Influence of fission-fragment yields on r-process nucleosynthesis

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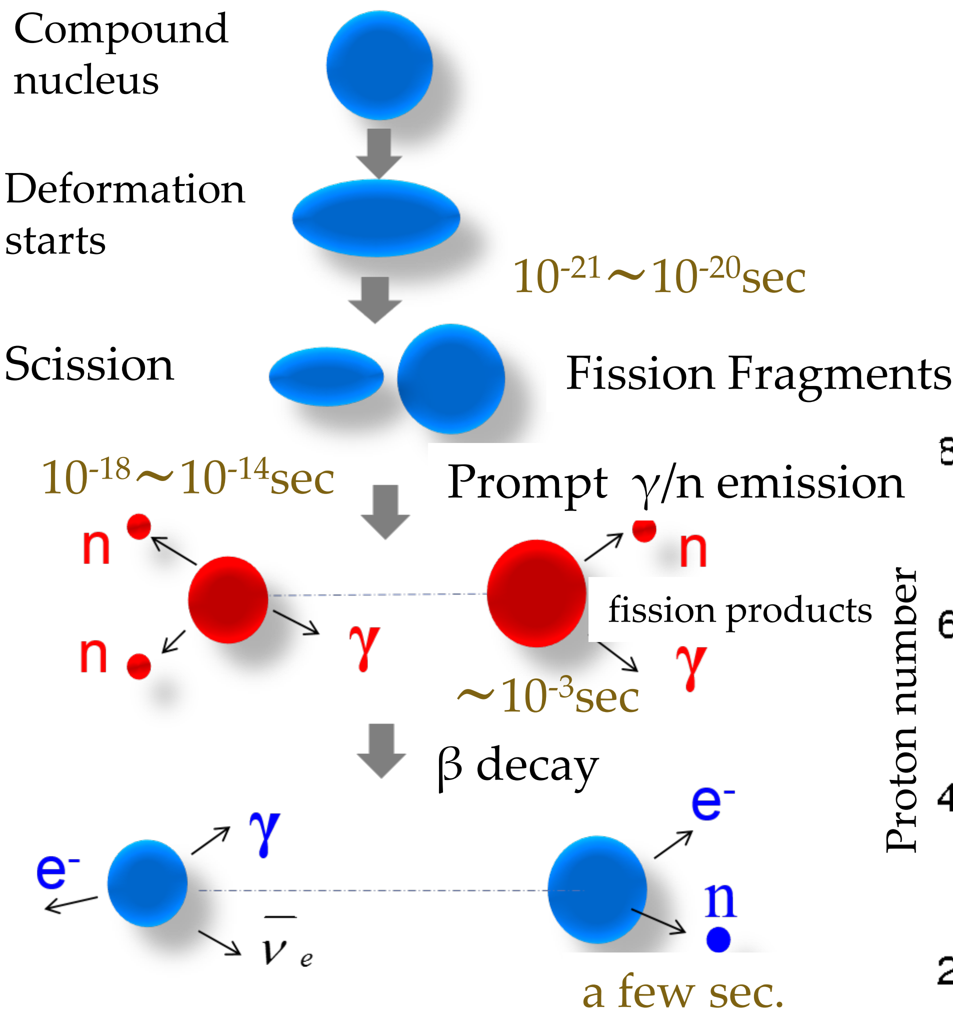
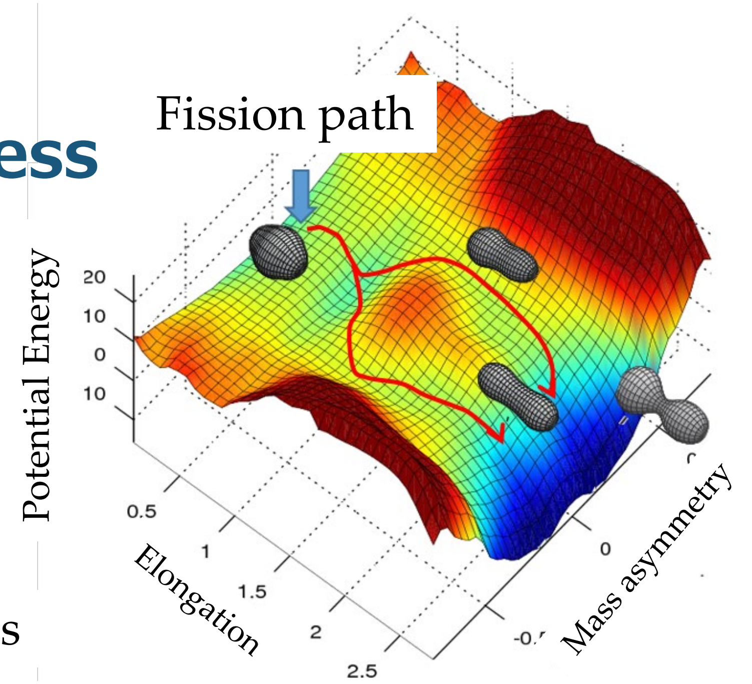
- KAKENHI Grant Number 18K03642 (JSPS)

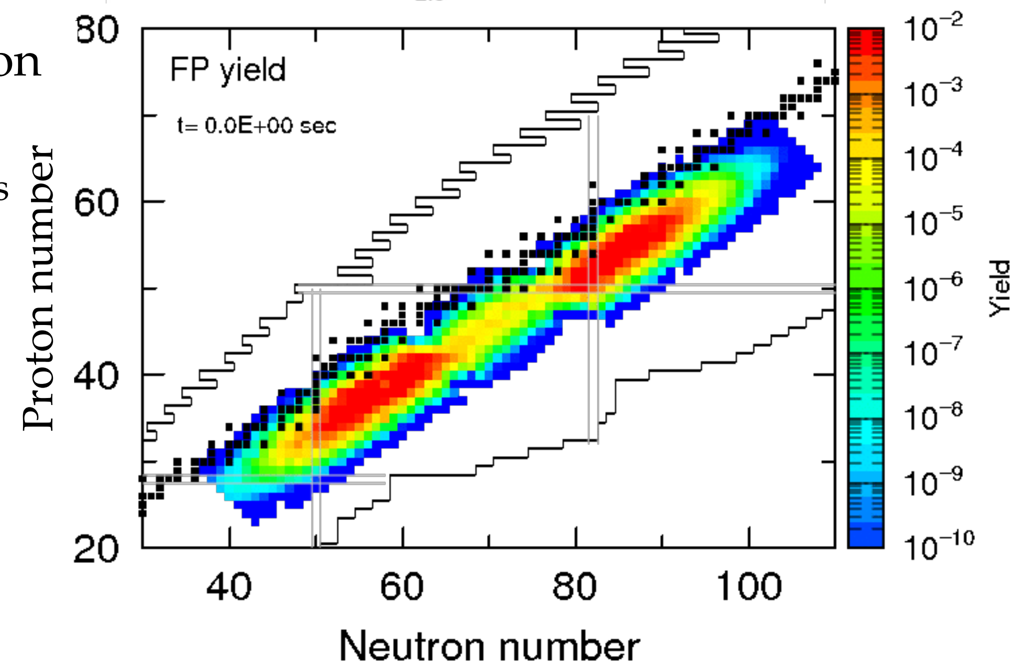
OMEG15, Kyoto, on July 2nd 2019

Introduction

Nuclear fission and r-process







cf) neutrons are captured earlier than decay process in r-procrss

Introduction Nuclear fission and r-process

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Discovery of nuclear fission
Nuclear fission model

r-process incl. fission cycles
Burbidge et al., 1957

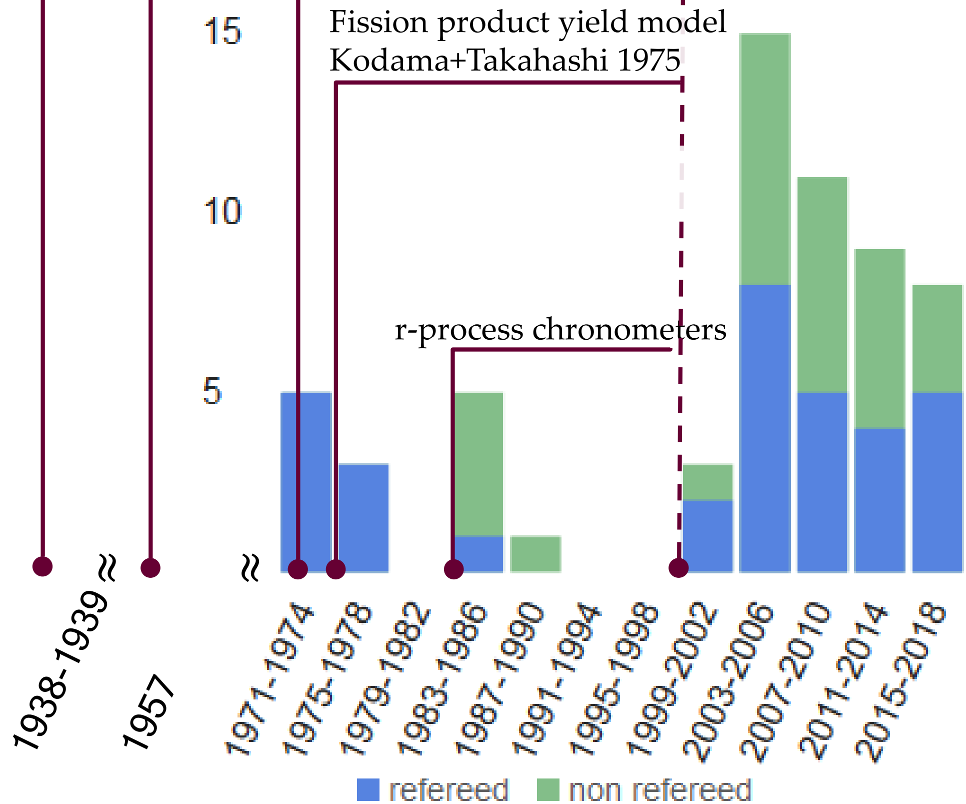
Two center shell model
Maruhn+Greiner 1972

Fission product yield model
Kodama+Takahashi 1975

r-process chronometers

r-process in SNe, NS mergers

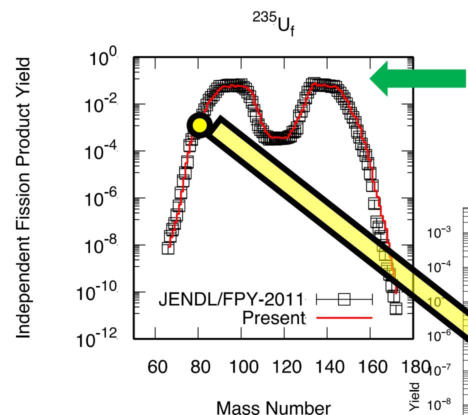
Japan GP (Wanajo, Otsuki, Nishimura, Shibagaki, Kajino etc.)
Basel GP, Darmstadt GP, LANL GP etc.



