Impact of Nuclear Structure on Fusion–Fission Dynamics in Superheavy Element Synthesis

Y. Aritomo[1], K. Kawai[1], K. Nakajima[1], S. Takagi[1,2], A. Yumikura[1]

[1]*Faculty of Science and Engineering, Kindai University, Osaka, Japan*
[2]*RIKEN Center for Computational Science, Kobe, Japan*

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24th COLLOQUE GANIL
21–25 Sept 2026
Bussang, France

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The University of Caen and Kindai University have singed an agreement for student and researcher exchange. July, 2026

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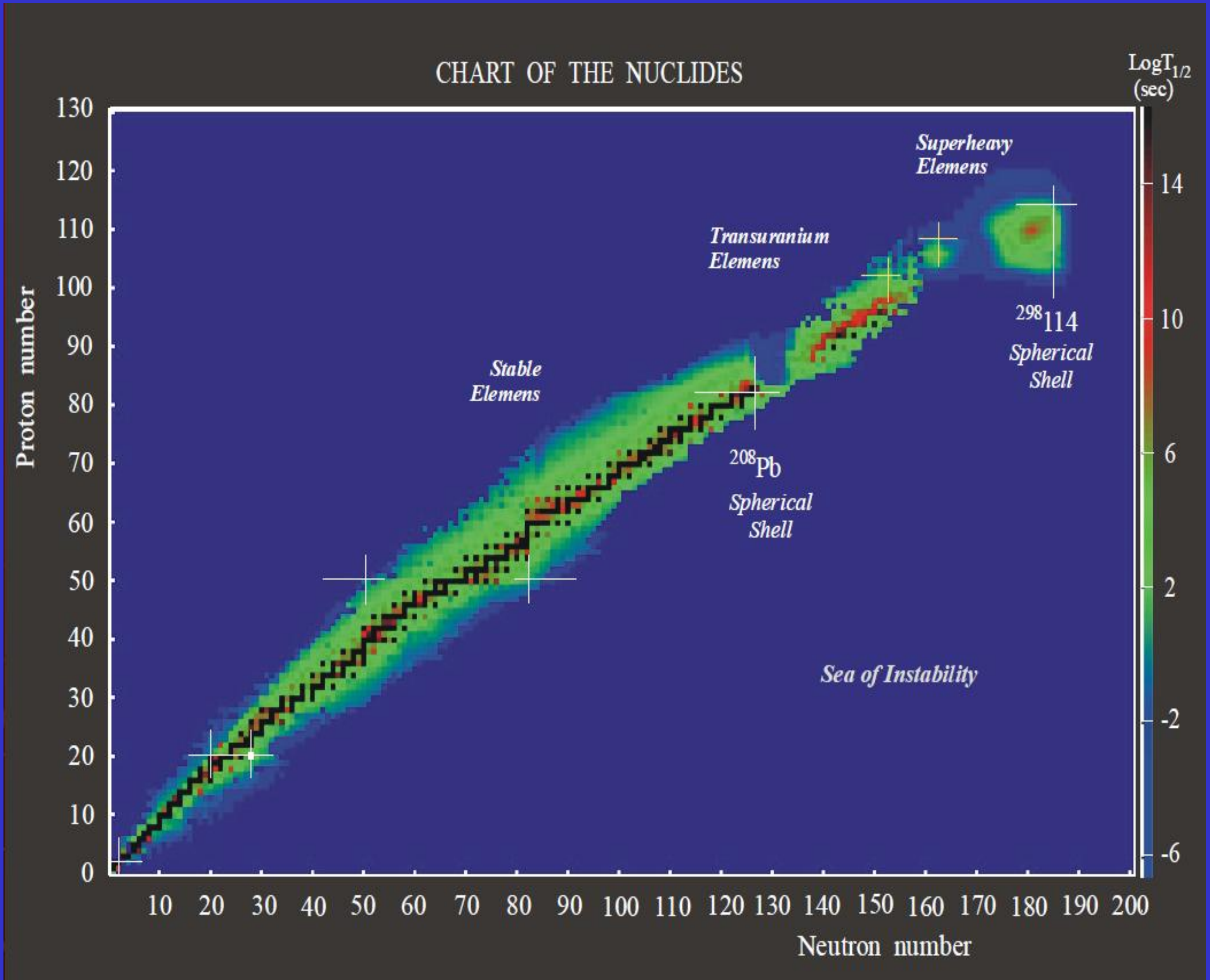
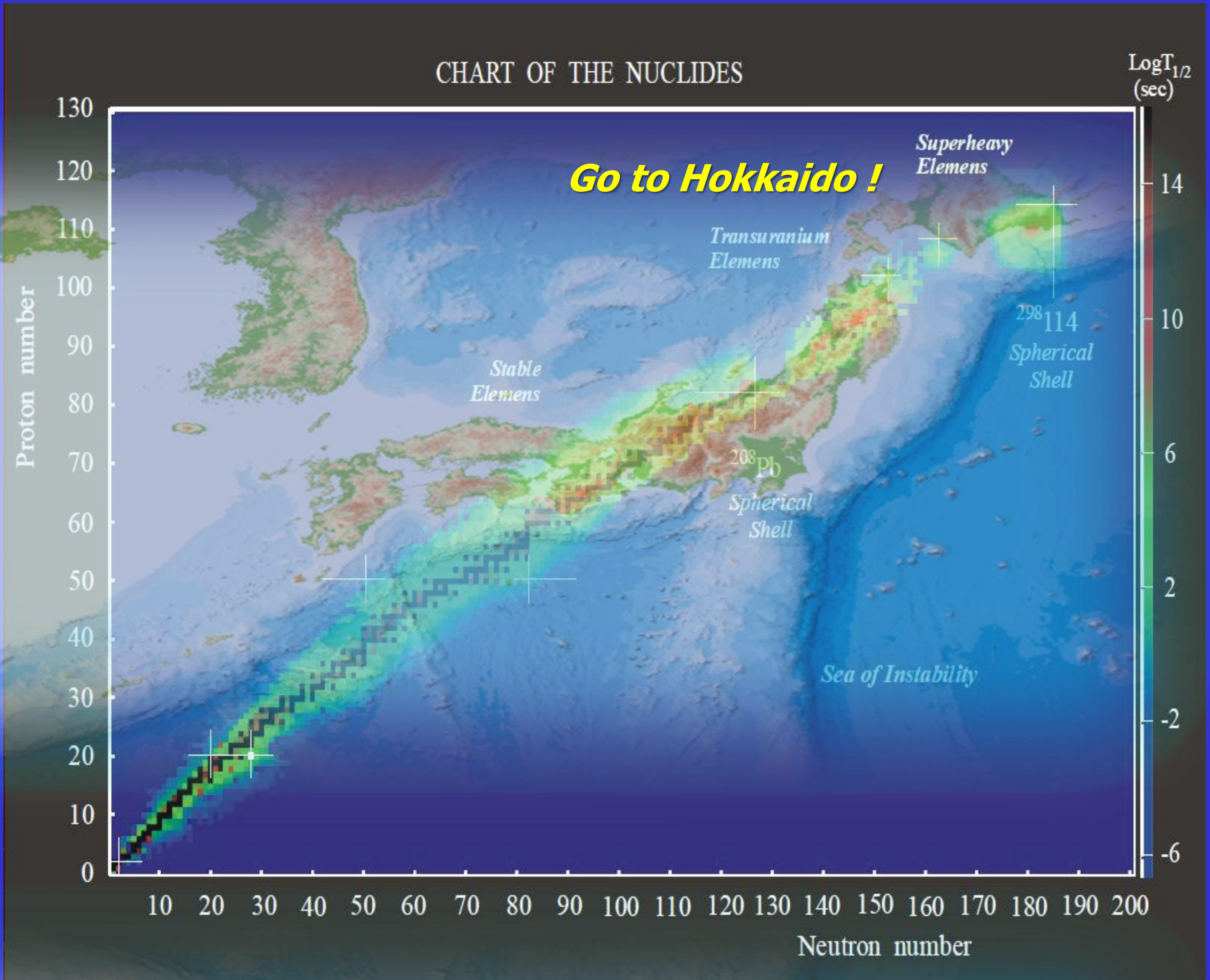
Contents

Nuclear Chart and Stability of Nuclei



Nuclear Chart and Stability of Nuclei



Way for synthesizing new SHE

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

2) Secondary beams (RI beams)

3) Transfer reaction U+Th, U+Cm

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← K. Kawai et.al.,
Phys. Rev. C 114, 014612 (2026)

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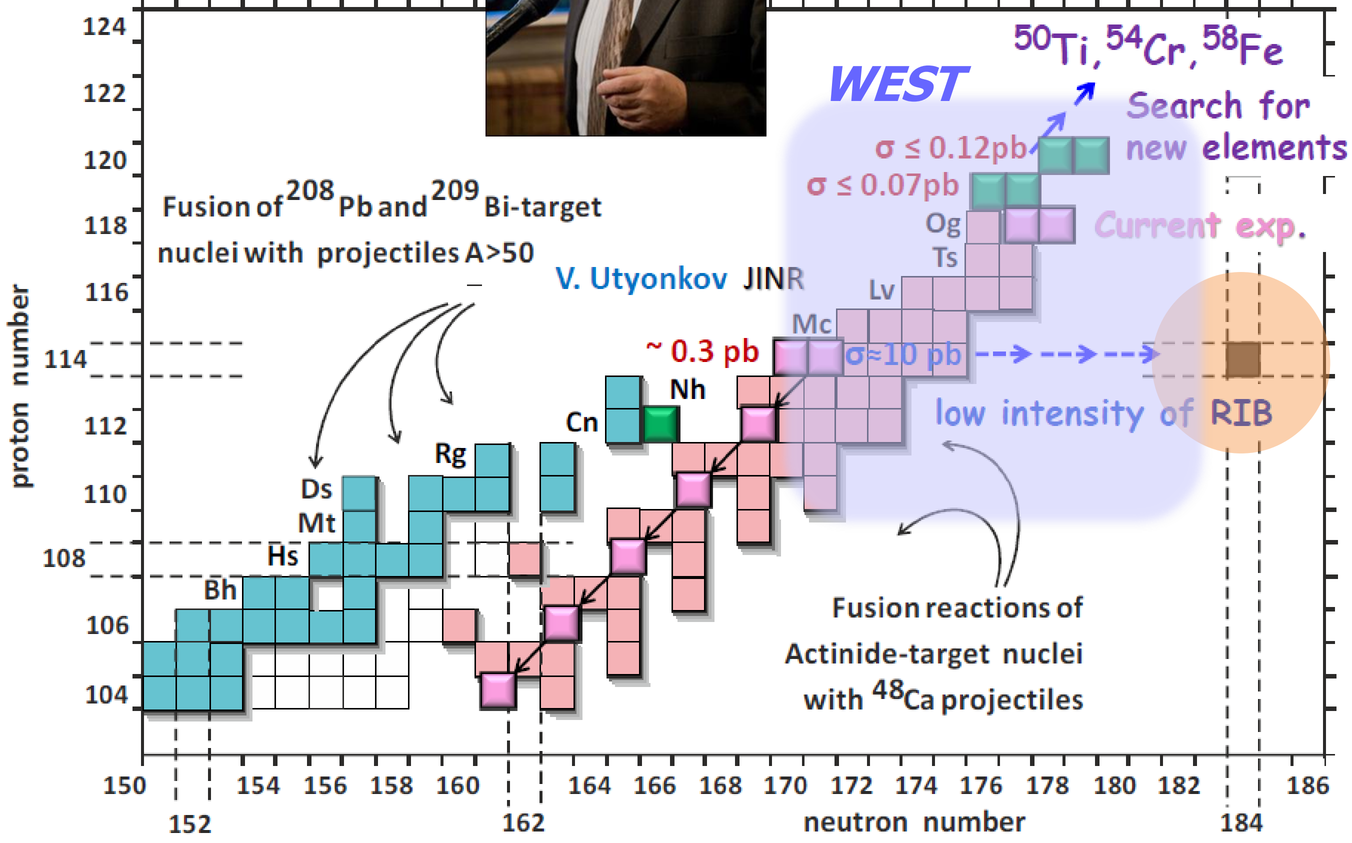
2) Secondary beams (RI beams)

← What RI nuclei (Target or Projectile) should be used ?

3) Transfer reaction U+Th, U+Cm

← K. Nakajima et.al.,
EPJ Web of Conferences 378, 02028 (2026)

Oganessian



Yuri Oganessian SHE-2017, Sept. 10-14, 2017, Kazimierz Dolny, Poland

$^{48}Ca + {}^{244}Pu \rightarrow {}^{292}Fl$ stable nuclei

Synthesis of New Elements

Reports of new elements

Cold fusion reaction Hot fusion reaction

1994

110 Ds $^{62}Ni + ^{208}Pb \rightarrow ^{269}110 + n$ (GSI)

111 Rg $^{64}Ni + ^{209}Bi \rightarrow ^{272}111 + n$ (GSI)

1996

112 Cn $^{70}Zn + ^{208}Pb \rightarrow ^{277}112 + n$ (GSI) ← named in Feb. 2010

1999

114 Fl $^{48}Ca + ^{244}Pu \rightarrow ^{289}114 + 3n$ (FLNR) ← named in May. 2012

2000

116 Lv $^{48}Ca + ^{248}Cm \rightarrow ^{292}116 + 4n$ (FLNR) ← named in May. 2012

2002

118 $^{48}Ca + ^{249}Cf \rightarrow ^{294}118 + 3n$ (FLNR)

2003

115 $^{48}Ca + ^{243}Am \rightarrow ^{288}115 + 3n \rightarrow ^{284}113 + \alpha$ (FLNR)

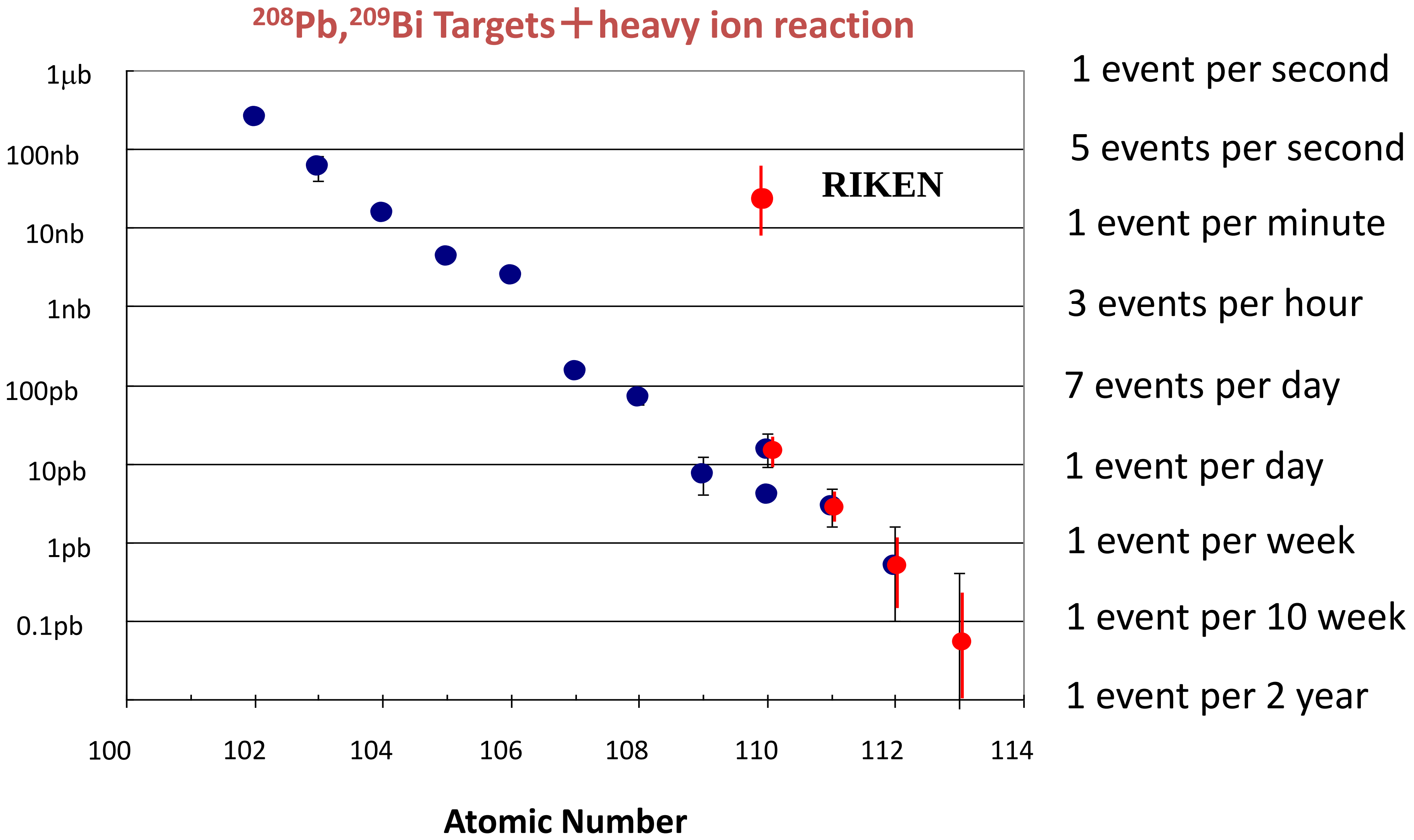
2004

113 $^{70}Zn + ^{209}Bi \rightarrow ^{278}113 + n$ (RIKEN)

