Dynamical Approach to Synthesis of Superheavy Elements

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Topics

Structure	Light Nuclei
Reaction	Superheavy Nuclei

Key Words

1. Shell Correction Energy

   Two-Center Shell Model

2. Dynamical Approach

Contants

1. Introduction
   - Super Heavy Elements
   - Stability of Nuclei, Shell effects
   - Synthesis of SHE

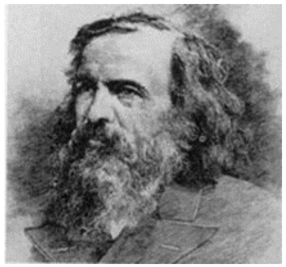
2. Experimental methods

3. Theoretical calculation
   - Dynamical model (Fluctuation Dissipation model)
   - Langevin equation

4. Calculation results
   - fusion-fission process

5. Further study

Periodic Table



	1	2	3	4	5	6	12	13	14	15	16	17	18
1	H 1												He 2
2	Li 3	Be 4						B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12						Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Zn	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Cd	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	La*	Hf 72	Ta 73	W 74	Hg	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr	Ra	Ac**	Rf 104	Db 105	Sg 106	Cn 2	113	114	115	116	117	118

114 → Fl flerovium

116 → Lv livermorium

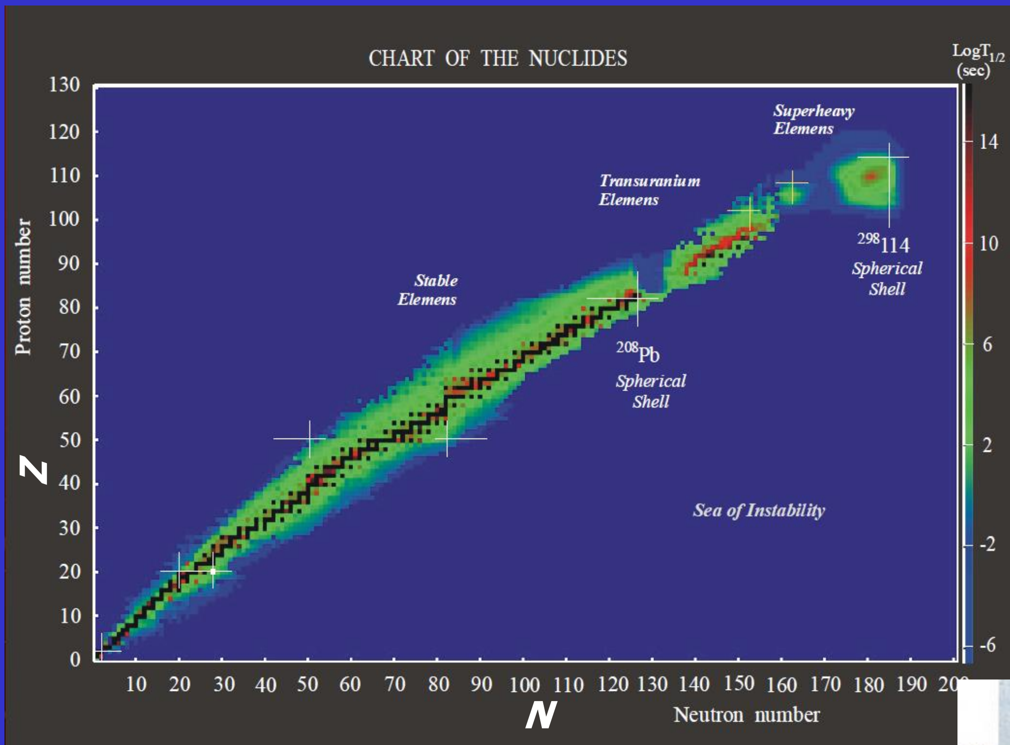
Менделеев(1834-1907)
1869

May 2012 IUPAC

La*	Lanthanides	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Ac**	Actinides	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Super Heavy Elements → less stable

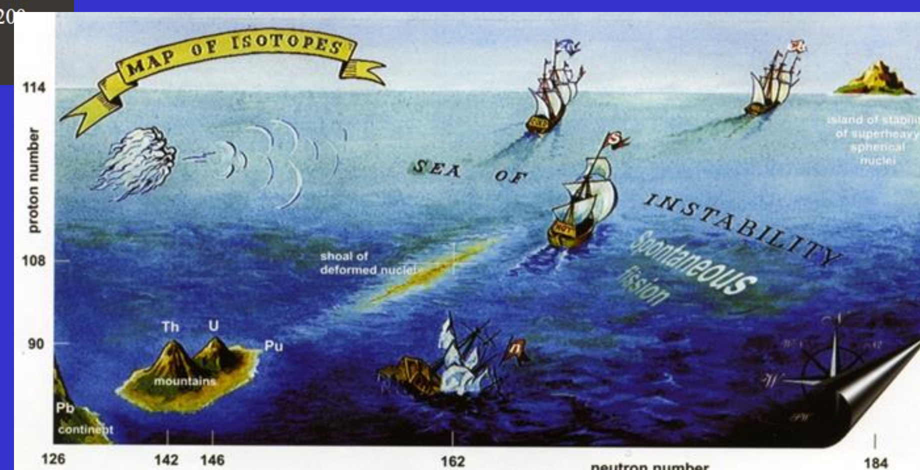
1. Introduction

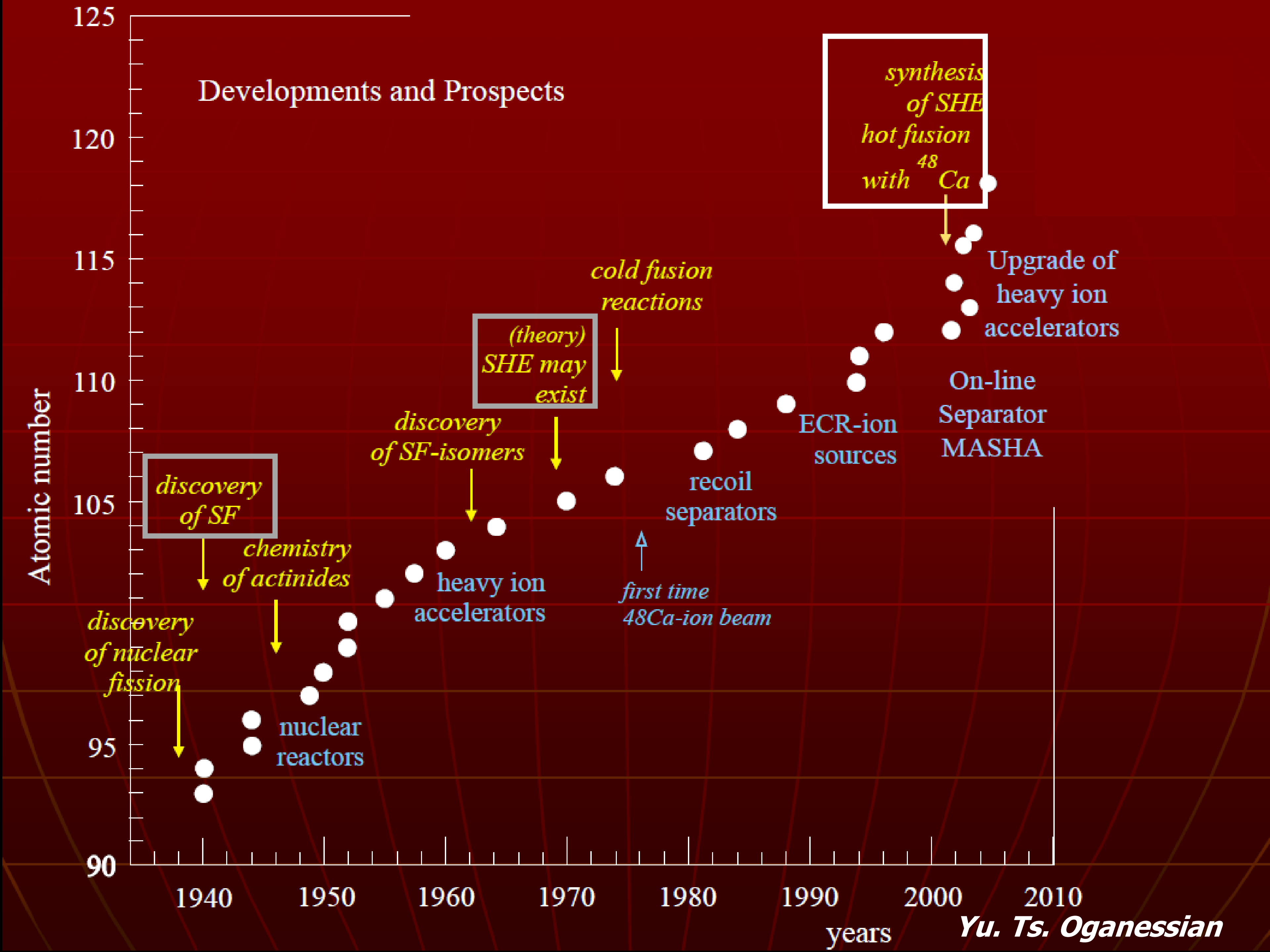


Our Interest

- Next magic number ←Z=82, N=126
- Verification of 'Island of Stability'
  (predicted by macroscopic-microscopic model in 1960's)
- Synthesis of new elements

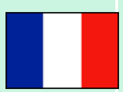
Nuclear Chart
Stability of nuclei





Developments and Prospects
Atomic number
125
120
115
110
105
95
90
1940
1950
1960
1970
1980
1990
2000
2010
years
discovery of nuclear fission
discovery of SF
chemistry of actinides
nuclear reactors
heavy ion accelerators
discovery of SF-isomers
(theory) SHE may exist
cold fusion reactions
first time 48Ca-ion beam
recoil separators
ECR-ion sources
synthesis of SHE hot fusion with 48 Ca
Upgrade of heavy ion accelerators
On-line Separator MASHA
Yu. Ts. Oganessian

Experimental setup for synthesis of SHE

Lab	Country	City	Accelerator	Separator
FLNR	Russia 	Dubna	U400 U400M	DGFRS VASSILISSA
GSI	Germany 	Darmstadt	UNILAC	SHIP TASCA
RIKEN	Japan 	Wako	RILAC	GALIS
LBNL	USA 	Berkeley	88-inch Cyclotron	BGS
GANIL	France 	Caen	*SPIRAL2's LINAC accelerator*	*S3 (Super Separator Spectrometer)*

