PARIS@VAMOS – wgląd w proces rozszczepienia z użyciem pomiaru promieniowania gamma

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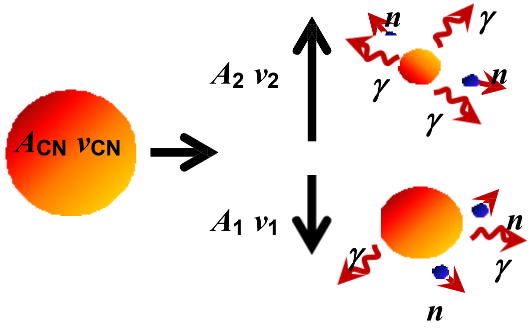
IFJ PAN, KRAKÓW

16/05/2024

Fission – 85 years known process



- Characterized by a dramatic rearrangement of nuclear structure;
- Important for fundamental and applications (energy, isotopes for medicine,…).

Still a lot of open questions

What is the nature of the driving force in fission dynamics?

What is the mechanism that generates excitation energy and angular momentum along the way to scission?

How are excitation energy and angular momentum shared between the fragments?

What is the role of shell effects and pairing correlations?

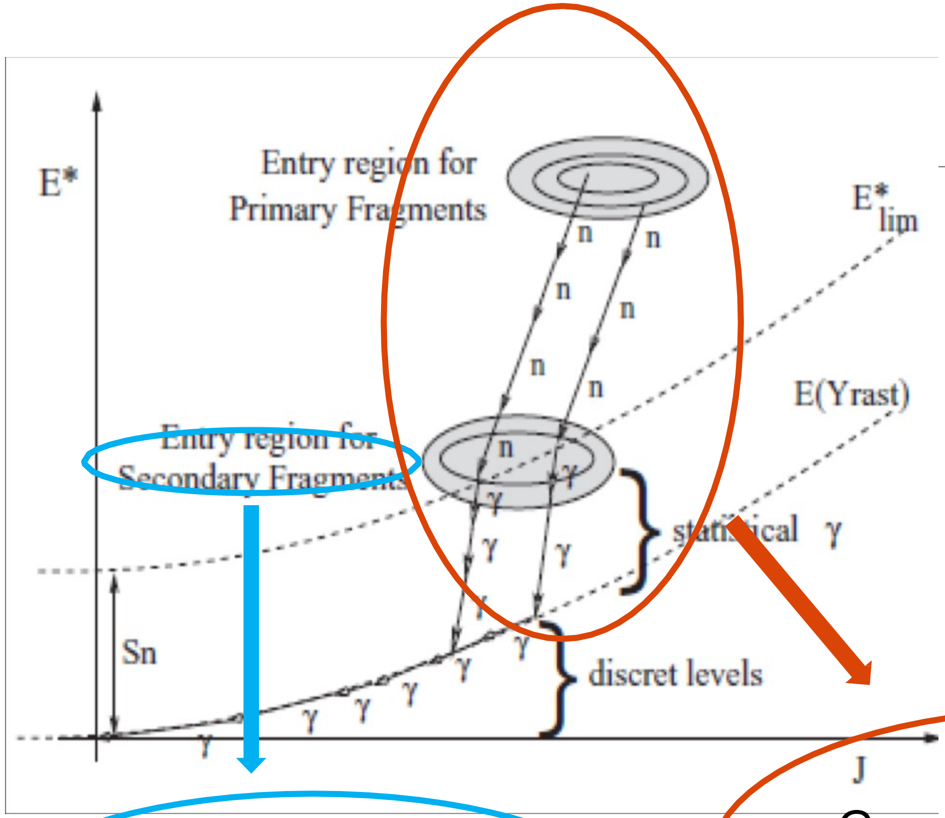
How fast is the snapping of the neck at splitting?

How much are the fragments still entangled immediately after scission?

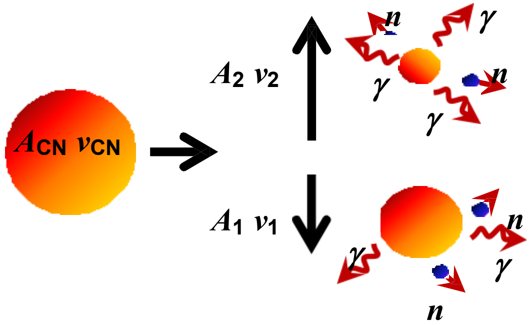
Recently published: J. Wilson, et al., „Angular momentum generation in nuclear fission”, Nature 590, 566–570 (2021)

Also works from UW from experiments at IJCLab:
K. Miernik, et al., „Fission of 215Fr studied with γ spectroscopic methods”, Phys. Rev. C 108, 054608

Fusion-fission reaction in inverse kinematics



Inverse kinematics provide the capability of fission fragments nuclear charge identification



magnetic spectrometer: angle, velocity and $(A,Z)_{FF}$ identification

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Gamma callorimeter: M_γ and E_γ spectrum up ~30 MeV

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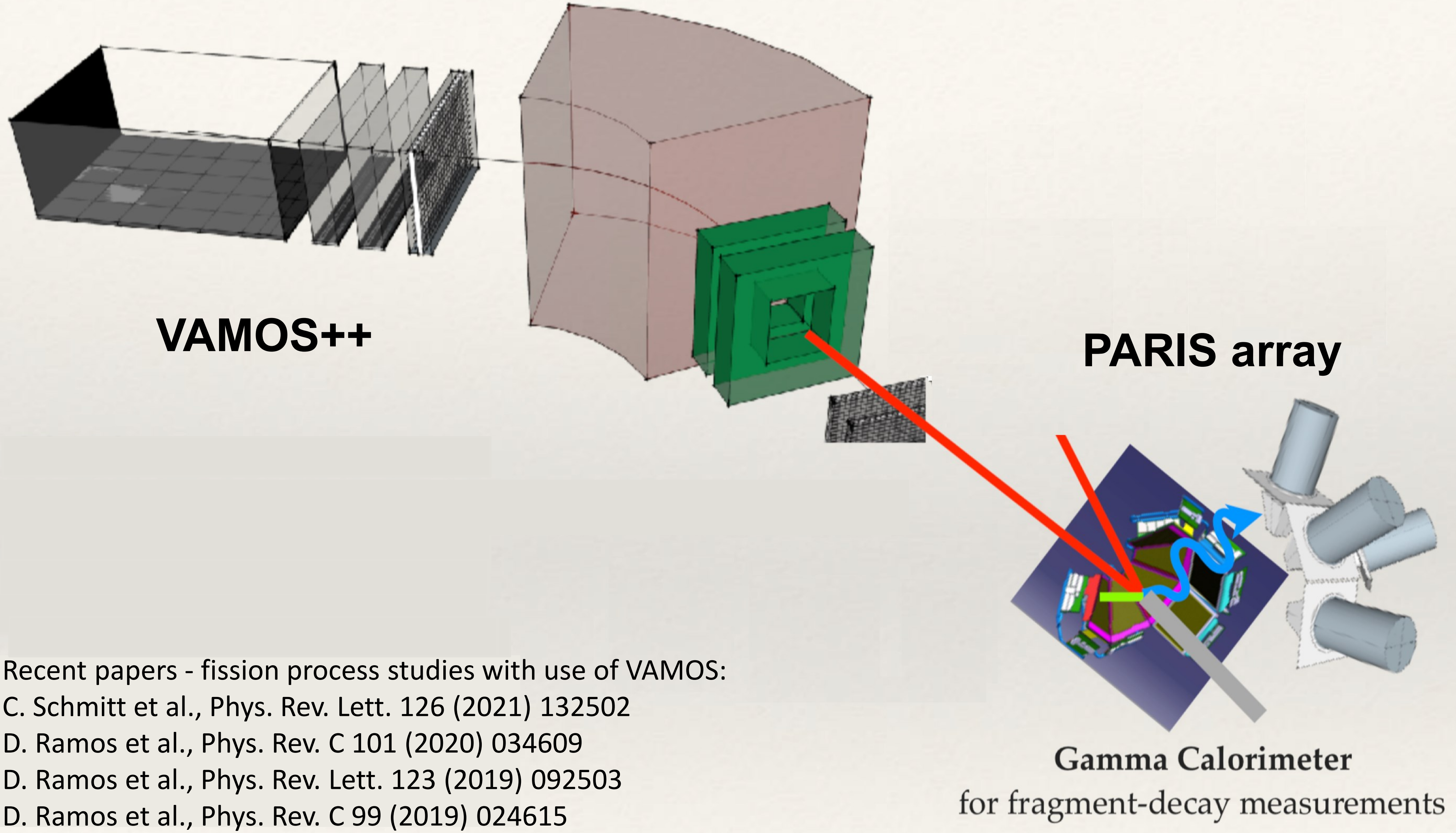
GANIL heavy beams

=

Unique Tool



Recent papers - fission process studies with use of VAMOS:
C. Schmitt et al., Phys. Rev. Lett. 126 (2021) 132502
D. Ramos et al., Phys. Rev. C 101 (2020) 034609
D. Ramos et al., Phys. Rev. Lett. 123 (2019) 092503
D. Ramos et al., Phys. Rev. C 99 (2019) 024615

PARIS campaign at GANIL in 2022

With VAMOS:

Insight into fission from the gamma probe: Going beyond current status with PARIS@VAMOS, *Ch. Schmitt, M. Cieamła et al.*

At LISE:

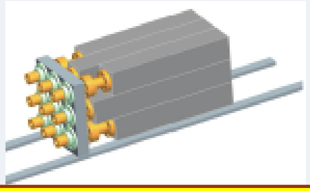
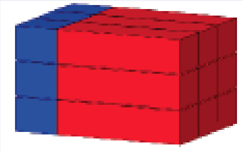
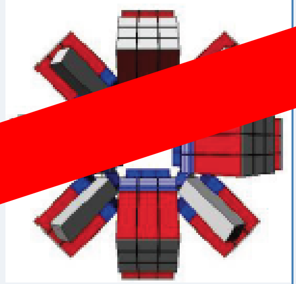
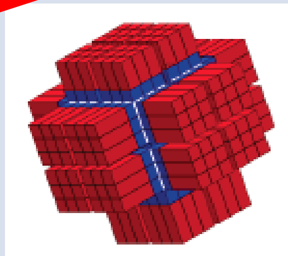
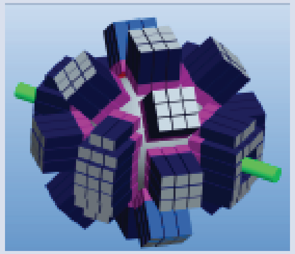
Study of deformed and spherical 2^+ states via Coulomb excitation and first time measurement of PDR in ^{34}Si, *R. Lica, S. Calinescu, O. Sorlin, et al.*

Study of Proton/Neutron contribution along Silicium isotopic chain, S. Grévy, R. Thomas, O. Sorlin et al.

