Fission yields of neutron-rich nuclei evaluated by the dynamical model

Award #$ 2020275

Shoya Tanaka[1], Nobuya Nishimura[2,1], Futoshi Minato[3,1], and Yoshihiro Aritomo[4]

[1]RIKEN Nishina Center for Accelerator-Based Science, RIKEN
[2]Astrophysical Big Bang Laboratory, CPR, RIKEN
[3]Department of Physics, Kyushu University
[4]Faculty of Science and Enginnering, Kindai University

Introduction

In the r-process, fission plays a fundamental role by recycling the matter during neutron irradiation and by shaping the final r-abundance distribution.
In this study, we present a new method to describe the dynamical-fission process and following prompt neutron emission.

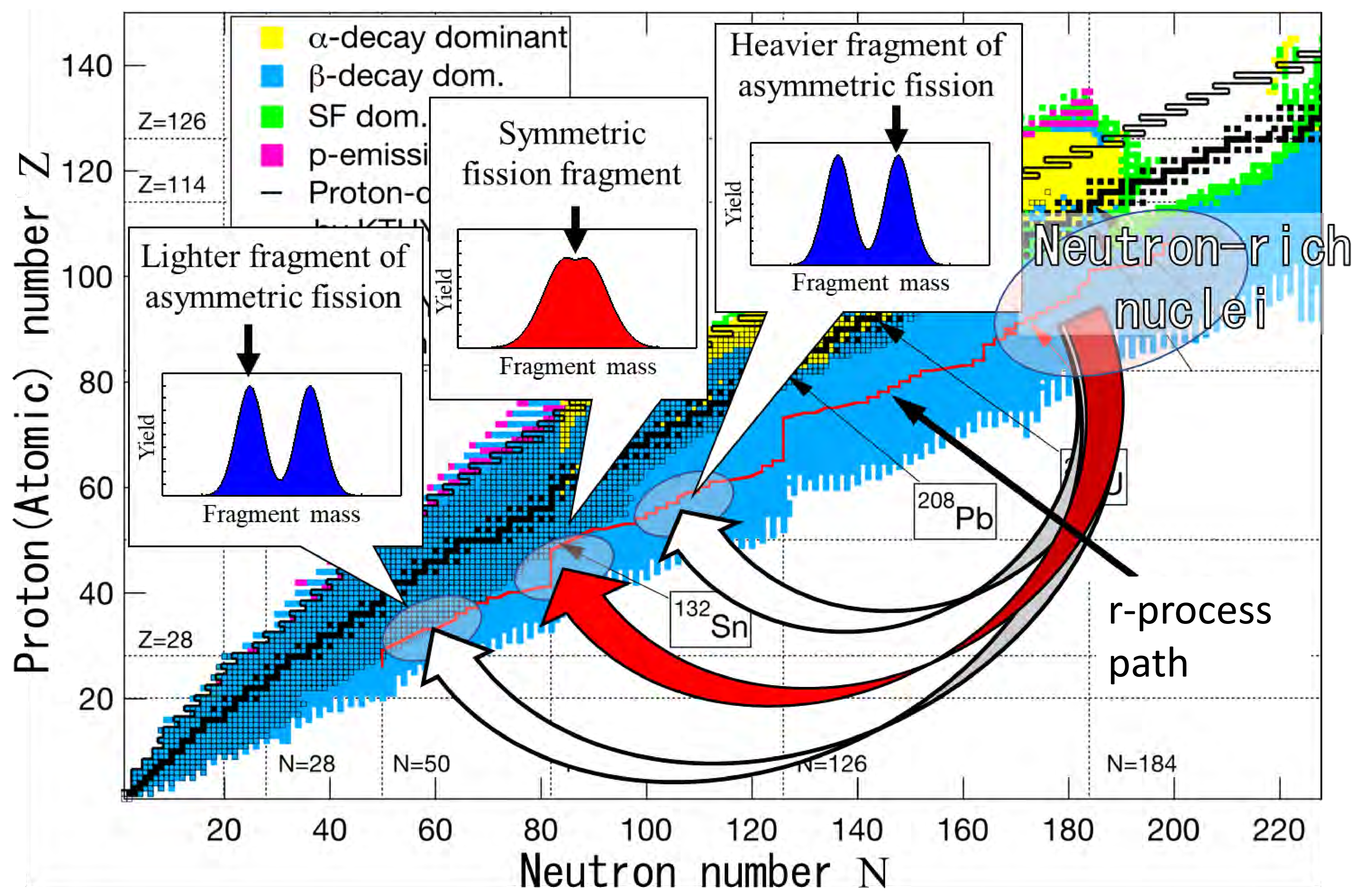

Fig. 1. r-process path and fission mode (mass-symmetric and asymmetric fission) effects in the nucleus chart [1].