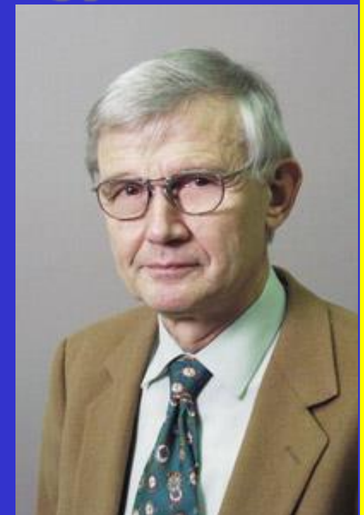
FLNR (Russia)

G.N. Flerov
(1913 -1990)

Yu.Ts. Oganessian
(1933-)

GSI (Germany)

P. Armbruster
(1931-)



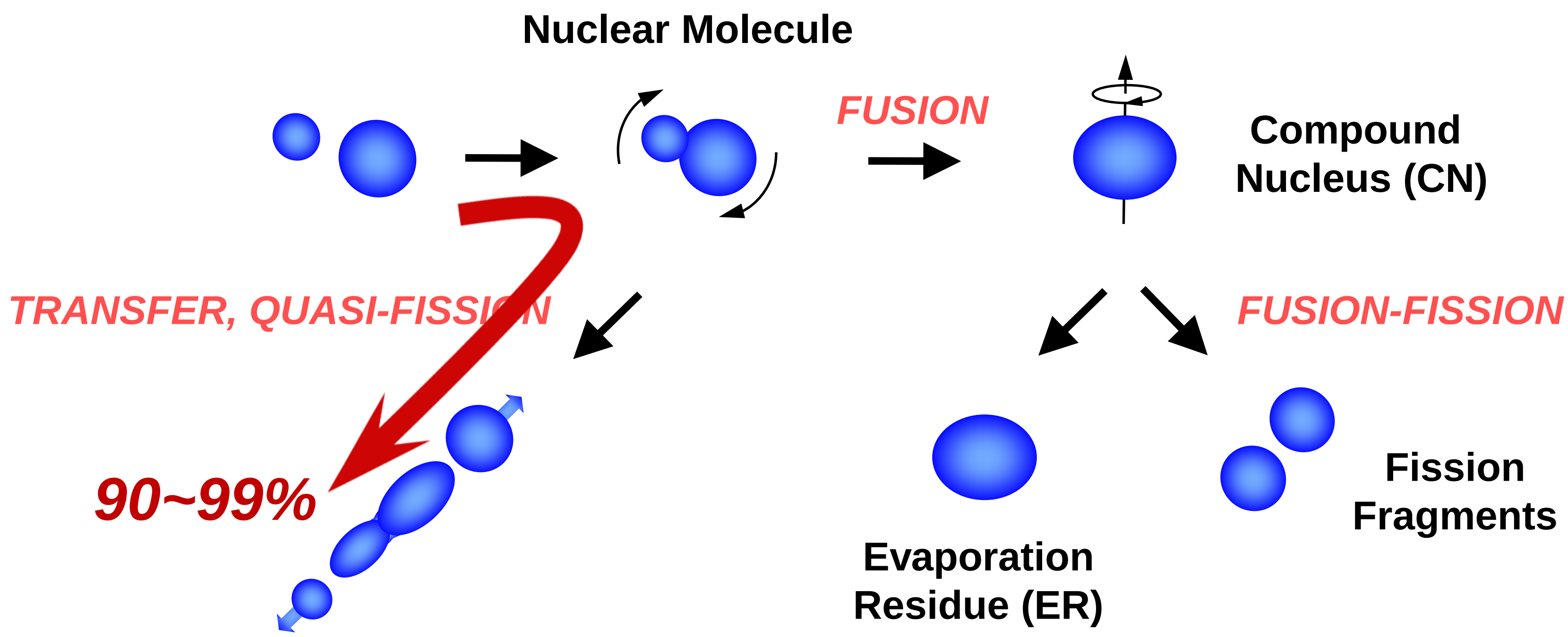
G. Muenzenberg
(1940-)

S. Hofmann
(1943-)

RIKEN (Japan)

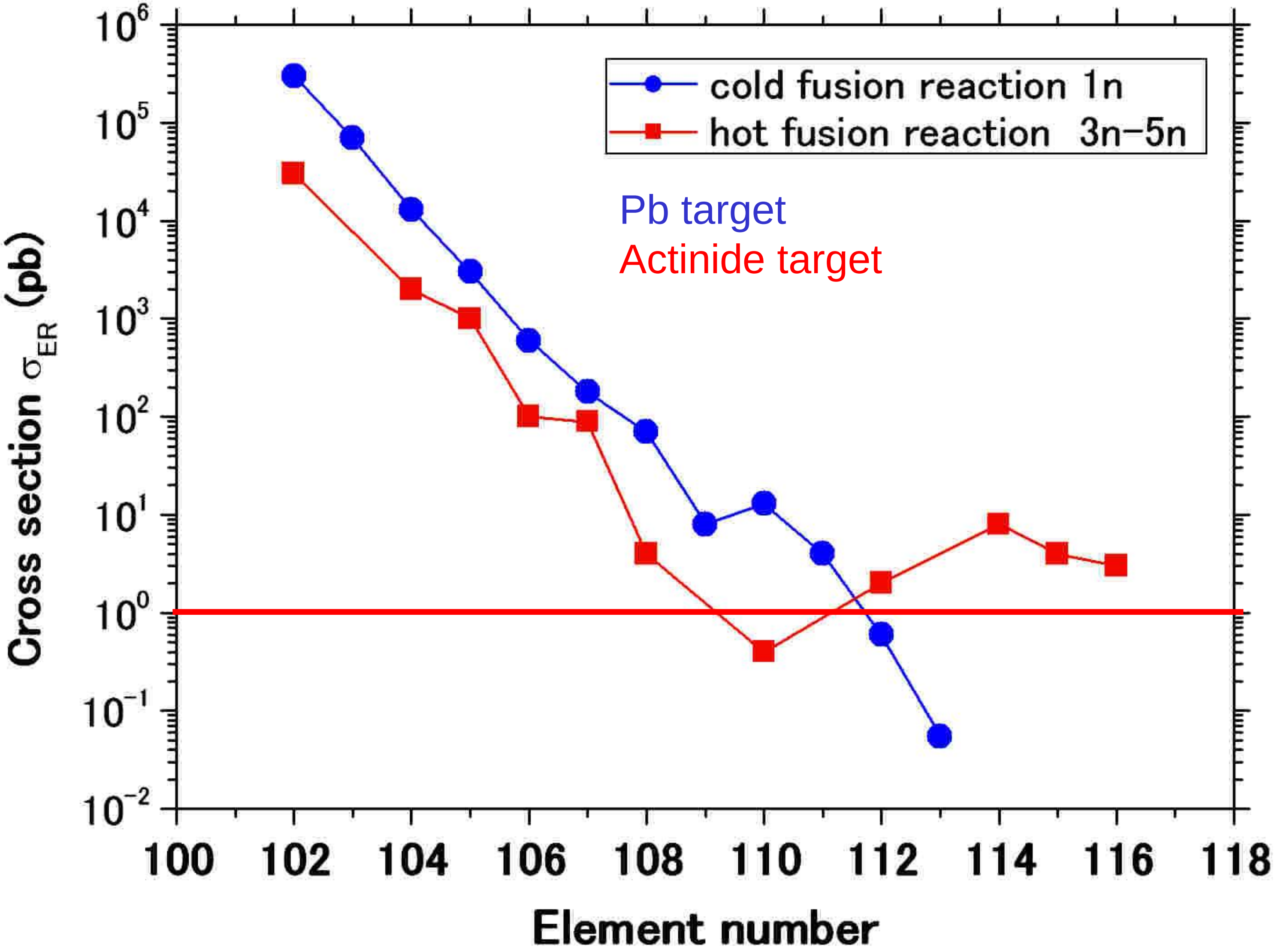
K. Morita
(1957-)

