STUDIES ON FISSION WITH ALADIN

DE LA RECHERCHE À L'INDUSTRIE

SOFIA
Fission yields measurement at GSI

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Available data

- Mass yields with good resolution
- Elemental yields
- Isotopic yields : little data in light fragments, even less for heavier fragments

Fission yields, why ?

- post-Fukushima accident : residual heat calculation
- Impact of N- and Z- shells on fission partition poorly understood

SOFIA

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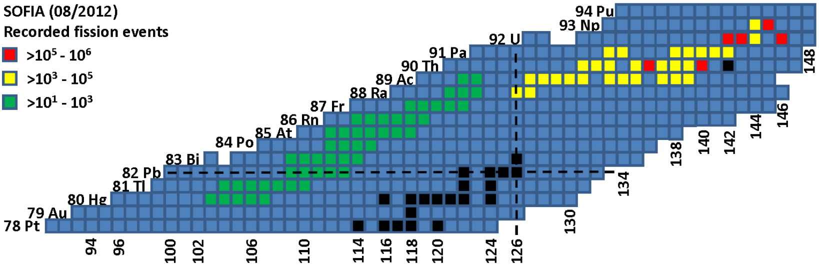
Studies On FIssion with ALADIN

- For the very **first** time, **fully** and **simultaneously** identify **both** fission fragments
- Measure also the **TKE**, as a function of asymetry
- For approx. 80 fissionning systems
  ranging from *Hg* ($Z = 80$) to *Np* ($Z = 93$)
  half of them measured for the 1st time

- At GSI, Darmstadt, Germany
- Produce a **secondary beam** of fissionable nuclei
- Induce its fission through **EM excitation**
- Identify **both fragments** with a high resolution recoil spectrometer

Investigate the (low-energy) fission process

Studied nuclei



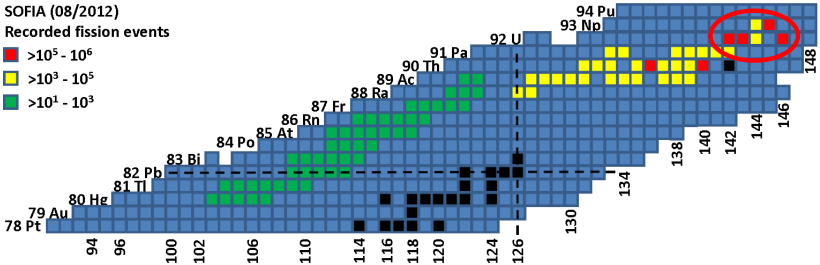
Actinides : High statistics for applications

- *U, Np*
- 1.5 days

Pre-actinides and lighter actinides : browse the nuclide chart

- Lower statistics, a few hours

Studied nuclei



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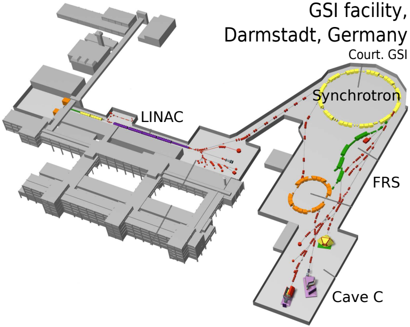
1. Secondary beam

2. Fission fragments
   - Set-up
   - Electromagnetic fission

3. Results : actinides
   - Fission modes
   - Elemental Yields
   - Isobaric and isotonic yield
   - Isotopic yields
   - Neutron multiplicity
   - TKE

4. Conclusion

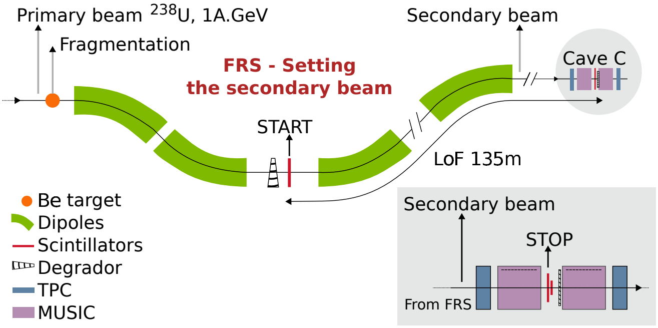


- ^{238}U accelerated up to $1A.GeV$
- Fragmentation reaction
- Secondary beam of actinide or preactinide

