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

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CONTENTS

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

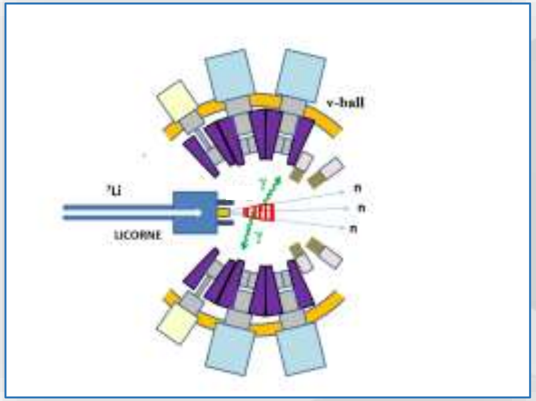
Challenges

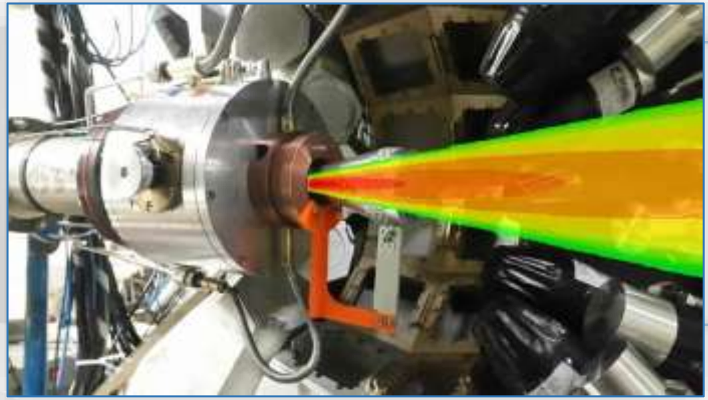
- It is confined to even-even fragments. Odd-even and odd–odd nuclei have fragmented, complex decay paths and poorer statistics
- Need to account for all intensity feeding the ground state, which is sometimes difficult
- Coincidence spectroscopy requires at least two known γ rays
- Precision is limited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





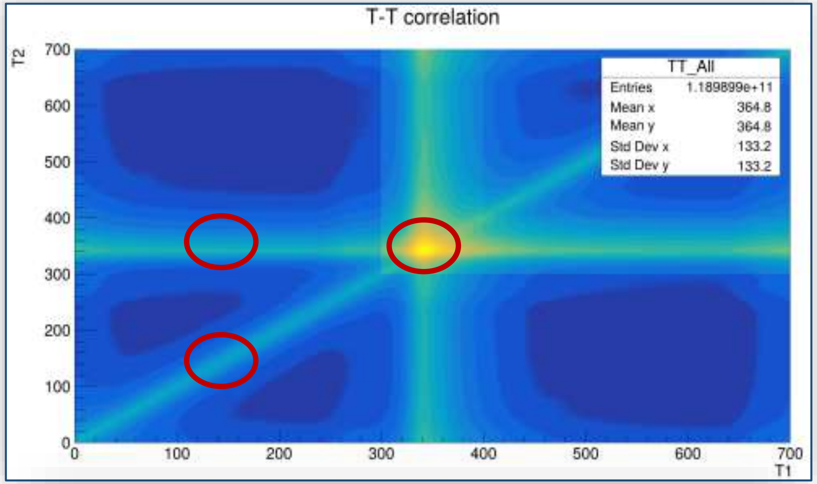
LICORNE/ν-ball coupling principle

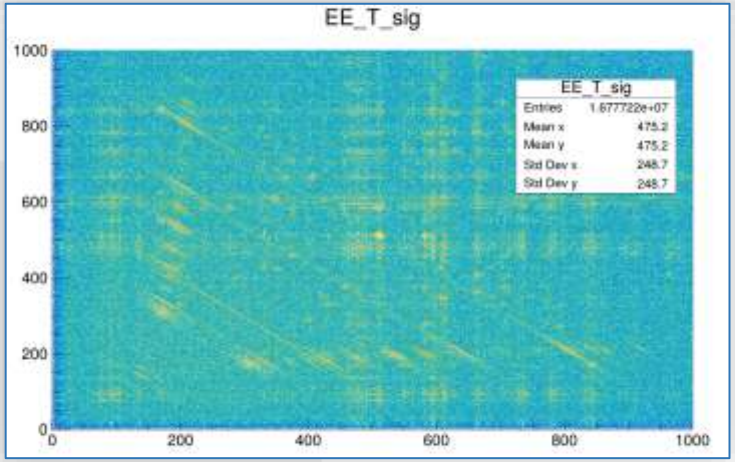
Primary beam 2×10^{11} /s	Target	Secondary beam 2×10^{7} /s	Sample
^{7}Li (16 MeV)	H_2	1.5 MeV neutrons	10^5 fissions/s
	3×10^{20} atoms/cm^2	high-flux, quasi-monoenergetic, and strongly directional	^{232}Th ~100 g

