Correlated transitions in TKE and mass distributions of fission fragments described by 4-D Langevin equation

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M. Usang et al.,
Scientific Reports **9**, 1525 (2019)

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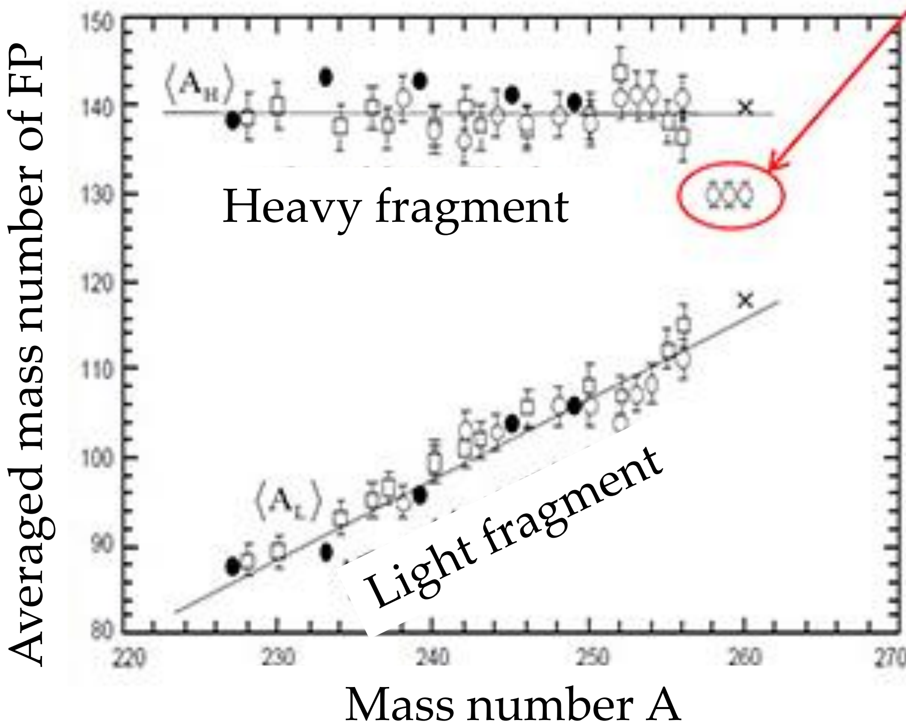
Background: Anomalies in FFMDs and TKEs

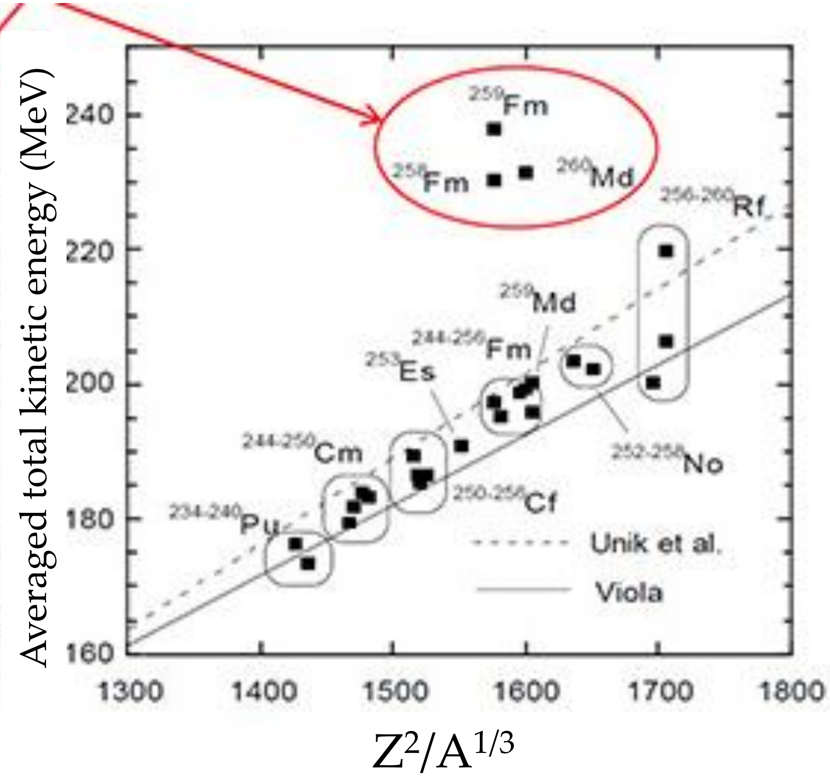
Anomaly in fission fragment masses and that in averaged TKE were experimentally discovered.

1. Sudden change in FFMD from asymmetric to symmetric.
2. High <TKE> far from Viola/Unik systematics

➔ No theory can explain these anomalies SIMULTANEOUSLY.
Some models can predict FFMDs, while few models can provide precise TKEs.