Fusion process in Superheavy mass region

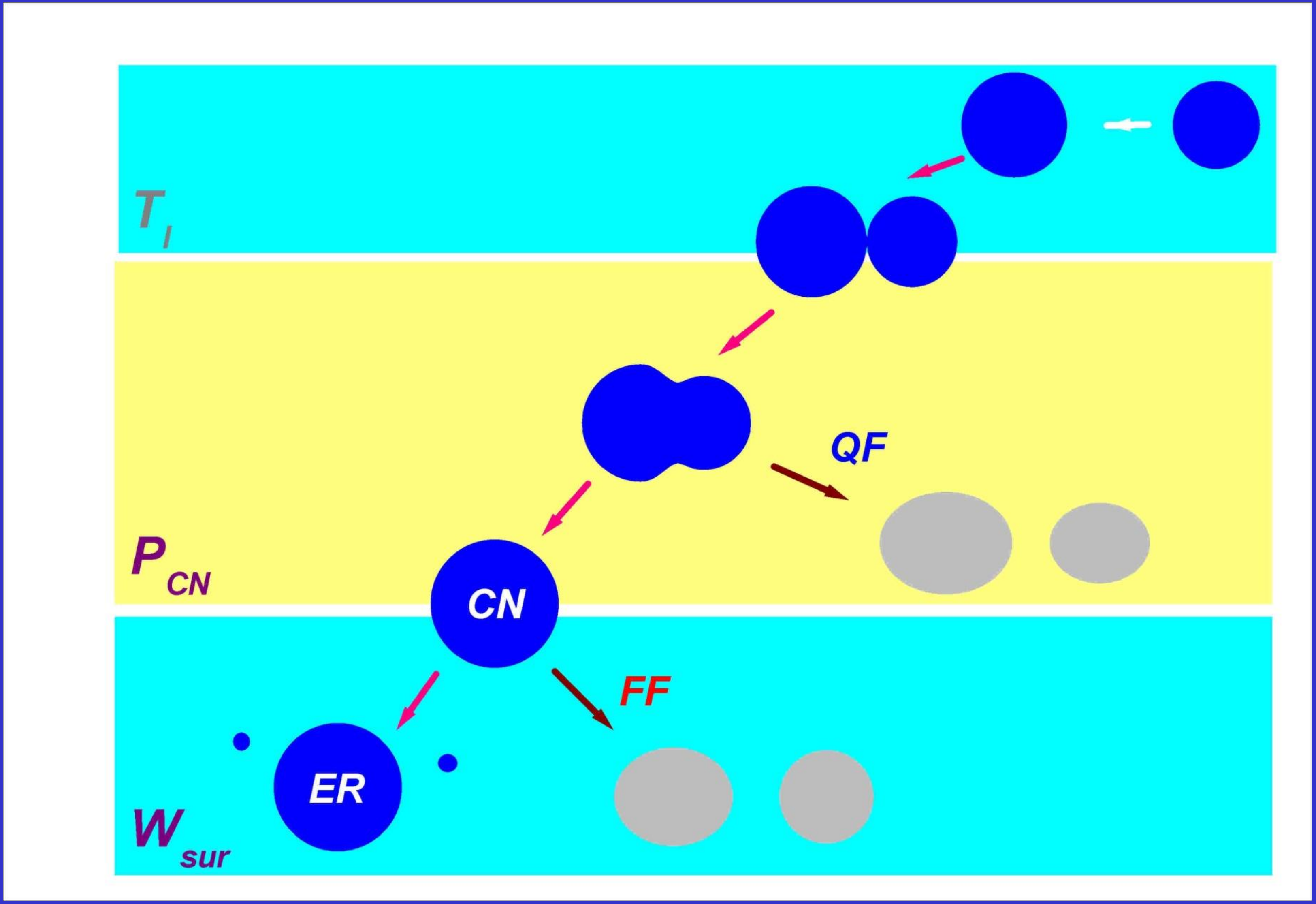


Experimental data

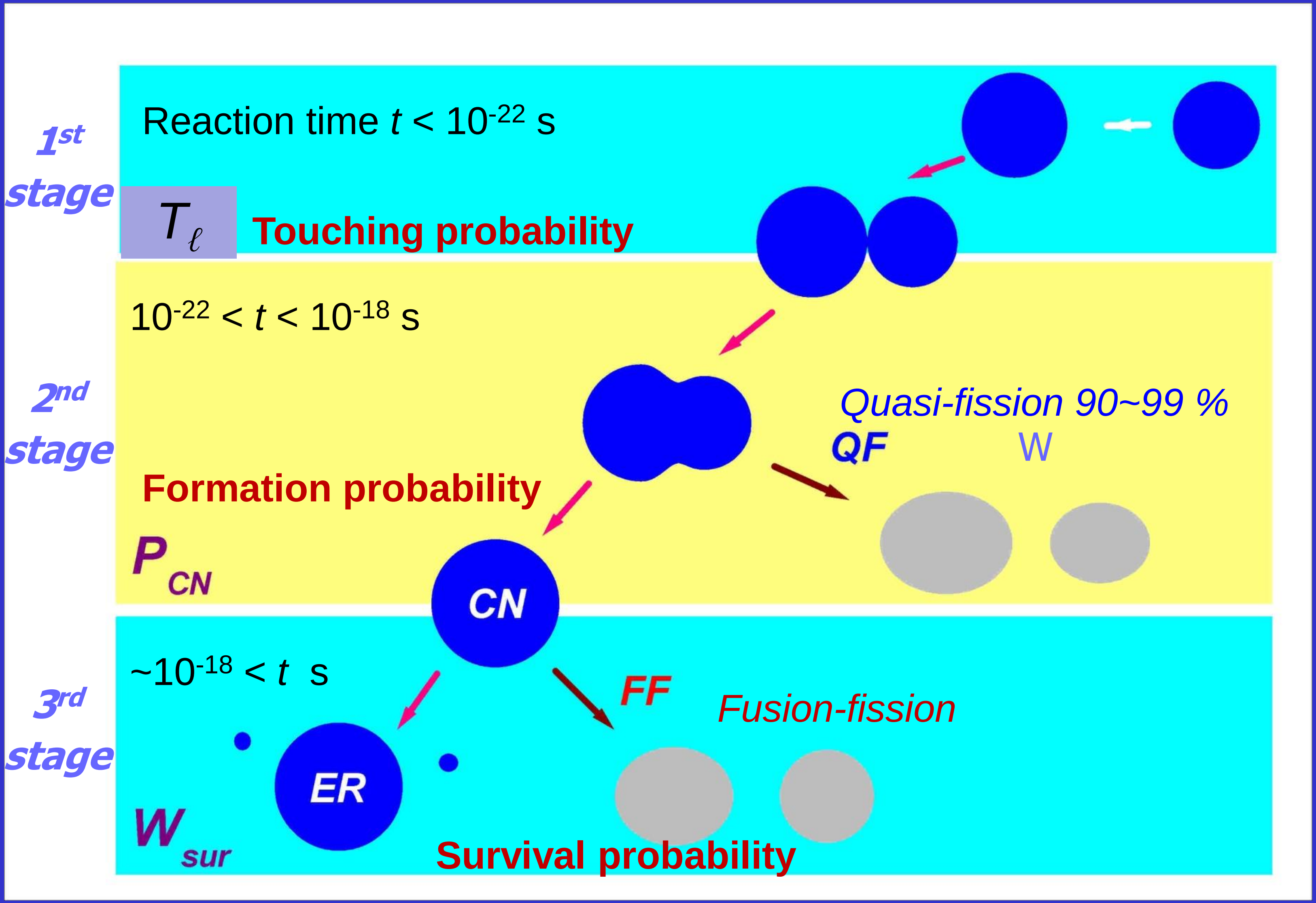
Evaporation residue cross sections



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



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



Synthesis of New Elements

Reports of new elements

Heavy ion reaction

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 $^{48}Ca + ^{244}Pu \rightarrow ^{292}114 + 3n$ (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

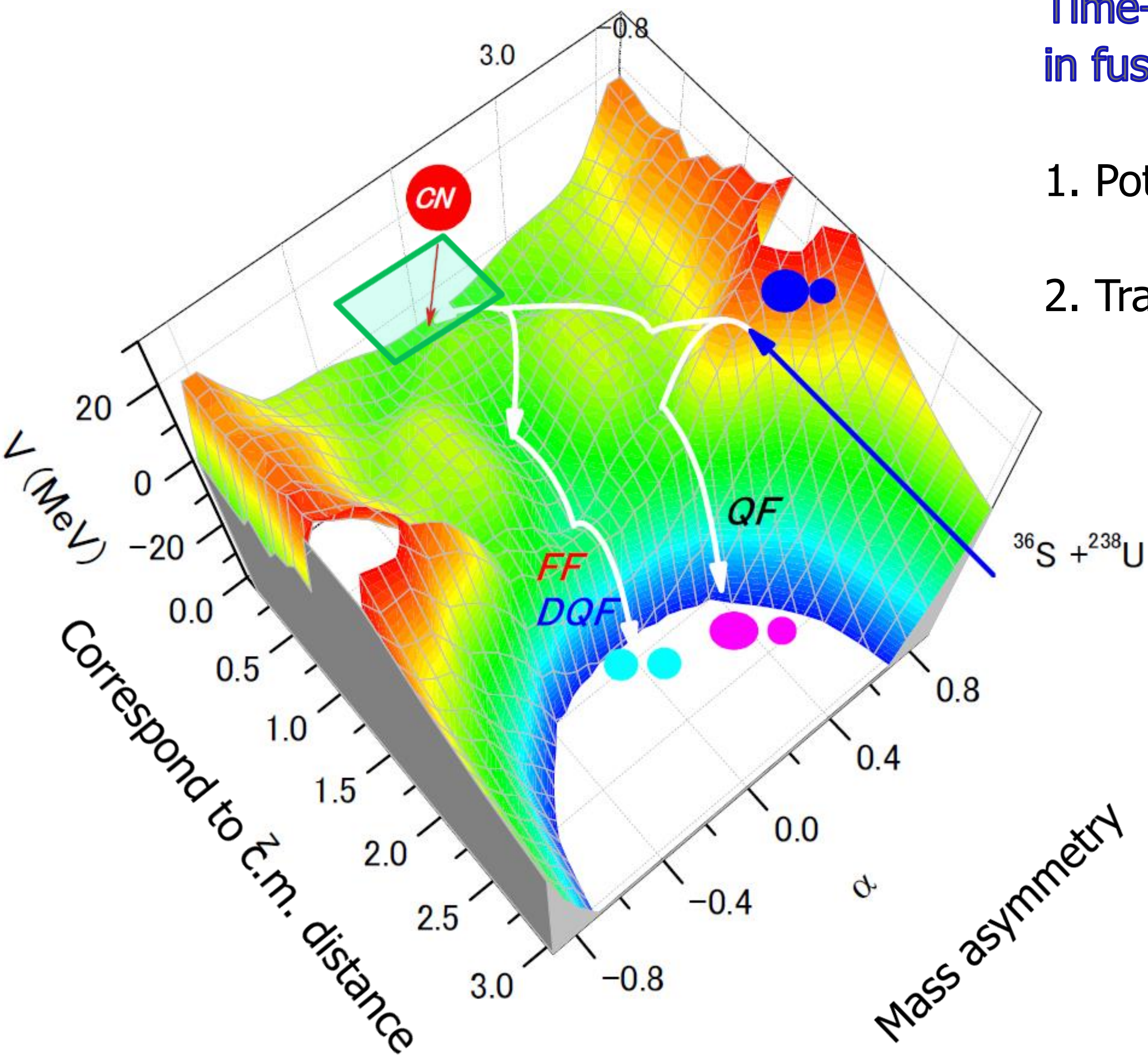
117 $^{48}Ca + ^{249}Bk \rightarrow ^{294,293}117 + 3\text{-}4n$ (FLNR)