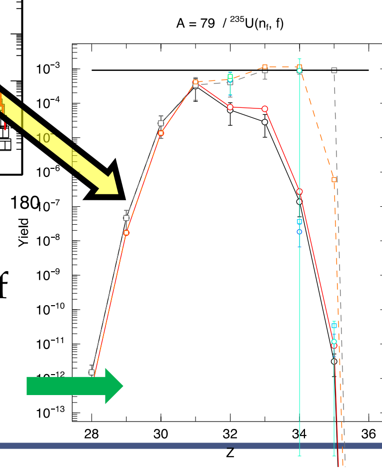
no. of results by ADS search with "fission x r-process"

【Quantities relating to r-process】

- Half life
- Fission barrier height
- Decay heat form FP
- Prompt neutrons
- **Fission Yields**



Mass distribution of fission fragments $Y(A)$ @n_{fast}+^{235}U



Charge distribution of fixed A, **Y(A, Z)**
≒ Gaussian dist.

- Influence of fission fragment mass yields on r-process nucleosynthesis

- Nuclear fission of SHE

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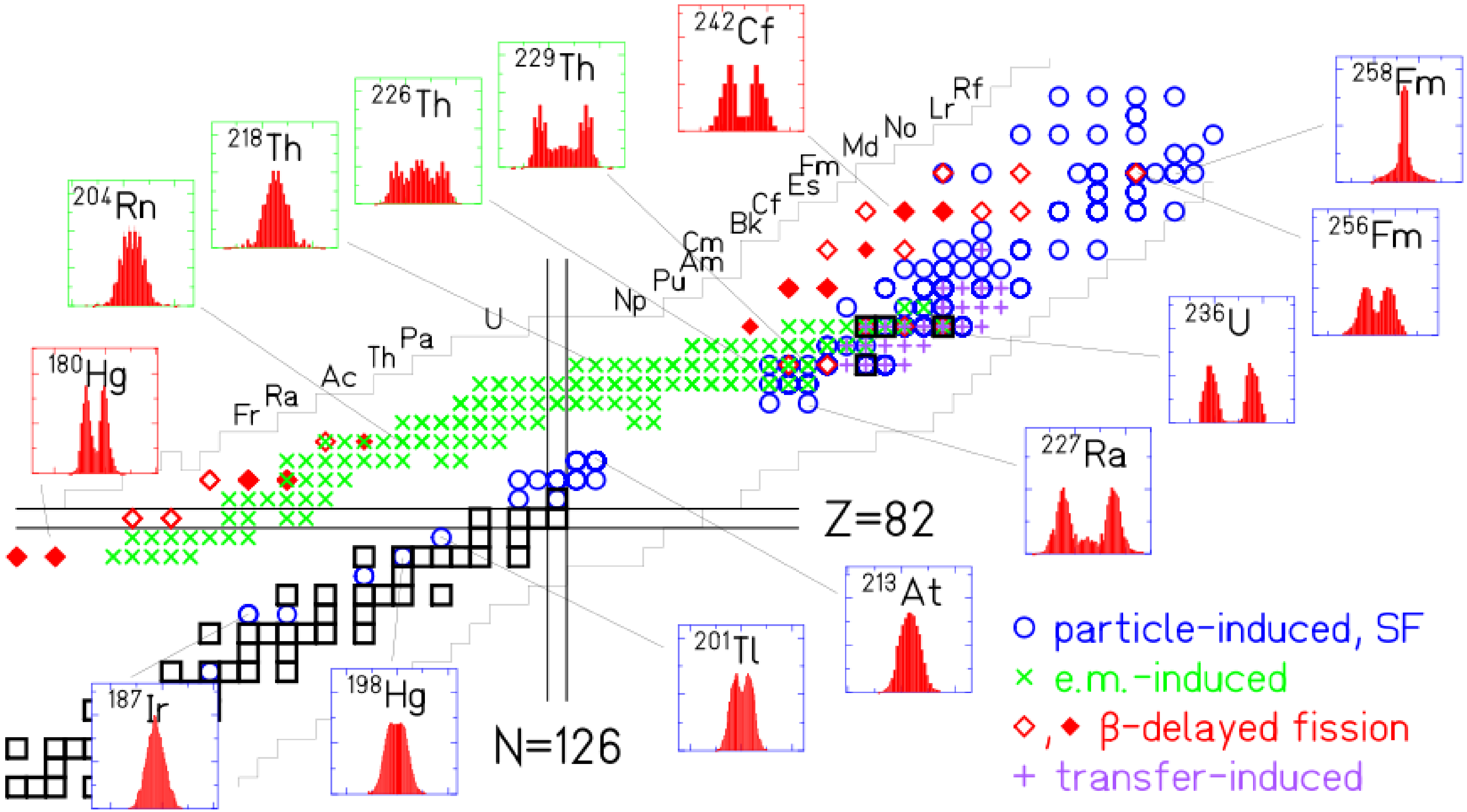
Introduction Nuclear fission and r-process

- ✓ Fission fragment mass distribution【Y(A)】is very sensitive to （Z, A） of the system
- ✓ Y(A) of very n-rich, heavy nuclei is model dependent



Model of fission fragment yield Y(Z,A)

Y(Z,A) : application of scission point model by Fong, Willkins

$\propto Z^2$ for fixed A

$$Y(Z,A) \propto \exp\left[-\frac{E_{\mathrm{LD}}(Z,A) + \Phi(E^*)\Delta E_{\mathrm{sh}}(Z,A)}{T(Z,A)}\right]$$

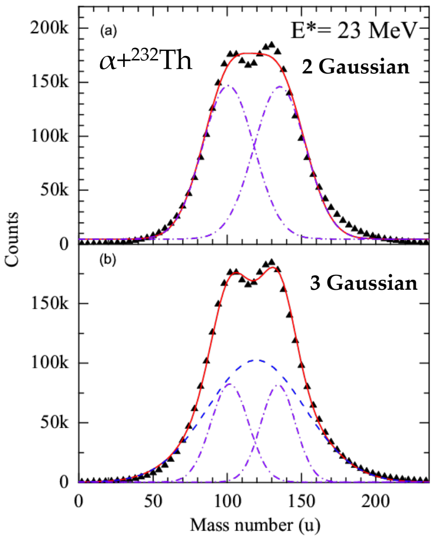
Gaussian distribution odd-even effects

$$\approx Y(A)\frac{1}{\sqrt{2\pi}\sigma(A)}\int_{-0.5}^{0.5}\exp\left[-\frac{\left(Z-Z_{\mathrm{p}}(A)+t\right)^2}{2\sigma(A)^2}\right]dt \times e^{-\frac{\Delta E_{\mathrm{sh}}(Z,A)}{E_d(A)}}$$

$\sigma(A) \approx 0.5,\ E_d(A) \approx 5-10MeV$

ΔE_{sh}: KTUY (Koura+2005)

Previous work using Two center shell model and three-dimensional Langevin model (Ohta+2007)



$$Y(A) = \frac{1}{\sqrt{2\pi}\sigma}(1-w_s)\left(e^{-(A_H-A)^2/2\sigma^2} + e^{-(A_L-A)^2/2\sigma^2}\right)$$ $Y_{asym}(A)$

$$+\ 2w_s\frac{1}{\sqrt{2\pi}\sigma}e^{-((A-N_{loss})/2-A)^2/2\sigma^2}.$$ 【$Y_{sym}(A)$】

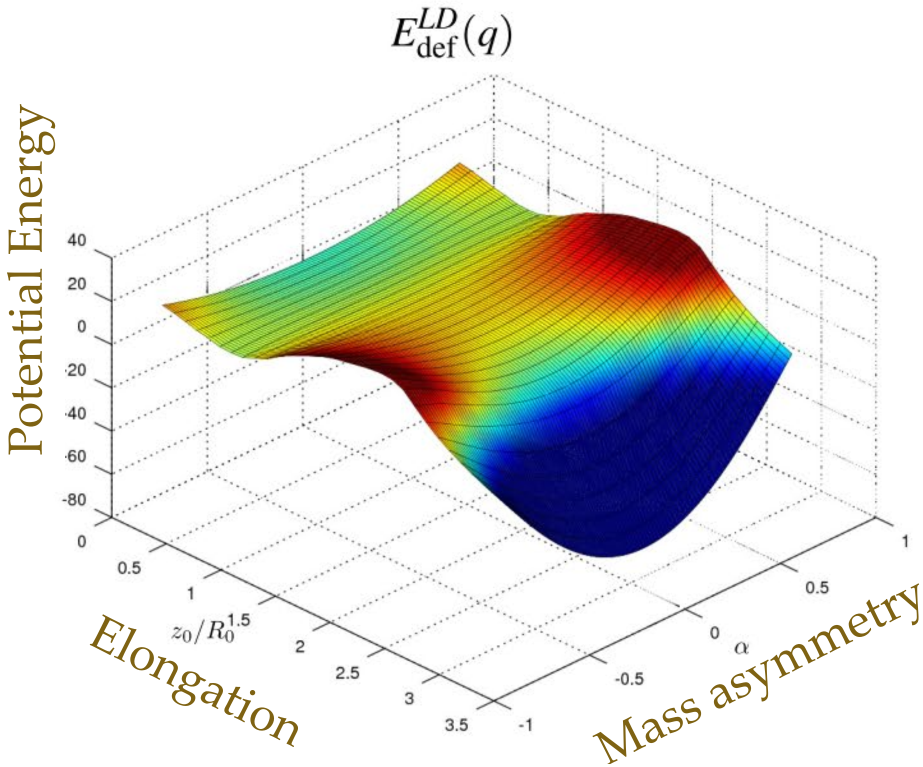
$N_{loss} = 2$

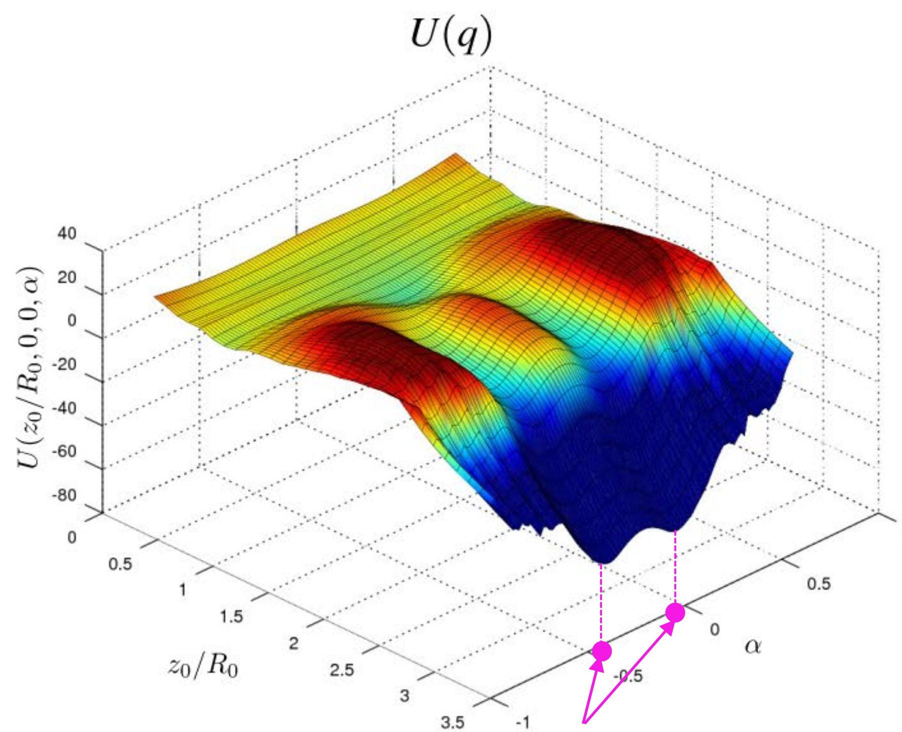
A_H, A_L determined by potential energy landscape

σ, W_s determined using results of 3D-Langevin calc.