Model

Multi-dimensional Langevin Equation

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

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

Friction dissipation — 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 [2]

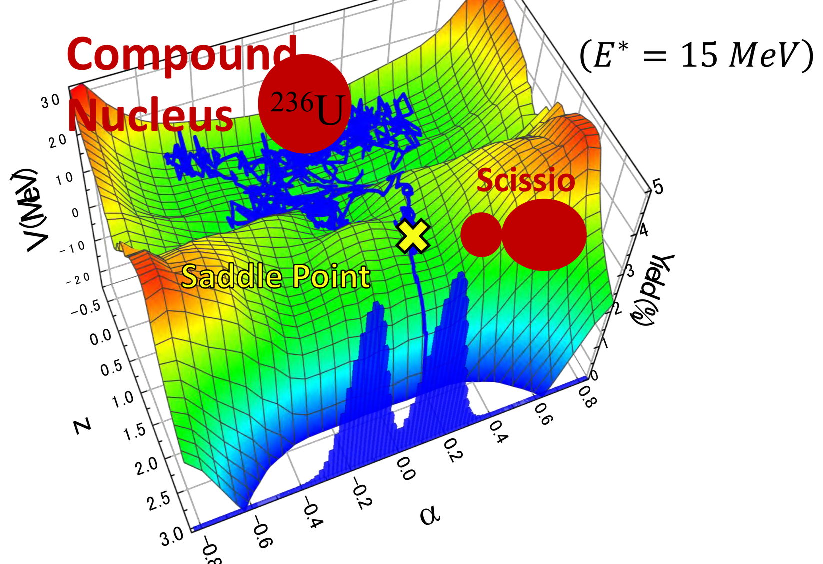

Fig. 2. Potential energy on the z–α plane for ^{236}U and a sample nuclear shape trajectory of asymmetric fission.

CCONE: comprehensive code for nuclear data evaluation

The CCONE code system integrates various nuclear reaction models needed to describe nucleon, light charged nuclei up to alpha-particle and photon induced reactions [3].

Results and Discussion

1. Results of fission fragment yields (^{236}U, E^*=9 MeV)

- Using a certain set of model parameters, we successfully reproduce the experimental data.
- The calculated $\langle \nu_n \rangle$ =2.517, the experimental $\langle \nu_n \rangle$ = 2.43 [4].

(a) The fission yields (b) The number of prompt neutrons (c) The independent fission yields

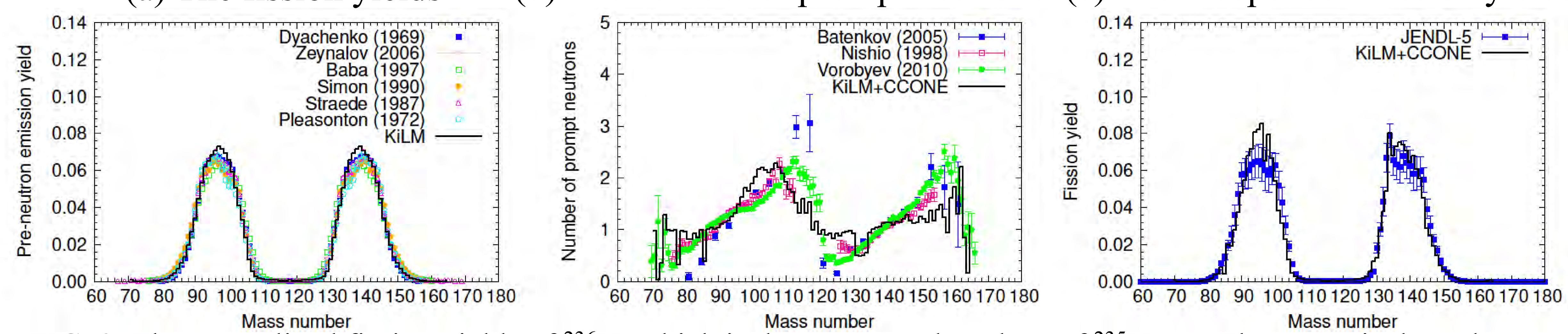

FIG. 3. The normalized fission yields of ^{236}U, which is the compound nucleus of ^{235}U + n. The numerical results are compared with several experimental data.

2. Fission of neutron-rich nuclei at two uranium isotopes

- We performed neutron emission calculations of very neutron-rich uranium isotopes where experimental data are unavailable.

