Probing Fission Dynamics using Fission Fragment Spectroscopy

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Nuclear Fission

- ✓ **Exothermic dynamical process**
- ✓ **Compound Nucleus shape evolution –**

  SADDLE ➡ SCISSION points
- ✓ **Collective rearrangement of nucleonic matter**
- ✓ **Emission of Prompt γ and Neutrons**

Complementary Fragments (FF1 & FF2)

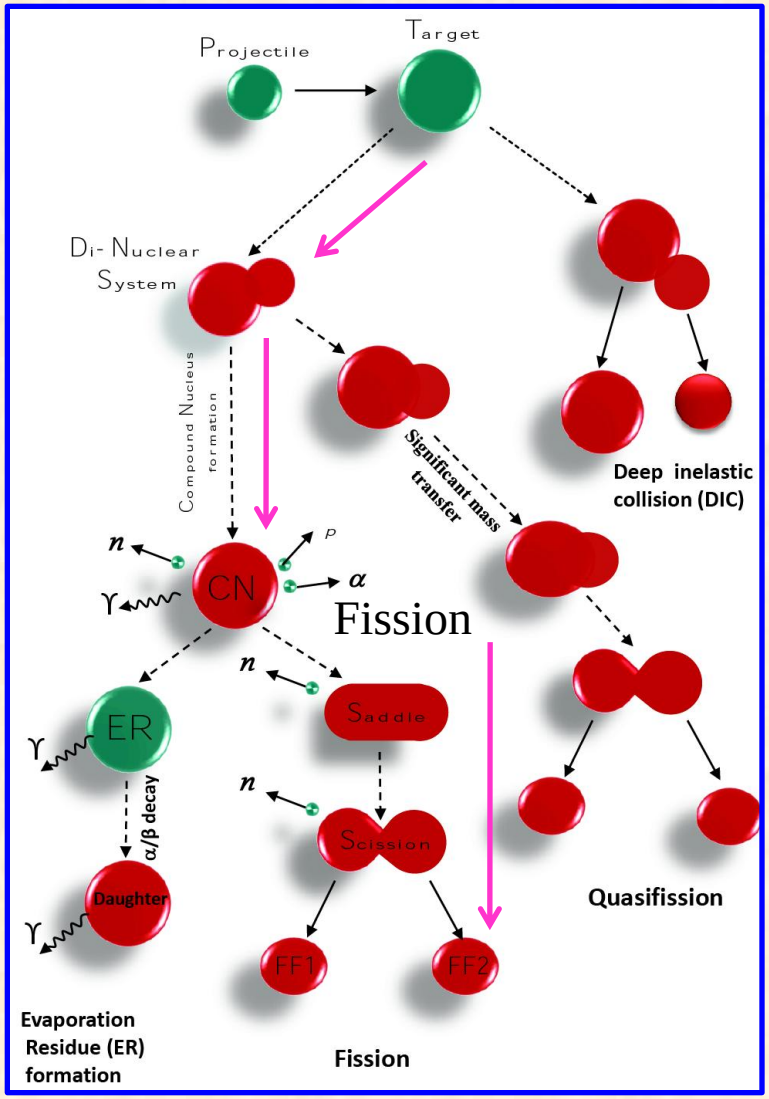
(*based on conservation of nucleons*)

$$\Delta E = (1/5)\ \varepsilon^2\ (2a_s A^{2/3} - a_c Z^2 A^{-1/3})$$

Prompt γ-spectroscopy:

◆

Fission Dynamics



Courtesy: PhD Thesis of S. Gupta, HBNI (2020)

Experimental Details

- ✓ Six Compton suppressed Clover detectors and one LEPS detector
  - 4 were at 90°, 2 were at 125°, LEPS was at 40°
- ✓ Self-supporting ^{232}Th target of thickness ≈ 25 mg/cm^2
- ✓ 30 MeV α particle beam; 6 days of experiment
- ✓ DSP based DAQ, consisting of 250 MHz 12-bit PIXIE-16 digitizers
- ✓ About 3.3 × 10^8 γ–γ coincidences were recorded

INGA @ VECC, Kolkata, India

Scenarios from Correlated Fission Fragments(FF):

Correlated Fragments

$$\alpha + {}^{232}\mathrm{Th}(Z = 90) \rightarrow {}^{236}\mathrm{U}^*(Z=92) \rightarrow \mathrm{FF1}(A_1,Z_1) + \mathrm{FF2}(A_2,Z_2)$$