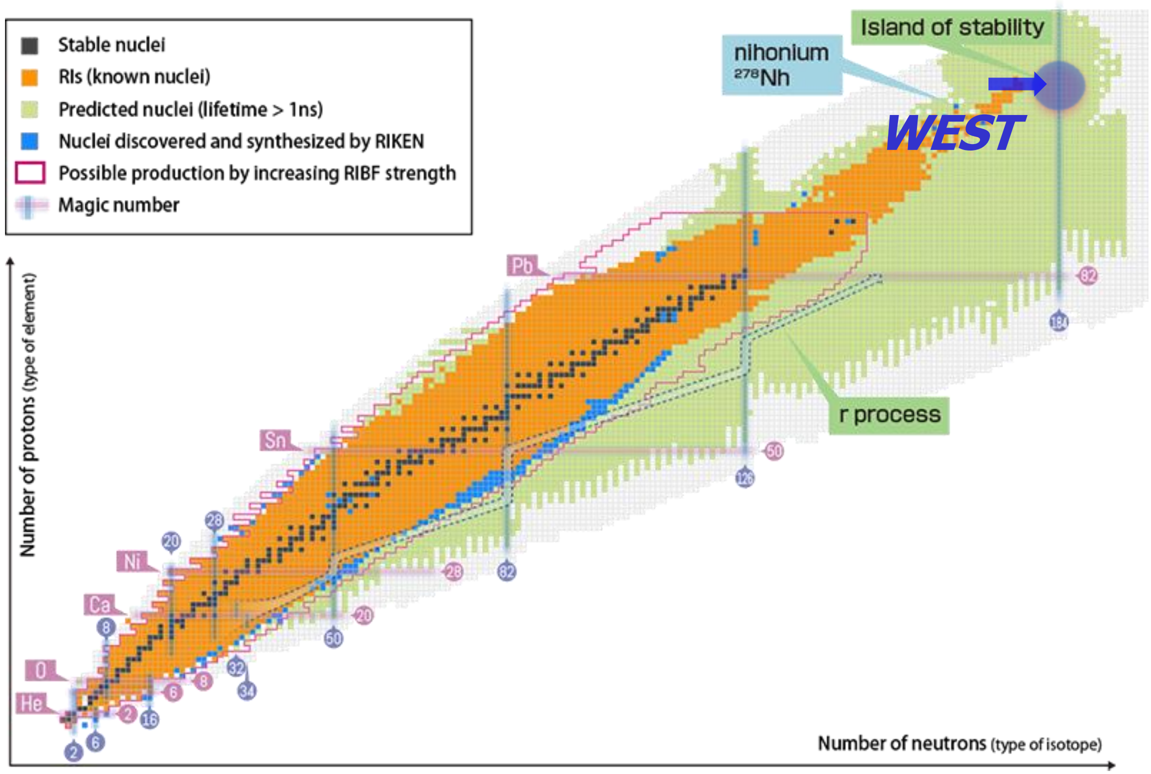
2010

117 $^{48}Ca + ^{249}Bk \rightarrow ^{294,293}117 + 3\text{-}4n$ (FLNR)

ease (or difficulty) of synthesis

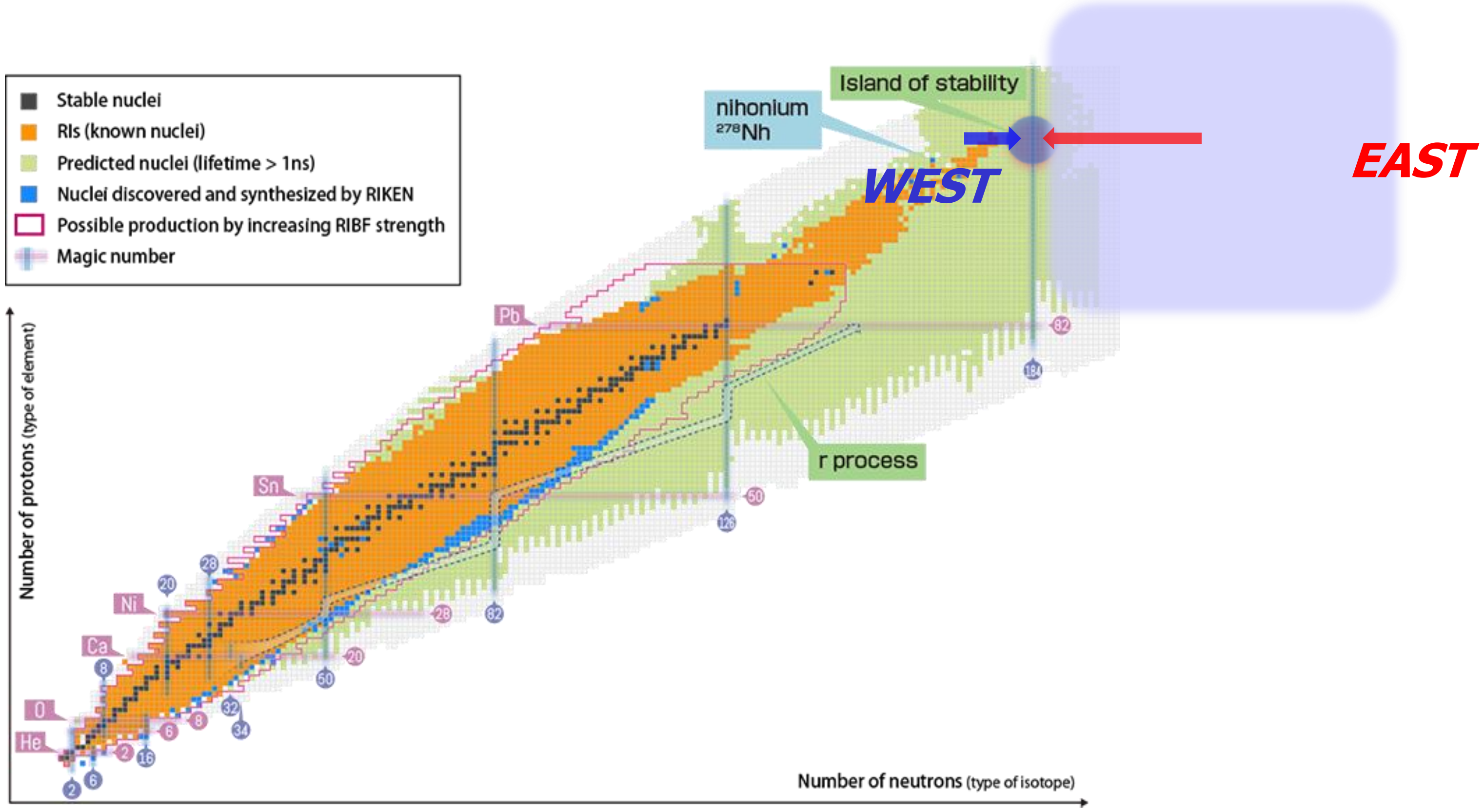


2012 K. Morita



Riken Nishina HP: https://www.nishina.riken.jp/ouen/en/factory.html

Using RI beams



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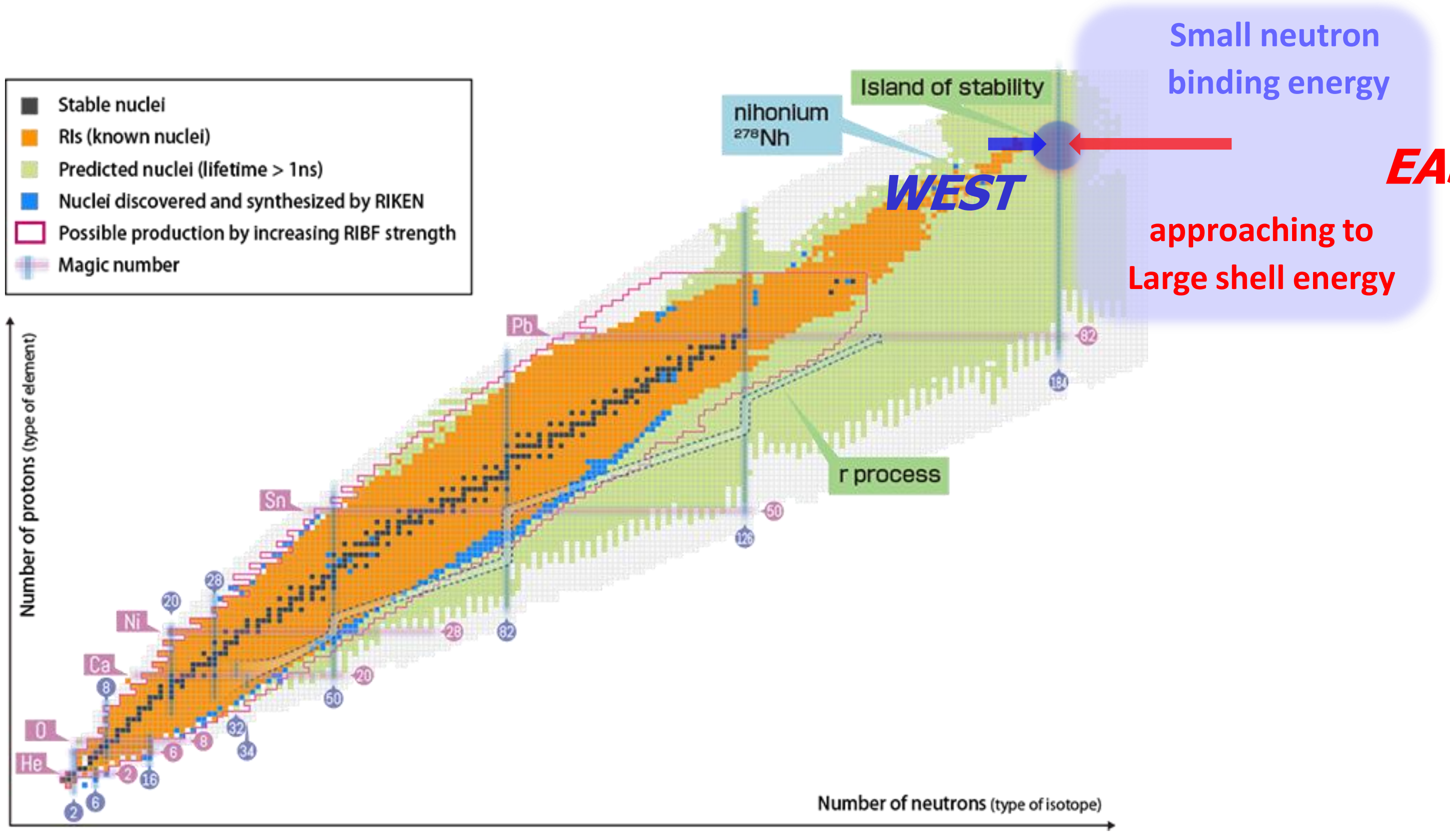

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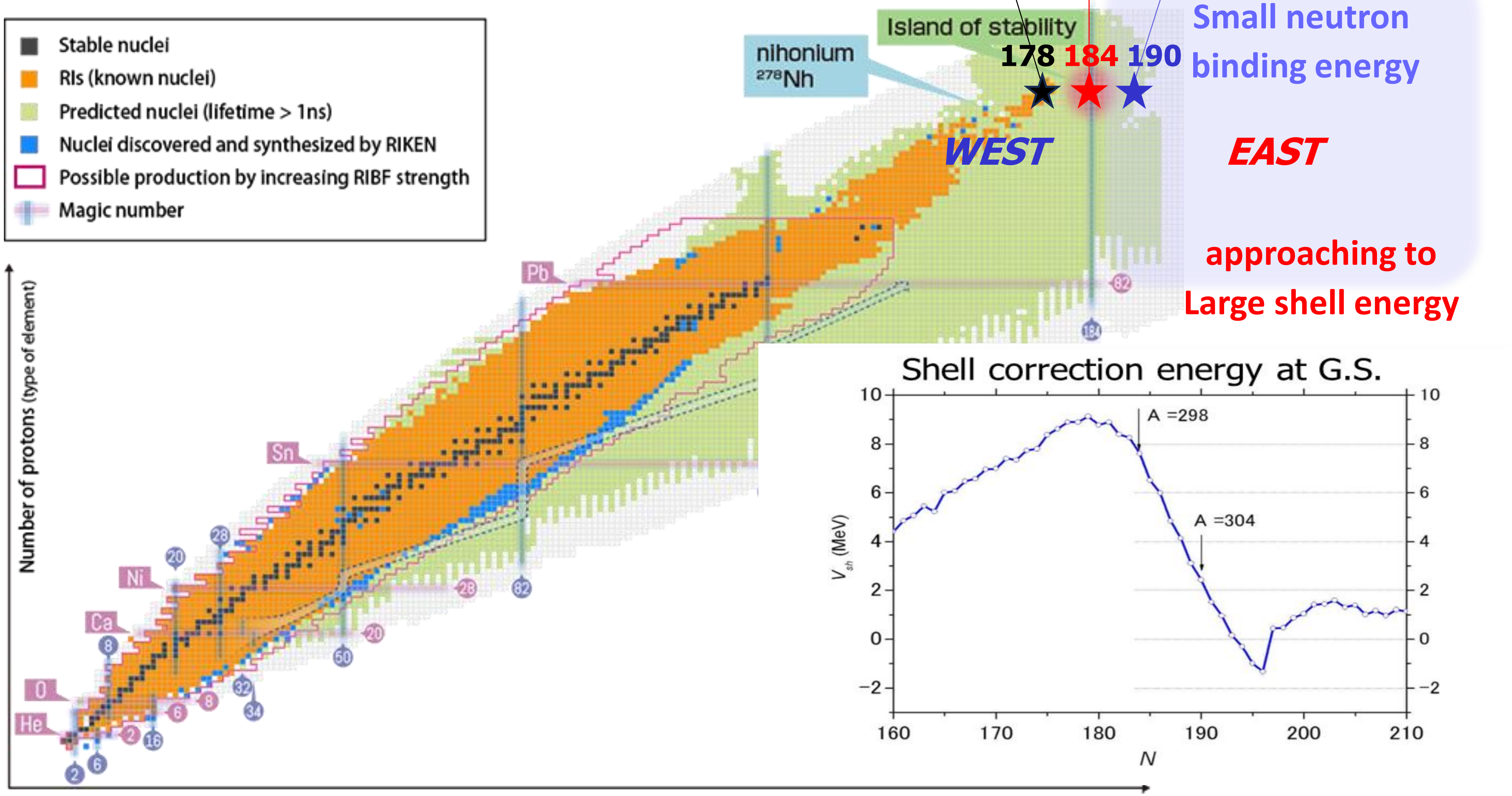
Using RI beams

