Fission Yield Analysis of Neutron-Induced Fission on Th-232

S. Liu[1,2], J. N. Wilson[1,3], D. Thisse[3], N. Jovancevic[3], R. Canavan[3], M. Rudigier[3] and M. Lebois[3]
(1) Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
(2) Xi'an Jiaotong University
(3) Nu-Ball 1 Collaboration

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Motivation for Studying Th-232 Fission Yields

Upcoming experiment: Th-232(n,f) at NFS (5–40 MeV, planned at July)

Applied Motivation

- Fill the data gap (5–40 MeV, yields & spins)
- Measure En-dependence of fission observables
- ^{232}Th is key thorium cycle nucleus, but since it is a fertile nucleus isotopic yield data are lacking

Fundamental Motivation

- Look at the energy dependence of isotopic yields
- Probe of the energy sorting mechanism, and also evolution of angular momentum effects

➢ The ALTO ~2 MeV Th-232(n,f) data

- Measured Th-232(n,f) isotopic yields with 2 MeV neutrons from LICORNE coupled to thorium
- Acts as a preparatory work for the NFS campaign
- Study Th-232 background characteristics
- Analysis of isomer contributions and decay components
- Develop and validate the analysis method needed for the high-energy NFS data.

Advantages & Challenges for γ-ray Spectroscopy

Advantages

- Access to mass and charge yields in direct kinematics
- γ–γ (and γ–γ–γ) coincidences provide strong selectivity to isolate specific fragments from the global fission background
- HPGe high intrinsic energy resolution

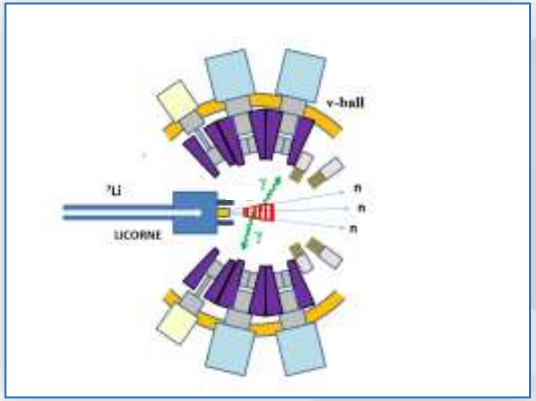
Challenges

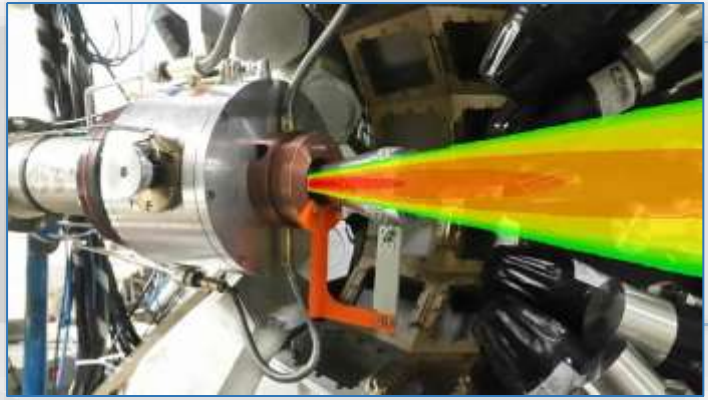
- It is confined to even-even fragments. Odd-even and odd–odd nuclei have fragmented, complex decay paths and poorer statistics
- Need to account for all intensity feeding the ground state, which is sometimes difficult
- Coincidence spectroscopy requires at least two known γ rays
- Precision is limited since we miss direct feeding of 0+ and 2+ states

New analysis method: Ratio based yield

- A new fission fragment yield reconstruction method is proposed for the first time.
- Based on the well characterized Cf-252 (sf) yield data and the gamma transitions, we build up a coefficient between real yield and selected transitions.
- This ratio is used to reconstruct the Th-232 (n,f) fission fragment yield.
- Key assumption: spin distribution of a given fragment doesn't change significantly with the fissioning system.