  Selected through the FRagment Separator -FRS
- Fission of secondary beam ions

  SOFIA around the ALADIN magnet in Cave-C

Secondary beam

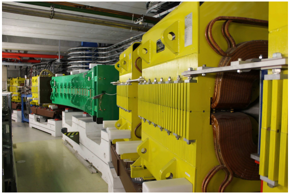


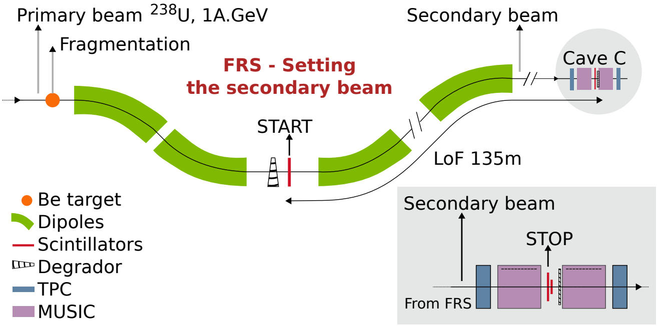
B Magnetic field — Dipoles

ρ Positions

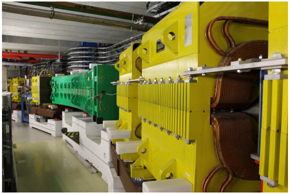
Z Charge — Ionisation chambers

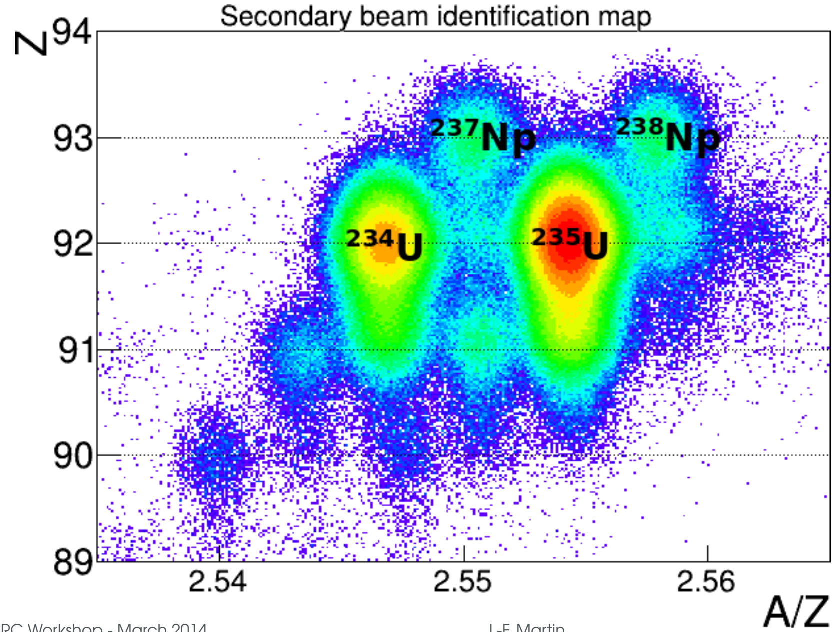
γv Velocity — ToF





$$\left.\begin{matrix} B \\ \rho \\ Z \\ \gamma v \end{matrix}\right\} (B\rho, Z, \gamma v) \rightarrow A$$




Secondary beam identification map
N
94
93
92
91
90
89
^{237}Np
^{238}Np
^{234}U
^{235}U
2.54
2.55
2.56
A/Z

1. Secondary beam
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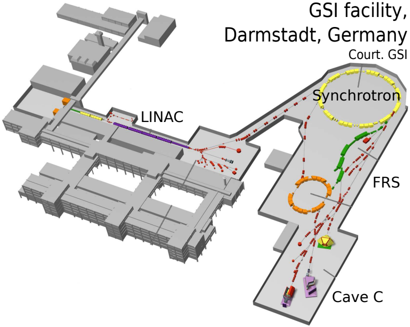
4. Conclusion



- ^{238}U accelerated up to $1 A.GeV$
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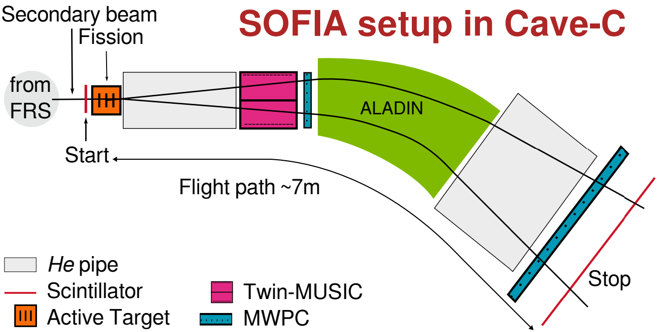
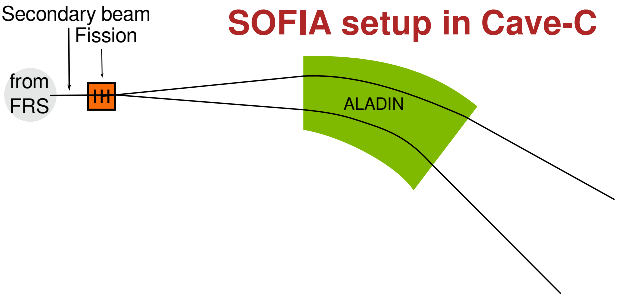
  SOFIA around the ALADIN magnet in Cave-C

Fission studies in Cave C

- All detectors developed by the SOFIA collaboration
- ΔE, $B\rho$, *ToF* technique applied to both fragments

