Neutron multiplicities in the ^{236}U(γ,f) reaction

SOFIA: Studies On FIssion with Aladin

FIESTA 2017 Workshop

Santa Fe, September 17-22, 2017

L. Grente, J. Taïeb, A. Chatillon for the R^{3}B-SOFIA collaboration.

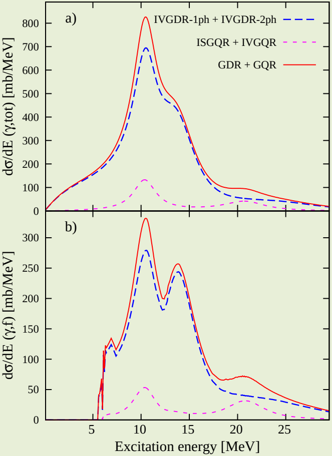
STUDIES ON FISSION WITH ALADIN

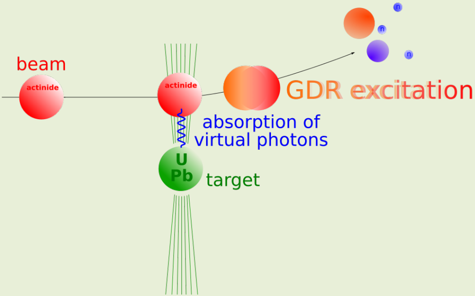
- CEA DAM/DIF, France
- IPNO, France
- CENBG, France
- GANIL, France
- GSI, Germany
- University of Santiago de Compostela, Spain
- University of Vigo, Spain
- Technical University of Chalmers, Sweden

Experimental method

- **Electromagnetic induced fission in inverse kinematics at relativistic energy**:
  $\Rightarrow$ same reaction mechanism than K.-H. Schmidth *et al.*
  $\Rightarrow$ fissioning nuclei accelerated up to 750 A.MeV at the GSI/FRS facility

Calculation for a 670A MeV ^{236}U beam on a ^{238}U target





a) $\langle E^* \rangle_{\gamma,tot} = 12.1$ MeV and $\sigma_{\gamma,tot} = 6.4$ b

b) **$\langle E^* \rangle_{\gamma,f} = 14.1$ MeV and $\sigma_{\gamma,f} = 2.9$ b**

^{236}U(γ,f) $\Leftrightarrow$ ^{235}U(n$_{8.5MeV}$,f)

Goals of the SOFIA experiment

PRIMARY GOAL : accurate measurement of fission yields

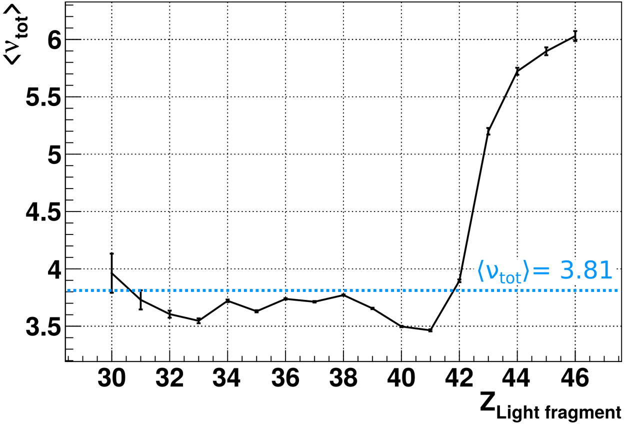
cf. Poster for experimental details and results on yields and TKE

Taking advantage of the specificity of the SOFIA set-up in which **nuclear charge** and **mass** of both fission fragments are measured in coincidence

- indirect measurement of the **total mean neutron multiplicity**
- from numerical treatment it is possible to extract:
  - ⇒ **Mass yields of the primary fragments**
  - ⇒ **Neutron multiplicity as function of the mass number of the primary fragments**
  - ⇒ done by Lucie GRENTE during her post-doc