Experimental Design & Setup





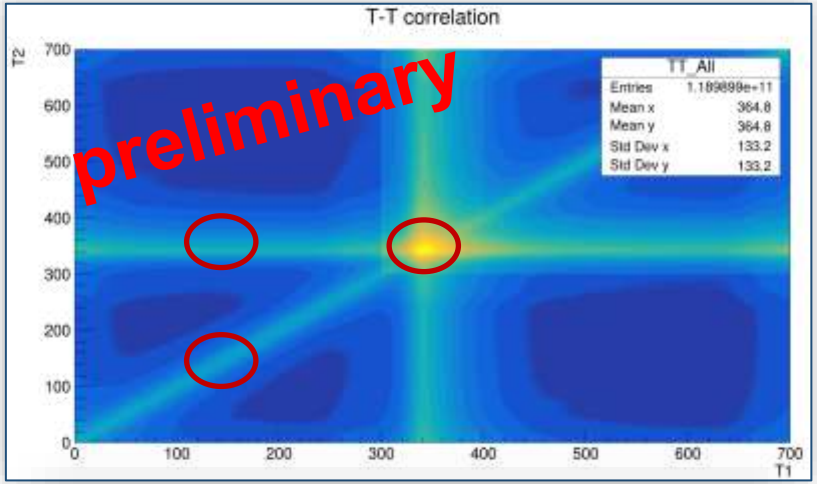
LICORNE/ν-ball coupling principle

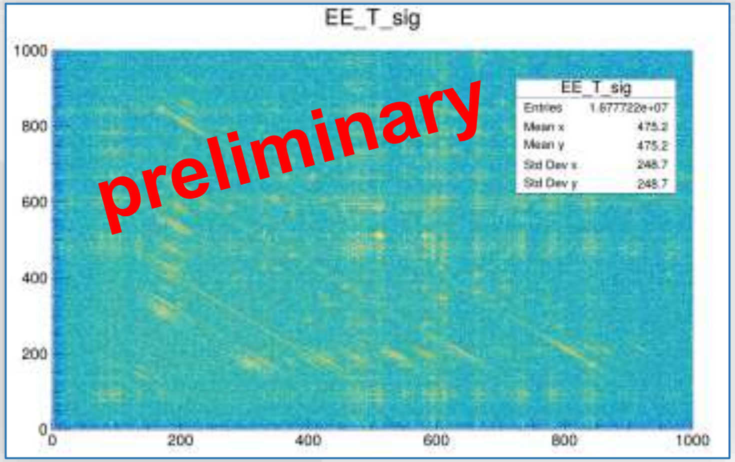
Primary beam 2×10^{11} /s	Target	Secondary beam 2×10^{7} /s	Sample
^{7}Li (16 MeV)	H_2	1.5 MeV neutrons	10^5 fissions/s
	3×10^{20} atoms/cm^2	high-flux, quasi-monoenergetic, and strongly directional	^{232}Th ~100 g

Expt.	Target mass	^{7}Li Current	E_n	Fission Rate	Time	Data	Total Fissions
^{232}Th(n,f)	129 g	80 nA	1.7 MeV	26 kHz	19 days	80 Tb	4.0×10^{10}

Data Analysis & Background Subtraction

- **Time Window for Prompt Fission Events: center at (345ns,345ns), 15~80ns radius.**
- **Gamma multiplicities ≥ 3**
- **Two Background Window: Same area as prompt window, Optimized parameters to reduce beta decay background.**
- **2D-SNIP (Sensitive Nonlinear Iterative Peak-clipping)* algorithm with energy dependent clipping window**
- **Treatment of the diagonal component**





