Reaction mechanism of fusion-fission process in superheavy mass region

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「微視的核反応理論による物理」
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1. Model

Coupled-channels method + Dynamical Langevin calculation

Trajectory analysis ← Langevin equation

Two center shell model

2. Results

$^{36}S + ^{238}U$ and $^{30}Si + ^{238}U$

Mass distribution of Fission fragments

Capture Cross-section

Fusion Cross-section

3. Mechanism of Dynamical process

Potential energy surface on scission line

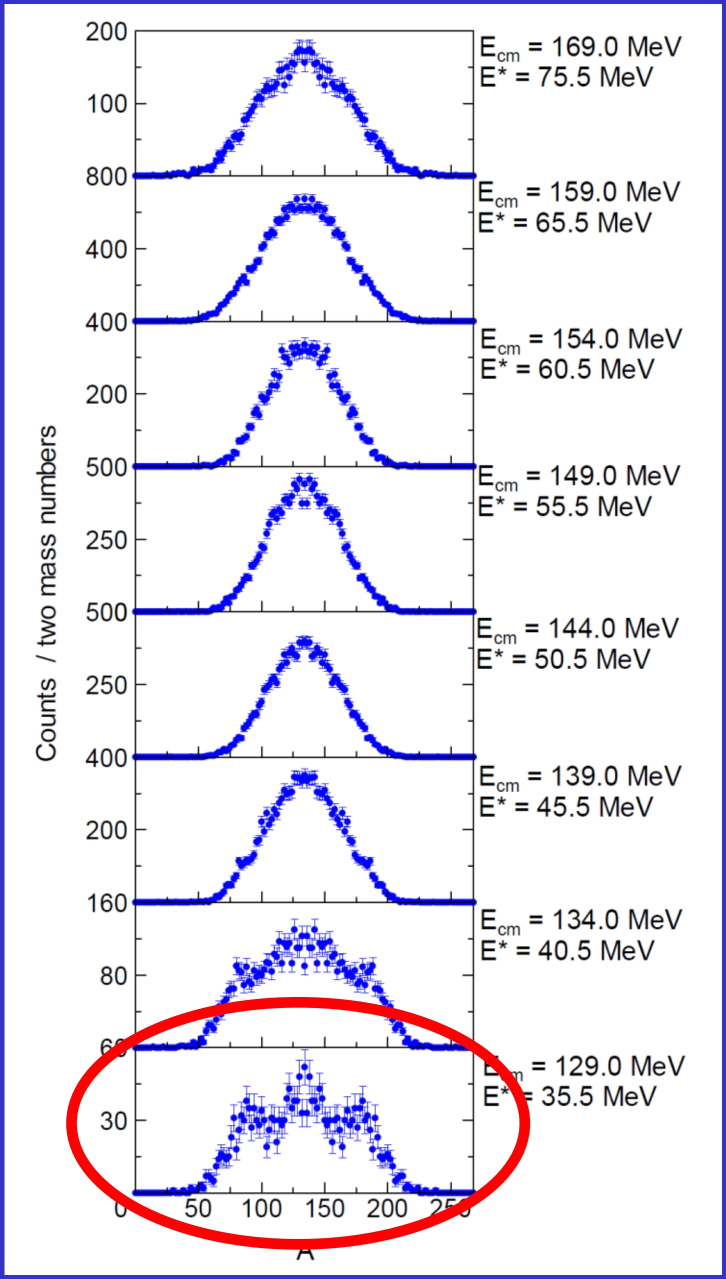
Analysis of trajectory behavior

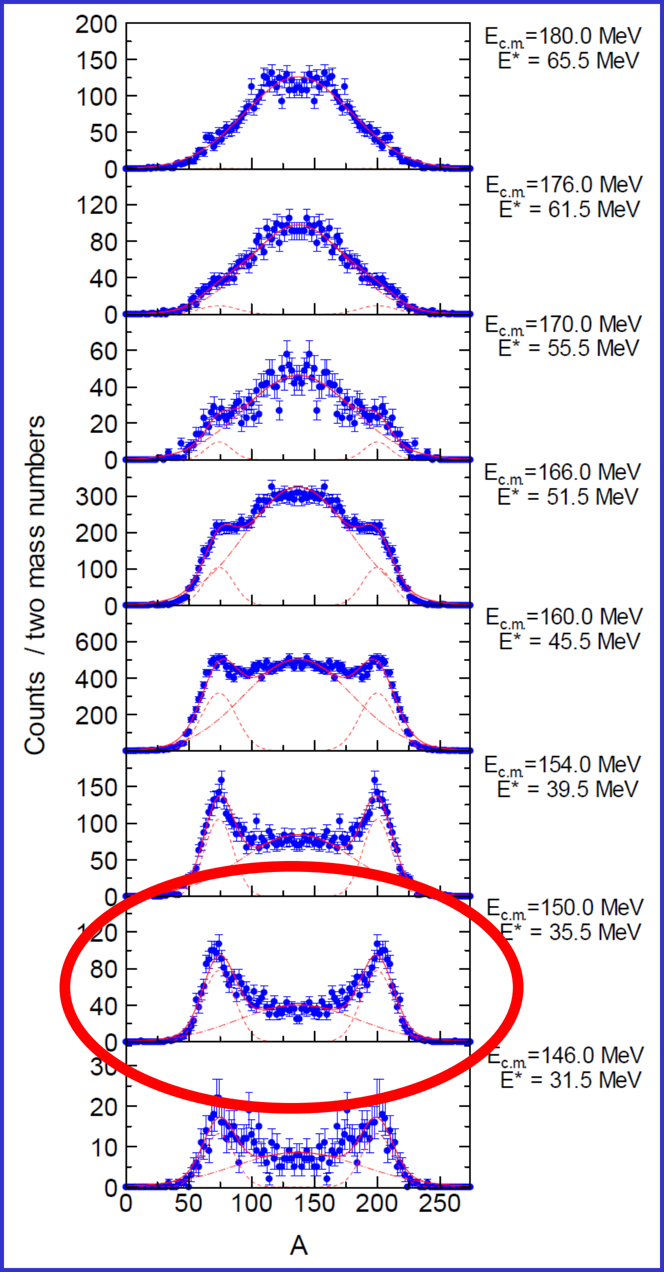
Analysis of probability distribution

4. Summary

← Zcn=106 $^{30}Si + ^{238}U$ $^{36}S + ^{238}U$ Zcn=108 →

Exp. by K. Nishio *et al.*





What we can obtain under the conditions

Phenomenalism

Dynamical Model based on Fluctuation-dissipation theory

(Langevin eq, Fokker-Plank eq, etc) ← Classical trajectory analysis

We can obtain…. *Fission, Synthesis of SHE*

Mass and TKE distribution of fission fragments *A_{CN} : 200~300*

Neutron multiplicity

Charge distribution

Cross section (capture, mass symmetric fission, fusion)

Angle of ejected particle, Kinetic energy loss (← two body)

Conditions

Nuclear shape parameter

Potential energy surface (LDM, shell correction energy, LS force)

Transport coefficients (friction, inertia mass) ← Liner Response Theory

Dynamical equation (memory effect, Einstein relation)

1. Model

1-1. Potential

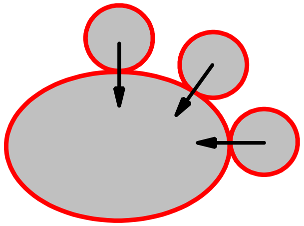
1-2. Dynamical Equation

1-3. Simulation of Experiment and Cross Sections

Estimation of cross sections

Capture Cross Section

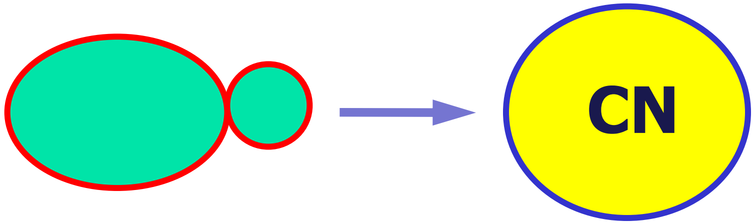
$$\sigma_{\rm cap}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm cap}(E;\theta),$$



$$\sigma_{\rm cap}(E;\theta) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T_\ell(E;\theta),$$