$Z_1 + Z_2 = Z = 92$ $\quad$ $A_1 + A_2 = 236$

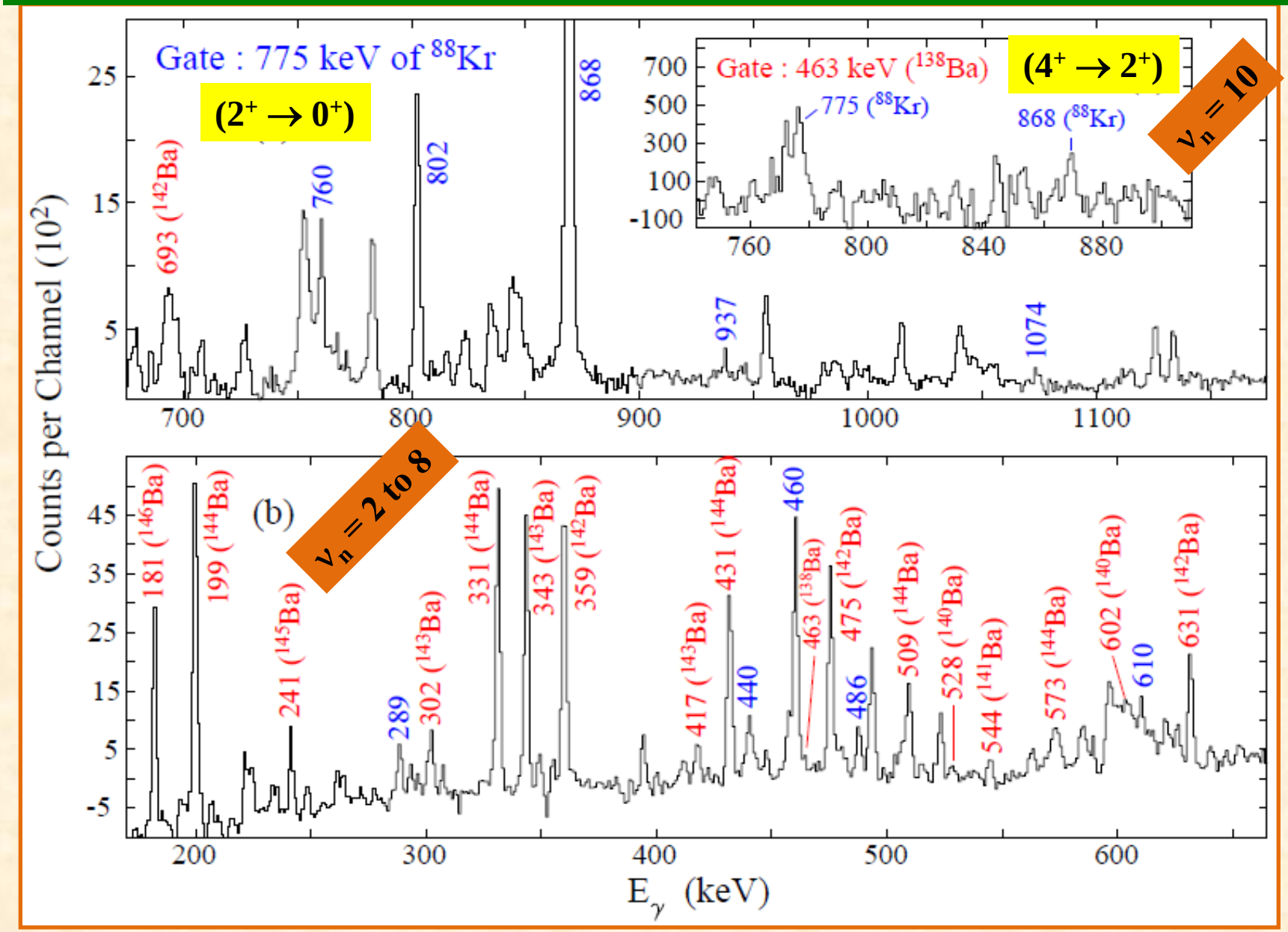
$Z_1 = Z_2 = Z/2 = 46$ (Pd) $\quad$ $A_1 = A_2 = A/2 = 118$ (Symmetric Fission)

$Z_1 < Z_2$ (General Case) $\quad A_1 < A_2$ (General Case) (Asymmetric Fission)

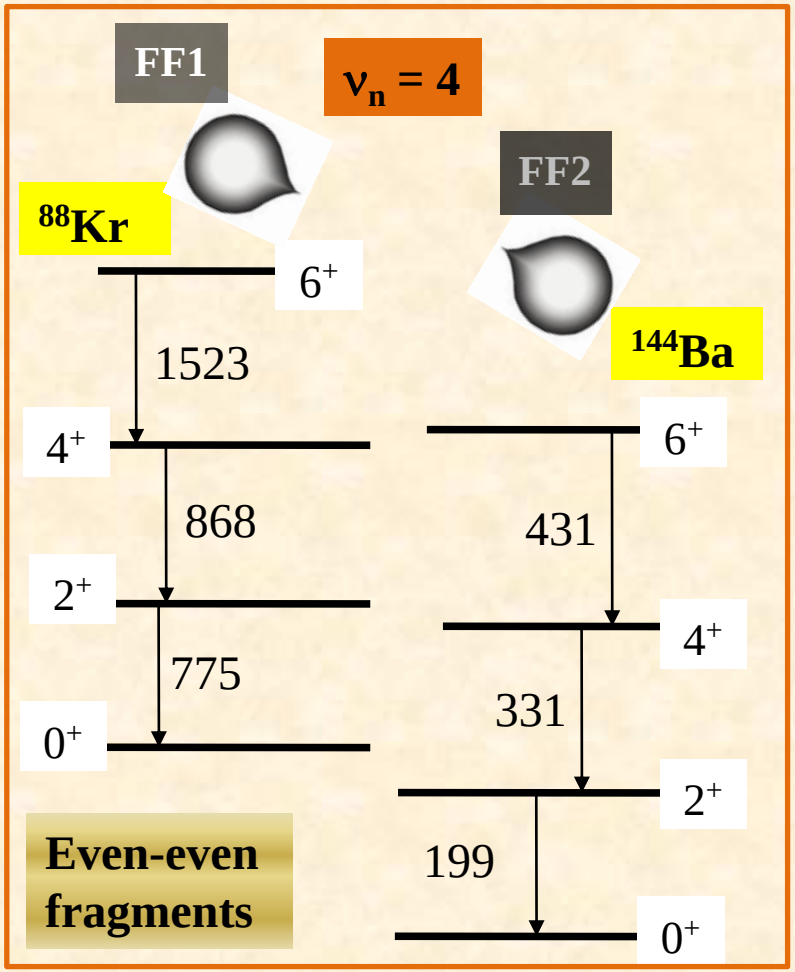
$A_1 + A_2 + \nu_n = 236$ $\quad$ ν_n : number of prompt neutrons (10)

