Effects of neutron emission during fission on fragment mass distribution calculated with dynamical model

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Introduction

Background

- Fission-fragment mass distributions (FFMDs) from low-energy fission of actinides from uranium to einsteinium show a double humped shape, with the heavy fragment mass around $A_H = 140$.
- These FFMDs have been interpreted to result from effects of nuclear shell structure.
- The measured FFMD from a the highly excited nucleus, is influenced by the effects of multi-chance fission, i.e. fission after the evaporation of neutrons [1,2].

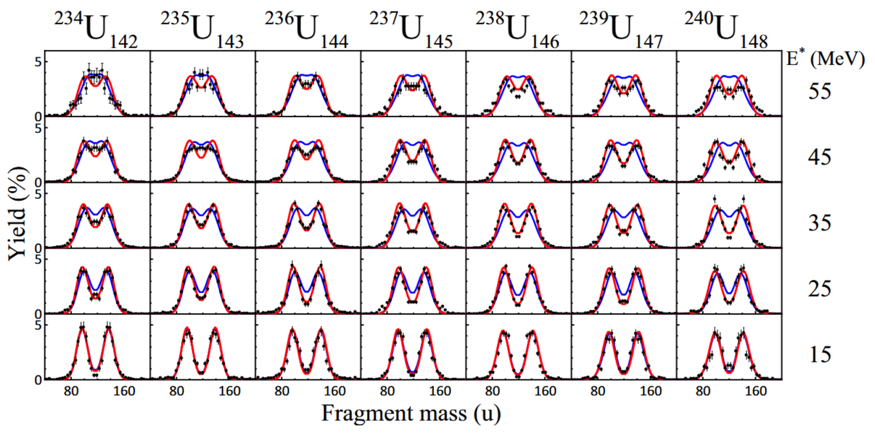

Figure 1: FFMDs of $^{234\text{-}240}$U compared with experimental data [1–3].

Multi-chance fission (MCF)

The process by which an excited nucleus emits neutrons and undergoes fission. Competition between neutron emission and fission.

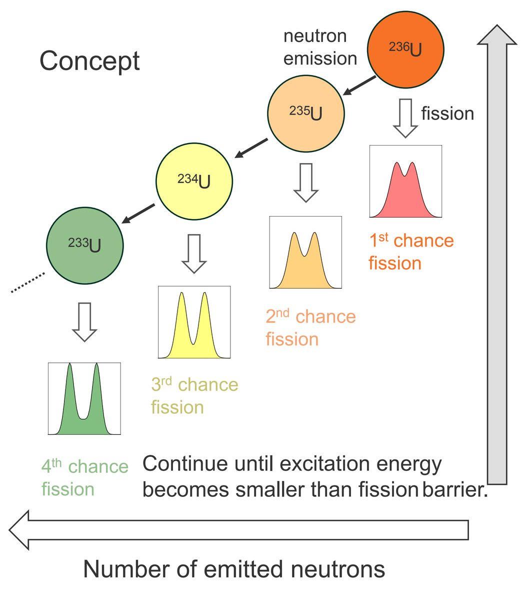

Figure 2: Concept of multichance fission.

Previous study:

The neutron emission from compound nucleus is calculated by the GEF code [4], then the Langevin calculation starts to obtain FFMDs [1,3].

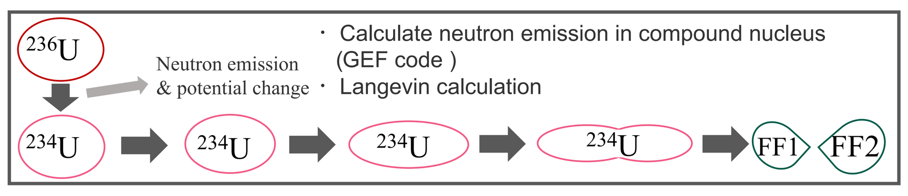

Figure 3: Previous study of MCF calculation [1,3].

Present study:

We calculate the neutron emission **dynamically** during fission process using by Langevin equation and statistical model. Neutrons can be evaporated at any stage of fission process. Neutron emission competes with nuclear shape changes.