Model of potential energy surface

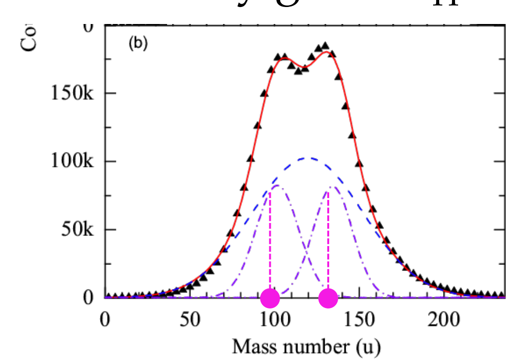
$$U(q) = E^{LD}_{\rm def}(q) + \sum_{n,p} \left[\Phi_{\rm shell}\delta E_{\rm shell}(q, T=0) + \Phi_{\rm pair}\delta E_{\rm pair}(q, T=0)\right]$$



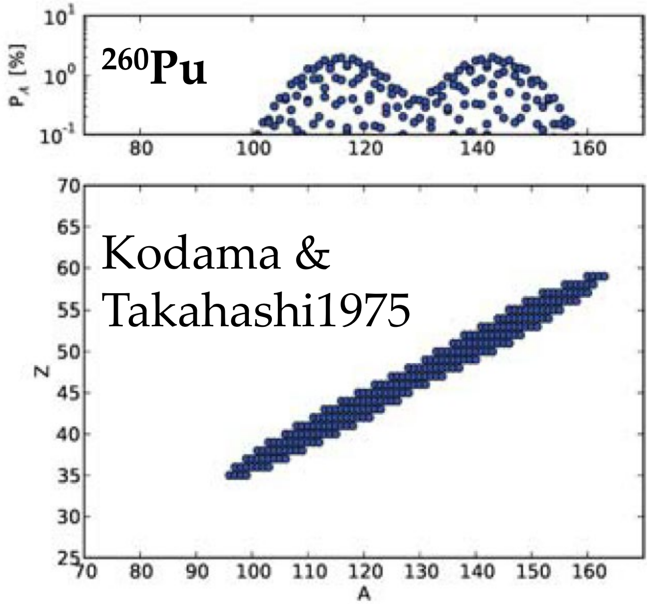


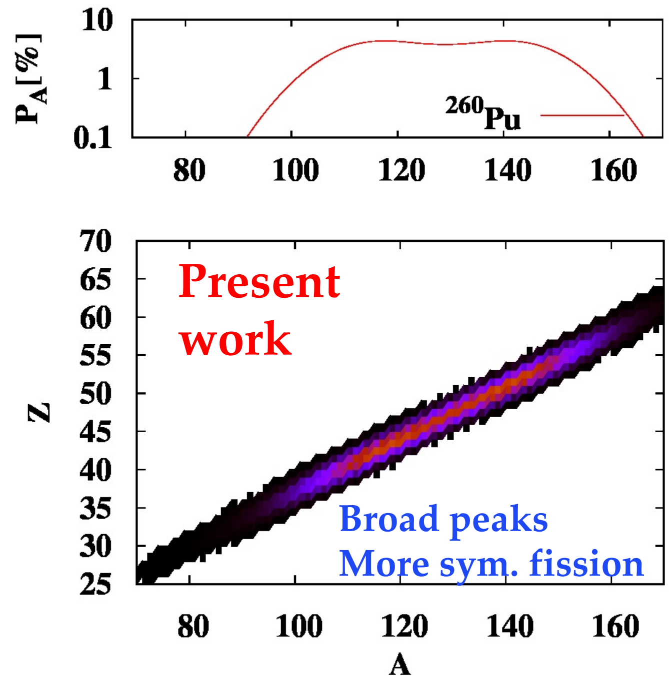
Potential valley gives A_H & A_L

$$Y(A) = \frac{1}{\sqrt{2\pi}\sigma}(1 - w_s)\left(e^{-(A_H - A)^2/2\sigma^2} + e^{-(A_L - A)^2/2\sigma^2}\right) + 2w_s\frac{1}{\sqrt{2\pi}\sigma}e^{-((A-N_{loss})/2-A)^2/2\sigma^2}.$$