Anomaly





Today's Topic:
Correlated transition between FFMDs and TKEs

M. D. Usang et al., *Scientific Reports* **9**, 1525 (2019)

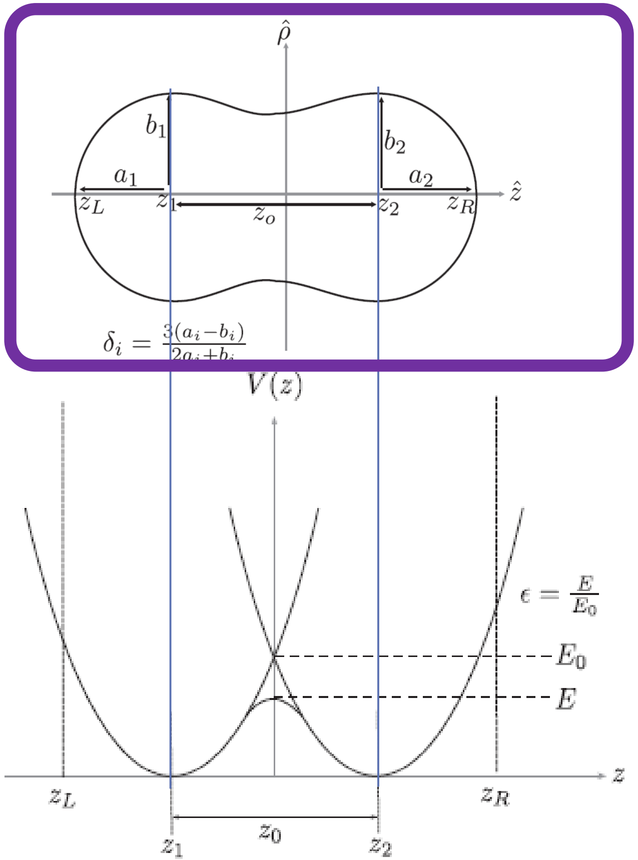
- **Aim**
  - To understand the sudden FFMD/TKE transitions in Fm-isotopes
- **Model**
  - 4D-Langevin model with two-center model, which can provide both FFMD and TKE(A) of ^{236}U precisely
- **Calculations**
  - From actinides to trans-actinides (from ^{236}U to ^{259}Lr)
- **Analysis**
  - Obtained TKEs following the Brosa fission model
  - Comparison between the TKEs and FFMDs

- **What we found twin transition in**

1. Symmetric modes from super-long to super-short mode
2. Dominant modes from asymmetric mode to symmetric mode at Fm, Md

4-dimensional Langevin model

C. Ishizuka et al, Phys. Rev. C 96, 064616 (2017)



$$
\begin{cases}
\dfrac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j \\[2ex]
\dfrac{dp_i}{dt} = \boxed{-\dfrac{\partial F}{\partial q_i}} - \dfrac{1}{2}\dfrac{\partial}{\partial q_i}(m^{-1})_{jk} p_j p_k - \gamma_{ij}(m^{-1})_{jk} p_k + g_{ij} R_j(t)
\end{cases}
$$

Drift term with Quantum Corr. Friction Random force

Diffusion term Fluctuation term

$$g_{ik} g_{kj} = T^* \gamma_{ij}, \quad \text{with} \quad T^* = \frac{\hbar\varpi}{2} \coth \frac{\hbar\varpi}{2T}$$

Shell corrections to the free energy F

derived from their formal definitions without any additional approximations.

[Ref] F. A. Ivanyuk, et al, Phys. Rev. C 97, 054331 (2018)

Macroscopic transport coefficients:

Collective inertia tensor $m_{\mu\nu}$:

The Werner-Wheeler approx. of the liquid drop mass tensor

The friction tensor $\gamma_{\mu\nu}$:

The wall-window friction formulation.

Shape parametrization in the two-center model proposed by Maruhn & Greiner 1972

$q_i=(z_0, \delta_1, \delta_2, \alpha)$ in 4D or $q_i=(z_0, \delta, \alpha)$ in 3D ($\delta_1=\delta_2$)

Fixed parameters

- Neck parameter $\varepsilon=E/E_0$
- The local frequency of collective motion ω

Brosa Fission model

Brosa et al.,Z. *Naturforsch* **41**(a), 1341–1346 (1986)

Brosa calculated the average TKE of the fission mode for given possible shapes of the nuclei.

Super-short Fission Modes

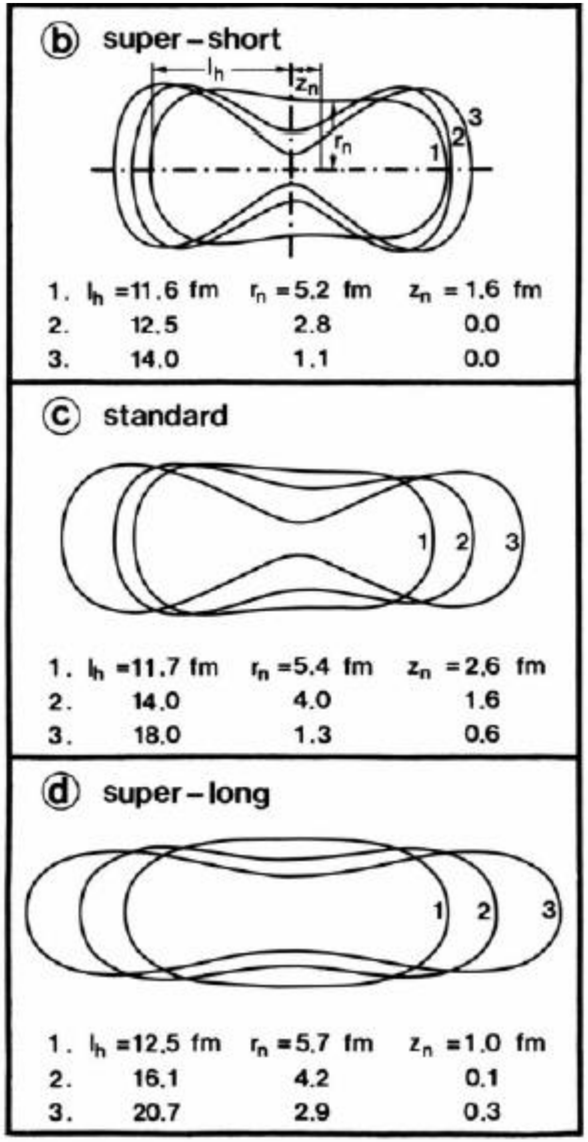
- Average TKE bigger than standard fission modes
- Both fragments are oblate