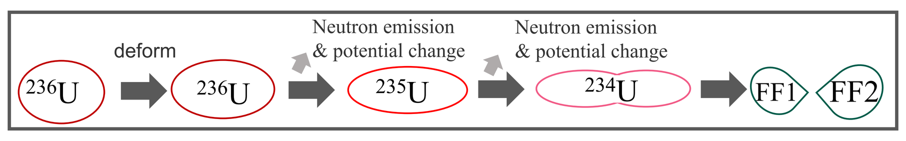

Figure 4: Present study of MCF calculation.

Models

Two-center Shell Model [5]

$$z=\frac{z_0}{BR},\ \delta=\frac{3(a-b)}{2a+b},\ \alpha=\frac{A_1-A_2}{A_1+A_2},\quad B=\frac{3+\delta}{3-2\delta},\ R=r_0A^{1/3},\ r_0=1.2\ [\text{fm}]$$

z : two center distance, δ : deformation, α : mass asymmetry

Two-center parametrization: $q=\{z,\delta,\alpha\}$

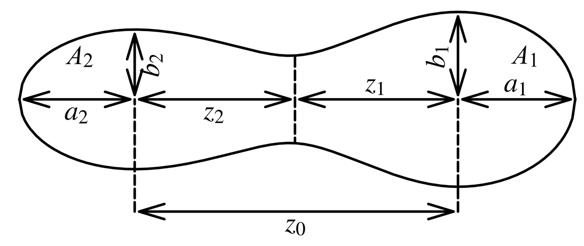

Figure 5: Two center Shell Model

Langevin Equation [7]

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

$$\frac{dp_i}{dt}=-\frac{\partial V}{\partial q_i}-\frac{1}{2}\frac{d}{dq_i}(m^{-1})_{jk}p_jp_k\underbrace{-\gamma_{ij}(m^{-1})_{jk}p_k}_{\text{dissipation}}+\underbrace{g_{ij}R_j(t)}_{\text{fluctuation}}$$

$$\langle R_i(t)\rangle=0$$

$$\langle R_i(t_1)R_j(t_2)\rangle=2\delta_{ij}\delta(t_1-t_2)\quad \text{(white noise)}$$

$$\gamma_{ij}T=\sum_k g_{ik}g_{jk}\quad \text{(Einstein relation)}$$

q_i : deformation coordinate(z,δ,α),
p_i : conjugate momentum,
m_{ij} : inertia mass (Werner-Wheeler approximation)[8],
γ_{ij} : one body friction (wall and window formula)[9],
g_{ij} : strength of random force

Potential energy surface

$$V(q,T)=V_{\rm LDM}(q)+V_{\rm SH}(q,T),$$
$$V_{\rm LDM}(q)=E_S(q)+E_C(q),$$
$$V_{\rm SH}(q,T)=E^0_{\rm SH}(q)\Phi(T),$$
$$E^0_{\rm SH}(q)=\Delta E_{\rm Shell}(q)+\Delta E_{\rm Pair}(q),$$
$$\Phi(T)=\exp\left(-\frac{a_nT^2}{E_d}\right),\quad E_d=20\ \text{MeV}[6]$$

E_S : generalized surface energy, E_C : Coulomb energy,
$\Delta E_{\rm Shell}$: shell correction energy, $\Delta E_{\rm Pair}$: pairing correction energy,
T : nuclear temperature, a_n : level density parameter

Neutron emission

Langevin equation and statistical model are coupled to describe neutron emission during fission process [10].

Lifetime of neutron emission τ_n and time step of Langevin calculation Δt are competing.

$$\frac{\Delta t}{\tau_n}\geq\zeta,\quad \tau_n=\frac{\hbar}{\Gamma_n}.$$

T_ℓ : transmission probability, U^* : effective excitation energy,
σ : spin dispersion parameter ($\sigma^2=\mathcal{I}T/\hbar^2$), $\mathcal{I}$: moment of inertia,
g_n : $2s_n+1$ (s_n : spin of neutron $(=1/2)$),
E_n : kinetic energy of evaporated neutron,
ζ : uniform random number $(0\leq\zeta\leq1)$

Neutron decay width Γ_n and level density ρ [11]

$$\Gamma_n=\frac{1}{2\pi\rho(U^*,J)}g_n\times\int_0^{U^*-B_n}\sum_\ell(2\ell+1)T_\ell(E_n)\rho(U^*-B_n-E_n,\ell)\,dE_n,$$

$$\rho(U^*,J)=\frac{\pi}{12a_n^{1/4}U^{*5/4}}\exp\left(2\sqrt{a_nU^*}\right)\times\frac{2J+1}{2\sqrt{2\pi}\sigma^3}\exp\left\{-\frac{(J+1/2)^2}{2\sigma^2}\right\}.$$

