融合ダイナミクスに起因する殻構造の変化を利用した未知超重元素生成の理論研究

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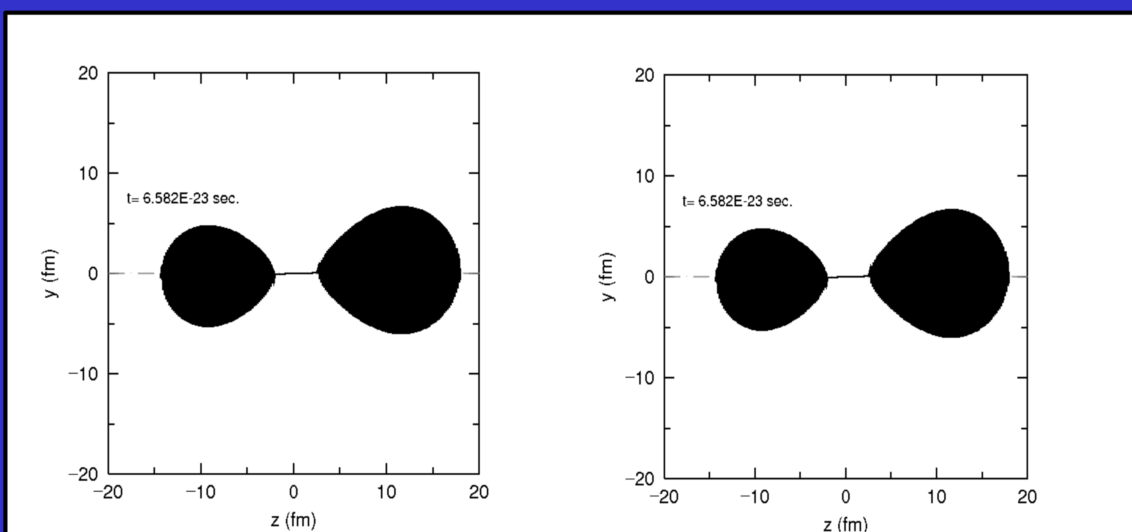

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2021年12月7日（火）
基研研究会 「核力に基づいた原子核の構造と反応」

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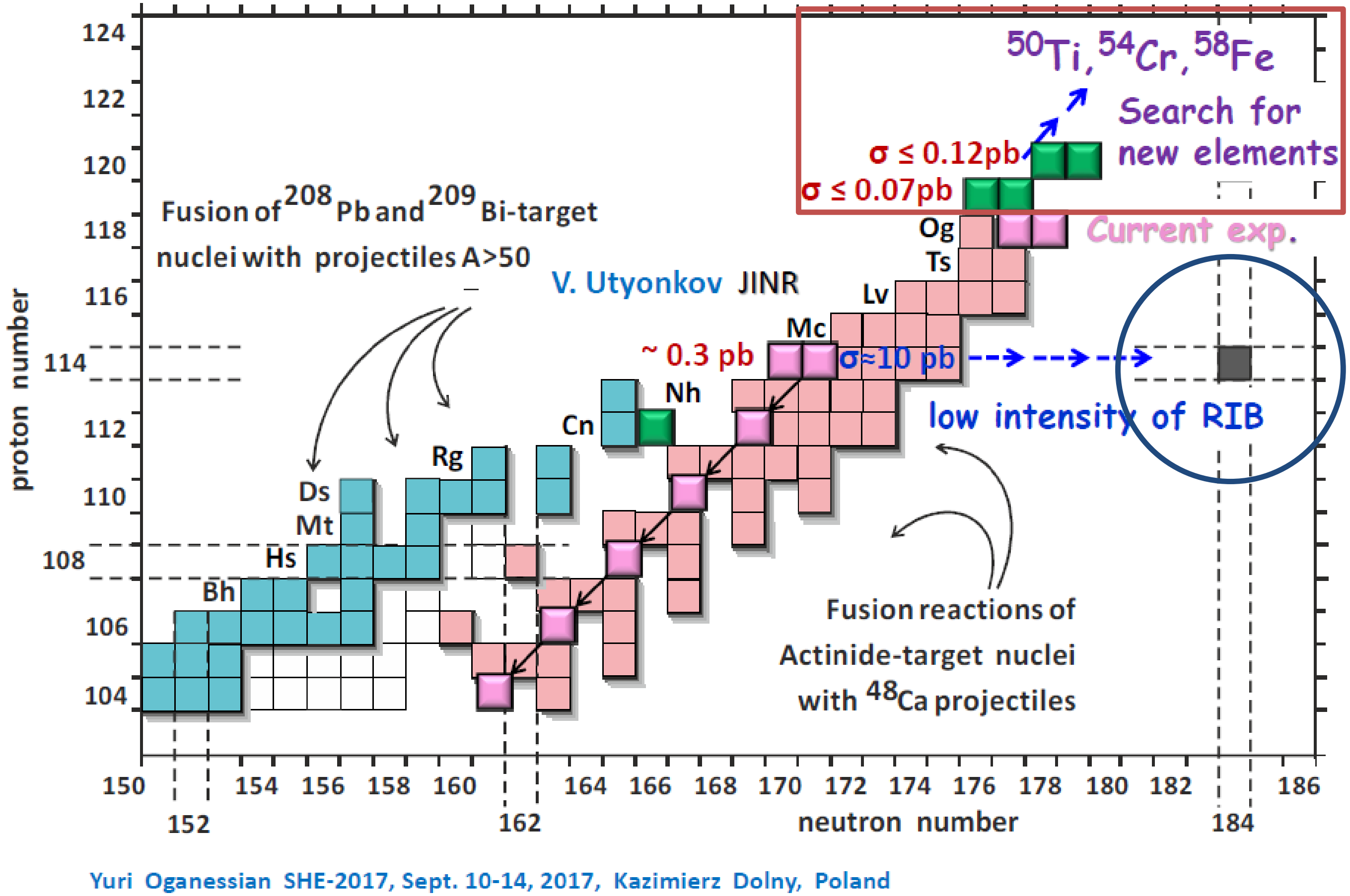
Introduction

New SHE(Z ≧ 119)