Coupled-channel method

Fusion Cross Section



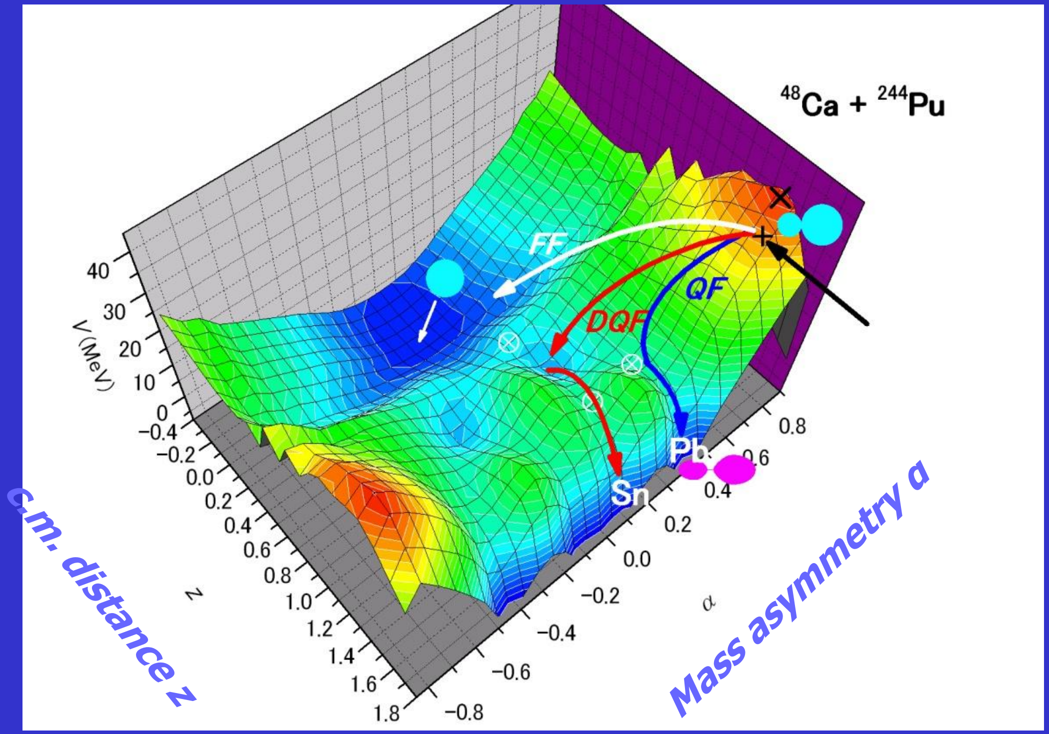
Formation probability P_{CN}

$$\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta),$$

$$\sigma_{\rm fus}(E;\theta) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)T_\ell(E;\theta)P_{\rm CN}(E,\ell,\theta)$$

Dynamical calculation
Langevin eq.

Model: Outlook of calculation methods



Time-evolution of nuclear shape in fusion-fission process

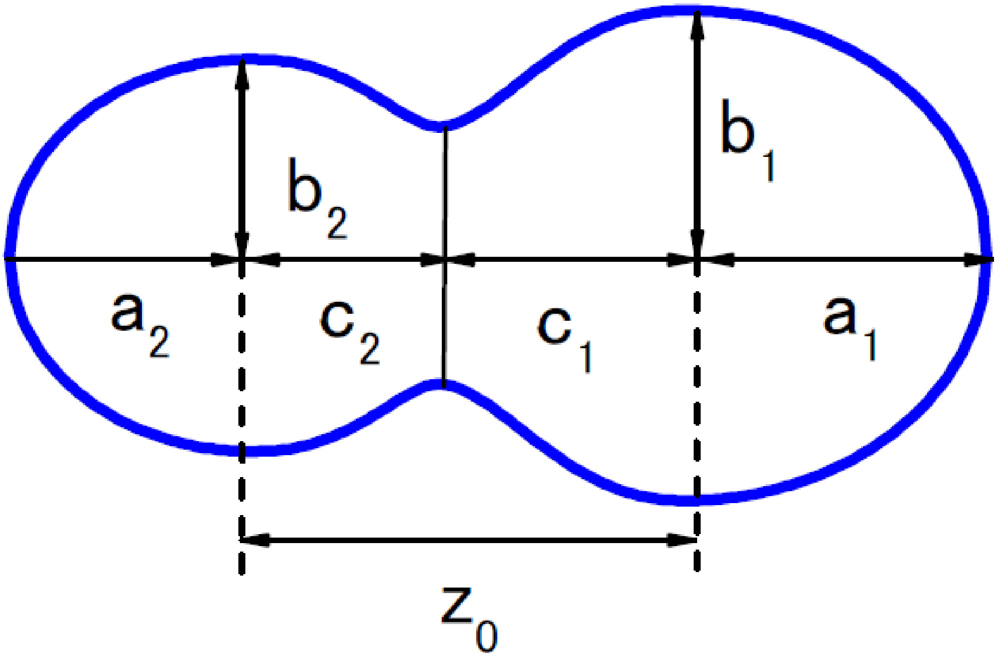
1. Potential energy surface

2. Trajectory → described by equations

Nuclear shape

two-center parametrization (z,δ,α)

(Maruhn and Greiner,
Z. Phys. 251(1972) 431)



$$q(z,\delta,\alpha)$$

$$z=\frac{z_0}{BR}$$

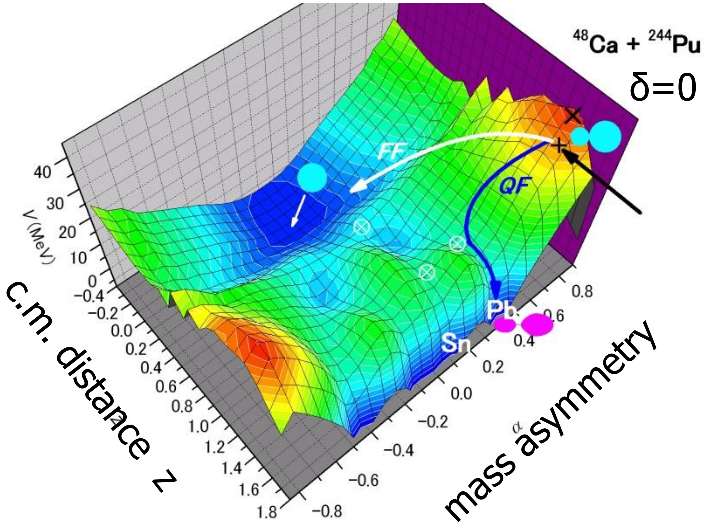
$$B=\frac{3+\delta}{3-2\delta}$$

R : Radius of the spherical compound nucleus

$$\delta=\frac{3(a-b)}{2a+b}$$

(δ1=δ2)

$$\alpha=\frac{A_1-A_2}{A_{CN}}$$



Trajectory which enters into the spherical region = fusion trajectory

Potential Energy

$$V(q,\ell,T) = V_{DM}(q) + \frac{\hbar^2 \ell(\ell+1)}{2I(q)} + V_{SH}(q,T)$$

$$V_{DM}(q) = E_S(q) + E_C(q)$$

$$V_{SH}(q,T) = E^0_{shell}(q)\Phi(T)$$

T : nuclear temperature

$E^* = aT^2$ a : level density parameter

Toke and Swiatecki

E_S : Generalized surface energy (finite range effect)

E_C : Coulomb repulsion for diffused surface

E^0_{shell} : Shell correction energy at $T=0$

I : Moment of inertia for rigid body

$\Phi(T)$: Temperature dependent factor

$$\Phi(T) = \exp\left\{-\frac{aT^2}{E_d}\right\}$$

$$E_d = 20\,\mathrm{MeV}$$

Multi-dimensional Langevin Equation

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

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

Friction dissipation

Random force fluctuation

Newton equation

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

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

q_i : deformation coordinate (nuclear shape)

two-center parametrization (z, δ, α) (Maruhn and Greiner, Z. Phys. 251(1972) 431)

p_i : momentum

m_{ij} : Hydrodynamical mass (inertia mass)