Standard Fission Modes

- Average TKE that scales with Coulomb repulsion systematics of Viola and Unik.
- One fragment is oblate and the other fragment is prolate.

Super-long Fission Modes

- Average TKE smaller than standard fission modes
- Both fragments are prolate



Results

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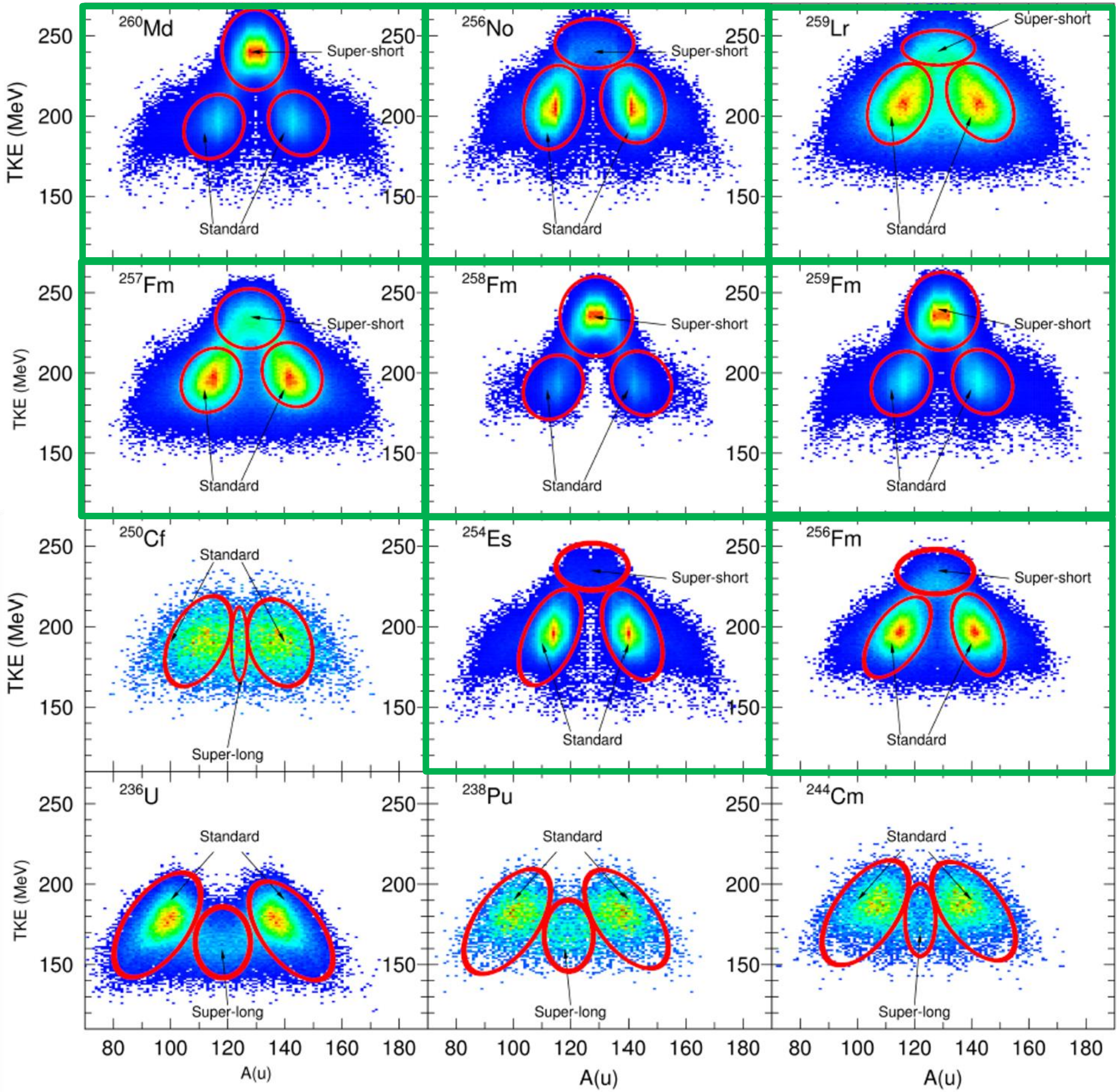
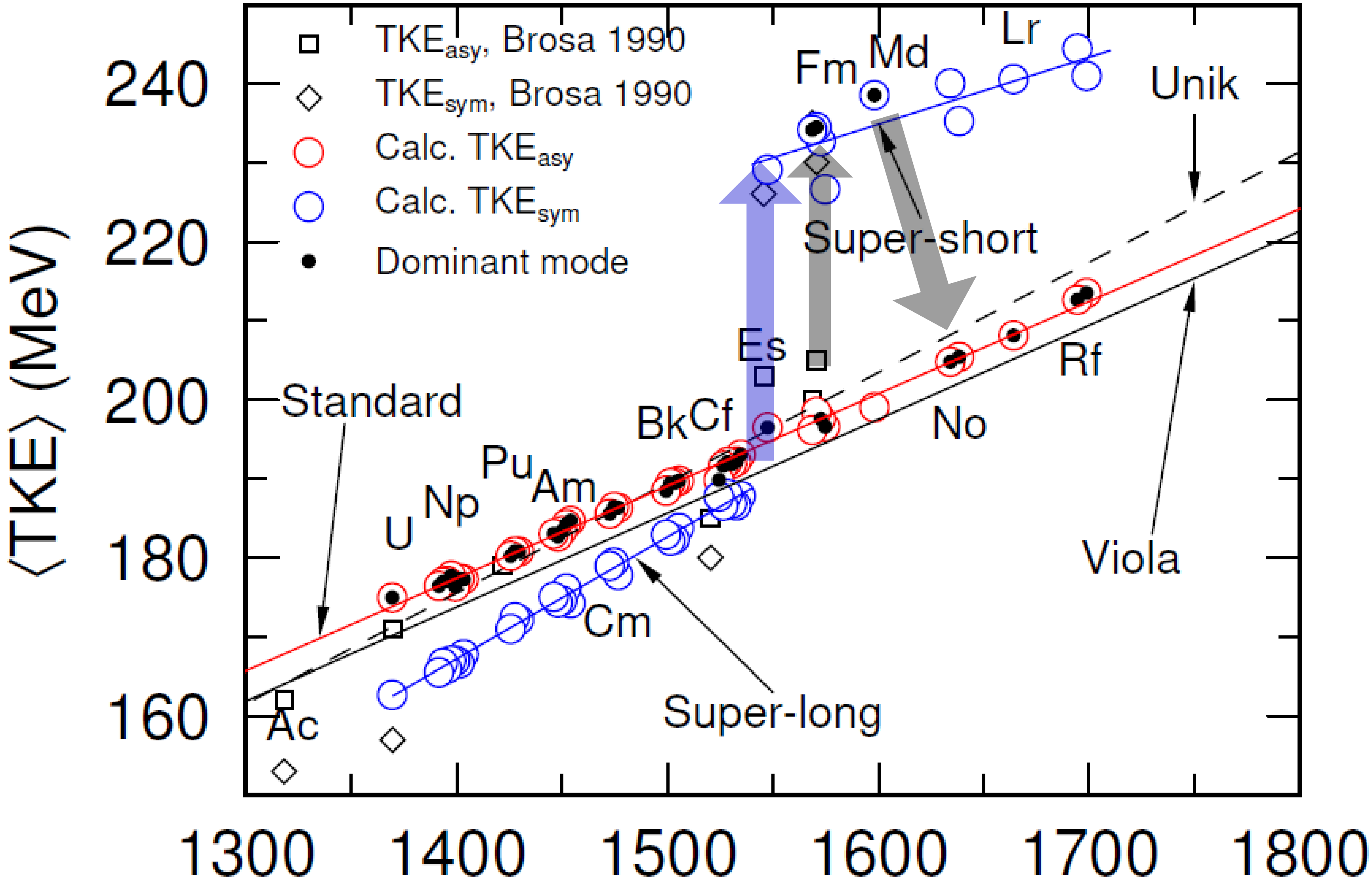