2. Model

2-1. Estimation of cross sections

2-2. Dynamical Equation

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



Time-evolution of nuclear shape in fusion-fission process

1. Potential energy surface

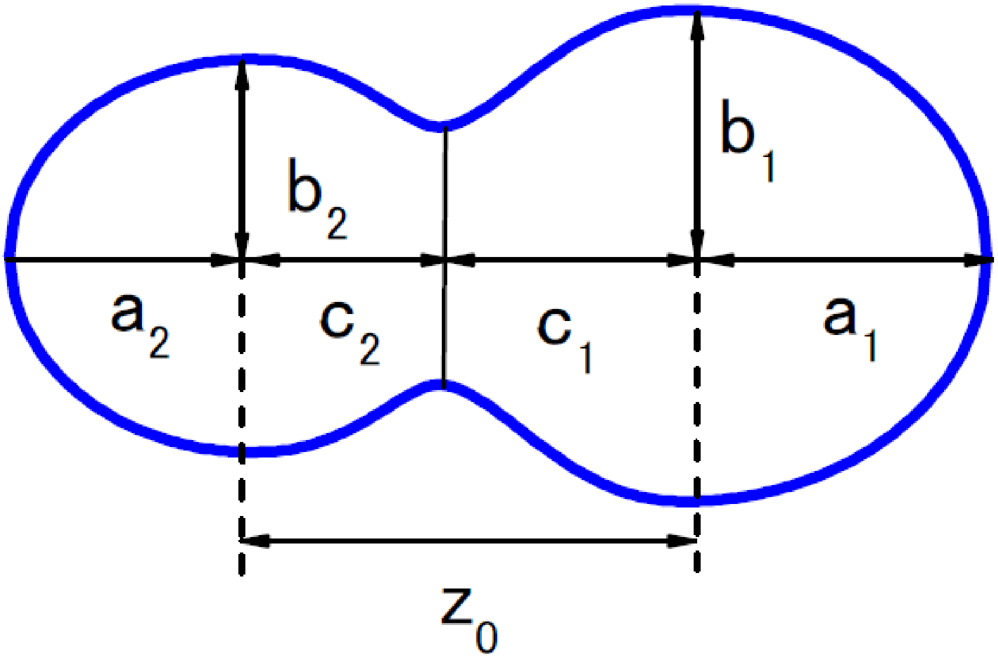
2. Trajectory → described by equations

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

$$\delta = \frac{3(a-b)}{2a+b}$$ (δ1=δ2)

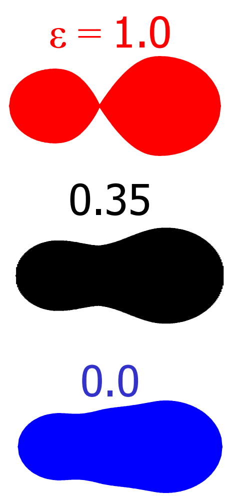
$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$

Two Center Shell Model

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

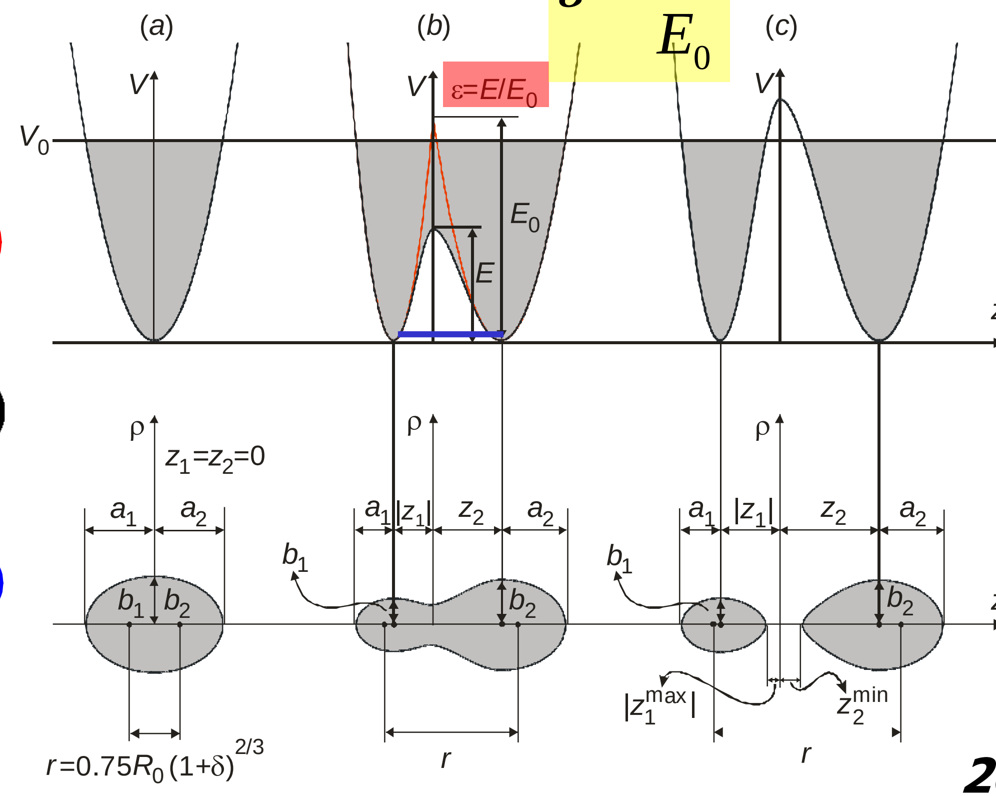
$$V(\rho,z) = \frac{1}{2}m_0 \begin{cases} \omega_{z1}^2 z'^2 + \omega_{\rho 1}^2 \rho^2, \quad z < z_1 \\ \omega_{z1}^2 z'^2 \left(1 + c_1 z' + d_1 z'^2\right) + \omega_{\rho 1}^2 \left(1 + g_1 z'^2\right)\rho^2, \\ \quad z_1 < z < 0 \\ \omega_{z2}^2 z'^2 \left(1 + c_2 z' + d_2 z'^2\right) + \omega_{\rho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

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



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

$$\varepsilon = \frac{E}{E_0}$$



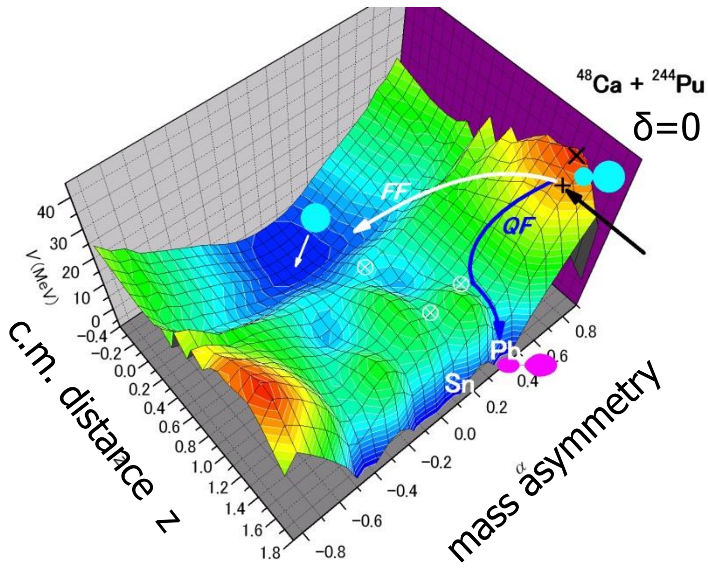
J. Maruhn and W. Greiner, Z. Phys, 1972

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

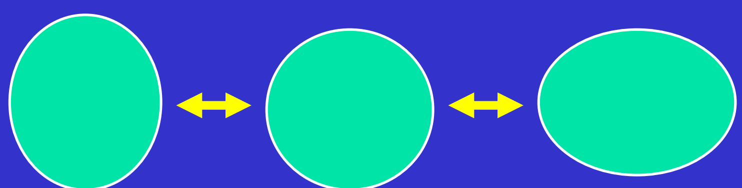
$$\Phi(T) = \exp\left\{-\frac{aT^2}{E_d}\right\}$$

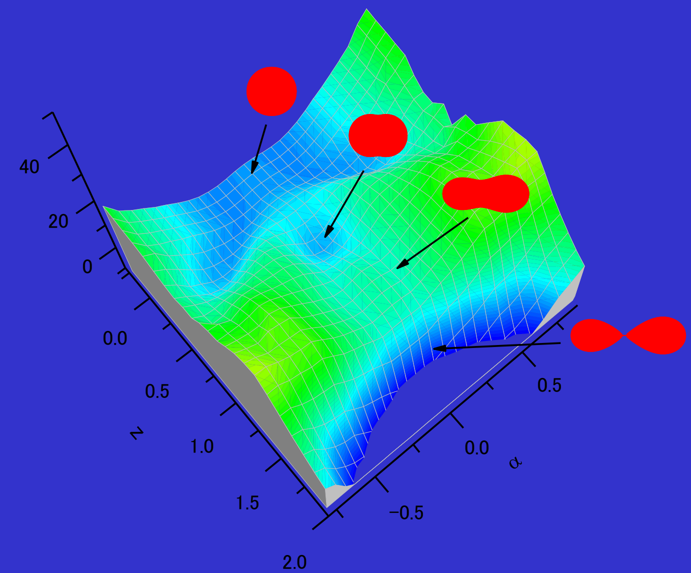
$$E_d = 20\,\mathrm{MeV}$$

Taking into account the <u>fluctuation around the mean trajectory</u>

<u>Thermal fluctuation</u> of nuclear shape

→ thermal fluctuation of collective motion





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

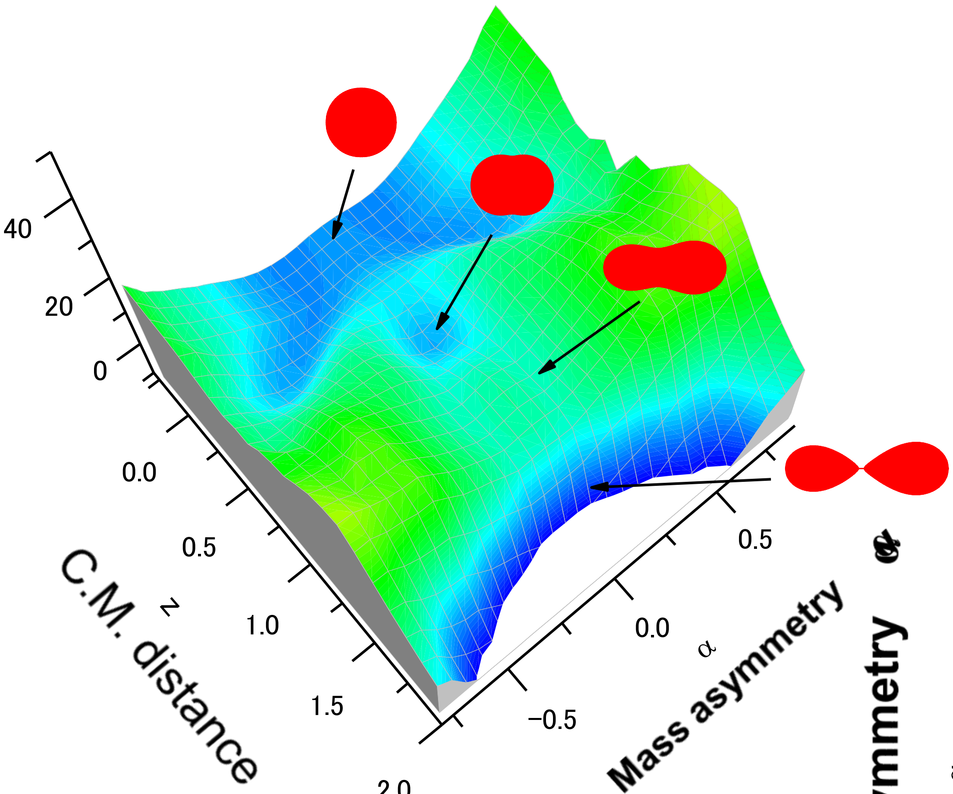
m_{ij} : Hydrodynamical mass (inertia mass)