At NFS:

Nuclear structure studies using neutron inelastic scattering reactions, example of the pygmy resonance in ^{140}Ce*,*
M. Vandebrouck, I. Matea et al.,

Photon Array for studies with Radioactive Ion and Stable Beam - PARIS (travelling detector)

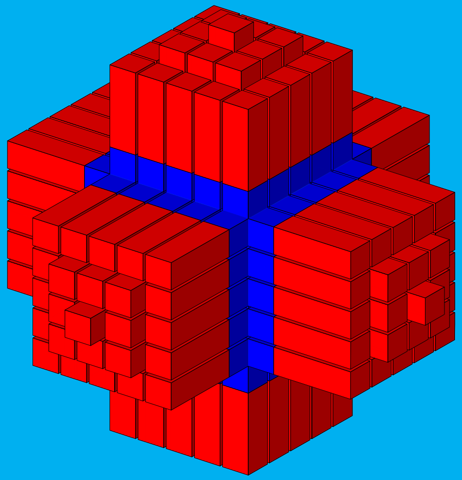
Phase 1 **2011/2012** PARIS cluster	1 cluster: 9 phoswiches		
2025? **PARIS 2π**	12 clusters: 108 phoswiches		
after2025	>24 phoswiches		

Today we have ~ 10 clusters (90 detectors)

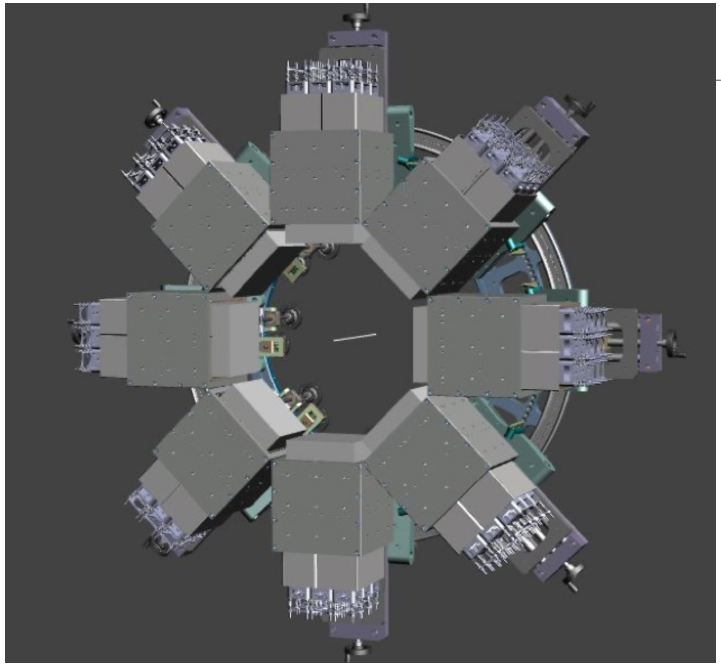
PARIS Project Manager: A. Maj (IFJ PAN Kraków)
PARIS is a collaborative project between France, Poland, Italy, India, Romania, Germany, UK and Turkey

PARIS is made of clusters:
Cluster = 9 phoswiches of $LaBr_3$:NaI or $CeBr_3$:NaI
Digital electronic basing on V1730 digitizer, which can be coupled to NUMEXO2 boards. Also other electronic used, by example FASTER digitizers (NFS exp. and @IJCLab)

Goal of the new MoU
4π mini-cube
(150 phoswiches)



PARIS array properties



Good energy resolution for low and high energy γ-rays

- 35 keV @ 1.332 MeV

Excellent Time resolution (below ~ 1 ns)

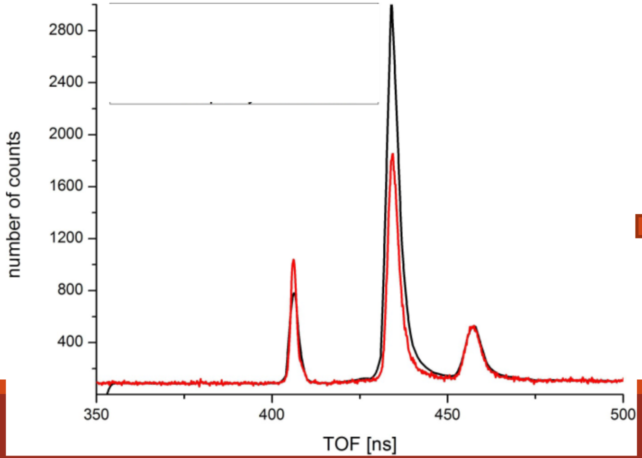
Measurement of gamma multiplicity from frontal $LaBr_3$ or $CeBr_3$

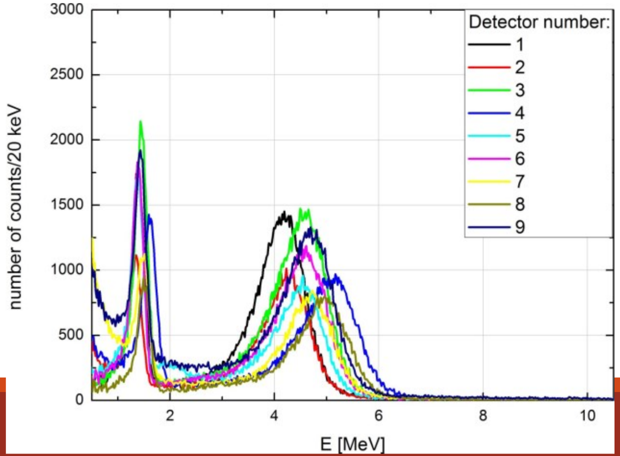
Large efficiency for high energy γ-rays (~ 5% at 10 MeV for 8 clusters)

72 phoswiches in 8 clusters

72 LaBr3:Ce or CeBre 2”x2” crystals in 8 clusters

~ 28 liters of NaI in 8 clusters





Previous use of PARIS in PFGS/PFNS:

E. Kozulin et al., Eur. Phys. J A 56 (2020) 6

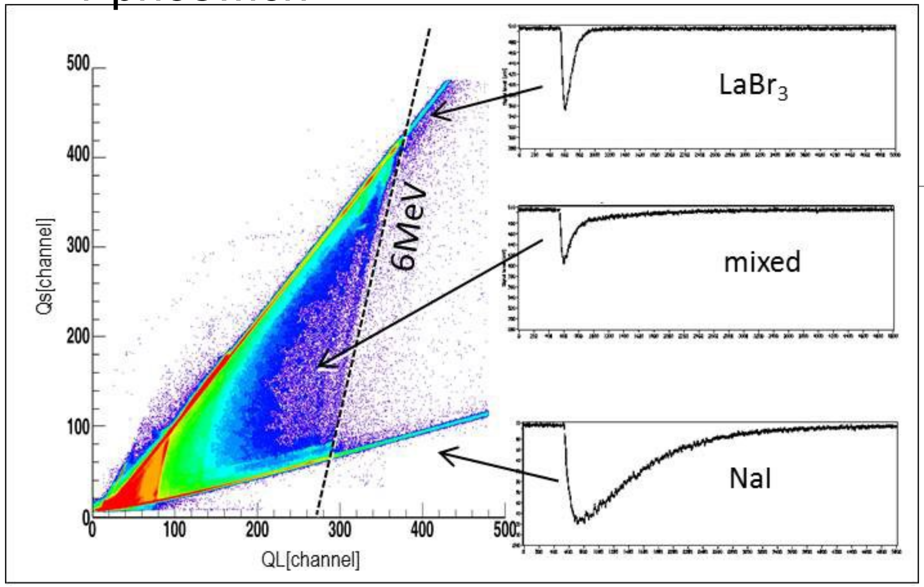
E. Vardaci et al., Phys. Rev. C 101 (2020) 064612

