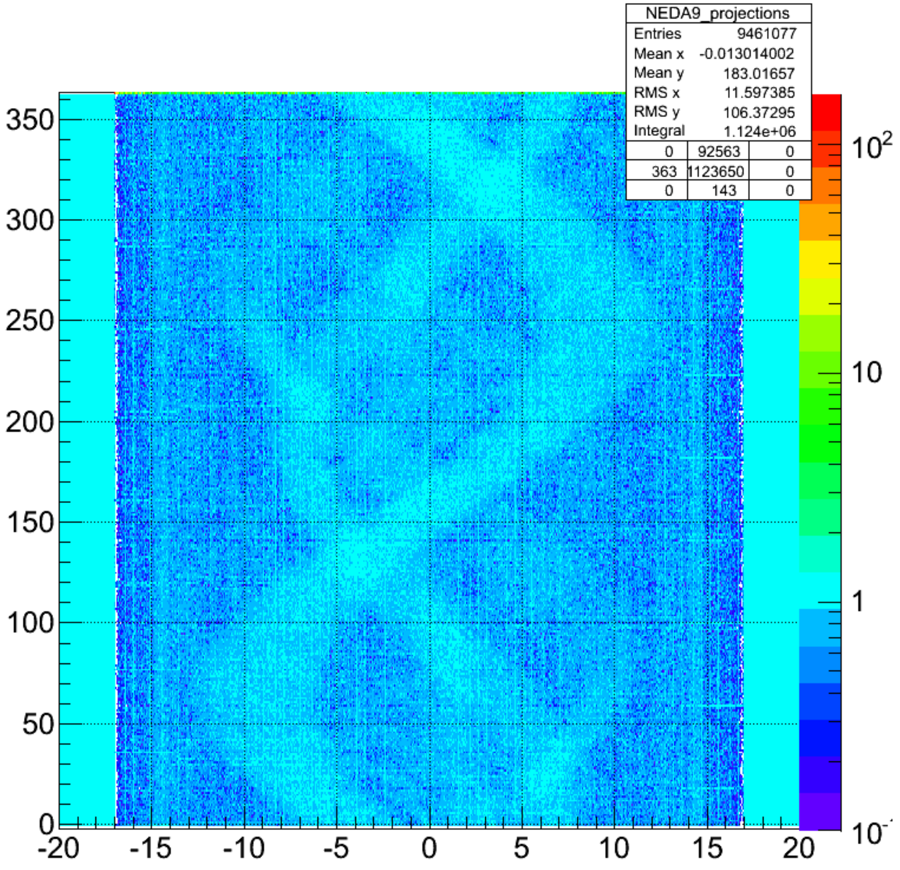
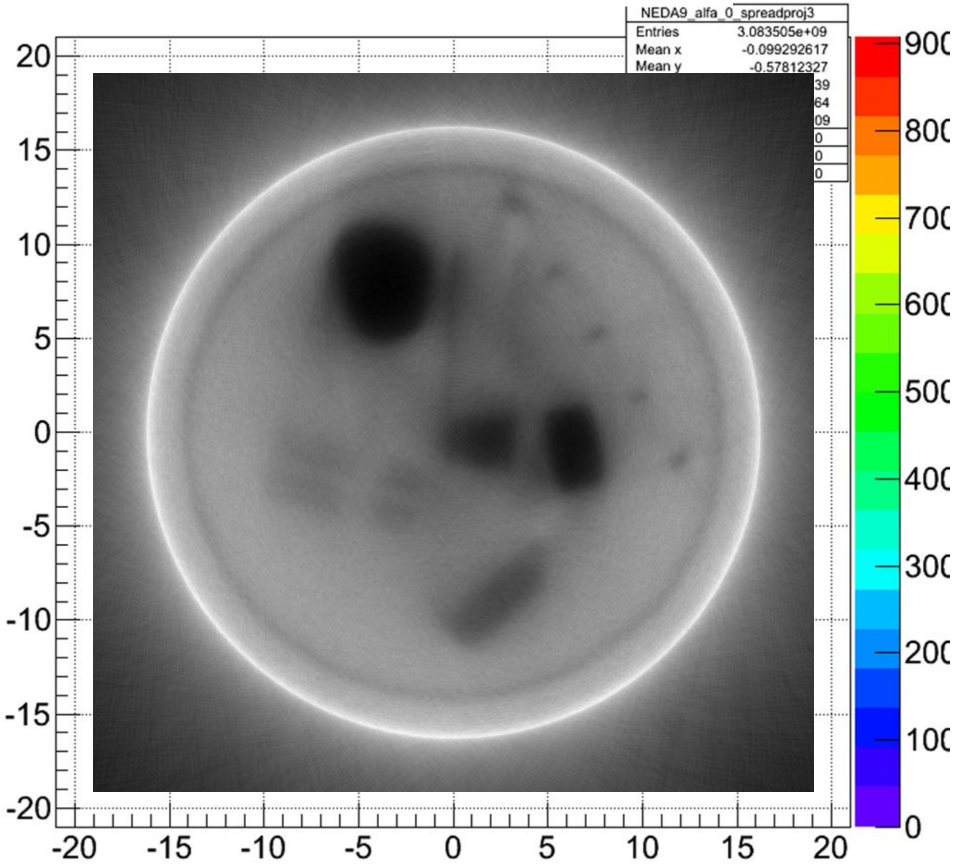