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

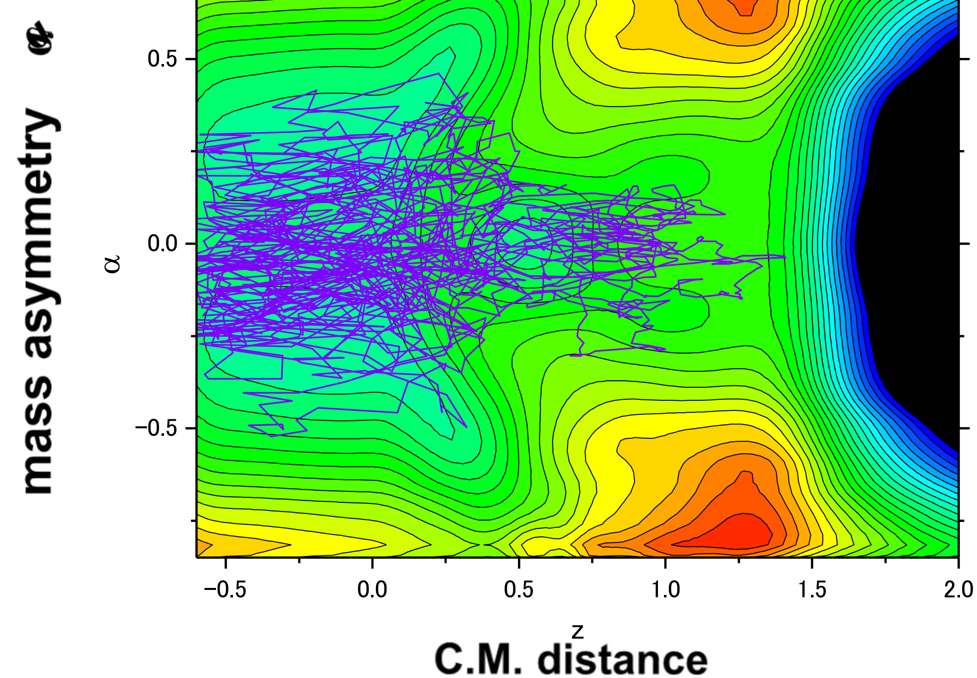
$$E_{\rm int} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q)$$

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

Fission process ^{240}U $E^* < 20$ MeV



Trajectory on potential energy surface

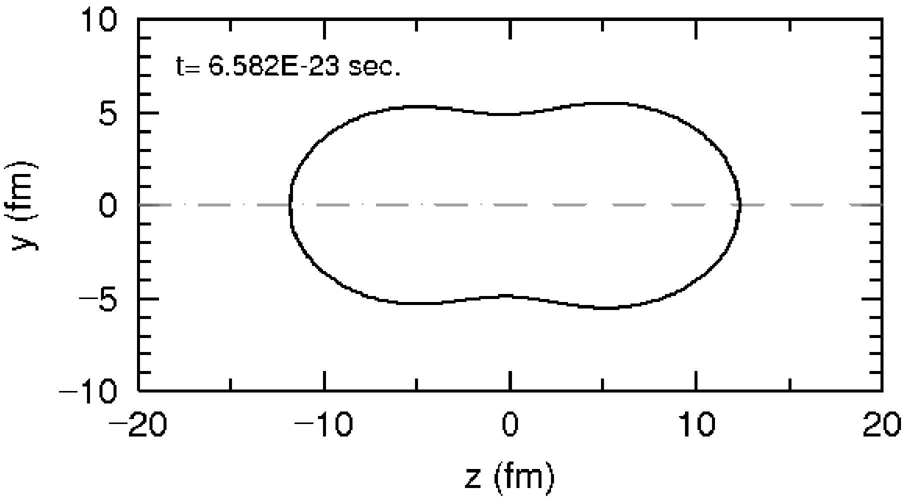


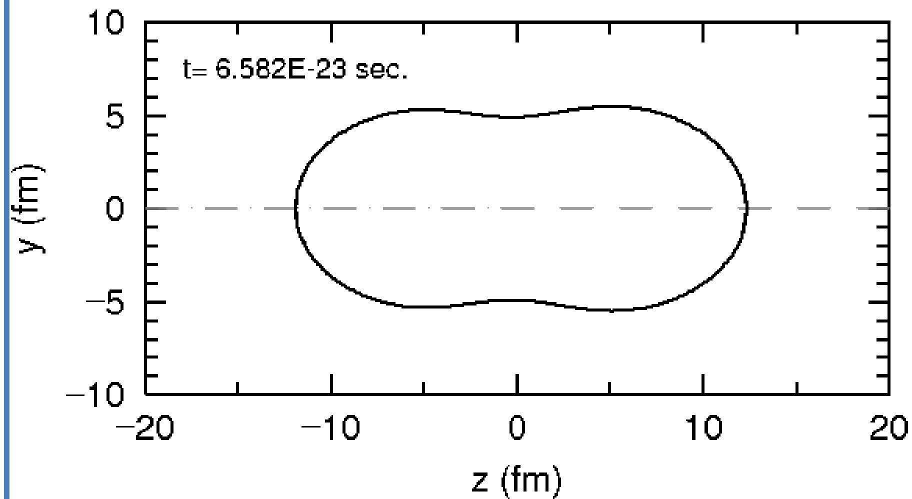
236U E*=20 MeV

揺動項なし Newton Eq

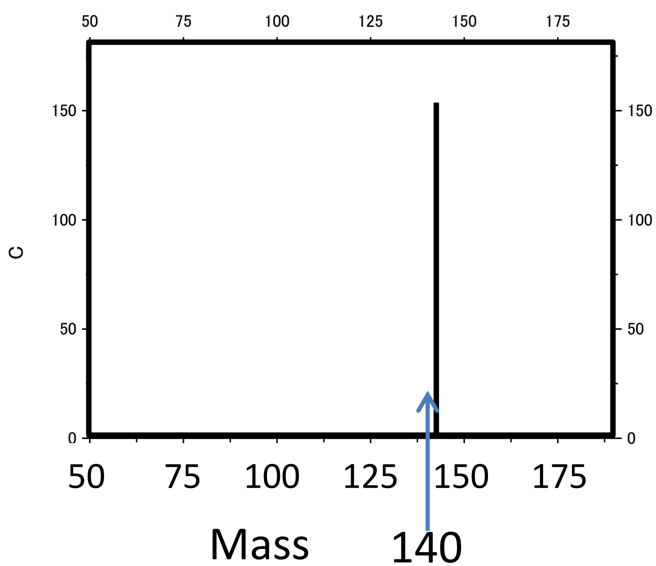
分裂過程

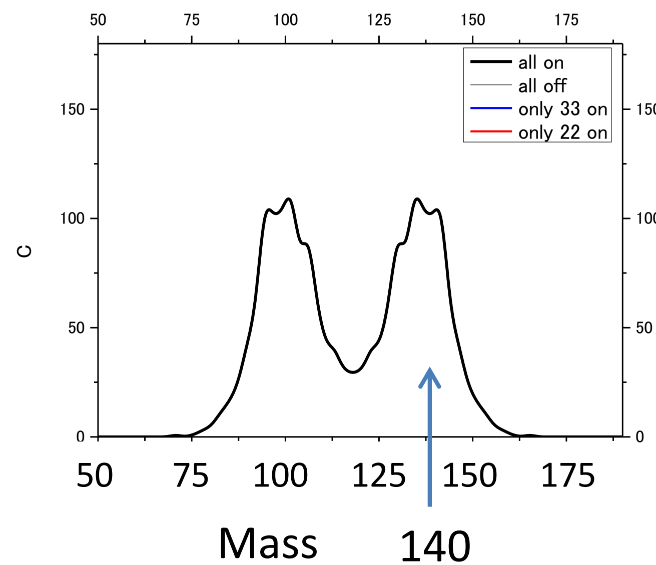
揺動項あり Langevin Eq.