Result and discussion

Fission fragment mass distributions (FFMDs)

- ✓ FFMDs for 21 nuclides ($^{234\text{-}240}$U, $^{236\text{-}240}$Np, and $^{238\text{-}244}$Pu) are shown with initial excitation energy range from $E^*=$ 15 to 55 MeV (10 MeV bin).
- ✓ Calculations that do not take into account neutron emission agree at low excitation energies, but at high energies, the distribution becomes a single peak.
- ✓ When neutron emission is taken into account, the distribution shows two peaks even in the high-energy region, especially for neutron-rich nuclei.

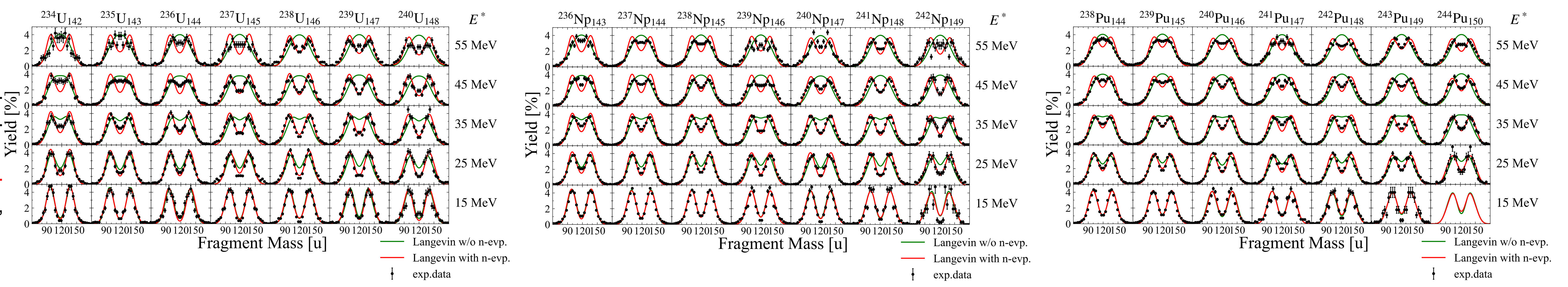

Figure 6: Fission fragment mass distributions for $^{234\text{-}240}$U, $^{236\text{-}240}$Np, and $^{238\text{-}244}$Pu with and without neutron emission compared with experimental data [1,2].

Prescission neutron multiplicity

- □ The number of neutrons emitted increases with the excitation energy and with the mass number of the initial compound nucleus.
- □ At energies above 35 MeV, our Langevin calculations give higher multiplicities than in GEF calculations for all systems.
- □ Total number of neutron emission is almost same with GEF calculation up to $E^*=$ 35 MeV for uranium and 25 MeV for neptunium and plutonium nuclides.

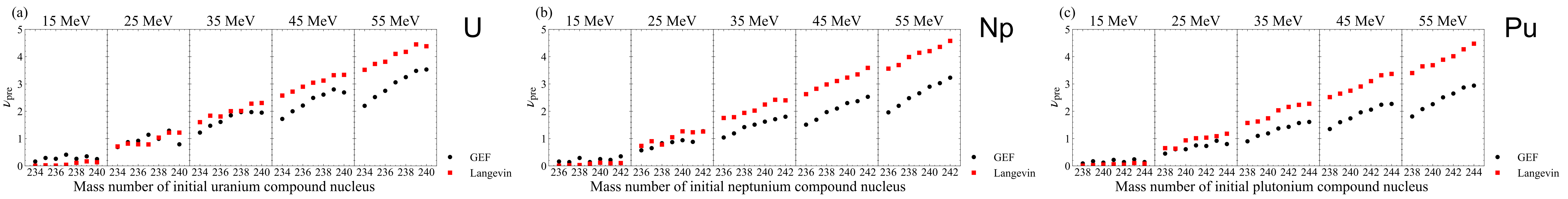

Figure 7: Comparison of the average number of neutrons emitted in fission of (a) $^{234\text{-}240}$U, (b) $^{236\text{-}240}$Np, and (c) $^{238\text{-}244}$Pu calculated by GEF [4] (black) and Langevin (red).