L. Qi et al., Eur. Phys. J A 56 (2020) 98

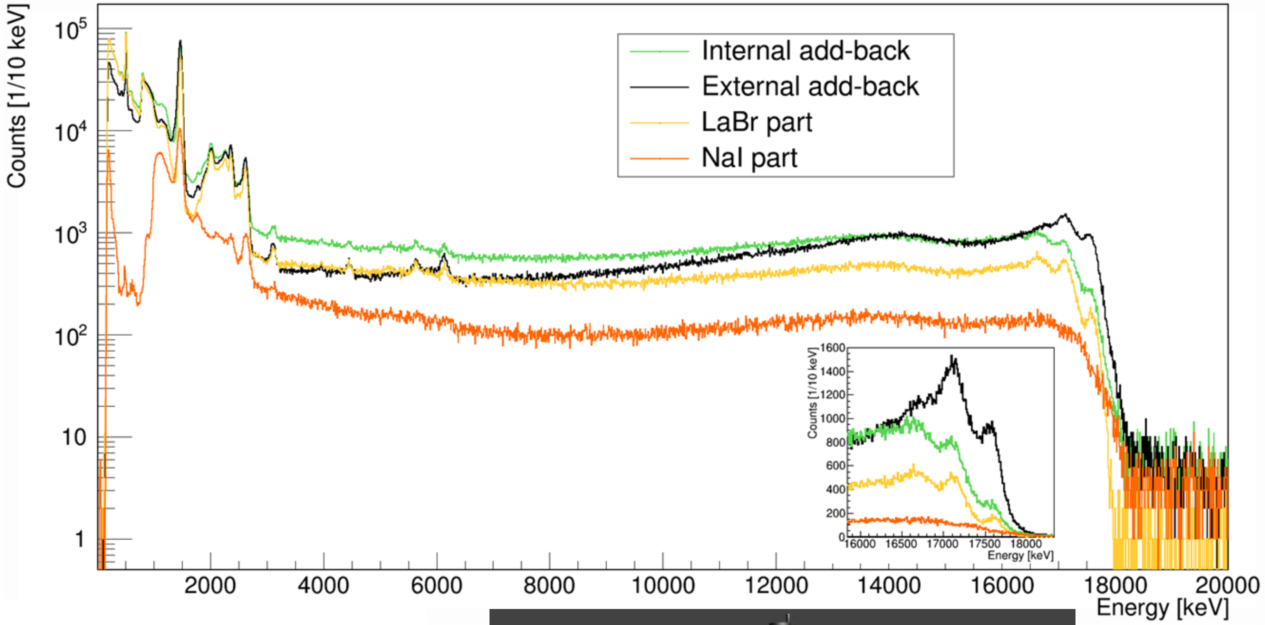
Example of neutron measured by PARIS via ToF

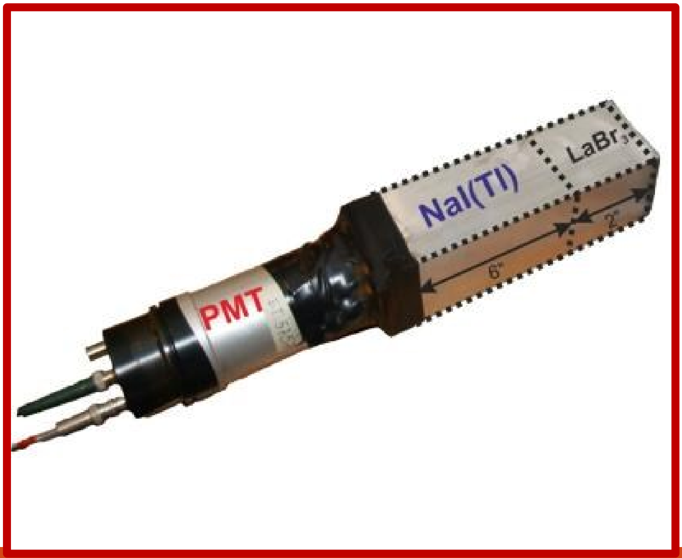
Examples of PARIS spectra

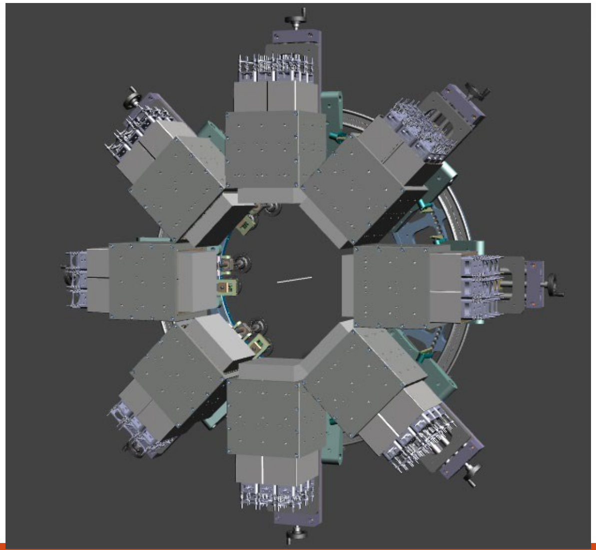
1 phoswich



1 cluster







VAMOS + PARIS& EXOGAM @ GANIL

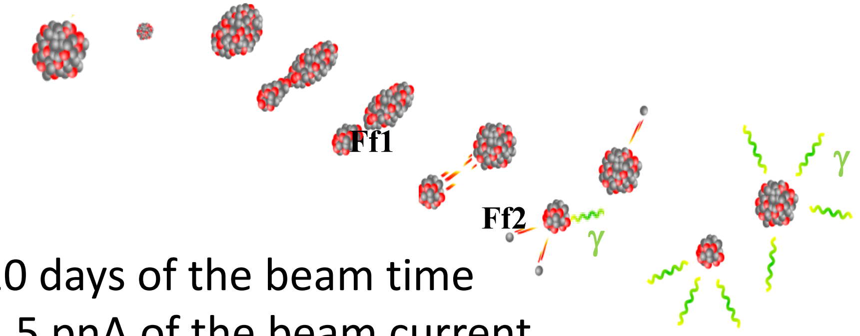
Ch. Schmitt, M. Ciemała, et al.

GANIL E826 : VAMOS+PARIS&EXOGAM experiment performed 2022

Fusion-fission in inverse kinematics

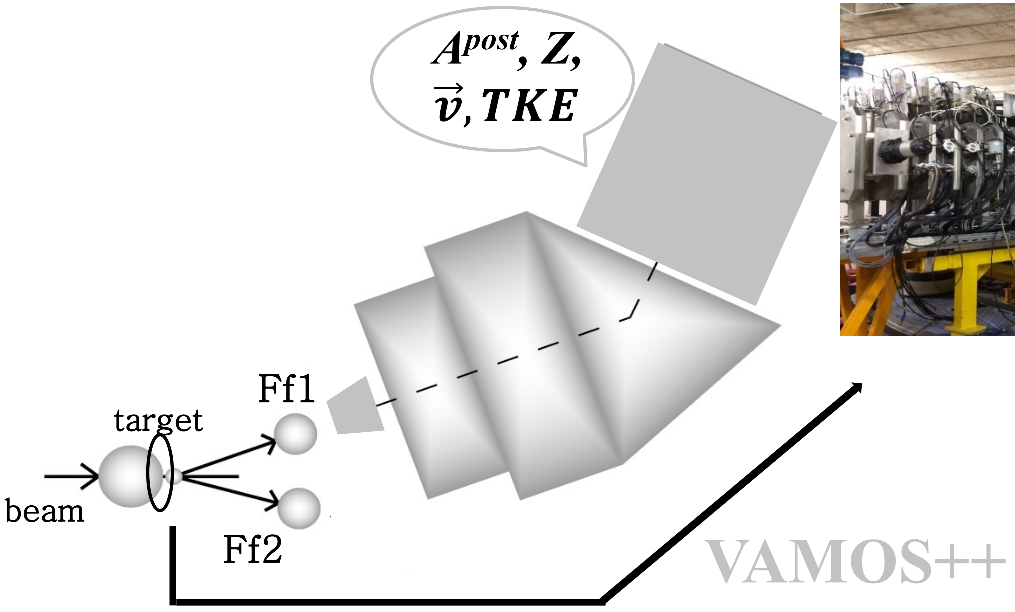
^{238}U + ^{9}Be → ^{247}Cm* (**E^{*}~ 43MeV**)

(5.88MeV/u) (500μg/cm2)



10 days of the beam time

1.5 pnA of the beam current



ϑ=21°, Bρ=1.1Tm

event by event

- ✓ **Ff's uniquely resolved / characterized in (A, Z, $\vec{v}$)**
- ✓ **PFGS and properties (E_{γ}, E_{γ}^{sum}, M_{γ})**
- ✓ **Neutrons (E_{n} , M_{n})**

PFGS

E_{γ}, E_{γ}^{sum}, M_{γ}, M_{n}

PARIS

Exogam

Experimental setup details

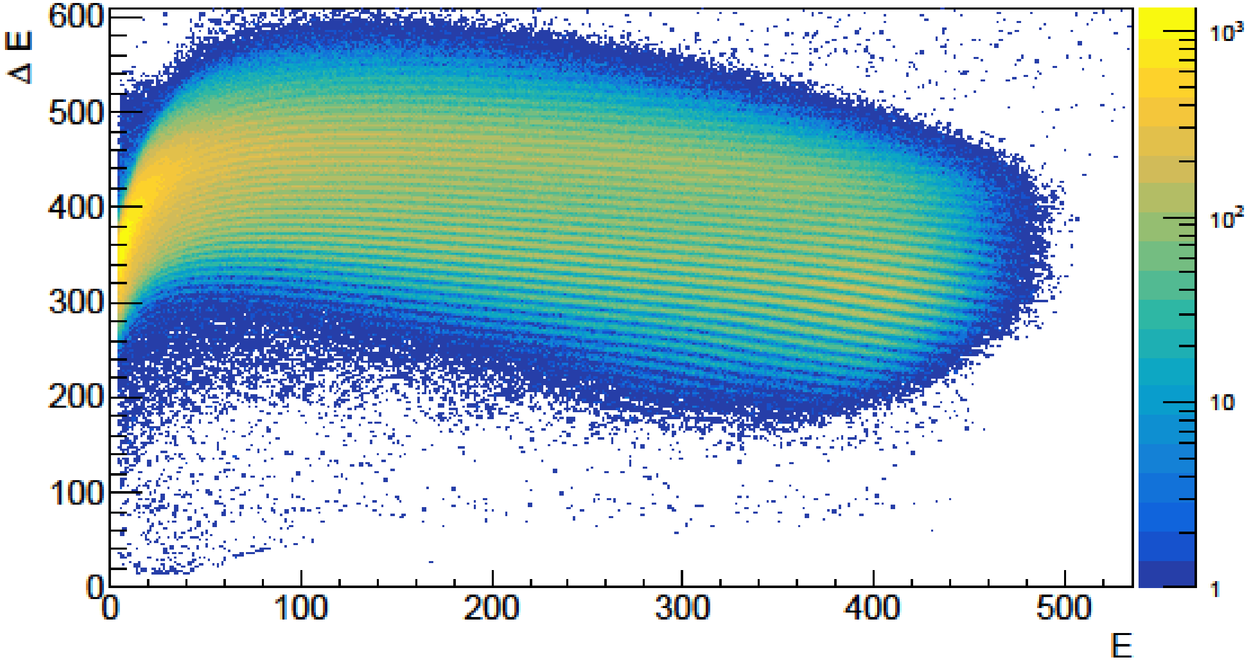
Digital readout with synchronization of the V1730 used for the PARIS detectors via AGAVA and GTS with NUMEXO2 boards (S. Brambilla and A. Goudsdaf)