Total neutron multiplicity as function of the nuclear charge

- Total neutron multiplicity (ν_{tot}) measured event by event
- ν_{tot} = A_{CN} - A_{FF1} - A_{FF2}



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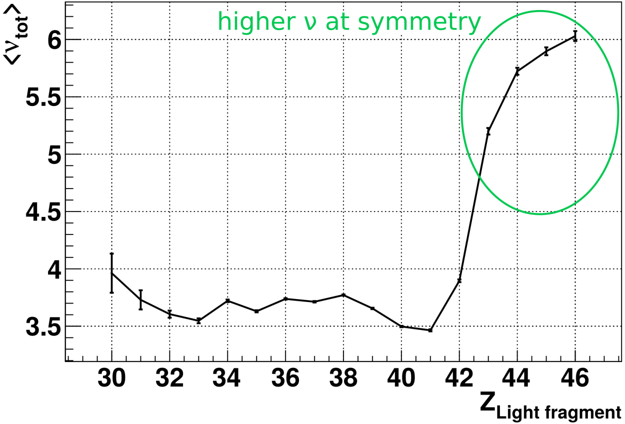
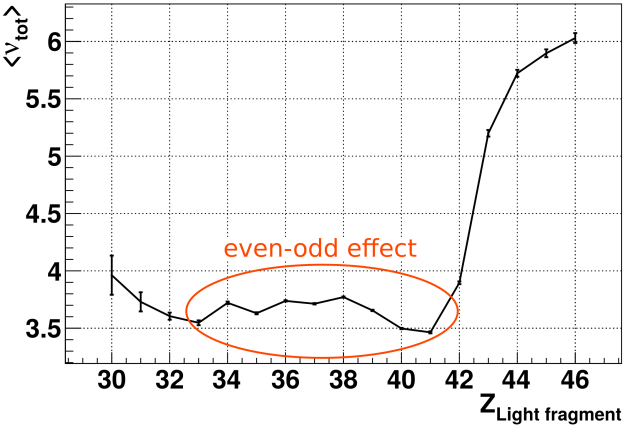
- Deformation energy converted into excitation energy



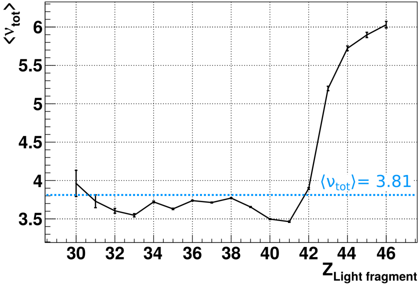
Total neutron multiplicity as function of the nuclear charge

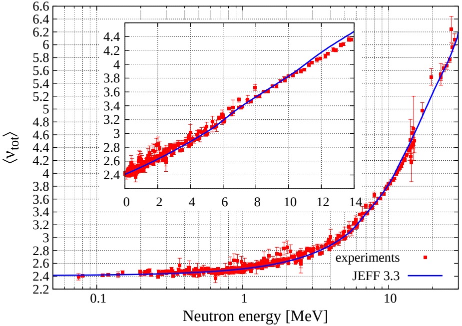
- Total neutron multiplicity (ν_{tot}) measured event by event
- $\nu_{tot} = A_{CN} - A_{FF1} - A_{FF2}$
- Deformation energy converted into excitation energy
- Q-value is higher in case of even-even splitting due to the proton pairing



Comparison of $\langle \nu_{tot} \rangle_{SOFIA}$ with evaluations and existing data