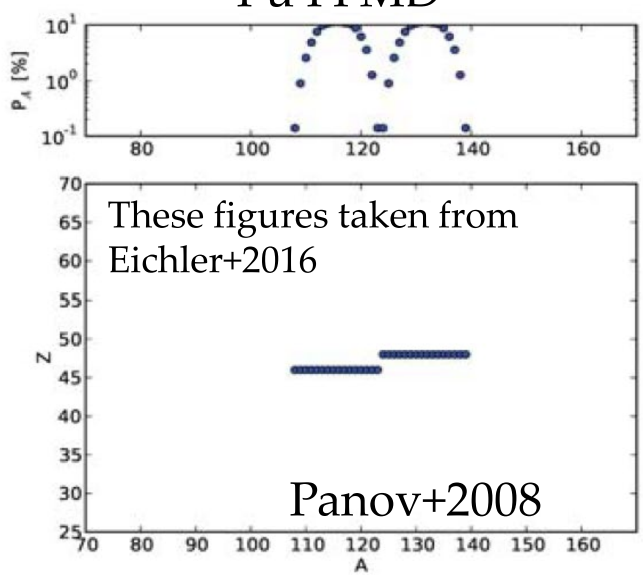


Result of Langevin calc. gives σ as a dynamic effect

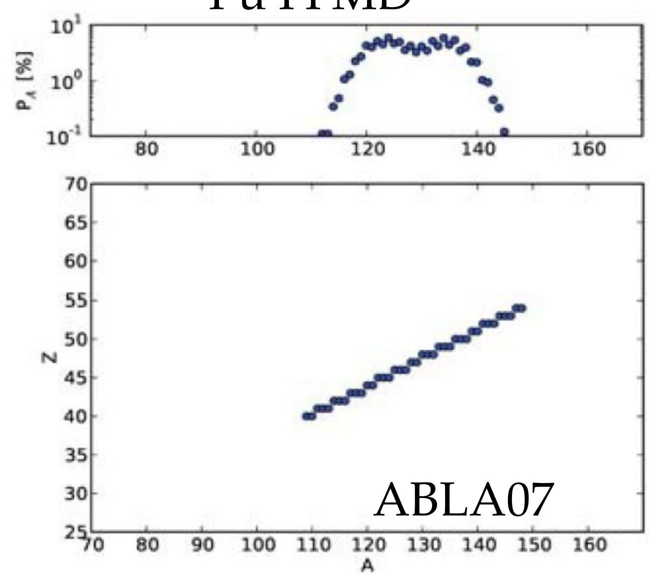




^{260}Pu FFMD

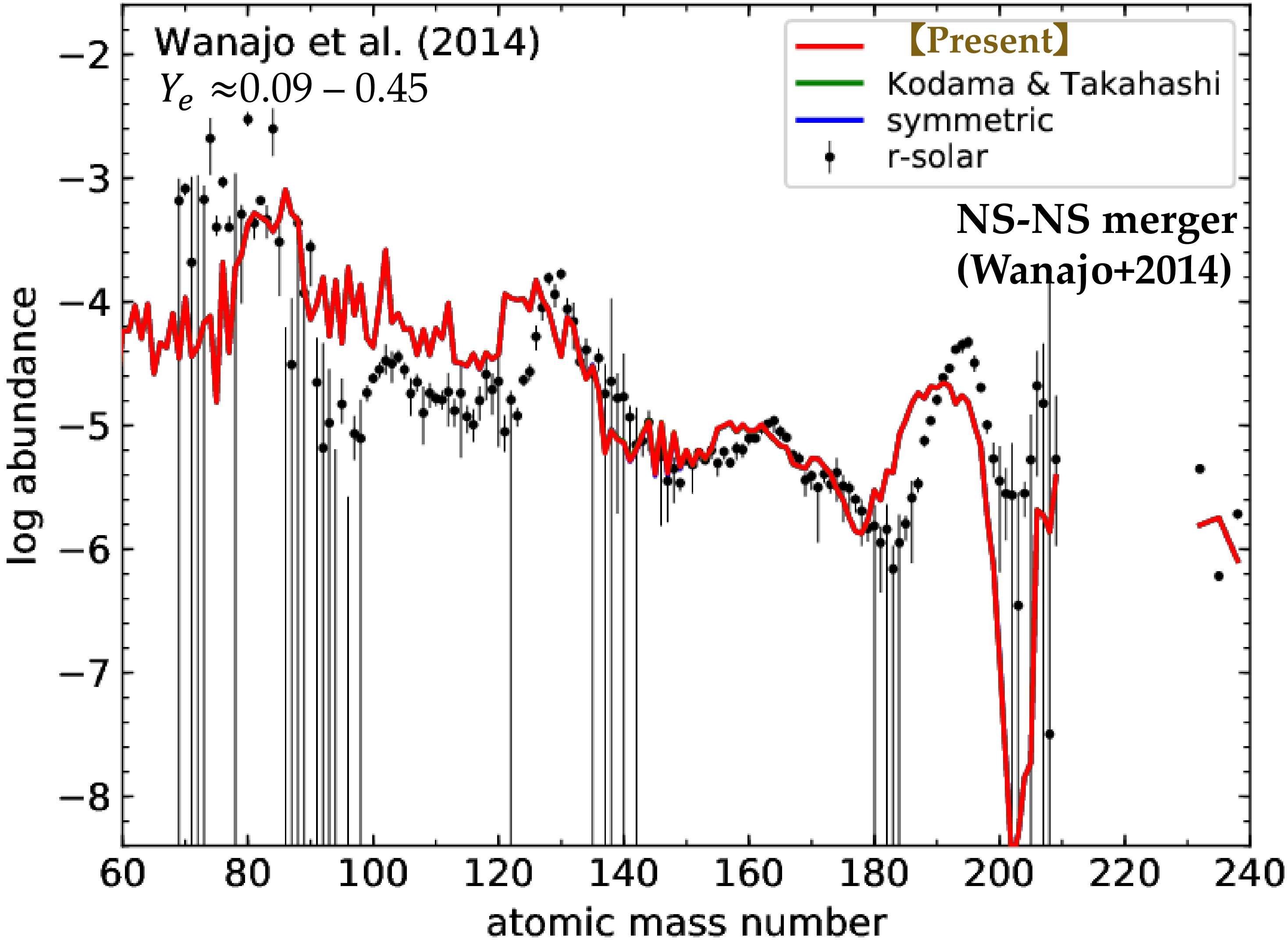


^{260}Pu FFMD



Results & Discussion

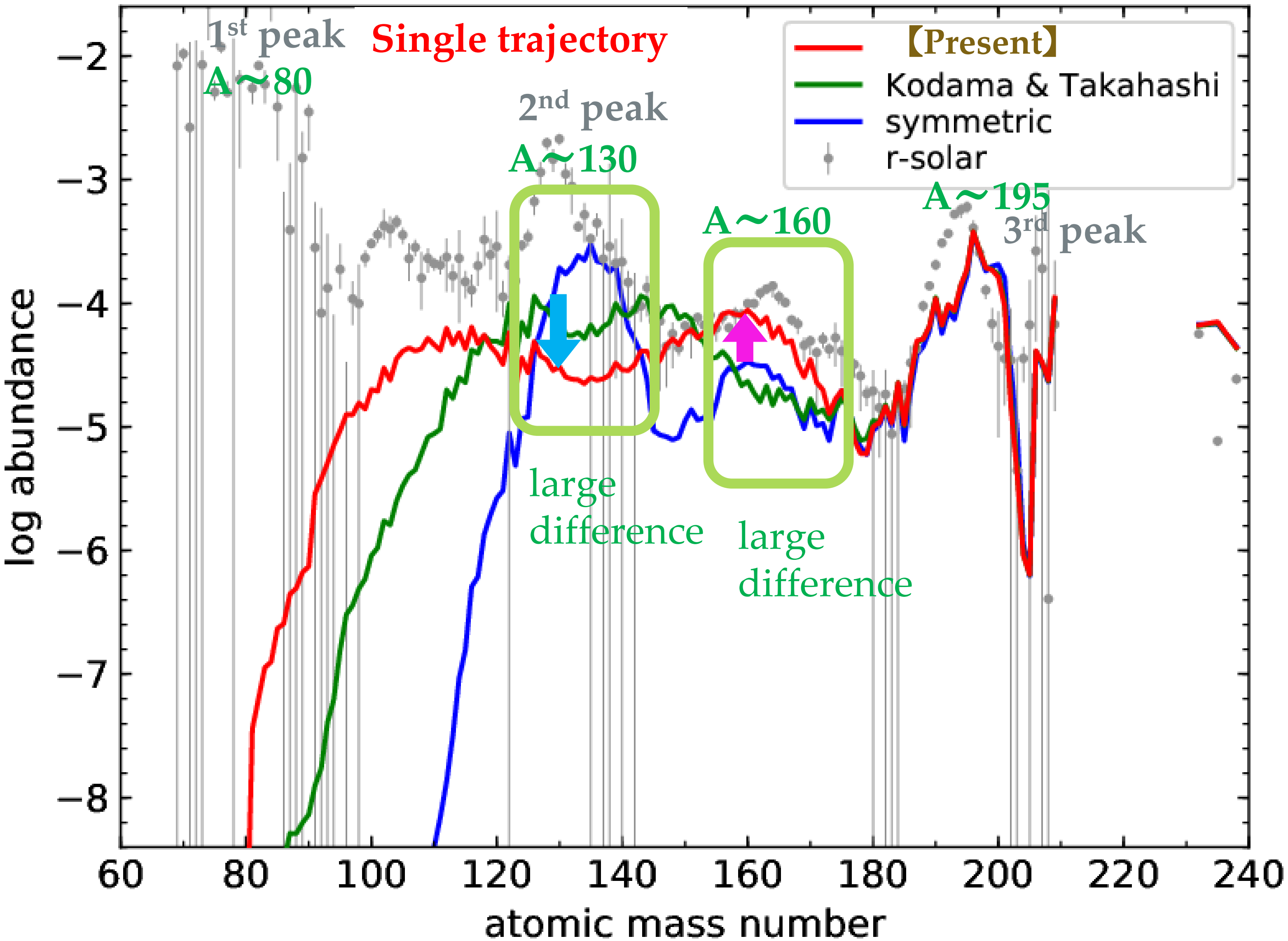
Influence of nuclear fission on r-process



Results & Discussion

Influence of nuclear fission on r-process

Single trajectory with **Ye=0.05** suggested by **BH-NS merger**



Summary of first part

- Test calculations to examine the influence of our Y(Z, A) on r-process in NS-NS, BH-NS mergers using following Y(Z,A) model

$$Y(Z,A) \approx Y(A)\frac{1}{\sqrt{2\pi}\sigma(A)}\int_{-0.5}^{0.5}\exp\left[-\frac{\left(Z-Z_{\mathrm{p}}(A)+t\right)^2}{2\sigma(A)^2}\right]dt \times e^{-\frac{\Delta E_{\mathrm{sh}}(Z,A)}{E_d(A)}}$$

New

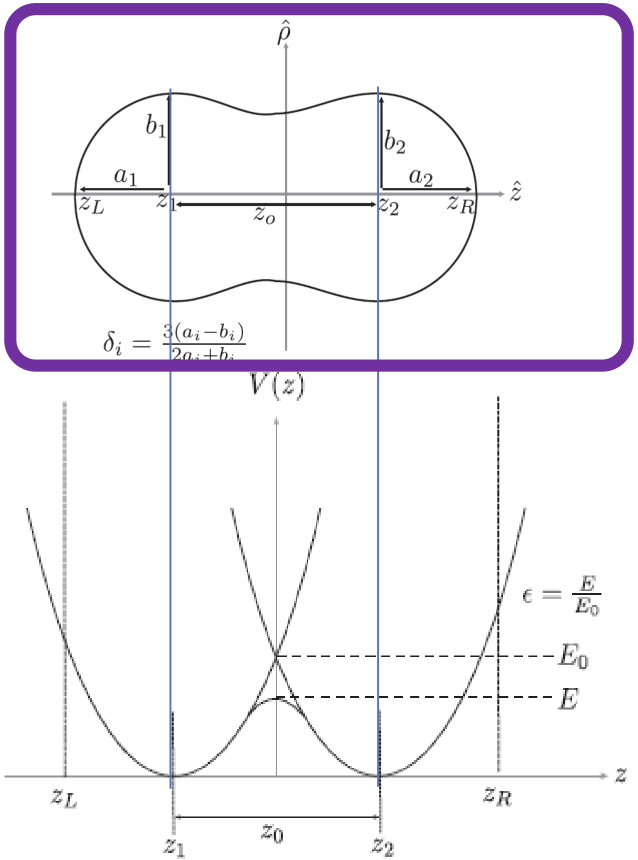
- Large difference due to Y(Z, A)-model can be seen at 2nd peak & rare earth peak of the solar abundance in the case of BH-NS mergers (Ye=0.05)

- Influence of fission fragment mass yields on r-process nucleosynthesis

- Nuclear fission of SHE

4-dimensional Langevin model

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



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

Drift term with Quantum Corr. — Friction (Diffusion term) — Random force (Fluctuation term)

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

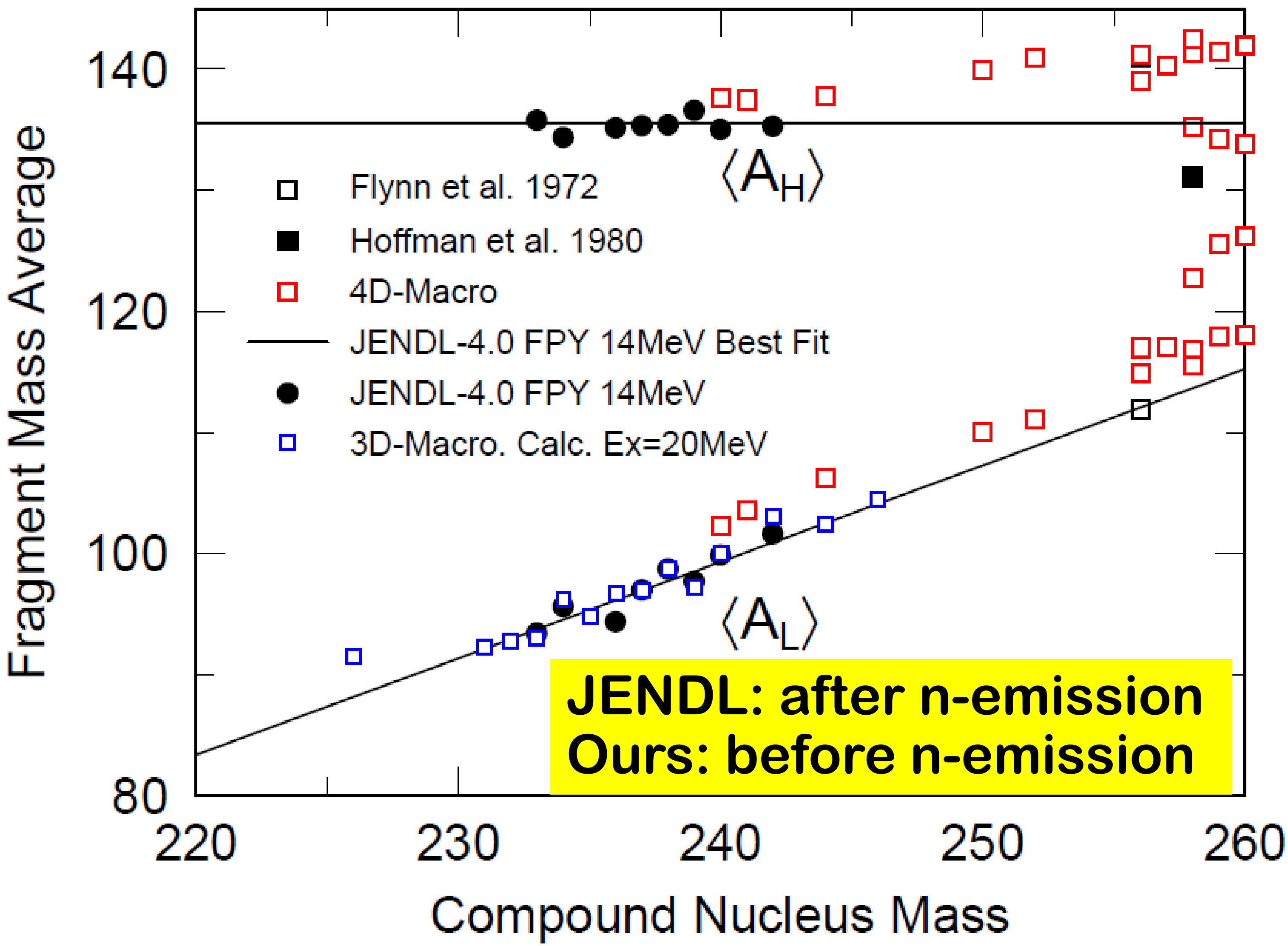
Shell corrections to the free energy F
derived from their formal definitions
without any additional approximations.
[Ref] F. A. Ivanyuk, et al, Phys. Rev. C 97, 054331 (2018)

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.

