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Characteristics of nuclear fission at high excitation energy

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Introduction

Experimental approach of nuclear fission at high excitation energy has been performed by proton induced fission and fusion fission.

Nuclear fission is an extremely complex reaction, and still not understood completely.
It has been considered that high excitation energy fission can be described by liquid drop model.

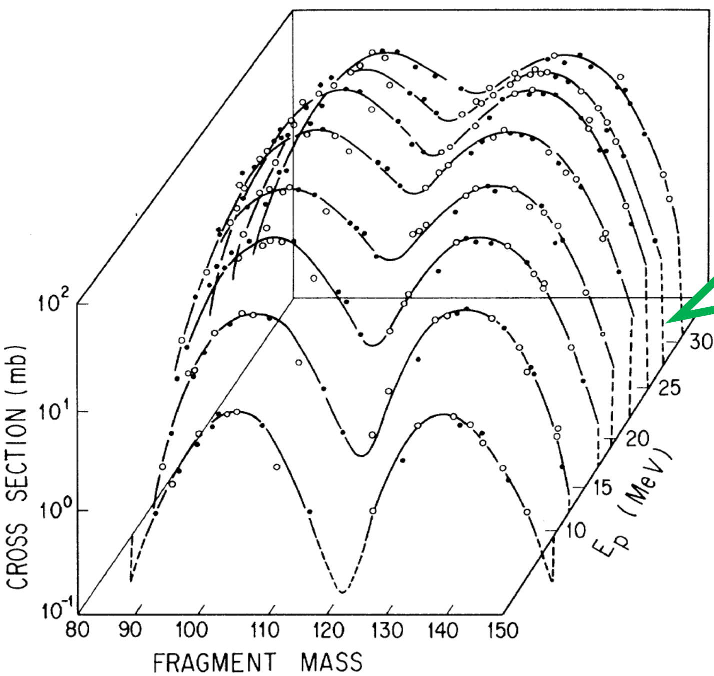


FIG. Incident energy dependence of mass yield curve measured in proton-induced fission of 237Np.

The yield in the valley of the mass distributions for symmetric divisions increase with increasing excitation energy, and that the peaks move slightly toward symmetry.
The double humped shape is understood as strong shell effects of doubly magic ^{132}Sn.

Motivation

- Treatment of shell structure at high excitation energy
- To understand fusion-fission process at super heavy element synthesis
- Evaluation of nuclear data for development of Accelerator Driven System (ADS)

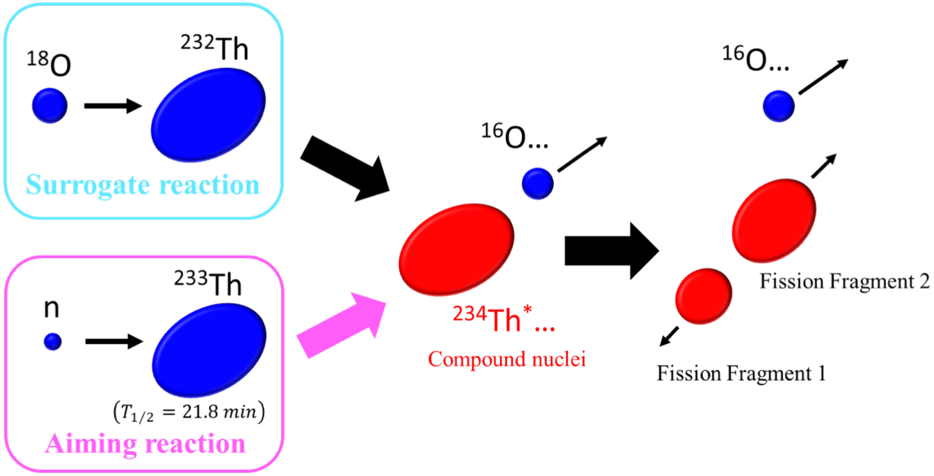
T. Ohtsuki, et al., Phys. Rev. C **44**, 4 (1991)

Experimental Approach at JAEA

Recently, we observed fission-fragment mass distributions (FFMDs) for Th, Pa, U, Np, and Pu isotopes populated in the excitation energy range from 10 to 60 MeV by multinucleon transfer channels in the reaction $^{18}O + ^{232}Th$ and $^{18}O + ^{238}U$ at the Japan Atomic Energy Agency tandem facility.

JAEA tandem accelerator facility

Multi-nucleon transfer reaction (MNT)