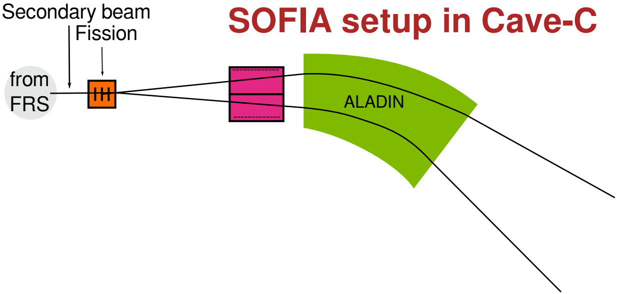




SOFIA setup in Cave-C

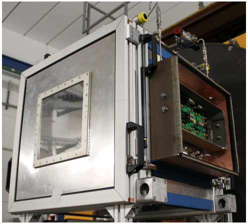
Active Target Fission

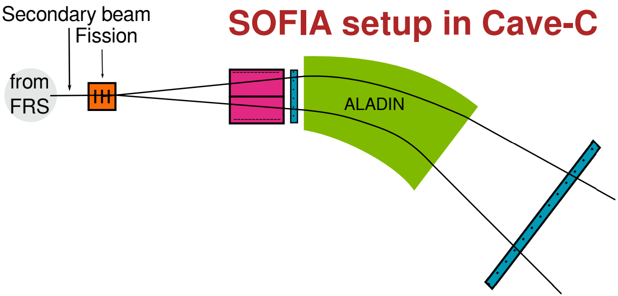
SOFIA Setup in Cave-C



Active Target Fission

Twin-MUSIC Charges $\sigma_{DE} = 0.4\ \%$

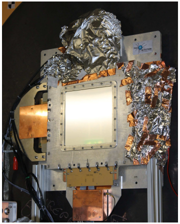


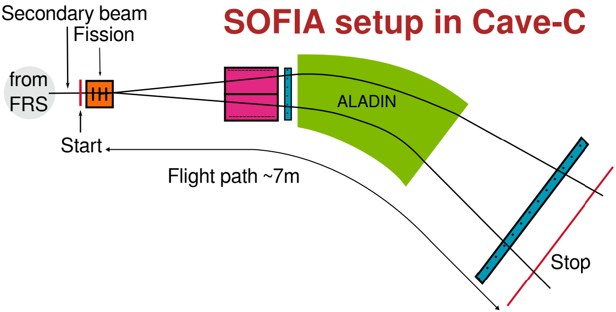


Active Target Fission

Twin-MUSIC Charges $\sigma_{DE} = 0.4\ \%$

MWPCs Positions $\sigma_X = 85\ \mu m$



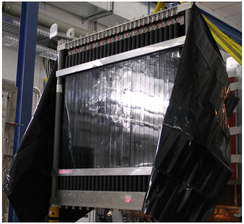


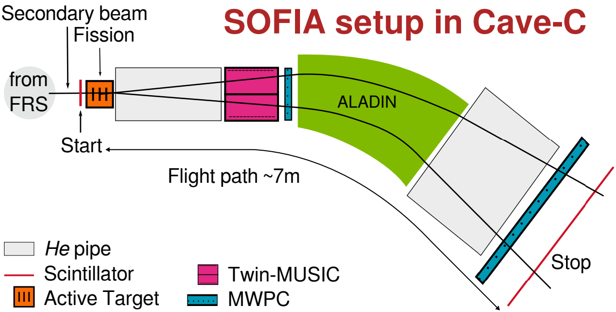
Active Target Fission

Twin-MUSIC Charges $\sigma_{DE} = 0.4\ \%$

MWPCs Positions $\sigma_x = 85\ \mu m$

ToF Velocity $\sigma_t = 17\ ps$

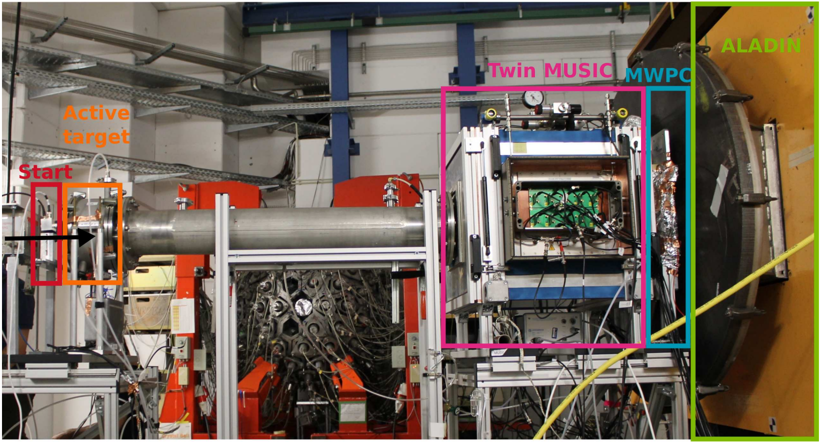




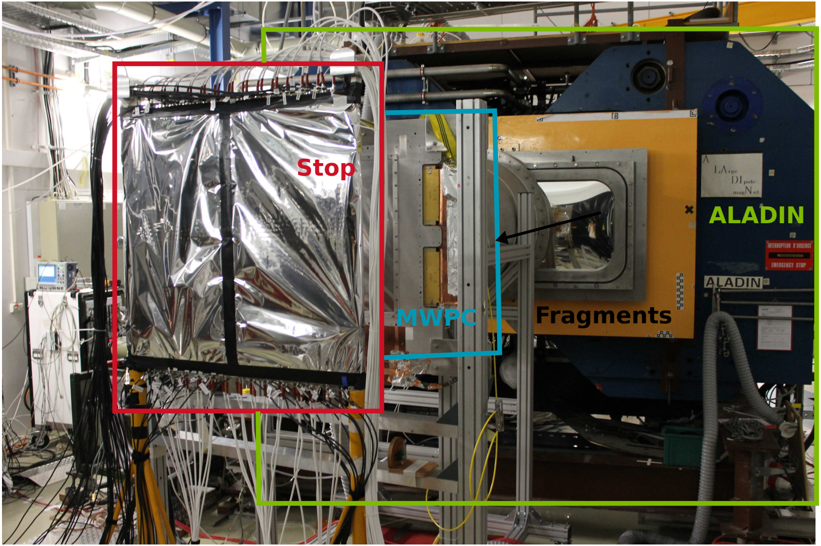
Active Target	Fission	
Twin-MUSIC	Charges	Z
MWPCs	Positions	ρ
ToF	Velocity	$\gamma\ v$
ALADIN	Dipole	B