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:**

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

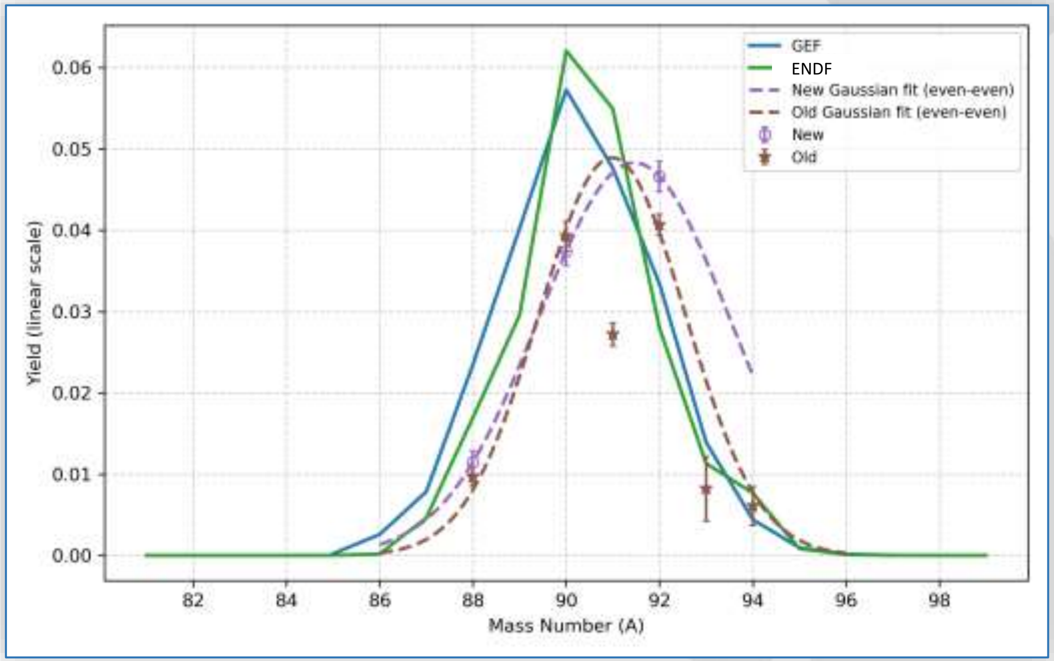
2. **Th-232 fission yields are derived based on the same transitions and ratios:**

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

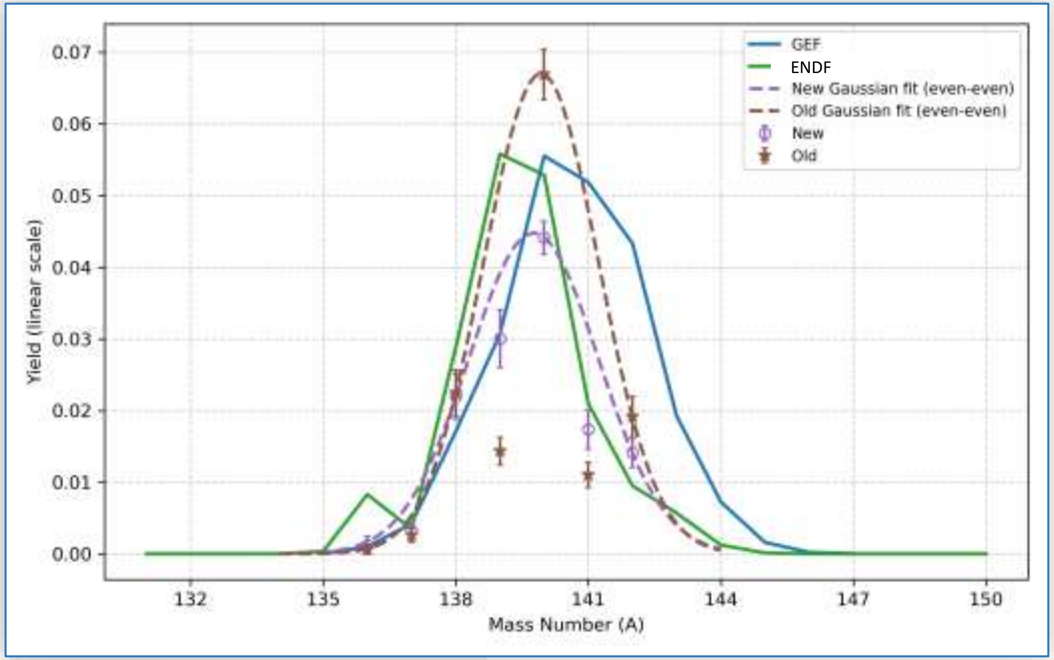
Yield Results – Major Pairs

- 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)



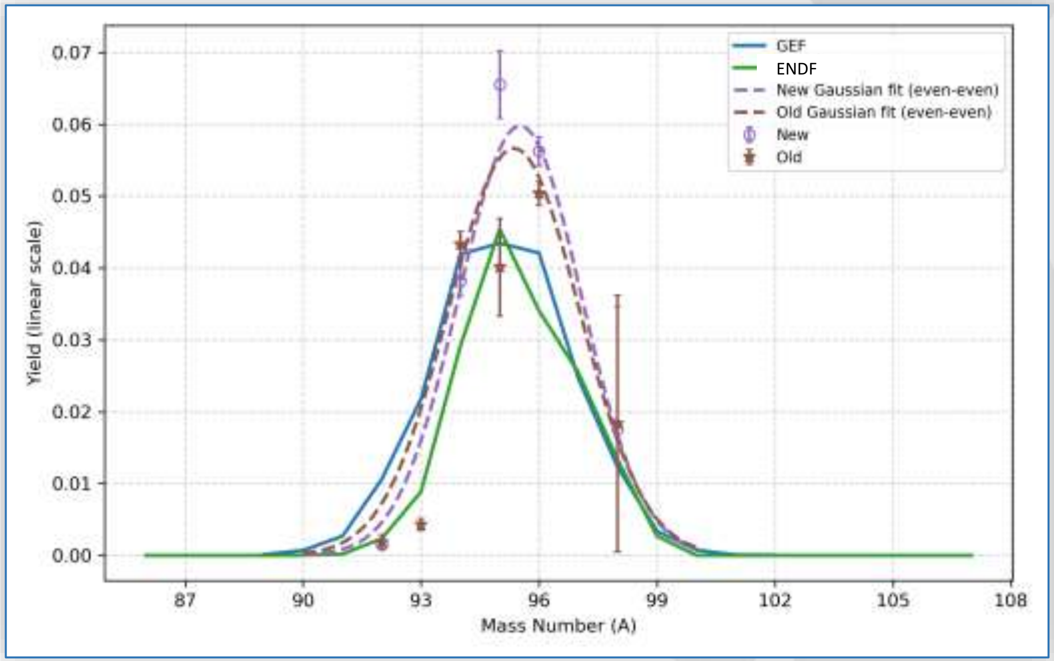
Xe (Z=54)