All of the PARIS shielded by design mu-metal magnetic field casings (PMTs sensitive to magnetic field)

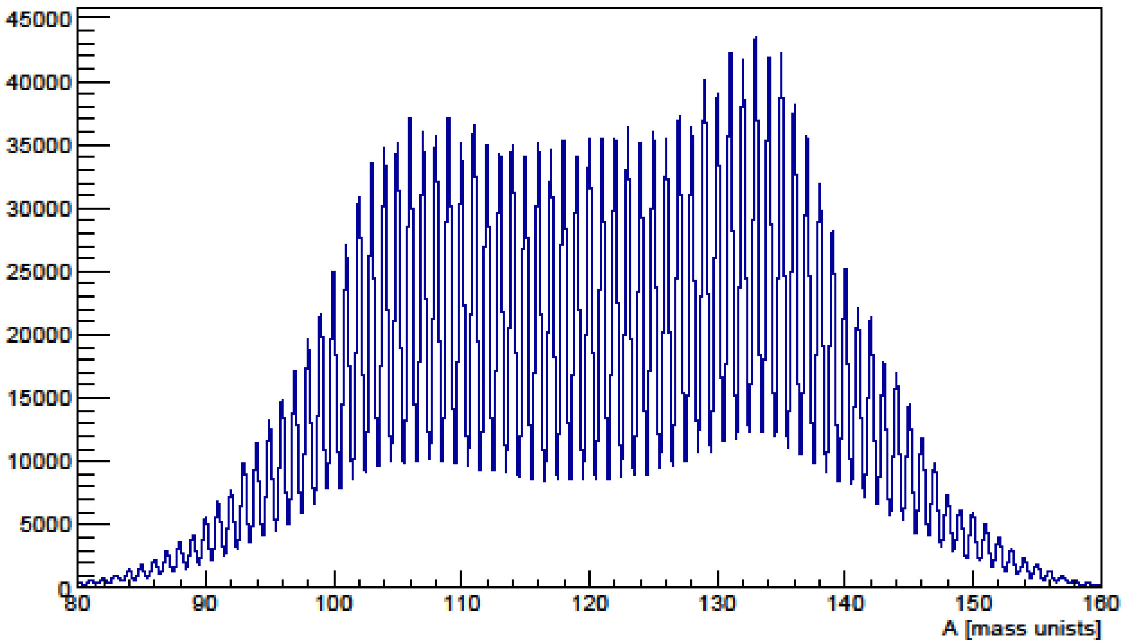
PARIS clusters
(8 in total = 72 phoswiches)
~27 cm distance around 90 degree in respect to center of the VAMOS

EXOGAM clovers (3)
~11 cm distance
back angles

A,Z, VAMOS spectrometer identification

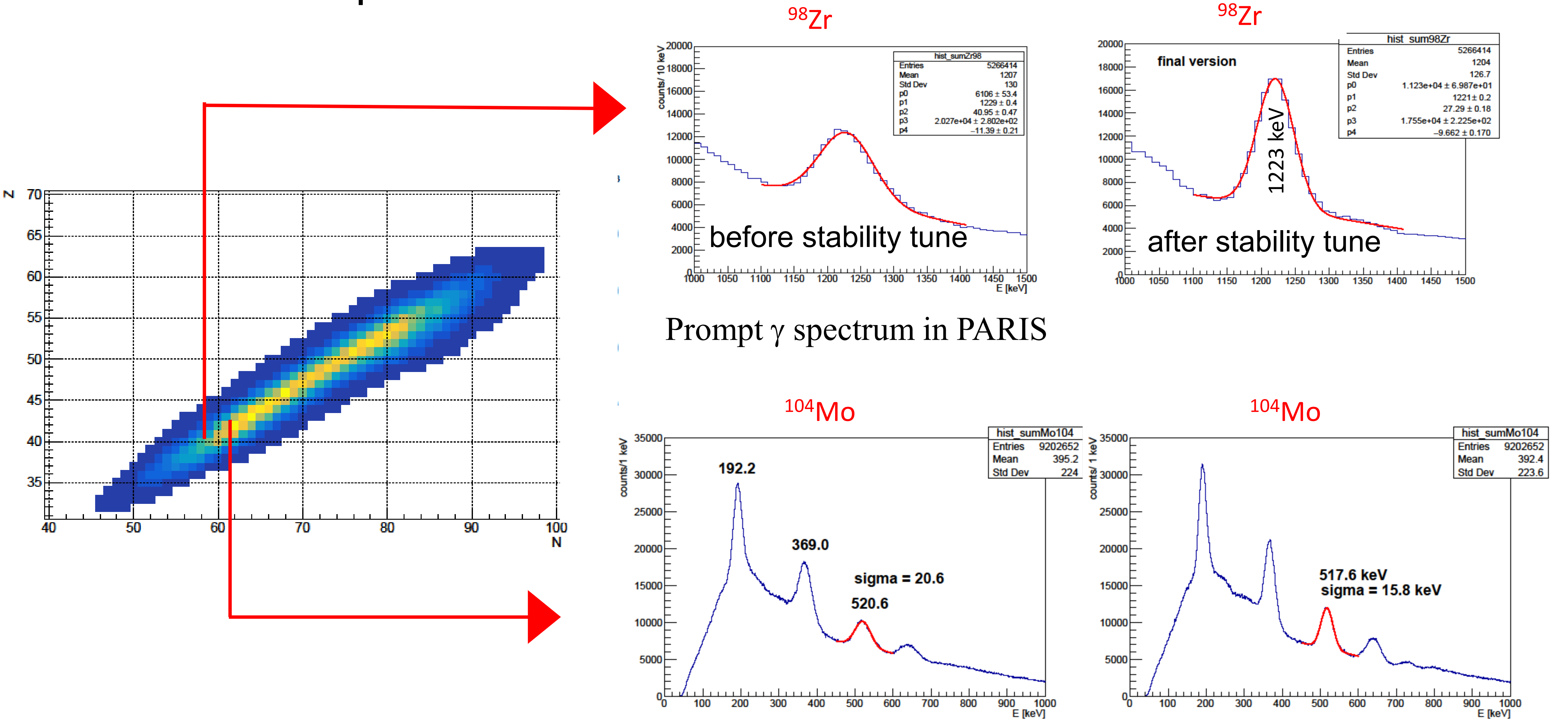


Correlation between the energy loss and total energy deposit in the VAMOS++ ionization chamber - Z identification