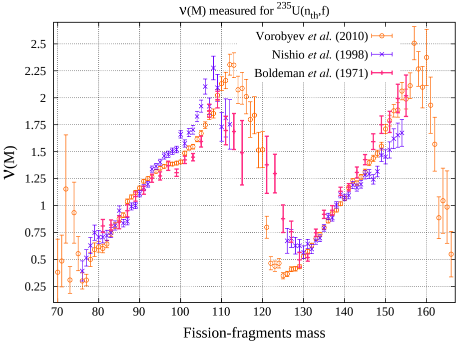
- SOFIA at $\langle E^* \rangle$=14.1 MeV
  - $\Rightarrow \langle \nu_{tot} \rangle_{SOFIA} = 3.81$ compared to $\langle \nu_{tot} \rangle_{th} = 2.45$
  - $\Rightarrow$ SOFIA data 4% above JEFF 3.3: question under discussion



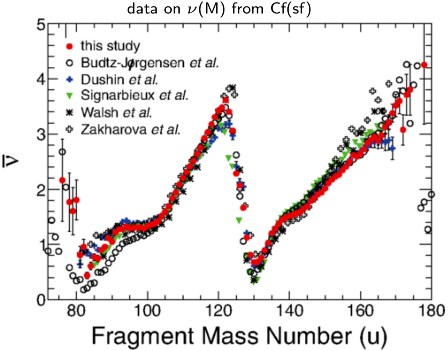


Existing measurement on the ⟨ν⟩(A)

- Mainly, data at thermal energy or for spontaneous fission
- Same trend between all data set
  - $\Rightarrow$ well-known sawtooth
  - $\Rightarrow$ shoulders at M $\sim$ 95 and M $\sim$ 140
- Slight discrepencies on the slope of the saw tooth
  - $\Rightarrow$ uncertainties on the FF energy losses in the target



J. W. Boldeman *et al.* Aust. J Phys. **24**, 821 (1971)
K. Nishio *et al.* NPA **632**, 540 (1998)
A. S. Vorobyev *et al.* EPJ Web. Conf. **8**, 03004 (2010)



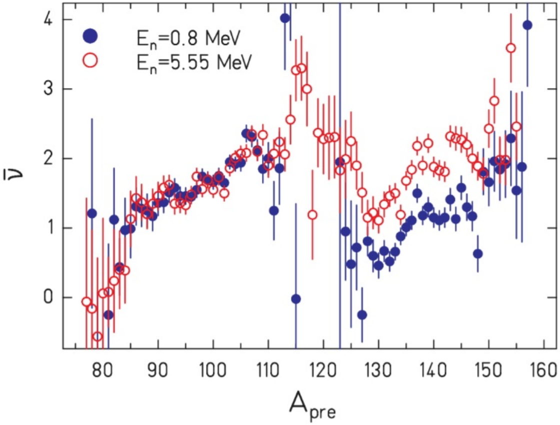
A. Göök *et al.* PRC **90**, 064611 (2014)

Evolution of $\langle \nu \rangle$(A) with excitation energy

- one measurement on ^{237}Np(n,f) at two neutron beam energies
- large uncertainties

  $\Rightarrow$ difficult experiment due to the drop of fission cross section and neutron flux
- increase of the multiplicity with E^* for the heavy fission fragments

Navqi *et al.*, PRC **34**, 218 (1986)



From SOFIA: data for ^{236}U(γ,f) for 1^{st}-chance only

- High statistics data with a good mass resolution for ^{234,235,236}U(γ,f)
- Removal of the contribution of 2^{nd} and 3^{rd} fission chances

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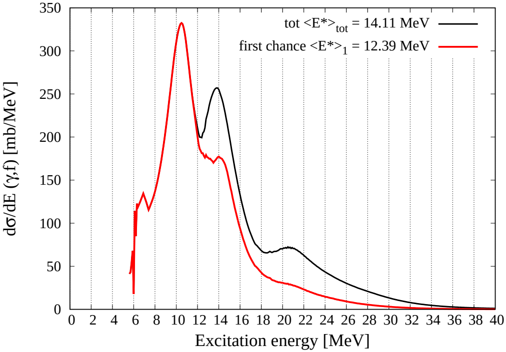
- Removal of the contribution of 2nd and 3rd fission chances
- From GEF : evaluation of the different fission chances contribution