*: Morháč et al., Applied Spectroscopy, 2008

Yield Reconstruction Strategies

Conventional γ-spectroscopy method

1. **Level-scheme construction & transition-intensity extraction**
   - A comprehensive level scheme is constructed for each fission fragment whenever possible.
   - Transition intensities are extracted using RadWare γ-ray analysis tools (peak fitting, coincidence gating, intensity balancing).
2. **Corrections applied to the raw transition intensities**
   - Ground-state side-feeding correction (0^+ feeding). The basic form of the probability distribution used for the extrapolation is:

$$P(I|\sigma^2) = \frac{2I+1}{2\sigma^2} \exp\left[-\frac{(I+1/2)^2}{2\sigma^2}\right]$$

   - Long-lived isomer correction: Using the known half-lives, the missing delayed component is re-added to the transition intensities to recover the full yield contribution.

Cf-252-based transition-ratio method

1. **Using the well-characterized Cf-252 spontaneous-fission dataset, we determine, for each major isotope, the ratio:**

$$Ratio = \frac{Y_{ENDF\ ^{252}Cf}}{I_{\gamma\ ^{252}Cf}}$$

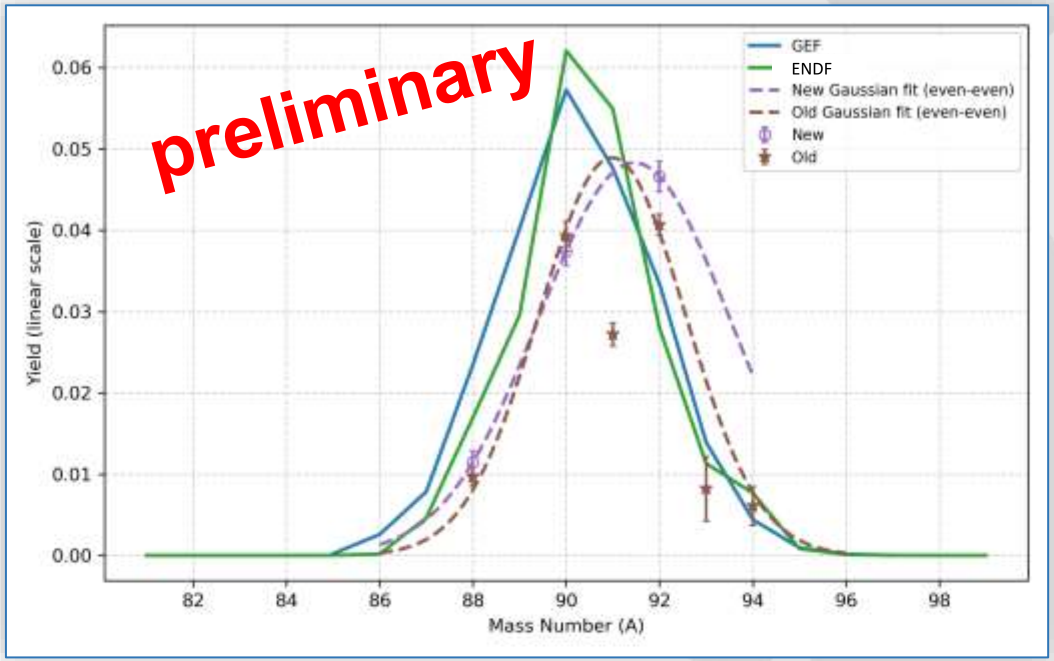
2. **Th-232 fission yields are derived based on the same transitions and ratios:**