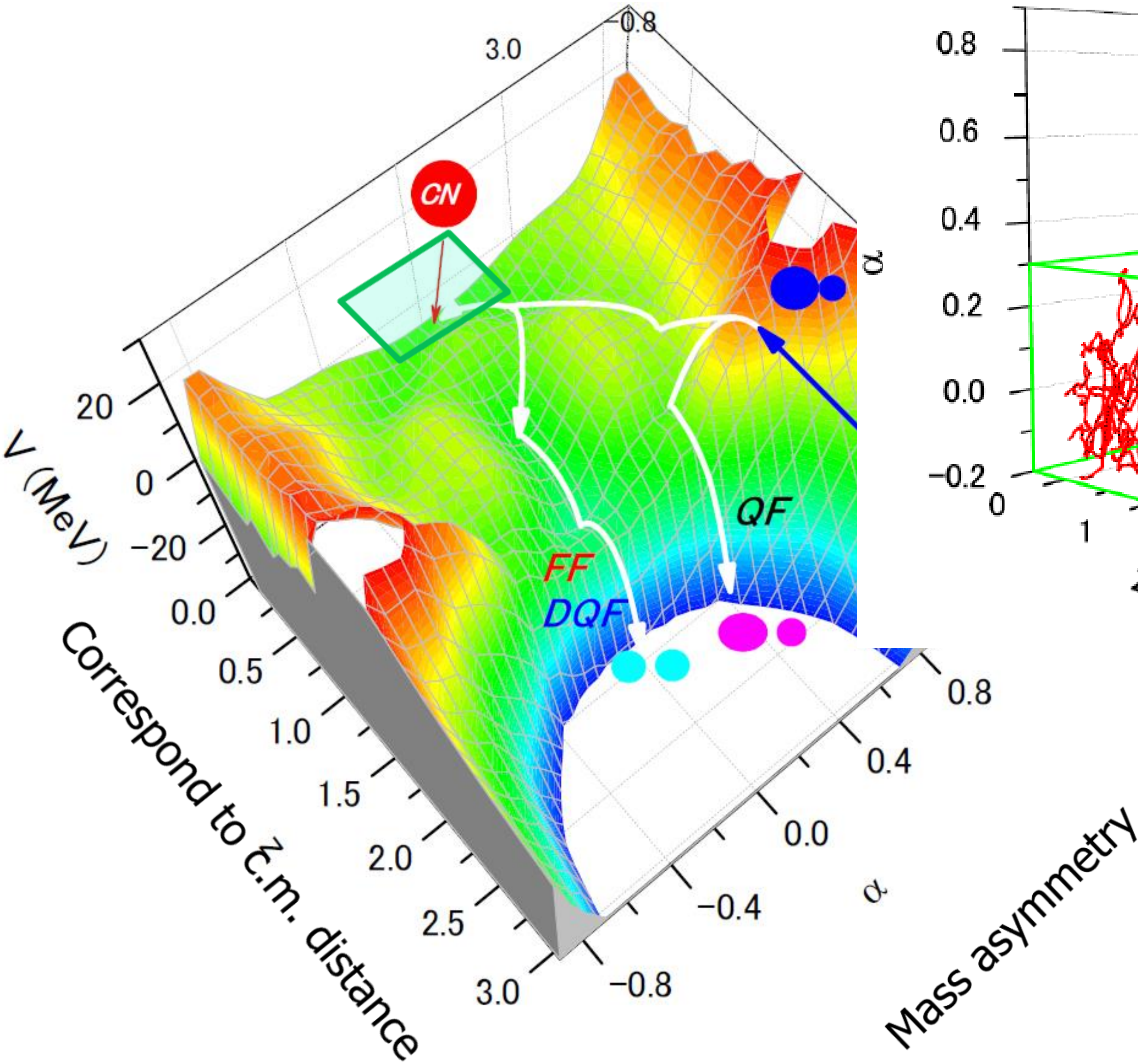


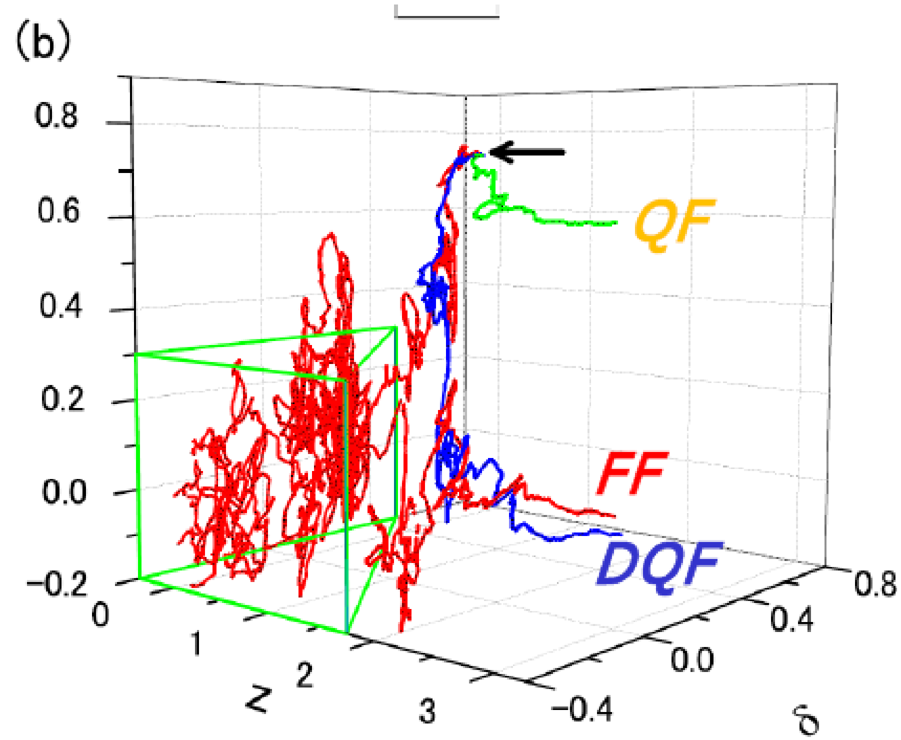
質量分布



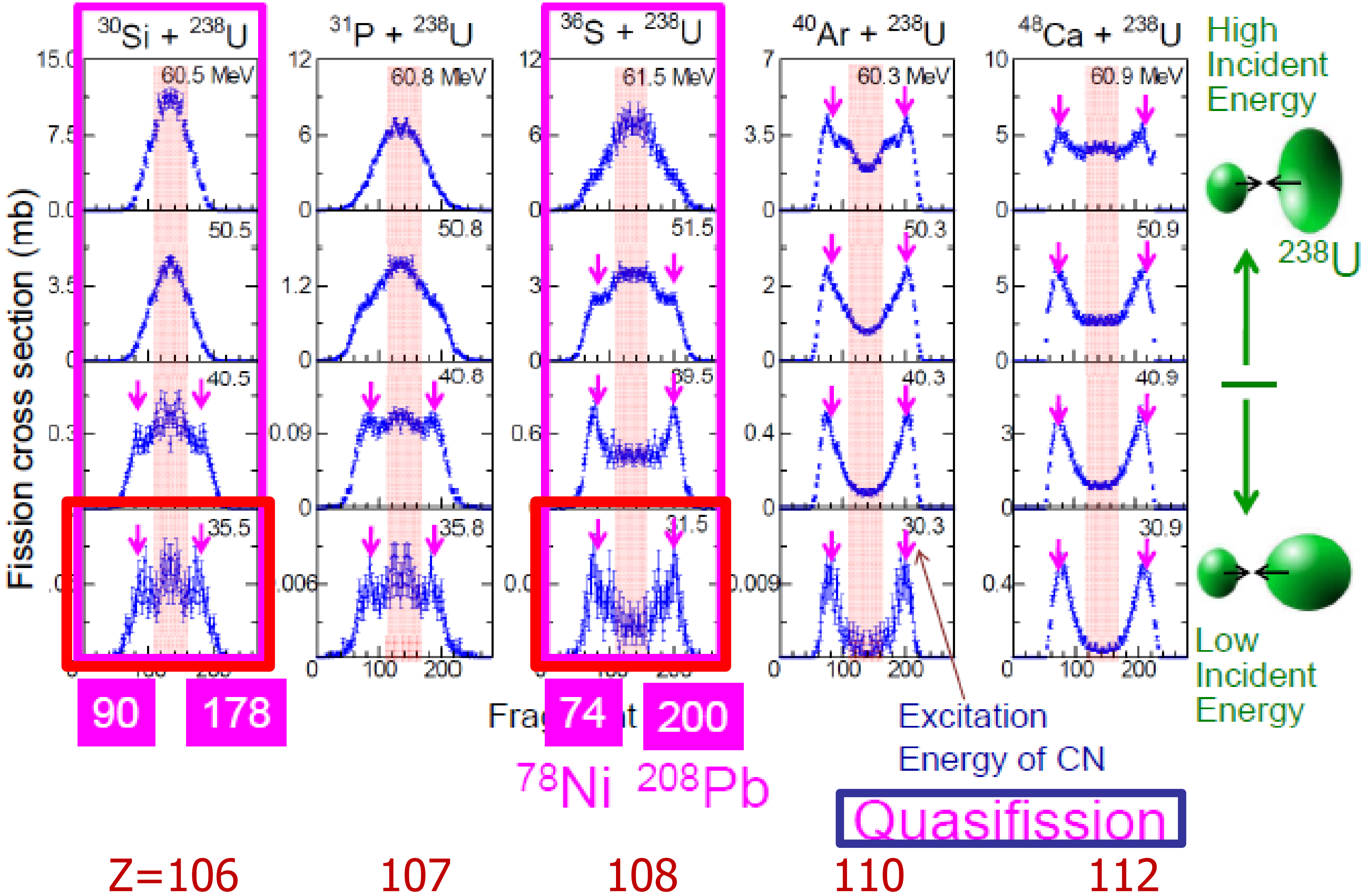


Overview of Dynamical Process in reaction $^{36}S+^{238}U$



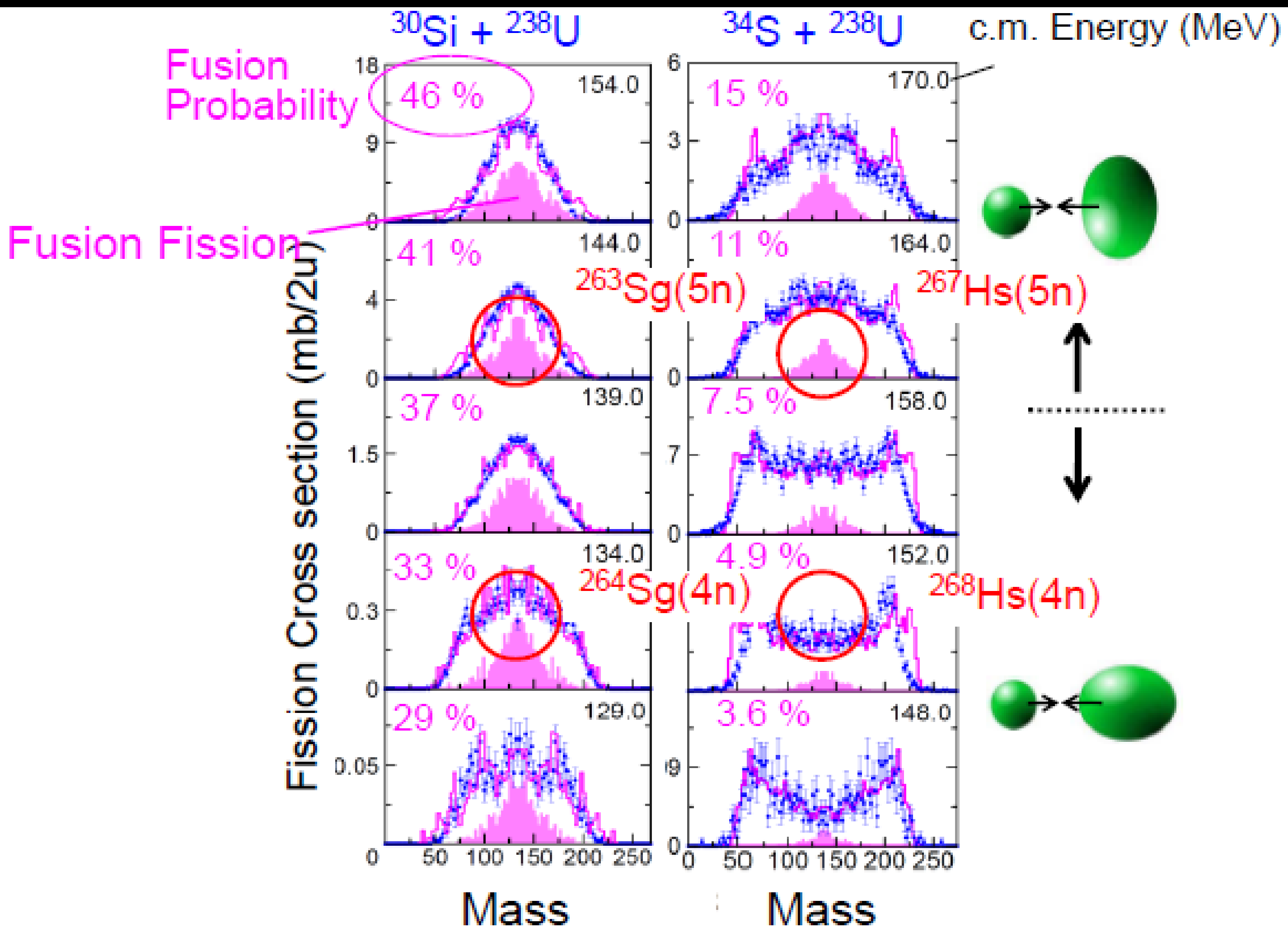


Projectile dependence of fragment mass distributions



Experiments by K. Nishio et al. (JAEA)

Calculated spectra for fusion-fission and quasi-fission

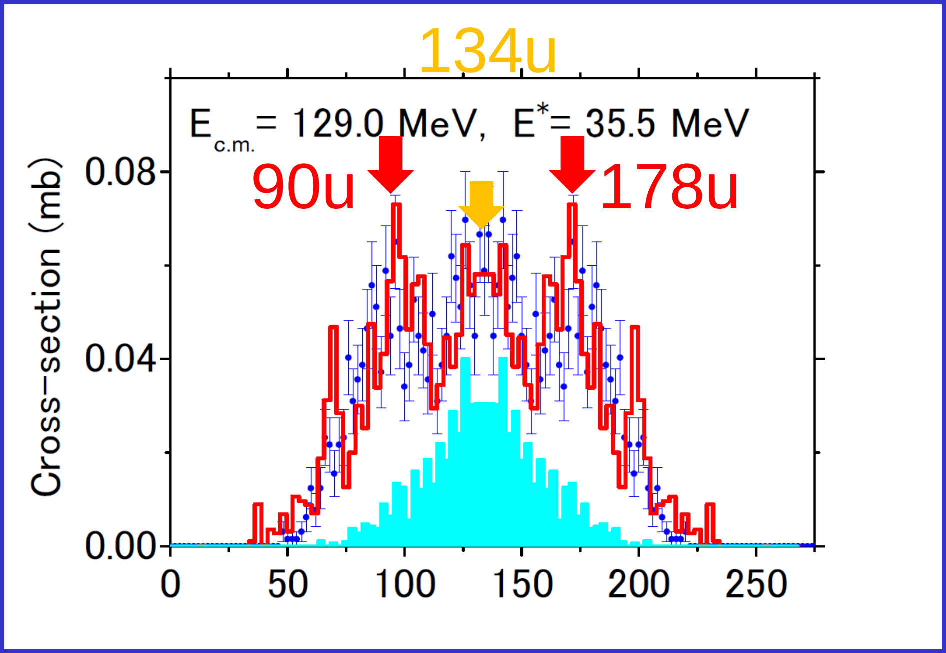


Experiments by K. Nishio et al. (JAEA)