Fission chance	Probability (%)
1st	77.8
2nd	17.0
3rd	4.8
4th	0.4

$$\langle E^* \rangle_{1^{st}chance} = 12.4 \text{ MeV}$$



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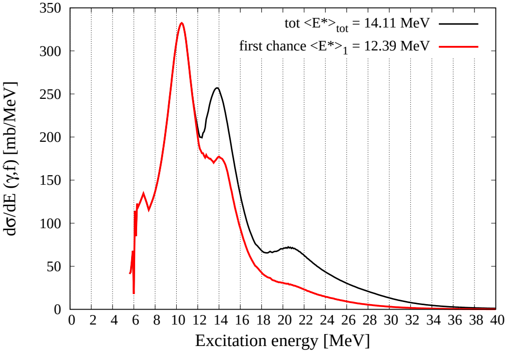
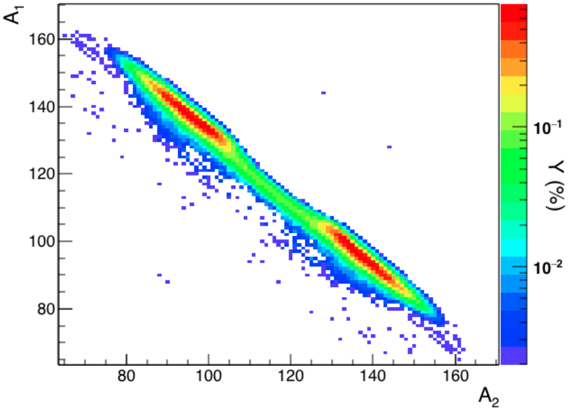


- Experimental results for 1st chance only
  $\Rightarrow$ $\langle \nu_{tot} \rangle_{1^{st}\,chance} = 3.66$ to compare with $\langle \nu_{tot} \rangle_{all\,chances} = 3.81$
  $\Rightarrow$ all the fission yields
  $\Rightarrow$ and ...

Mass correlation of both FF from ^{236}U(γ,f) - 1^{st} chance only



- Each square represents the **correlated mass yield Y(A_1,A_2)**
- For each fragment of mass A_1: probabilities to be produced with fragments of mass A_2
- For each of these partners of mass A_2: probabilities to be produced with fragments of mass A_1
- Coupled system in mass which carries out the information on the neutron multiplicity
  $\Rightarrow$ A_i = 236 - A_j - $\nu_{tot(i,j)}$
  $\Rightarrow$ **coupled system in neutron multiplicity**

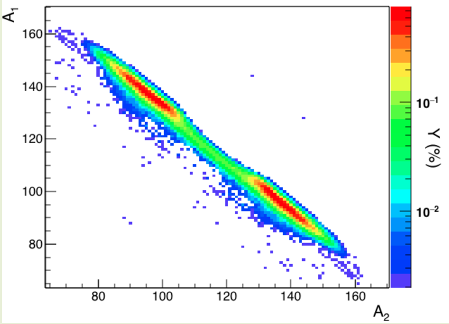
The coupled system in equation

- M: mass of the fragment before neutron emission
- A: mass of the fragment after neutron emission
- ν: neutron multiplicity per fragment of mass A
- X(M): mass yields before neutron emission
- $P^M(\nu)$: probability for a primary fragment of mass M, to emit ν neutrons