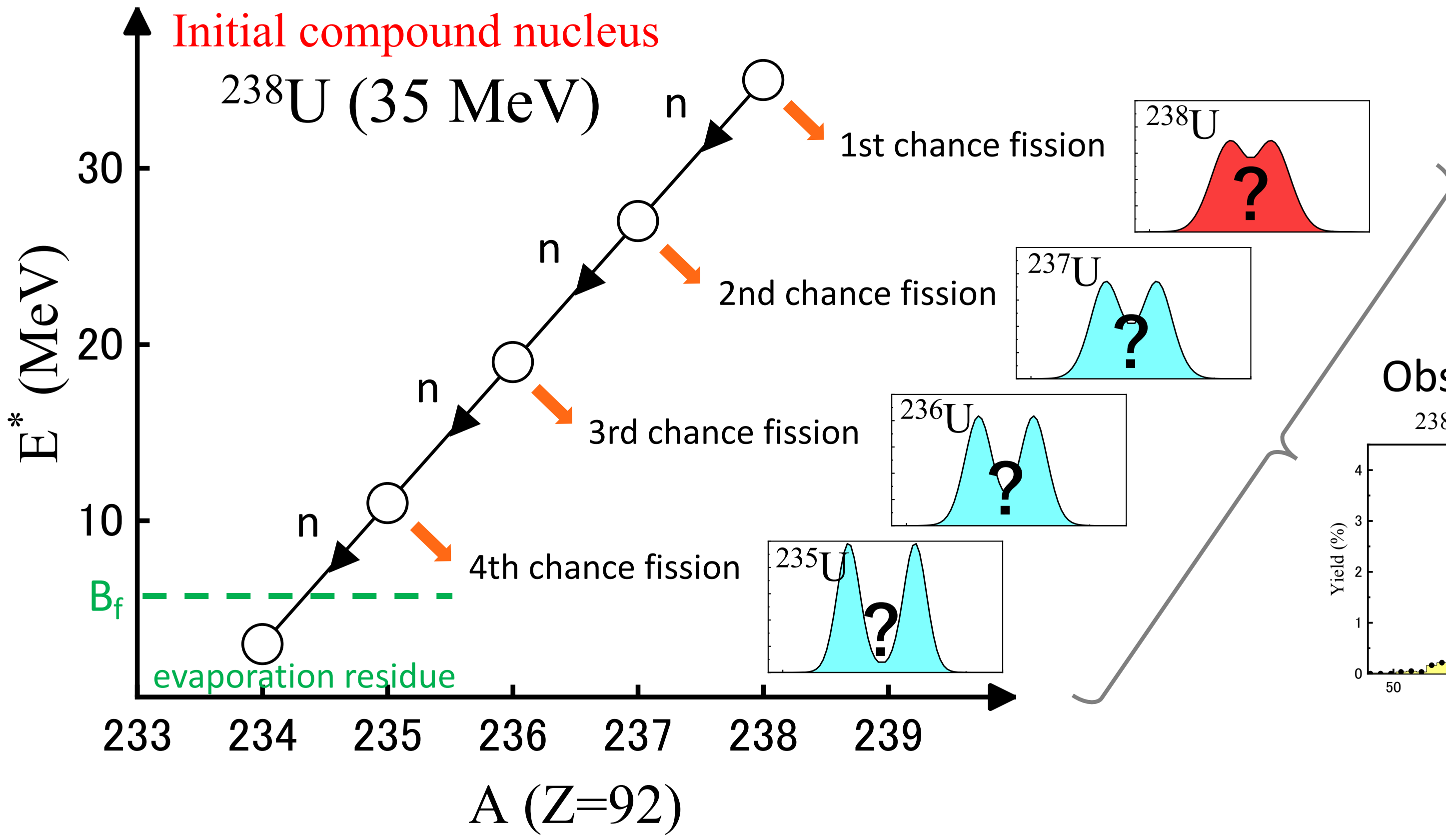
MNT can produce many nuclei in one reaction depending on different transfer channels including neutron-rich nuclei which cannot be accessed by fusion reaction.

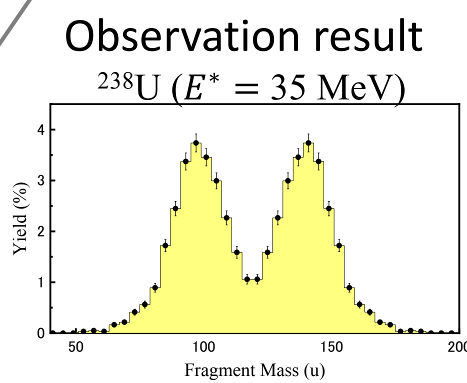
Another unique feature is that the excitation energy of the fission system distributes widely, so that the excitation energy dependence of the fission properties can be obtained.

R. Leguillon et al., Physics Letters B **761** 125-130 (2016).
K. Hirose, K. Nishio, S. Tanaka, et al., Phys. Rev. Lett. **119**, 222501 (2017).