$$Y_{^{232}Th} = I_{\gamma\ ^{232}Th} * Ratio$$

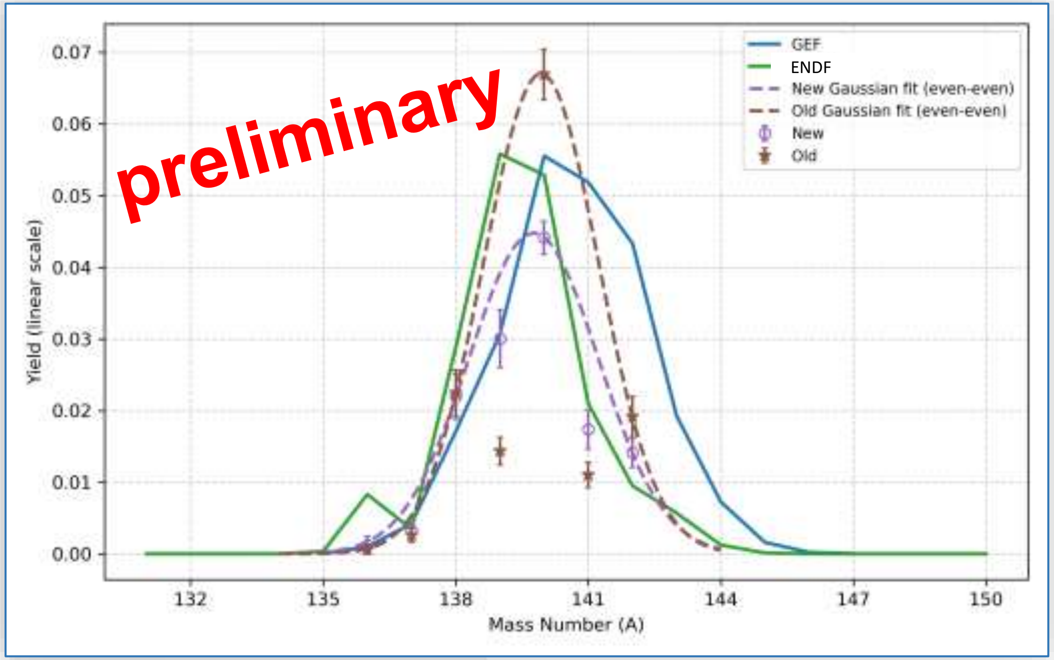
Yield Results – Major Pairs

- Kr–Xe pair:

- New (purple): yields obtained with the Cf-252 ratio–based normalization,
- Old (brown): yields from the conventional γ-spectroscopy method.



Kr (Z=36)

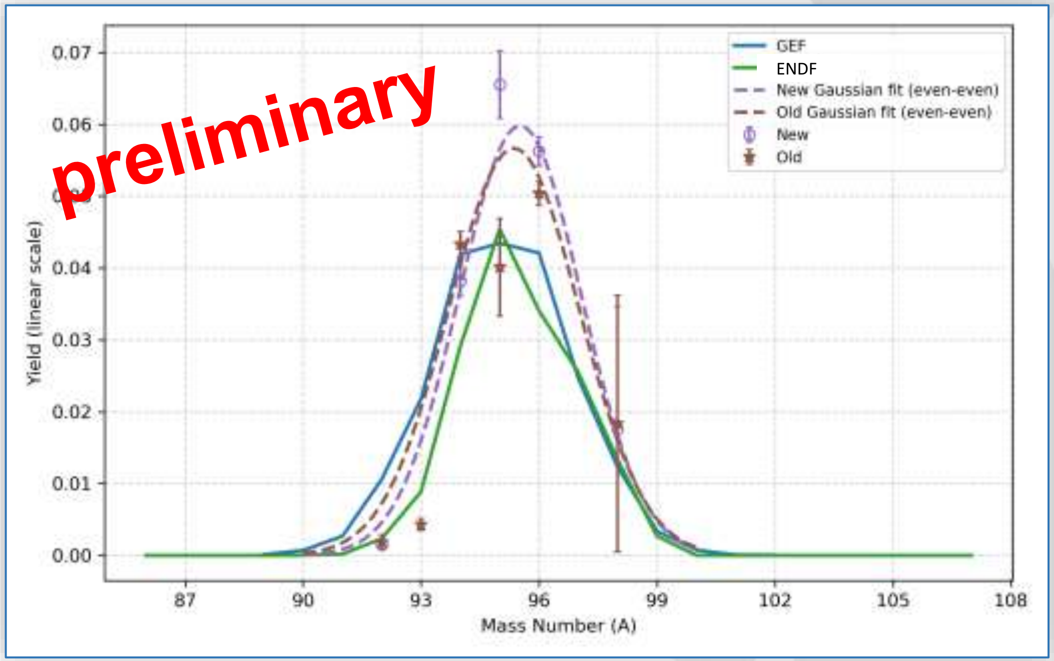


Xe (Z=54)