Island of Stability

Oganessian

Way for synthesizing new SHE

1) Ti, Cr, Fe etc. beams ← ^{48}Ca beams
   Actinide target

2) Secondary beams

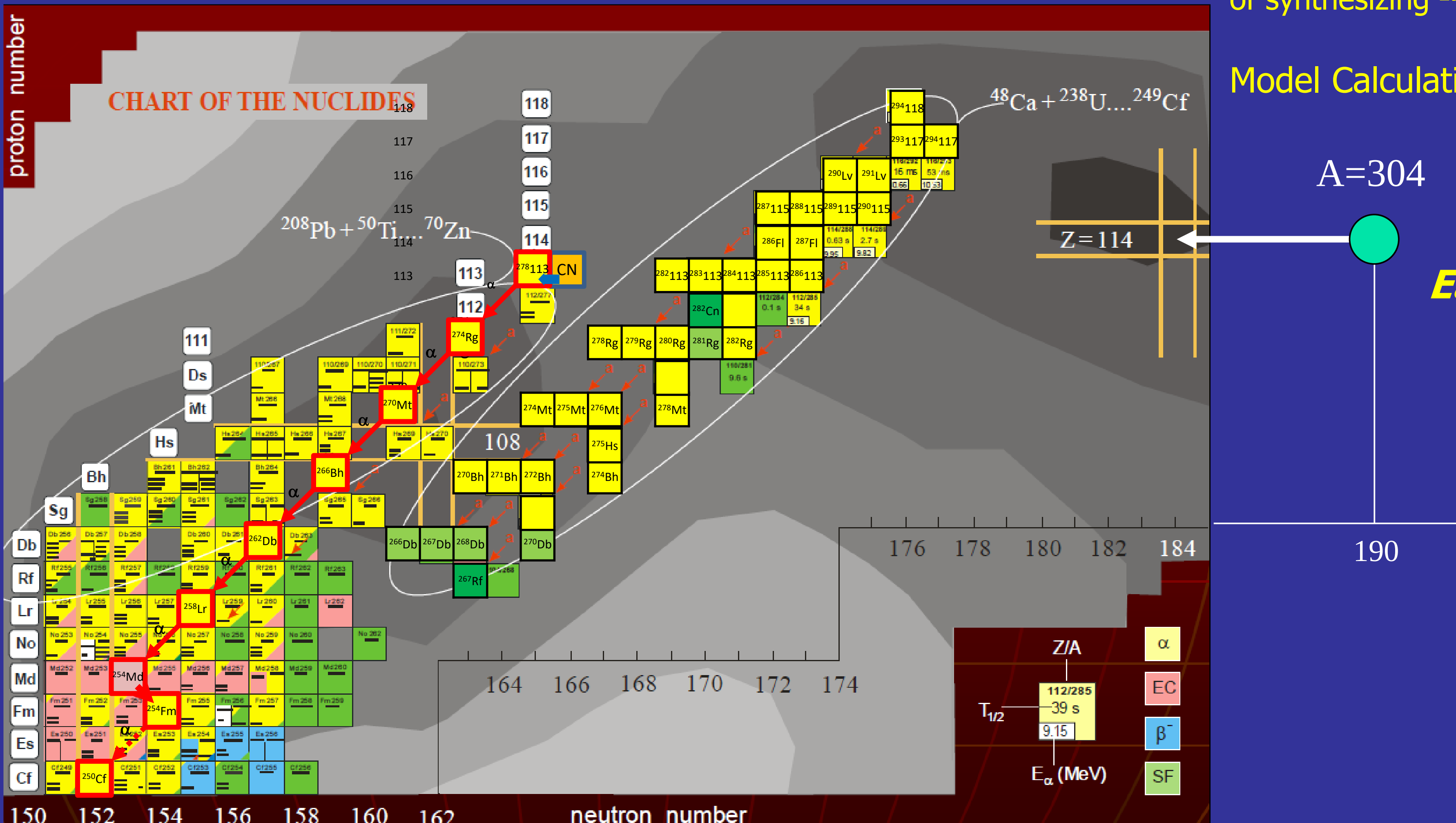
3) Transfer reaction U+Th, U+Cm

Introduction

Z=114
N=184

Possibility of synthesizing $^{298}114$

Model Calculation



Yu. Ts. Oganessian and K. Morita

Goal after 30 years

New Approach to explore Island of Stability

Use Property of Shell Structure of SHE

Goal after 30 years

New Approach to explore Island of Stability

Use Property of Shell Structure of SHE

1) Suppress the dissipation of Kinetic Energy *1st 2nd Stage*

2) Dynamical Shell Effect during fusion process
2nd pocket in deformed area *1st 2nd Stage*

3) Singularity of the survival probability in neutron rich region
(East side of Island Stability) *3rd Stage*

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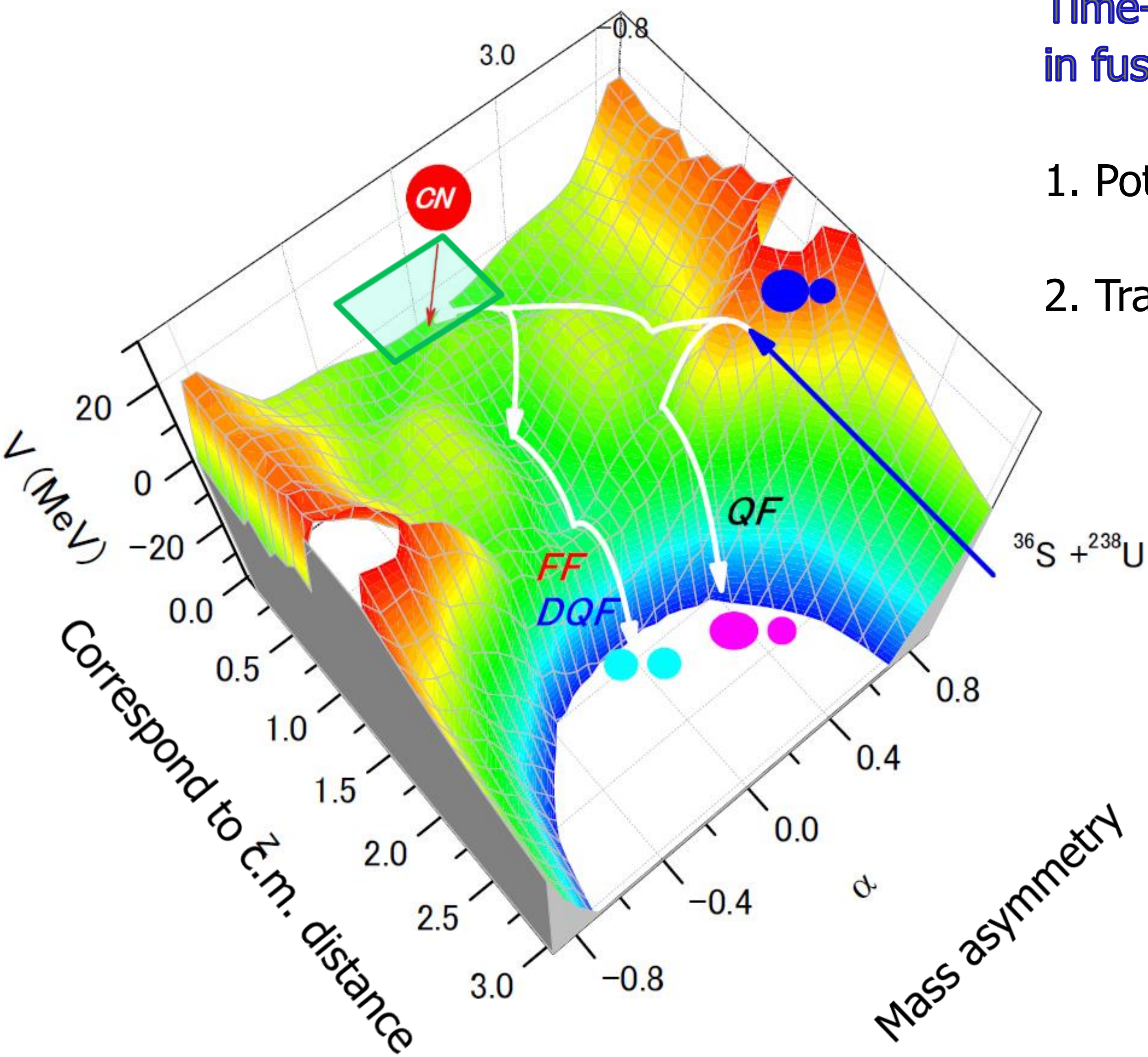
Overview of Dynamical Process in reaction $^{36}S+^{238}U$



