The evaluation of the fission mode and fragment yields of neutron-rich nuclei by the dynamical model

Shoya Tanaka[1], Nobuya Nishimura[1,2], Itoshi Nishimura[3], Yoshihiro Aritomo[3]

[1]*RIKEN Nishina Center for Accelerator-Based Science, RIKEN* [2]*Astrophysical Big Bang Laboratory, CPR, RIKEN*
[3]*Graduate School of Science and Engineering, Kindai University*

E-mail: shoya.tanaka@riken.jp

Introduction

r-process and nuclear fission

The rapid neutron-capture process (r-process) of stellar nucleosynthesis explains the production of the stable (and some long-lived radioactive) neutron-rich nuclides heavier than iron observed in stars of various metallicities and the Solar System.
In the r-process, fission plays a fundamental role by recycling the matter during neutron irradiation and by shaping the final r-abundance distribution.
Nevertheless, due to the difficulty of experimental approaches, most of the fission data available for r-process calculations are based on theoretical predictions with phenomenological models.

In this study, we focused on the transition of fission mode from asymmetric to symmetric in neutron-rich isotopes. We investigated the fission of neutron-rich nuclei by a theoretical calculation based on the dynamical model and employ Langevin equations.

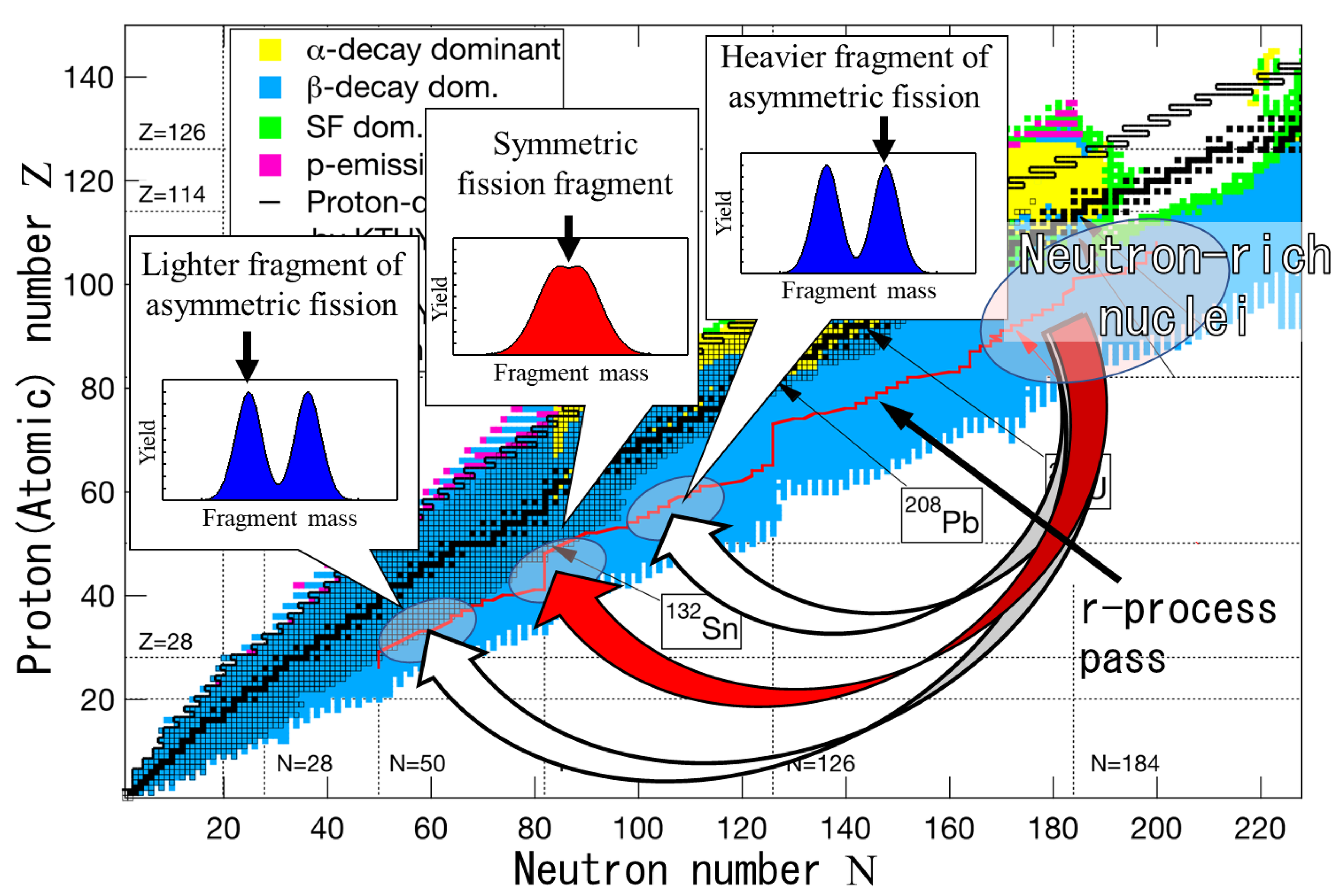

Fig. 1. r-process path and fission mode (mass-symmetric and asymmetric fission) effects in the nucleus chart [H. Koura et al., Prog. Theor. Phys. **113** (2005).].