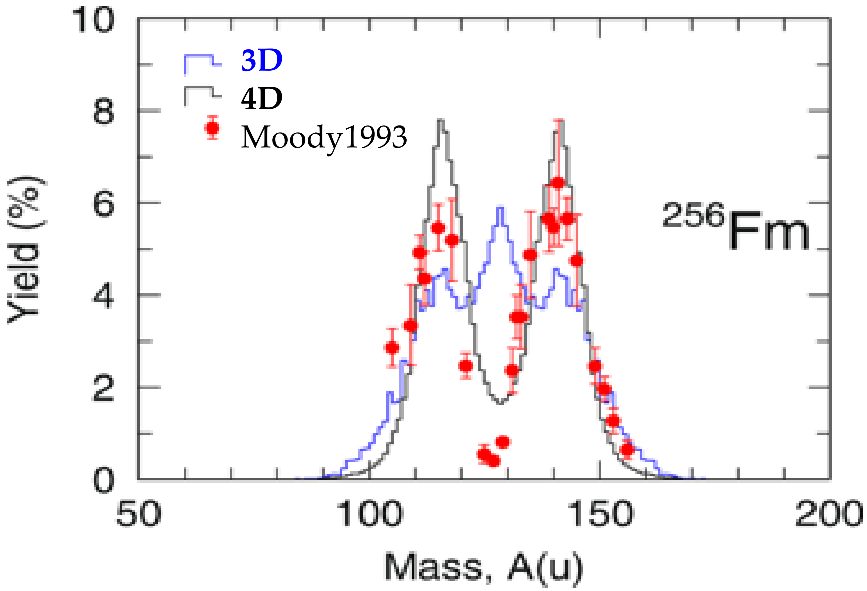
Shape parametrization in the two-center model proposed by Maruhn & Greiner 1972
$q_i=(z_0, d_1, d_2, a)$ in 4D or $q_i=(z_0, d, a)$ in 3D ($d_1=d_2$)
Fixed parameters

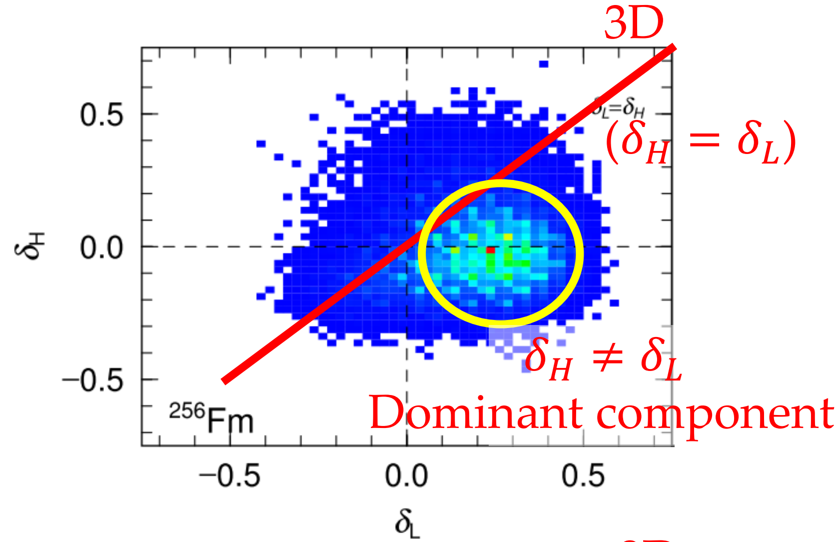
- Neck parameter $e=E/E_0$
- The local frequency of collective motion ω

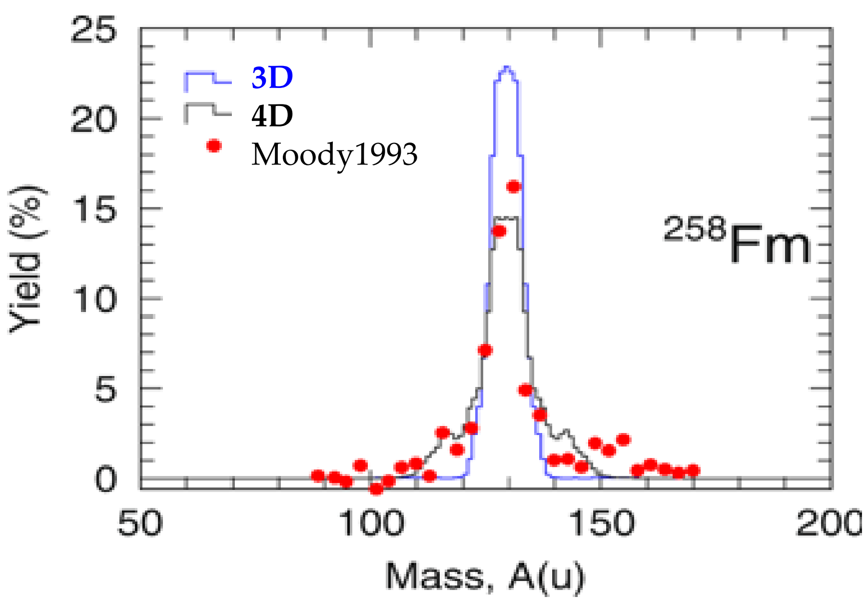
Fragment masses of spontaneous fissions

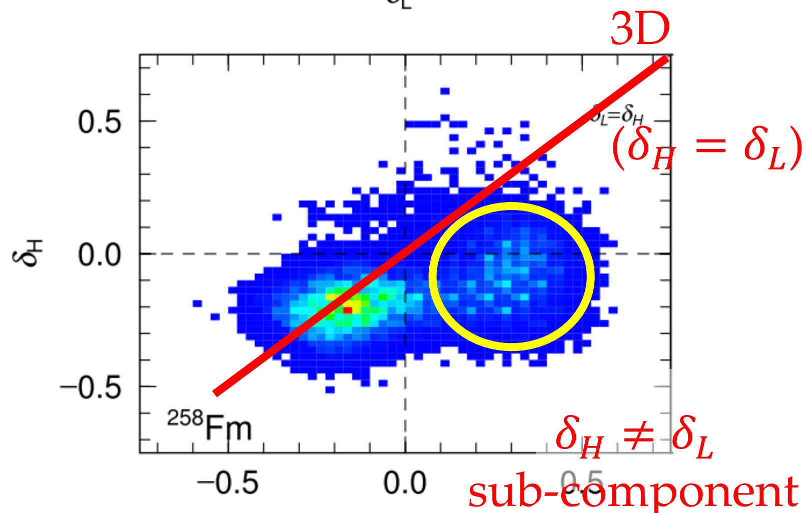


Results







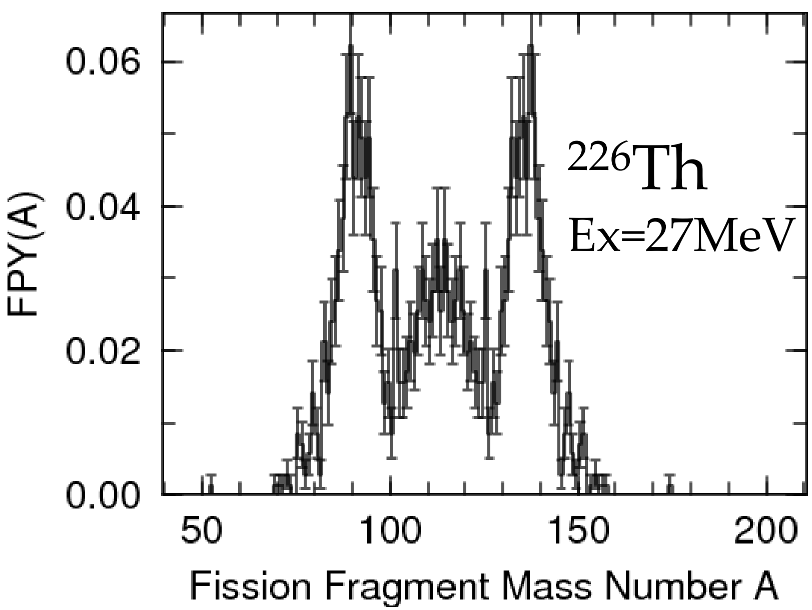


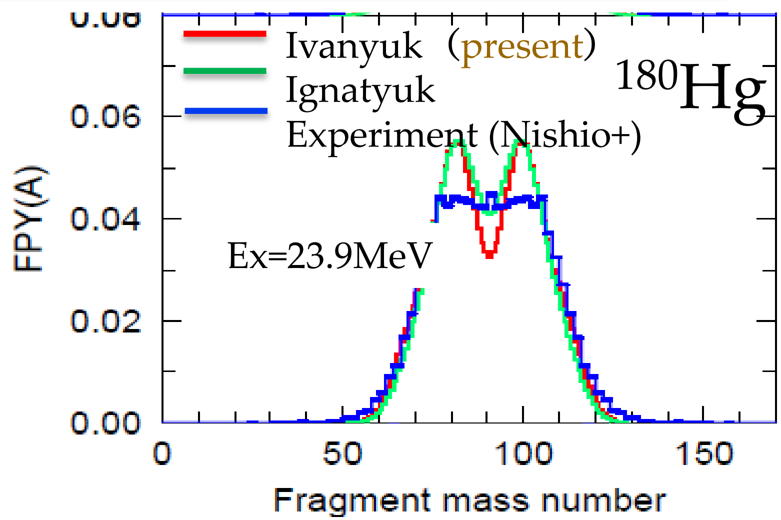
M. Usang et al.,
Scientific Reports **9**, 1525 (2019)