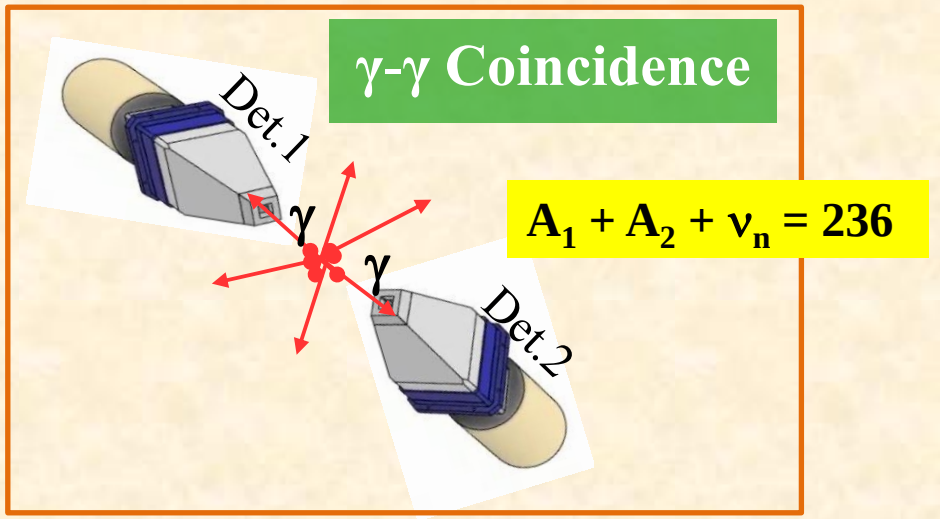
Coincidence spectra from correlated fission fragment pairs :

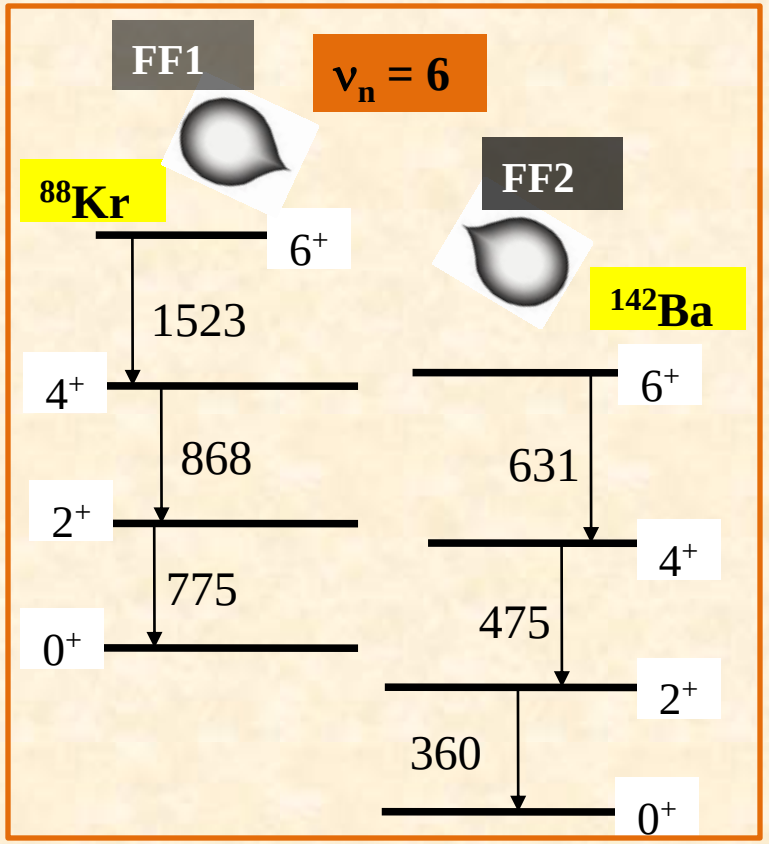
$A_1 + A_2 + \nu_n = 236$ Kr (FF1) and Ba (FF2)



Analysis Procedure: Extraction of Fragment Yields







Detail Analysis Procedure:
Aniruddha Dey *et al.*,
Phys. Rev. C 103 (2021) 044322

Necessary Corrections

Fission Fragment Spectroscopy (FFS)

Low-lying Isomers

Precursors β-decay

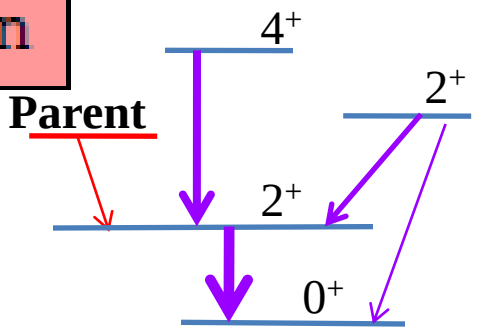
Non-yrast feedings

Internal Conversion

Direct side-feedings

γ feeding

β-feeding



✓Fragment nucleus produce directly from fission: Genuine event

✓Parent nuclide β-decays to the concerned fragment nucleus : Bias

Correction Measures:

(a)Efficiency correction for both the gated (FF1) and observed (FF2) transitions

(b) Correction due to internal conversion phenomena

[~1% (^{118}Cd) to 74%(^{150}Ce)]

Z = 48 **Z = 58**

(c) Correction due to isomeric level (no need!)