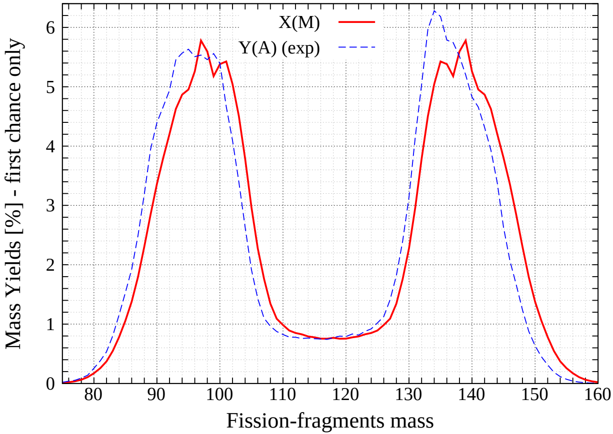
Measured correlated mass yield $Y(A_1,A_2)$

$$Y(A_1, A_2) = \sum_{\nu_1=0}^{236-A_1-A_2} P^{M_1}(\nu_1) P^{M_2}(\nu_2) X(M_1)$$

- **hyp 1: $P^{M_i}(\nu_i)$ gaussian**
  $\Rightarrow$ 3 sets of independant parameters
  $\langle\nu\rangle$(M), σ(M), X(M_i)
- **hyp 2: $\langle\nu\rangle$(M), σ(M) Fourier series**
  $\Rightarrow$ cut in the high frequency domain
- **χ^2 minimization using MIGRAD**
  $\Rightarrow$ from the CERN library MINUIT



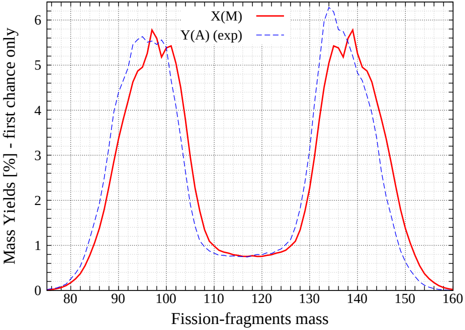
Pre- and post neutron emission mass yields for the 1^{st}-chance fission

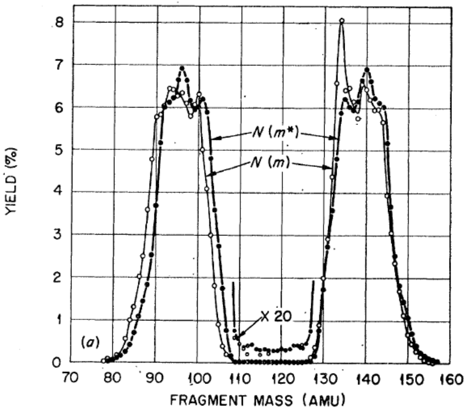


- subtraction of higher chances on post neutron emission mass yields
- minimization procedure gives the primary fission fragments mass yields
- important results for further comparison with models
  - ⇒ first fission chance only
  - ⇒ fission fragment yields before neutron emission

Comparison of pre neutron emission mass yields with thermal data

- at symmetry: higher valley
  $\Rightarrow$ due to the higher excitation energy ($\langle E^* \rangle_{SOFIA,1^{st}\,chance}$=12.4 MeV)
- at asymmetry: same structure of the primary fragment mass yields
  $\Rightarrow$ shift of one mass