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

$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q)$$

E_{int} : intrinsic energy, E^* : excitation energy

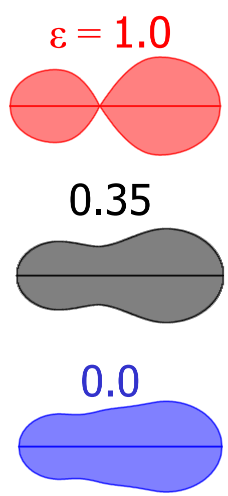
Two Center Shell Model

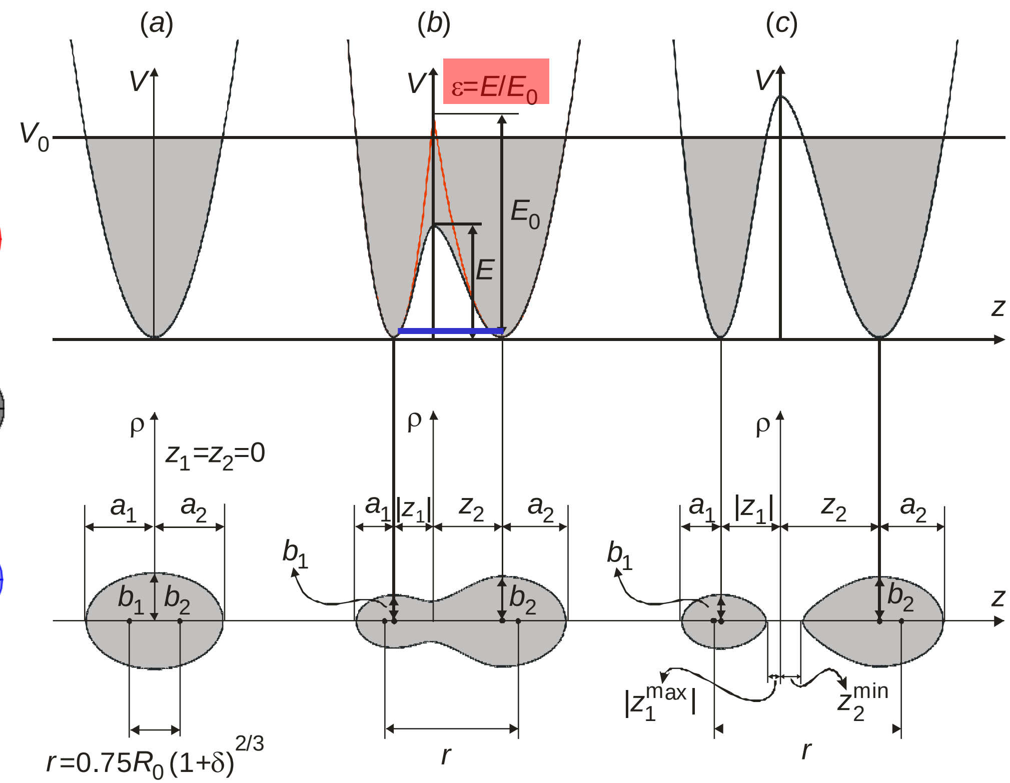
$$\hat{H} = -\frac{\hbar^2}{2m_0}\nabla^2 + V(\mathbf{r}) + V_{\mathrm{LS}}(\mathbf{r},\mathbf{p},\mathbf{s}) + V_{\mathrm{L}^2}(\mathbf{r},\mathbf{p}).$$

$$V(\rho,z) = \frac{1}{2}m_0 \begin{cases} \omega_{z1}^2 z'^2 + \omega_{\rho 1}^2 \rho^2, \quad z < z_1 \\ \omega_{z1}^2 z'^2 \left(1 + c_1 z' + d_1 z'^2\right) + \omega_{\rho 1}^2 \left(1 + g_1 z'^2\right)\rho^2, \\ \quad z_1 < z < 0 \\ \omega_{z2}^2 z'^2 \left(1 + c_2 z' + d_2 z'^2\right) + \omega_{\rho 2}^2 \left(1 + g_2 z'^2\right)\rho^2, \\ \quad 0 < z < z_2 \\ \omega_{z2}^2 z'^2 + \omega_{\rho 2}^2 \rho^2, \quad z > z_2, \end{cases}$$

Neck parameter is the ratio of smoothed potential height to the original one where two harmonic oscillator potential cross each other

$$z' = \begin{cases} z - z_1 & z < 0 \\ z - z_2 & z > 0 \end{cases}$$

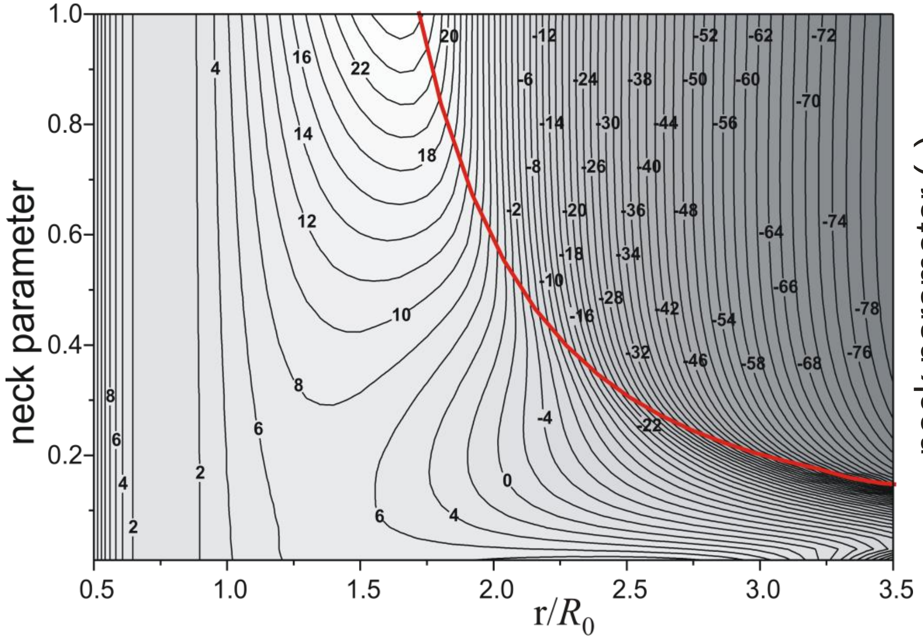


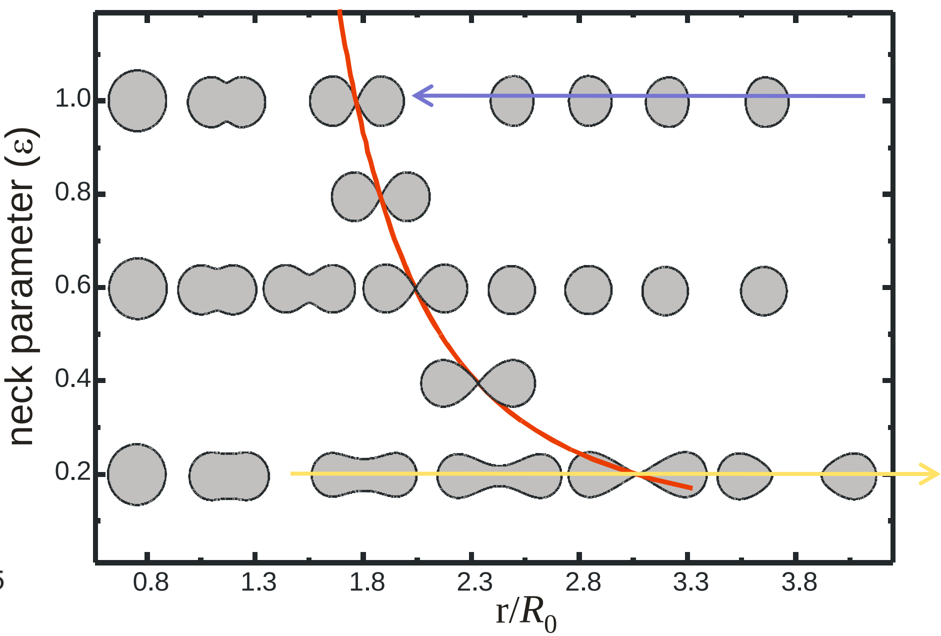


J. Maruhn and W. Greiner, Z. Phys, 1972

Time dependent adiabatic fusion-fission potential

^{224}Th





$$V_{\text{adiab}}(r,\delta,\alpha,\varepsilon;t) = V_{\text{adiab}}(r,\delta,\alpha,\varepsilon=1)\cdot\exp\left(-\frac{t}{\tau_\varepsilon}\right) + V_{\text{adiab}}(r,\delta,\alpha,\varepsilon=\varepsilon_{out})\cdot\left[1-\exp\left(-\frac{t}{\tau_\varepsilon}\right)\right]$$

Time-dependent weight function

$$\tau_\varepsilon = 10^{-20} \ \text{sec}$$

V. Zagrebaev, A. Karpov, Y. Aritomo, M. Naumenko and W. Greiner, Phys. Part. Nucl. 38 (2007) 469

2. Results

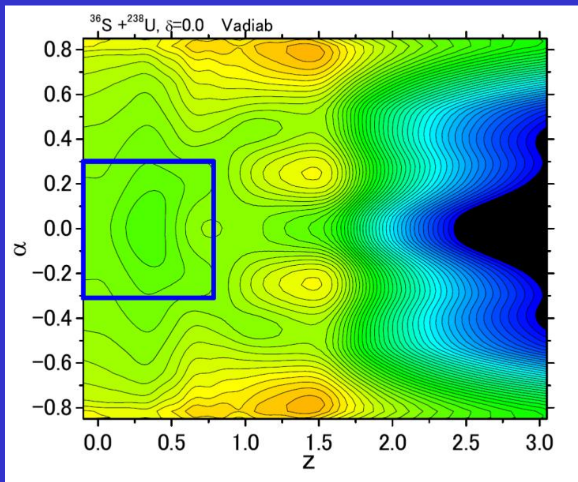
1. Capture and Fusion Cross sections
2. Mass distribution of Fission Fragments

$^{34,\,36}S+^{238}U$ and $^{30}Si+^{238}U$

Touching probability ← CC method

Perform a trajectory calculation
starting from the touching distance between target and projectile
to the end each process.