Time-evolution of nuclear shape in fusion-fission process

1. Potential energy surface

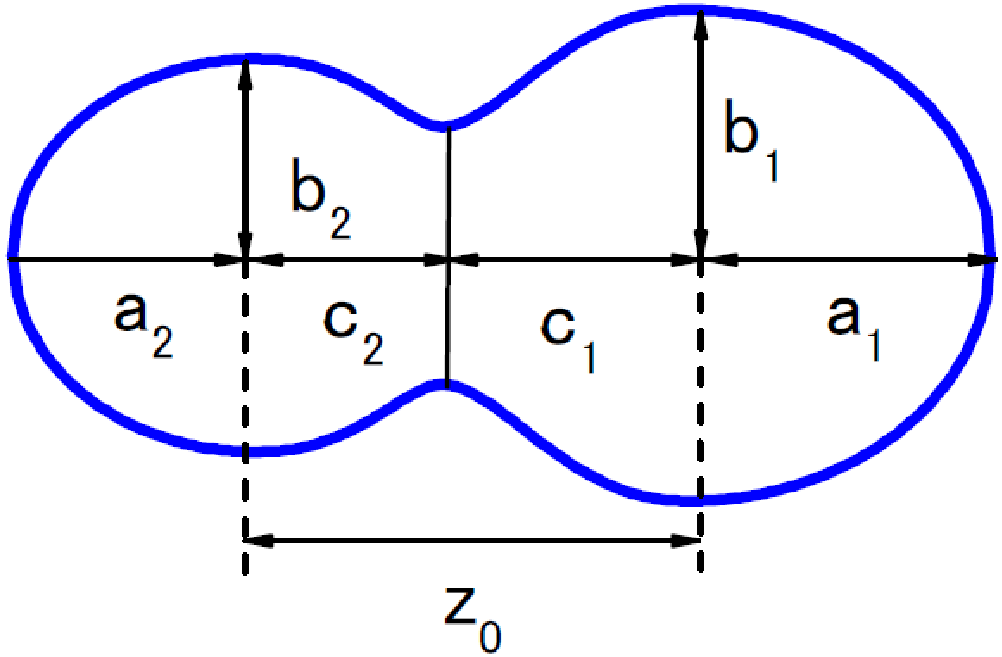
2. Trajectory → described by equations

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

$$\delta = \frac{3(a-b)}{2a+b} \qquad (\delta_1 = \delta_2)$$

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

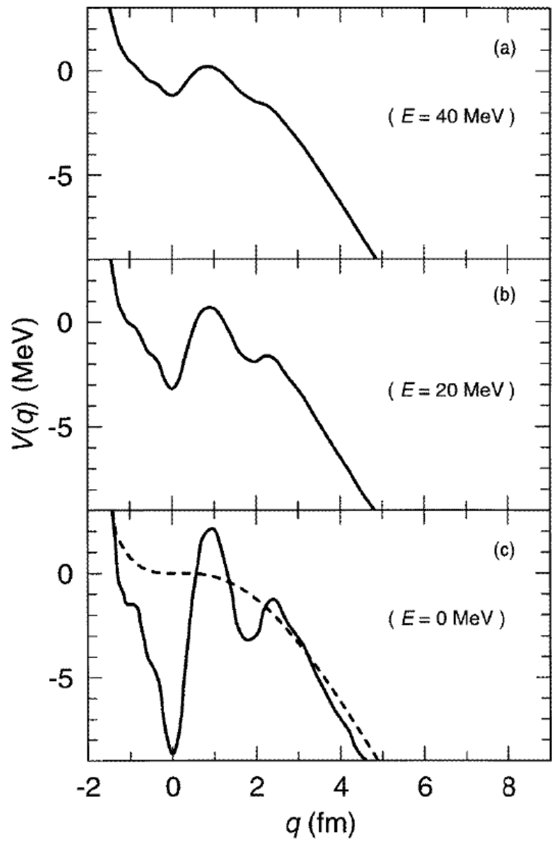
Potential Energy

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

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

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

$^{298}114$



T : nuclear temperature

$E^*=aT^2$ $\quad a$: 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

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