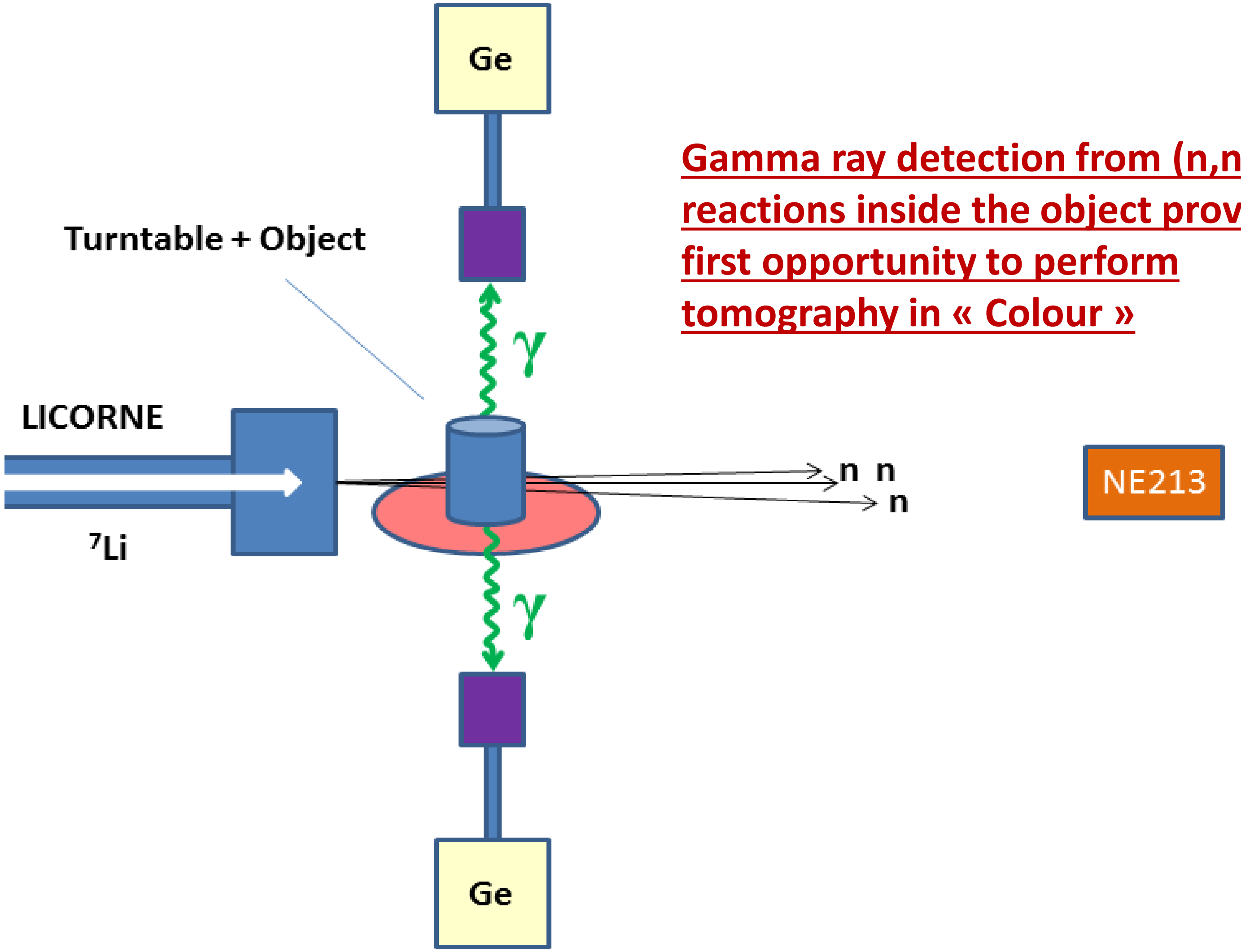
Fast neutron tomography: Reconstruction complex objects