Fusion box and Sample trajectory $^{36}S+^{238}U$



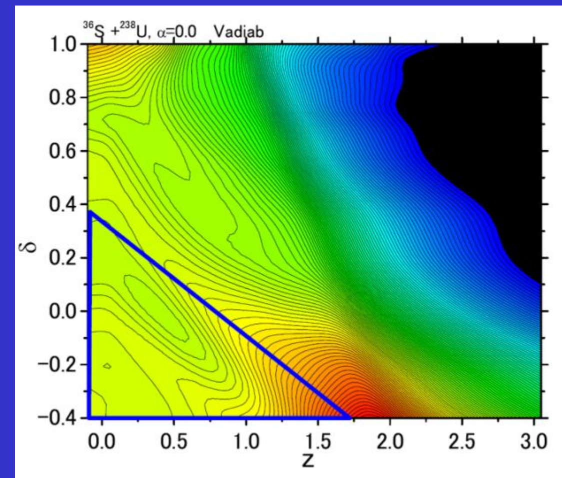
z-α

δ=0

E*= 40 MeV

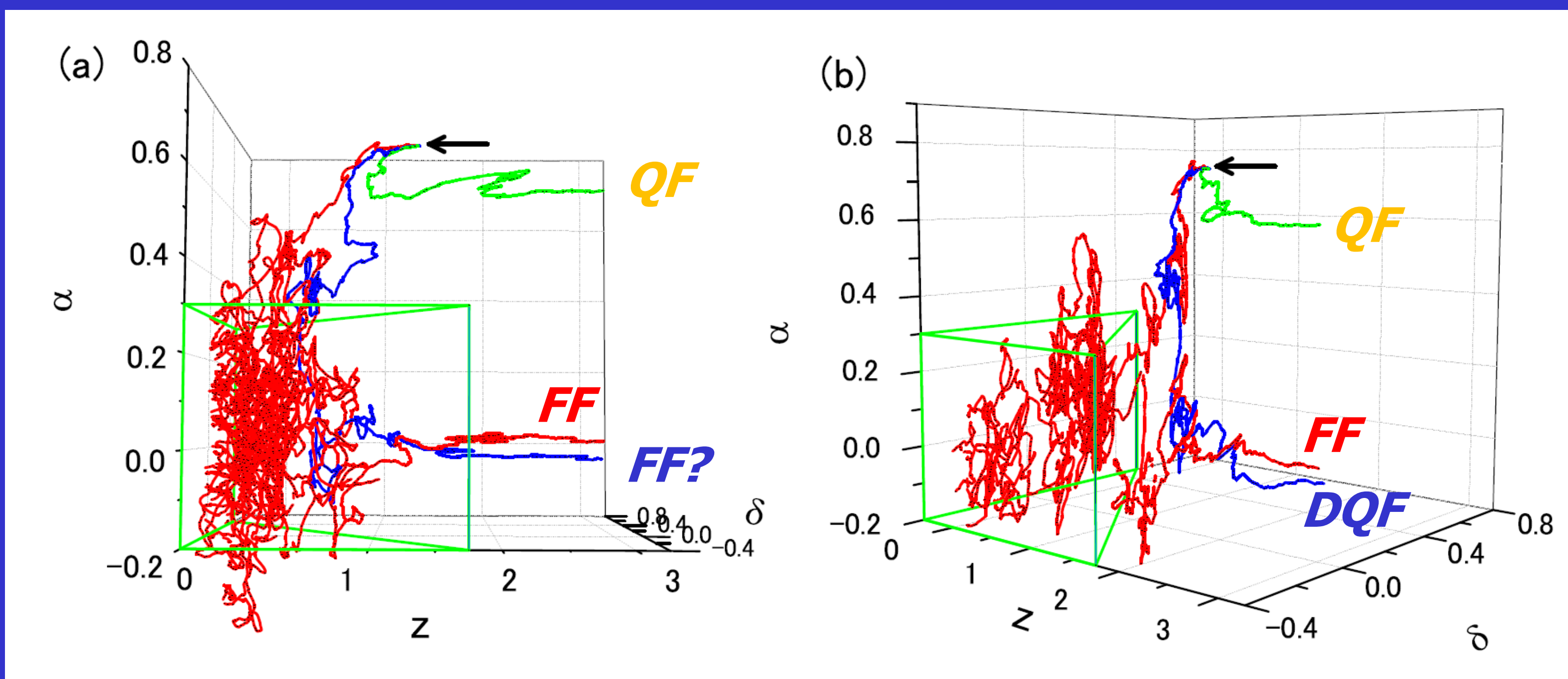
L = 0

θ = 0



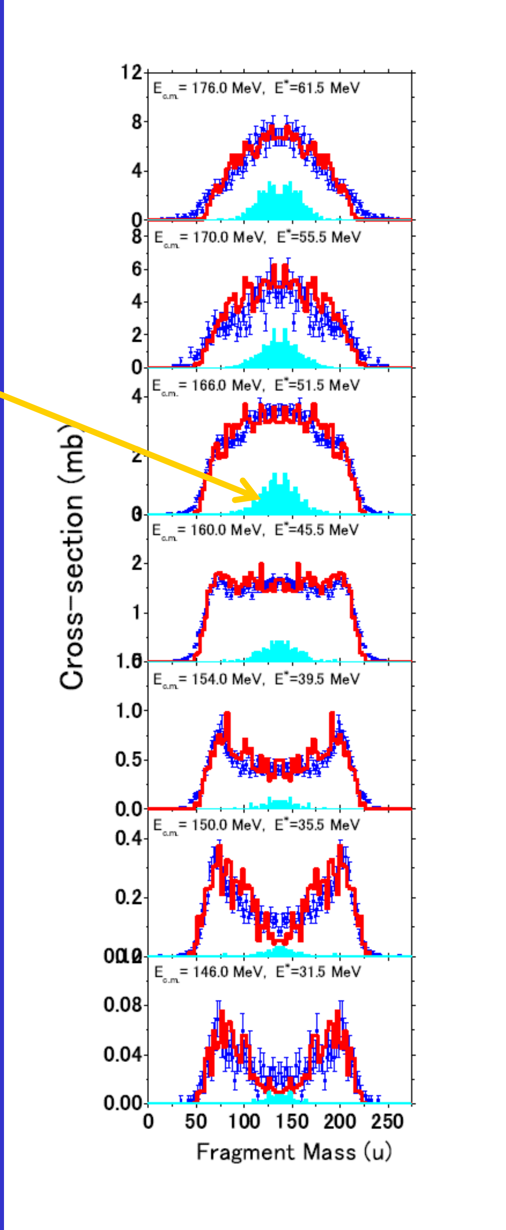
z-δ

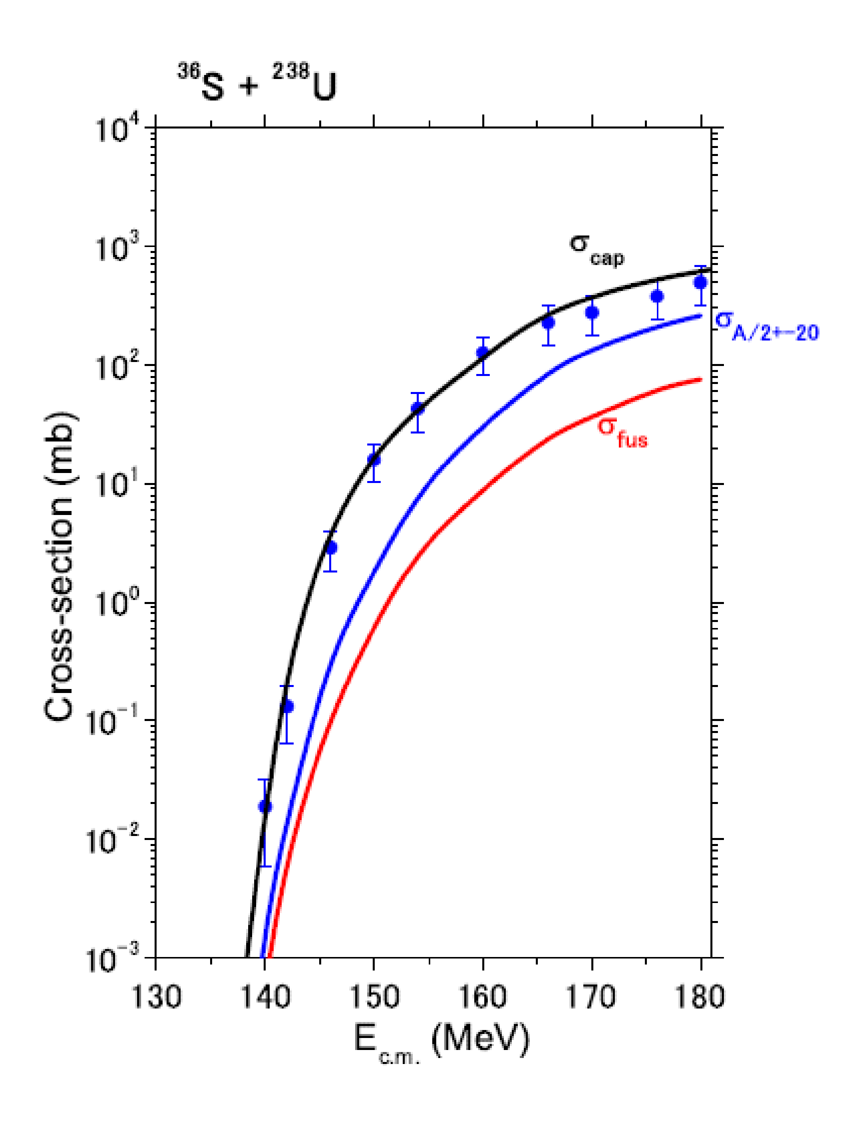
α=0



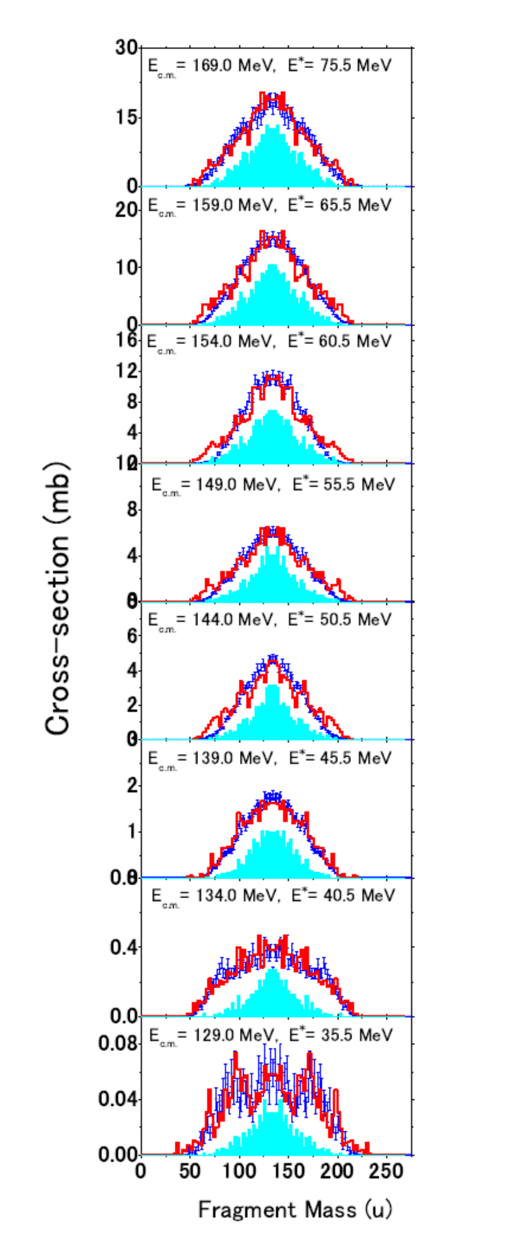
Results $^{36}S+^{238}U$ MDFF and Cross sections