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

Fission barrier recovers at low excitation energy

A. V. Ignatyuk, et al 21, 485 (1974); Sov. J. Nucl. Phys. 21, 255 (1975)

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

ordinary differential 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)

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

Fluctuation-dissipation theorem

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)

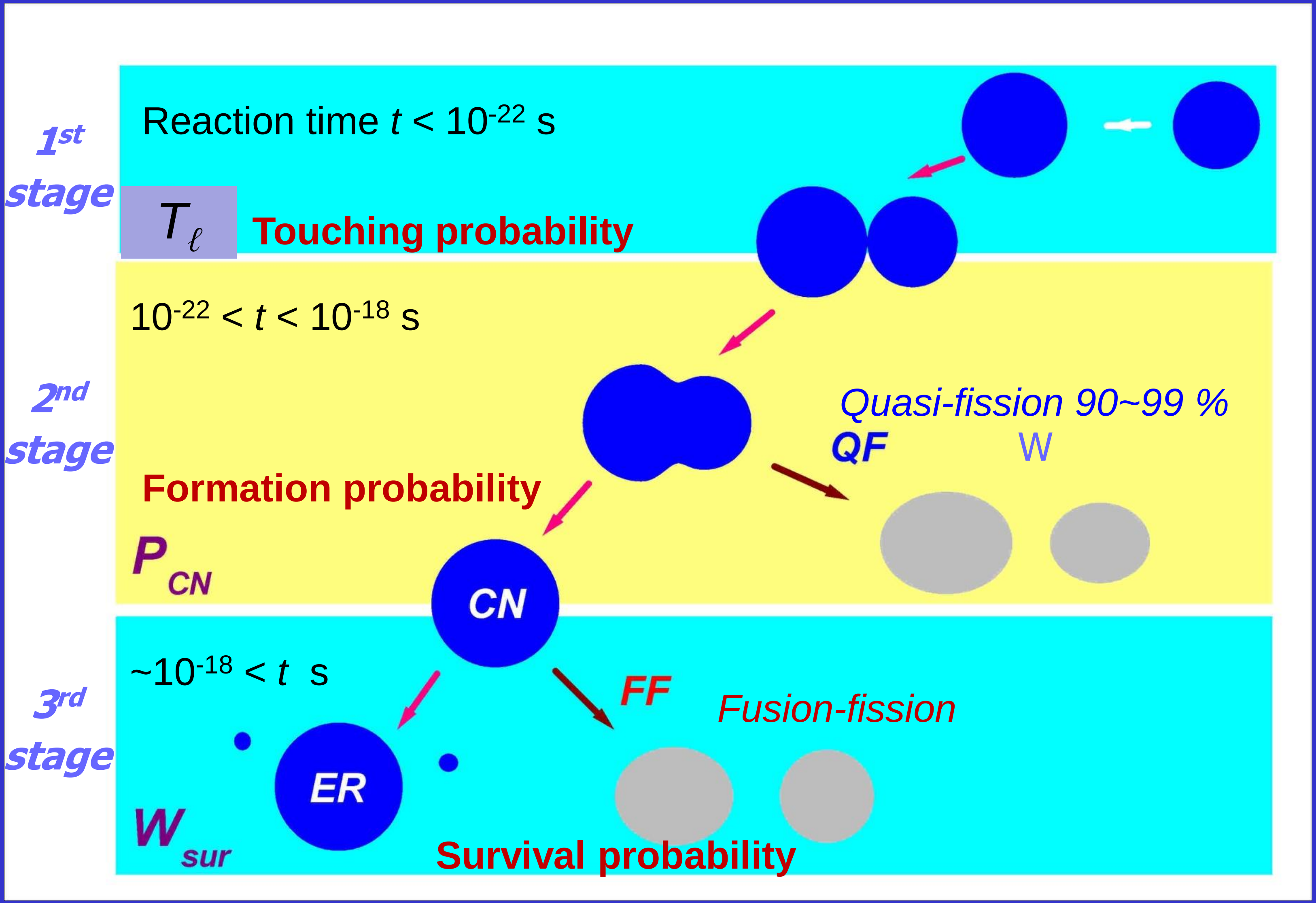
γ_{ij}: Wall and Window (one-body) dissipation （friction ）

Yamaji (TCSM)
Hofmann
Ivanyuk

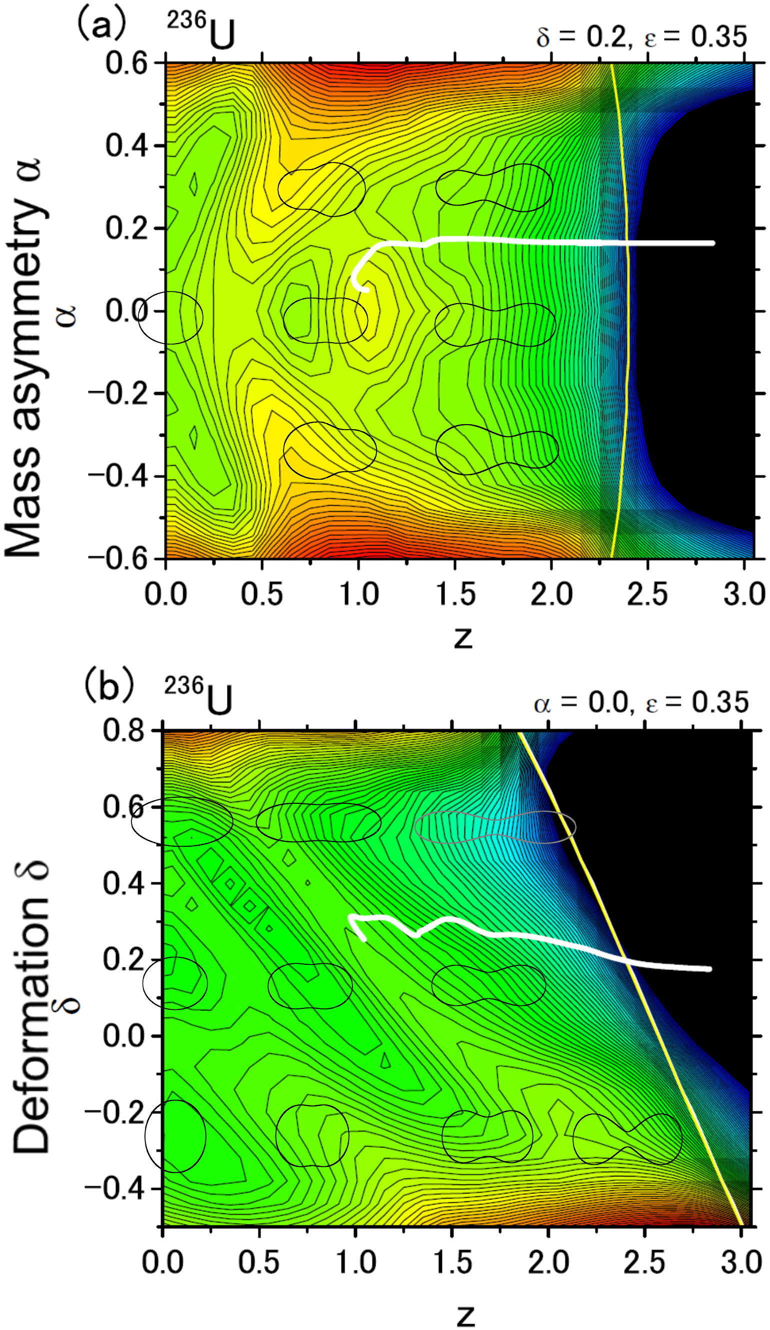
$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q)$$