Yield Results – Major Pairs

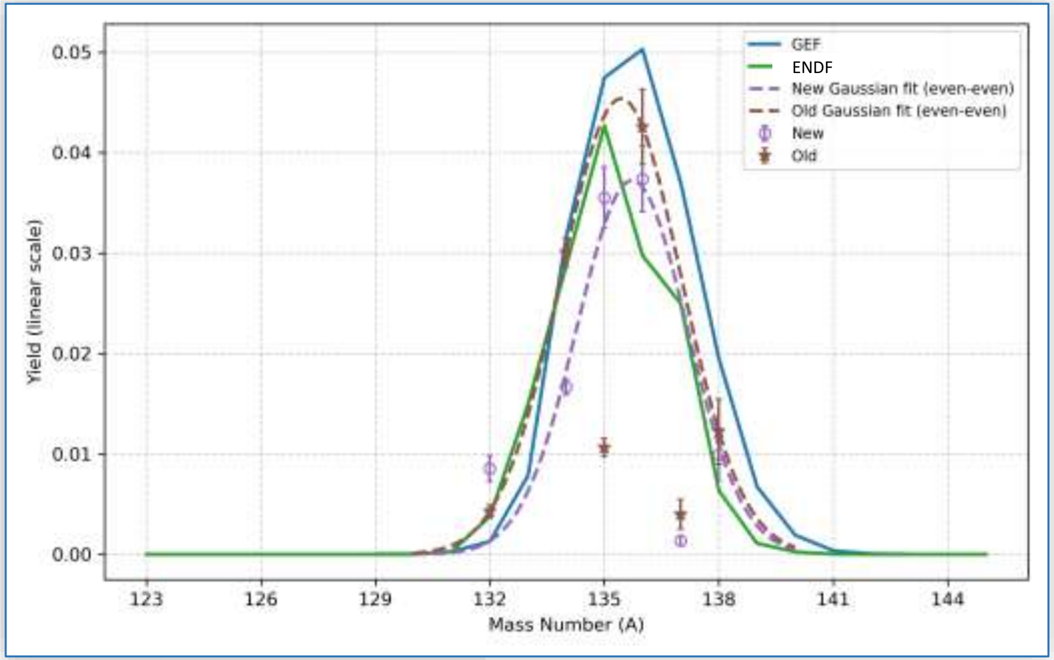
➢ Sr–Te pair:

➢ New (purple): yields obtained with the Cf-252 ratio–based normalization,

➢ Old (brown): yields from the conventional γ-spectroscopy method.



Sr (Z=38)

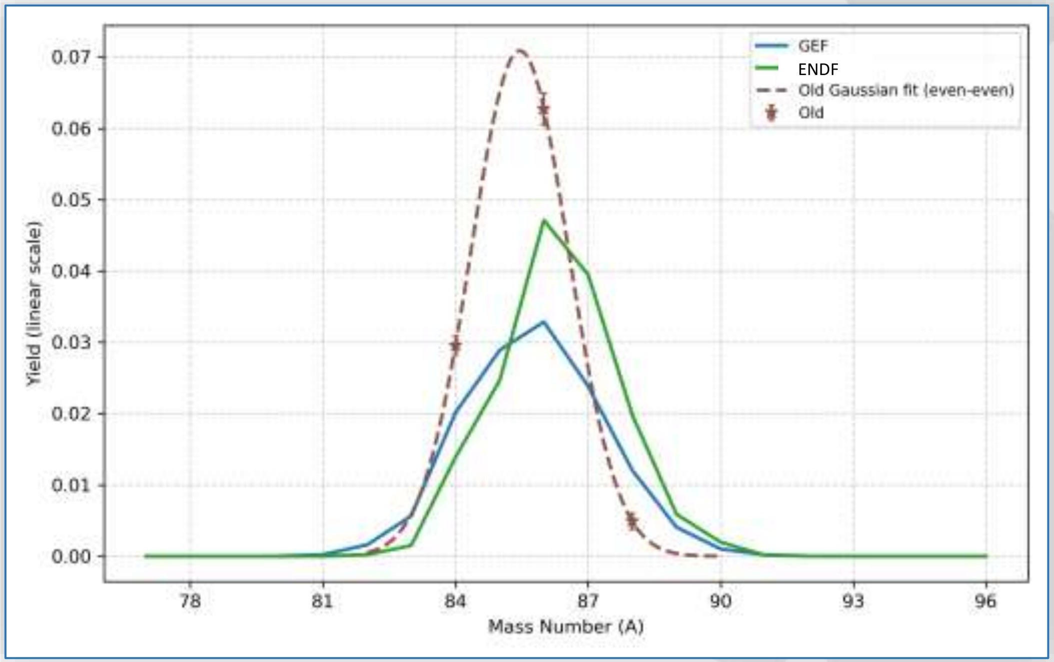


Te (Z=52)

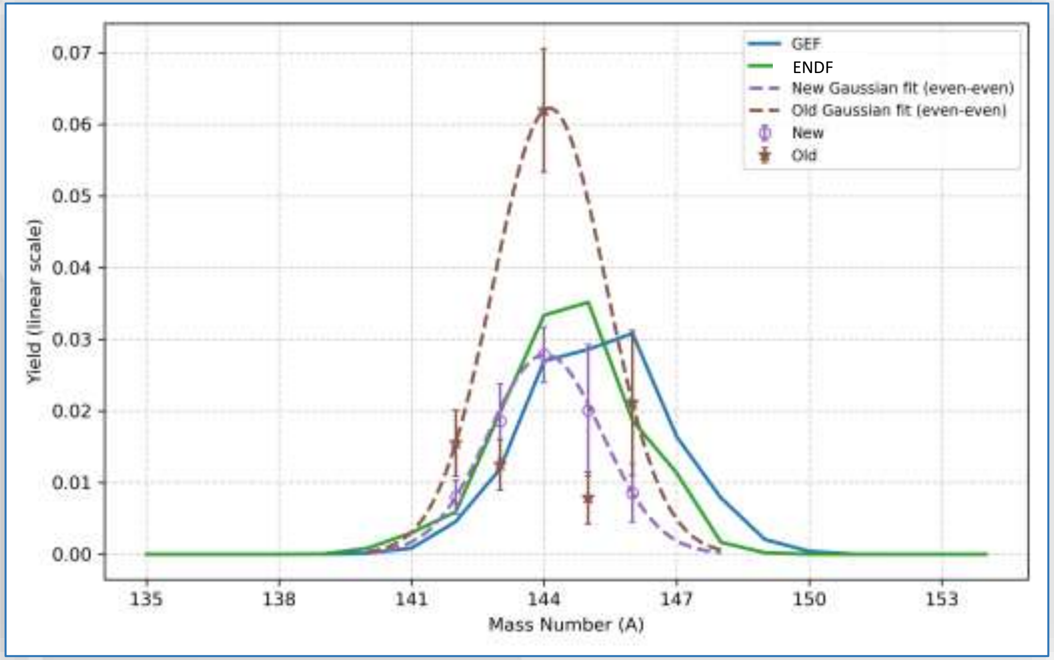
Yield Results – Major Pairs

- Se–Ba pair:

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



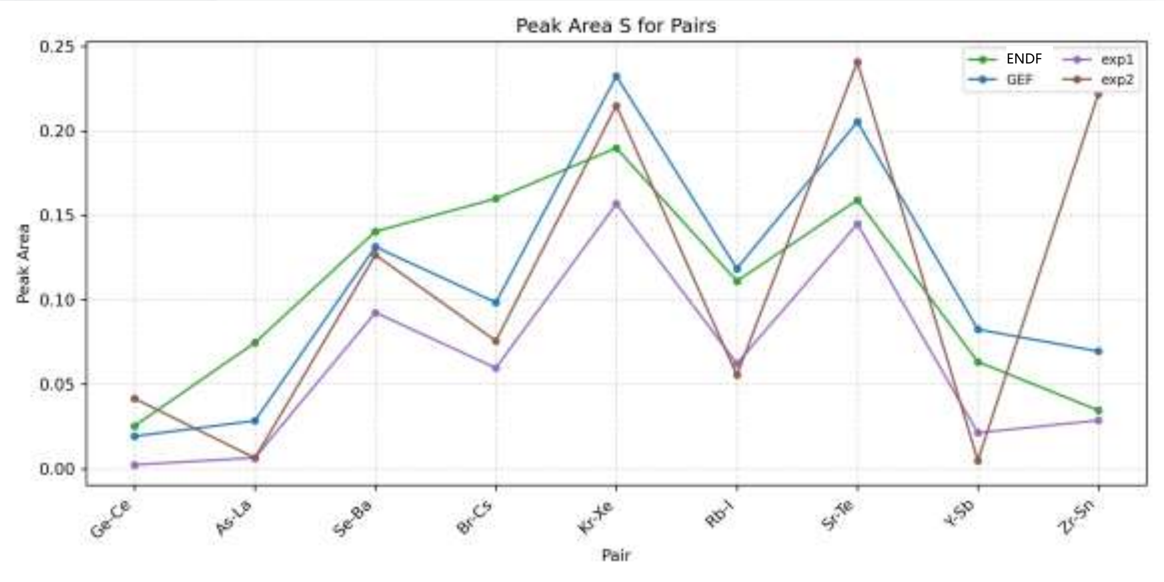
Se (Z=34)



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.**

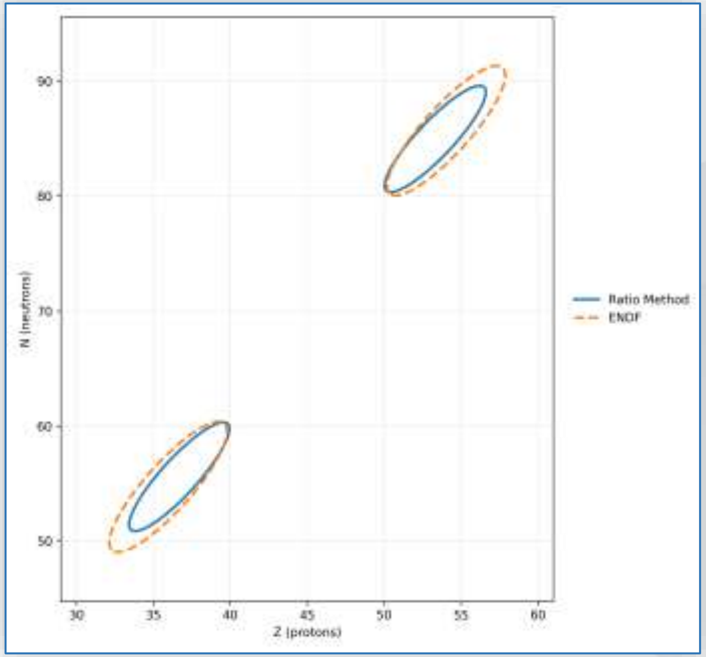


- **exp1 (purple): yields obtained with the Cf-252 ratio–based normalization,**
- **exp2 (brown): yields from the conventional γ-spectroscopy method.**

- **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.**

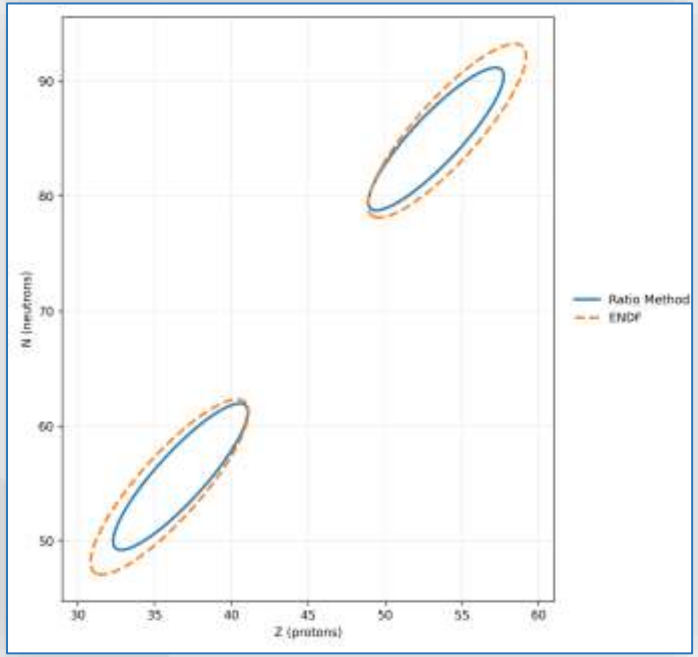
Global Yield Estimation via 2D Gaussian Fit*

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.