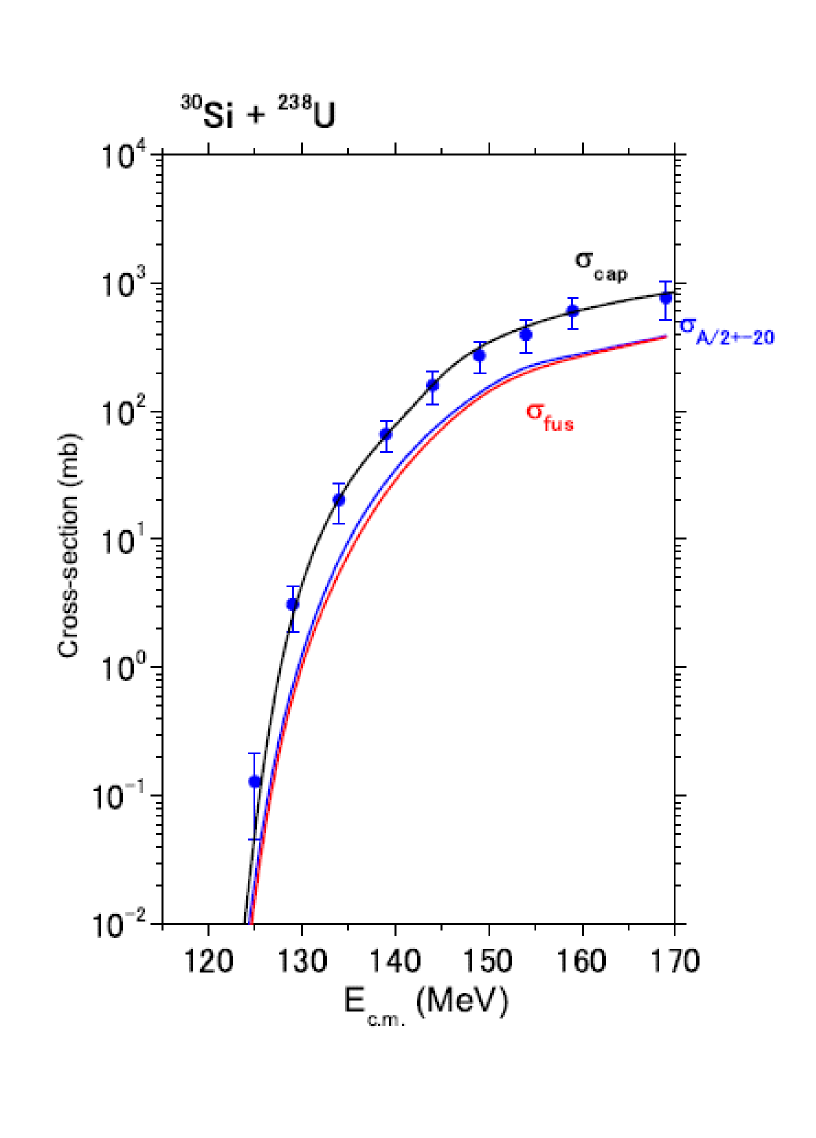
FF process





Results $^{30}Si+^{238}U$ MDFF and Cross sections

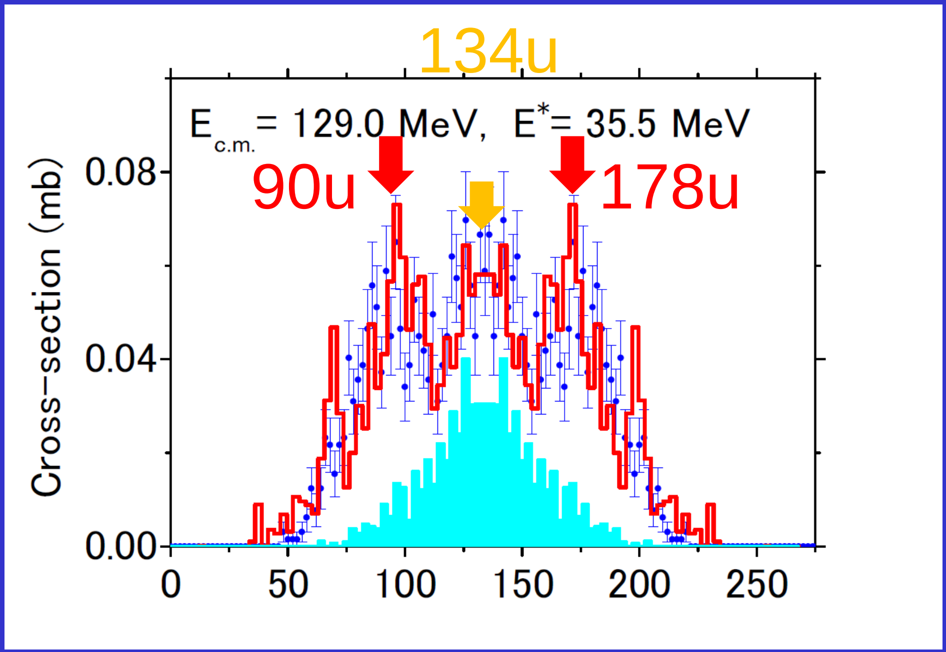




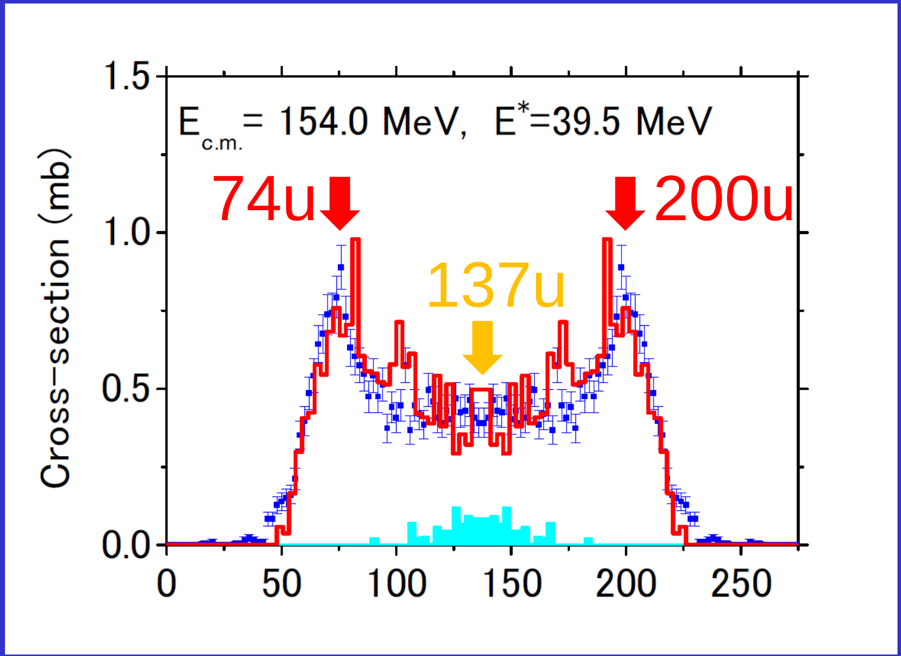
3. Mechanism of Dynamical process

MDFF at Low incident energy