Detected post-neutron mass spectrum

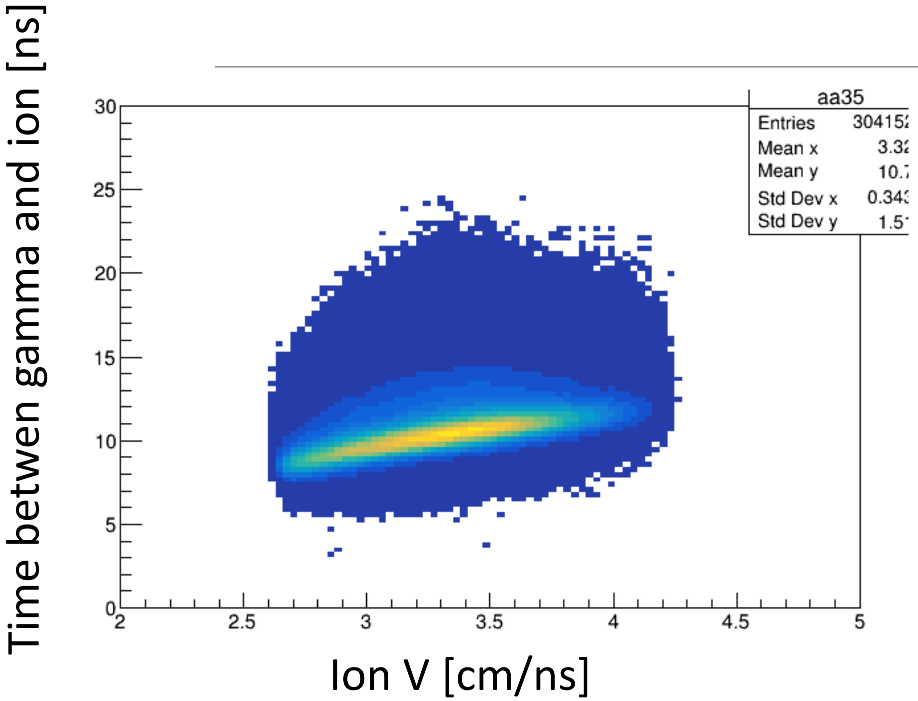
Isotopic identification in VAMOS++



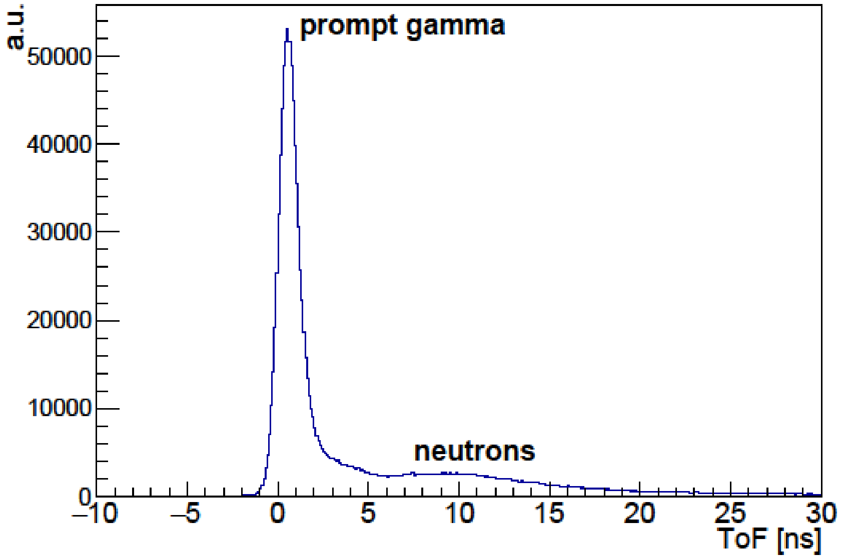
after tuned callibration

after stability tune based on 511 keV line

Promp gamma-ray: time measurement



Event by event ion velocity correction of ToF

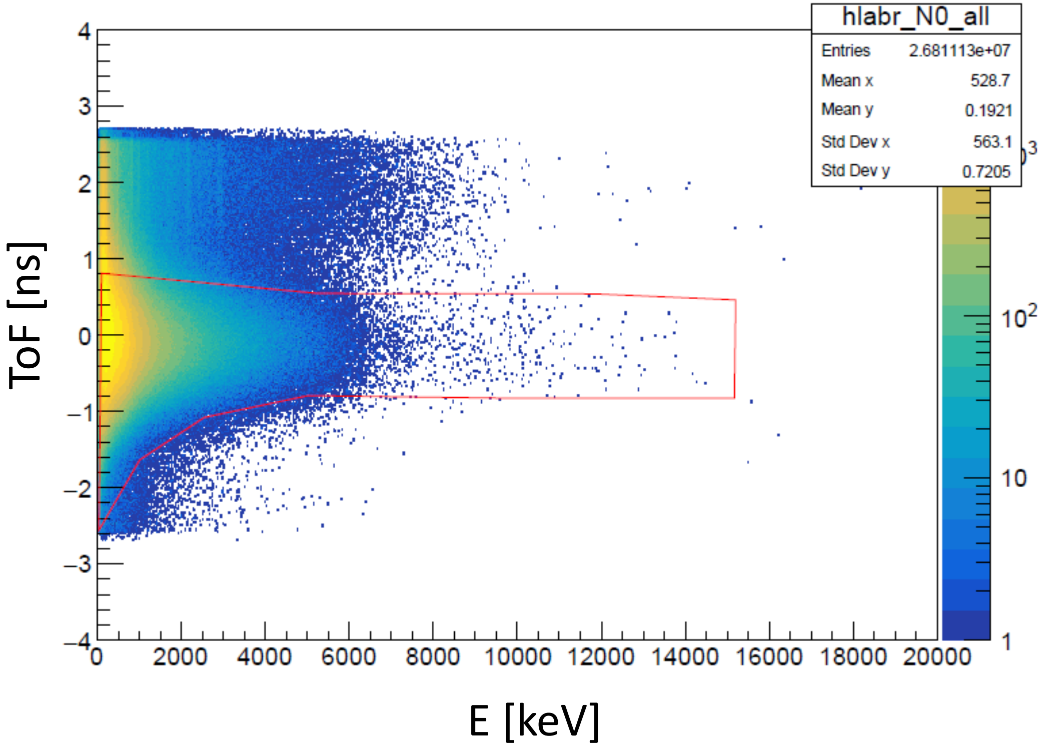


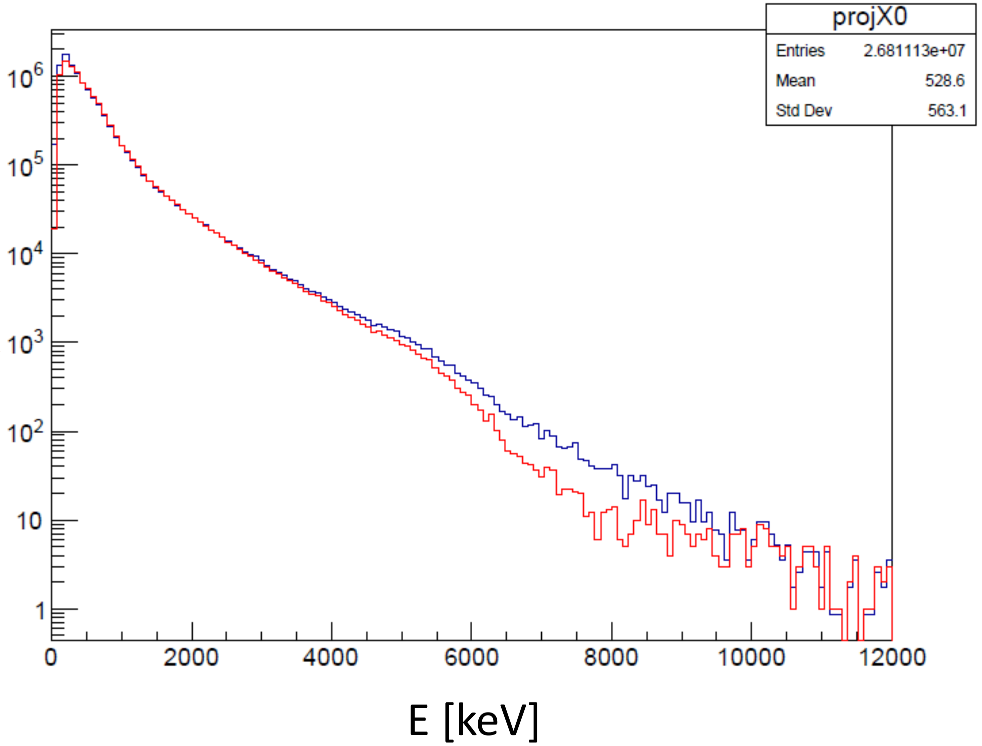
ToF sigma for prompt gamma peak ~0.8 ns

Promp gamma-ray: time measurement

Shape of the background in high energy (6-10 MeV) gamma-ray region

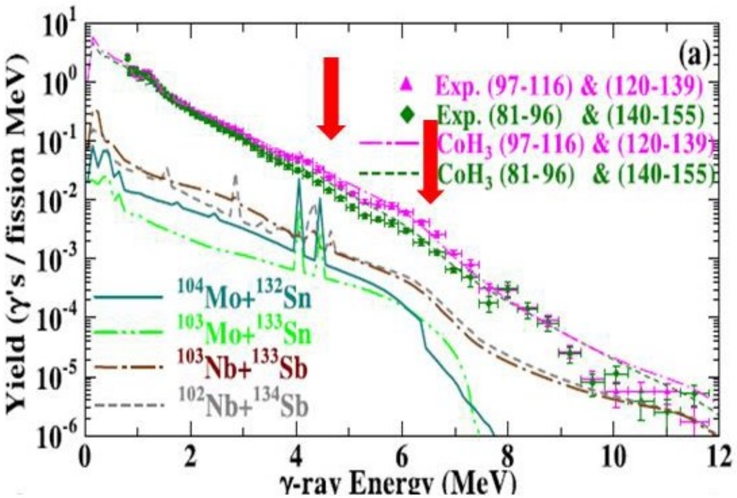
Perfect **time resolution** of PARIS is crucial for the high Energy region of the gamma-ray spectrum



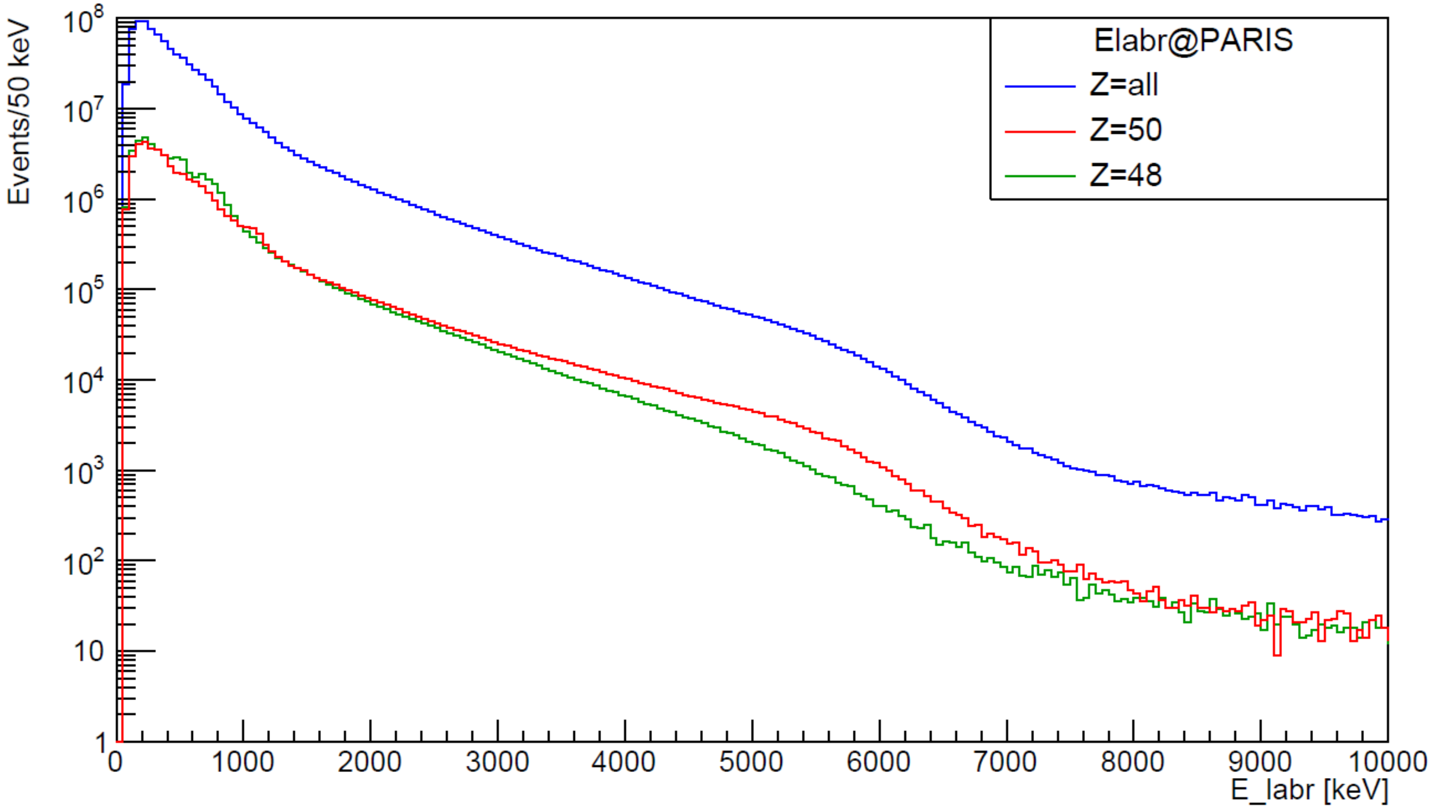


Z gated γ properties - PFGS

PFGS shape and "bump" ?