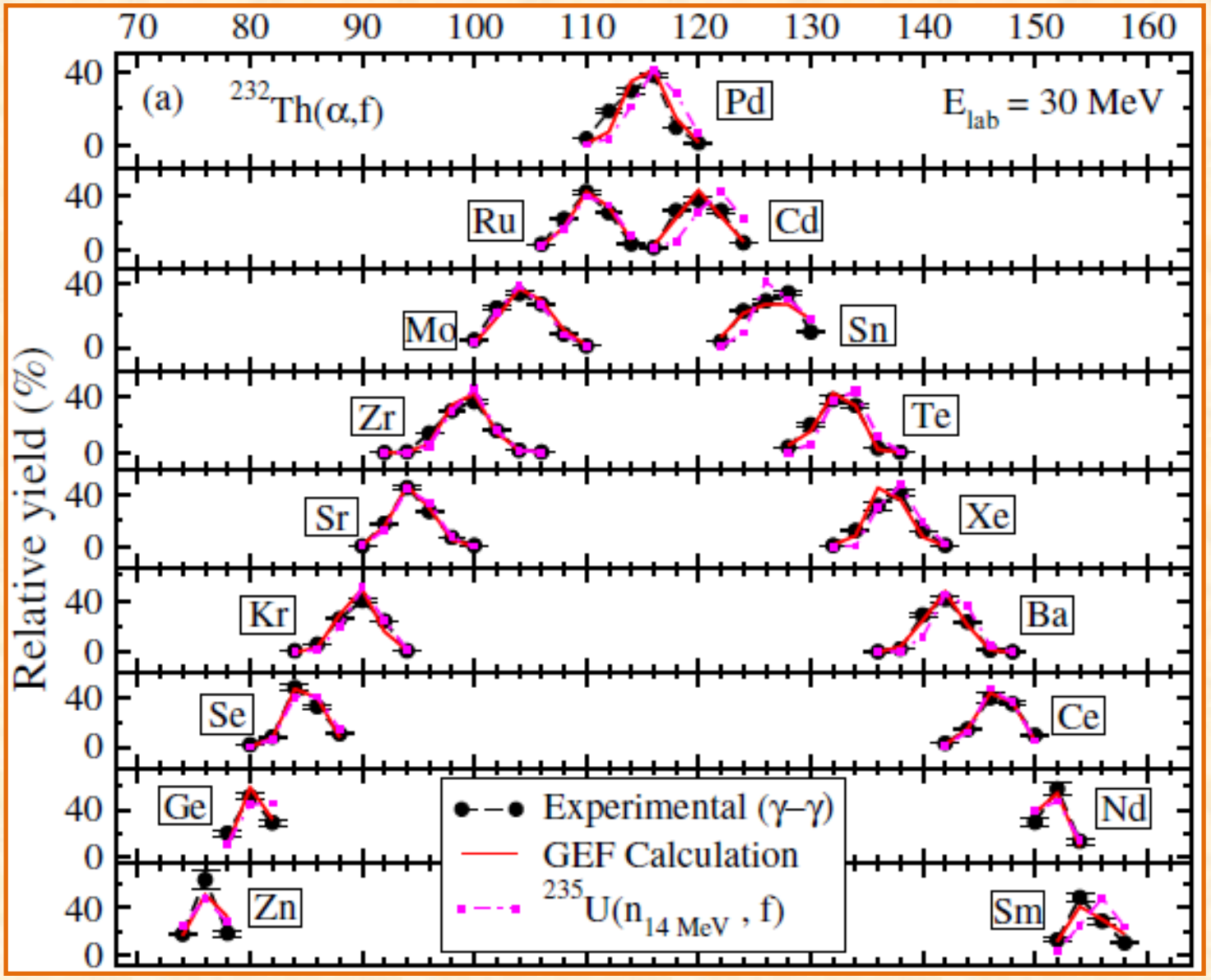
(d) Correction from Precursors' Beta-decay

[~ 2% (^{86}Se) to 98%(^{92}Zr)]

(e) Correction due to discrete side-feeding

[~13% (^{98}Zr)]

Experimental Results: Relative coincidence isotopic yield distribution



✓9 complementary FF pairs

✓89 number of even-even fragments

✓β_2 ~ 0.07 (^{128}Sn) to 0.42 (^{100}Sr)

✓N/Z = 1.30 (^{92}Zr)

✓N/Z = 1.65 (^{138}Te)

α + ^{232}Th at 30 MeV

E_{ex} = 21.5 MeV

surrogate

^{1}n + ^{235}U at 14 MeV

E_{ex} = 20.5 MeV

Aniruddha Dey *et al.*, Phys. Letts. B 825 (2022) 136848

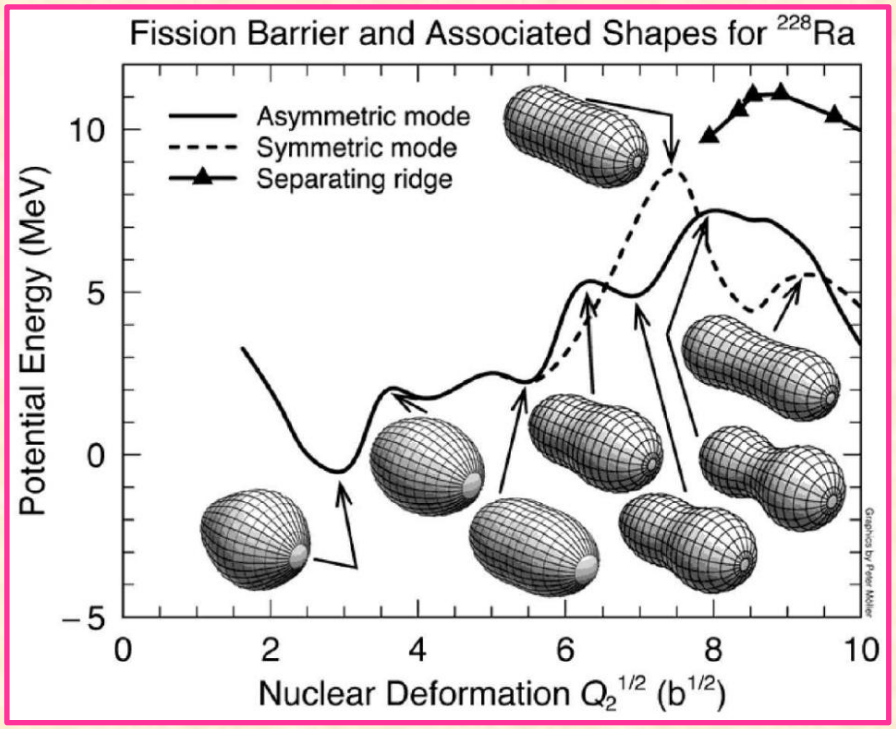
✓Shell Effect (SE)