$^{30}Si+^{238}U$

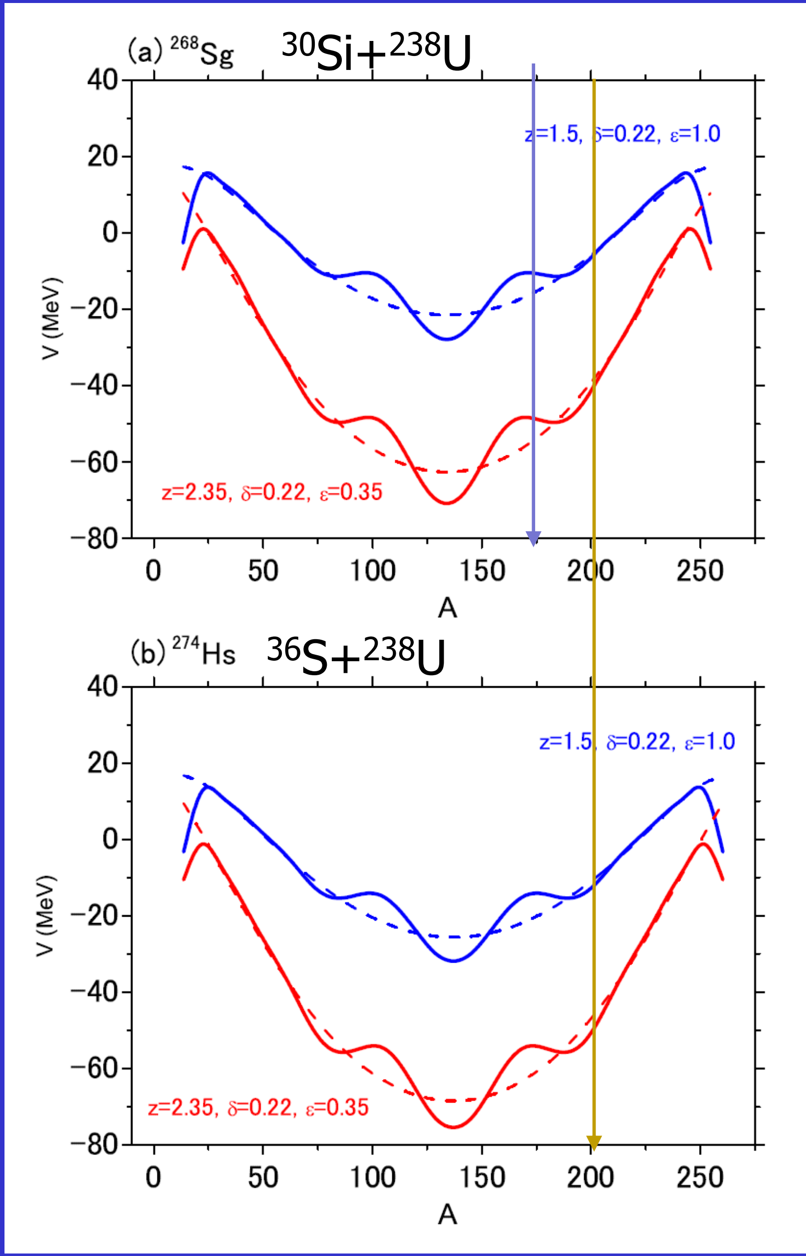


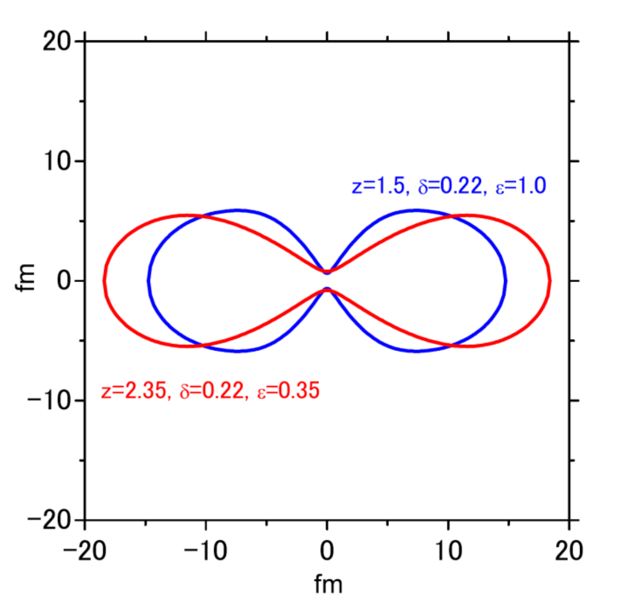
$^{36}S+^{238}U$

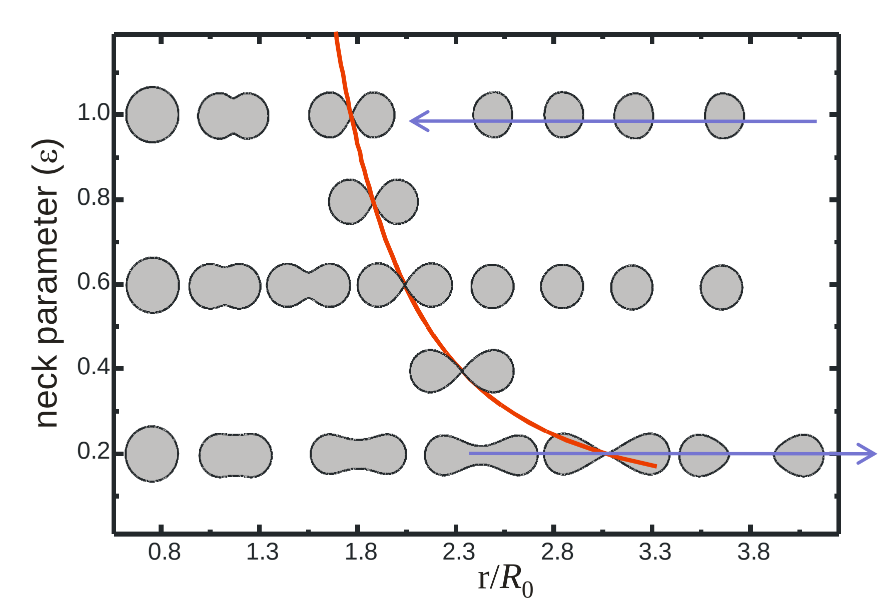


Clarification of the mechanism of Fusion-fission process

(a) 1-dim Potential energy on scission line