Courtesty of B. Wasilewska

COLOUR tomography with fast neutrons



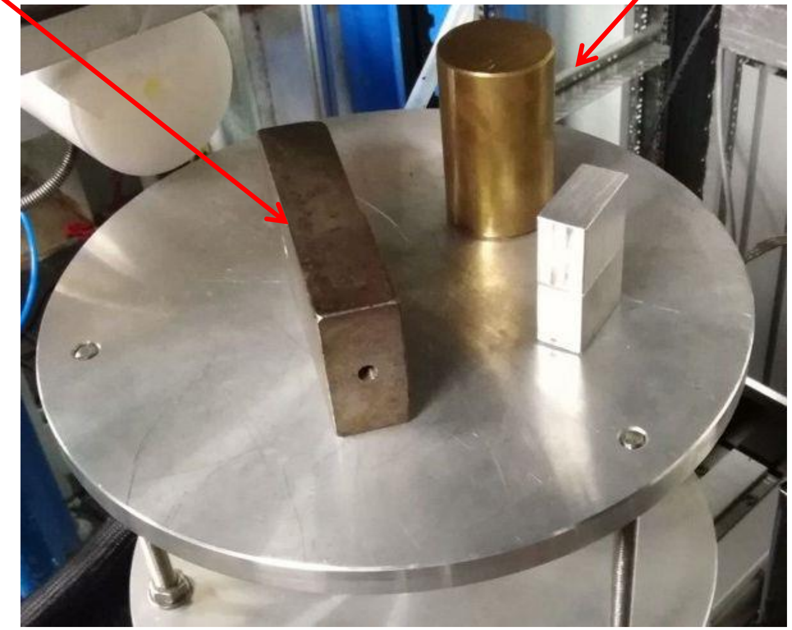
Gamma ray detection from (n,n'γ) reactions inside the object provide the first opportunity to perform tomography in « Colour »