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

$$\sigma_{ER} = \frac{\pi\hbar^2}{2\mu_0 E_{cm}} \sum_{\ell=0}^{\infty} (2\ell+1) T_\ell(E_{cm},\ell) P_{CN}(E^*,\ell) W(E^*,\ell)$$



Without fluctuation



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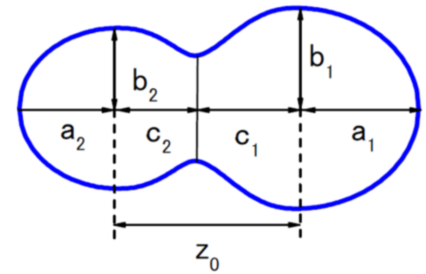

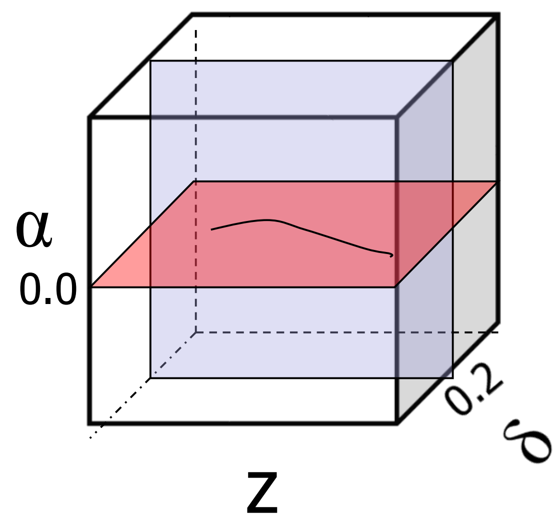

Projection on two-dim. plane

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4. まとめ

Test Calculation

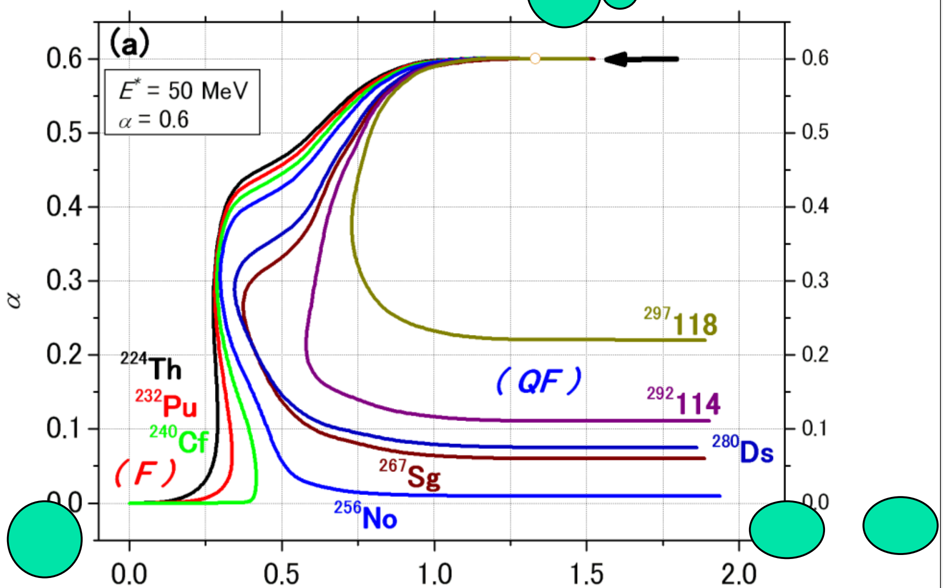
Potential LDM

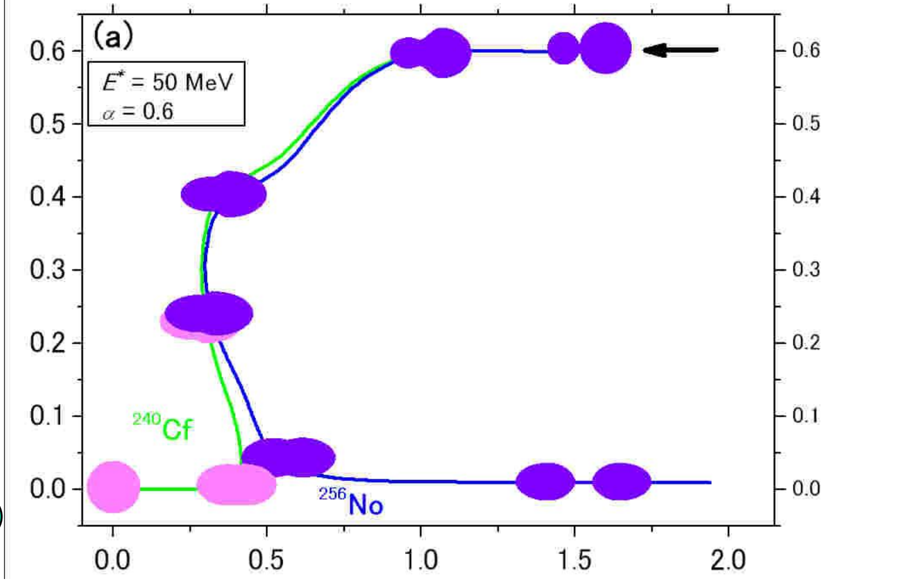
Trajectory without fluctuation

Starting point at $\alpha = 0.6$ Virtual combination

Produce Th, Pu, Cf, No, Sg, Ds, Fl, Og

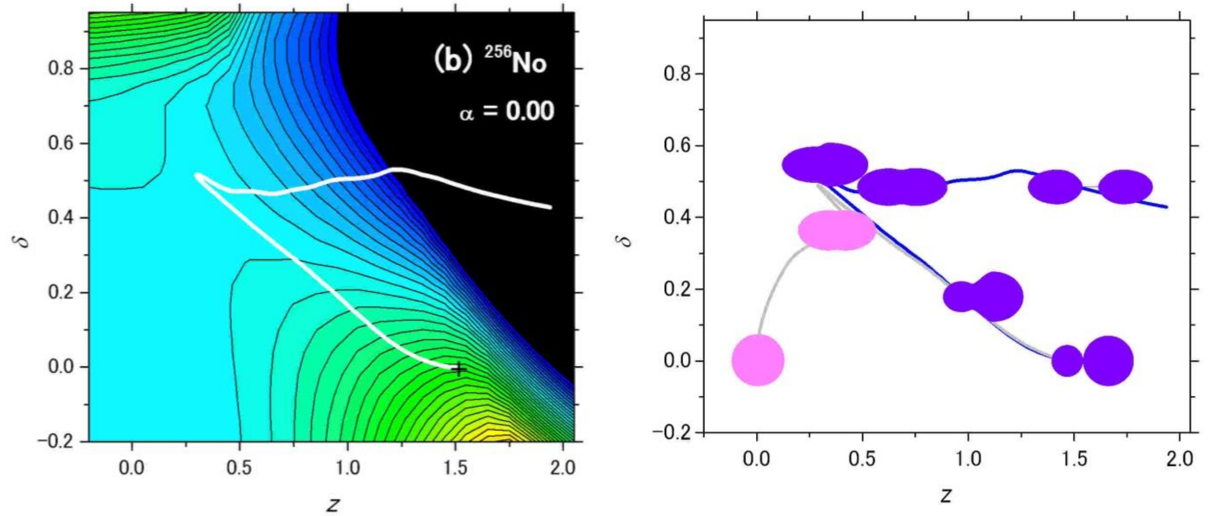
V_{LD} mean trajectory

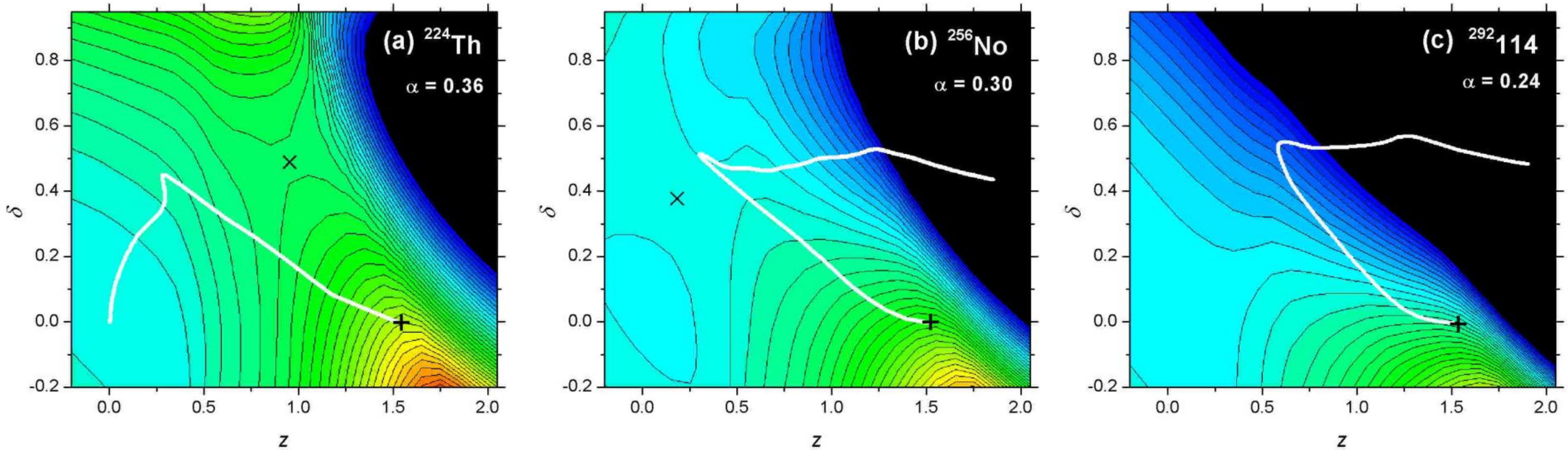




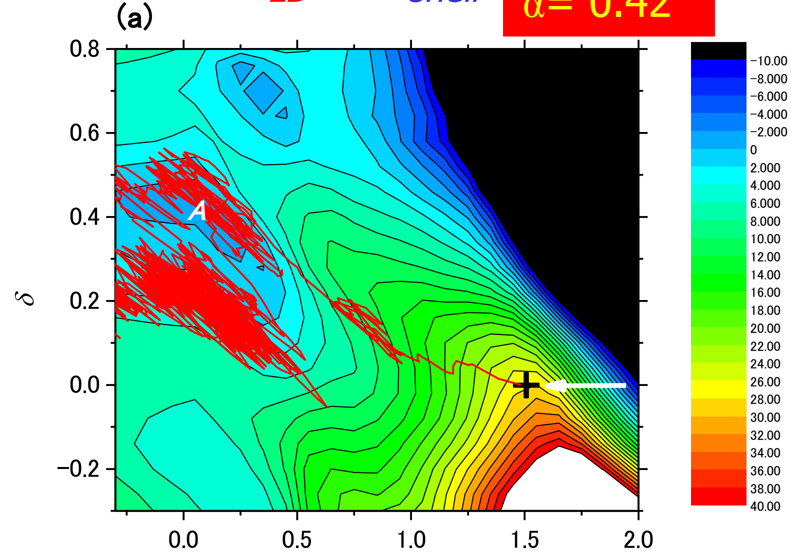
The essential point is
in the relation between
fusion saddle point on z-δplane
and
turning point of the trajectory.