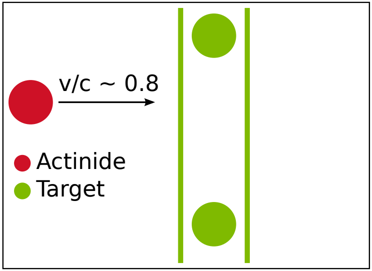
$$(B\rho, Z, \gamma v) \to A$$

Pictures

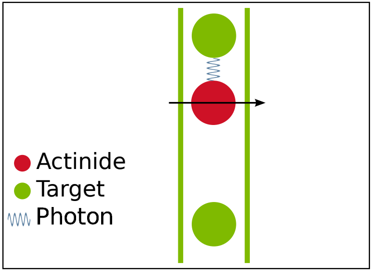


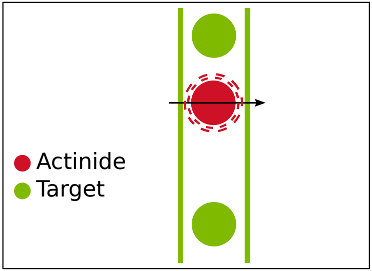
Pictures

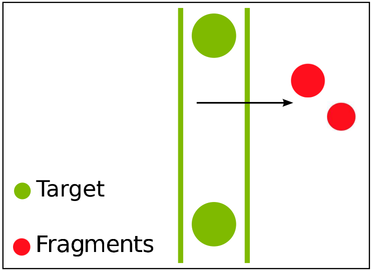

Stop
MWPC
Fragments
ALADIN
LArge DIpole magNet
ALADIN
EMERGENCY STOP


v/c ~ 0.8
Actinide
Target

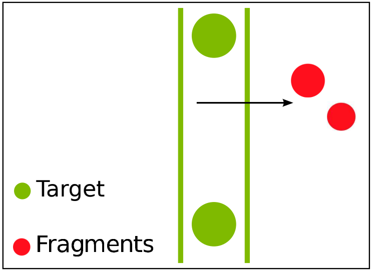
EM fission

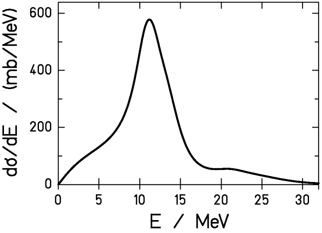



Actinide
Target


Target
Fragments

EM fission





Excitation energy distribution after EM excitations. K.-H. Schmidt *et al.*, N.P.A., 2000

Same as photofission

$$< E^* >= 12 MeV \quad \Leftrightarrow \quad 7 MeV \text{ neutron}$$

$$^{238}Np(EM, f) \approx {}^{237}Np(n_{7\ MeV}, f)$$

1 Secondary beam

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3 Results : actinides
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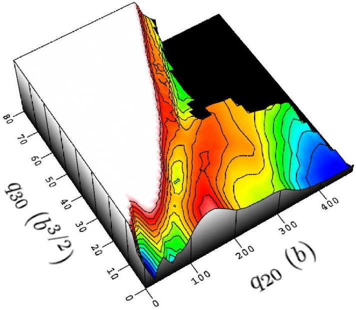
4 Conclusion