Nuclear Fission at High Excitation Energy

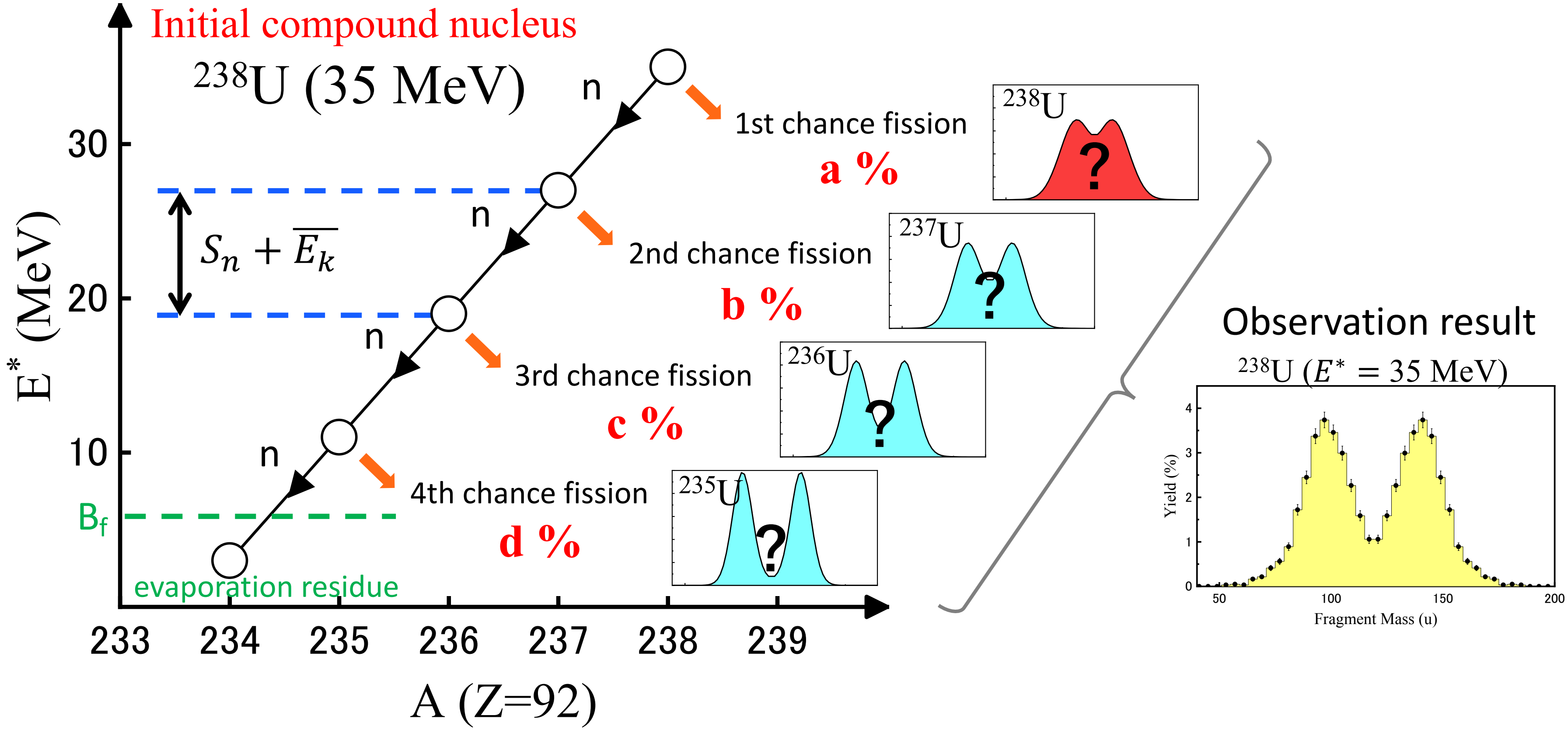
A schematic representation of multichance fission





The highly excited compound nucleus can decay either by first-chance fission, or by single neutron emission, leading to the less excited one-neutron less nucleus.
The competition between neutron evaporation and fission continues until the excited residual nucleus cannot fission anymore.

Outlook of Calculation Method



1. Fraction for each fission chance is calculated by statistical model using the GEF code [1].
2. FFMD for each fission chance is calculated by Langevin calculation.

FFMDs for each fission chance (1) which multiplied by the fraction (2) are summed to obtain the distribution to be compared with the experimental data.

K.-H. Schmidt, B. Jurado, C. Amouroux and C. Schmitt Nuclear Data Sheets 131 (2016).

$\bar{E}_k = 1.9\ MeV$ (Calculated by PACE2 code) A. Gavron, Phys. Rev. C 21, 230 (1980).

Mass table: P. Möller, A.J. Sierk , T. Ichikawa, H.Sagawac Atomic Data and Nuclear Data Tables 109–110 (2016) 1–204

Outlook of Langevin Approach

Multi-dimensional Langevin Equation

$$\frac{dq_i}{dt} = (m^{-1})_{ij} p_j$$

Friction Random Force

Dissipation Fluctuation

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk} p_j p_k - \gamma_{ij}(m^{-1})_{jk} p_k + g_{ij} R_j(t)$$

$$\sum_k g_{ik} g_{jk} = T\gamma_{ij}$$ Einstein relation

Potential Energy

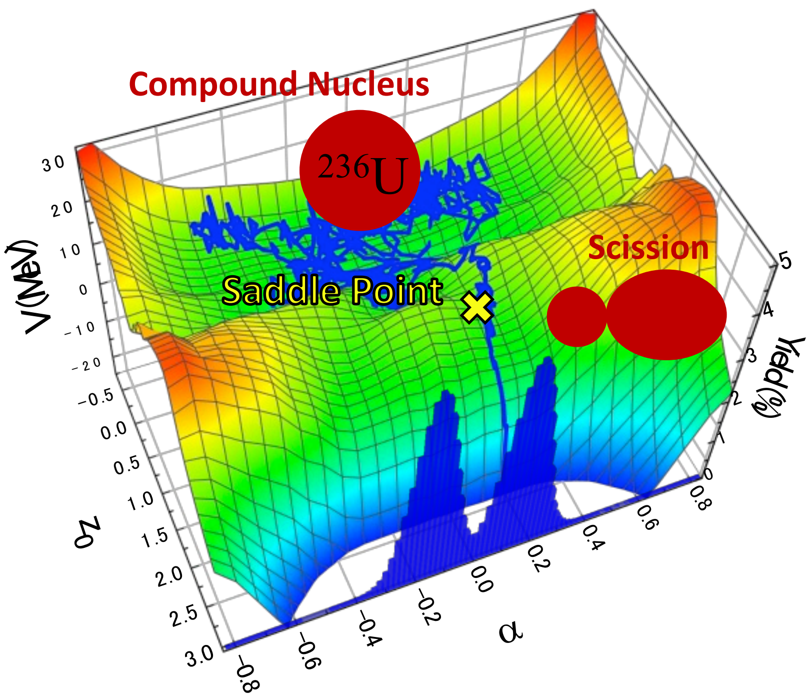
$$V(q,l,T) = V_{LD}(q) + E^0_{shell}(q) exp\left(-\frac{aT^2}{E_d}\right)$$