Trajectory is projected onto z-δ plane at α which corresponds to turning point



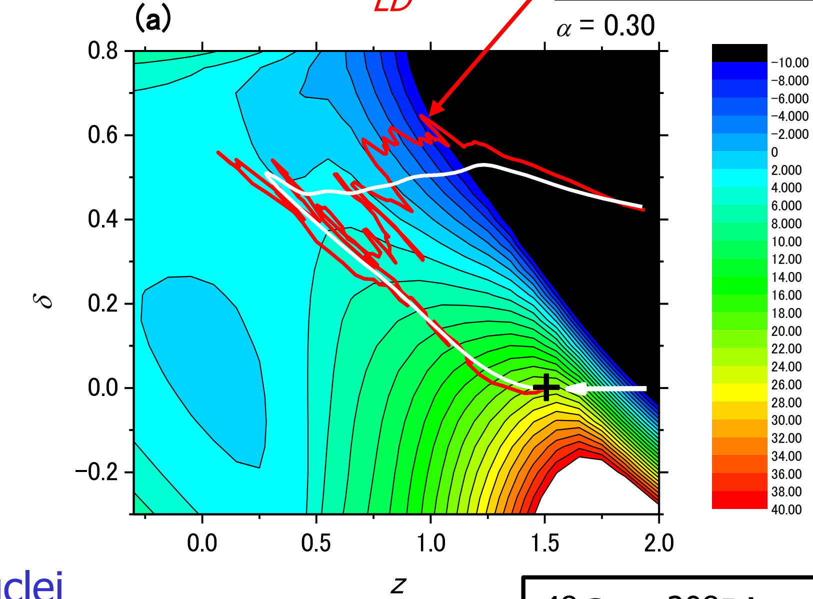


$V_{LD} + E^0_{shell}$ α= 0.42



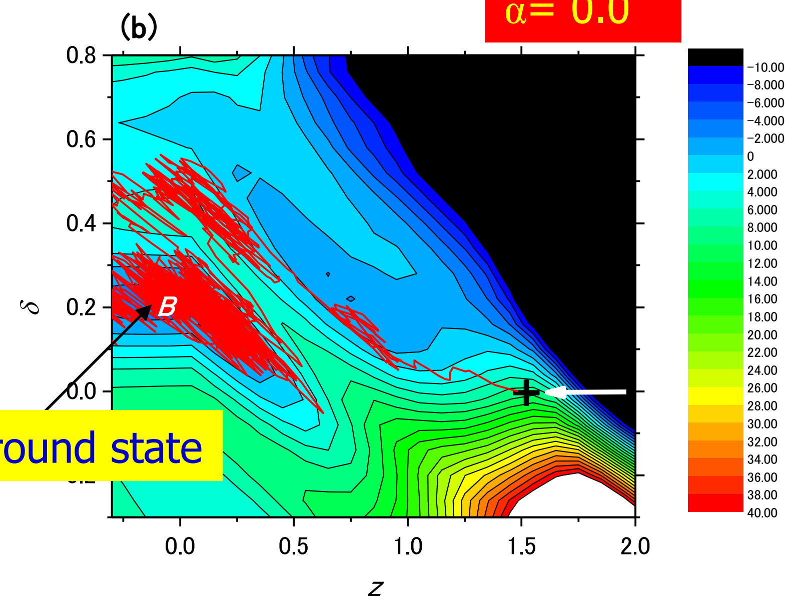
V_{LD}

With fluctuation



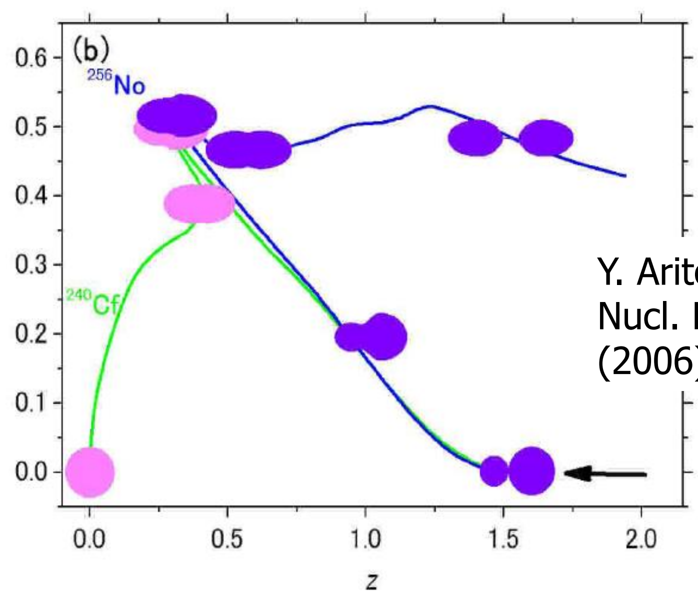
Effects from contact point to compound nuclei

α= 0.0



Ground state

$^{48}Ca+^{208}Pb \rightarrow ^{256}No$



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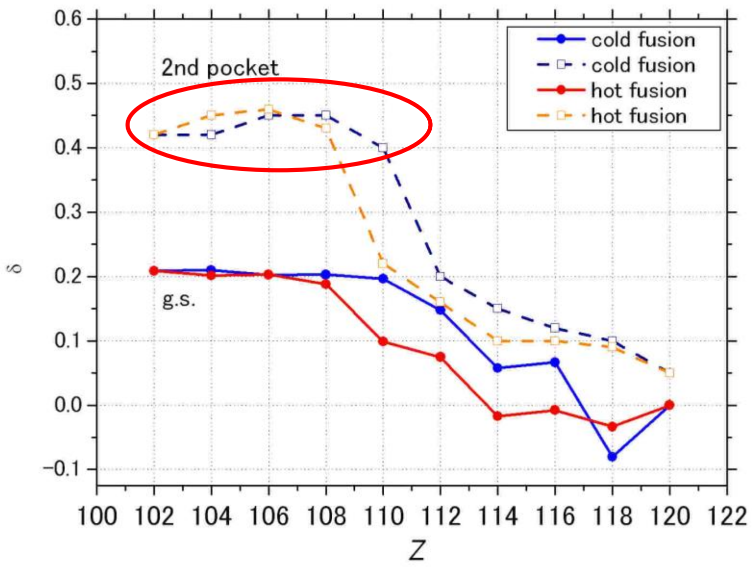
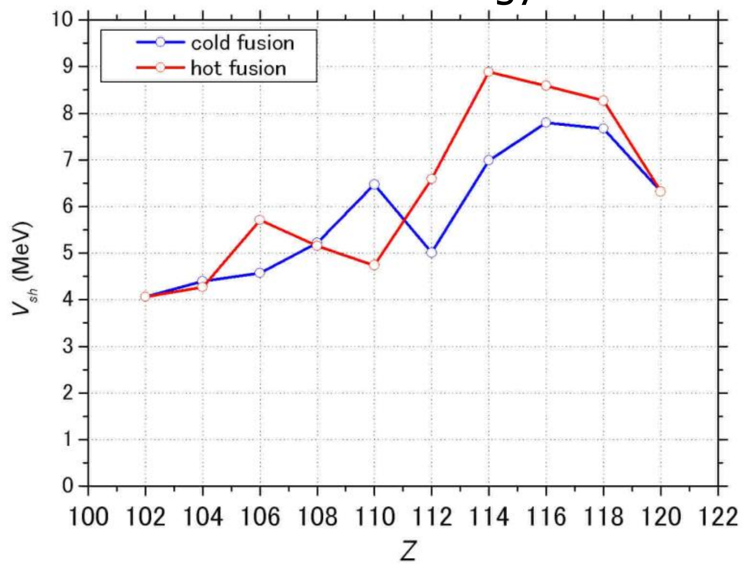
Deformation