S_n = 6 5 4 MeV

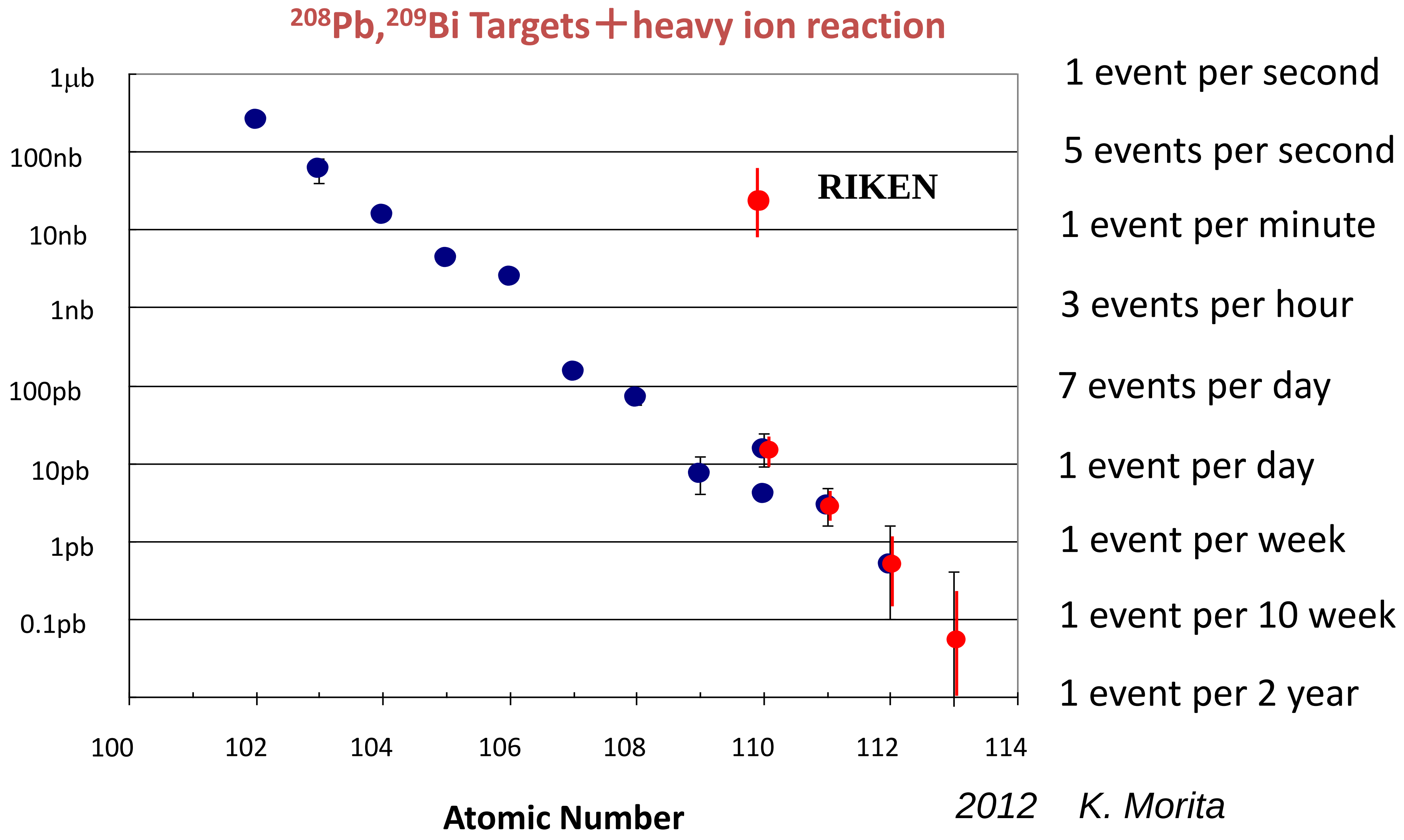


Small neutron binding energy

approaching to Large shell energy

Riken Nishina HP: https://www.nishina.riken.jp/ouen/en/factory.html

ease (or difficulty) of synthesis



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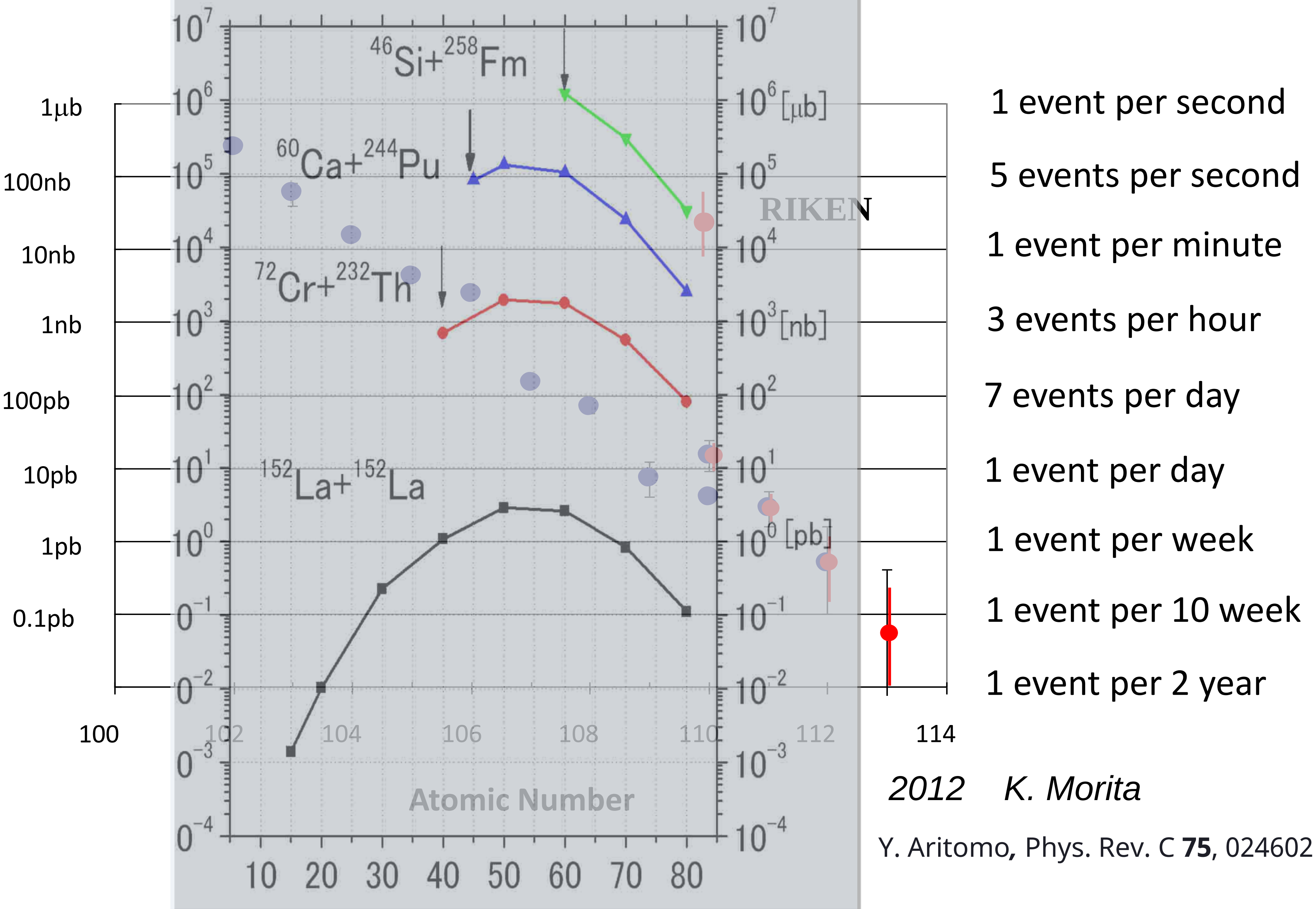
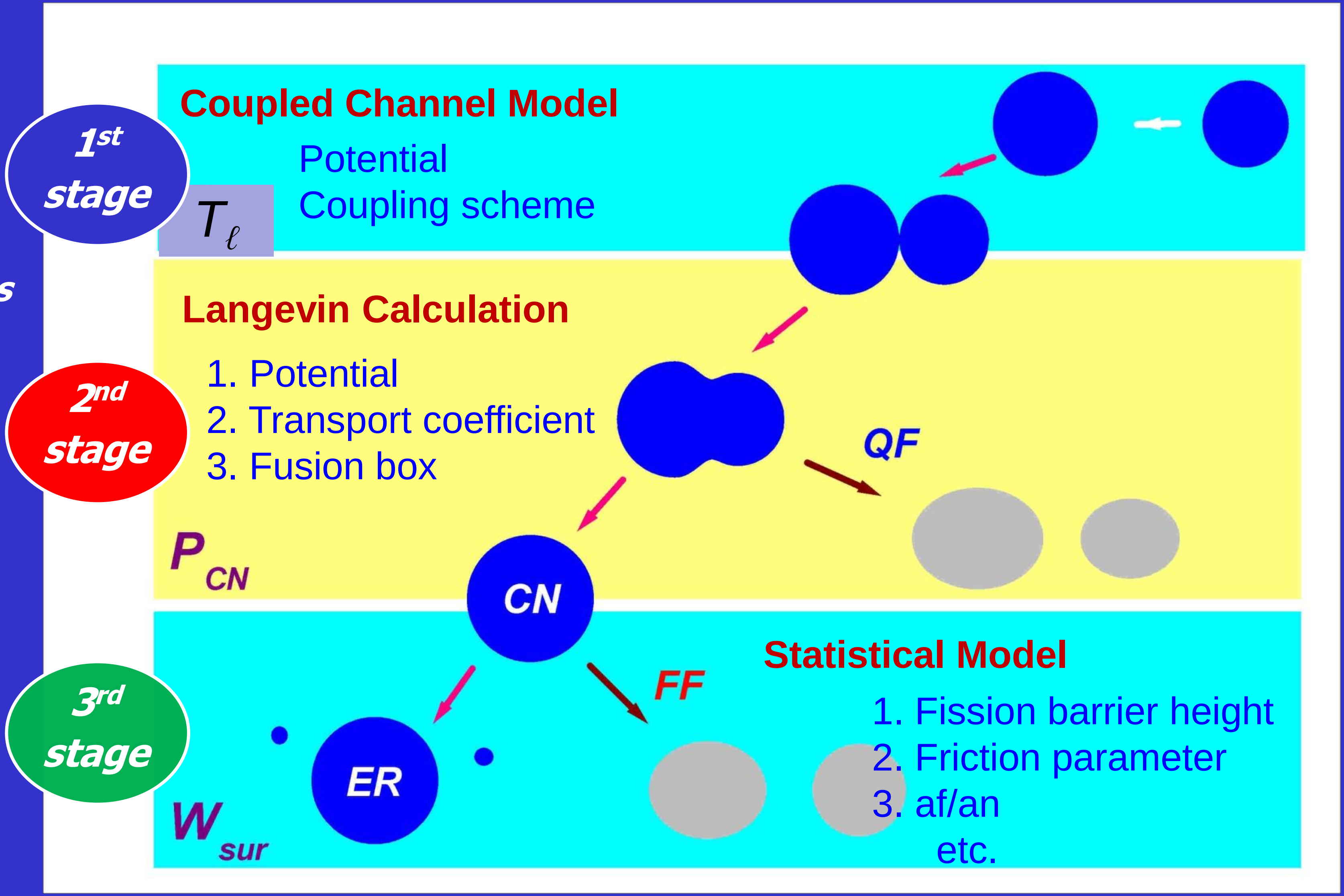


2012 K. Morita

Y. Aritomo, Phys. Rev. C **75**, 024602 (2007)

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

Divide the whole process into three stages



Advantages of Each Stage

1. Suppression of incident energy dissipation
ADVANTAGE using Nuclei with Strong Shell Structure

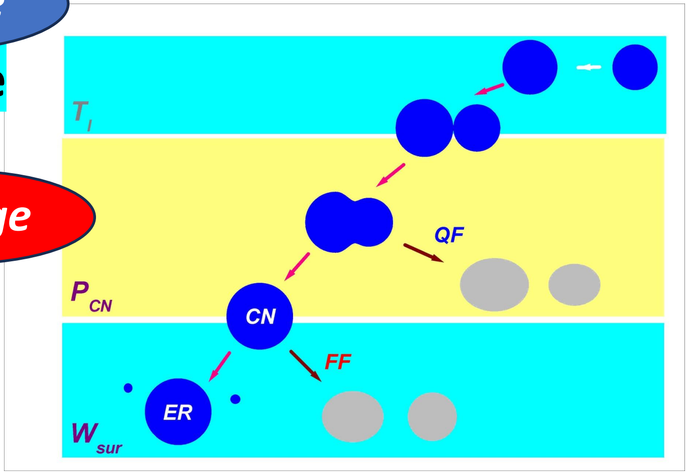
1-stage

2. Use of the second pocket in fusion process
ADVANTAGE using the Spherical Target

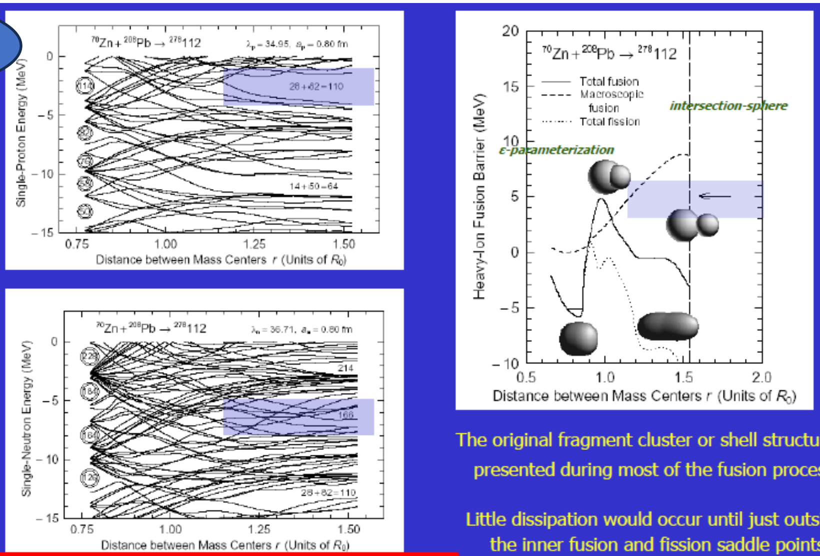
2-stage

3. Rapid and many neutron emissions
ADVANTAGE using RI beams

3-stage



1-stage



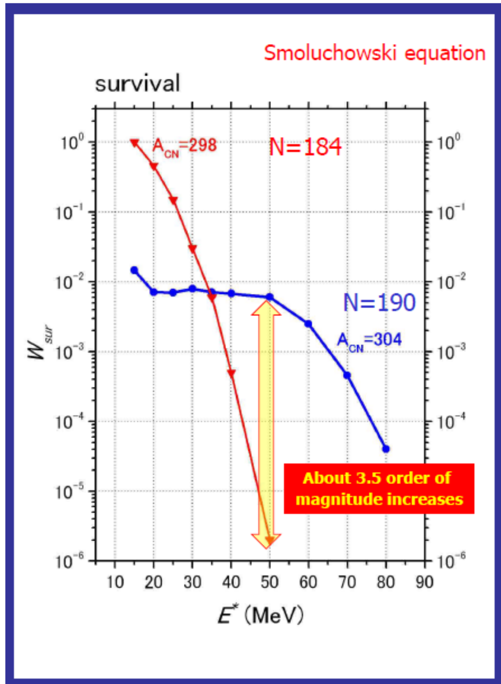
In dynamical model, we use microscopic friction, which depends on the temperature.

The original fragment cluster or shell structure is presented during most of the fusion process.

Little dissipation would occur until just outside the inner fusion and fission saddle points
→ *reduce the extra energy in the entrance channel to reach the compound nucleus.*

P. Moller, J.R. Nix, P. Armbruster, S. Hofmann, G. Munzenberg, Z. Phys. A 359, 251 (1997)
Single-particle enhancement of heavy-element production

3-stage



Due to many neutron emissions

① Approaching to **Island of Stability** (large Vsh)

Due to many neutron emissions
→ E* of CN decreases

② Recovers of **shell correction energy** Vsh

→ large fission Barrier

Advantages of Each Stage

1. Suppression of incident energy dissipation — *1-stage*

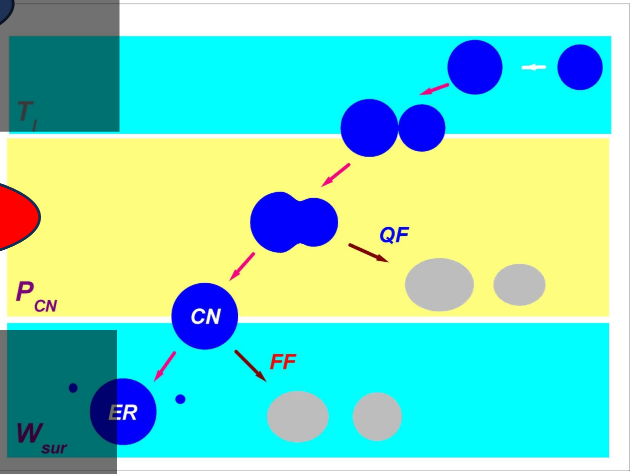
ADVANTAGE using Nuclei with Strong Shell Structure

2. Use of the second pocket in fusion process — *2-stage*

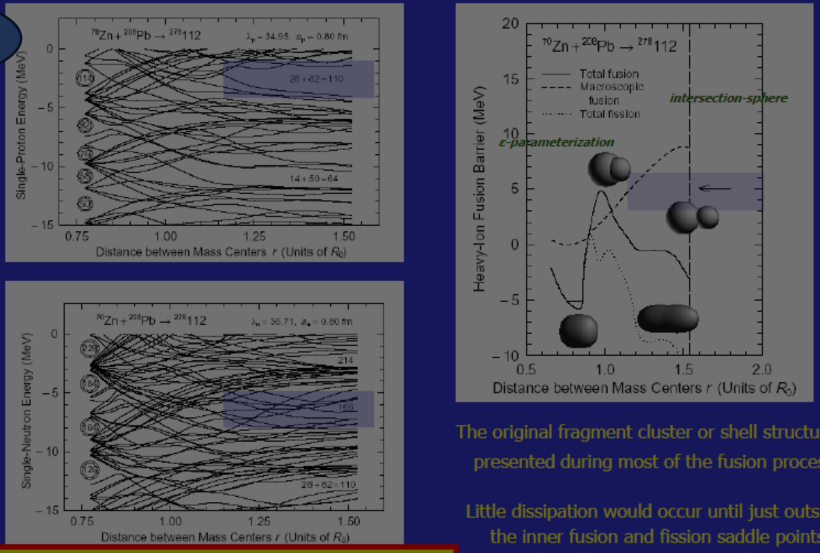
ADVANTAGE using the Spherical Target

3. Rapid and many neutron emissions — *3-stage*

ADVANTAGE using RI beams



1-stage



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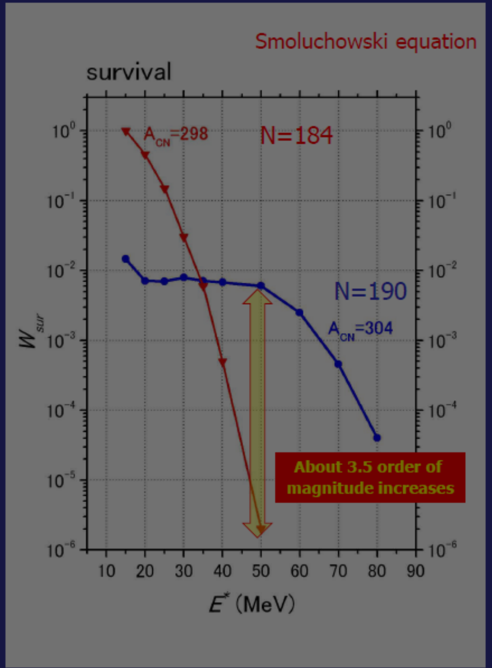

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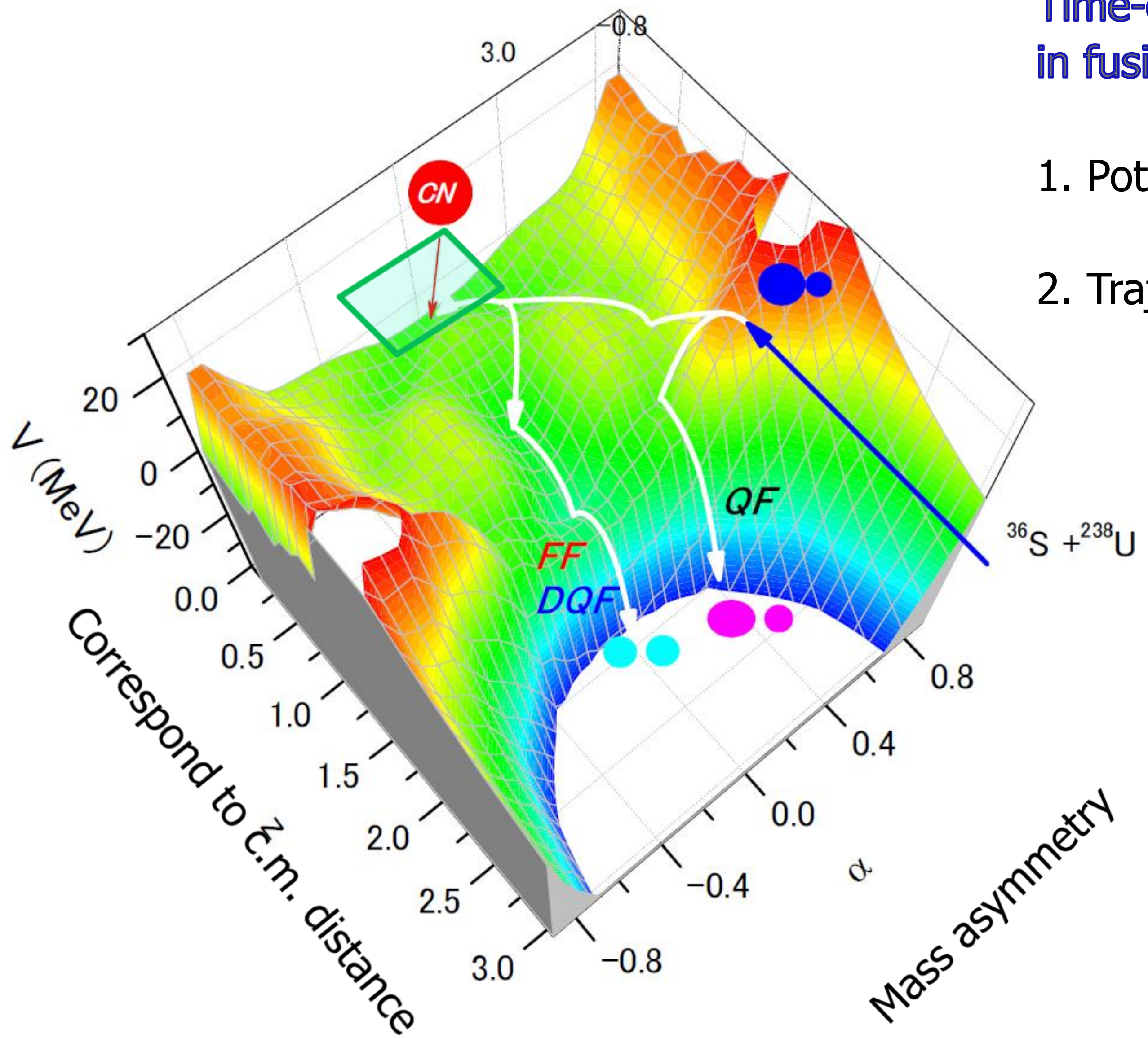