Model

Multi-dimensional Langevin Equation

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

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk}p_j p_k - \underbrace{\gamma_{ij}\,(m^{-1})_{jk}p_k}_{\text{Friction dissipation}} + \underbrace{g_{ij}R_j(t)}_{\text{Random force fluctuation}}$$

$\langle R_i(t)\rangle = 0, \langle R_i(t_1)R_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$: white noise (Markov process),
$\sum_k g_{ik}g_{jk} = T\gamma_{ij}$: Einstein relation (Fluctuation-dissipation theorem)

Nuclear Shape: $q = \{z, \delta, \alpha\}$ (z: center distance, δ: deformation, α: mass asymmetry)
m_{ij}: Hydrodynamical mass (inertia mass), γ_{ij}: Wall and Window (one-body) dissipation (friction)

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

Potential energy in dynamical model

$$V(q,l,T) = V_{LDM}(q) + \frac{\hbar^2 l(l+1)}{2I(q)} + V_{SH}(q,T)$$
$$V_{LDM}(q) = E_S(q) + E_C(q)$$
$$V_{SH}(q,T) = E_{shell}^{T=0}(q)exp(-aT^2/E_d)$$

E_S: Generalized surface energy (finite range effect),
a: level density parameter (Toke and Swiatecki),
E_C: Coulomb repulsion for diffused surface,
$E_{shell}^{T=0}$: Shell correction energy, I: Moment of inertia for rigid body
Shell damping energy: E_d = 20 MeV [1]

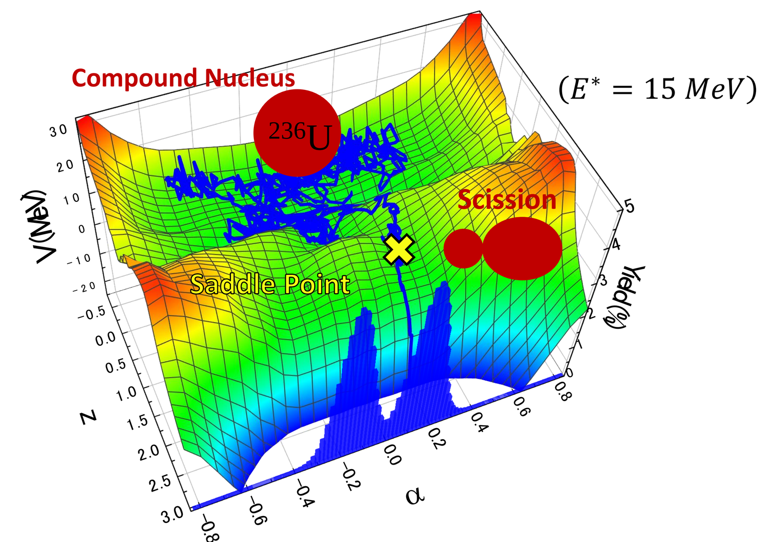

Fig. 2. Potential energy on the z−α plane for ^{236}U and a sample nuclear shape trajectory of asymmetric fission is shown.

- The asymmetric fission fragment mass distribution (FFMD) is attributed to the influence of strong shell effects of doubly magic ^{132}Sn.

[1] A. V. Ignatyuk, G. N. Smirenkin, and A. S. Tishin, Sov. J. Nucl. Phys. **21**, 255 (1975).

Results and Discussion

1. A dramatic change of the fission mode at Fermium isotopes

The fission of fermium nuclides $^{254\text{-}257}$Fm at low excitation energy was studied using the dynamical model. The mass distributions of fission fragments show a dramatic change from an asymmetric shape for the lighter fermium isotopes to sharp symmetric fission for the heavier isotopes. This trend has been already observed experimentally [2]. The sudden change of the FFMD is strongly regulated by the structure of the second fission barrier and the dynamical motion of the nucleus in the second minimum [3].