Probability of neutron emission

- The most of neutrons are emitted near the ground-state shape.
- The second minimum at $z=0.7$ is the another neutron emission point.
- Neutrons are emitted at any shape of nucleus from the saddle point to near the scission point of $z>1$.

Symbol

× Ground state

+ Second minimum

○ First barrier

▽ Second barrier

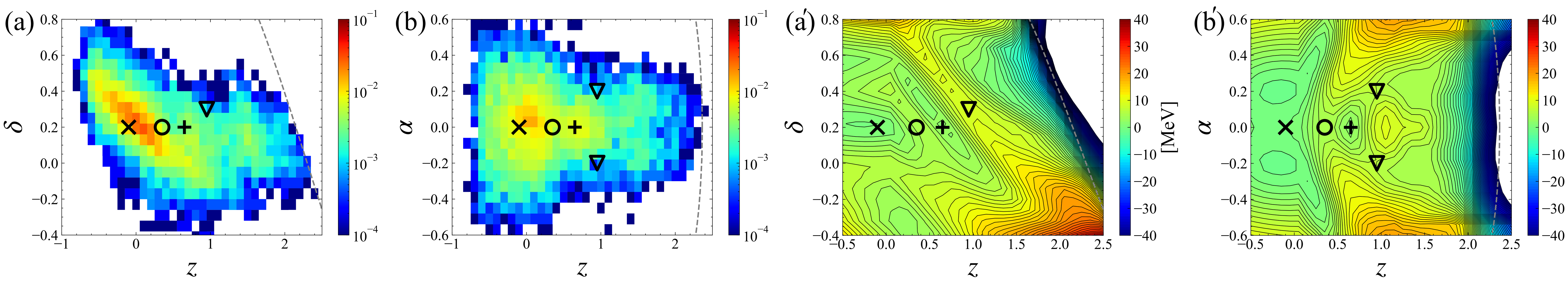

Figure 8: The left two figures show the probability of neutron emission in the deformation space of (a) (z,δ) and (b) (z,α) for ^{238}U. The right two figures show the potential energy surface of ^{238}U in the deformation space of (a') (z,δ) and (b') (z,α). The gray line indicates the scission line.

Conclusion

- Fission fragment mass distributions are calculated in the Langevin equations for 21 U, Np, and Pu nuclei, and their excitation energy dependence is obtained from an initial excitation energy $E^*=$ 15 to 55 MeV.
- Neutron emission is handled through the evolution of nuclear shape from the ground state to the scission point, in contrast to the usual statistical model.
- The present calculation treating neutron emission during fission demonstrates that measured FFMDs can adequately predict the FFMDs for high-energy fissions, thus can be alternative to the traditional approach of treating multichance fission.
- Concerning the origin point of neutrons, they are mostly emitted from the ground-state shape. However, neutrons are emitted in all the shape of shape evolution down to the scission point, by showing relatively large neutrons around the second minimum.

References

[1] K. Hirose *et al.*, Phys. Rev. Lett. **119**, 222501 (2017).
[2] M. J. Vermeulen *et al.*, Phys. Rev. C. **102**, 54610 (2020).
[3] S. Tanaka *et al.*, Phys. Rev. C. **100**, 64605 (2019).
[4] K.-H. Schmidt *et al.*, Nucl. Data Sheets **131**, 107 (2016).
[5] J. Maruhn and W. Greiner, Z. Phys. **251**, 431 (1972).
[6] A. V. Ignatyuk, G. N. Smirenkin, and A. S. Tishin, Sov. J. Nucl. Phys. **21**, 255 (1975).
[7] Y. Aritomo and M. Ohta, Nucl. Phys. A **744**, 3 (2004).
[8] K. T. R. Davies, A. J. Sierk, and J. R. Nix, Phys. Rev. C. **13**, 2385 (1976).
[9] A. J. Sierk and J. R. Nix, Phys. Rev. C. **21**, 982 (1980).
[10] P. Fröbrich, I. I. Gontchar, and N. D. Mavlitov, Nucl. Phys. A **556**, 281 (1993).
[11] S. F. Mughabghab and C. Dunford, Phys. Rev. Lett. **81**, 4083 (1998).