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

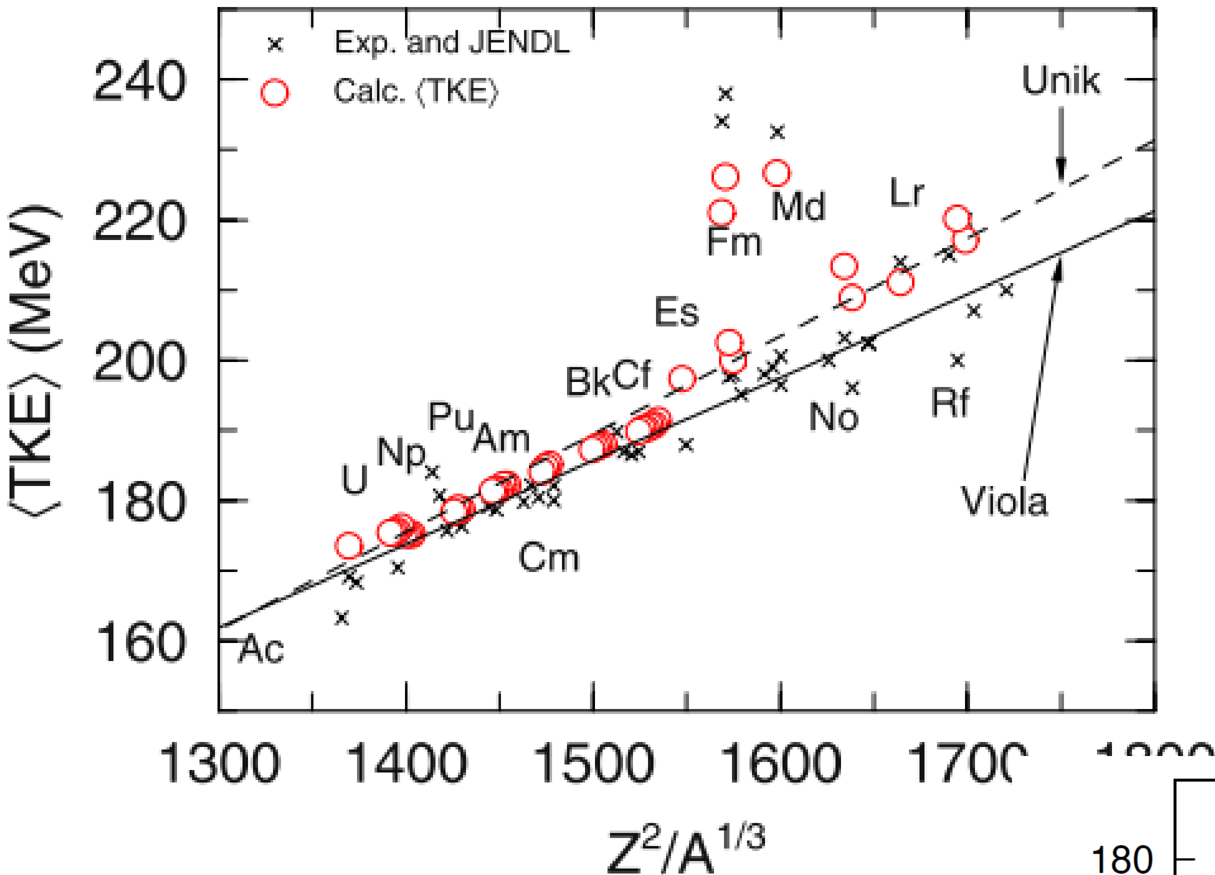
Two-center model parametrization, 4D-Langevin model,
Finite-depth Woods-Saxon type (mean-field) potential to calculate single-particle energy and shell corr.

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



M. Usang et al.,
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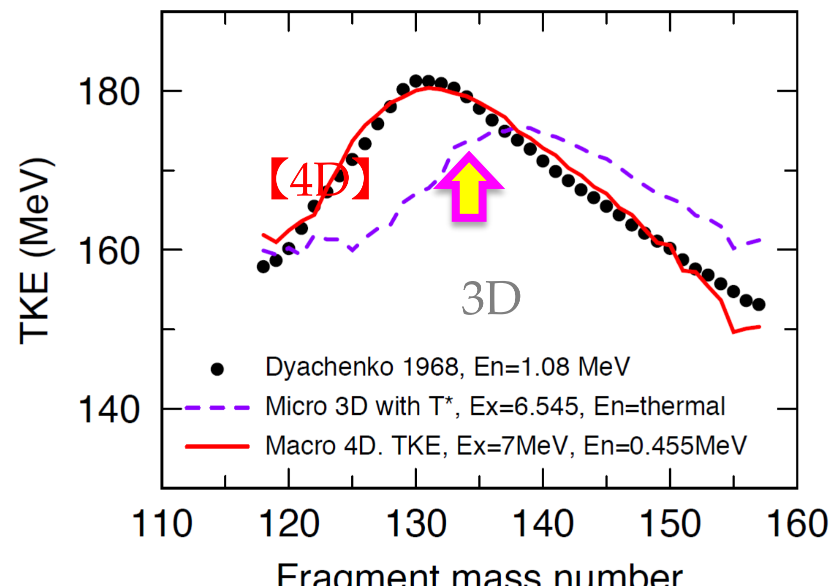
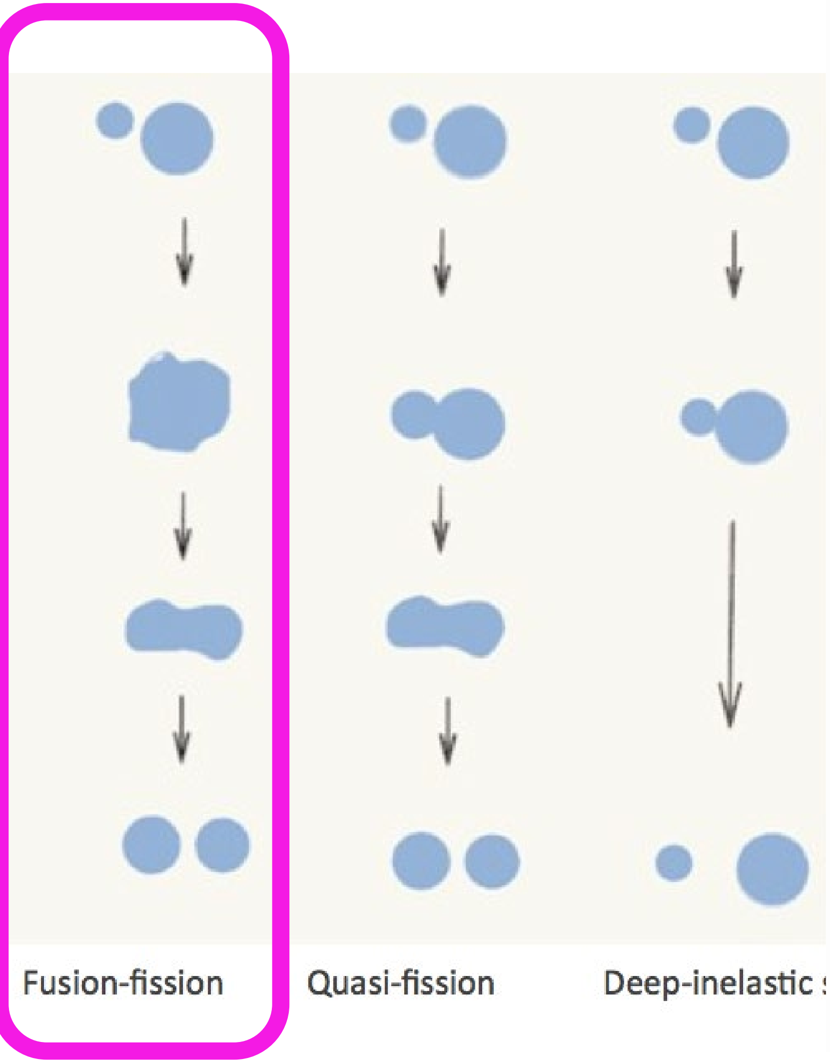
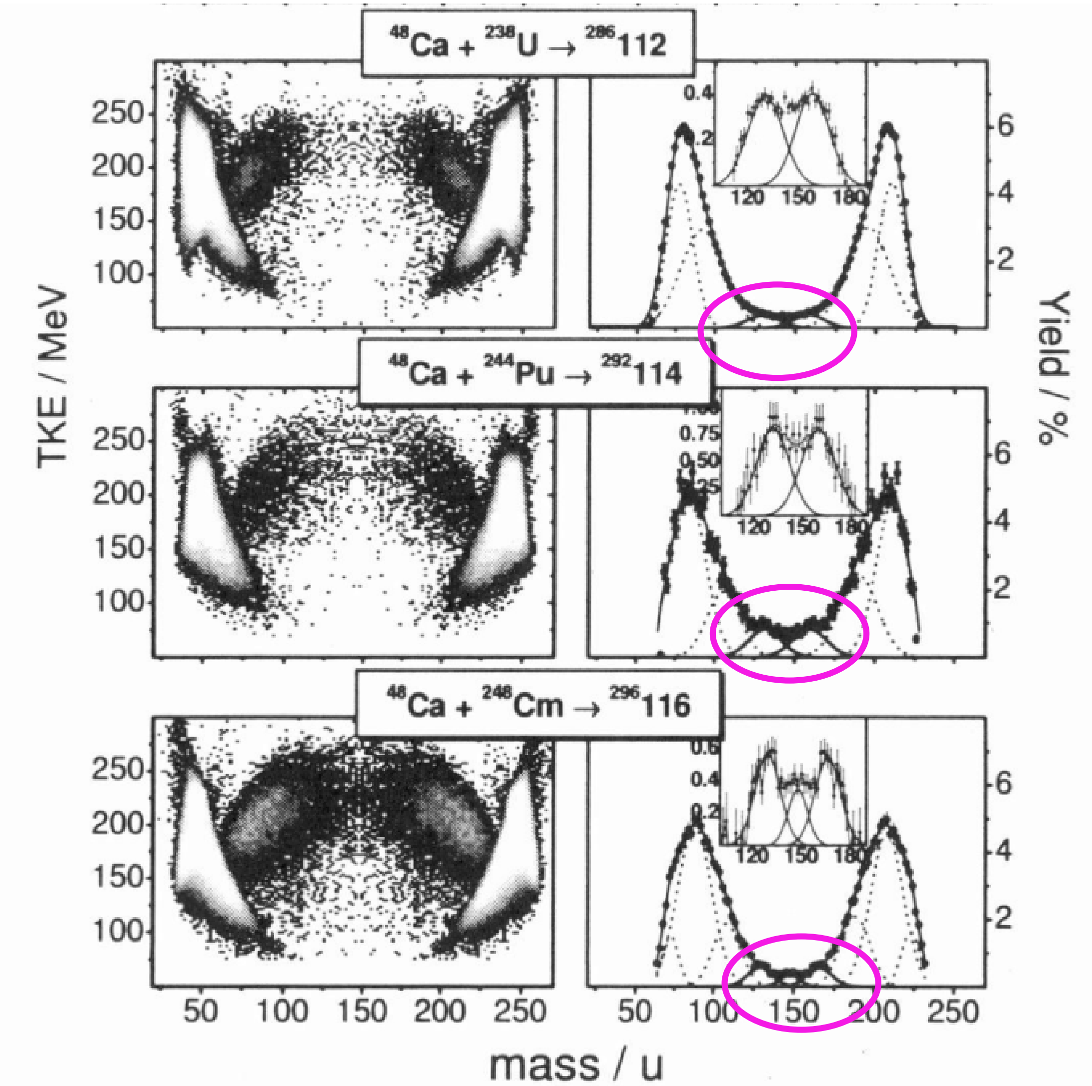