Fission modes interpretation

- Various path on PES correspond to fission modes
- For actinides, three main modes : SL, ST1, ST2
- Shell effects govern the modes
- TKE probes the scission configuration



Potential energy surface of ^{238}U, HFB + Gogny D1S calculation, *Court. N. Dubray (CEA)*

Fission modes

Fission modes for actinides

ST 1

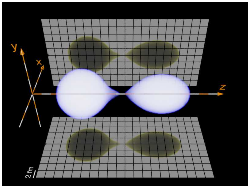
- Asymmetric
- Sph. ${}^{132}_{50}Sn$
- High TKE

ST 2

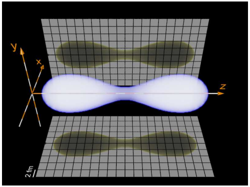
- Very Asymmetric
- Medium TKE

SL

- Symmetric
- Def. FF
- Low TKE



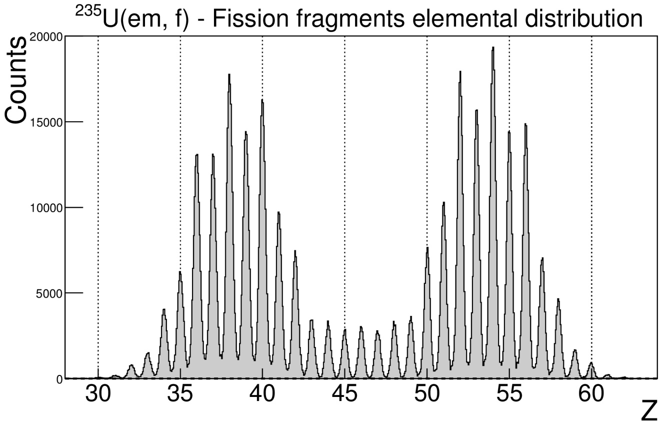
${}^{238}U$



${}^{238}U$

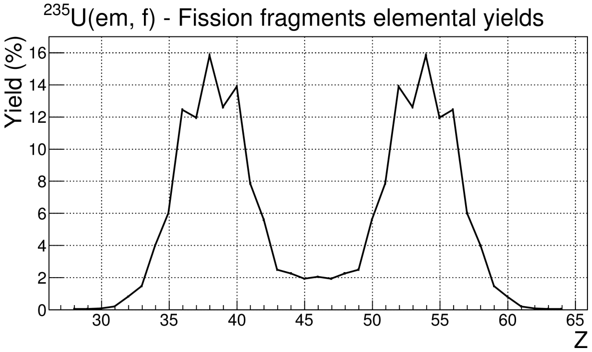
Scission configurations, HFB + Gogny D1S calculation
Court. N. Dubray (CEA)

Z distribution

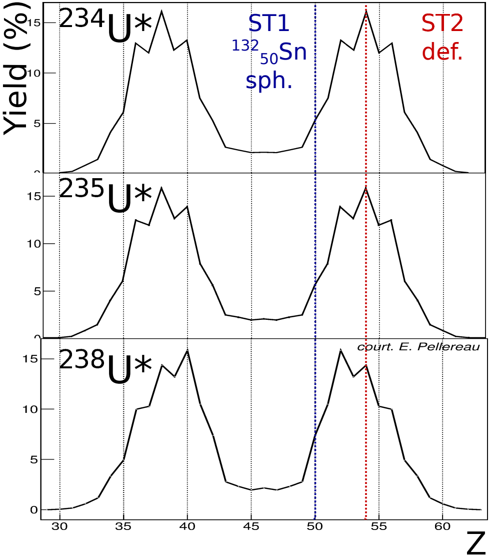


- Complete disentanglement of charges
- Landmarks : even-odd staggering and $Z = 54$
- Width of gaussians 0.41 *FWHM*

Z yield



- Statistical uncertainty : ranging from 0.3 % to 1.2%
- Fine even-odd staggering (incl. at symmetry)
- Sharp increase at $Z = 50$
- Strong contribution of $Z = 54$
- Asymmetric/symmetric ratio $\rightarrow$ $E^{*} \approx 13 - 14\ MeV$