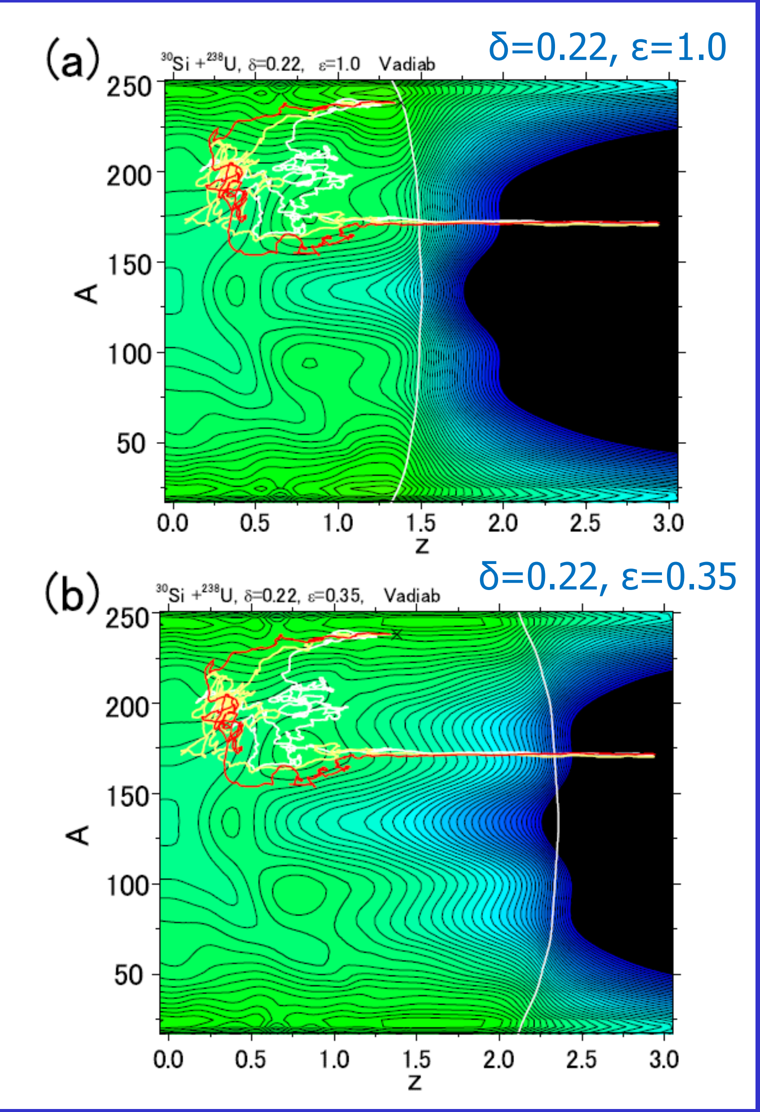




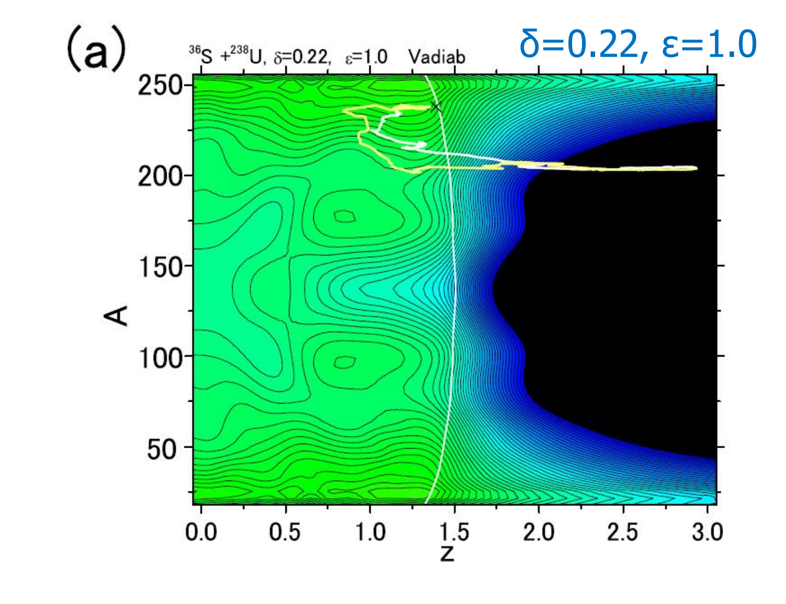


(b) Trajectory Analysis on Potential Energy Surface z-A plane

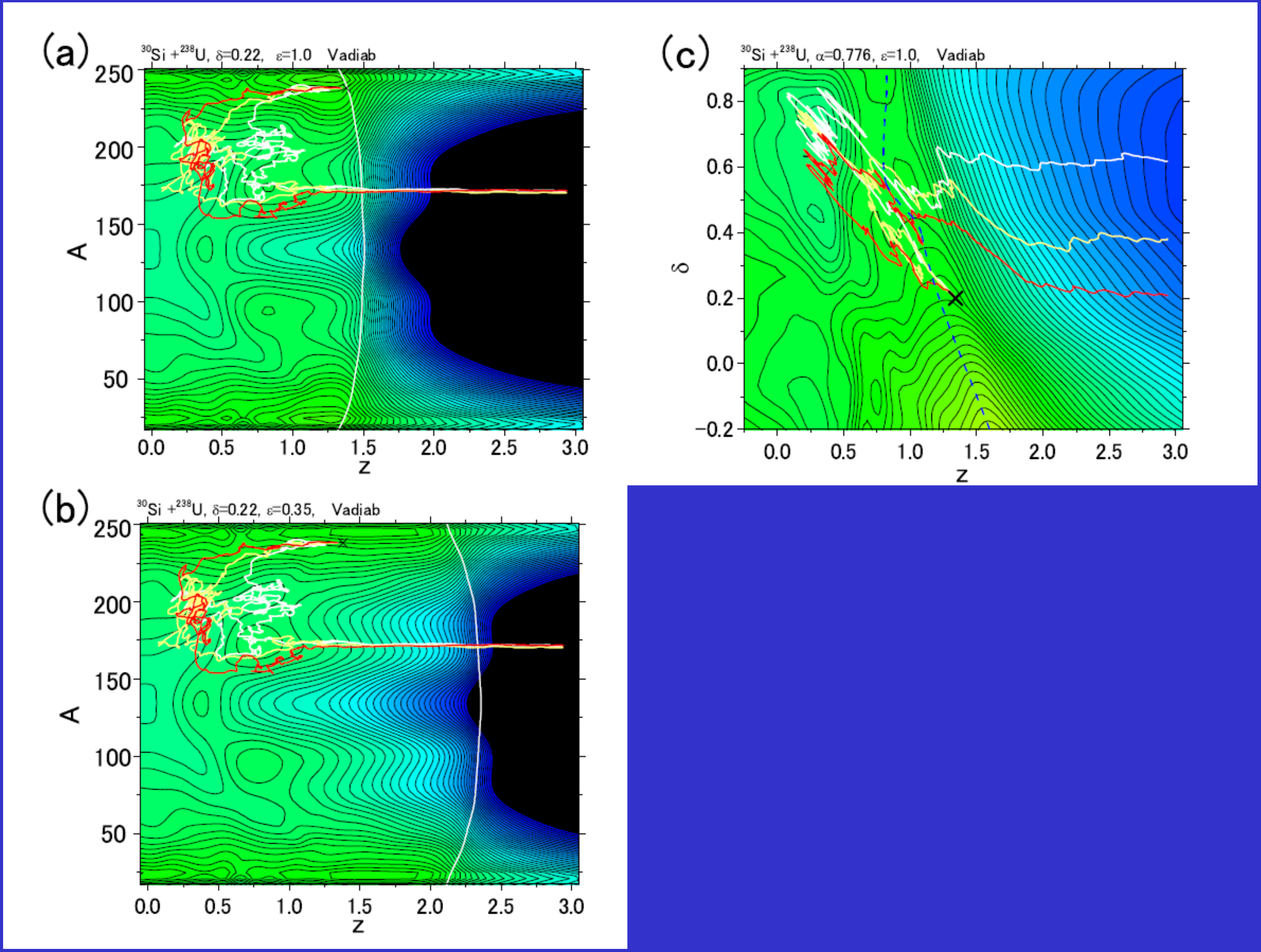
$^{30}Si+^{238}U$ E^* = 35.5 MeV
L=0, θ=0