m_{ij} : Hydrodynamical mass

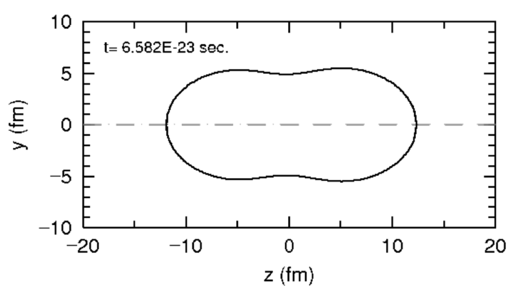
γ_{ij}: Wall and Window (one-body) dissipation

$$\langle R_i(t)\rangle = 0, \langle R_i(t_1) R_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$$

: white noise (Markovian process)



■ Definition of Nuclear Shape $q\{z, \delta, \alpha\}$



z: Center of Mass Distance

δ: Deformation

α: Mass Asymmetry

Time evolution of nuclear shape is traced from the compound state to the scission point by solving the Langevin equations.

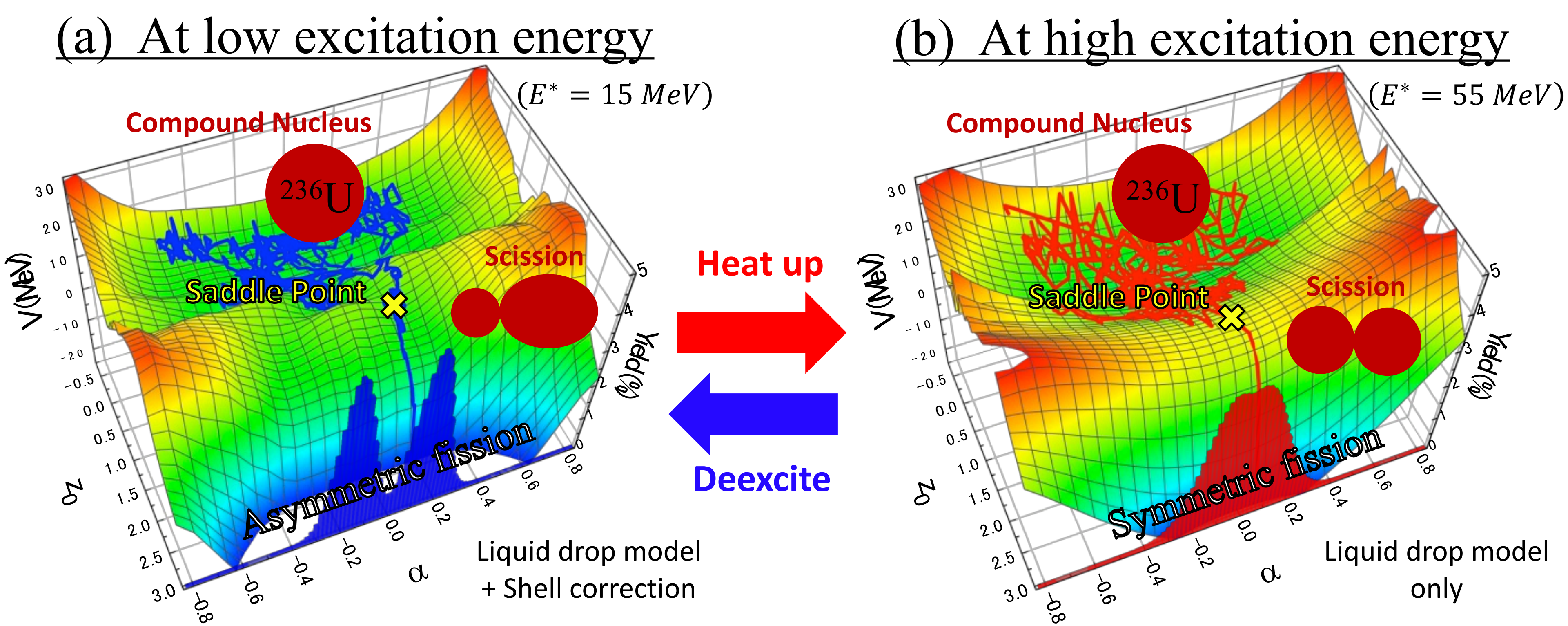