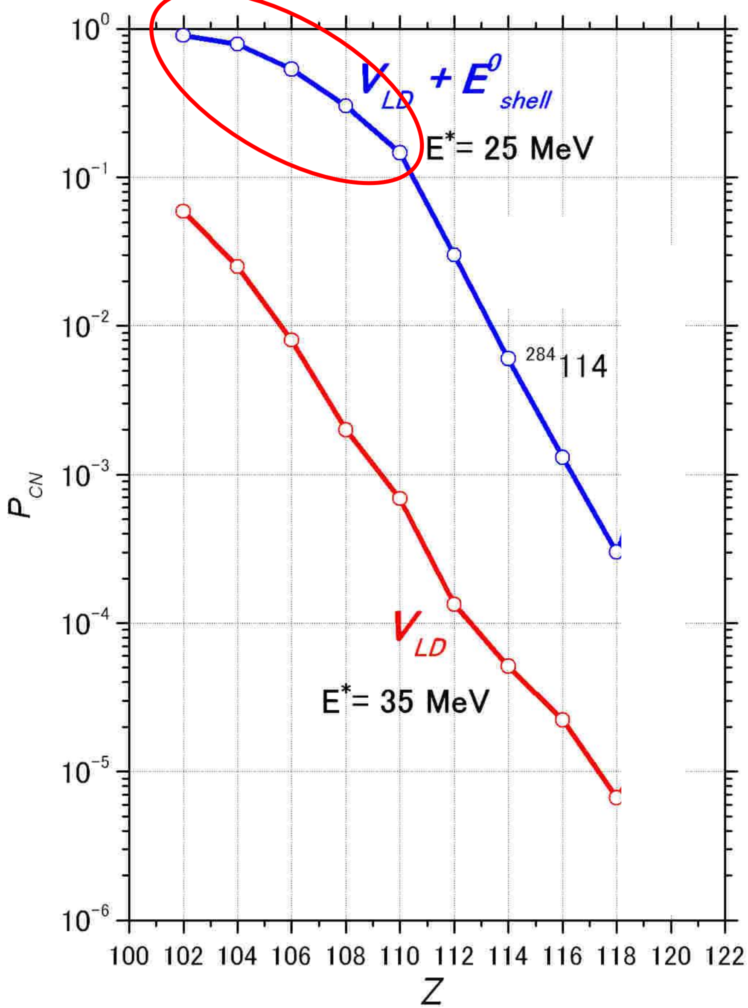


Shell correction energy

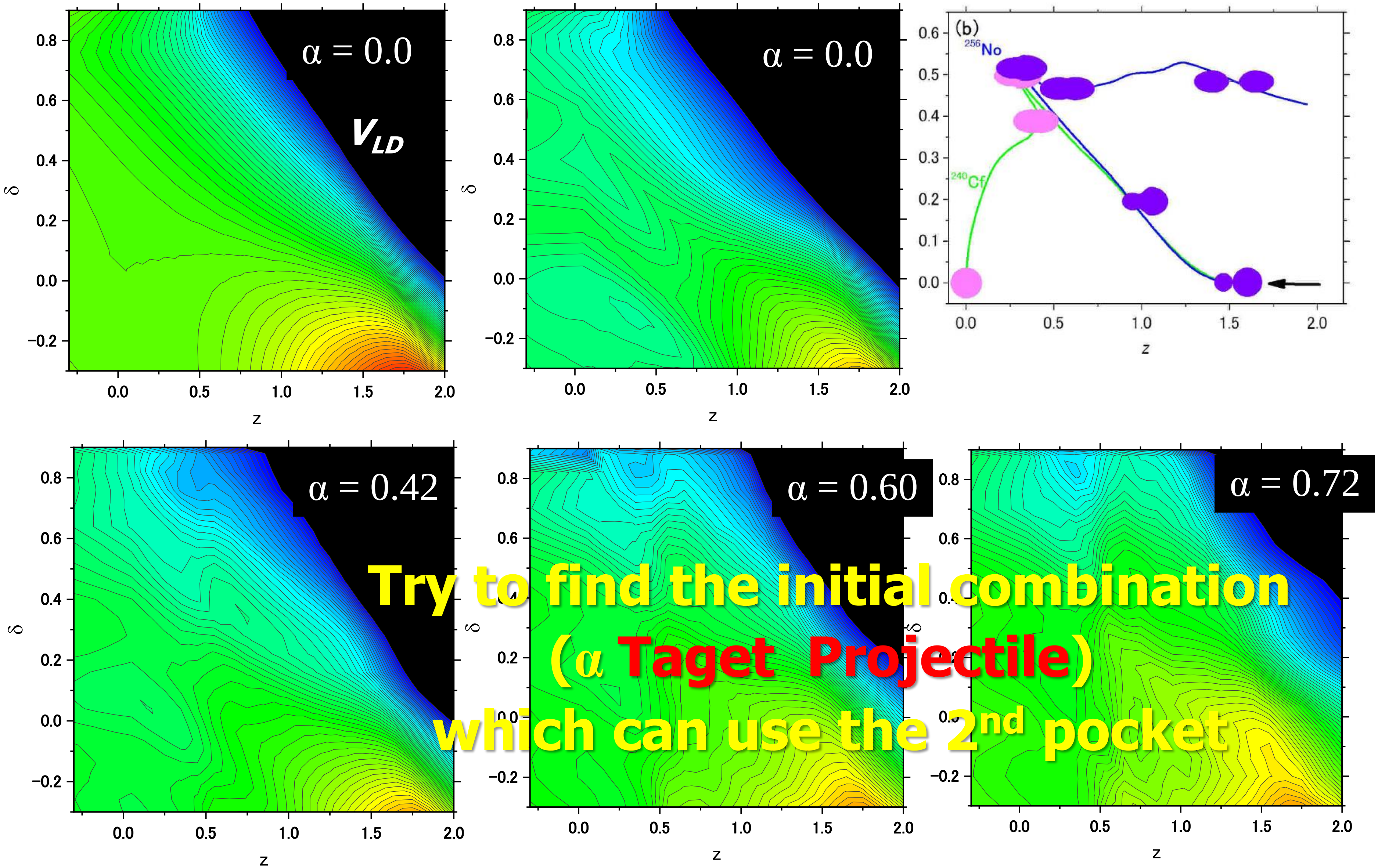


Fusion probability

cold fusion reaction system



Z= 120 $^{54}Cr + ^{248}Cm \rightarrow ^{302}120$ (α = 0.64)

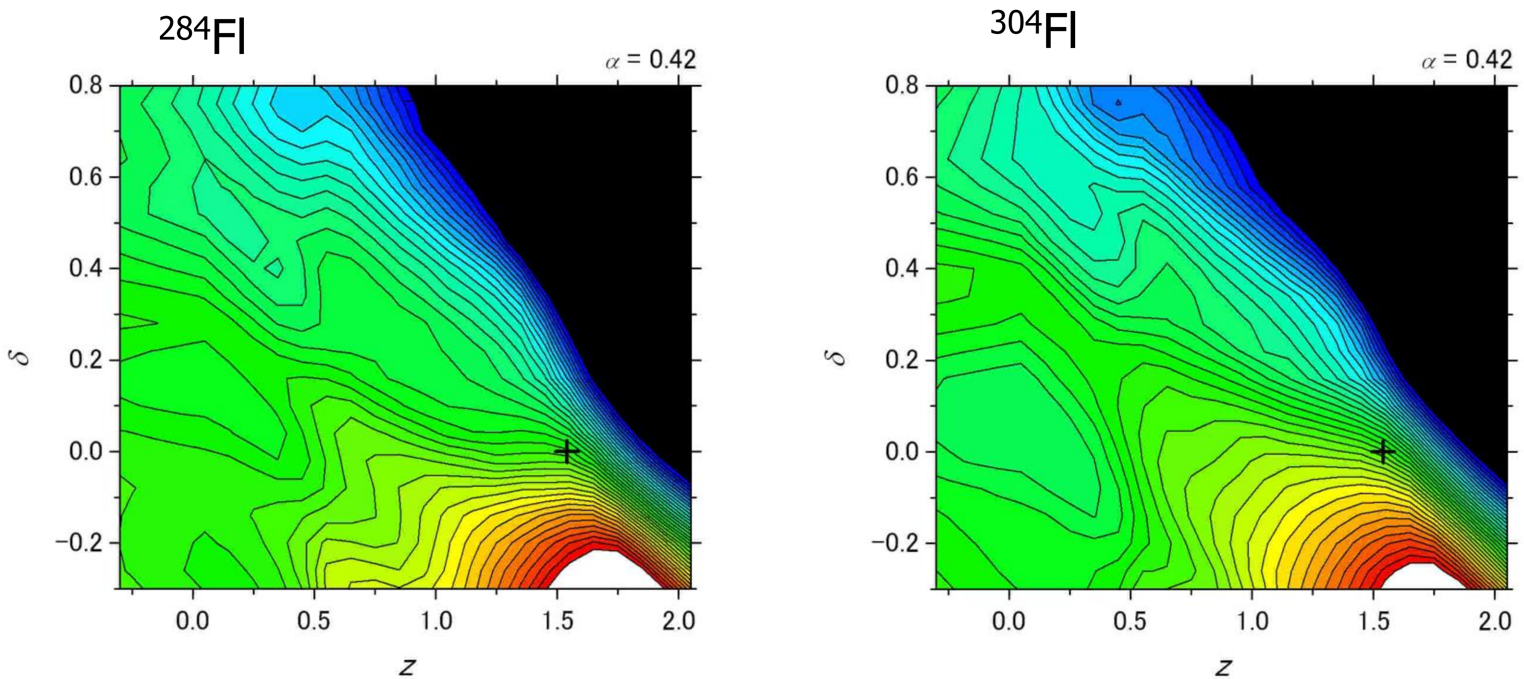


Try to find the initial combination

(α Taget Projectile)

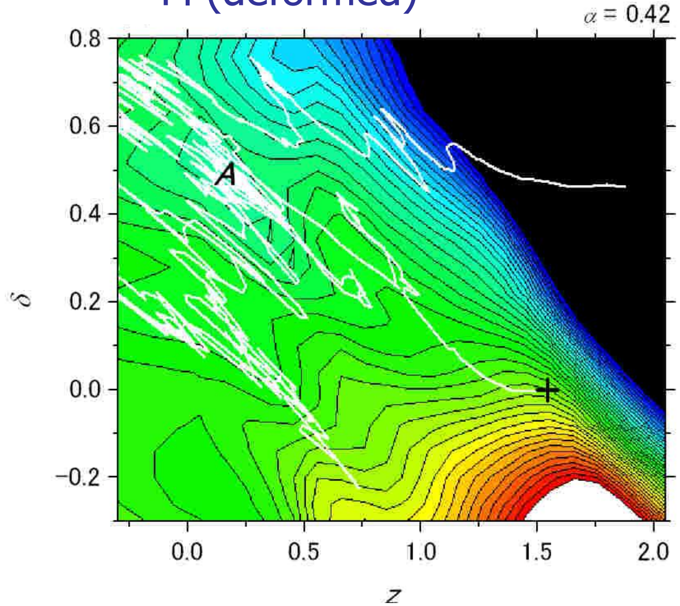
which can use the 2nd pocket

($^{50}Ti + ^{250}Cf \rightarrow ^{300}120$ (α = 0.67))