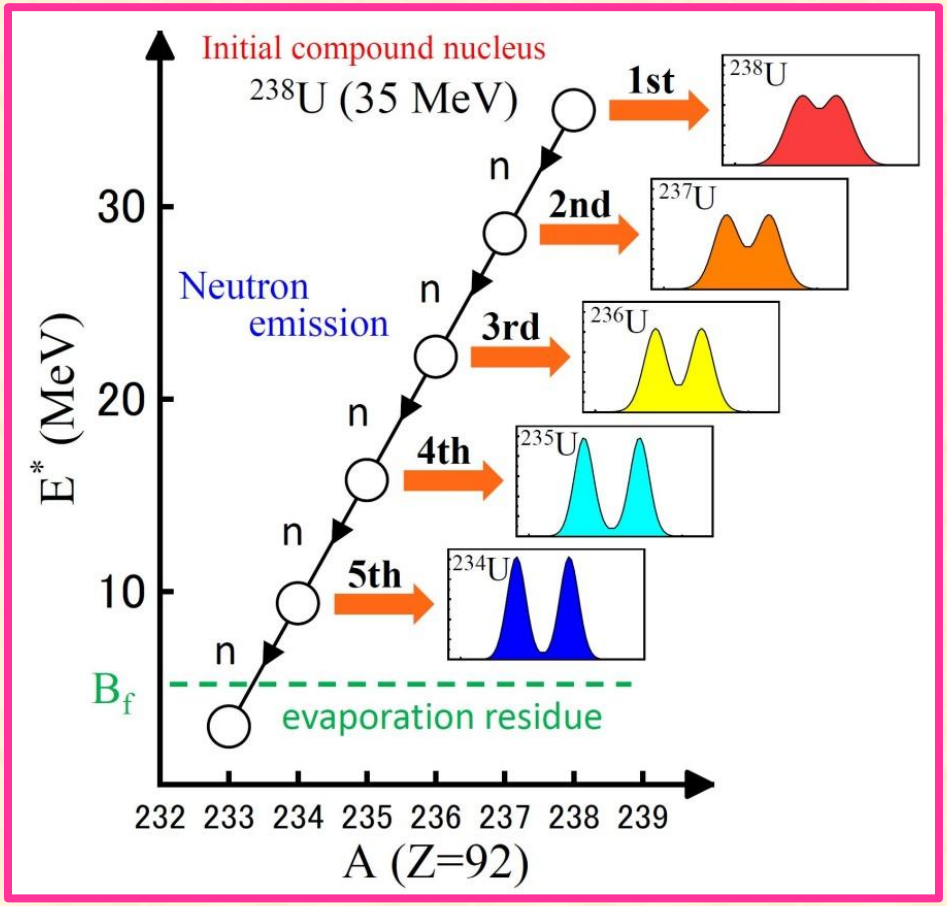
✓Multi-Chance Fission (MCF)

α + ^{232}Th @ 30 MeV

E_{ex} = 21.5 MeV

- Influence of Shell-Structural Effect
- Multi-Modal fission channels
- High Energy – Low SE; High MCF
- Low Energy – Low MCF; High SE



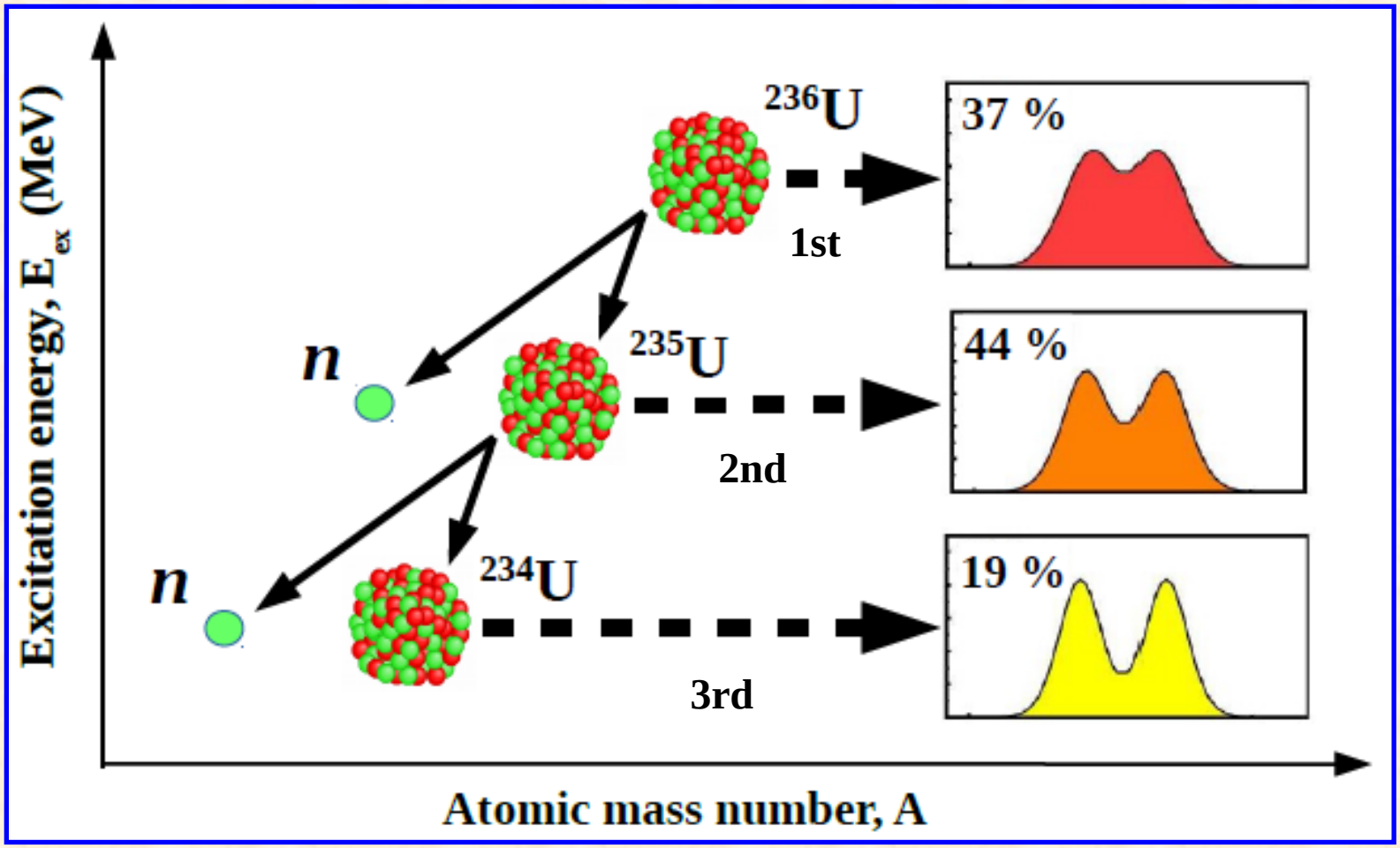


K.Hirose *et al.*, PRL 119, 222501 (2017)