Temperature dependence of PES

Potential Energy

A simplified Fermi-gas form

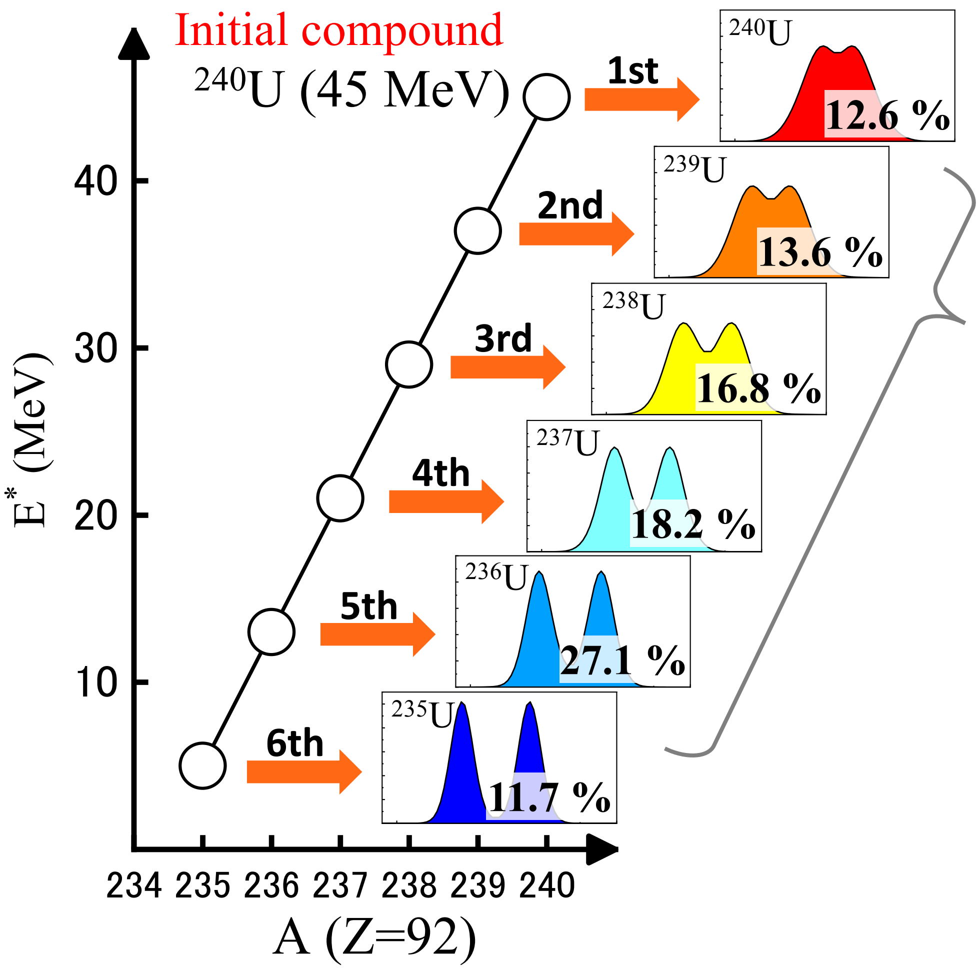
$$V(q,l,T) = V_{LD}(q) + E^0_{shell}(q)exp\left(-\frac{aT^2}{E_d}\right)$$

Shell damping energy:
$E_d = 20\ MeV$

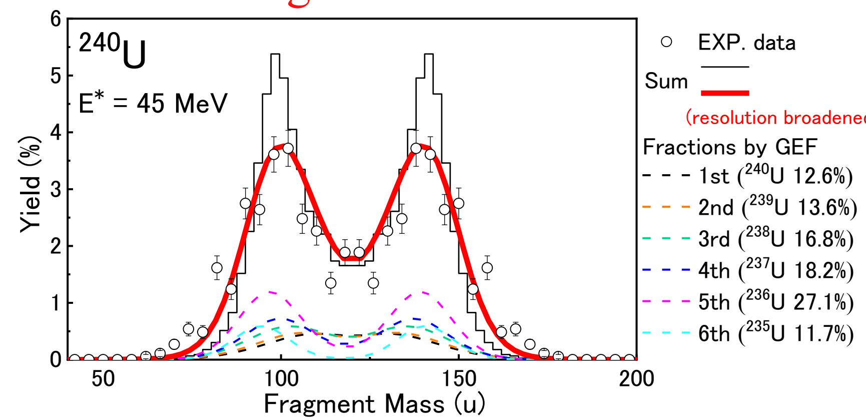


■ The asymmetric mass distribution is attributed to the influence of strong shell effects of doubly magic ^{132}Sn. With increasing excitation energy, due to a reduced importance of shell effects, the transition to predominant symmetric (liquid-drop) type fission should occur.