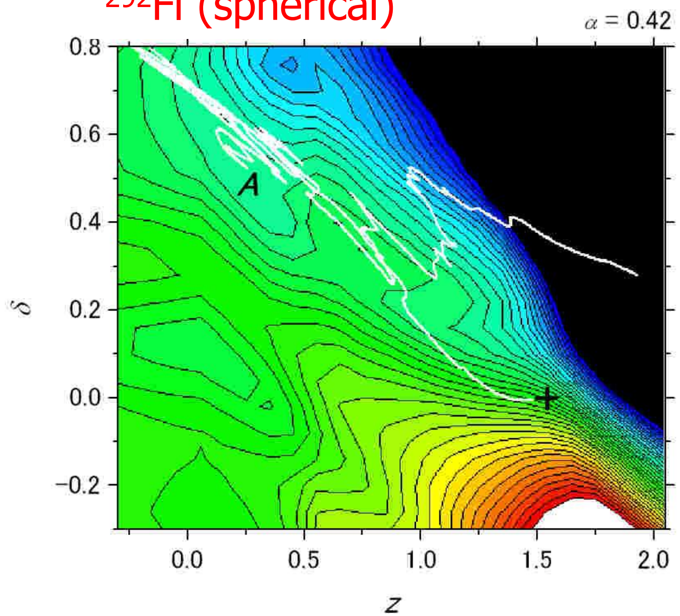


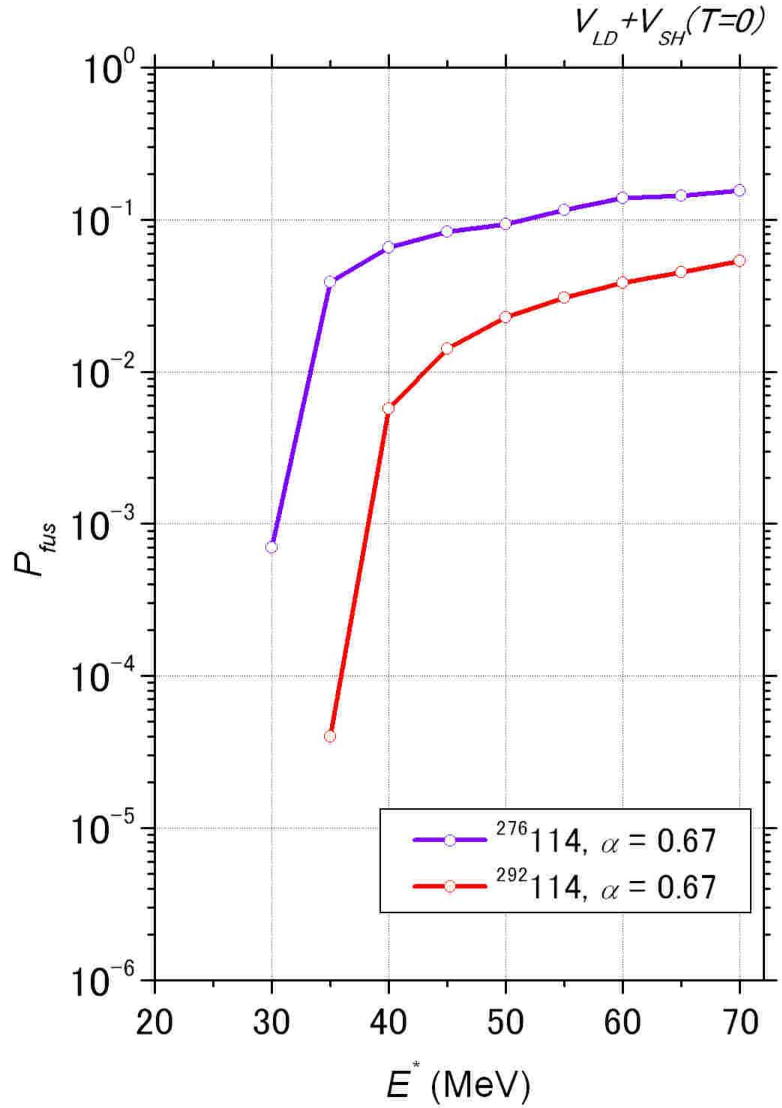
^{284}Fl
α = 0.42
^{304}Fl
α = 0.42
0.8
0.6
0.4
0.2
0.0
−0.2
δ
0.0
0.5
1.0
1.5
2.0
z

^{276}Fl (deformed)



^{292}Fl (spherical)





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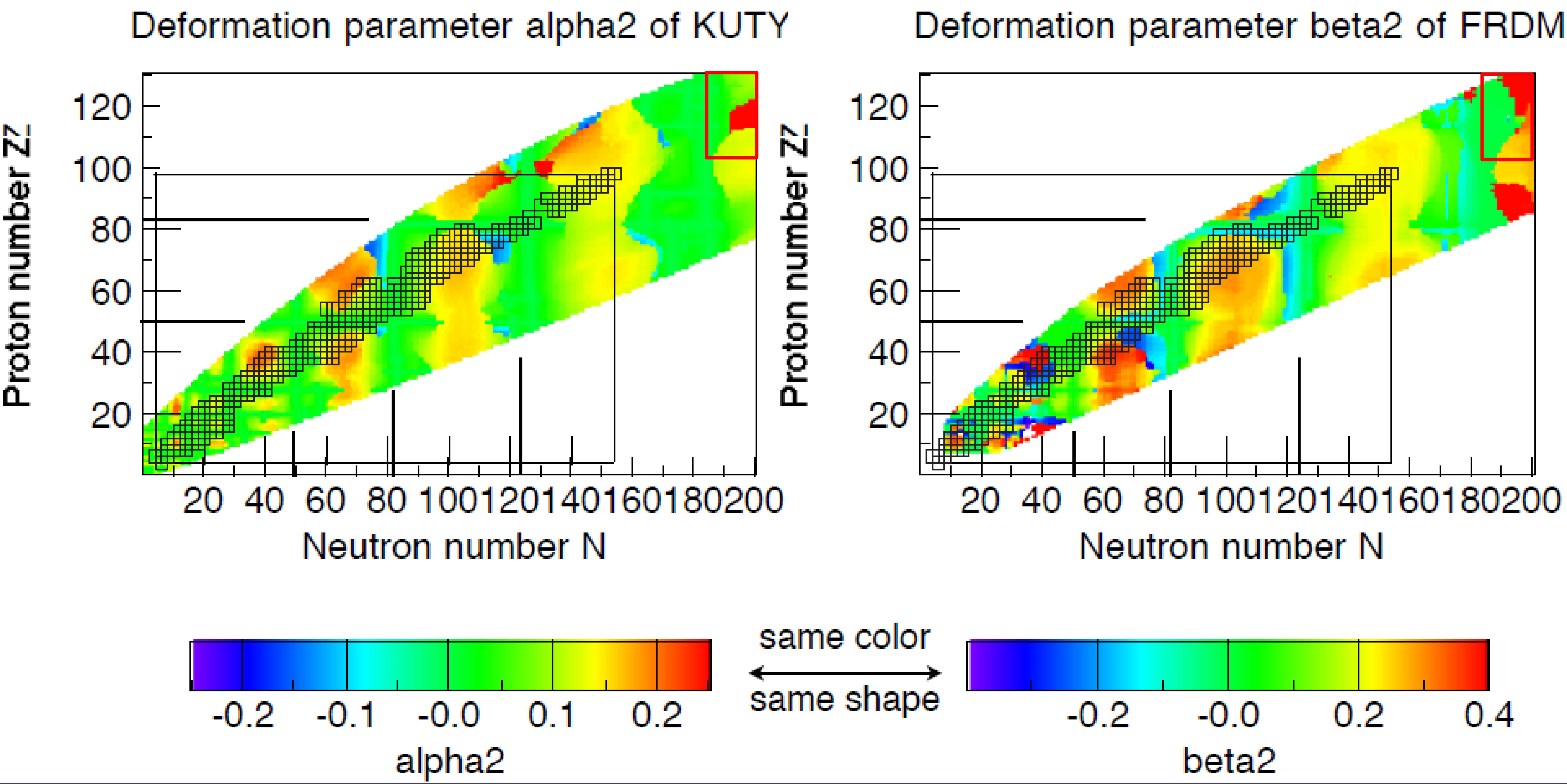
Deformation parameter alpha2 of KUTY
Deformation parameter beta2 of FRDM
Proton number ZZ
Neutron number N
120
100
80
60
40
20
20 40 60 80 100120140160180200
same color
same shape
-0.2 -0.1 -0.0 0.1 0.2
alpha2
-0.2 -0.0 0.2 0.4
beta2

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まとめ

- これまでの手法の延長線上では、新元素の合成および安定の島への到達は難しい。
- 融合過程における動力学的な殻効果を利用することで、融合確率が増大する。
- 中性子過剰領域では、基底状態での変形度が大きくなるため、2nd pocketを利用した融合が可能であろう。
- Z≧119や安定の島に到達するために、様々な系でのより詳細な軌道の解析を行う。

ご清聴ありがとうございました