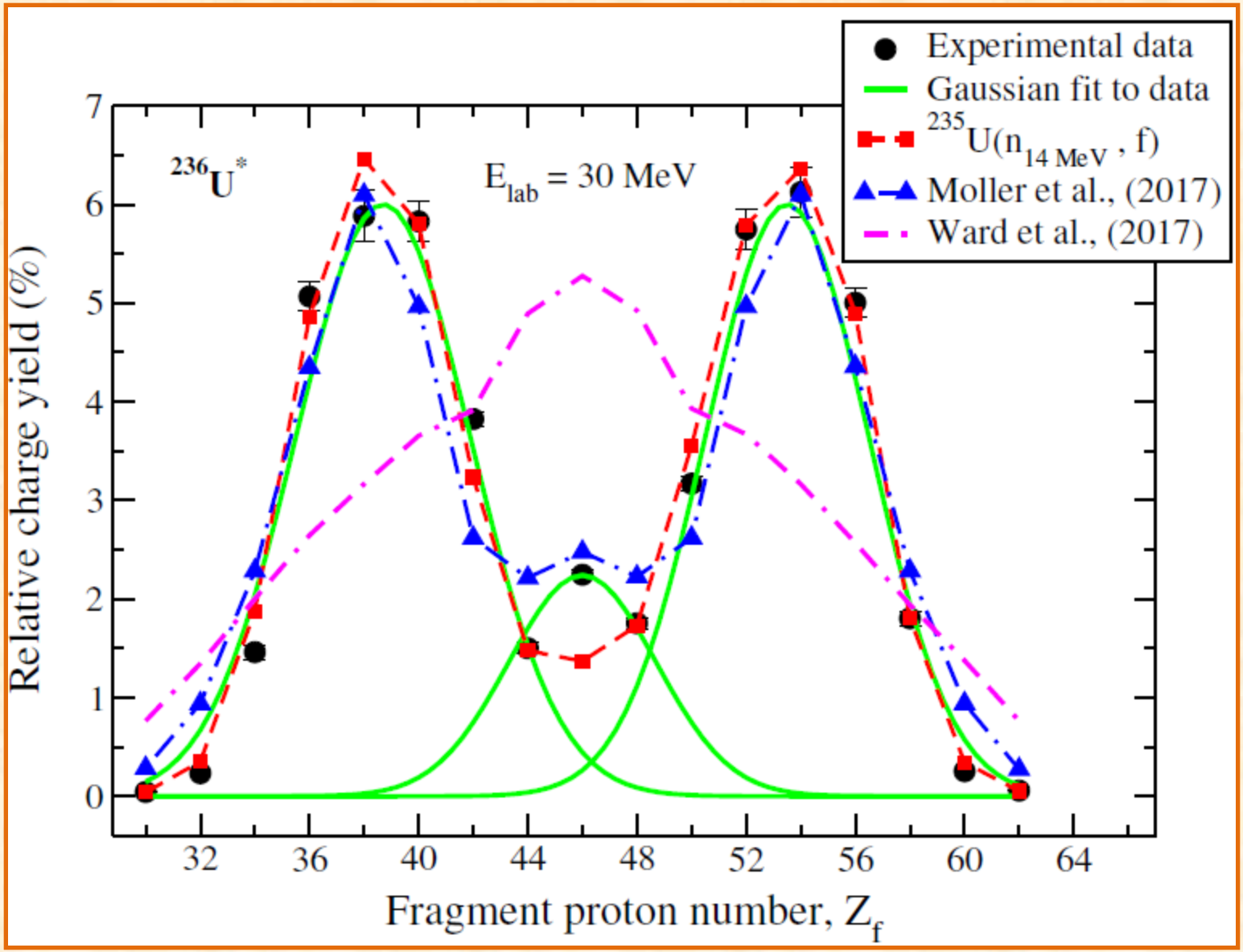
P.Moller *et al.*, Nature 409, 785 (2001)