Results and Discussion



(b) This study calculation result
including Multi-chance Fission

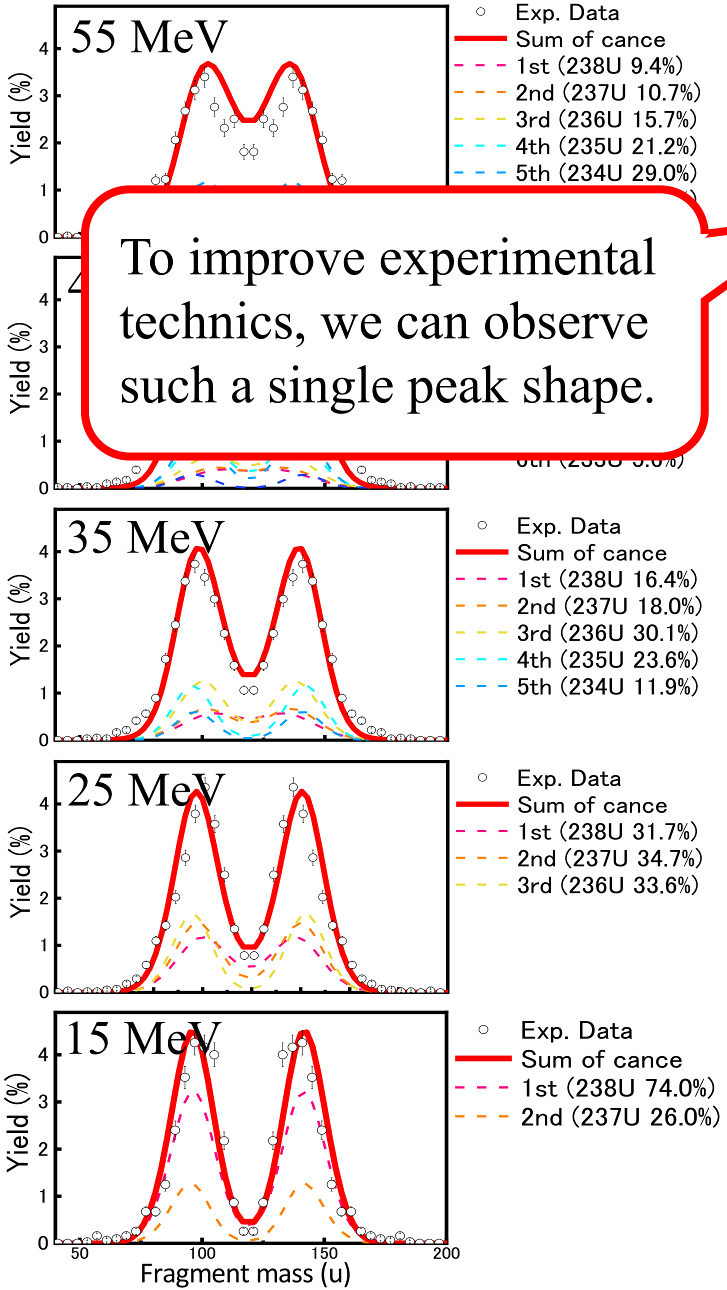


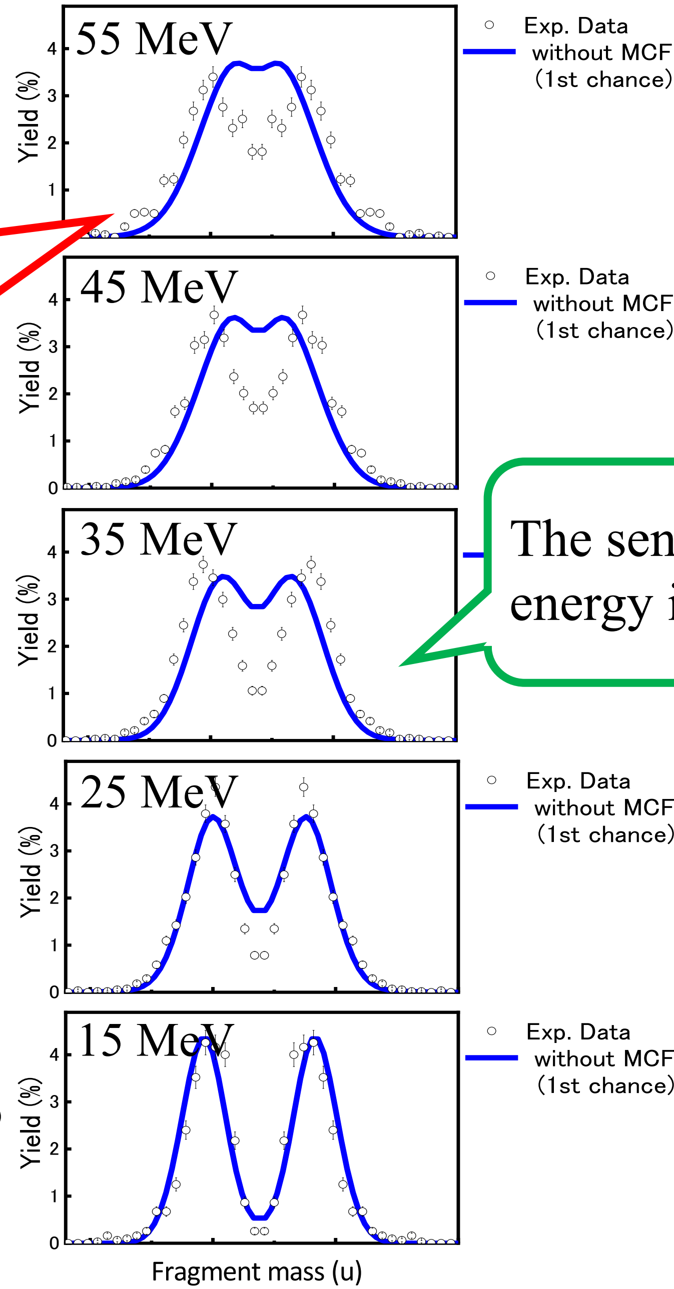
's predominantly symmetric fission due
ts.

Ds for a given initial high excitation
cited lighter isotopes produced via the

- Observation result contains the components of various nuclear fission with reduced excitation energy originated from multichance fission.