Systematics



M. Usang et al.,
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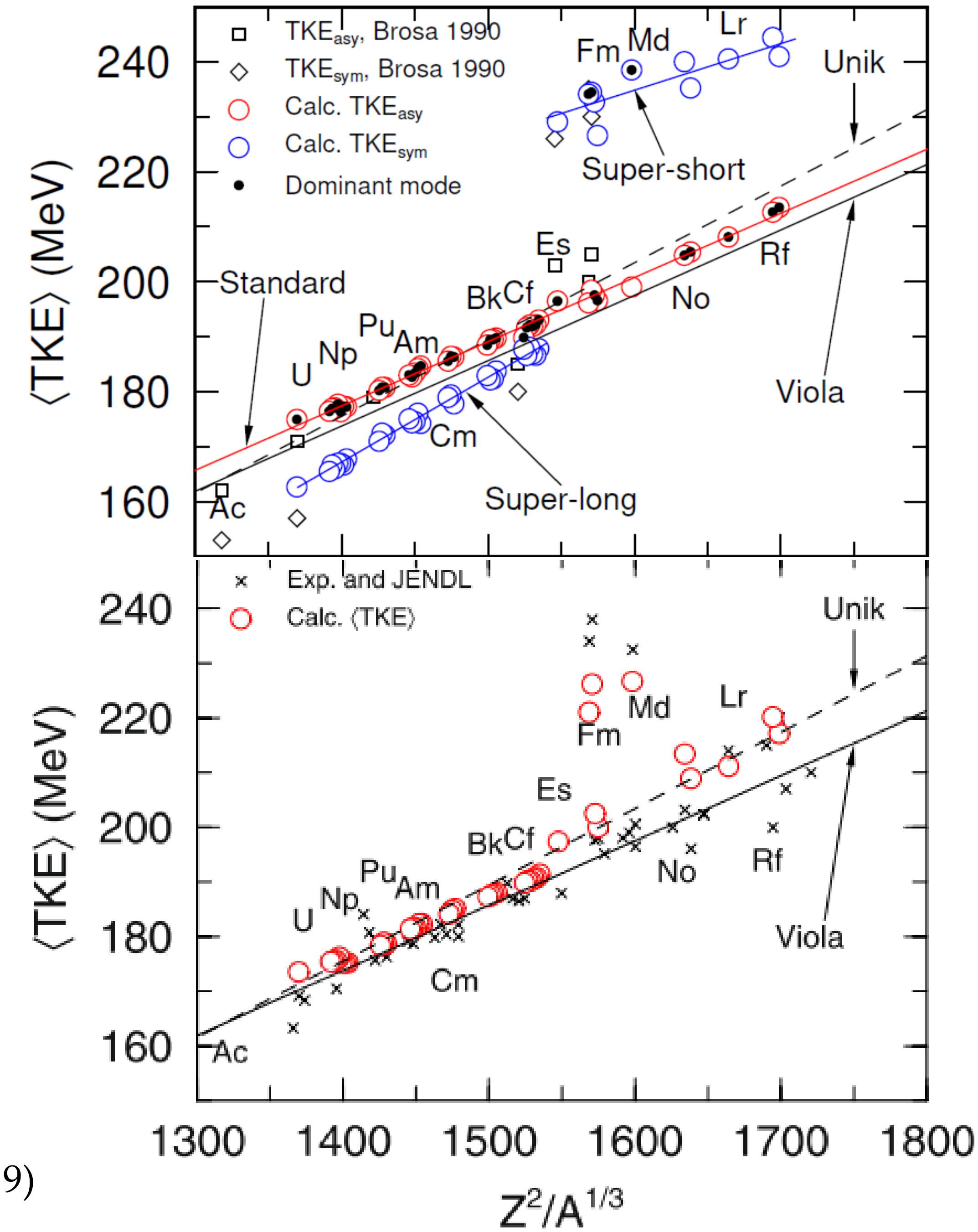
Systematics