$^{36}S+^{238}U$ E^* = 39.5 MeV
L=0, θ=0



Trajectory Analysis on Potential Energy Surface $^{30}Si+^{238}U$

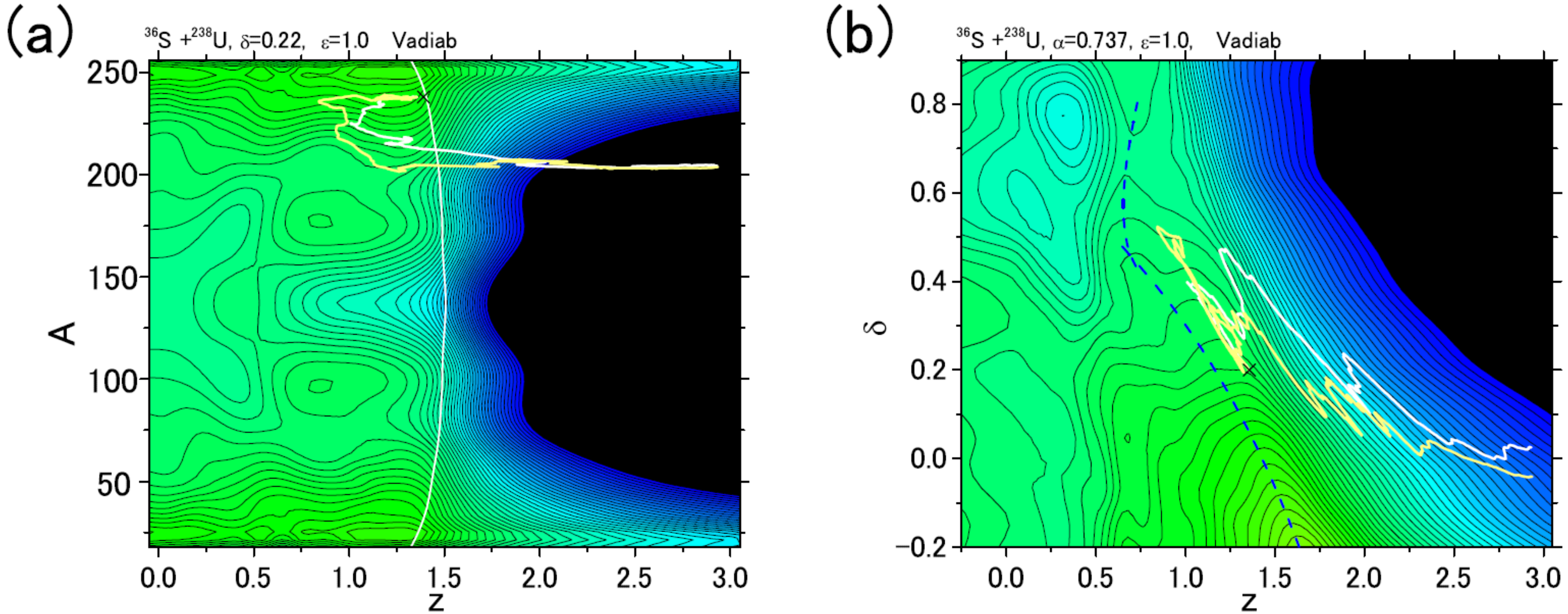


E^* = 35.5 MeV

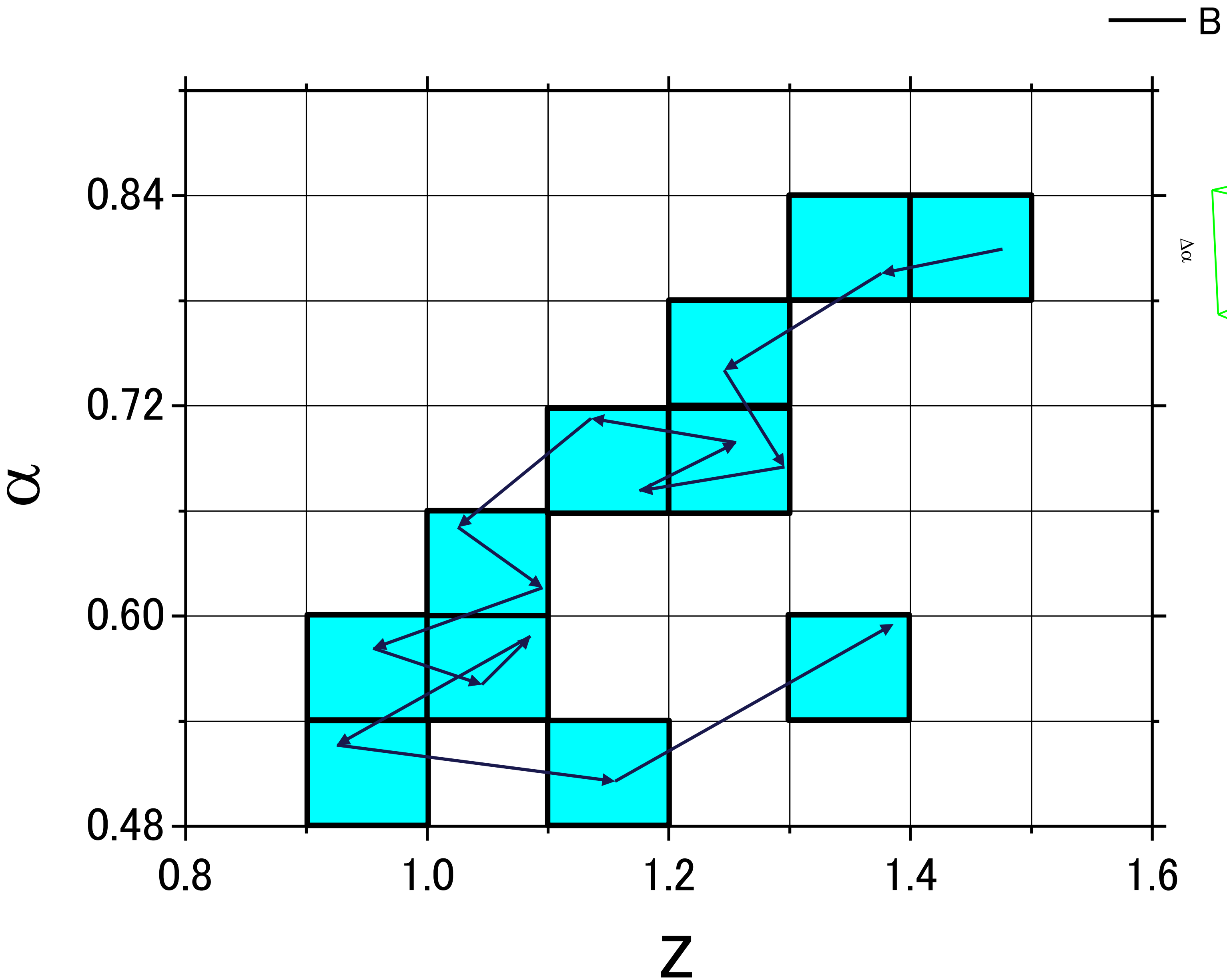
L=0, θ=0

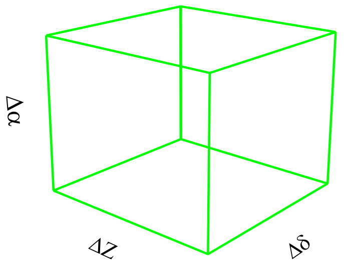
Trajectory Analysis on Potential Energy Surface $^{36}S+^{238}U$

E^* = 39.5 MeV
L=0, θ=0



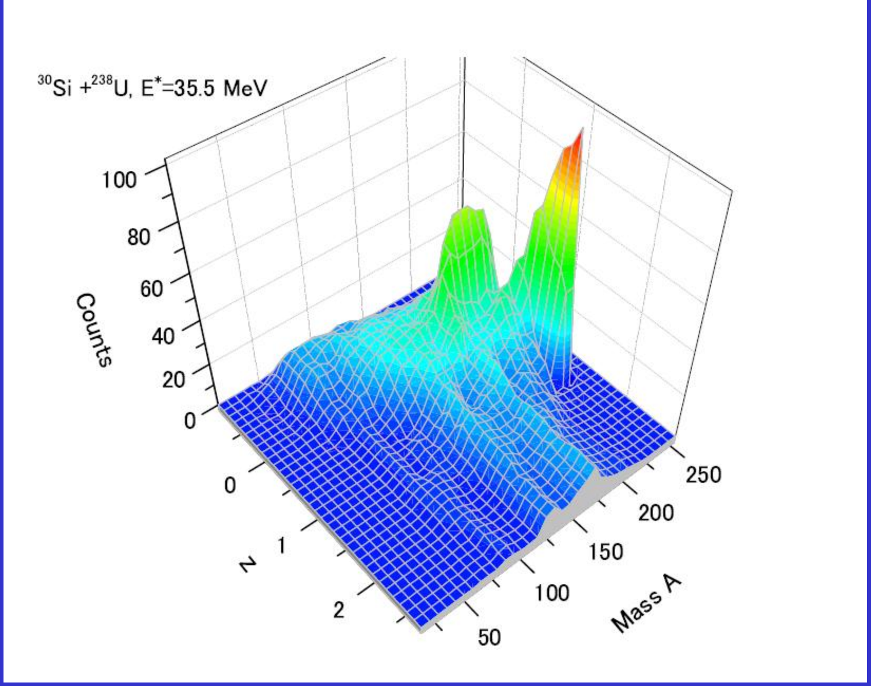
Trajectory Analysis ← using ALL trajectories

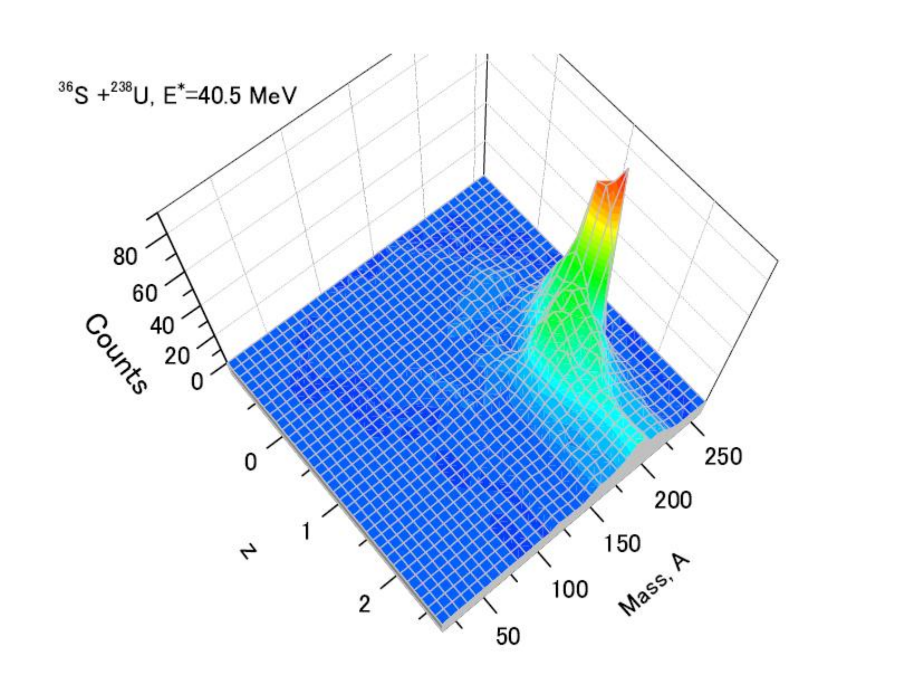




~40,000 points

(c) Trajectory Analysis → "*Probability* Distribution"





*E** =
35.5 MeV
L=0, θ=0

*E** =
39.5 MeV
L=0, θ=0

4. Summary

1. In order to analyze the fusion-fission process in superheavy mass region, we apply the Couple channels method + Langevin calculation.

2. Incident energy dependence of mass distribution of fission fragments (MDFF) is reproduced in reaction $^{36}S+^{238}U$ and $^{30}Si+^{238}U$.

3. The shape of the MDFF is analyzed using
   (a) 1-dim potential energy surface on the scission line
   (b) sample trajectory on the potential energy surface
   (c) *probability distribution*

4. The relation between the touching point and the ridge line is very important to decide the process → fusion hindrance
   leading to synthesize SHE