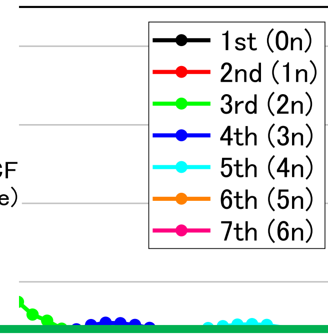
Excitation energy dependence of ^{238}U





To improve experimental technics, we can observe such a single peak shape.

ance fission



The sensitivity of excitation energy is greatly different.

n energy, the number
ce increases.

technics and
sion neutron and
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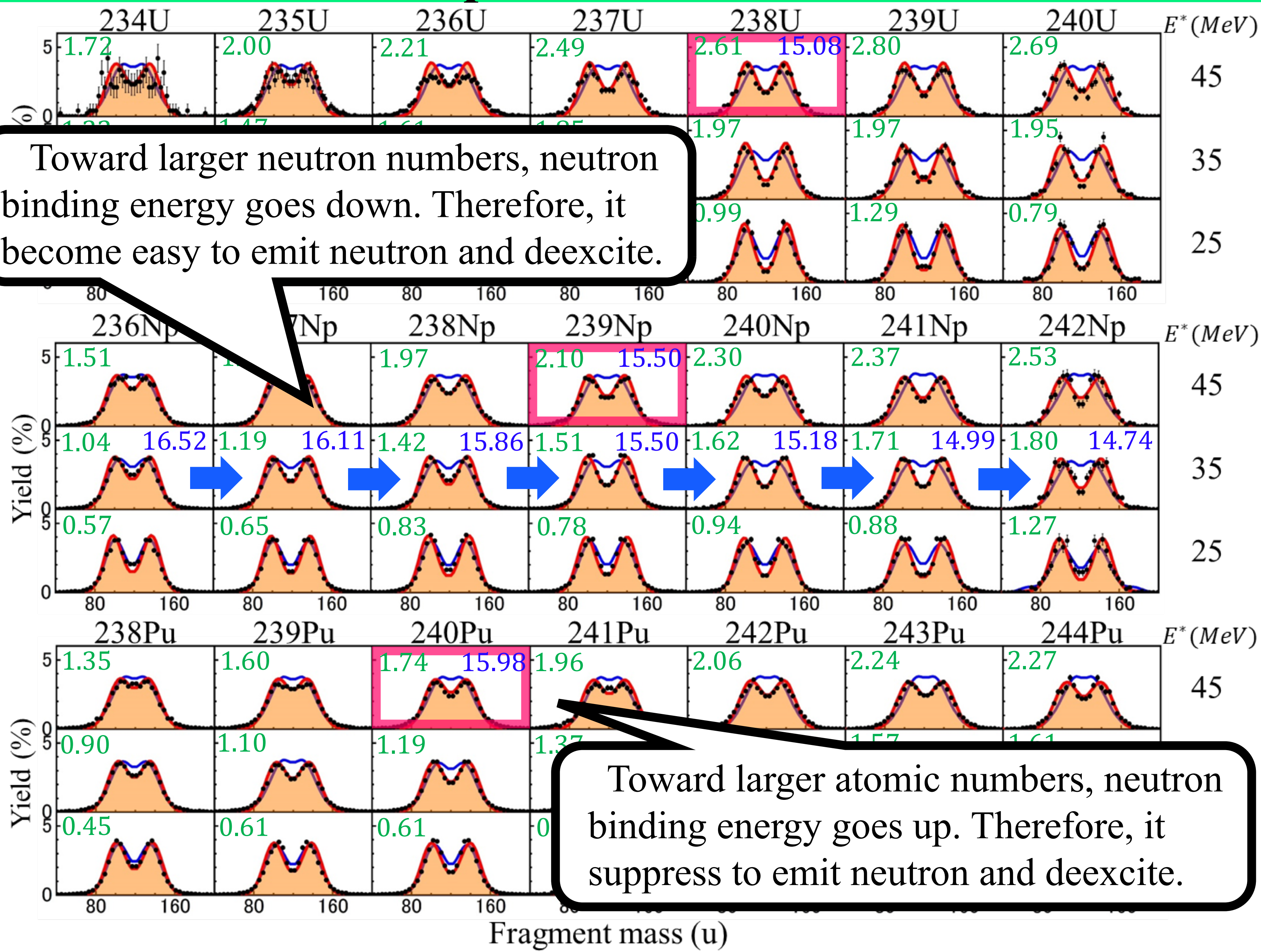
k shape
tion energy.

Atomic number and Neutron number dependence

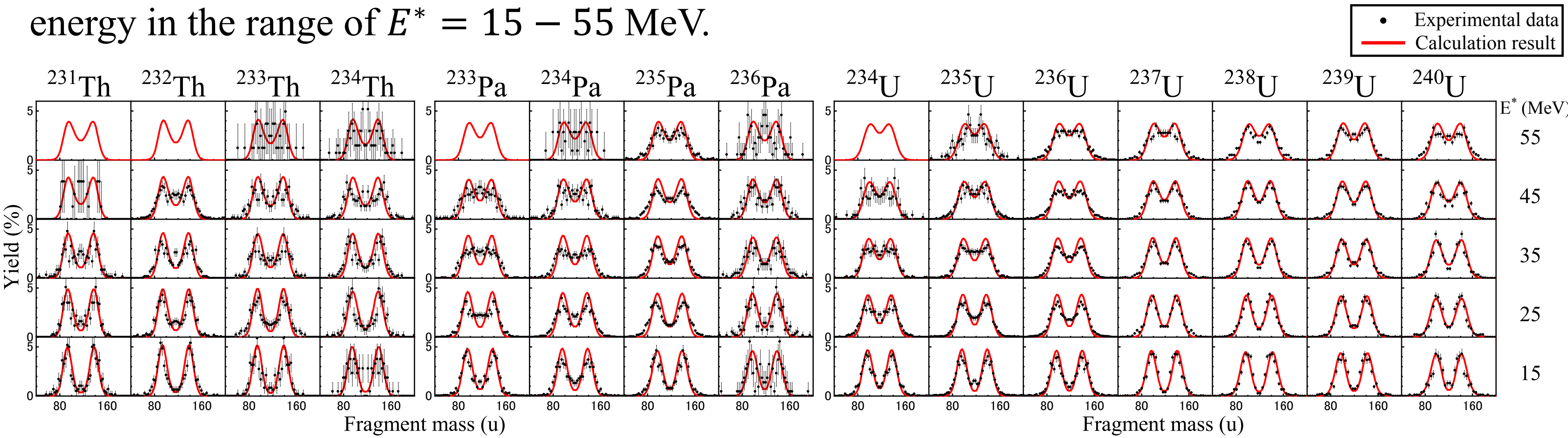
$\langle\nu\rangle$: average number of neutron emission