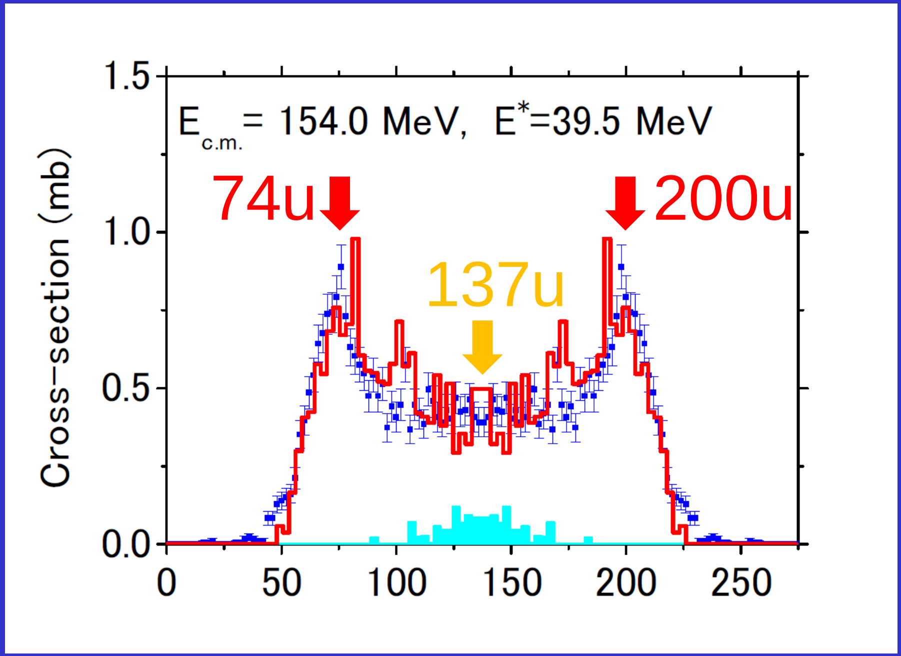
4. Mechanism of Dynamical process

MDFF at Low incident energy

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



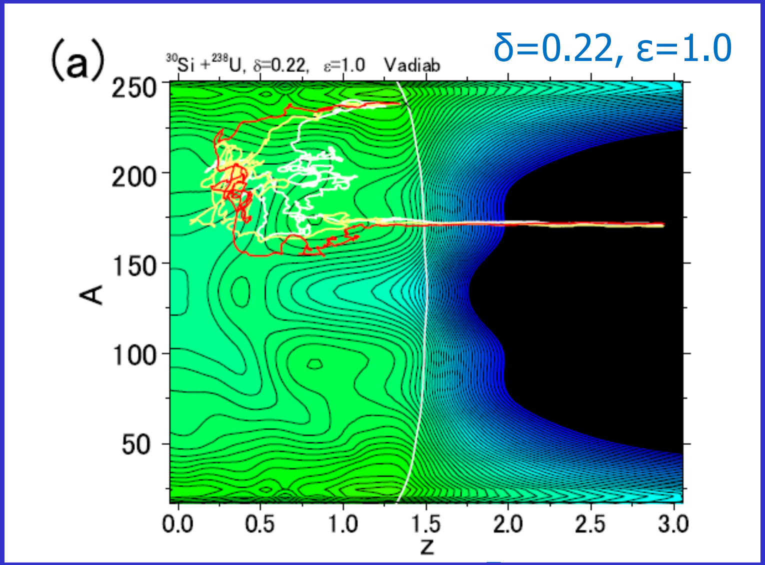
$^{36}S+^{238}U$



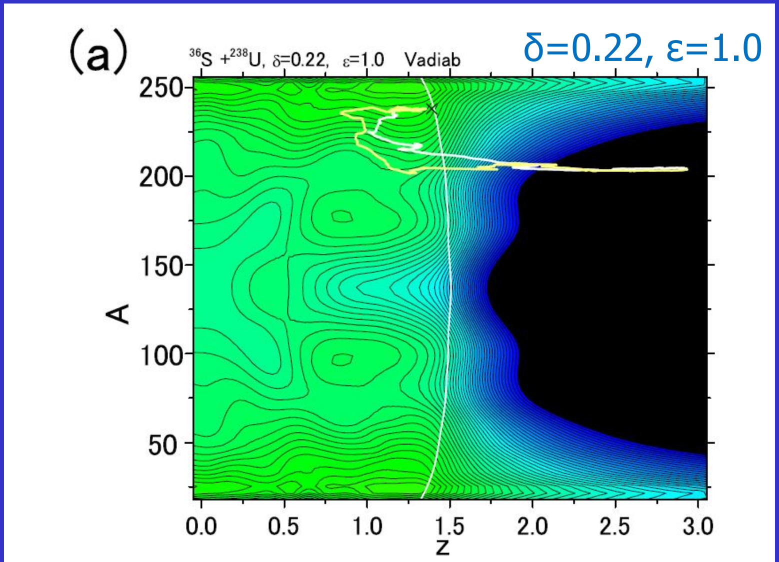
Clarify the origin of the difference

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

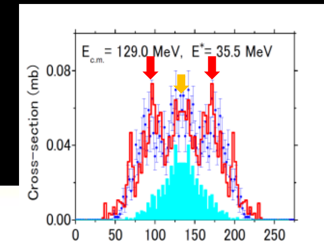
$^{30}Si+^{238}U$ $E^* = 35.5$ MeV
L=0, θ=0