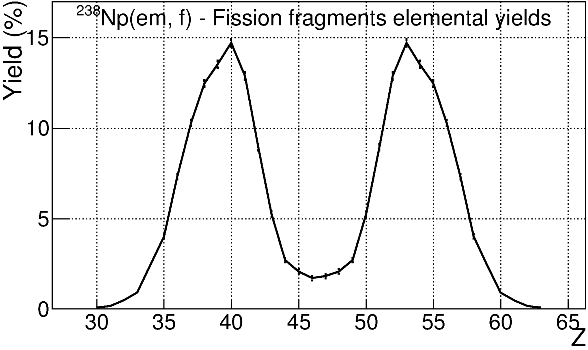


$Y_{Z_{FF}}(A)$

- A ↑
- A/Z gets closer to 132/50, *a.k.a.* ^{132}Sn
- ST1 gets more favorable

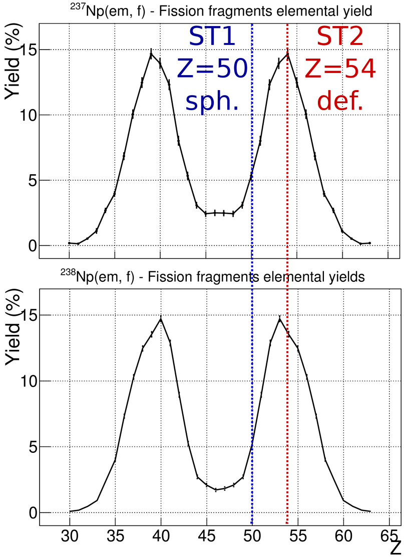
Z yield

SOFIA
Studies On FIssion with ALADIN



- Softer even-odd staggering
- Symmetric mode is populated
- Sharp increase at $Z = 50$
- Asymetric/symetric ratio $\rightarrow E^* \approx 13 - 14\ MeV$

Z yield : systematics



$Y_{Z_{FF}}(A)$

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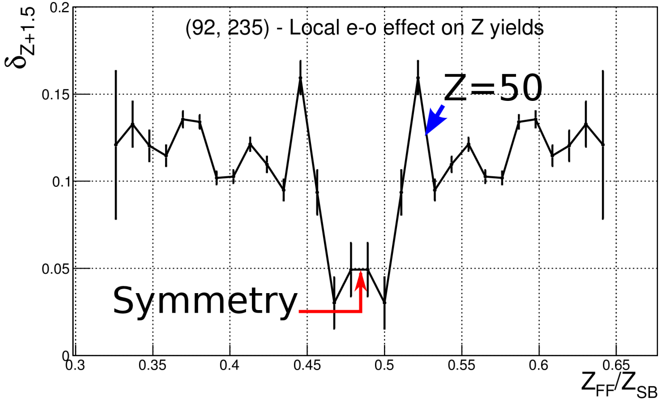
- ST1 gets more favorable

Z yield : e-o staggering



Local even-odd staggering vs Z for ^{235}U

- Very low staggering at symmetry
- Staggering increases with asymmetry

Z yield : Sum Up

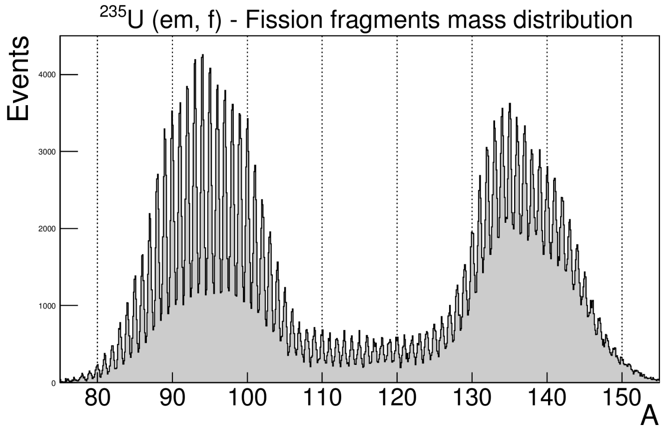
Z yield - Resolution

- No ambiguity on Z identification
- Measurement resolution is excellent
- High statistics lessens the uncertainty under 1%

Z yield - Physics

- No proton evaporation -> configuration at scission
- ST1 gains amplitude when the ratio A/Z comes closer to that of ^{132}Sn
- Even-odd staggering depends on the partition

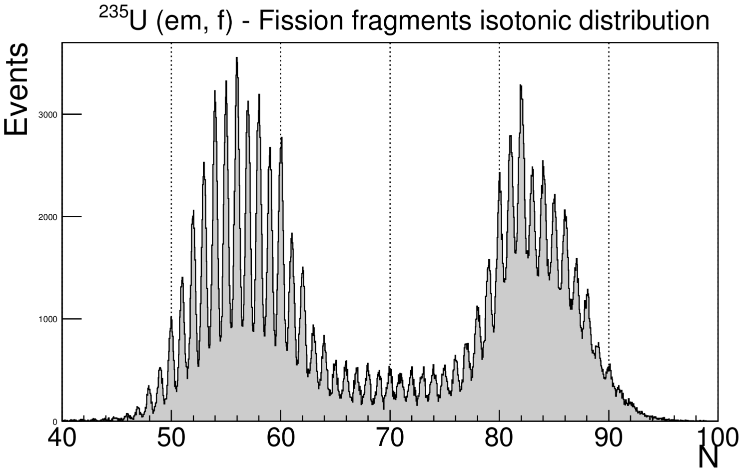
A distribution



Uncertainties

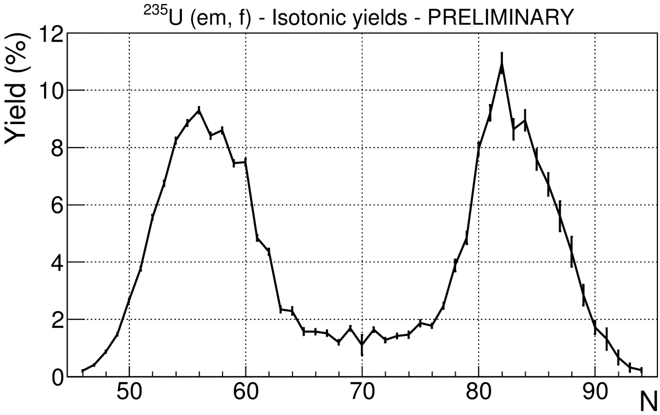
- Width of gaussians 0.58 – 0.75 *u.m.a. FWHM*
- Statistical uncertainty : 1.6 % to 3%