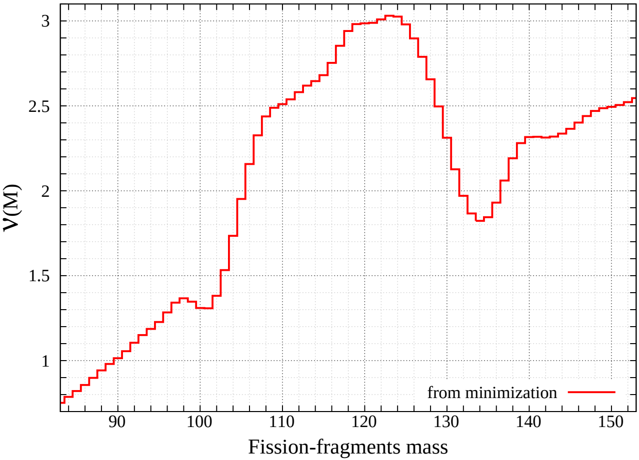




H. W. Schmitt *et al.*, Phys. Rev. **141**, 1146 (1966)

⟨ν⟩(M): result from the minimization procedure

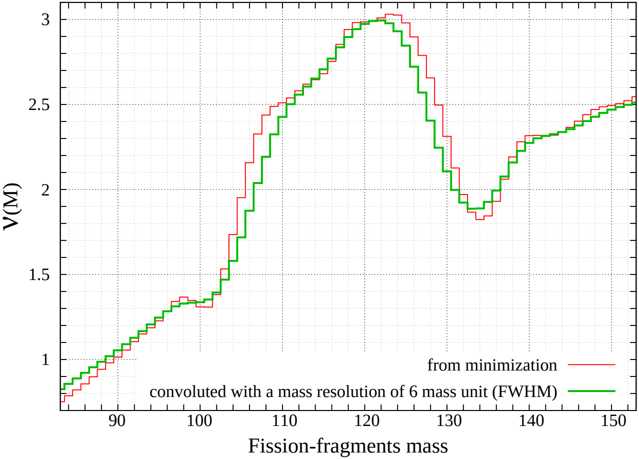
direct result from the minimization procedure



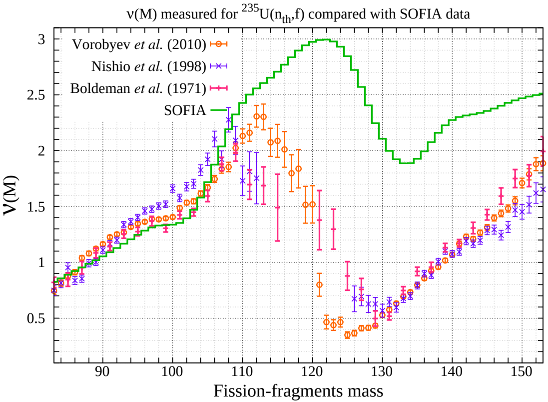
⟨ν⟩(M): result from the minimization procedure

direct result from the minimization procedure

deterioration of the mass resolution to compare with data obtained in ^{235}U(n_{th},f)



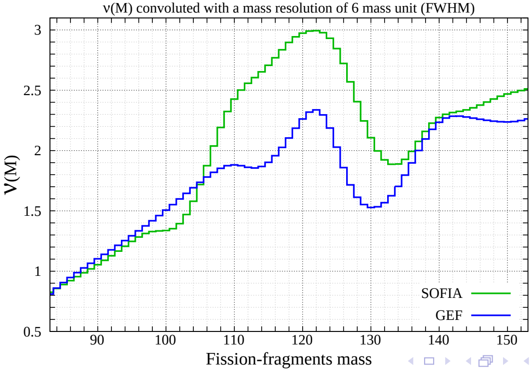
$\langle\nu\rangle$(M) comparison with ^{235}U(n$_{th}$,f)



- **in the light fragments, similar ν(M) at two different excitation energies**
- similar shoulders at M $\sim$ 95 and M $\sim$ 140
- from SOFIA data: $\langle\nu\rangle_{LIGHT}$=1.40, $\langle\nu\rangle_{HEAVY}$=2.26 $\langle E^*\rangle_{1^{st}\,chance}$=12.4 MeV
- from Nishio *et al.*: $\langle\nu\rangle_{LIGHT}$=1.42, $\langle\nu\rangle_{HEAVY}$=1.01 thermal neutrons
- **additional excitation energy is going in the heavy fission fragment**