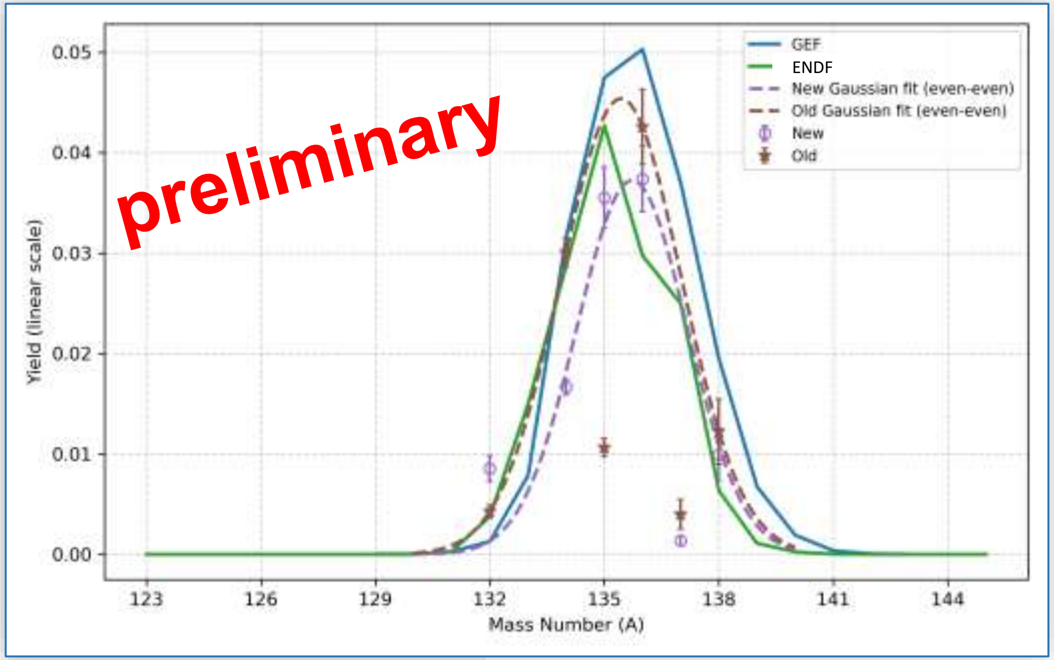
Yield Results – Major Pairs

- **Sr–Te pair:**

- **New (purple): yields obtained with the Cf-252 ratio–based normalization,**
- **Old (brown): yields from the conventional γ-spectroscopy method.**