Colour tomography with fast neutrons

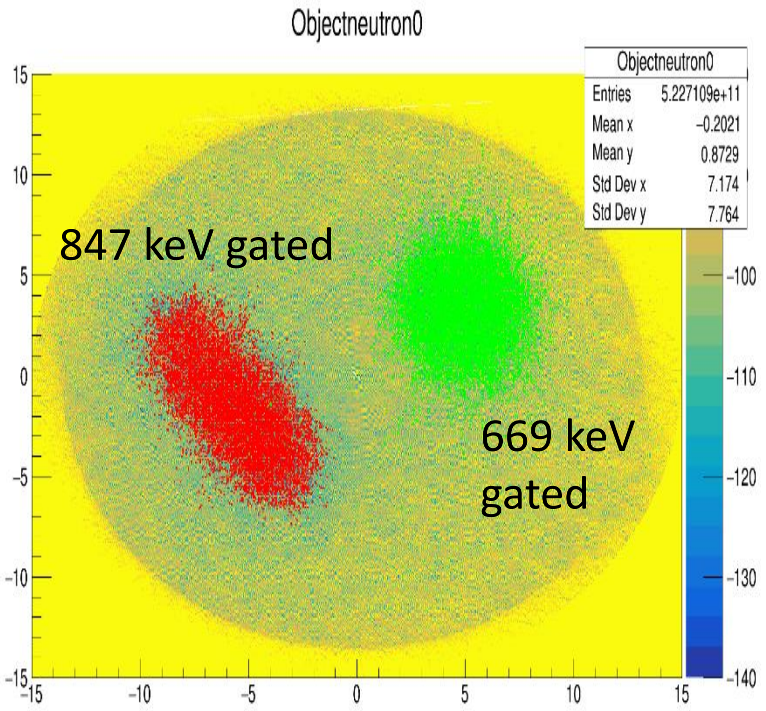
Brass cylinder

Fe block

Optical image



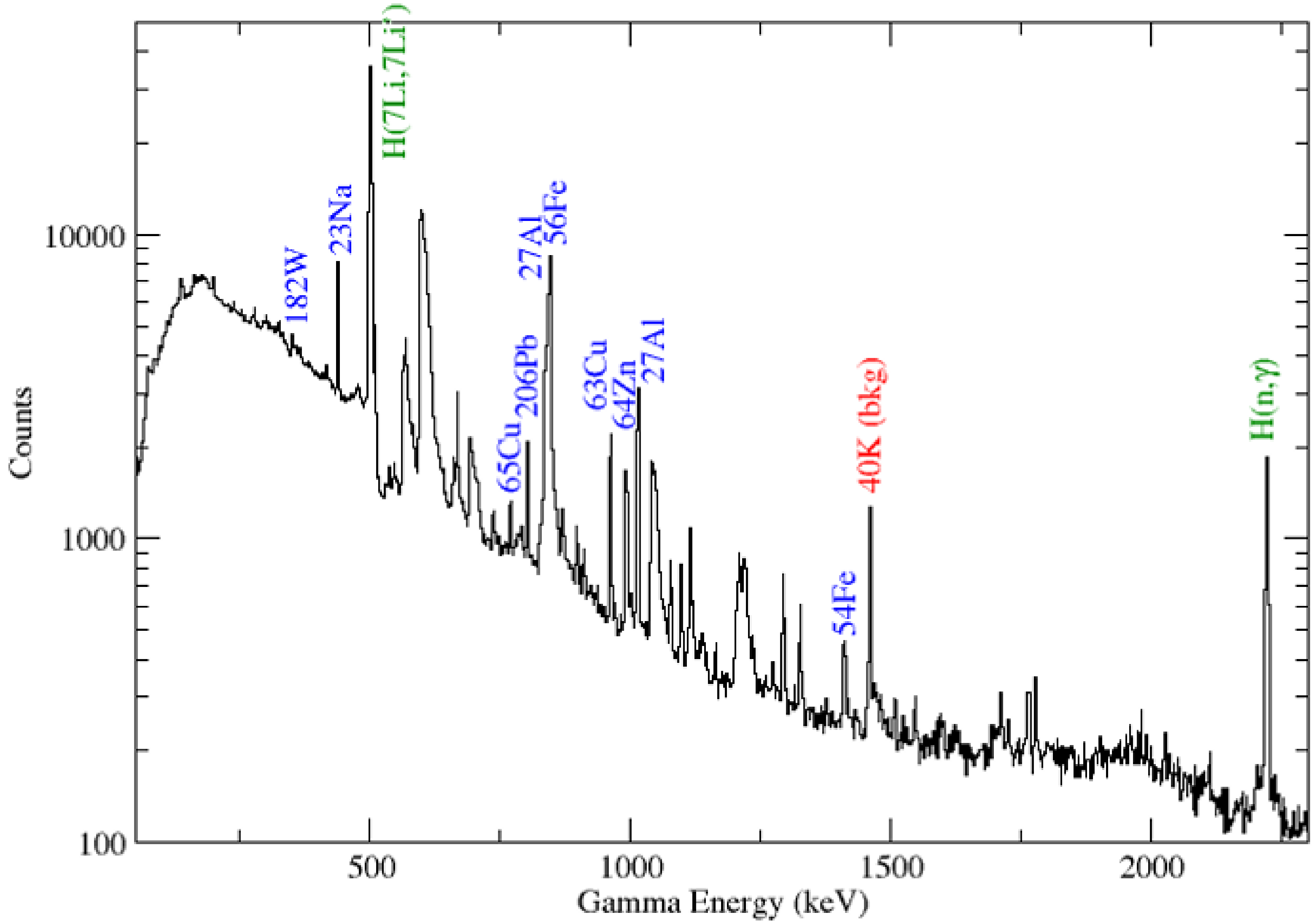
Partial colour image



Fast neutron colour tomographic "painting"

Iron block
Brass cylinder
Salt jar
Aluminium block
Lead block
Tungsten collimator
Germanium half-cylinder

Fast neutron colour tomographic "painting"