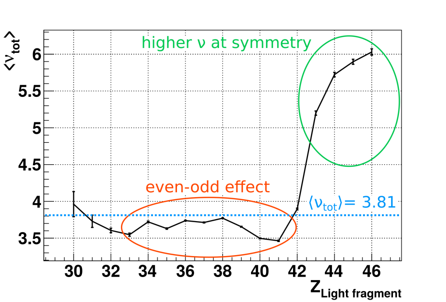
Energy sorting hypothesis

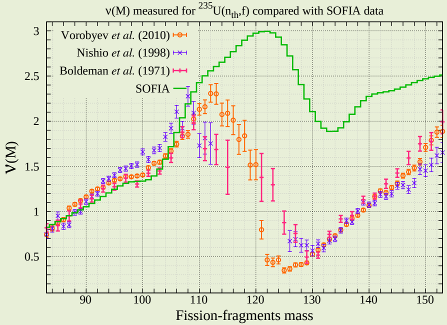
- K.-H. Schmidt and B. Jurado
  - ⇒ Phys. Rev. Lett. **104** 212501 (2010)
  - ⇒ Phys. Rev. C **83** 061601(R) (2011) / Phys. Rev. C **84** 059906(E) (2011)
  - ⇒ Phys. Rev. C **83** 014607 (2011)
- fission described with a constant temperature level density: $T \propto A^{-2/3}$
- **at scission, intrinsic excitation energy transferred from the fragment with the higher temperature (light) to the fragment with the lower temperature (heavy)**



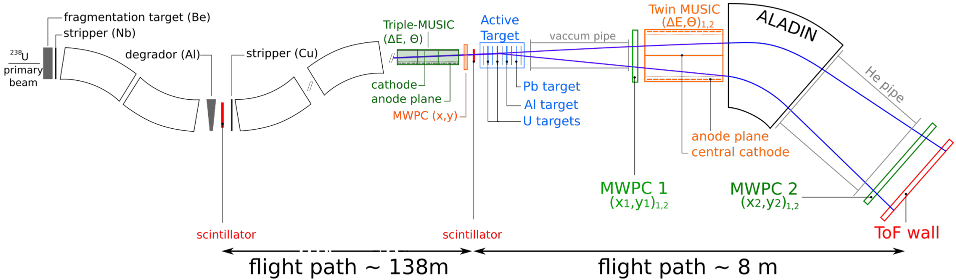
- 2 experiments with different fissioning nuclei studied
  - ⇒ Isotopic identification of fissioning nucleus and both fission fragments
  - ⇒ High statistics data taken for ^{234,235,236}U
  - ⇒ Electromagnetic induced fission
  - ⇒ $\langle E^* \rangle_{SOFIA}$=14.1 MeV and $\langle E^* \rangle_{SOFIA,1^{st}chance}$=12.4 MeV
- Thanks to the precision reached: results on prompt neutron multiplicity
  - ⇒ **Average total prompt neutron multiplicity**
  - ⇒ **Prompt neutron multiplicity per mass of primary fragment**

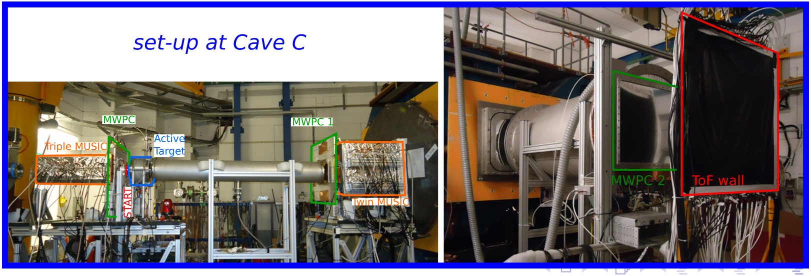
Prompt neutron multiplicity in ^{236}U(γ,f) studied with SOFIA