Time-evolution of nuclear shape in fusion-fission process

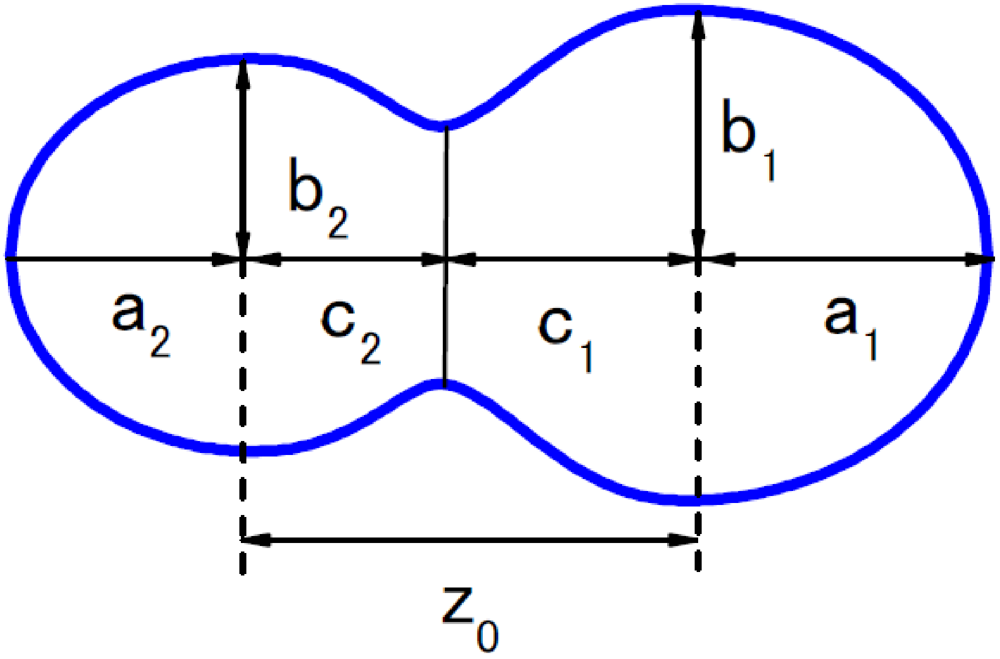
1. Potential energy surface

2. Trajectory → described by equations

Nuclear shape

two-center parametrization (z,δ,α)

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



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

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

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

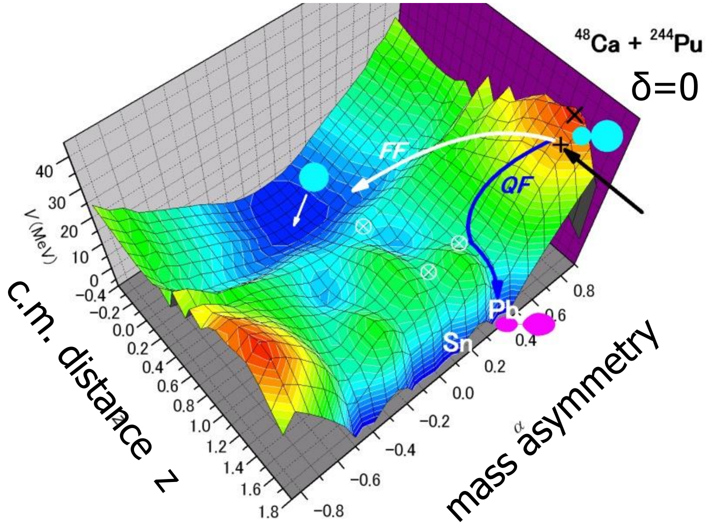
R : Radius of the spherical compound nucleus

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

(δ1=δ2)

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

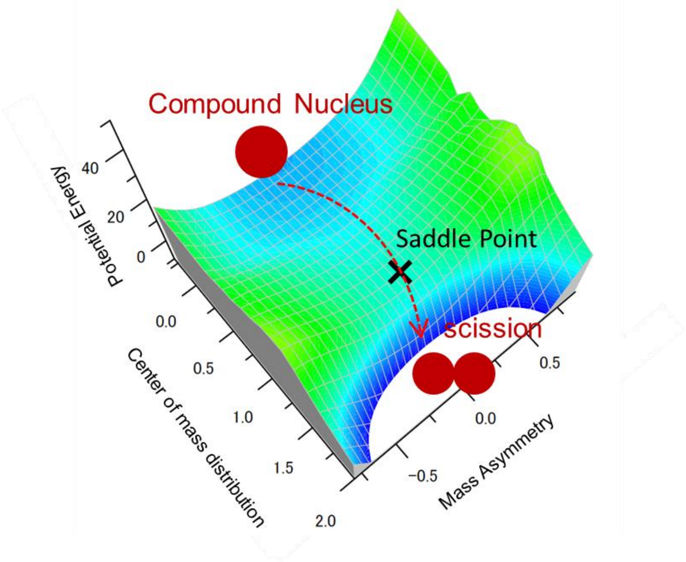
Trajectory which enters
into the spherical region
= fusion trajectory



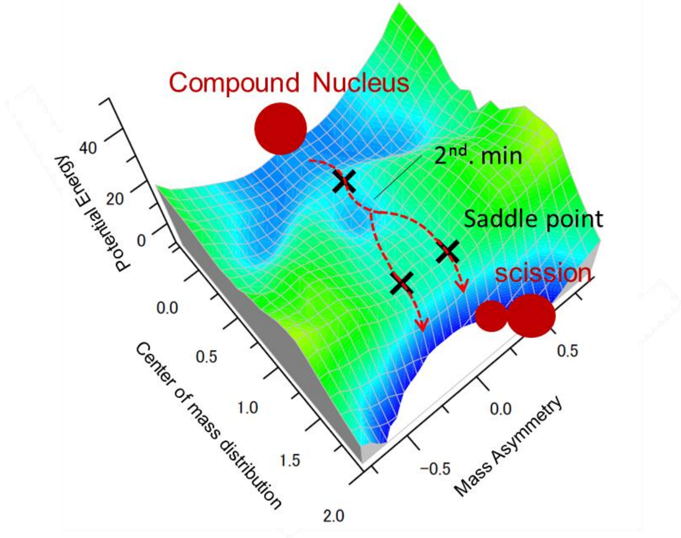
Potential energy

$$V(q,T) = V_{LD}(q) + V_{SH}(q,T)$$

Liquid drop model



Liquid drop and
Shell correction energy



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

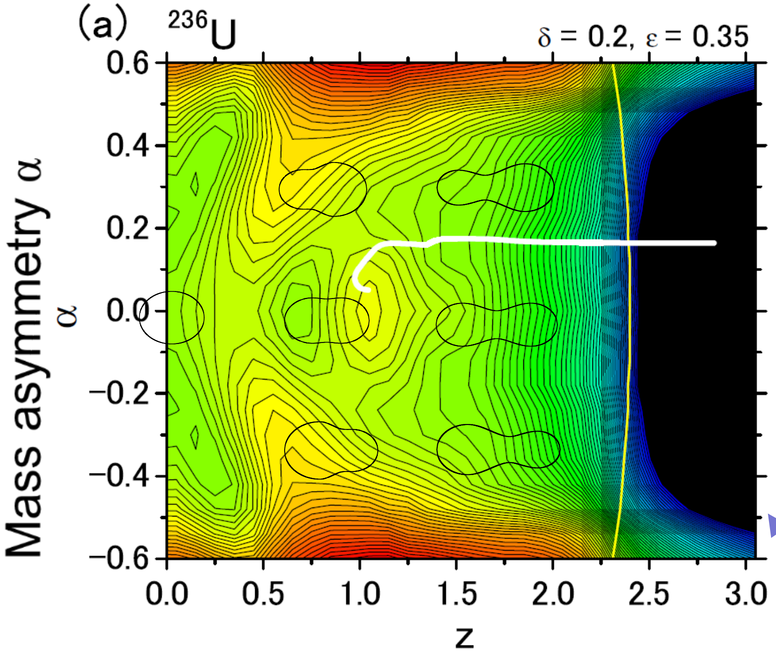
m_{ij} : Hydrodynamical mass (inertia mass)

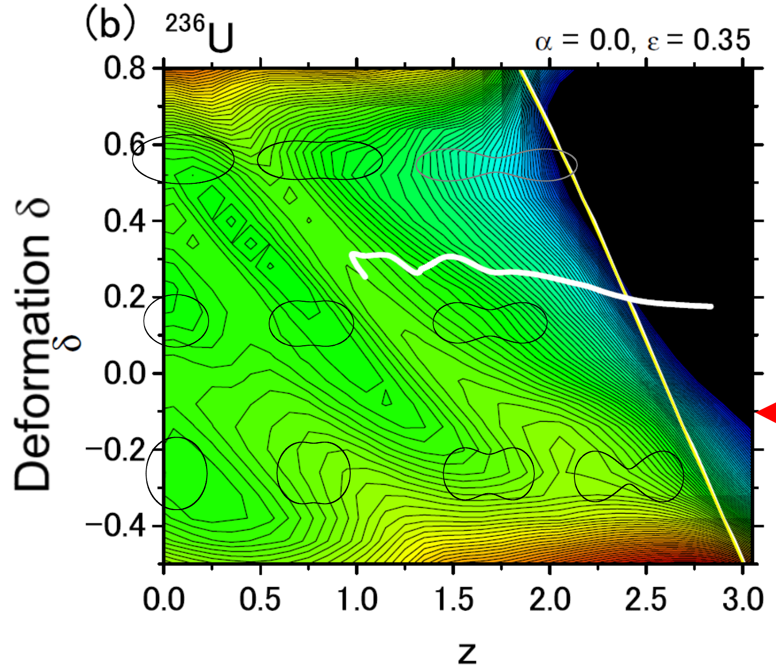
γ_{ij}: Wall and Window (one-body) dissipation （friction ）

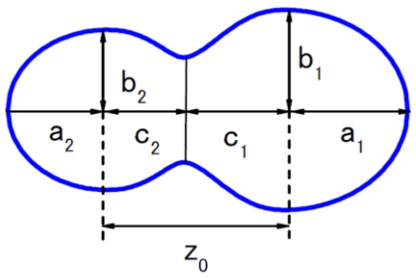
$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q)$$

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

Without fluctuation







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R: Radius of the spherical compound nucleus

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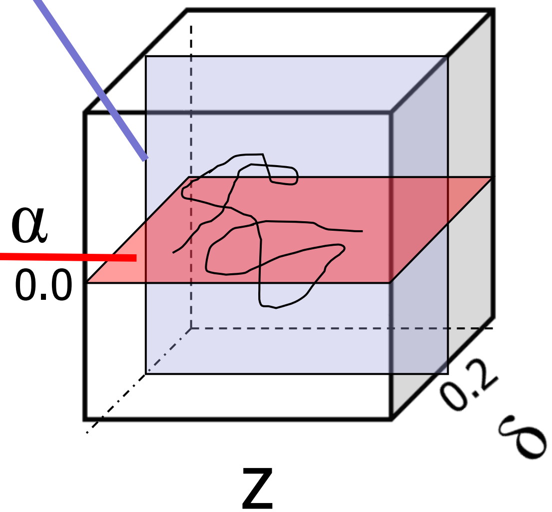
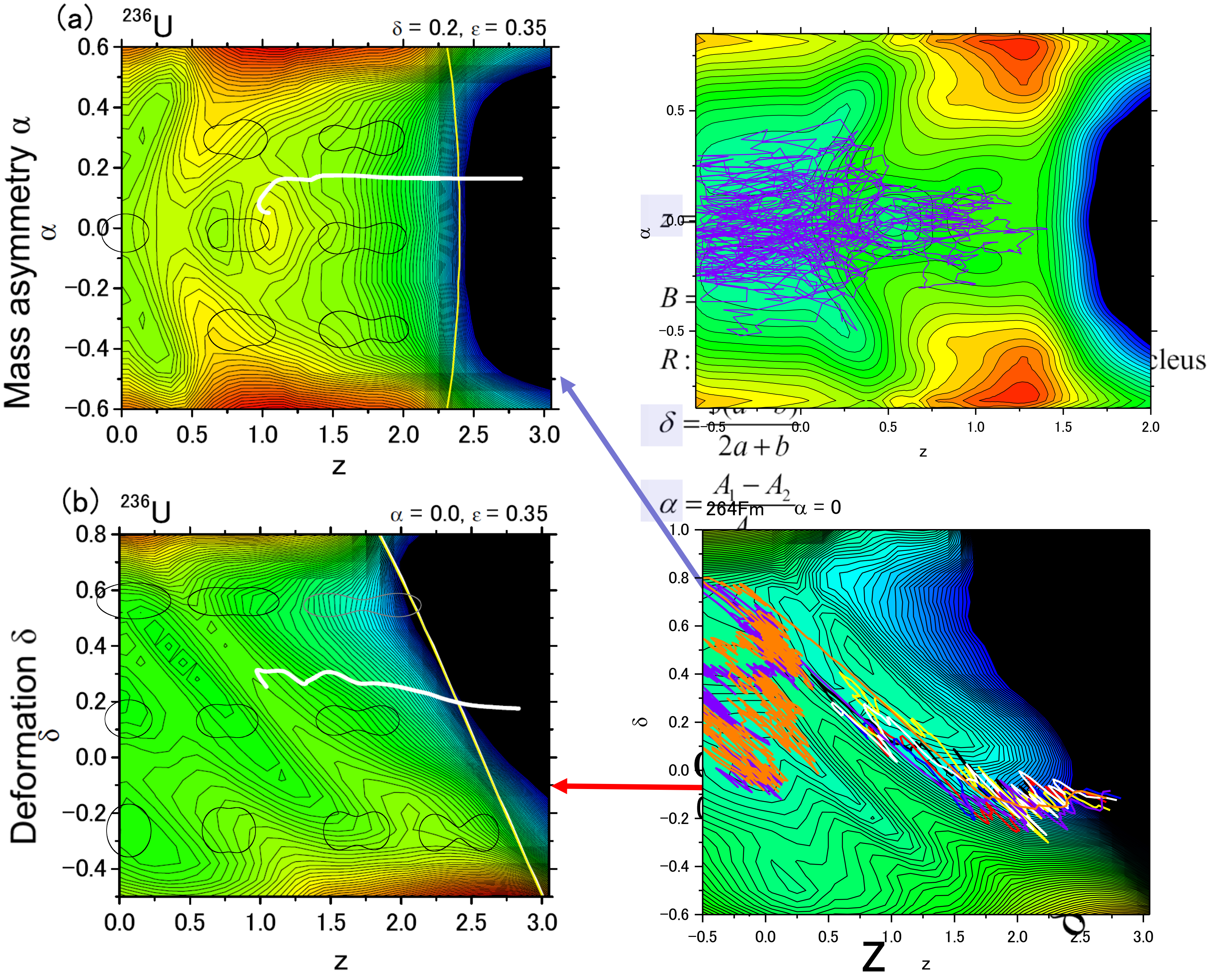
$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$