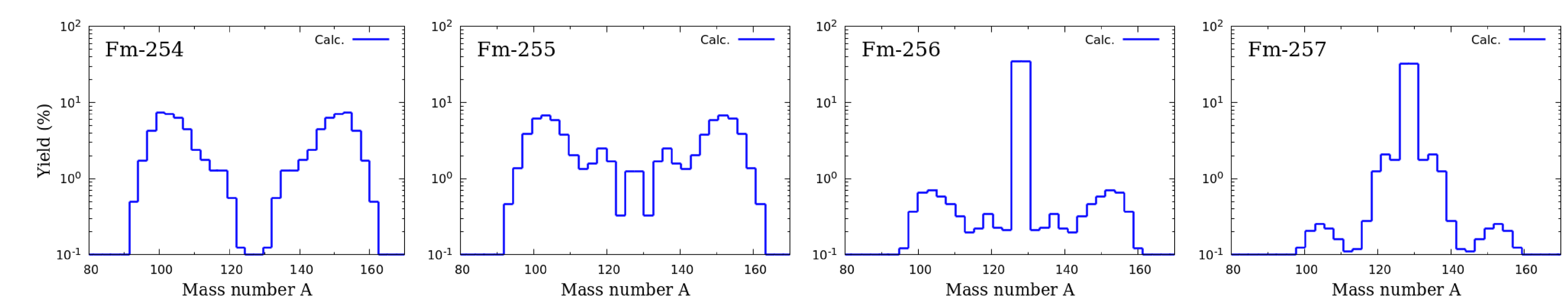

Fig. 3. Calculation results of a fission fragment mass distribution for $^{254\text{-}257}$Fm (E^*=7 MeV).

2. Fission of neutron-rich nuclei at Uranium isotopes

We perform a series of fission calculations for the neutron-rich actinoid nuclei. A similar trend which is the dramatic change of FFMDs for fermium isotopes was also observed in uranium isotopes in this calculation. This trend did not appear in the results of the GEF model code [4].

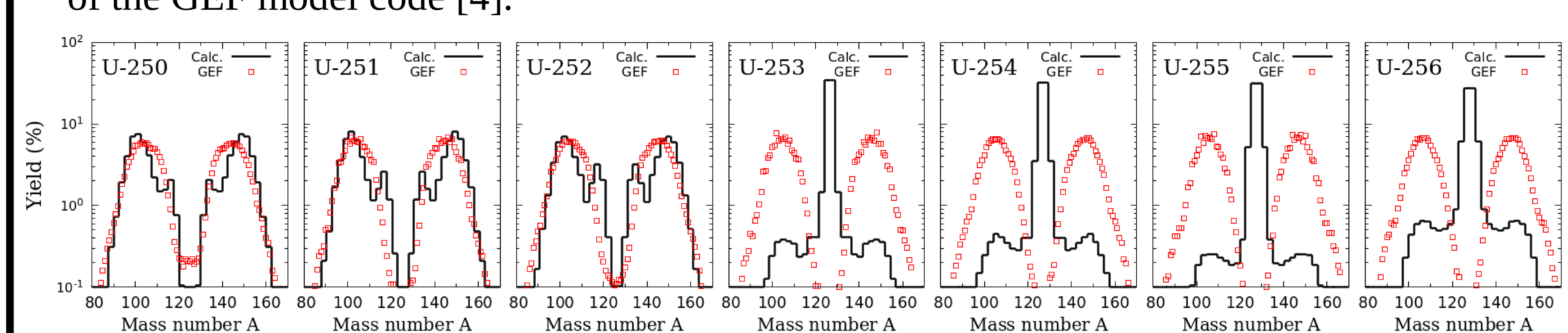

Fig.4. The calculation results of fission fragment mass distributions (FFMDs) for ^{250}U to ^{256}U with the excitation energy of E^*=7 MeV. The present work is compared with the data from GEF code [4].

3. Fission fragment charge distribution by the UCD assumption

The charge distribution of fission products is a fundamental quantity for the determination of the production rate of individual isotopes. Thus, it is essential nuclear data to compare experiments with r-process calculations.

We calculate the charge distribution based on the assumption of unchanged charge distribution (UCD). Figure 5 shows the fission fragment distribution on the N-Z plane for ^{236}U. It well reproduces the experiment.