Experimental PFGS (pink triangles and green diamonds) for cold-neutron-induced fission of ^{236}U two different fragment pair mass range By H. Makii et al., Phys. Rev. C 100 (2019) 044610.



Detailed shape of the prompt fission γ spectrum

High Energy region of gamma-ray spectrum - literature

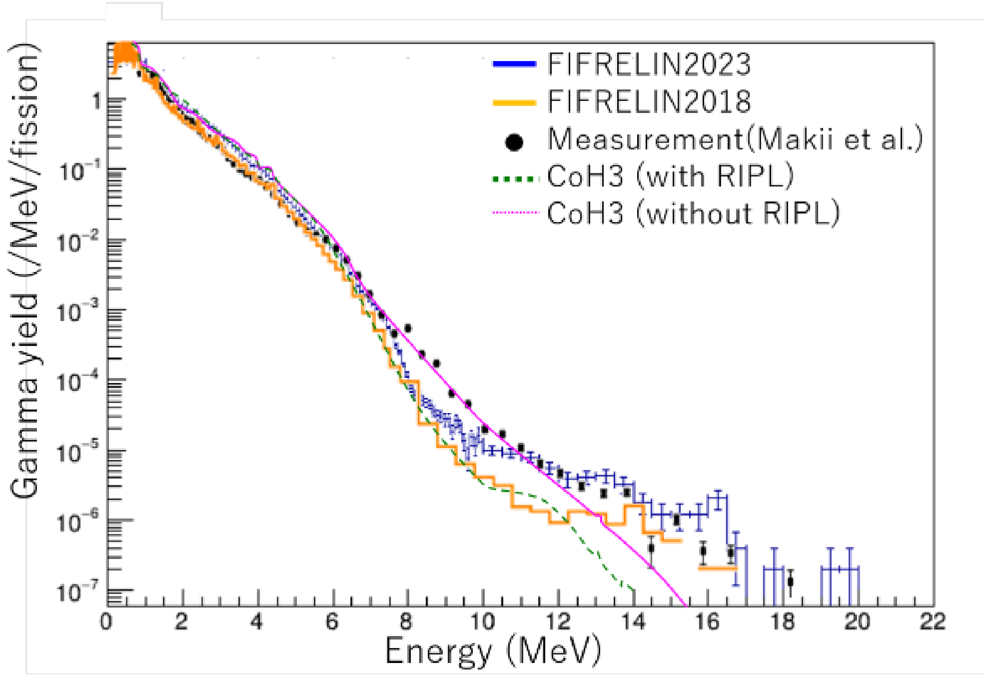
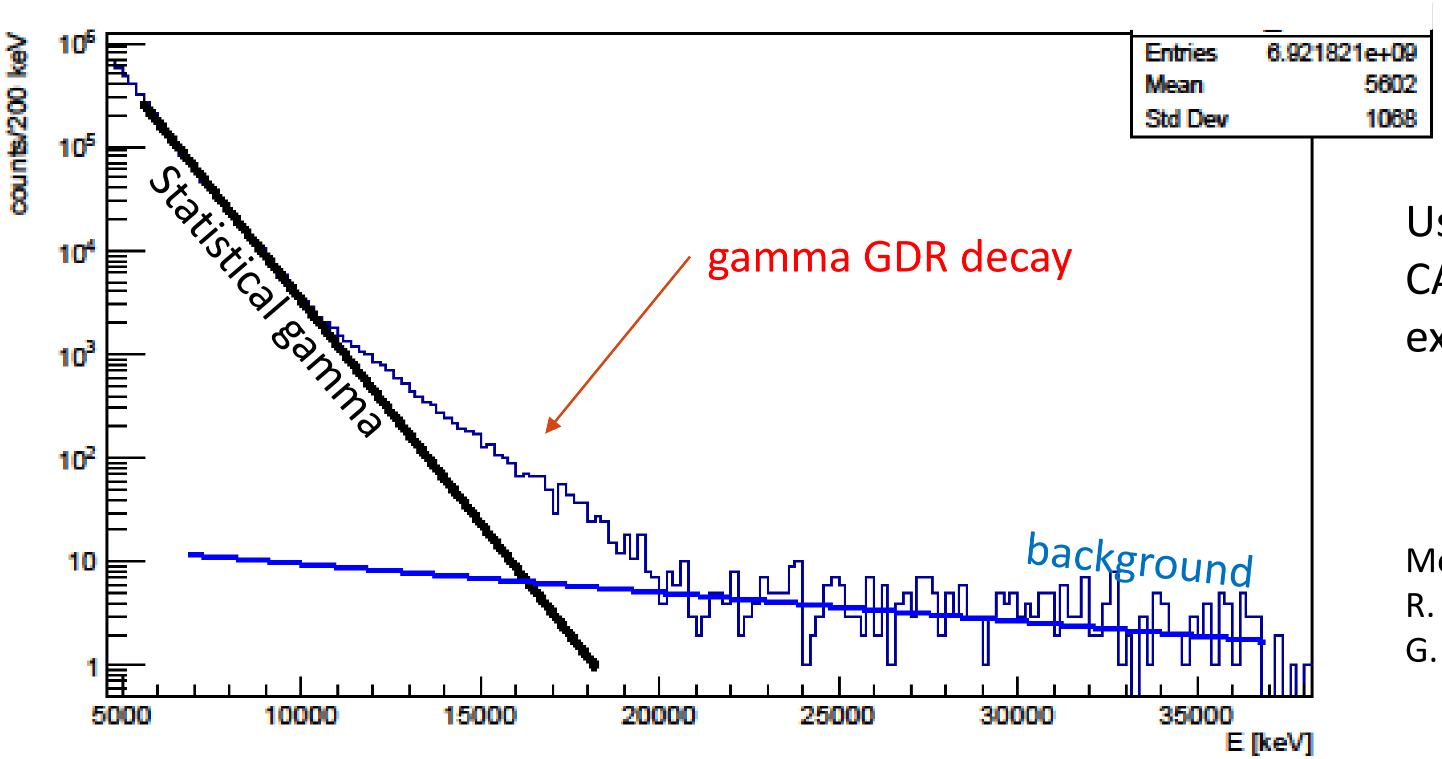


Figure 1. Gamma-ray spectra calculated by FIFRELIN 2023 and 2018 in this study, measurement data by Makii *et al*, and calculated with CoH3 [19].

T. Ogawa, et al., "Investigation of the structure in 235U(nth,fis) prompt gamma energy spectrum by FIFRELIN", EPJ Web of Conferences 294, 02003 (2024)

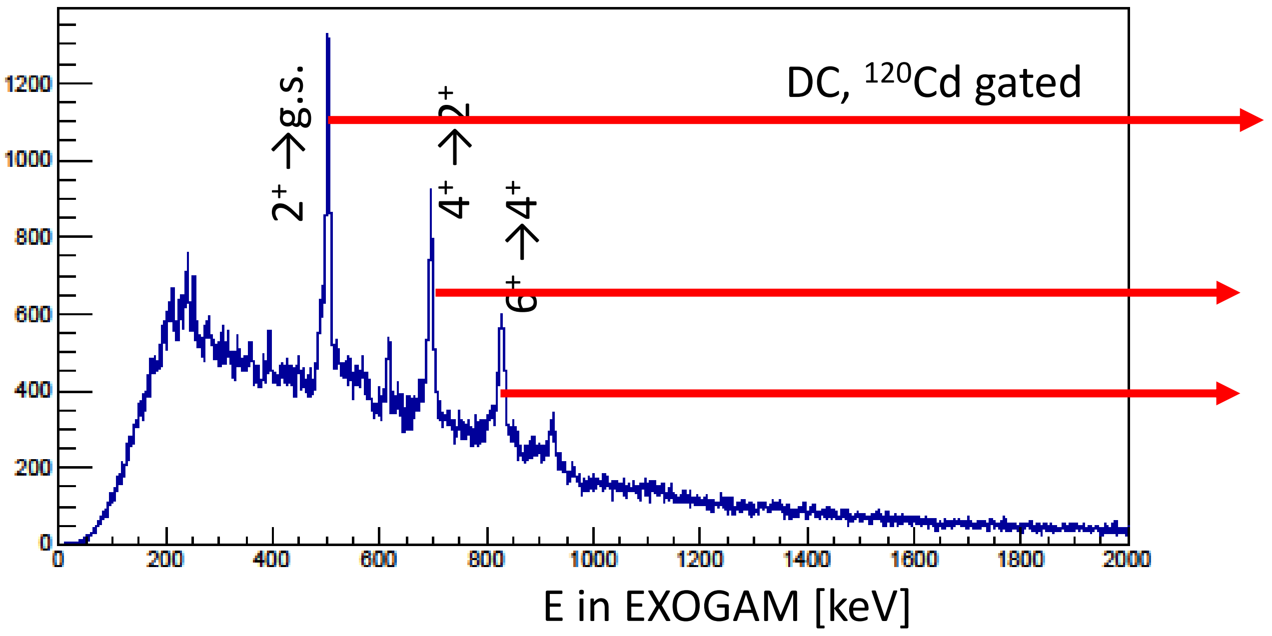
Gamma GDR Decay prompt gated



Use of the statistical model codes like CASCADE, GEMINI++ make possibility to extract fission time scale.