3D coordinate space



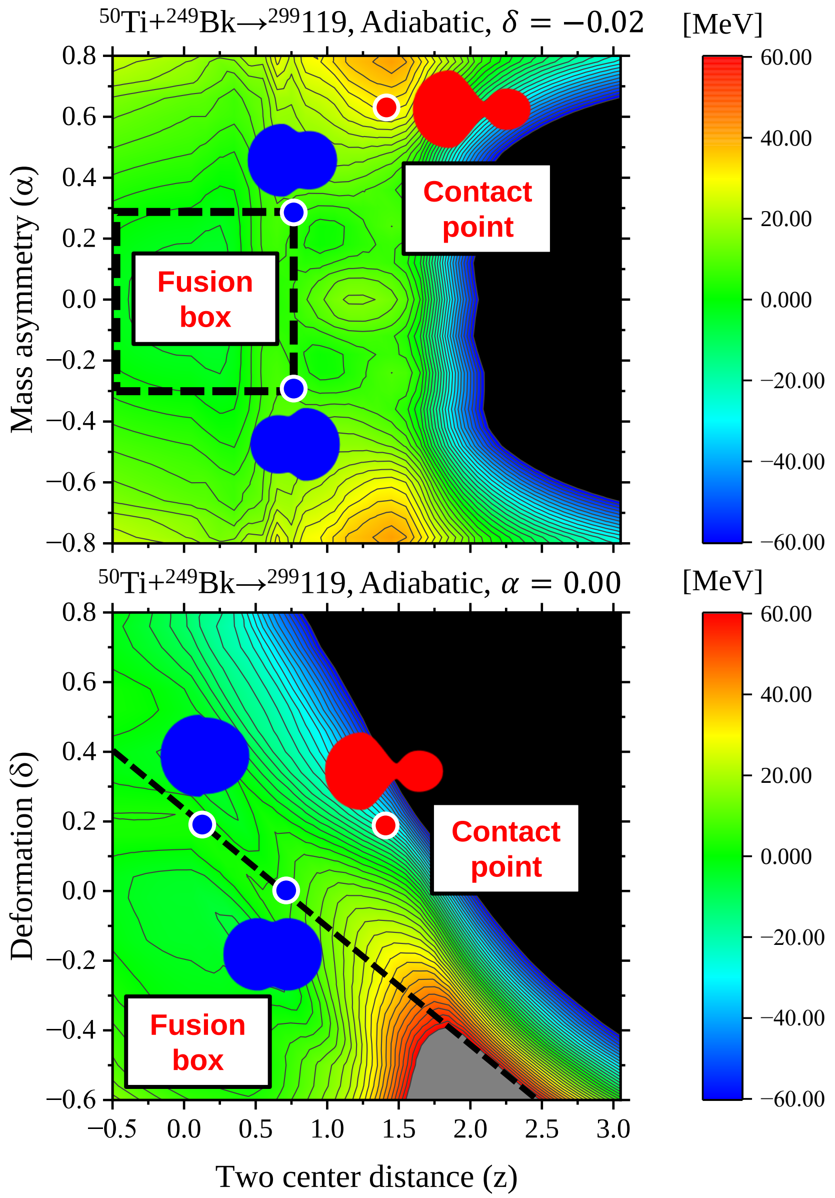
Projection on two-dim. plane

Without fluctuation



Projection on two-dim. plane

Fusion box



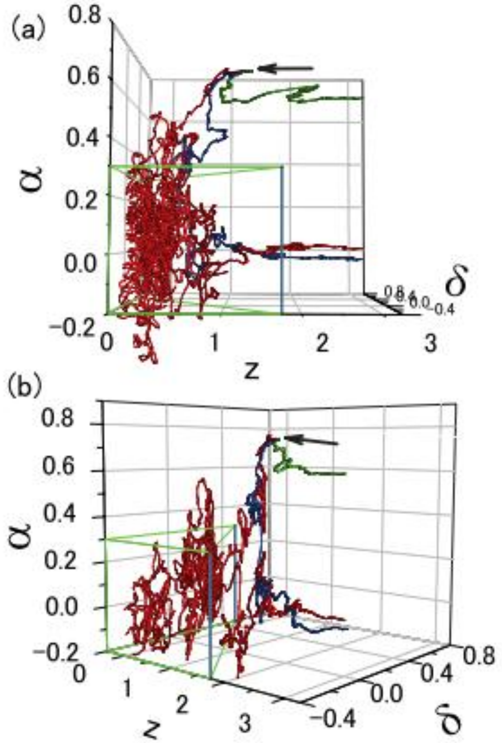
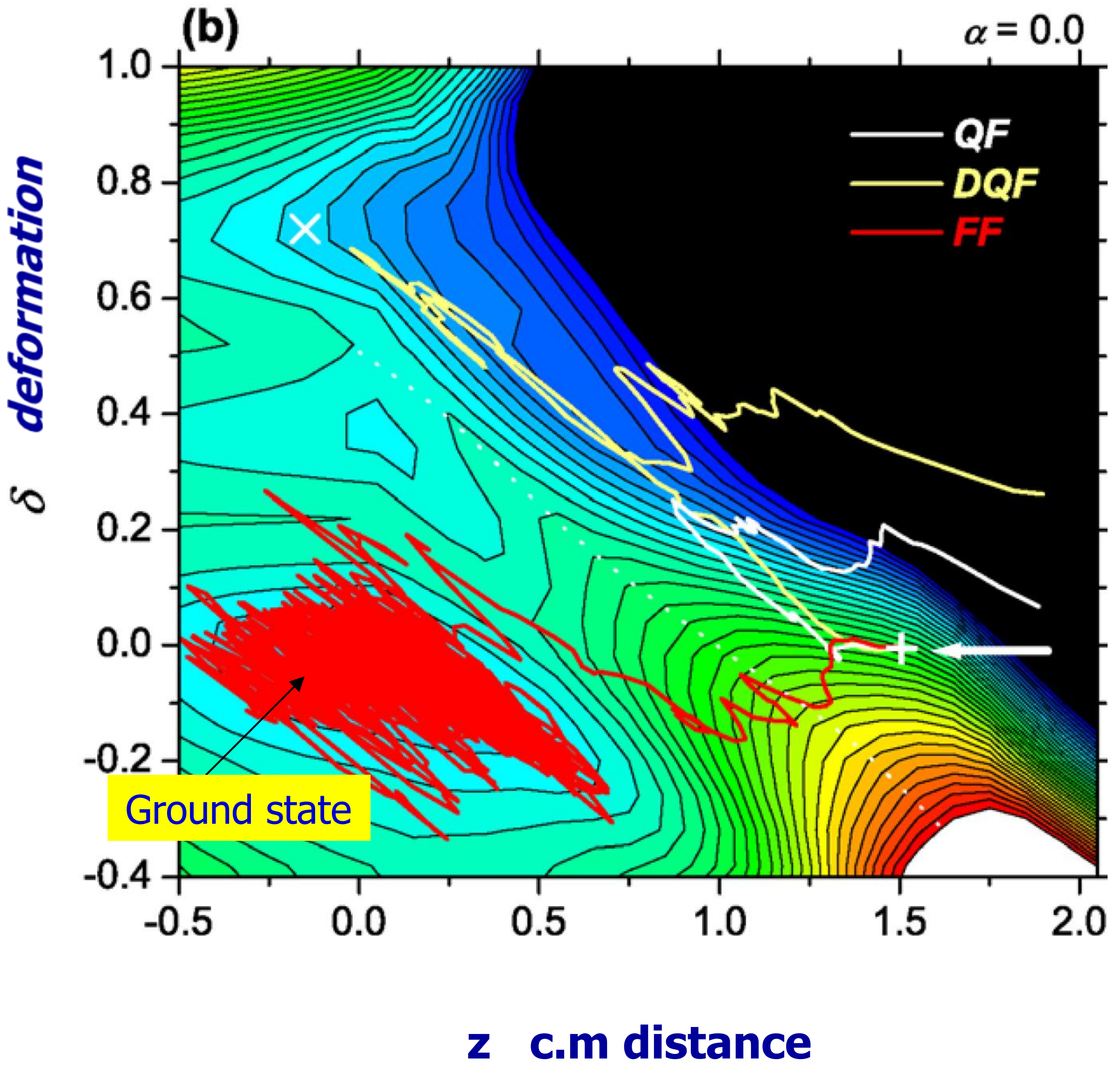


FIG. 11. (Color online) Sample trajectories in the three-dimensional coordinate space, $\{z, \delta, \alpha\}$, for the ^{36}S + ^{238}U reaction at $E^* = 35.5$ MeV. The arrow denotes the entrance point, where the Langevin calculations are started. The box represents the fusion box. The trajectories are plotted in the direction of the δ axis (a) and also in a different angle (b). The green, blue, and red lines represent QF, DQF, and FF, respectively.

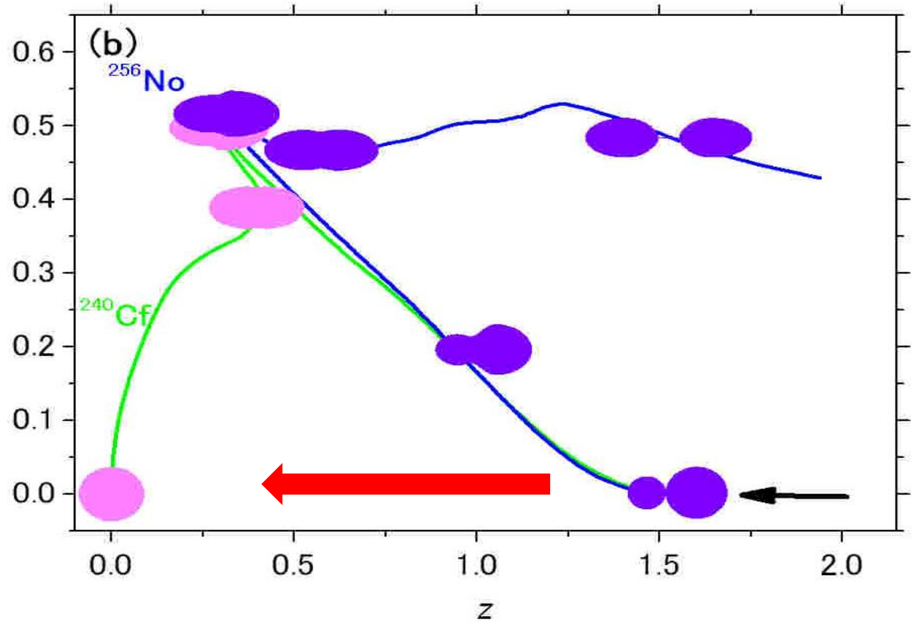
Y. Aritomo, *et al.*, Phys. Rev. C **85**, 044614 (2012)

Contents

$^{48}Ca + {}^{244}Pu$

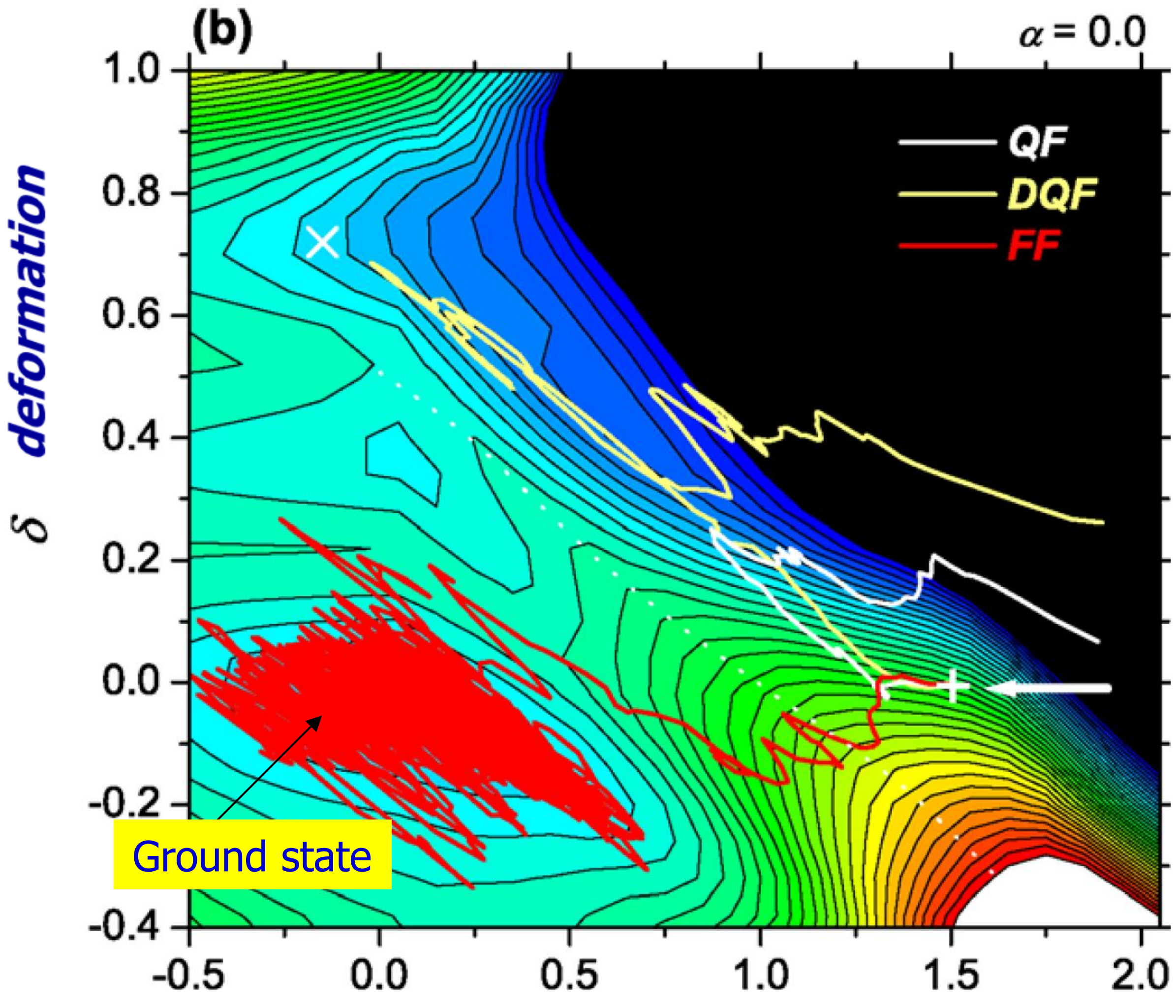


(b)
α = 0.0
QF
DQF
FF
Ground state
δ deformation
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
-0.5
0.0
0.5
1.0
1.5
2.0
z c.m distance



(b)
256No
240Cf
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.0
0.5
1.0
1.5
2.0
z