Multichance fission probability: Calculated following GEF

$\alpha + {}^{232}\mathrm{Th}$ @ 30 MeV $\quad E_{ex} = 21.5$ MeV



Experimental Results: Relative charge yield distribution



Symmetric fission: 16%
Asymmetric fission: 84%

Ward *et al.*

First Chance Fission

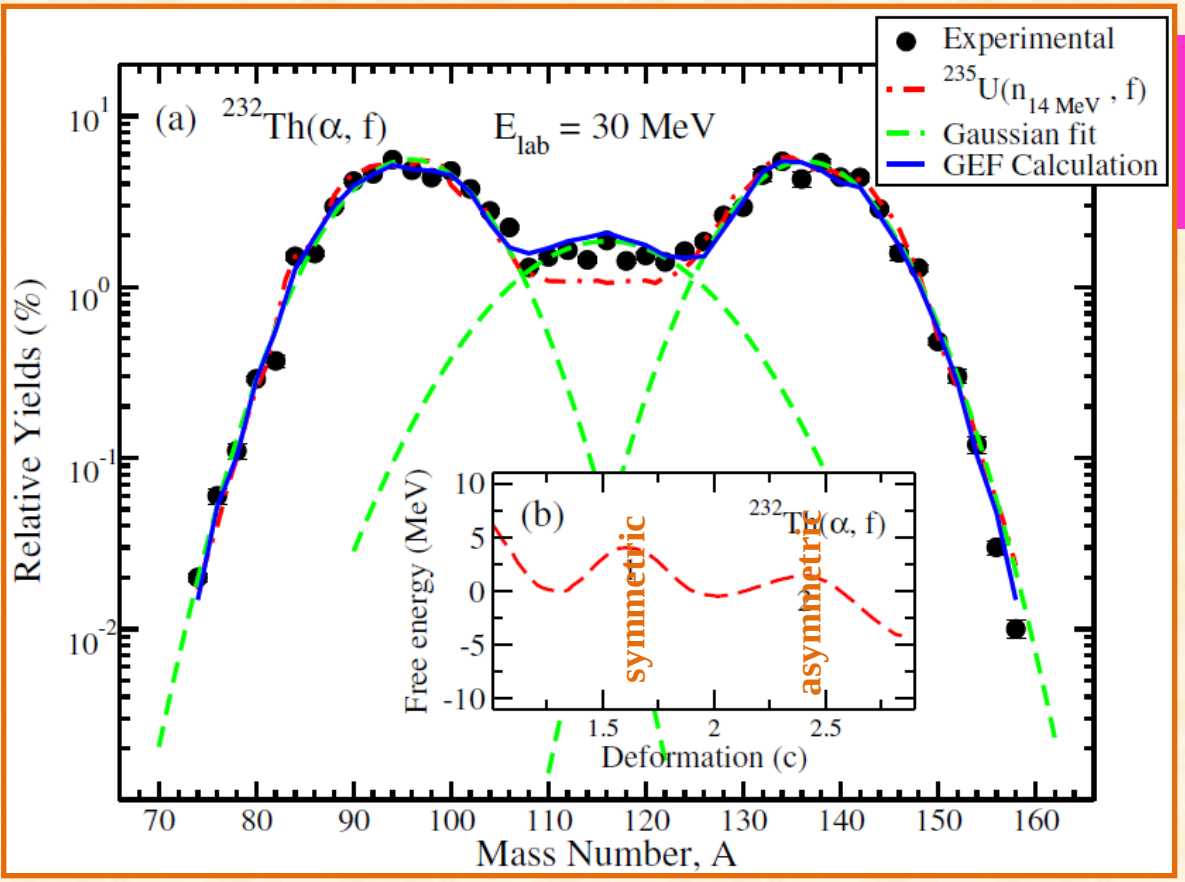
Moller *et al.*

Multi Chance Fission

Symmetric partition: (Pd-Pd) & (Ru-Cd)

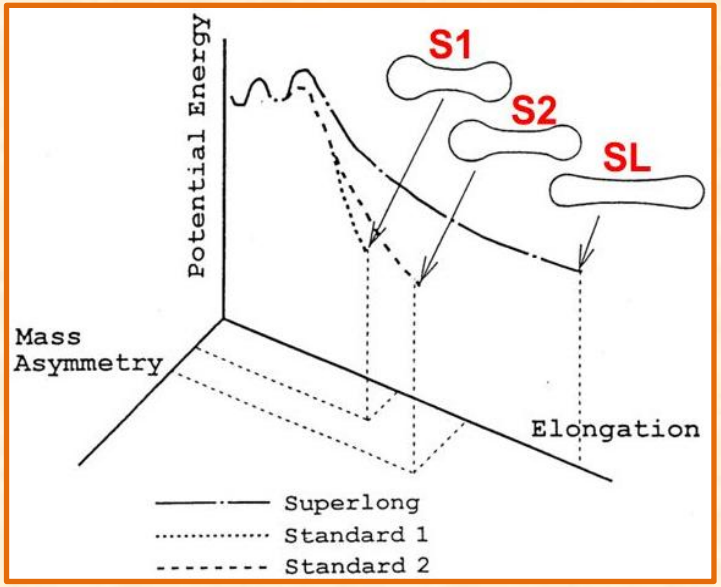
Importance of Multi-chance fission

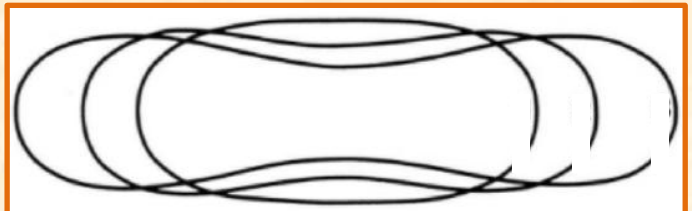
Experimental Results: Mass yield distribution profile



✓Covers A = 74 – 158 mass range
✓Persistence of two Compound Nucleus modes of fission

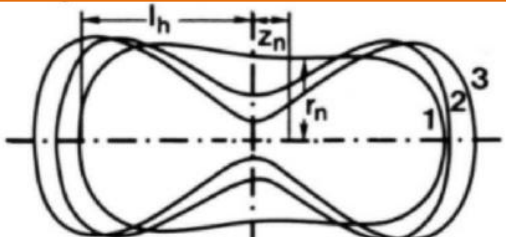
Brosa modes





Super-long Mode (SL)

(Symmetric Mode)



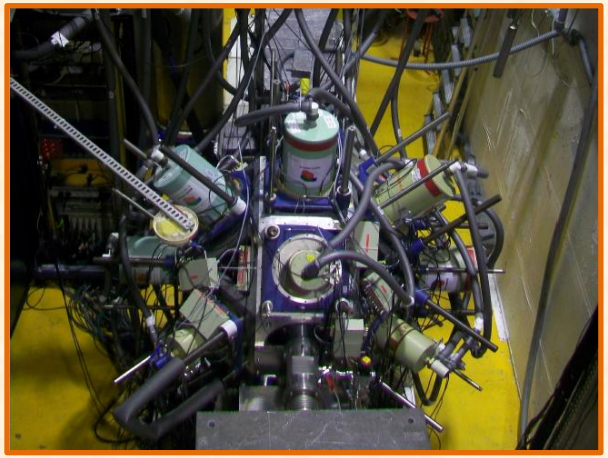
Standard Mode (S1, S2)

(Asymmetric Mode)