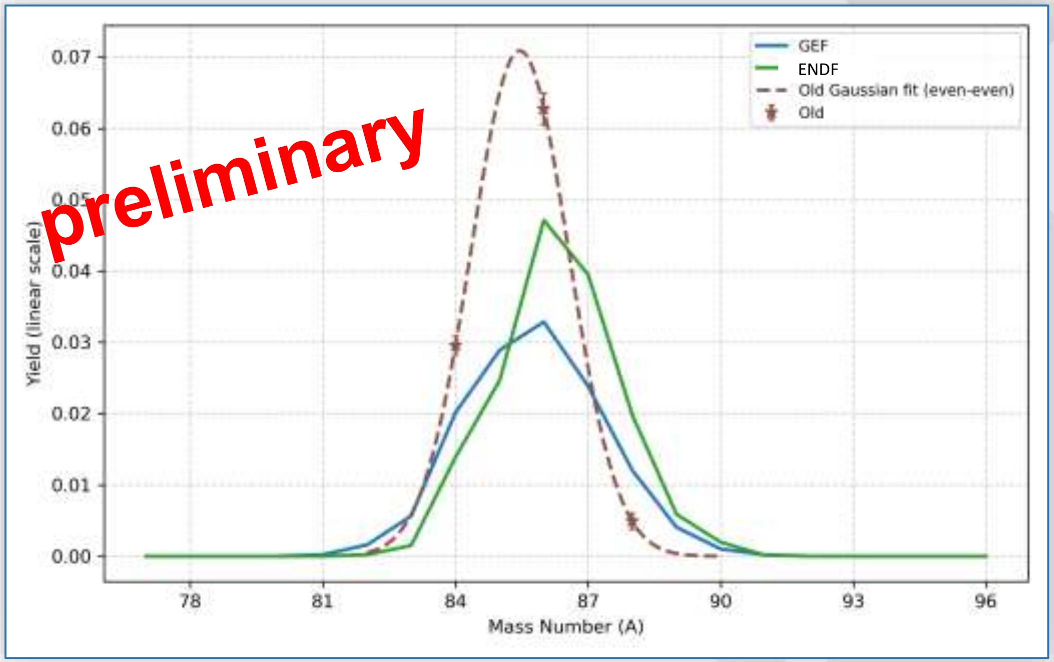
Sr (Z=38)



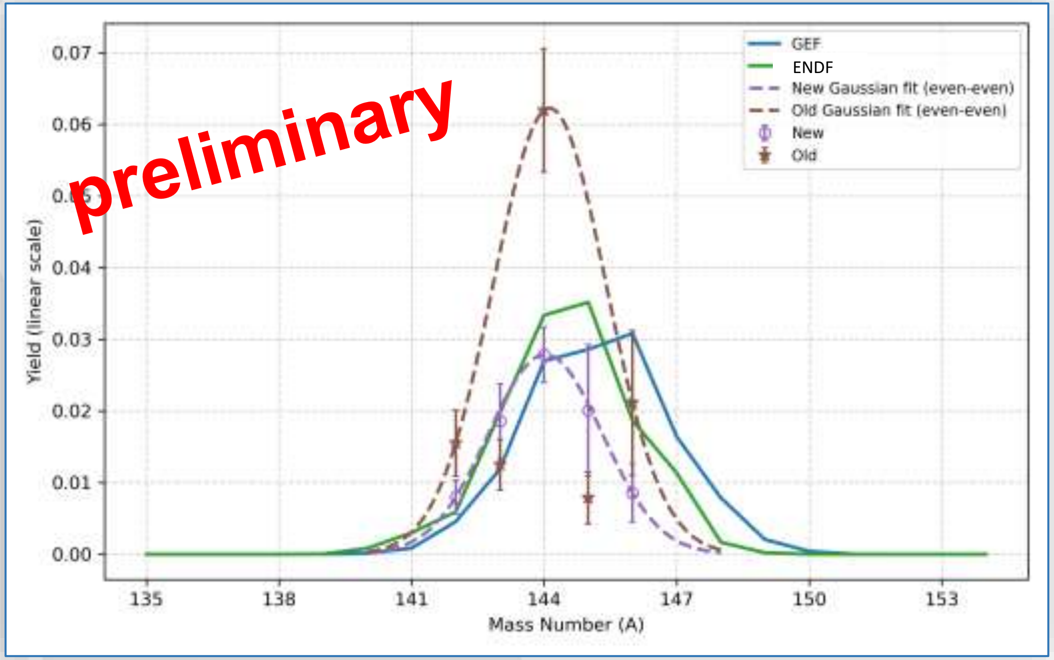
Te (Z=52)

- Se–Ba pair:

- New (purple): **yields obtained with the** Cf-252 ratio–based normalization,
- Old (brown): **yields from the** conventional γ-spectroscopy method,



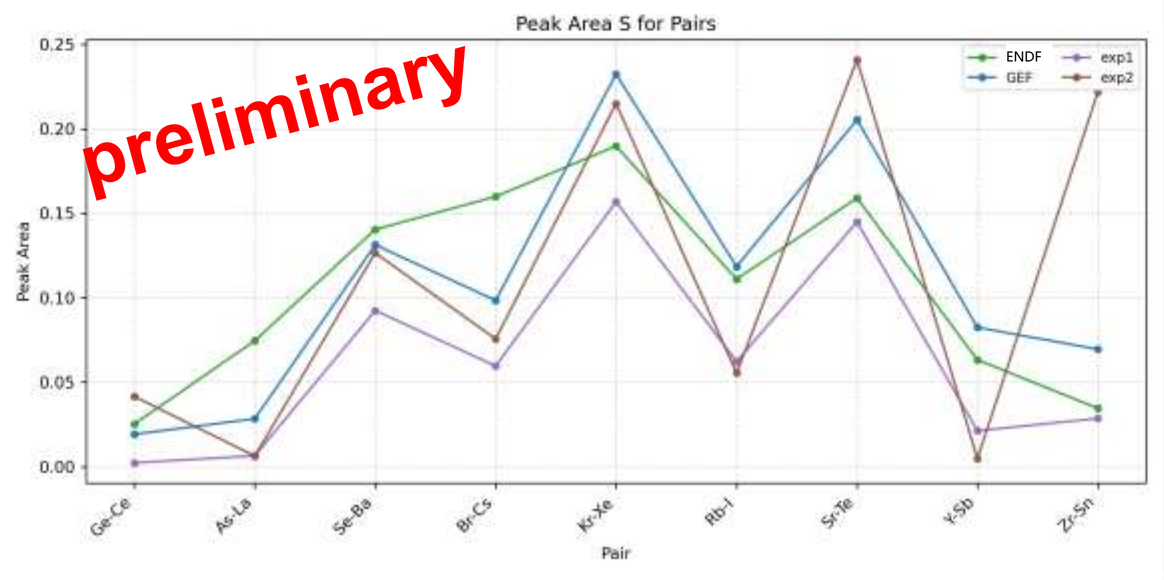
Se (Z=34)



Ba (Z=56)

Yield Results – Global fit of fragment-pair distributions

- All fragment pairs are fitted **consistently on a pair-by-pair basis.** For a given pair, the **peak width** and **peak area** are taken to be common to both fragments, while the **peak position** are treated as free fit parameters.
- In cases with **insufficient data** (e.g. missing information on the light fragment), the peak width is **interpolated from neighbouring fragment pairs**, and only the remaining parameters are fitted.



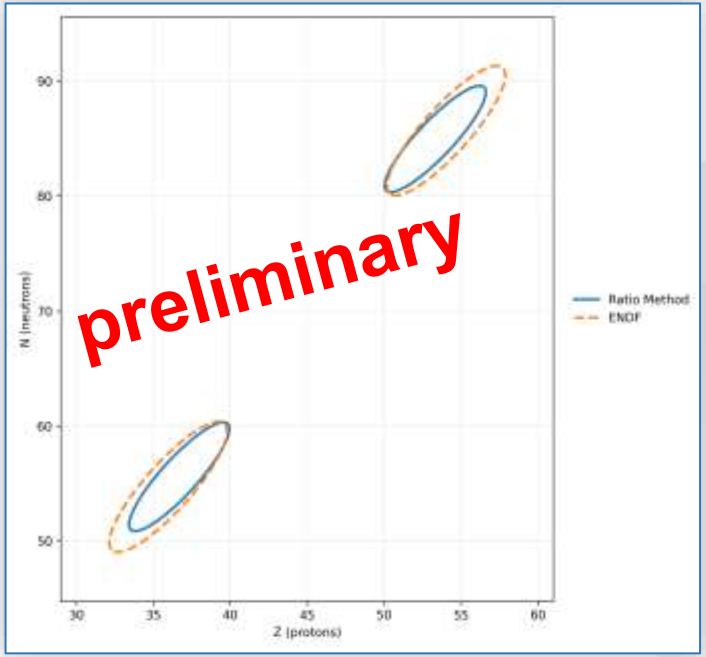
- **exp1 (purple):** yields obtained with the **Cf-252 ratio–based normalization,**
- **exp2 (brown):** yields from the **conventional γ-spectroscopy method.**