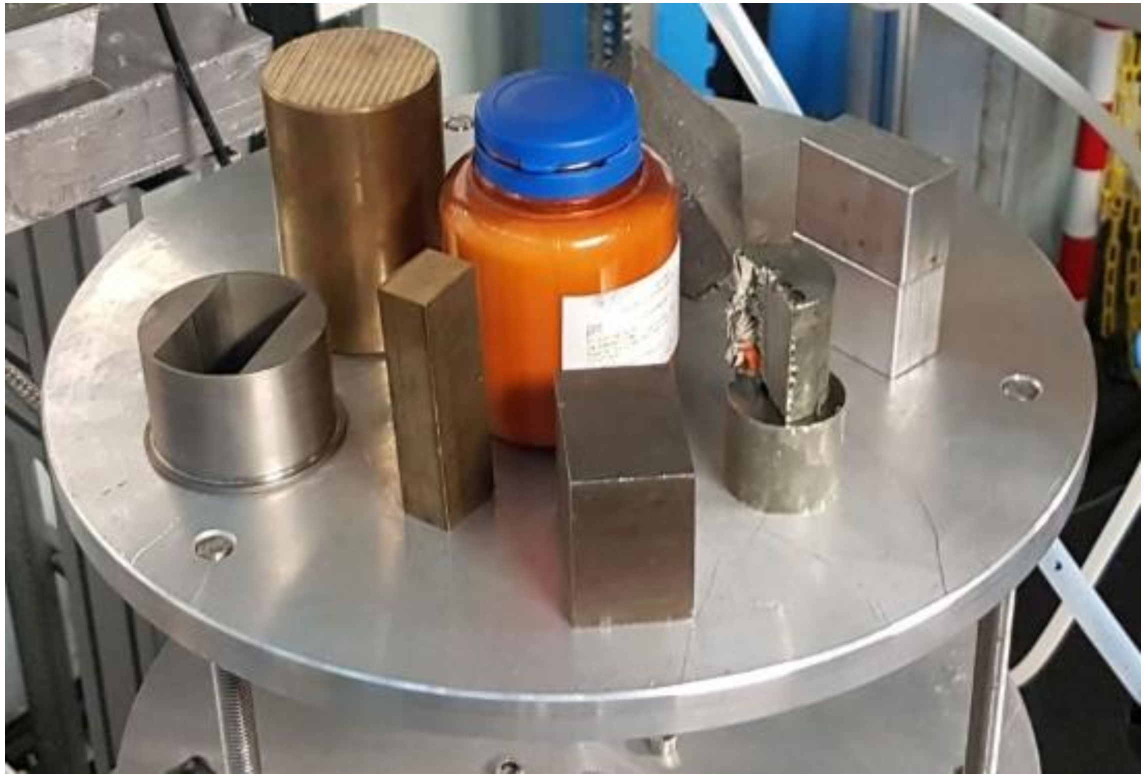


Gamma lines from:

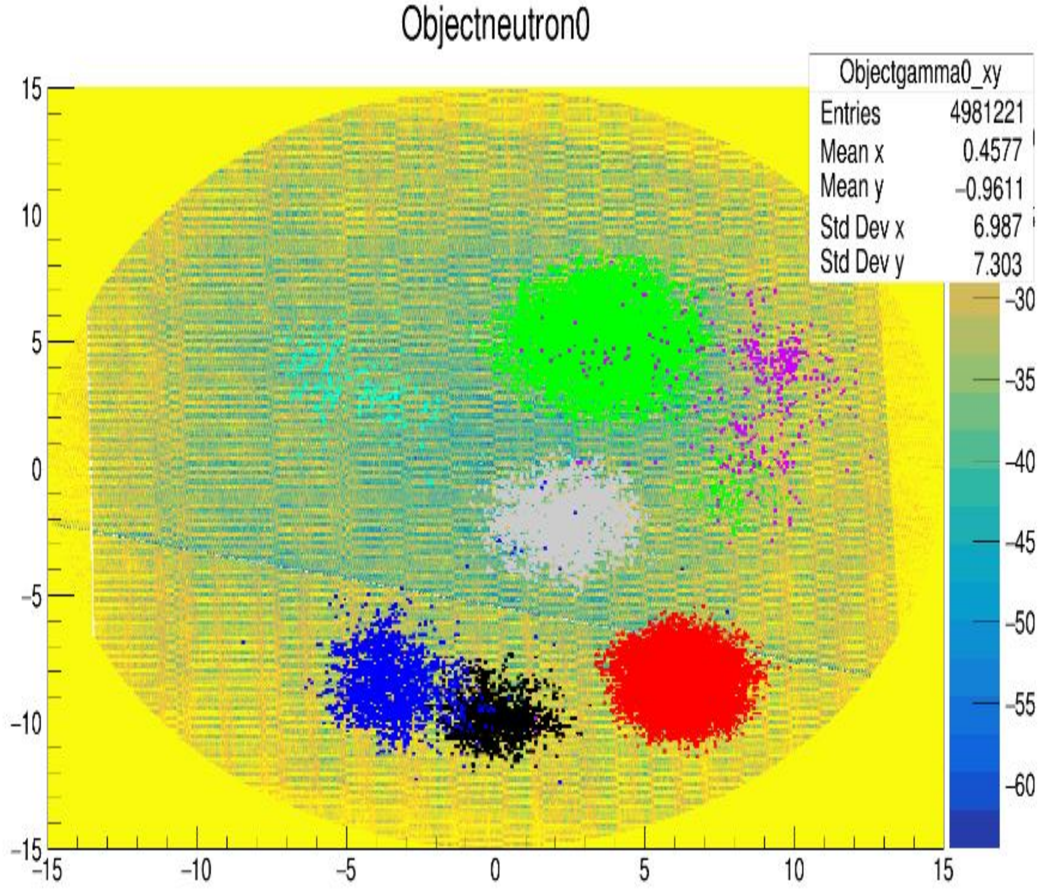
54,56Fe
63,65Cu
64Zn
23Na
27Al
206Pb
182W

Fast neutron colour tomographic “painting”

Optical image



Reconstructed colour image



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