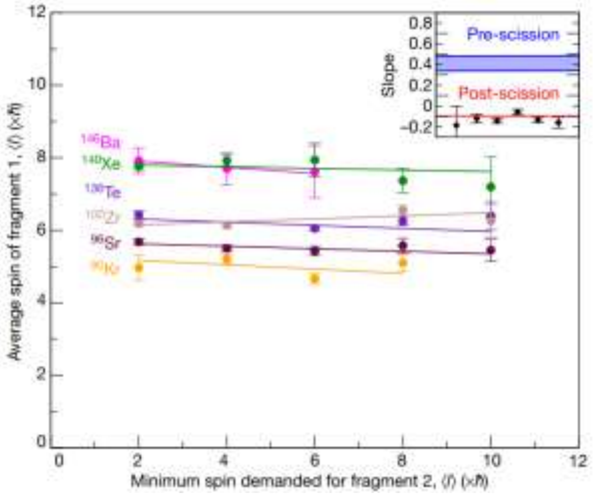


*: by M. Krzysztof (to be published)

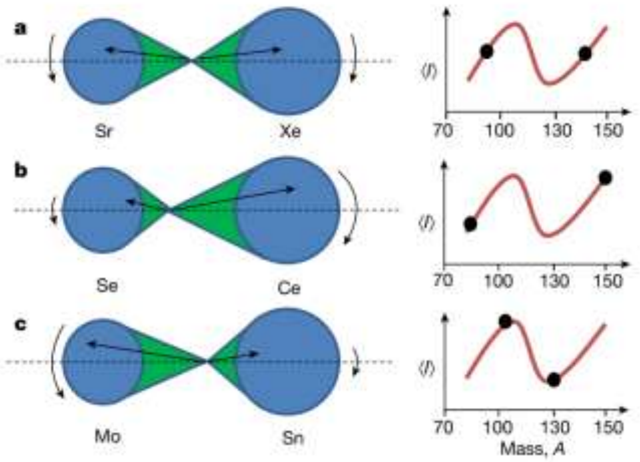
Conclusion

- 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.

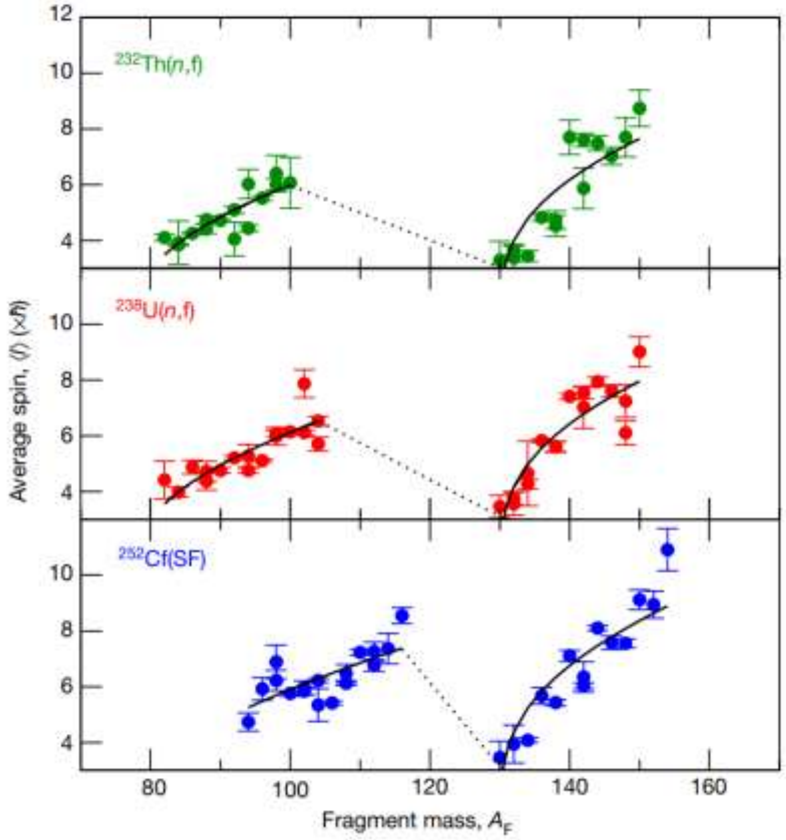
Thanks for listening!



Correlation between fragment spins, J.N. Wilson, 2021



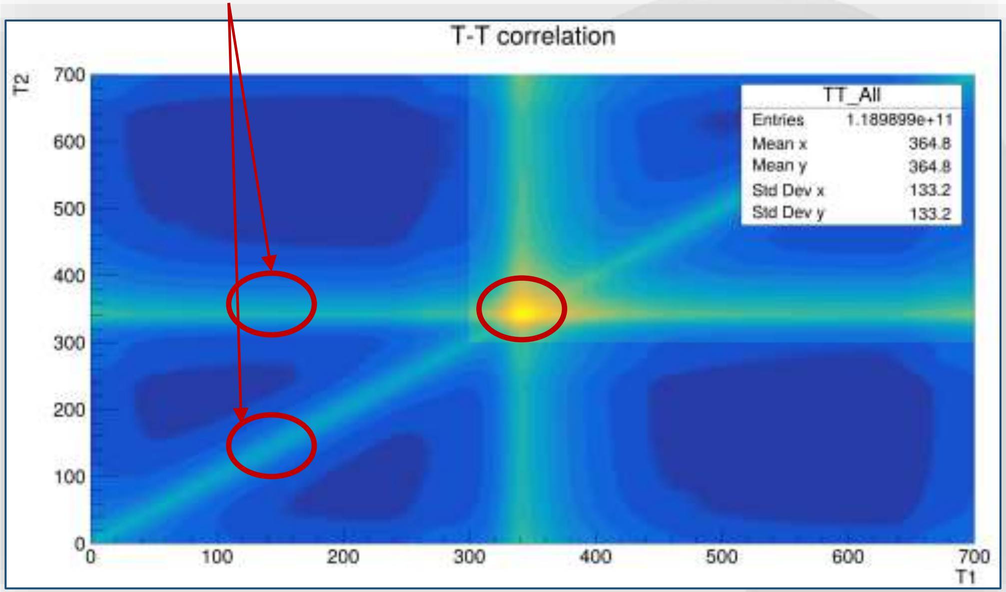
Schematic diagram of post-scission angular momentum generation, 2021