Methods described by example in:
R. Butsch, et al., Phys. Rev. C 44 (1991), 1515-1527.
G. van't Hof, et al. Nucl. Phys. A 638 (1998) 613-661.

^{120}Cd example FF discrete gamma and FOLD equivalance



FF120Cd gated $\langle FOLD_{PARIS} \rangle = 2.66(1)$

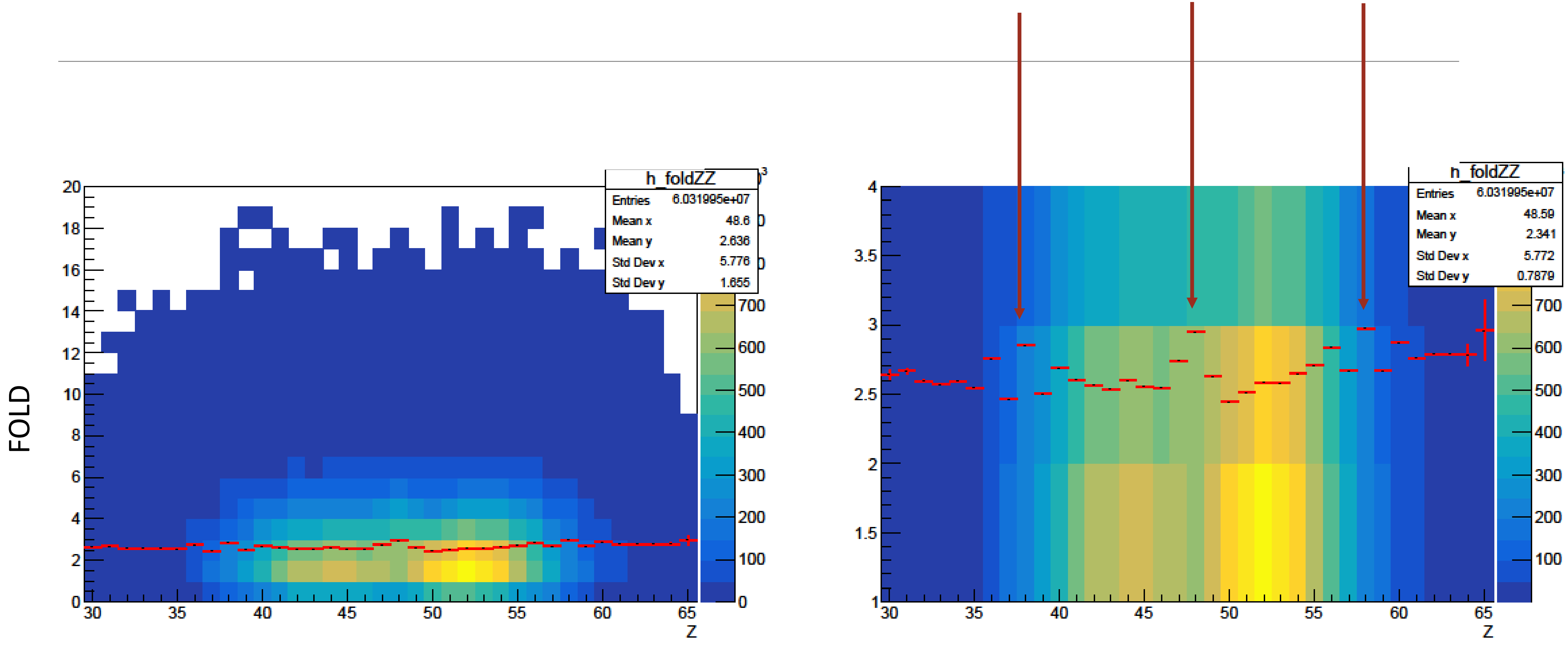
FF120Cd &&FF$_1$ L≥2 $\langle FOLD_{PARIS} \rangle = 2.94(1)$

FF120Cd &&FF$_1$ L≥4 $\langle FOLD_{PARIS} \rangle = 3.07(1)$

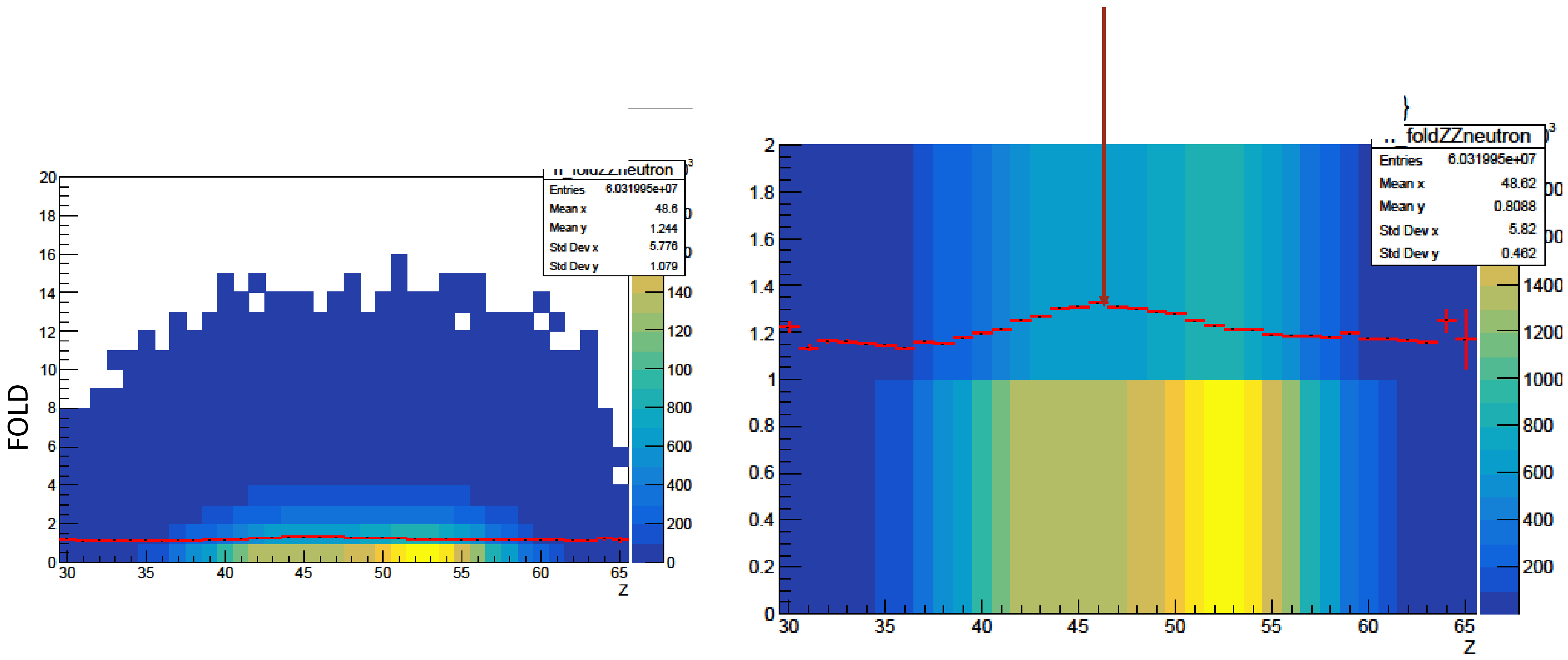
FF120Cd &&FF$_1$ L≥6 $\langle FOLD_{PARIS} \rangle = 3.31(1)$

Z gated γ properties – FOLD of PFGS, $^{247}Cm^*$

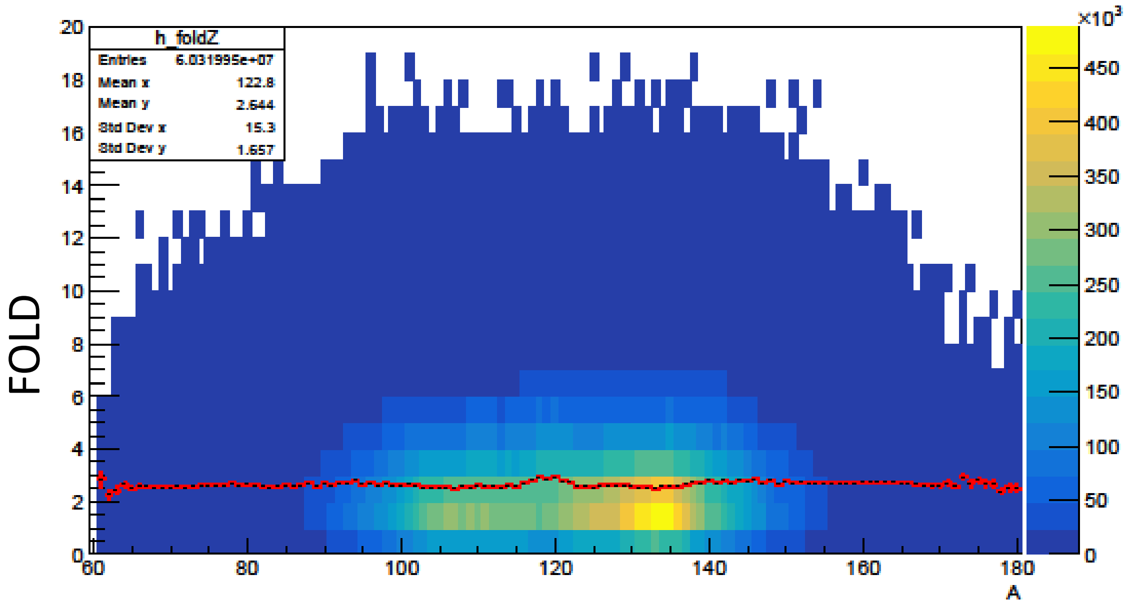
FOLD → gamma multiplicity → summ of fission fragment L_1 and L_2