Dominant modes @TKE anomalies

Standard mode
↓
Super-short mode
↓
Standard mode

Symmetric modes @TKE anomalies
↓
Super-long mode

Super-short mode



M. Usang et al., *Scientific Reports* **9**, 1525 (2019)

Results

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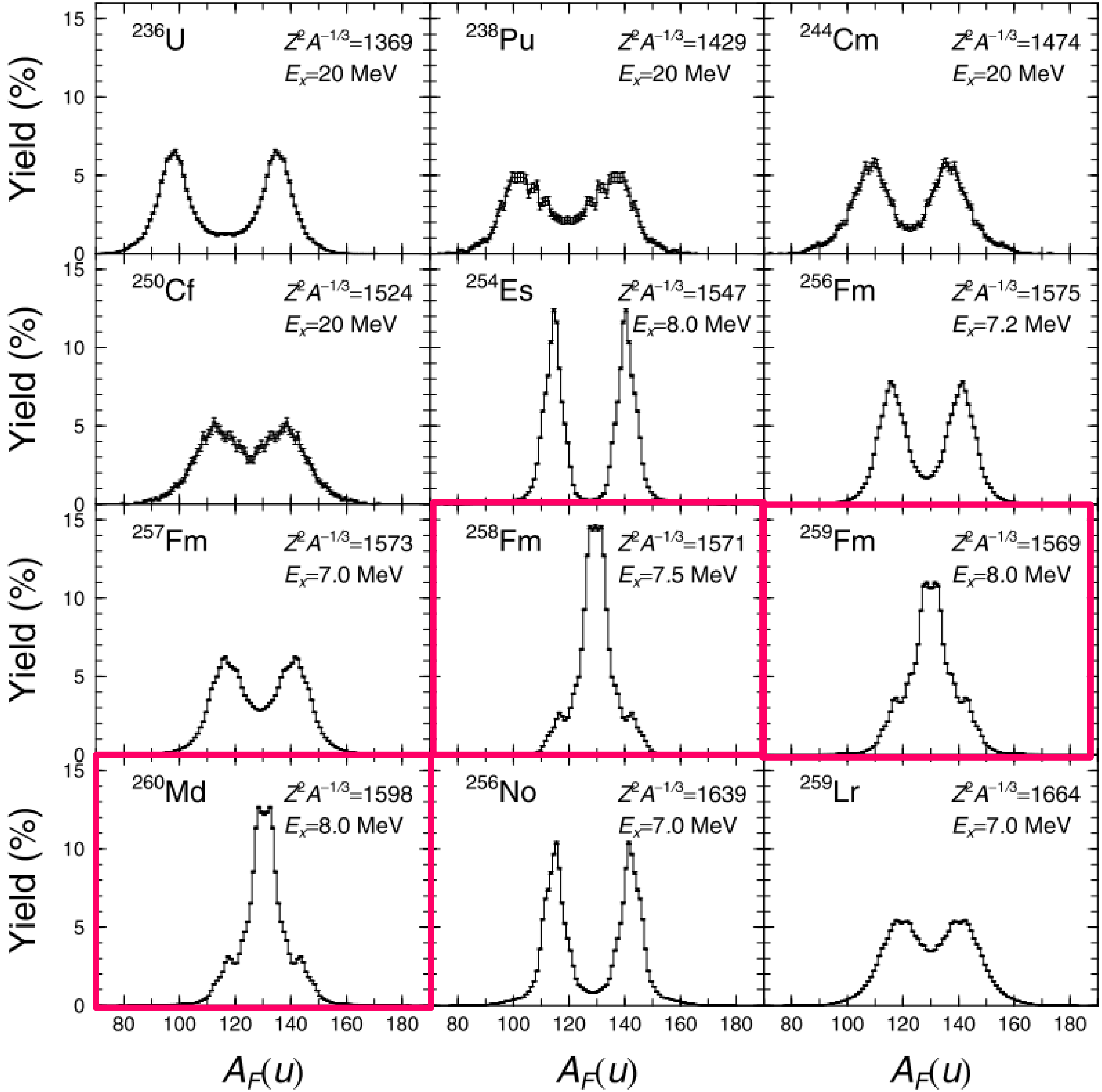
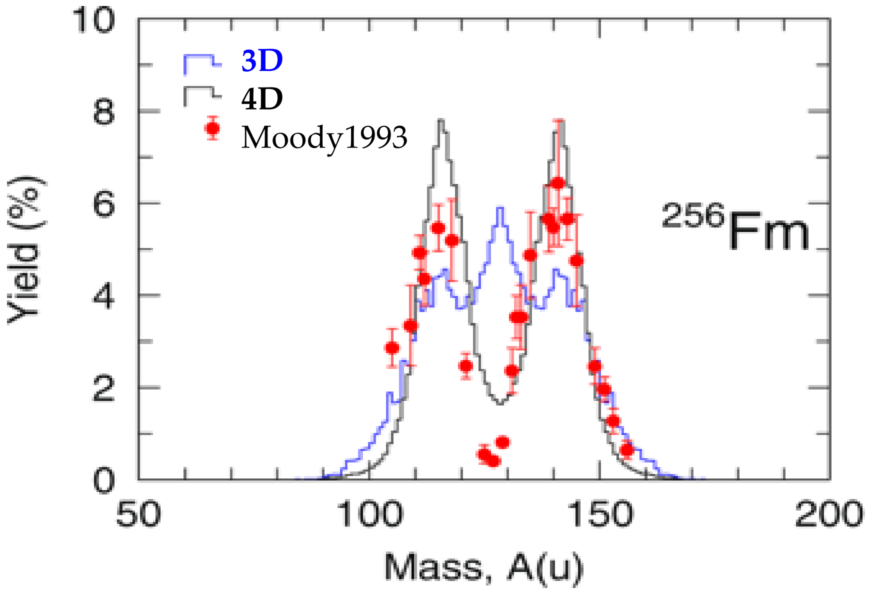
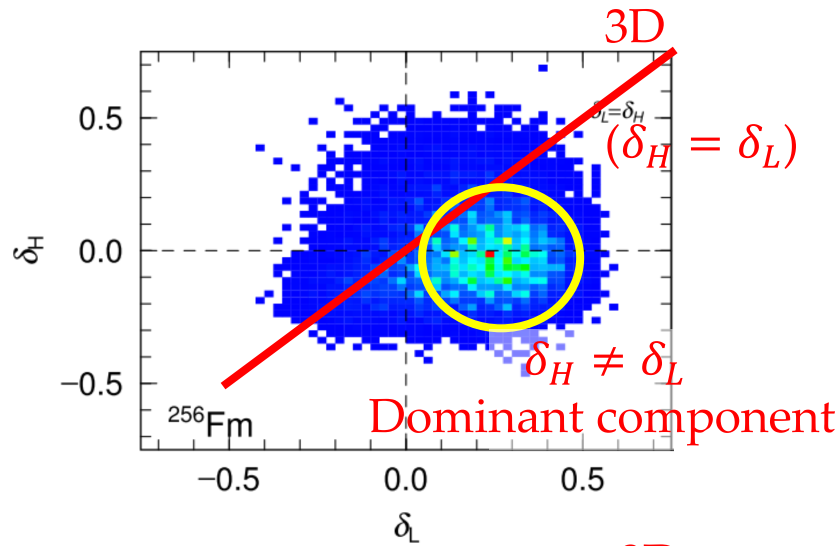
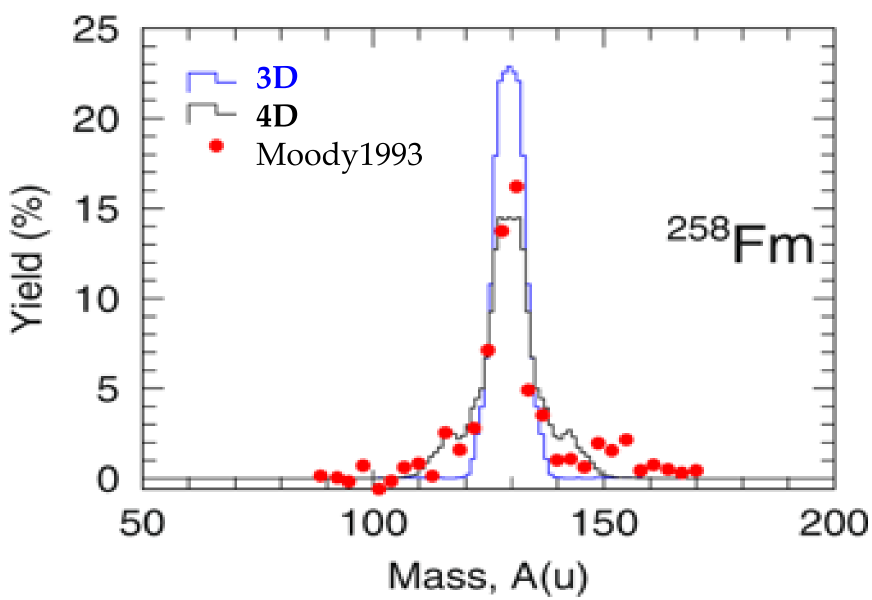
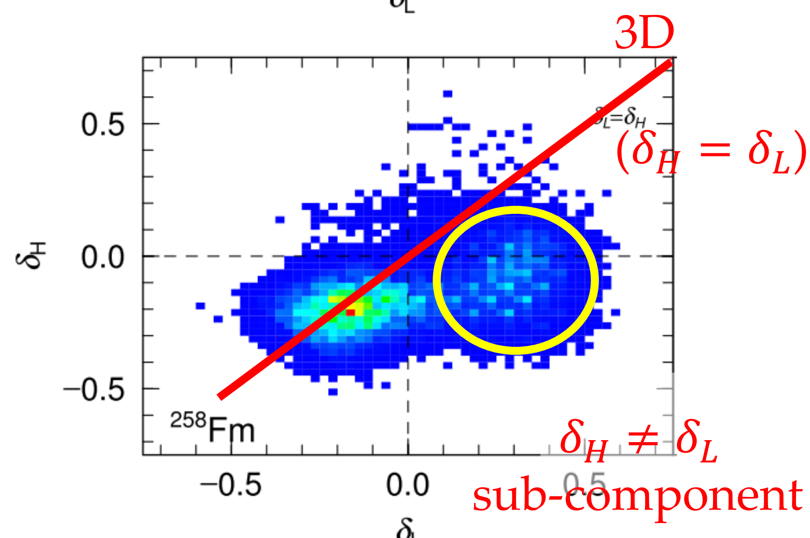