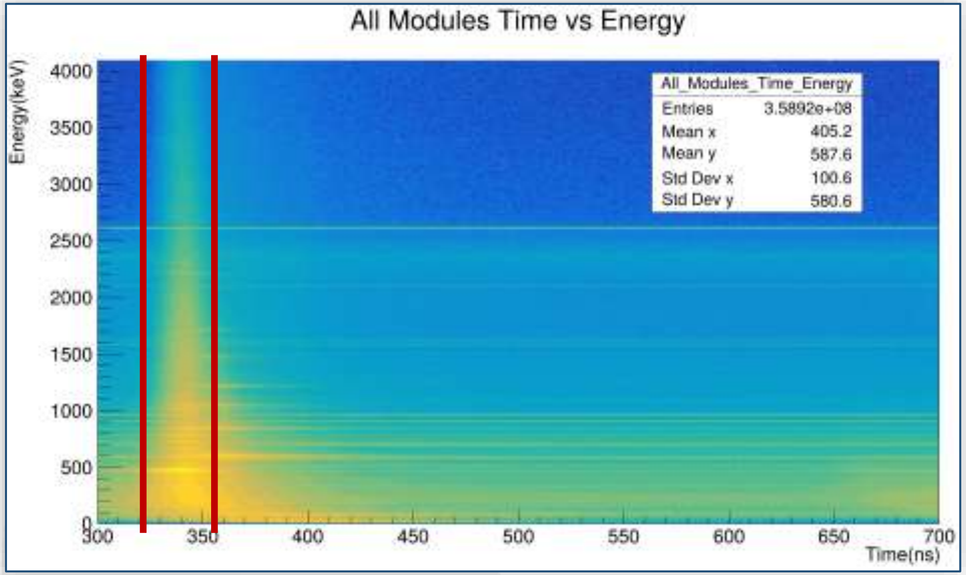


Dependence of average spin on fragment mass, J.N. Wilson, 2021

Backup

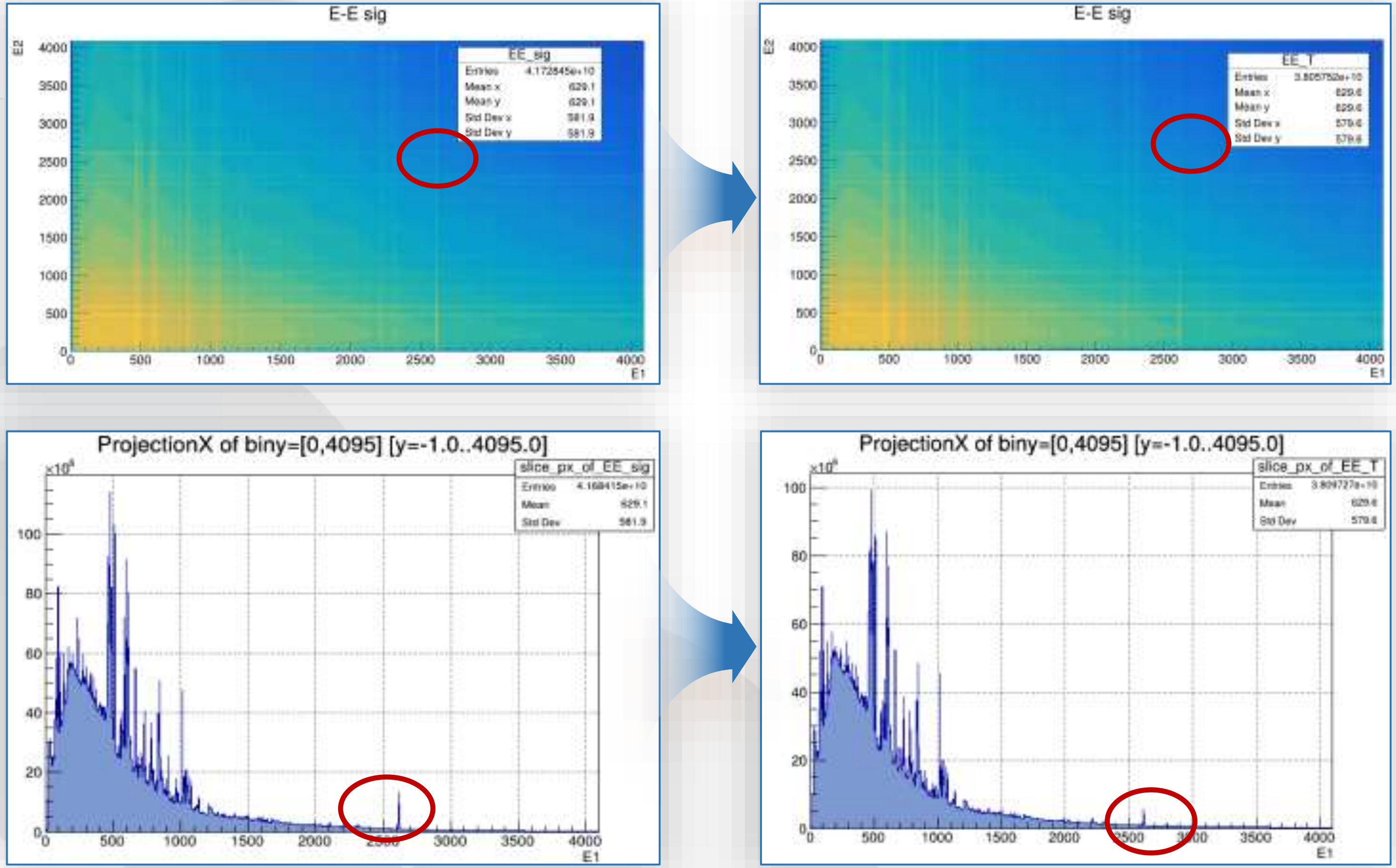
- **Time Window for Prompt Fission Events：** center at (345ns,345ns), 15~80ns radius.
- **Gamma multiplicities ≥ 3**
- **Two Background Window:** Same area as prompt window, Optimized parameters to reduce Th-233 beta decay background correlations