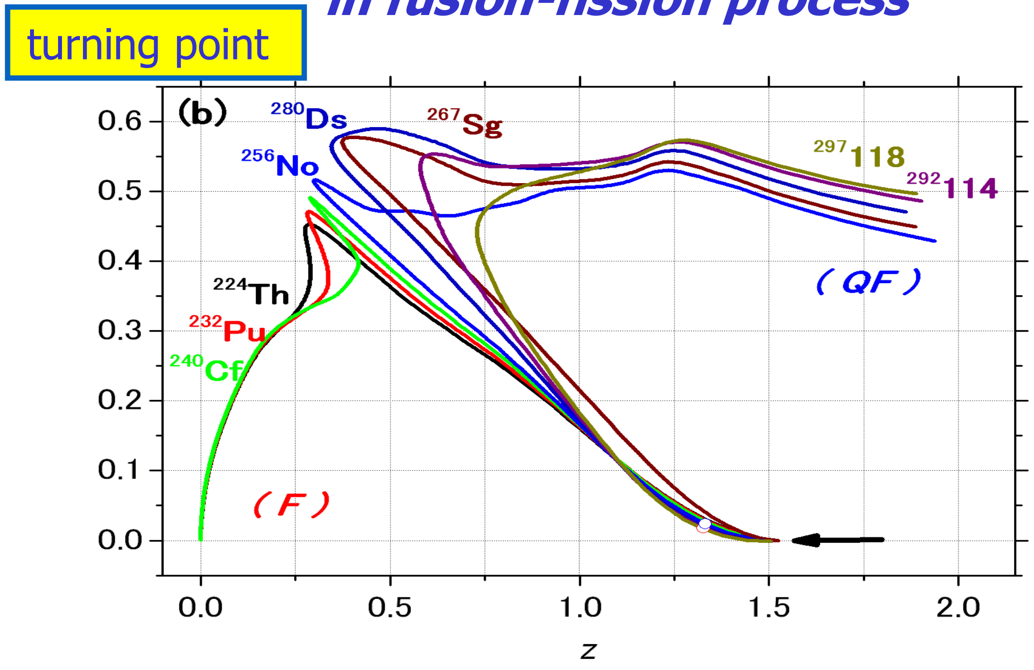
^{48}Ca + ^{244}Pu



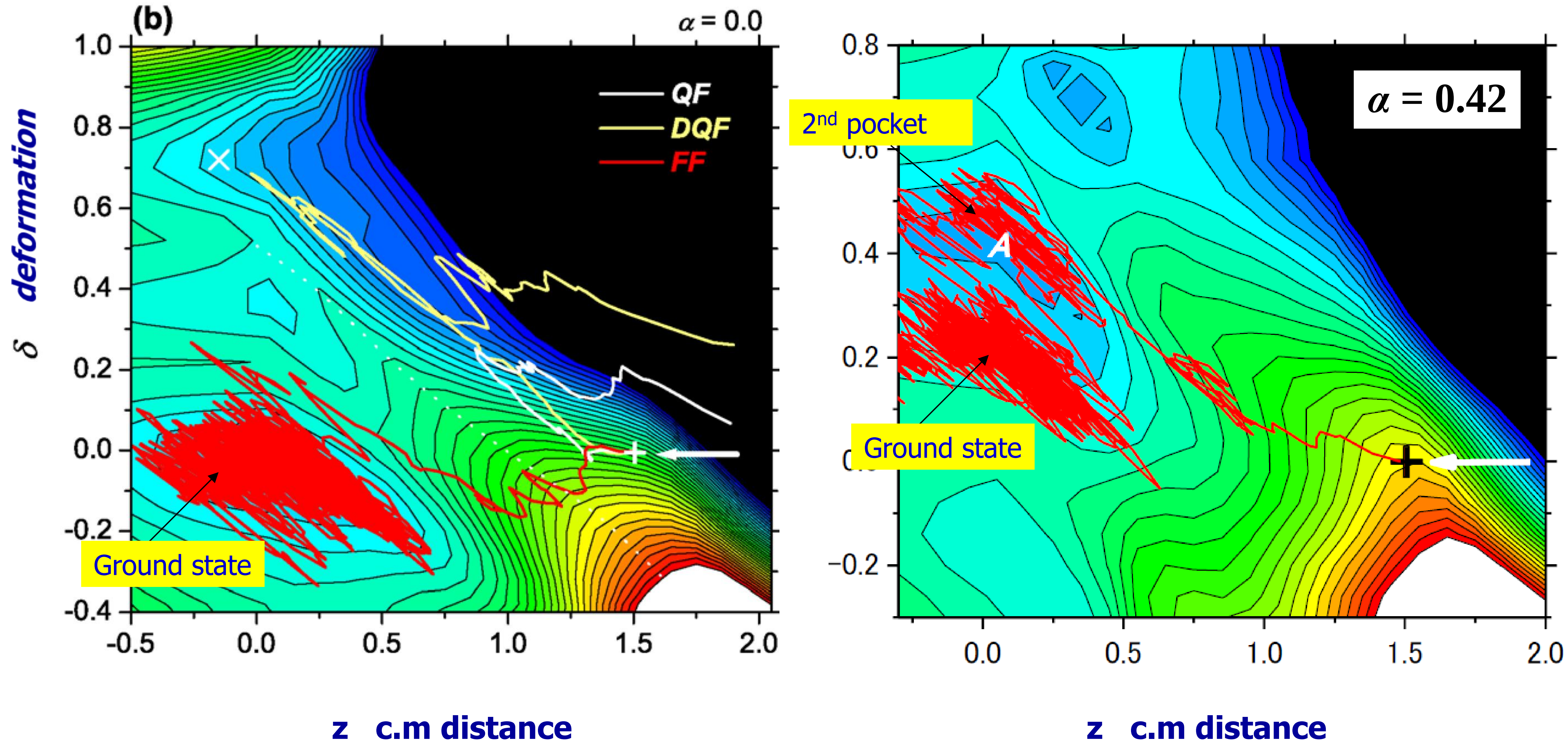
z c.m distance

To produce Th, Pu, Cf, No, Sg, Ds, Fl, Og

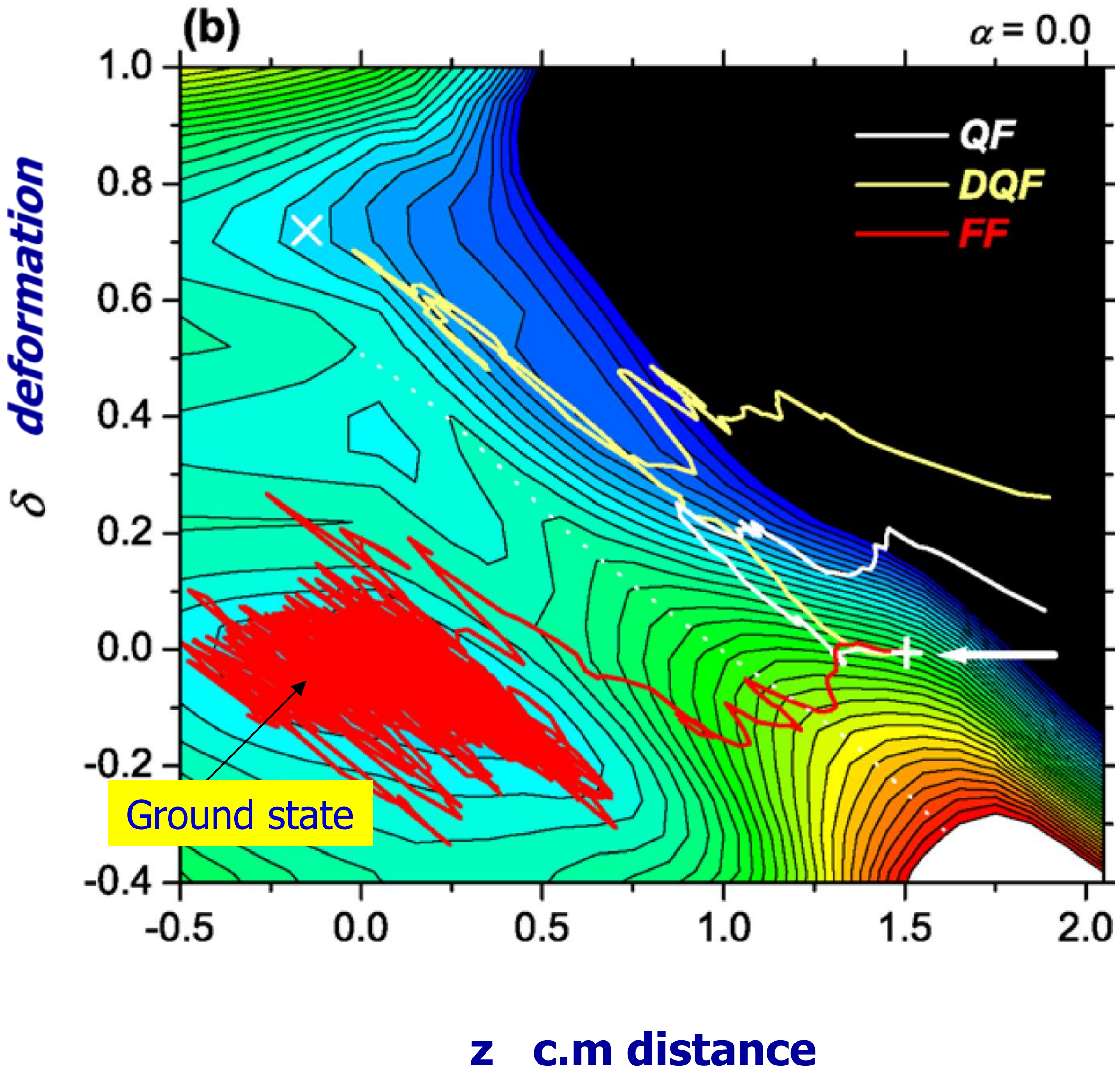
Gross tendency of the trajectories in fusion-fission process



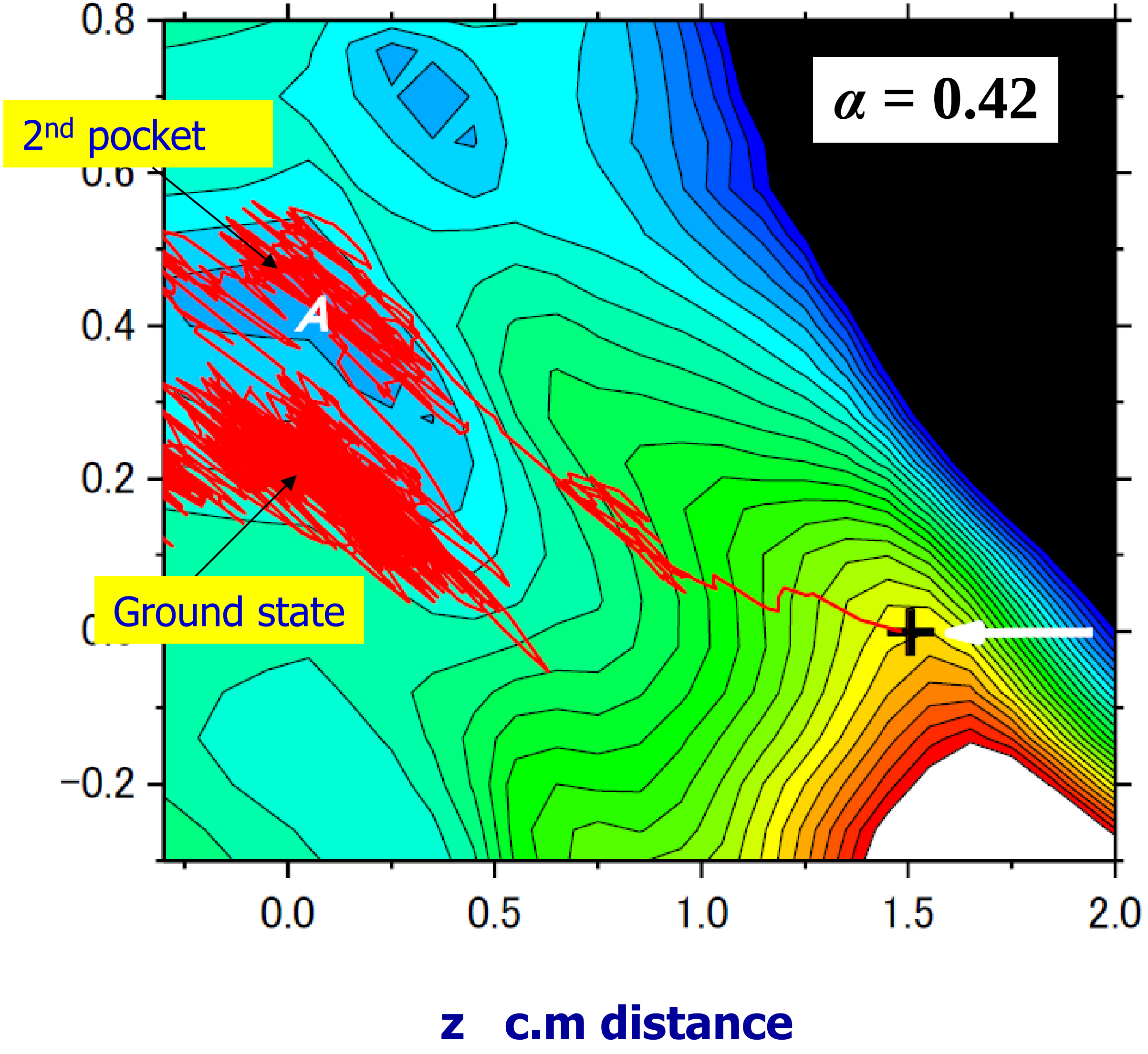
^{48}Ca + ^{244}**Pu** ^{48}Ca + ^{208}**Pb**

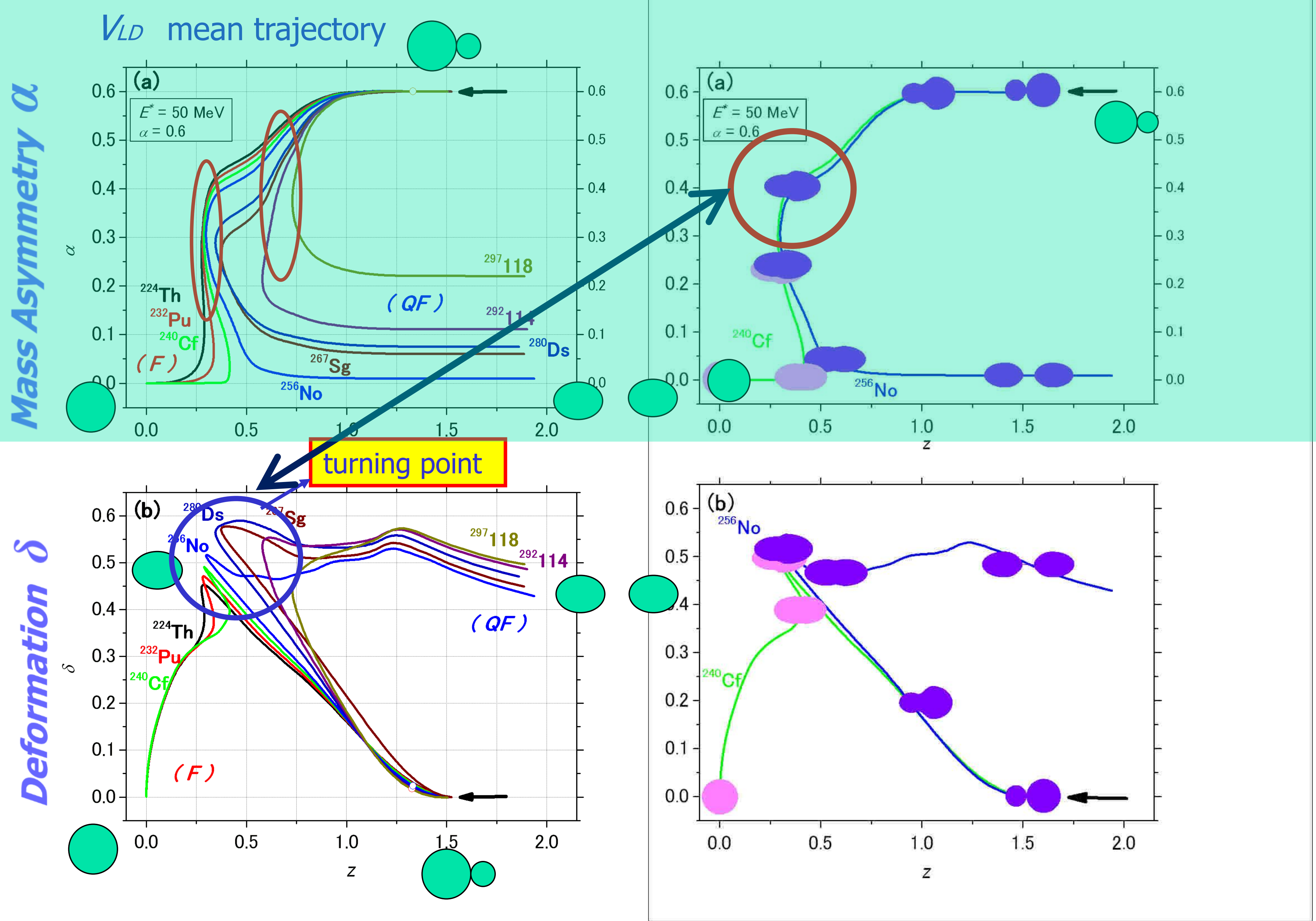


$^{48}Ca + ^{244}Pu \rightarrow ^{292}Fl$



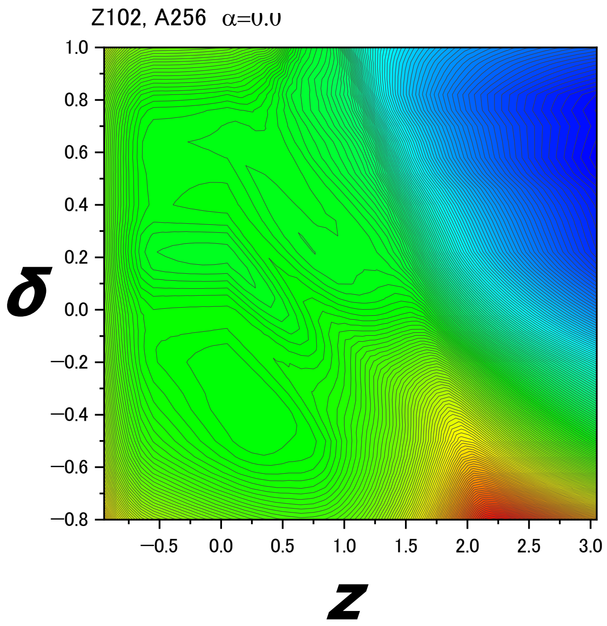
$^{48}Ca + ^{208}Pb \rightarrow ^{256}No$



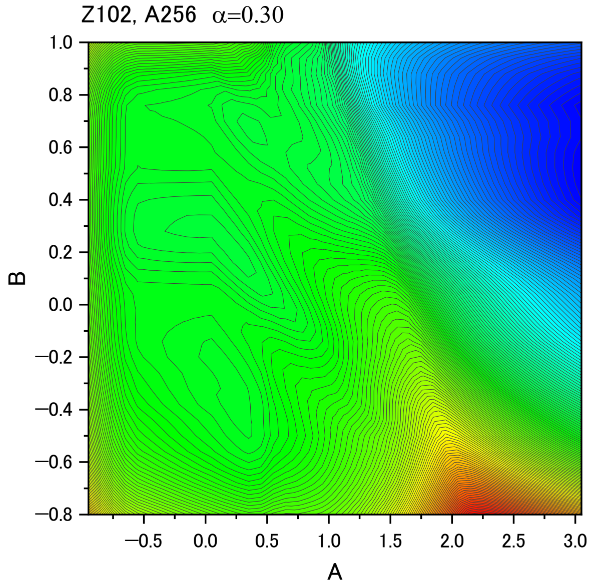


V_{LD} mean trajectory
Mass Asymmetry α
Deformation δ
(a)
E^* = 50 MeV
α = 0.6
^{224}Th
^{232}Pu
^{240}Cf
^{256}No
^{267}Sg
^{280}Ds
^{292}114
^{297}118
(F)
(QF)
turning point
(b)
z

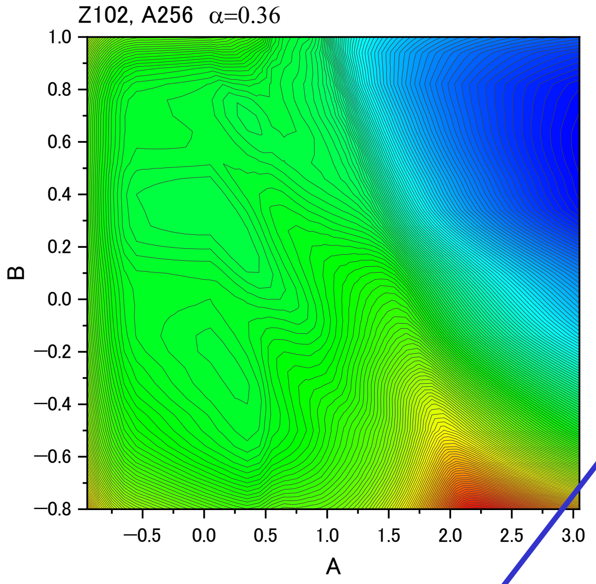
$\alpha = 0.0$



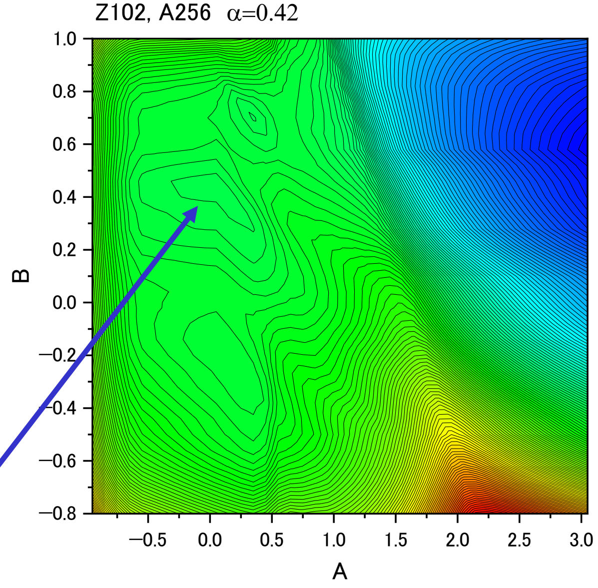
$\alpha = 0.30$

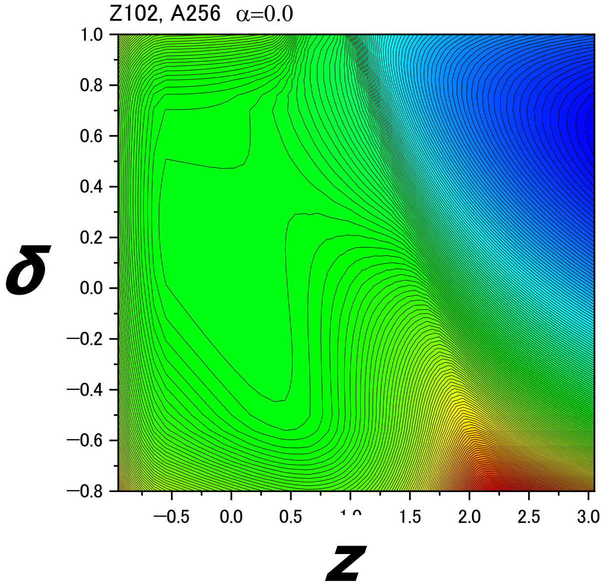


$\alpha = 0.36$



$\alpha = 0.42$

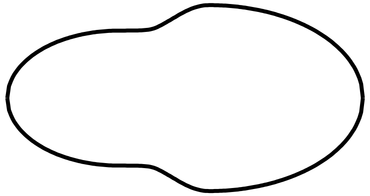




$^{48}Ca + ^{208}Pb \rightarrow ^{256}No$

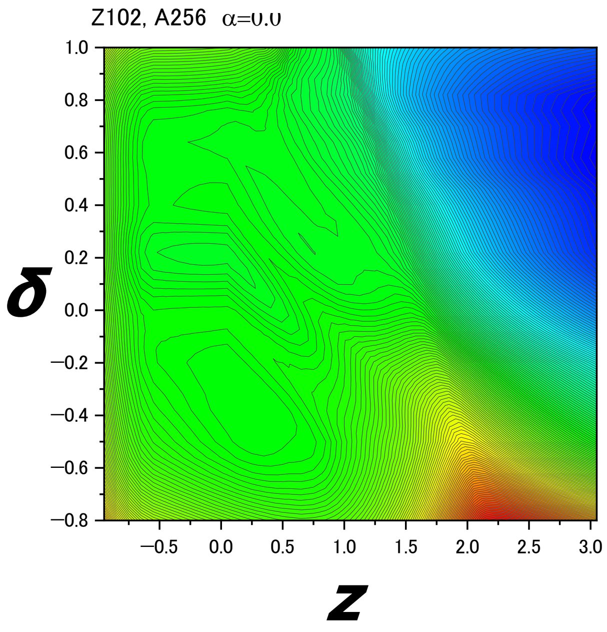
$\alpha = 0.42$

$\delta = 0.40$

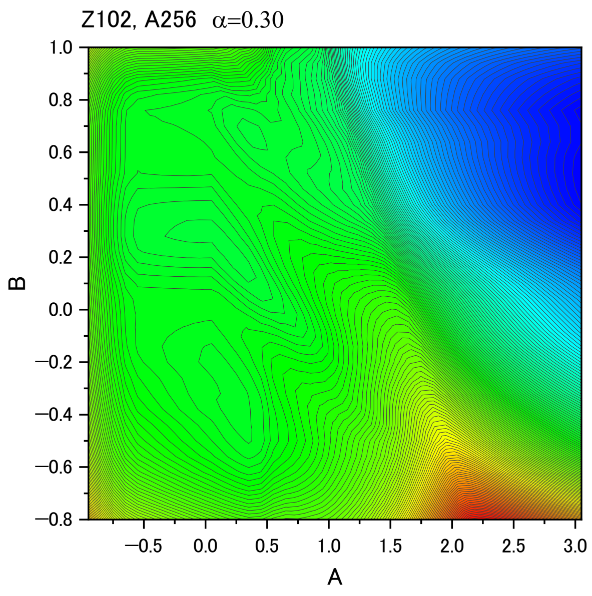


2nd Pocket
α=0.42
Corresponds to
N=110 deformed shell
184W (Z=74, N=110)
186Os (Z=76, N=110)