- The resulting distributions clearly exhibit a pronounced **odd–even staggering** in the Th-232(n,f) system, and this staggering pattern is consistently visible in **all data sets** (evaluations, model predictions, and both experimental reconstructions.

Yield Results – Global fit of fragment-pair distributions

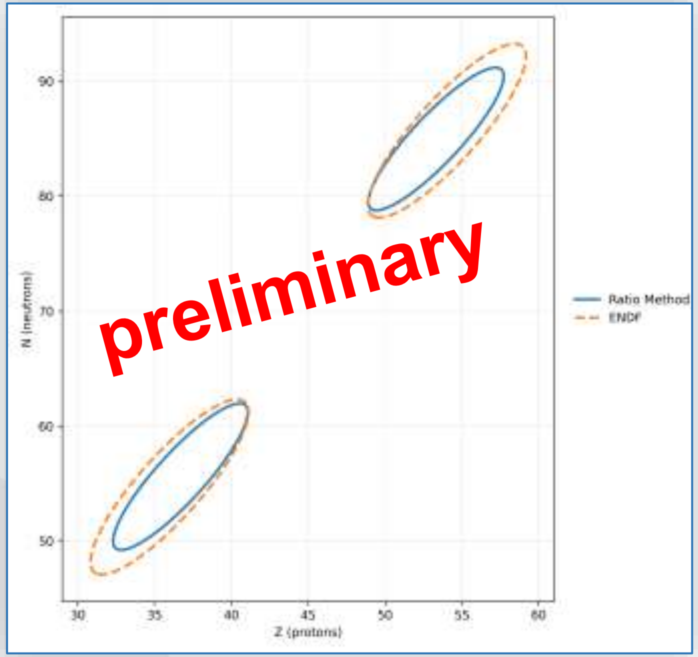
Global Yield Estimation via 2D Gaussian Fit*

Odd Z | **Even Z**



Constrained fit

- Light and heavy fragment groups share the same σ_Z and correlation ρ, i.e. only the centroids $(\sigma_N^L, \mu_N^L)$and $(\mu_Z^H, \sigma_N^H, \mu_N^H)$are independent, $\mu_Z^L = 90 - \mu_Z^H$.
- This reduces the number of free parameters and forces a symmetric shape for the two Gaussians in the Z–N plane.
- The figure shows the 2.5σ contour of the fitted two-dimensional Gaussian distribution.



*: by M. Krzysztof (to be published)

Conclusion

- **Implemented a new technique based on ratio with ^{252}Cf which links for the first time gamma ray measurements with the gold standard from direct techniques**
- **Measured ^{232}Th isotopic yields (~2MeV) with two complementary methods:**
  - **Conventional γ-spectroscopy (RadWare, side-feeding and isomer corrections) with even-Z nuclides.**
  - **Cf-252–based transition ratios, which allows odd-Z yield reconstruction.**
- **For key fragment pairs (Kr–Xe, Sr–Te, Se–Ba), experimental yields are globally consistent in magnitude with ENDF/GEF, but some show systematic shifts, indicating differences in neutron emission and clear odd–even staggering.**
- **Performed global fits in the Z–N plane using 2D Gaussian fit.**

Thanks for listening!