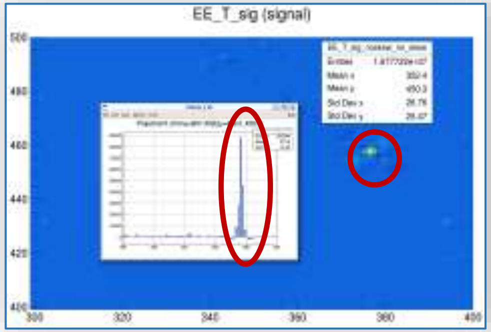
Backup

- **By reducing the decay-gated time window, the 2.6 MeV decay γ peak from the ^{232}Th chain is strongly suppressed, demonstrating efficient removal of the thorium decay background.**

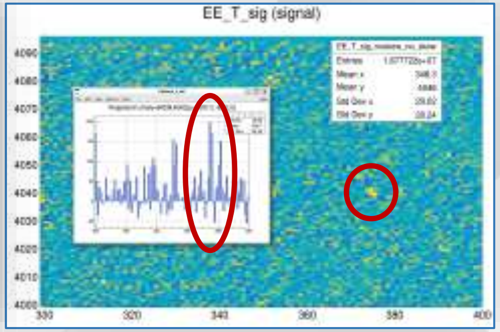


Backup

Window = 3, suitable for low energy

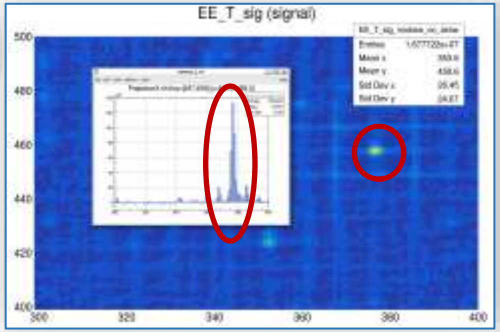


clean and well-defined peak

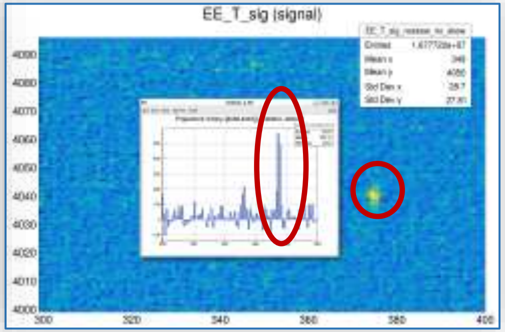


buried peak

Window = 9, suitable for high energy



background misidentified as a peak



clean and well-defined peak

➢ Concept (from Morháč et al., 2008)

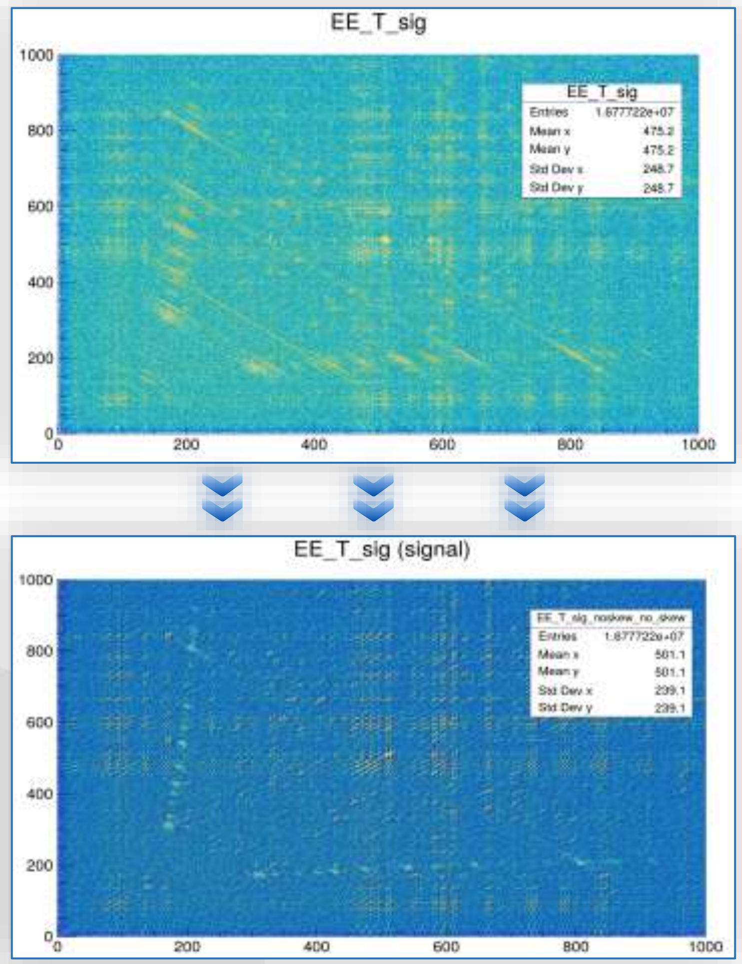
- **The SNIP (Sensitive Nonlinear Iterative Peak-clipping) algorithm estimates background by iteratively clipping peaks while preserving slowly varying structures.**
- **For a 2D matrix $V(i,j)$,each iteration uses a clipping window $p$to compare the pixel with a smoothed approximation from its neighbourhood:**
  - $V^{(p)}(i,j) = \boldsymbol{min}\left(V^{(p-1)}(i,j), B^{(p)}(i,j)\right)$
- **where $B^{(p)}(i,j)$ is a prediction of the background from surrounding pixels.**
- **For $B^{(p)}(i,j)$:**
  - **Second-order operator removes slow-varying background (Selected)**
  - **Fourth-order operator absorbs broad structures (Compton, ridges)**