Results of fission calculation of ^{274}Hs - $^{306}122$

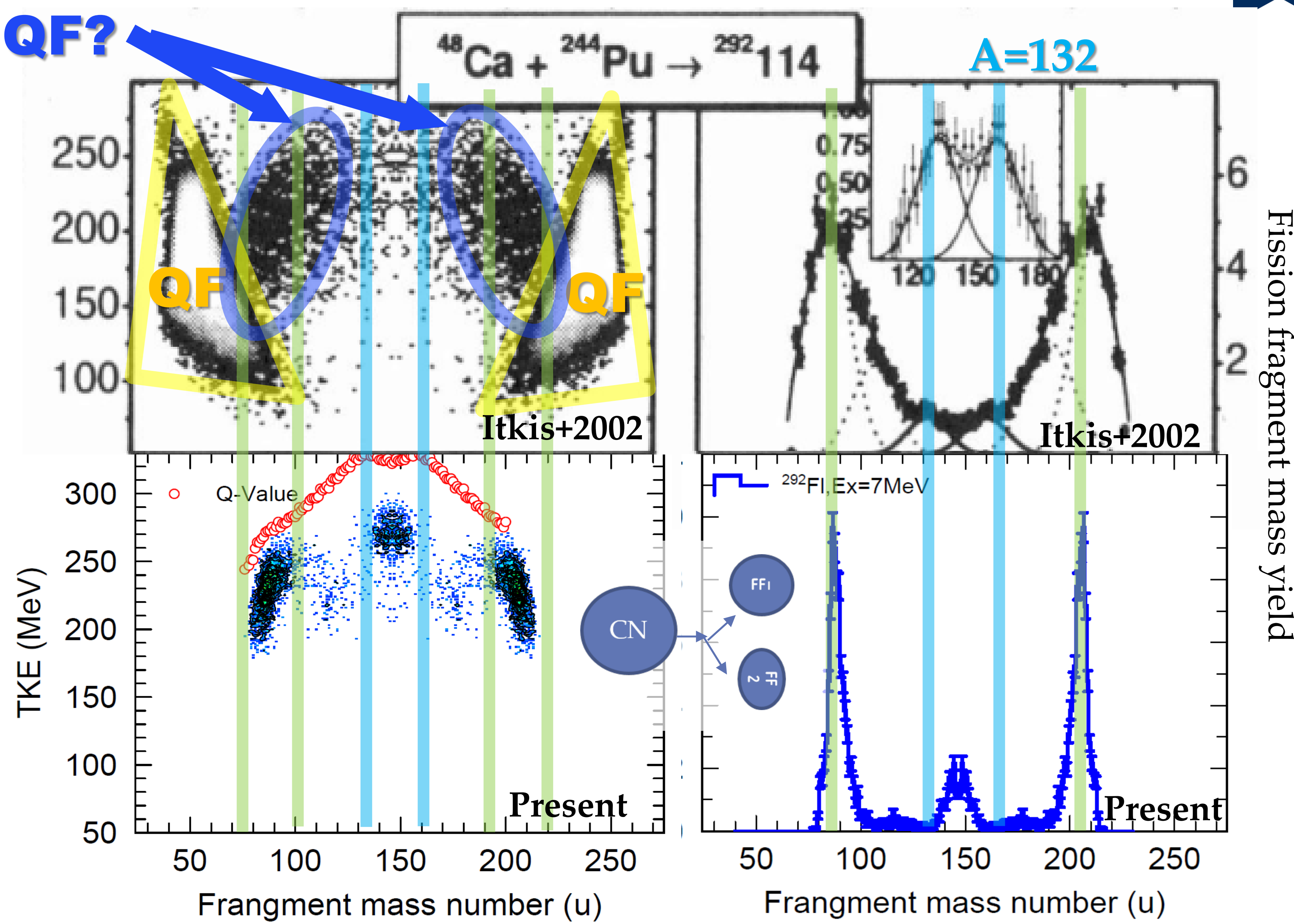
How we can find fusion-fission components in experimental data of SHE fission-like events

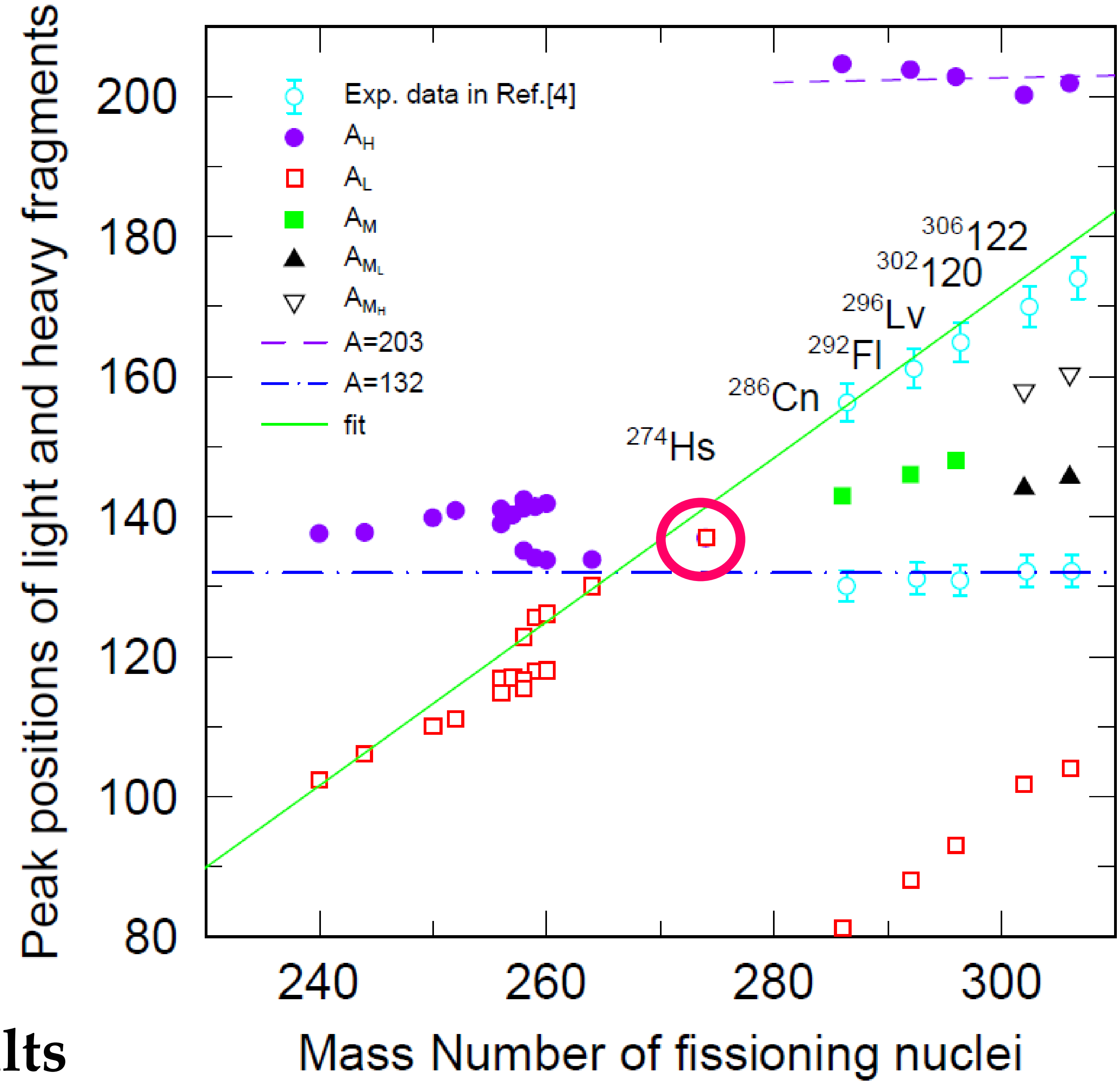




Itkis+2002

Results


QF?
$^{48}Ca + ^{244}Pu \rightarrow ^{292}114$
A=132
QF
QF
Itkis+2002
Itkis+2002
Fission fragment mass yield
Q-Value
TKE (MeV)
Present
CN
FF1
FF2
^{292}Fl,Ex=7MeV
Present
Frangment mass number (u)
Frangment mass number (u)



Results

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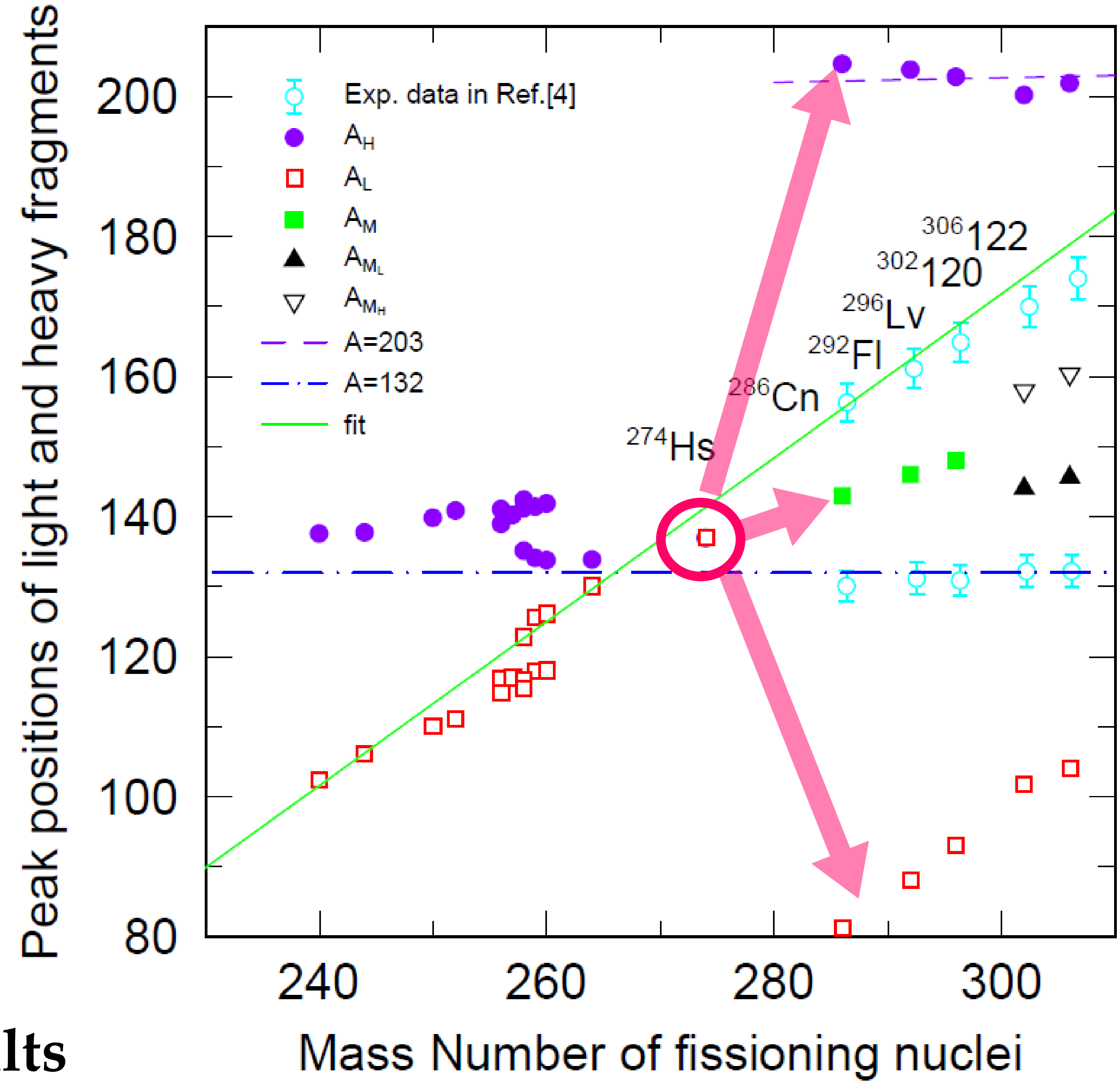
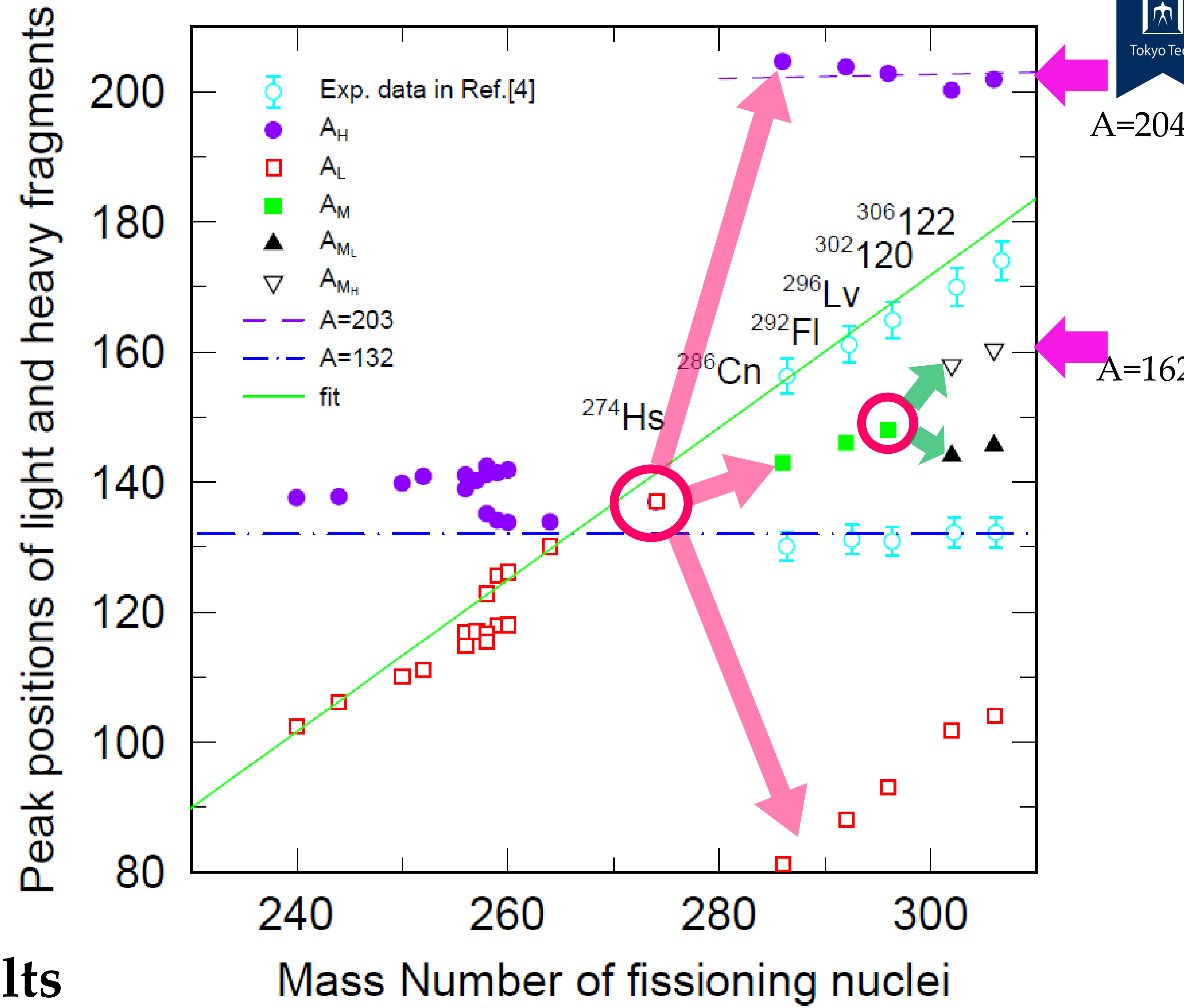