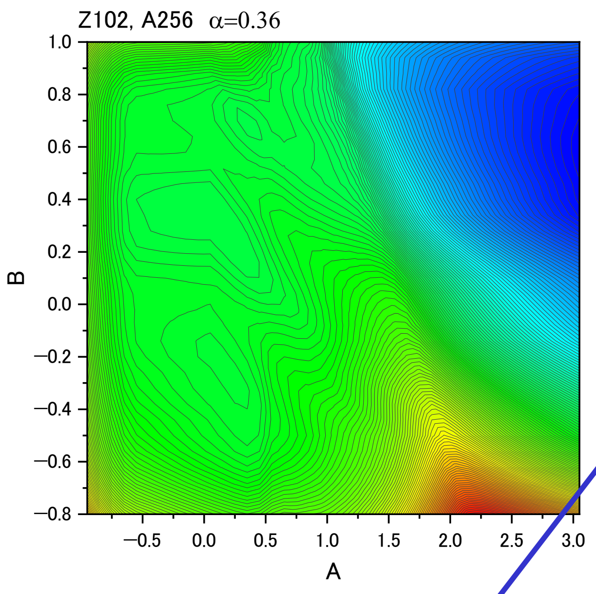
$\alpha = 0.0$



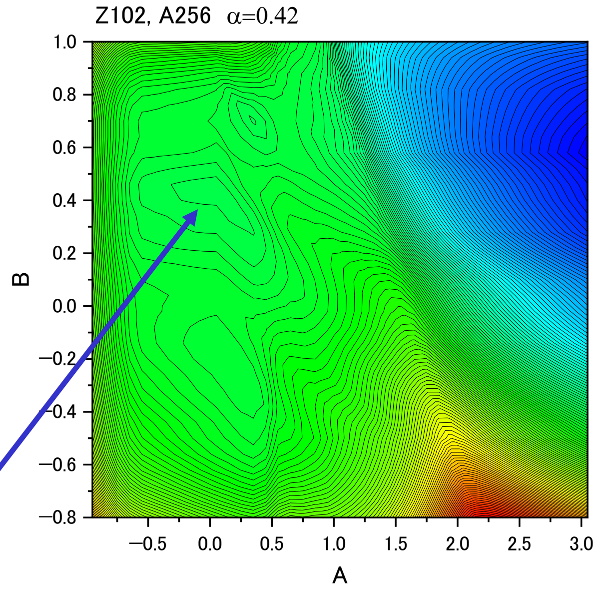
$\alpha = 0.30$

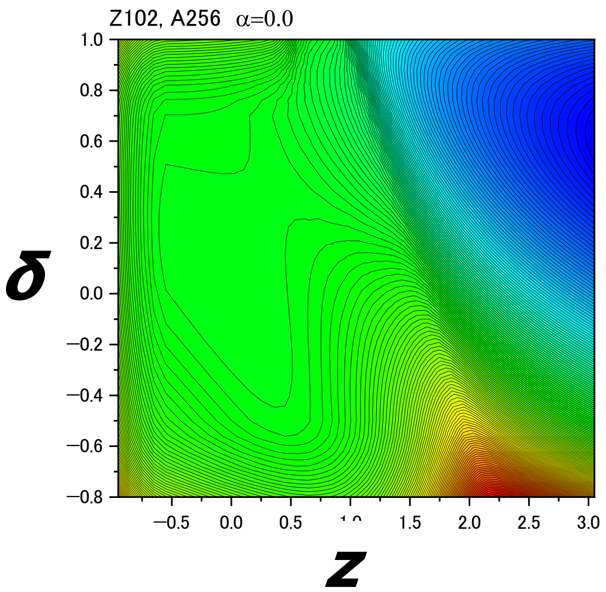


$\alpha = 0.36$



$\alpha = 0.42$

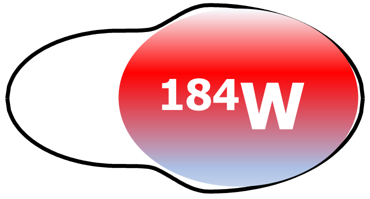




$^{48}Ca + {}^{208}Pb \rightarrow {}^{256}No$

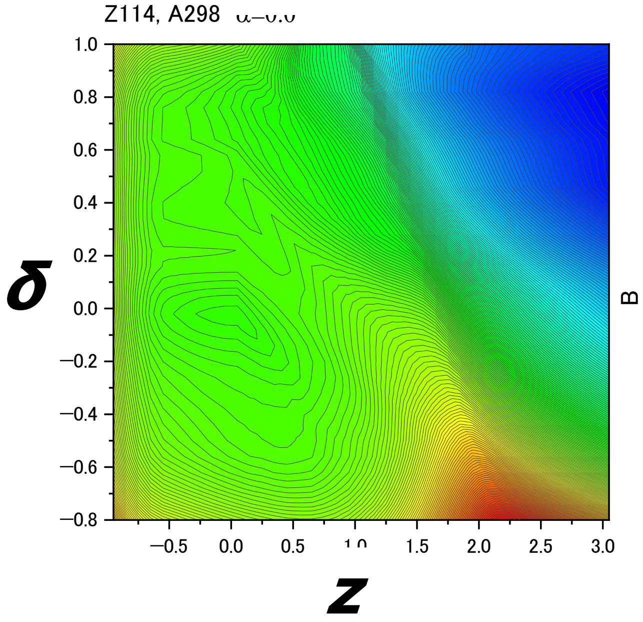
$\alpha = 0.42$

$\delta = 0.40$

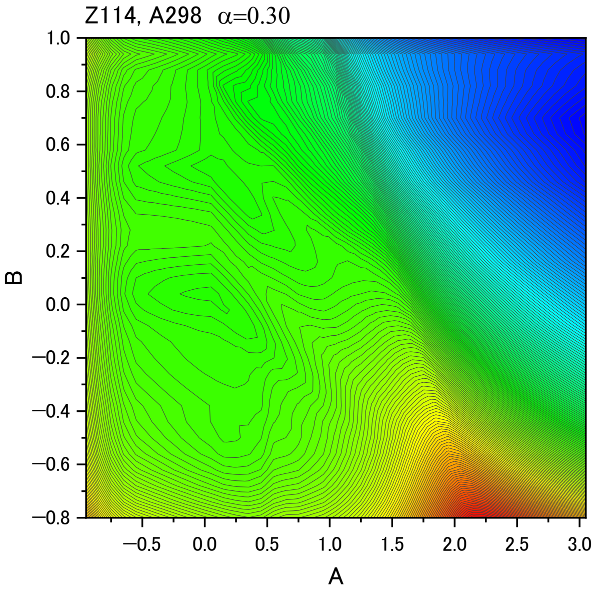


2nd Pocket
α=0.42
Corresponds to
N=110 deformed shell
184W (Z=74, N=110)
186Os (Z=76, N=110)

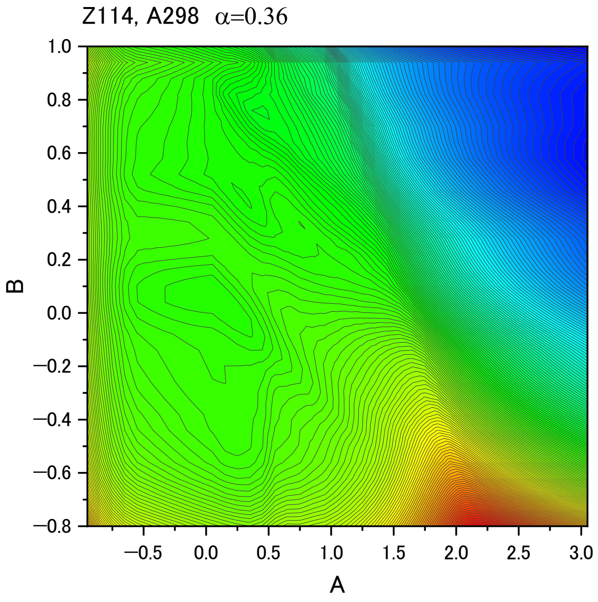
α = 0.0



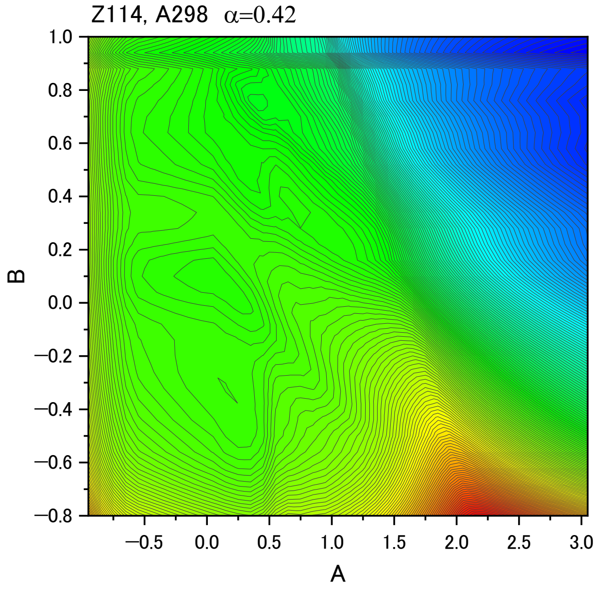
α = 0.30

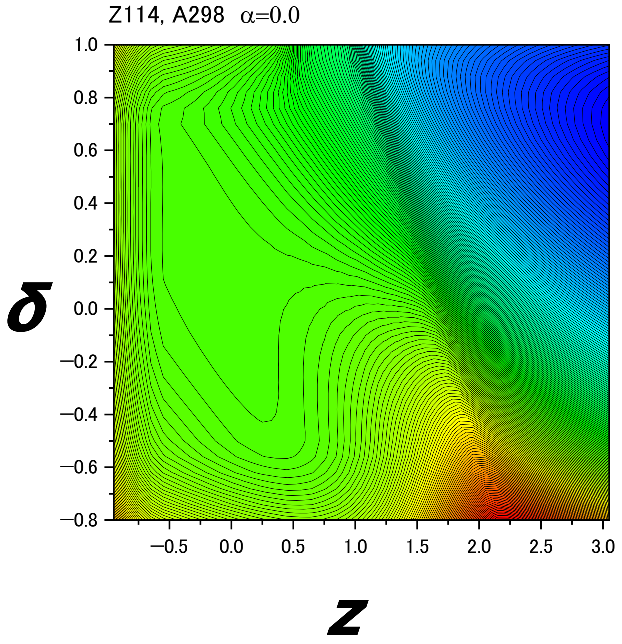


α = 0.36



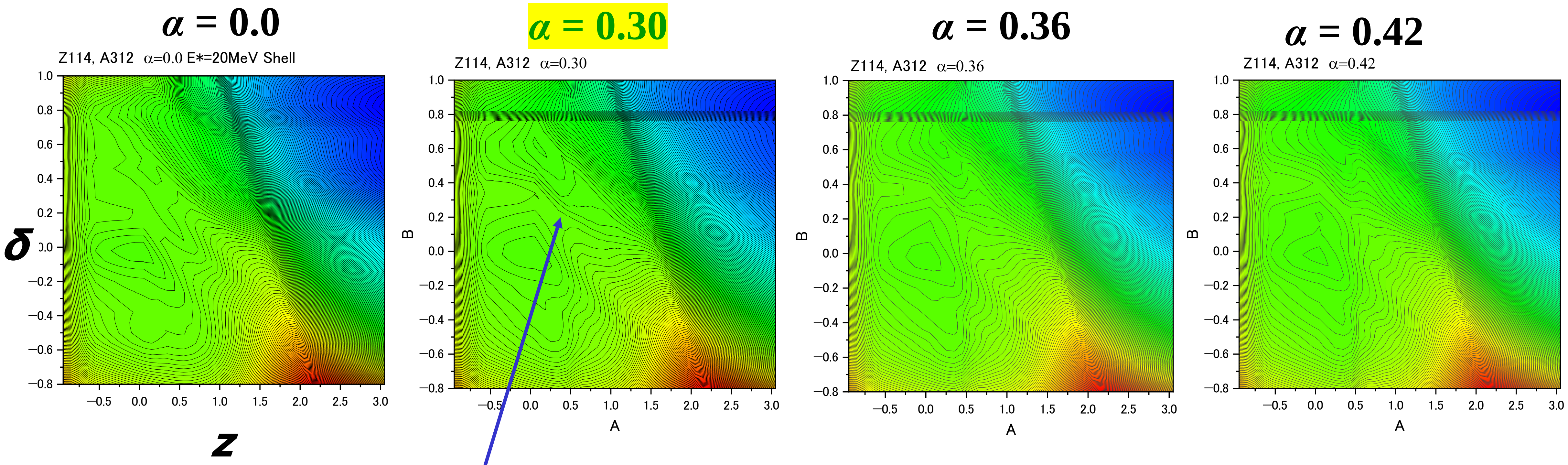
α = 0.42





$^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu} \rightarrow {}^{292}\mathrm{Fl}$