➢ Our improvements

- **Introduced energy-dependent window size**
- **ensuring that the spectrum remains smooth and does not develop discontinuities when the window size changes.**

Backup

- **Residual diagonal after 2D-SNIP**
  - **After applying 2D-SNIP, the main remaining background structure appears along the $E_1 + E_2$ = constant diagonal.**
  - **These events correspond to single-γ Compton scattering, where one γ triggers two detectors.**
  - **In the γ–γ matrix, such events form a straight line with slope –1, indicating constant total γ energy.**
- **Treatment of the diagonal component**
  - **The γ–γ matrix is decomposed diagonal by diagonal (each constant-sum line).**
  - **For each diagonal slice, a separate 1D background-smoothing subtraction is performed.**
  - **This removes the Compton-scattering contribution while preserving true γ–γ coincidence peaks.**



Global Yield Estimation via 2D Gaussian Mixture Fit

- **The ratio-based method cannot provide yields for all isotopes because Cf-252 and Th-232 fragment distributions do not fully overlap.**
- **To recover missing yields and obtain a global, model-independent estimate, we follow the approach of M. Krzysztof (to be published) and perform a global fit of all fragments in the Z–N plane.**

1.Bivariate Gaussian for one fragment group

$$f(Z,N|\mu_Z,\mu_N,\sigma_Z,\sigma_N,\rho) = \frac{1}{2\pi\sigma_Z\sigma_N\sqrt{1-\rho^2}} \exp\left[-\frac{Q(Z,N)}{2(1-\rho^2)}\right]$$

$$Q(Z,N) = \left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2 + \left(\frac{N-\mu_N}{\sigma_N}\right)^2 - 2\rho\left(\frac{Z-\mu_Z}{\sigma_Z}\right)\left(\frac{N-\mu_N}{\sigma_N}\right)$$

2. Two-component mixture

$$f_{mix}(Z,N) = \frac{1}{2} f_{light}(Z,N) + \frac{1}{2} f_{heavy}(Z,N)$$

3. Parameter Determination: Maximum log-Likelihood

$$\mathcal{L}(\theta) = \prod_i w_i f_{mix}(Z_i,N_i|\theta)\,, w_i = \frac{Y(Z_i,N_i)}{\sum Y}$$

$$\max\{\ln \mathcal{L}(\theta)\} \rightarrow (\mu_Z,\mu_N,\sigma_Z,\sigma_N,\rho)$$

Motivation for Studying Th-232 Fission Yields

➤ **Growing interest in thorium-based reactor technologies**

- **Thorium-based molten salt reactors have gained substantial attention in recent years as a promising option within Generation-IV reactor concepts. Their intrinsic safety properties, high fuel utilization, and proliferation resistance make thorium an appealing alternative to uranium-based fuel cycles**

➤ **Industrial progress demonstrates practical feasibility**

- **Recent developments—such as demonstrations of the Th-232 → U-233 breeding process in prototype thorium reactors (e.g., China's MSR research program)—have further highlighted the industrial relevance of thorium fuel**

➤ **Fission yields play a crucial role in reactor performance**

- **Accurate fission product yields are essential for**
  - **predicting decay heat and radiotoxicity**
  - **ensuring safety margins and long-term operation reliability**

➤ **Current knowledge of Th-232 fission yields is still limited**

- **Experimental data for neutron-induced fission of Th-232 remain scarce**
- **Th-232 is not a fissile nuclide, which is hard to directly measure the isotopic yield**

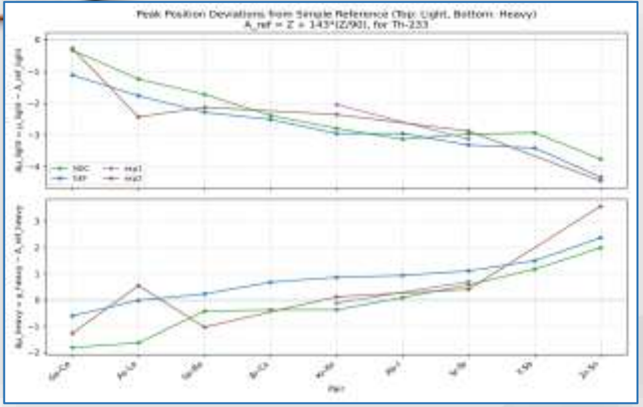
http://www.xinhuanet.com/photo/20251101/2b9aded50ca4452e80aaf8a7f48d4b12/c.html

Conclusion

Methodological conclusions

1. **Cf-252–based approach as a powerful complement**
   The Cf-252–based ratio method provides more accurate yield reconstruction for many specific isotopes (in particular those well populated in Cf-252(sf)), and can serve as an alternative or complement to the conventional spectroscopy approach.
2. **Limitations from incomplete coverage**
   Because the fission fragment distributions of Cf-252 (sf) and Th-232 (n,f) do not completely overlap, the yields of some fragments, especially those in the light-fragment region, are absent.
3. **Increasing potential with more data**
   As more experimental data and better evaluations become available, the applicability and reliability of the ratio-based method will steadily improve, giving it strong prospects for future use in fission-yield studies.
4. **Hybrid strategies in the presence of missing data**
   Conventional spectroscopy (e.g., even–even fragments or global fits) can be used to supplement missing nuclides, leading to a more complete set of fragment yields.

Yield Results – Global fit of fragment-pair distributions



Peak positions of individual fragments

- To better visualise the evolution of the fragment peak positions, we introduce a simple reference baseline:
- $A_{ref} = Z + 143 * \left(\frac{Z}{90}\right)$
- Due to the different fragment distributions in Cf-252(sf) and Th-232(n,f), the ratio-based method provides peak-position information only for a limited subset of fragments.

Sum of peak positions for fragment pairs

- The second plot shows the sum of the peak positions for each fragment pair, which approximates the reconstructed total mass of the fission system.
- Again, because of the restricted overlap between Cf-252 and Th-232 fragment yields, the ratio-based method can only provide complete peak-position information for two fragment pairs over the full range.