Results









M. Usang et al.,
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Results

$\delta_H = \delta_L$ (3D)

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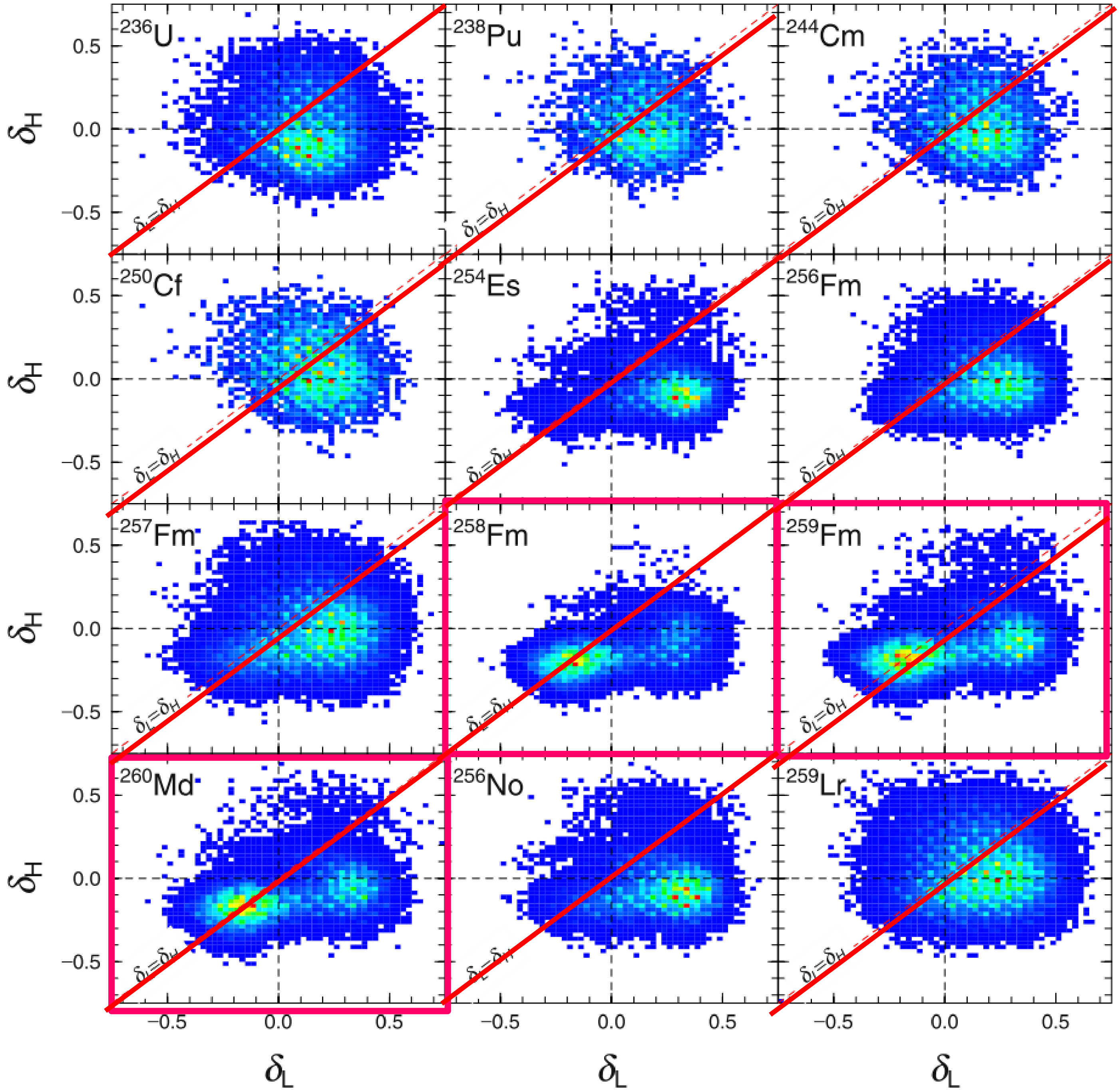
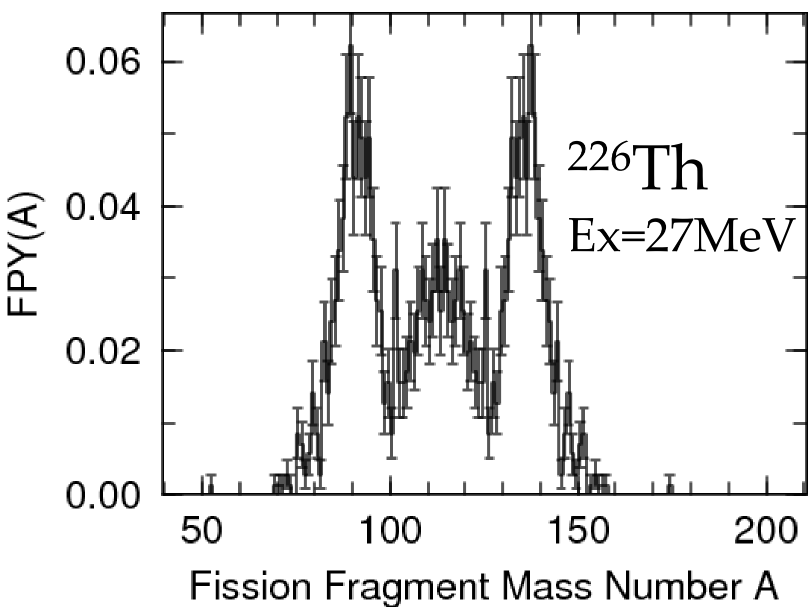
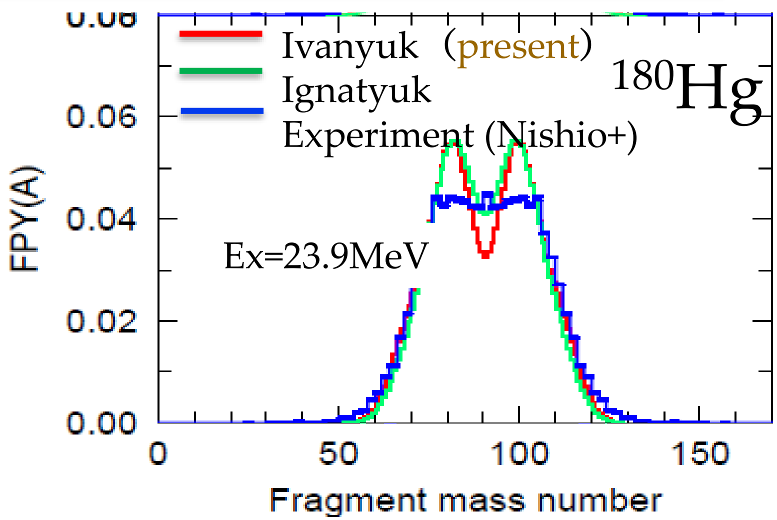


^{226}Th (Ex=27MeV) and ^{180}Hg

Two-center model parametrization, 4D-Langevin model,
Finite-depth Woods-Saxon type (mean-field) potential to calculate single-particle energy and shell corr.

Shell corr. calculated exactly starting from their definitions
Without any approximation.
Ivanyuk et al. (2018) Phys. Rev. C 97, 054331]





	<TKE>
Present (with Ivanyuk+2018)	**137.92 MeV**
Nishio+2015, ^{180}Hg*	131.7(10) MeV
βDF study of ^{180}Tl, ^{180}Hg	133.2(14) MeV
Viola systematics	142.1 MeV

Conclusion and way forward

- Our 4-D Langevin calculations reveals that
  - the standard fission modes are dominant except ^{258}Fm, ^{259}Fm and ^{260}Md
  - the symmetric component **switches from super-long to super-short fission mode from** Es to larger fissioning system.
  - when the fragments of **^{258}Fm, ^{259}Fm and ^{260}Md** prefers double magic configuration, the only channel available in the symmetric component is super-short
- 4-D Langevin equation allows natural transition from ^{256}Fm to ^{258}Fm.
- **3D Langevin is not sufficient to describe all possible fission path.**

- Shell correction factor approximates higher temperature potential energy surfaces by moderating the contribution of shell correction.
- However, we noticed that careless applications of shell correction may give misleading conclusions. Thus we suggest either judicious choice of shell corrections depending on experimental situations
  - Ivanyuk et al. (2018) [Phys. Rev. C 97, 054331] shell correction factors for various fissioning systems
  - calculate shell corrections for a given temperature.

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Thank you for your attention.