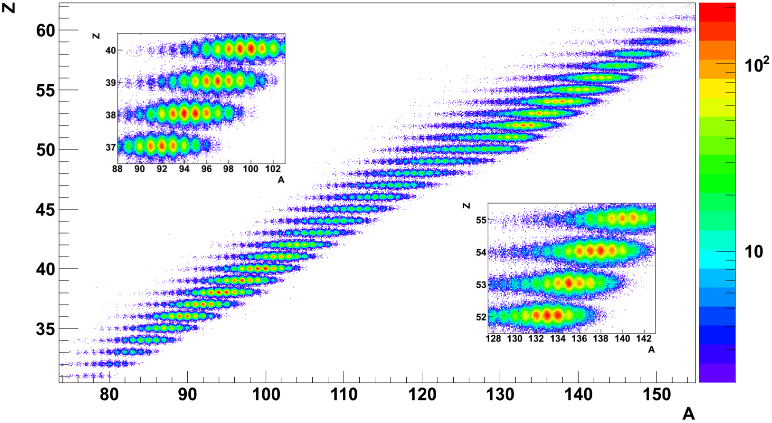
Schematic drawing of the set-up built in October 2014





Result from SOFIA: Isotopic distribution of the FF from ^{236}U(γ,f)

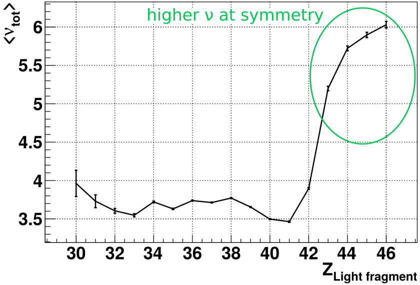
- Mass resolution ΔA = 0.55 to 0.8 mass unit FWHM
- Charge resolution ΔZ = 0.31 to 034 charge unit FWHM
- Fission fragments after prompt neutrons evaporation and before β^- decay

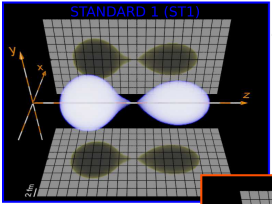


⇒ starting point to extract the average total prompt neutron muliplicity

$\langle \nu_{tot} \rangle (Z)$ as a signature of the fission modes

- Observation of higher multiplicity at symmetry
  - $\Rightarrow$ Super-Long (SL) fission mode: deformed configuration at scission
  - $\Rightarrow$ evaporation of neutrons by the fragments



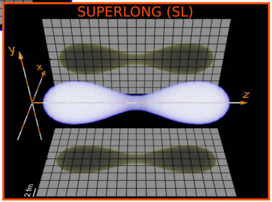


SCISSION CONFIGURATION

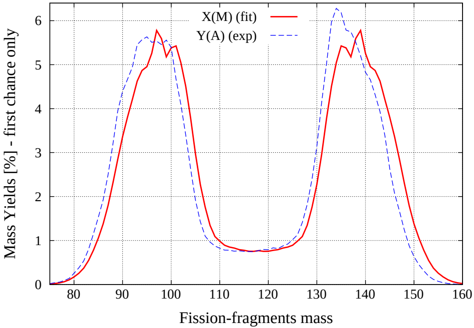
total nucleon density
^{238}U case

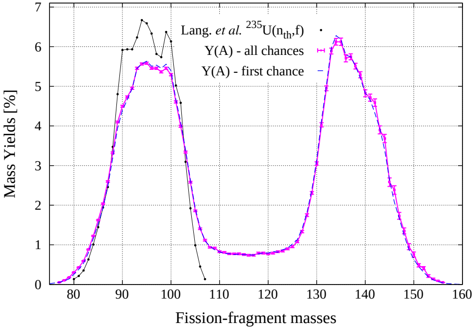
static HFB calculation,
Gogny D1S

courtesy of N. Dubray
(CEA,DAM,DIF)



Mass yields


X(M) (fit)
Y(A) (exp)
Mass Yields [%] - first chance only
Fission-fragments mass
0
1
2
3
4
5
6
80
90
100
110
120
130
140
150
160


Lang. et al. 235U(nth,f)
Y(A) - all chances
Y(A) - first chance
Mass Yields [%]
Fission-fragment masses
0
1
2
3
4
5
6
7
80
90
100
110
120
130
140
150
160