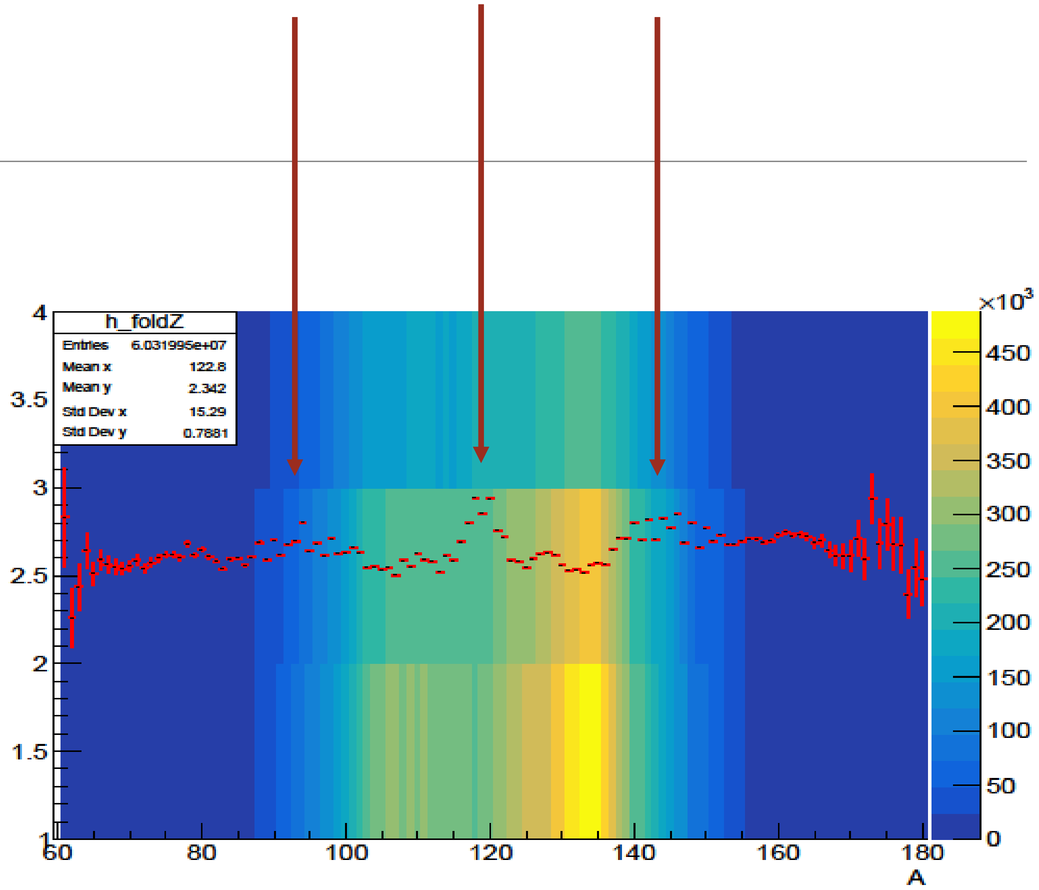


Z gated neutron properties – FOLD of PFNS, $^{247}Cm^*$

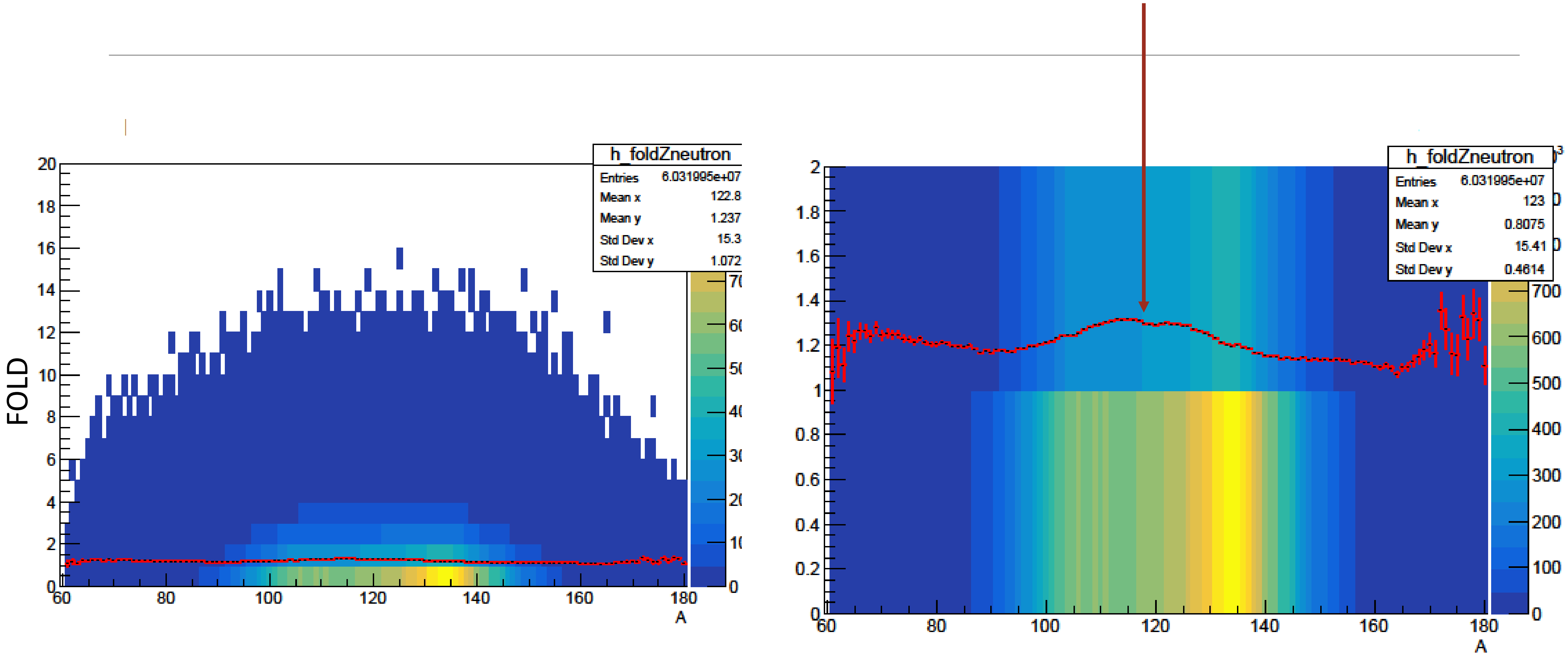


A gated γ properties – FOLD of PFGS, ^{247}Cm*





A gated neutron properties – FOLD of PFNS, $^{247}Cm^*$



Perspectives for next experiments@GANIL

Systematic study of fusion-induced fission with, by example, $^{238}U+^{12}C$ and $^{238}U+^{26}Mg$ with use of VAMOS + PARIS + EXOGAM combined setup.

Possible extension by adding second arm or coupling with the SPIDER telescope → evolution of fission properties with excitation energy, as well as to quasi-fission like mechanisms.

Perspectives for experiments@CCB IFJ PAN

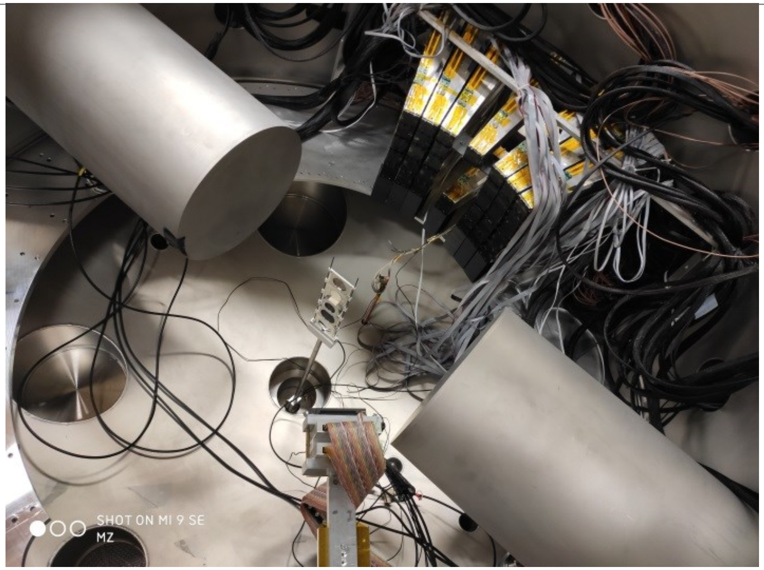
COFFEE: Cracow-Orsay Fission Fragment Exclusive Experiments

Proton induced fission

Detectors:

- KRATTA,
- plastic array,
- gamma-ray detection, PARIS, large volume $LaBr_3$

and possibly HPGe



The high excitation energies at CCB will allow study of the fission of ^{232}Th as well as of *sub-actinide* nuclei such as ^{208}Pb, ^{197}Au, ^{196}Pt, ^{186}W, etc. where fission barrier heights are around 25-30 MeV. With addition of a fission fragment detector these fission events will come for "free" along with some of the future experiments in the current research program into giant collective resonances already underway at CCB.

Sumary and perspectives

Unique dataset for the PFGS (and PFNS) together with isotopically identified fission fragments was collected during experiment at GANIL with use of coupled VAMOS++ and PARIS+EXOGAM.

Undergoing careful **analysis** including **deconvolution** of FOLD and Energy spectra allowing to shed more light on the fission process, especially with comparison to the models available on the market. **Perfect time resolution** provide very clean gamma-ray Energy spectrum in the high energy region.

Giant Dipole Reconance gamma decay visible in the measured prompt gamma energy spectrum, which makes possible to extract fission time scale.

Systematic study of fusion-induced fission in the future with, by example, $^{238}U+^{12}C$ and $^{238}U+^{26}Mg$ with use of VAMOS + PARIS + EXOGAM combined setup. Possible extension by adding **second arm** or coupling with the SPIDER telescope → evolution of fission properties with excitation energy, as well as to quasi-fission like mechanisms.

New program of fission studies emerging at CCB (IFJ PAN) using proton induced fission.

Acknowledgements

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