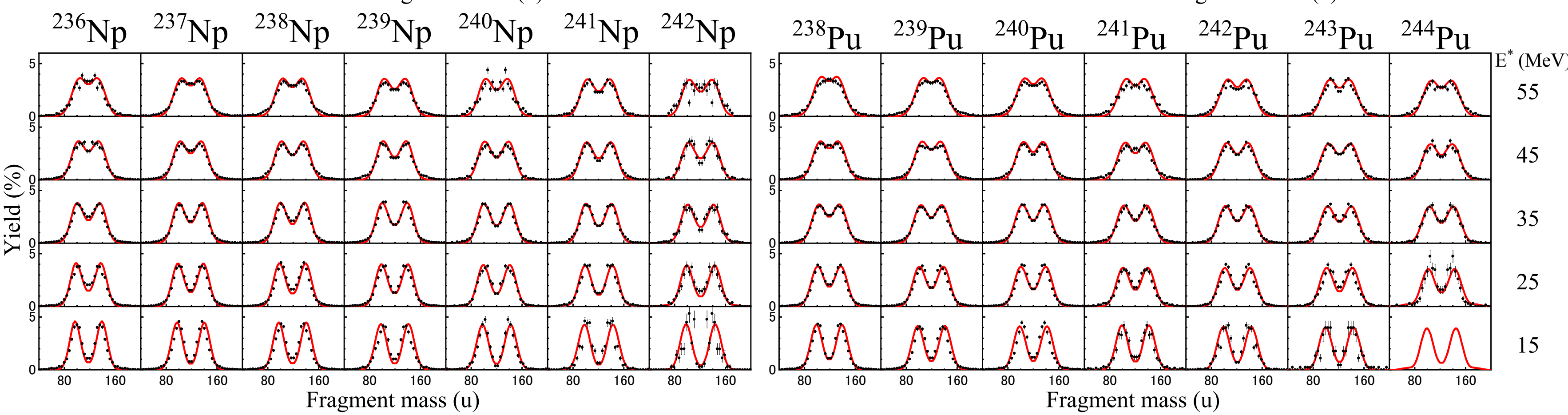
S_{2n}: two neutron separation energy



Summary of calculation results

Calculated FFMDs of the Th, Pa, U, Np, and Pu isotopes and their dependence of excitation energy in the range of $E^* = 15 - 55$ MeV.





The calculation taking into account the MCF (red curves) shows good agreement with the experimental data for mass asymmetry and peak-to-valley (P/V) ratio.

All experimental data are observed in tandem accelerator facility at Japan Atomic Energy Agency [5,6].

[5] R. Leguillon et al., Physics Letters B **761** 125-130 (2016). [6] K. Hirose, K. Nishio, S. Tanaka, et al., Phys. Rev. Lett. **119**, 222501 (2017).

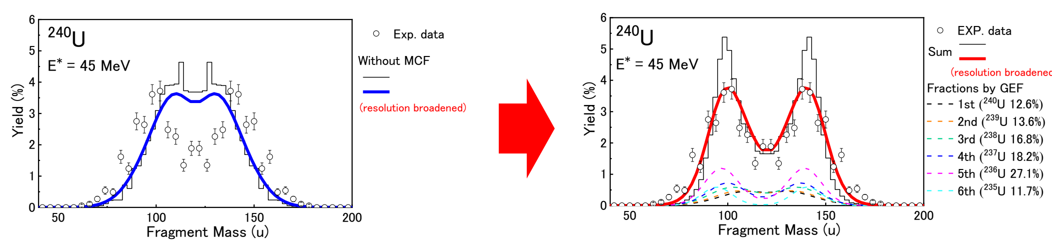
Summary

- Fission fragment mass distributions (FFMDs) are affected by multi-chance fission, and this shape changes significantly at high excitation energy. This result suggests that the consideration of multi-chance fission is essential to interpret and evaluate fission observables.

- A persistence of predominantly asymmetric FFMDs at high excitation energy is not a signature of survival of shell effects in the initial compound.

- We indicate change of FFMDs in peak-to-valley ratio toward atomic number and neutron number by multi-chance fission for the first time.

- For systematic understanding of nuclear fission from highly excited states, we aim to clarify effects of multi-chance fission for other fission observables (e.g. total kinetic energy of fission fragments and neutron multiplicity), and discussion with experimentalists has been started.



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