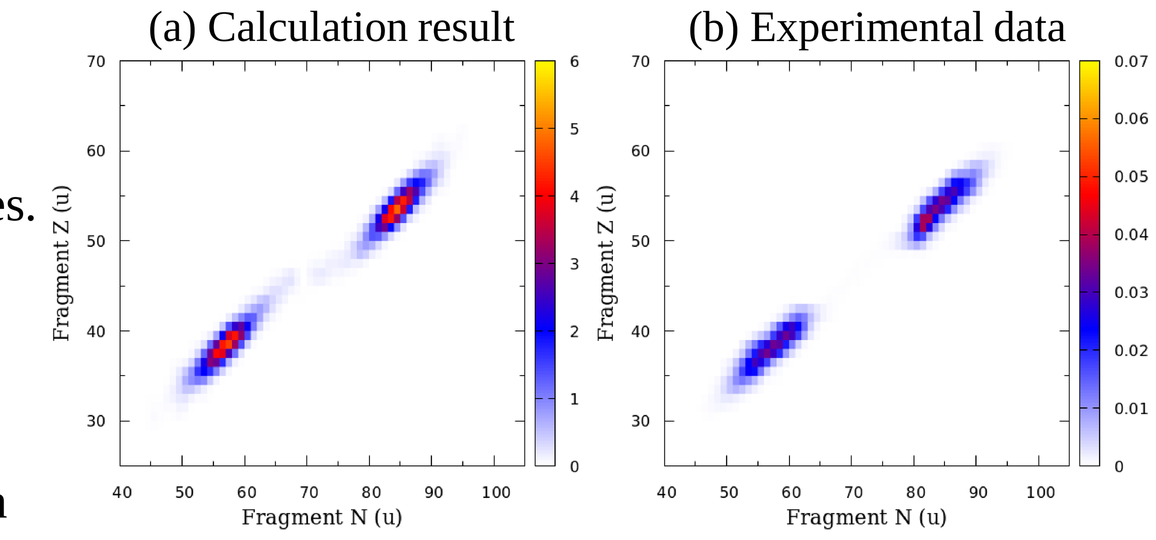

Fig. 5. (a) The calculation result of fission fragment distribution on the N-Z plane for U-236 (E^*=10 MeV) is plotted. The calculation result is compared with the experimental data of U-235 neutron-induced fission (E_k=500 KeV) from JENDL-4.0 [5].

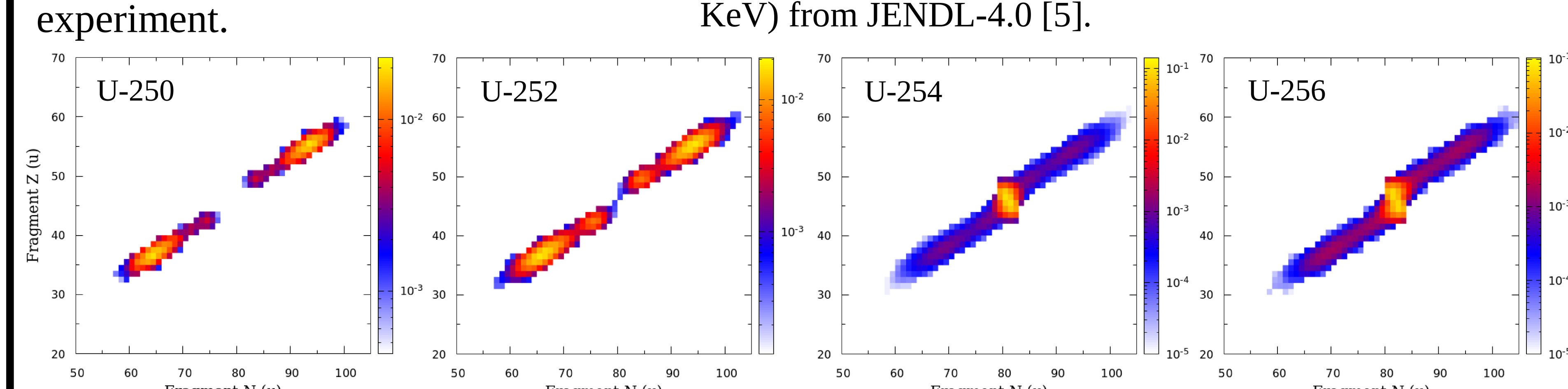

Fig. 6. The calculation results of fission fragment distribution on the N-Z plane for uranium isotopes (E^*=7 MeV) are plotted.

[2] D. C. Hoffman, J. B. Wilhelmy, J. Weber, W. R. Daniels, E. K. Hulet, R. W. Lougheed et al., Phys. Rev. C **21**, 972 (1980).
[3] Y. Miyamoto, Y. Aritomo, S. Tanaka, K. Hirose, and K. Nishio, Phys. Rev. C **99**, 051601(R) (2019).
[4] K.-H. Schmidt, B. Jurado, C. Amouroux, and C. Schmitt, Nucl. Data Sheets **131**, 107 (2016).
[5] K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, J. Katakura, and N. Otuka: Journal of Korean Physical Society **59** (2011) 1046.

Summary and Perspectives

- Nuclear fission plays an essential role in nucleosynthesis by the r-process.
- We calculated fission fragment mass distributions of neutron-rich nuclei by the dynamical model calculation.
- The dramatic change of fission mode was observed for fermium and uranium isotopes.
- Such systematic behavior can be significant to shape the final abundances of the r-process calculations.
- In future work, the mass number and charge distribution of fission fragments, kinetic energy, prompt neutron number, lifetime, etc., which are necessary for numerical data available for r-process calculations, will be evaluated for each nuclide simultaneously, and a fission database will be constructed.