Exp. data in Ref.[4]
A_H
A_L
A_M
A_ML
A_MH
A=203
A=132
fit
306 122
302 120
296 Lv
292 Fl
286 Cn
274 Hs
Peak positions of light and heavy fragments
Mass Number of fissioning nuclei
200
180
160
140
120
100
80
240
260
280
300

Results

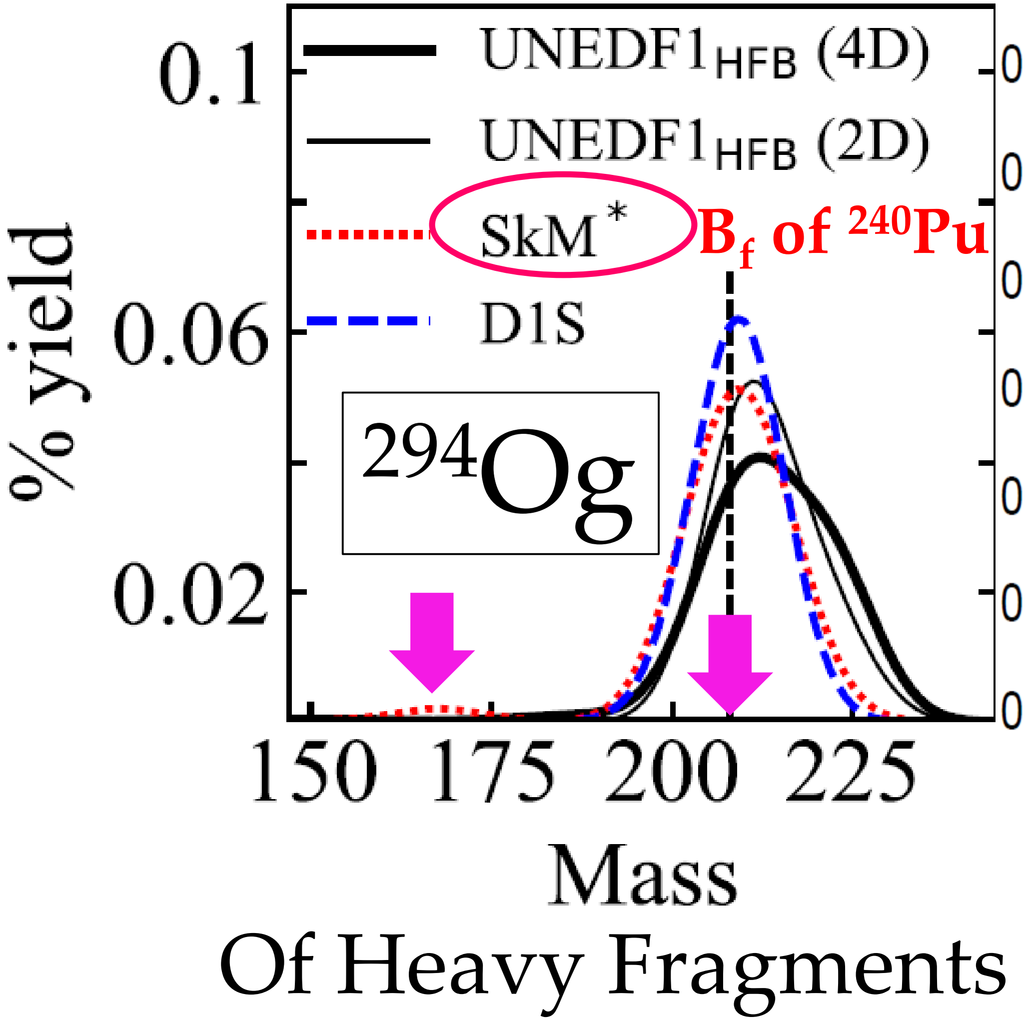


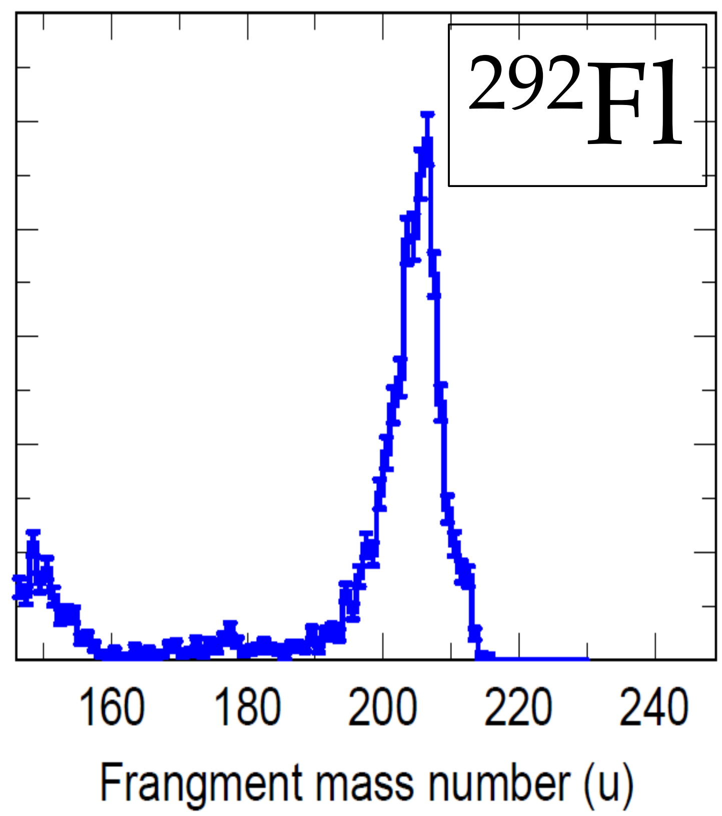
Exp. data in Ref.[4]
A_H
A_L
A_M
A_{M_L}
A_{M_H}
A=203
A=132
fit
$^{306}122$
$^{302}120$
^{296}Lv
^{292}Fl
^{286}Cn
^{274}Hs
A=204
A=162
Peak positions of light and heavy fragments
Mass Number of fissioning nuclei

Results

Comparison with recent microscopic study

Z. Matheson et al., Phys. Rev. C **99**, 041304(R) (2019)
Microscopic study on fission of ^{294}Og, using DFT





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- Large difference due to Y(Z, A)-model can be seen at 2nd peak & rare earth peak of the solar abundance in the case of BH-NS mergers (Ye=0.05)

Summary of second part

- Systematic fission study of SHEs using 4D-Langevin model
  - Our TKEs overlapped with "quasi-fission" components
  - FFMDs of SHEs are completely different from those of Actinides.
  - <AH> of SHEs is almost constant (not A=140 but A=208).

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http://www.nr.titech.ac.jp/~chiba/LANEconf2019/index.html#CT

23-25 October, 2019
at Tokyo Institute of Technology, Ookayama, Tokyo

The international workshop on nuclear physics for astrophysical phenomena

Invited Speakers:
Sven Åberg (Lund Univ.)
Matthew Mumpower (LANL, US)
Stephane Goriery (ULB, Belgium)
Hiroyuki Koura (JAEA, Japan)
Gabriel Martinez Pinedo (TUD, Germany)
Jorgen Randrup (LBNL, US)
Yuichiro Sekiguchi (Toho Univ., Japan)
Shinya Wanajo (AEI, Germany)
Tadashi Yoshida (Tokyo Tech., Japan)