N Distribution



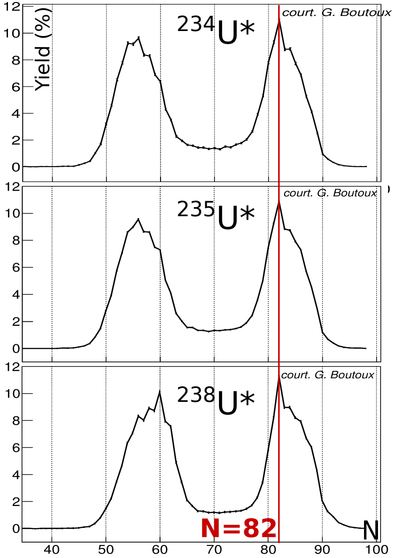
- $N = A - Z$
- Landmarks : even-odd staggering and $N = 82$

N Distribution



- After prompt neutron evaporation
- Signature of closed shell N=82

Isotonic yields : Systematics



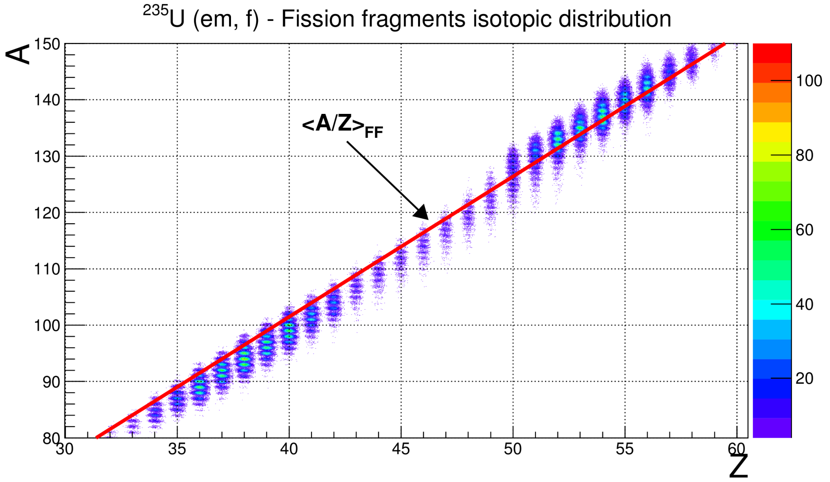
$Y_{N_{FF}}(A)$

- Heavy fragment plays a leading role at scission
- Even-odd staggering (incl. n evap.)

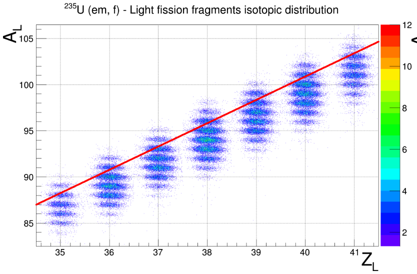
Isotonic yields : Sum Up

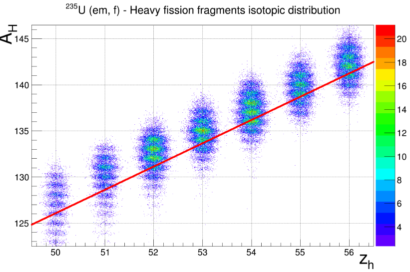
Isotonic yields

- From Z and A yield measurements
- After prompt neutron evaporation
- Yet, enriched with information on shells and magicity
- Shell $N = 82$ figures prominently
- Even-odd staggering over the full range of fission fragments,
  - Scission configuration, combined with
  - Neutron evaporation



235U (em, f) - Fission fragments isotopic distribution
A
150
140
130
120
110
100
90
80
30
35
40
45
50
55
60
Z
<A/Z>FF
100
80
60
40
20