(a) ^{250}U, E^*=9 MeV (b) ^{255}U, E^*=9 MeV (c) The number of prompt neutrons

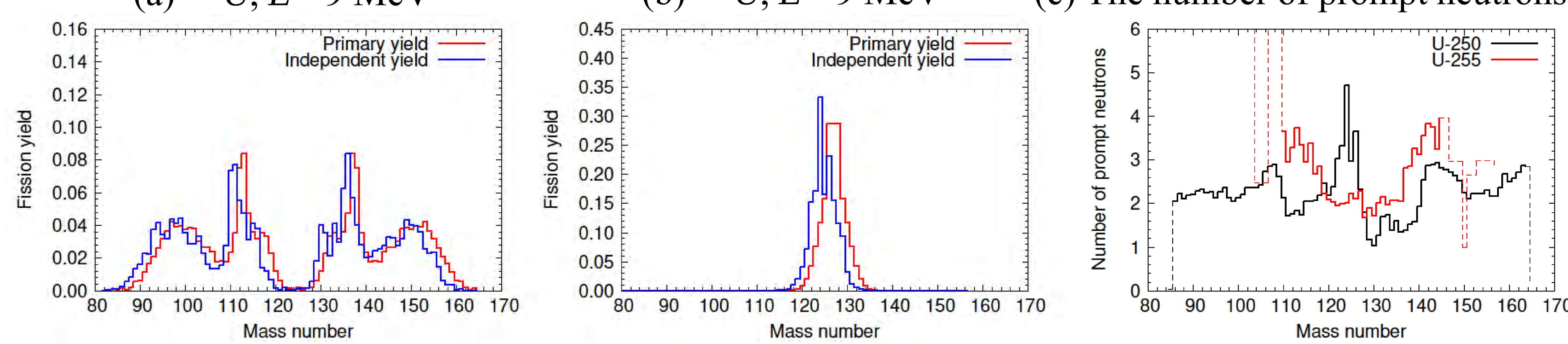

FIG. 4. The normalized fission yields of ^{250}U (a) and ^{255}U (b), which compare the primary yield distribution and the independent fission yields. The number of prompt neutrons as a function of fragment mass for ^{250}U (black line) and ^{255}U (red line) as shown in graph (c).

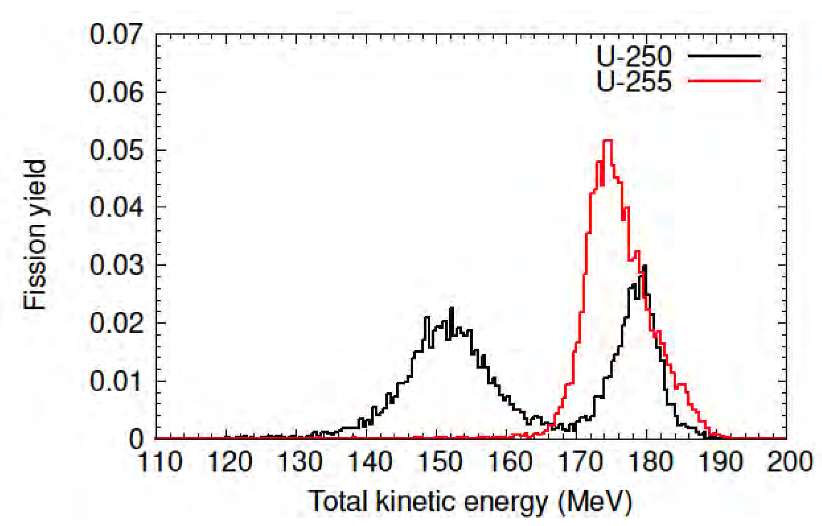

FIG. 5. The fission yield distributions in the TKE for ^{250}U (black line) and ^{255}U (red line).

- The dramatic change of fission mode was observed for neutron-rich uranium isotopes.
- ^{250}U : $\langle \nu_n \rangle$ = 4.185, and ^{255}U : $\langle \nu_n \rangle$ = 3.434.
- ^{250}U : $\langle$TKE$\rangle$ =162.50, and ^{255}U : $\langle$TKE$\rangle$ = 175.85 MeV.
- From these results, the number of prompt neutrons does not necessarily increase with neutron number.

Summary

- Our framework is highly reproducible in the experiments and shows that the number of emitted neutrons after fission differs significantly in neutron-rich uranium fission depending on distributions of fission variables.

References
[1] H. Koura et al., Prog. Theor. Phys. 113 (2005).
[2] A. V. Ignatyuk et al., Sov. J. Nucl. Phys. 21, 255 (1975).
[3] O. Iwaoto et al., Nuclear Data Sheets, Vol. 131 (2016).
[4] O. Iwamoto, et al., Japanese evaluated nuclear data library version 5: Jendl-5, J. Nucl. Sci. Technol. 60, 1 (2023).