❖Aniruddha Dey *et al.*, PLB 825 (2022) 136848

❖Brosa *et al.*, Phys. Rep. 197 (1990) 167

❖ A. Chaudhuri *et al.*, PRC 91 (2015) 044620

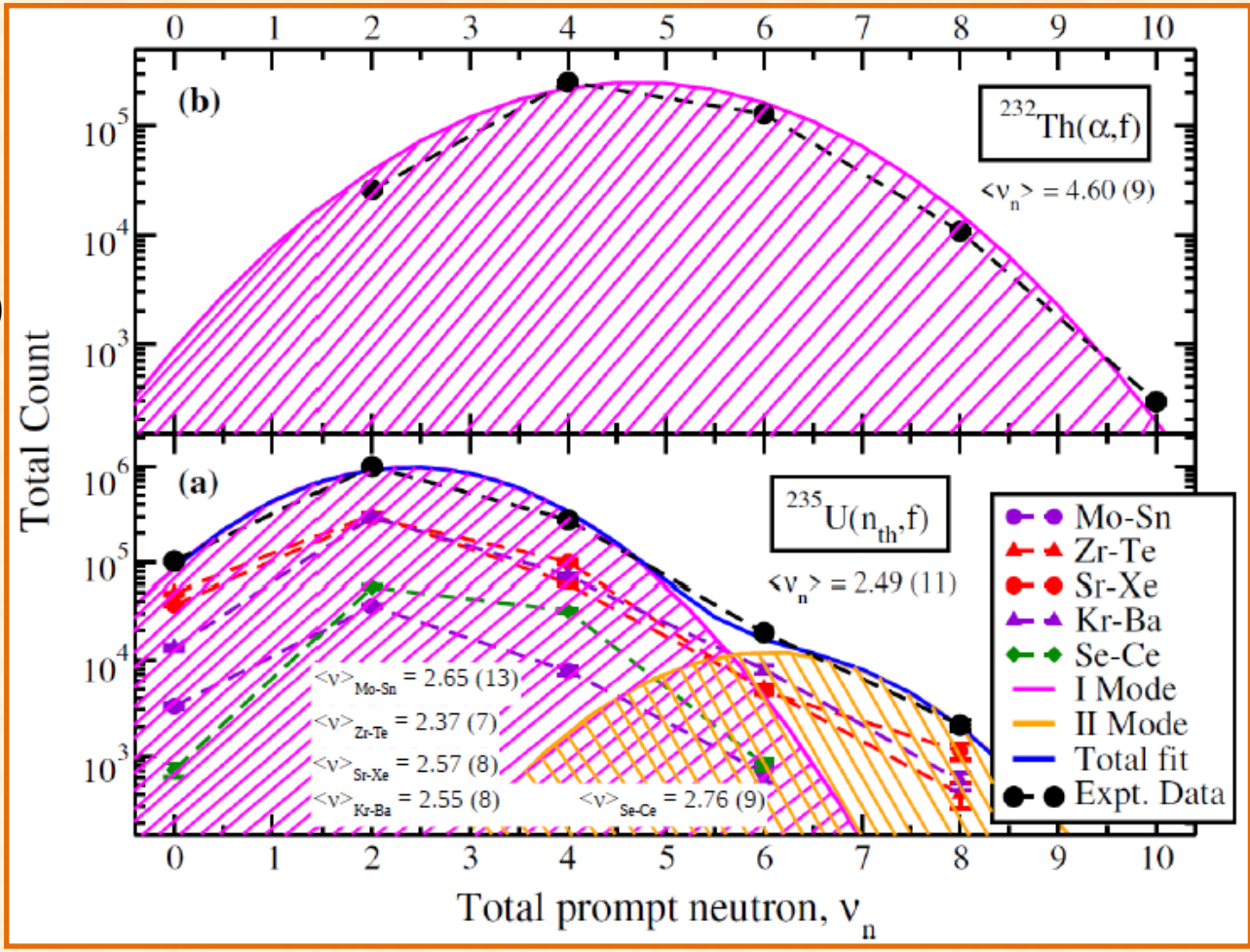


EXILL @ ILL, Grenoble, France

Gaussian Fit: σ = 6.04 ± 0.4 u (both set of data)
Additional Fit: σ ~ 2.4 ± 0.7 u (for ILL data)

Second hot fission mode

VECC Data: ^{232}Th(α,f) @ 30 MeV
E_{ex} = 21.5 MeV

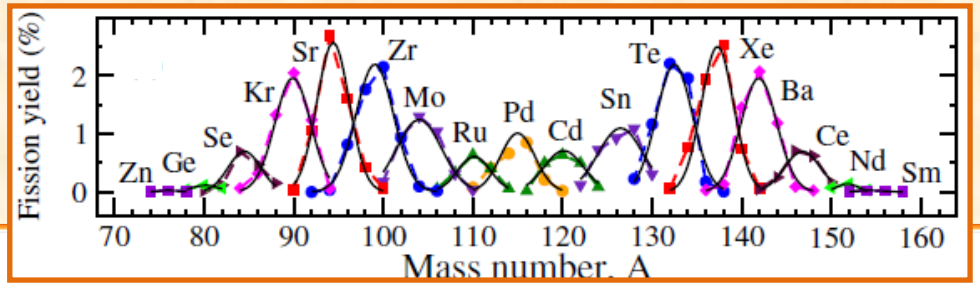


ILL Data: ^{235}U(n_{th},f)
E_{ex} = 6.5 MeV

- ✓Second hot fission mode (in %) : **1.2 ± 0.3**
- ✓Hyper deformed structure: Neutron rich Te, Xe, and Ba

❖Aniruddha Dey *et al.*, ***under review***

Summary



❖$\alpha + {}^{232}Th \rightarrow {}^{236}U^{*}$ @ E_{lab} = 30 MeV VECC-INGA Campaign

❖$n_{th} + {}^{235}U \rightarrow {}^{236}U^{*}$ EXILL Campaign

❖Fission Fragment Spectroscopy: Complicated Task: Comprehensive Fission Dynamics

❖Simultaneous measurement of the mass and charge yield distribution

❖Presence of triple-hump distribution: Contribution from

(a) SL (Super long Symmetric mode)

(b) Two asymmetric modes of

17% Symmetric and 83% Asymmetric contributions Standard I and Standard II

❖Persistence of two competitive compound nucleus fission modes in the low-energy Fission of $^{236}U^{*}$ (*surrogate to 14 MeV neutron induced fission of ^{235}U*)

❖Evidences for the possible co-existing effects of shell closure and multi-chance fission

❖Presence of Second Hot Fission Mode: Possible Energy Mapping

Collaborators

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- ✓ **Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia**

Aniruddha Dey

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File Number: CRG/2021/004680

❖VECC-INGA Campaign
❖EXILL Campaign