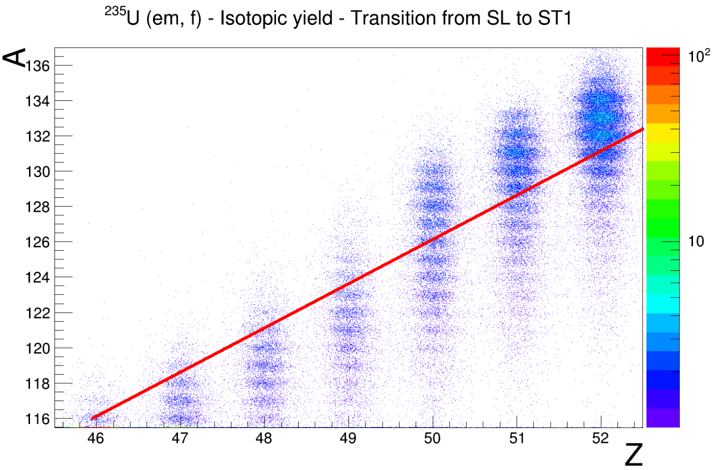




Very high resolution

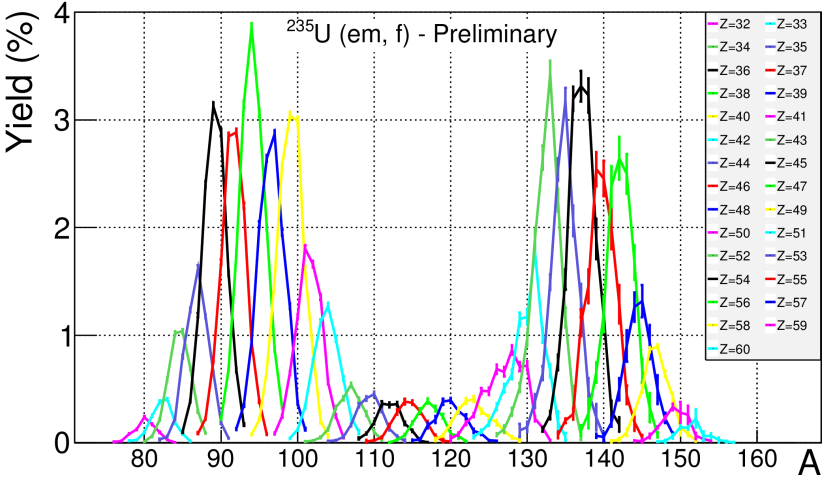
Heavy fragments are more demanding

Isotopic distribution



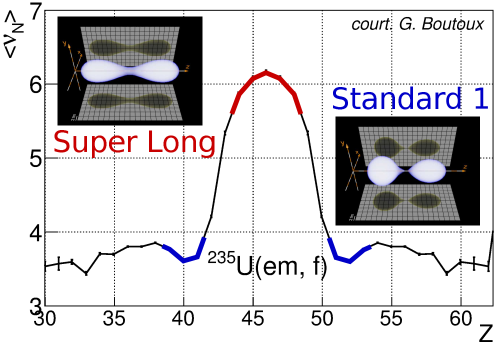
Sharp deviation from mean A/Z at transition $Z = 49$, $Z = 50$

Isotopic yields



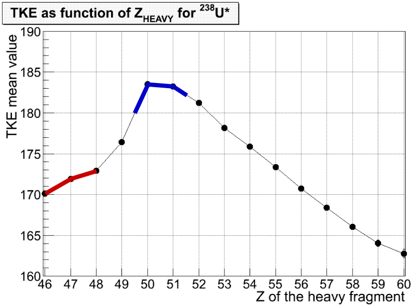
ν_n

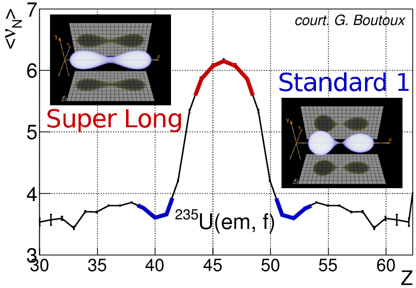
- Indirect neutron multiplicity measurement :
  $\nu_n = A - (A_L + A_H)$
- Made possible by excellent resolution on mass



- Mean value is coherent with ($E^* \approx 13 - 14\ MeV$)
- Fission modes are reflected on neutron multiplicity
  - High multiplicity for SL (highly deformed fragments)
  - Sharp drop at $Z = 50$ ST1
- Deformation plays prominently on ν
  - E_{def} relaxes into $E*$, released through n emission

TKE





Total Kinetic Energy

Closely related to the scission configuration :

- N, Z partition : coulomb parameter is $Z/A^{1/3}$
- Deformation

Court. G. Boutoux, N. Dubray

Conclusion

- Experiment in Aug. 2012
- For the very first time, both fragments are fully and simultaneously identified
- With unprecedented resolution
  - Paramount for the applications
- Over 80 nuclei
  - Overview on the nuclear landscape
- New experiment in September 2014
  - Many improvements : count better, count faster
  - Measure $^{236}U \approx ^{235} U + n$

SOFIA Collaboration

DE LA RECHERCHE À L'INDUSTRIE
cea

GSI

IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

CENBG

GANIL
spiral2
laboratoire commun CEA/DSM CNRS/IN2P3

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

UNIVERSIDADE
DE VIGO

AVANCEZ
1829
CHALMERS
UNIVERSITY OF TECHNOLOGY