$^{48}Ca + {}^{264}Pu \rightarrow {}^{312}Fl$

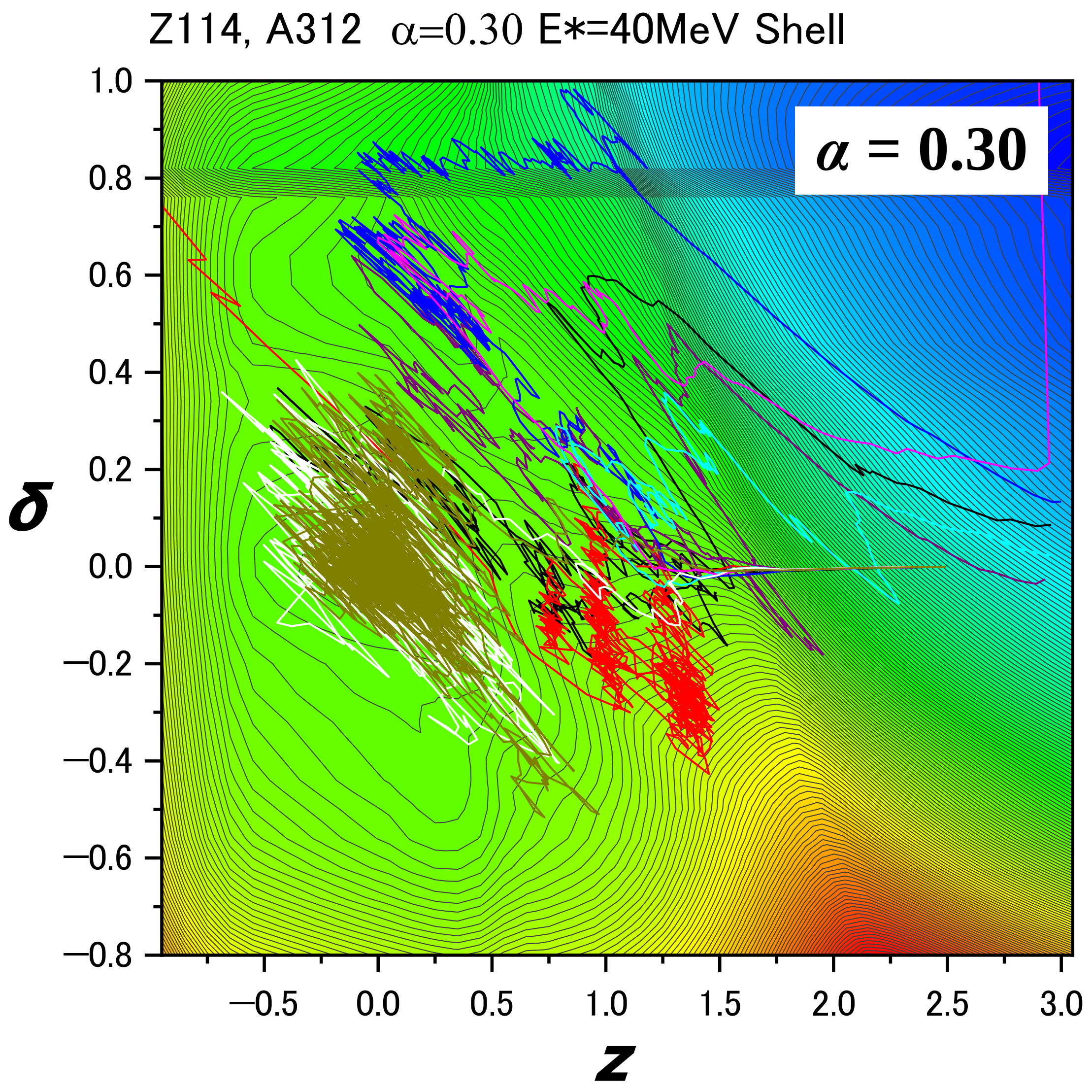


$\alpha = 0.30$

$\delta = 0.10$

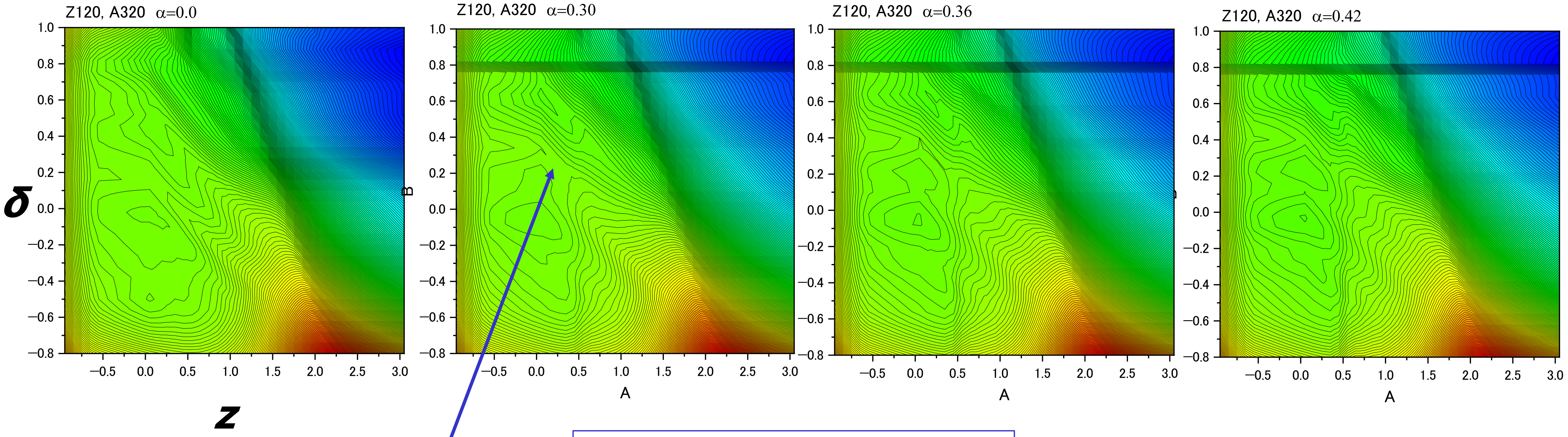
Flat region
α=0.30
Corresponds to
N=126 Spherical shell
208Pb (Z=82, N=126)

$^{48}Ca + {}^{264}Pu \rightarrow {}^{312}Fl$



^{58}Fe + ^{262}Pu → ^{320}120

$\alpha = 0.0$ | $\alpha = 0.30$ | $\alpha = 0.36$ | $\alpha = 0.42$

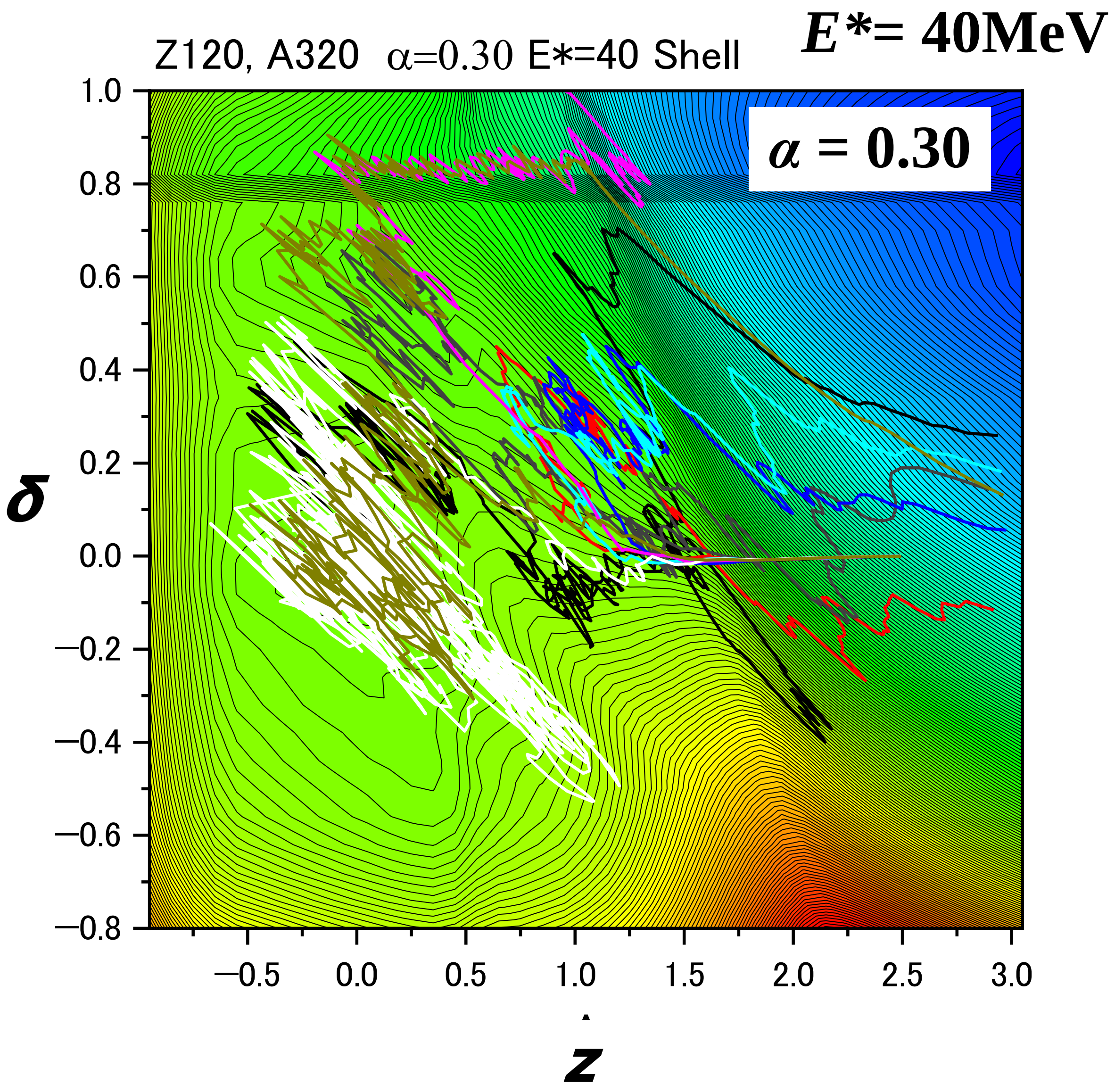


$\alpha = 0.30$

$\delta = 0.10$

Flat region
α=0.30
Corresponds to
N=126 Spherical shell
208Pb (Z=82, N=126)

$^{58}Fe + {}^{262}Pu \rightarrow {}^{320}120$



Summary and Conclusion

ADVANTAGE using Nuclei with Strong Shell Structure, Spherical Target, RI beams

1. Suppression of incident energy dissipation

2. Use of the second pocket in fusion process

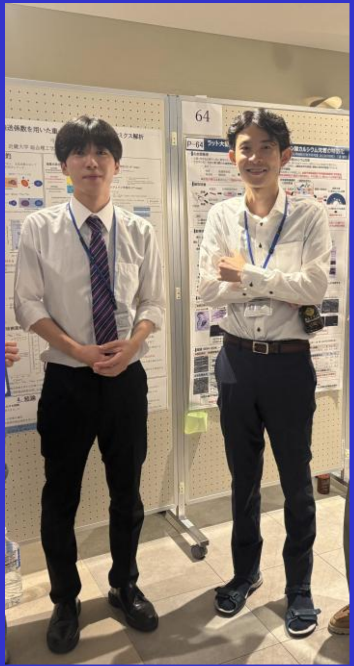
3. Rapid and many neutron emissions

We need information
on the highly accurate properties of SHE in the neutron-rich region
← Study of Nuclear Structure

Shell correction energy
Deformation of g.s.
mass, neutron separation energy → more accurate mass table for unknown region

Collaborators

近畿大学
KINDAI UNIVERSITY



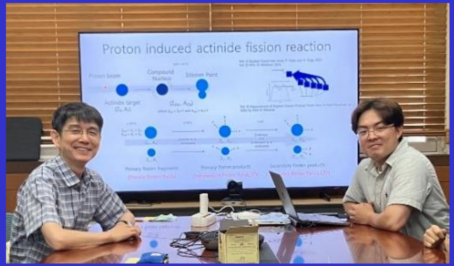
K. Kawai, K. Nakajima
A. Yumikura
Kindai University

RIKEN R-CCS

S. Takagi
RIKEN

KOGAKUIN UNIVERSITY

N. Nishimura
Kogakuin Univ.



PUSAN NATIONAL UNIVERSITY

C. Song,
C. Lee

CENS CENTER FOR EXOTIC NUCLEAR STUDIES

ibs 기초과학연구원 Institute for Basic Science

Y. Kim,
I. Shin
IBS, Korea

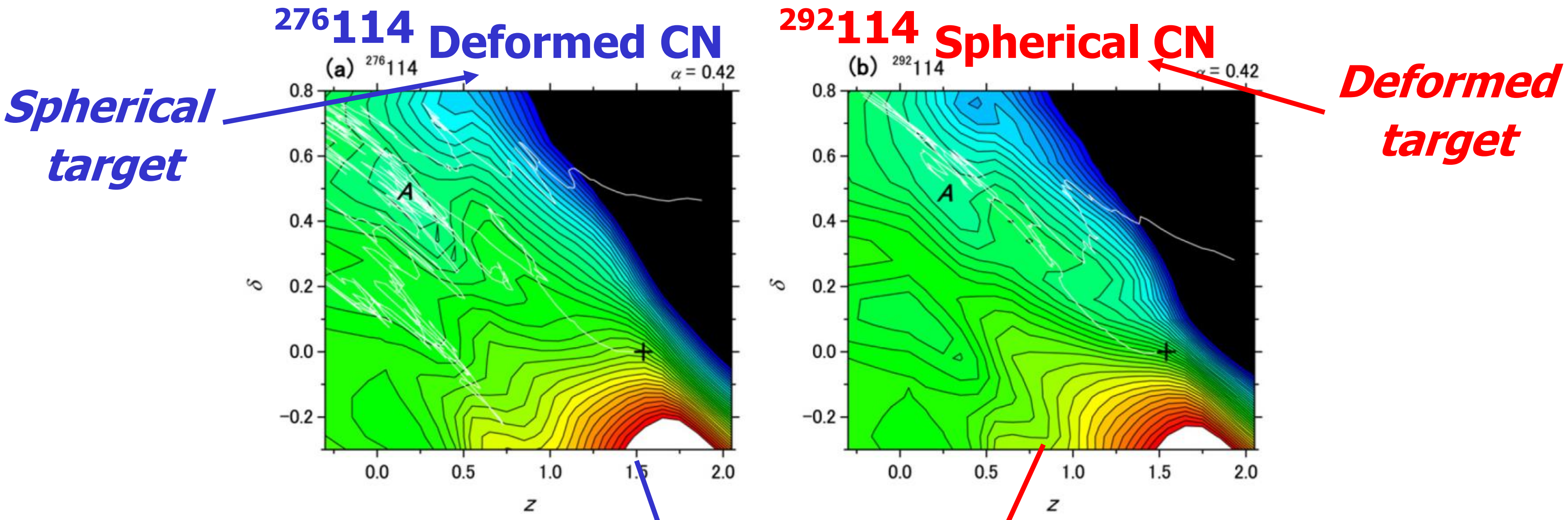
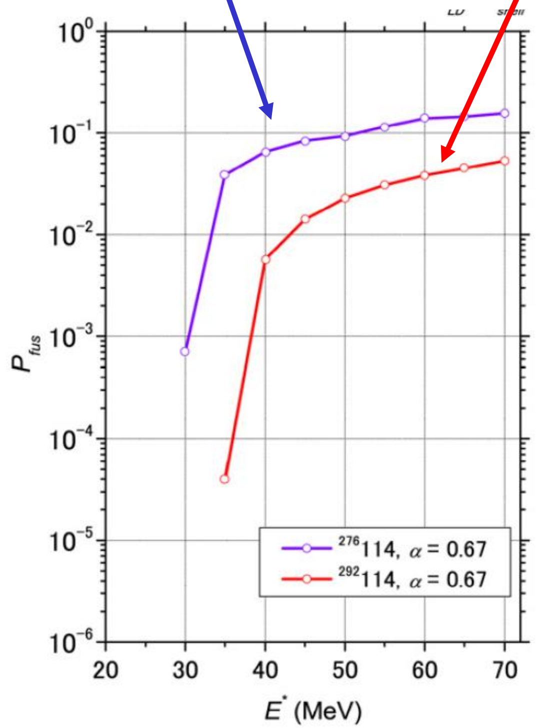
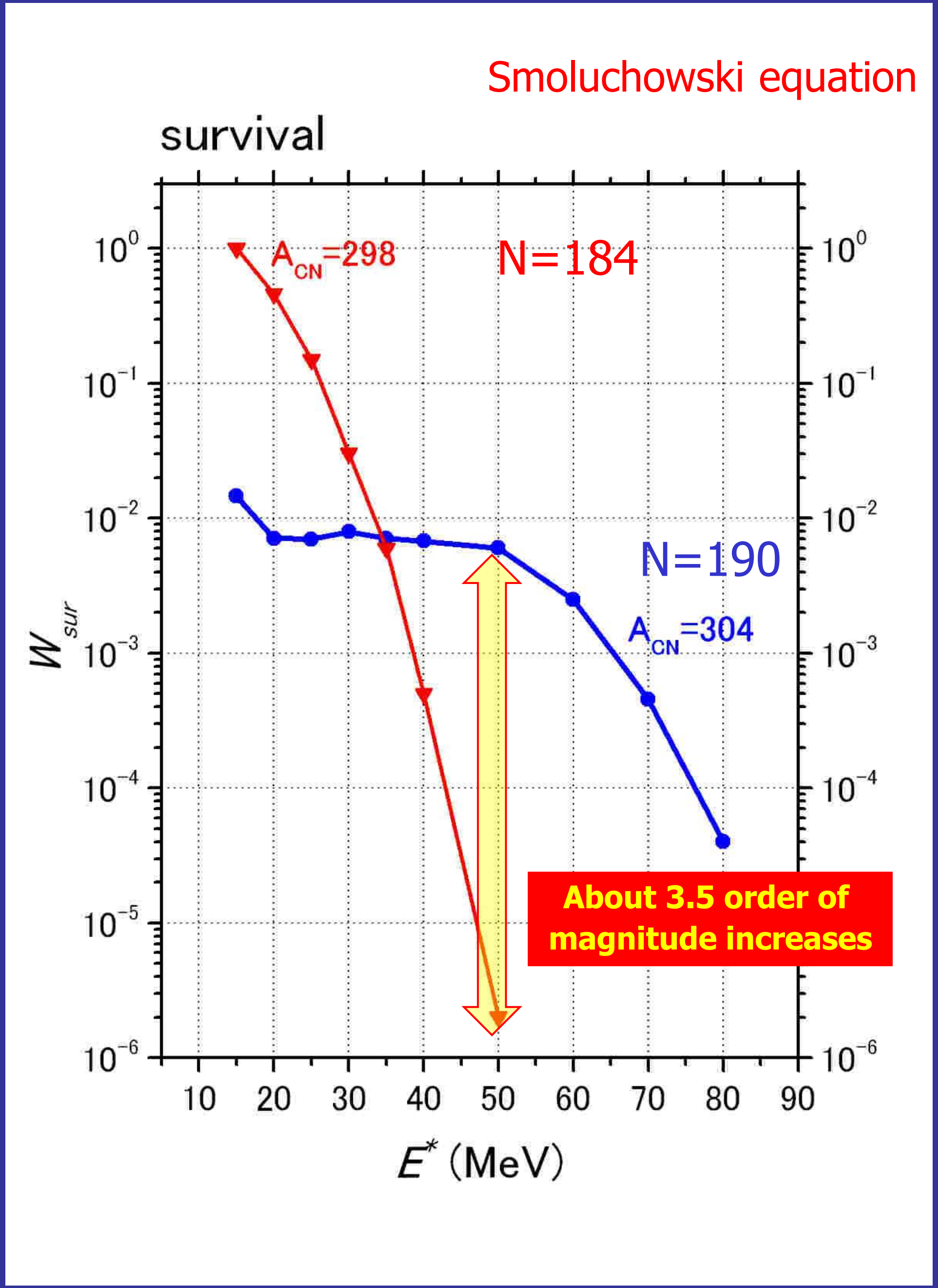


Fig. 8. (Colour online.) Sample trajectory projected onto the z–δ plane at $\alpha = 0.42$ of $V_{LD} + E^0_{shell}$ for (a) $^{276}114$ (deformed nucleus) and (b) $^{292}114$ (spherical one). The trajectory starts at $\alpha = 0.67$ and $E^* = 40$ MeV. Symbols are given in the text.



Y. Aritomo
Nucl. Phys. A 780
(2006) 222



Due to many neutron emissions

① Approaching to **Island of Stability** (large Vsh)

Due to many neutron emissions
→ E* of CN decreases

② Recovers of **shell correction energy** Vsh

→ large fission Barrier

deformation of the nucleus