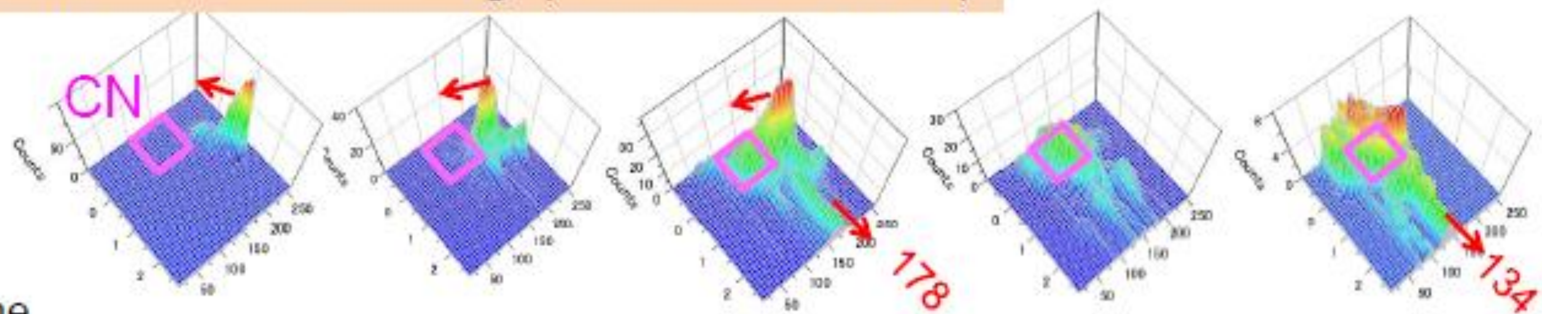
$^{36}S+^{238}U$ $E^* = 39.5$ MeV
L=0, θ=0



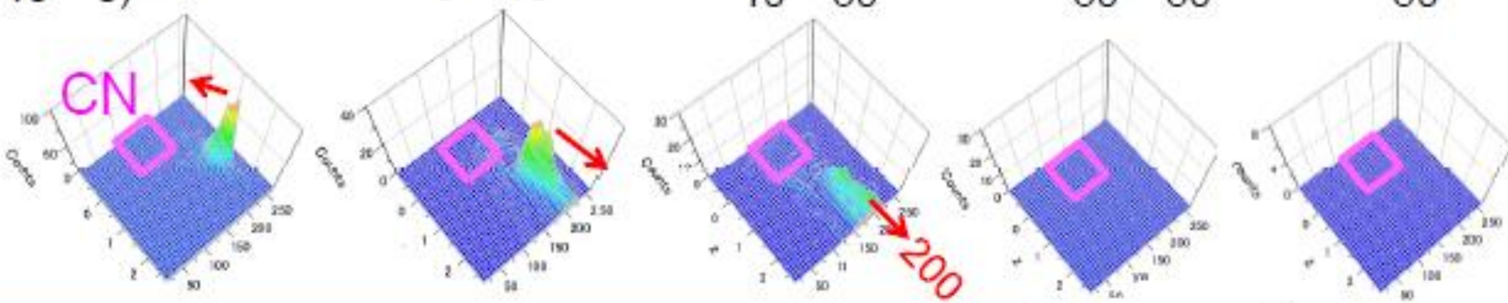
Time evolution of probability distribution



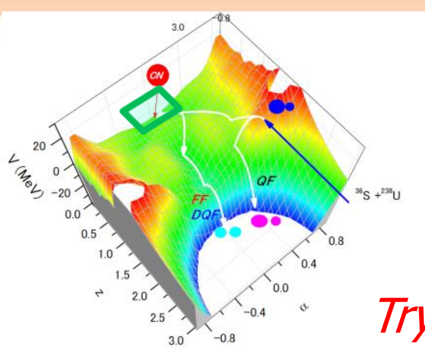
$^{30}Si + ^{238}U \rightarrow ^{268}Sg$ (E*=35.5 MeV)

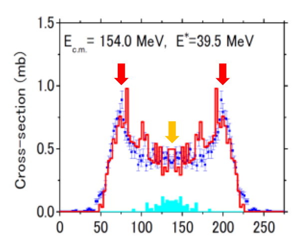


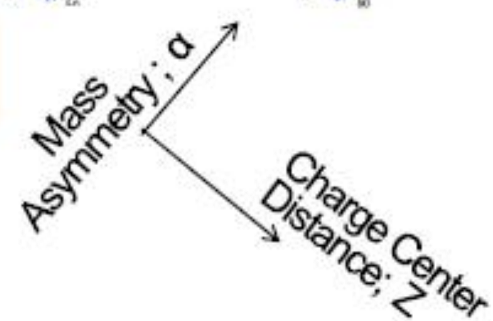
Time ($\times 10^{-21}$ s) 0 - 5 5 – 10 10 – 30 30 – 50 50 -



$^{36}S + ^{238}U \rightarrow ^{274}Hs$ (E*=40.5 MeV)



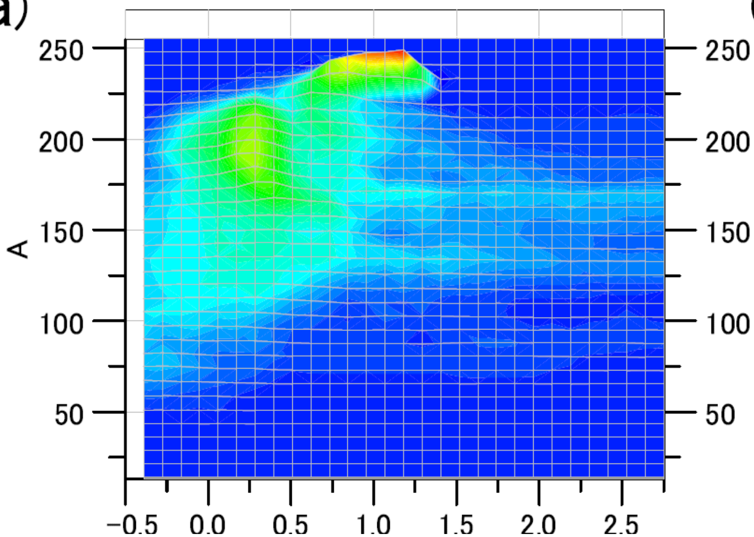




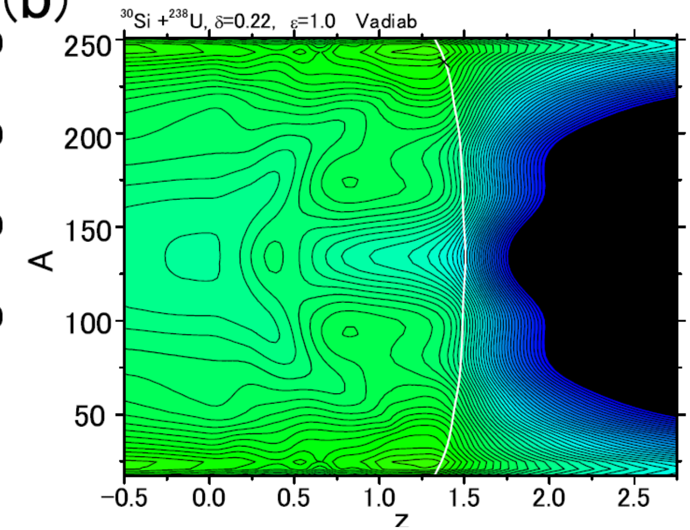
Try to clarify the origin of difference between the both cases →

Probability distribution on the z-A plane

(a)

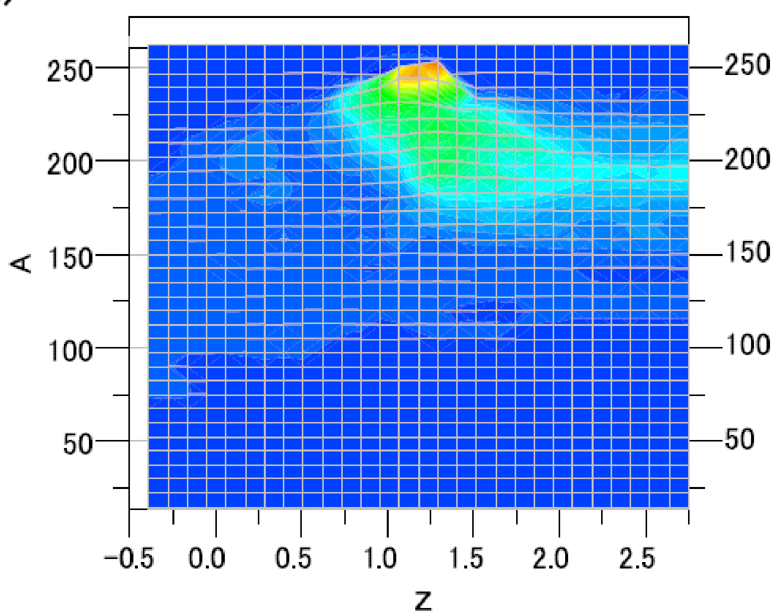


(b)

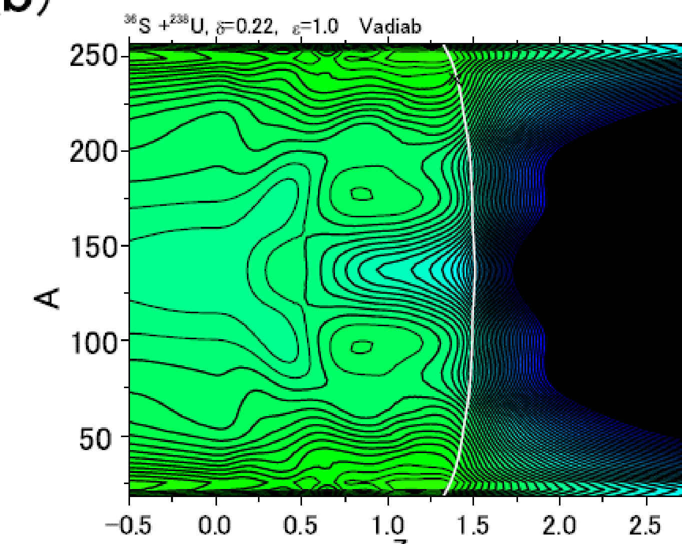


$^{30}Si+^{238}U$

(a)

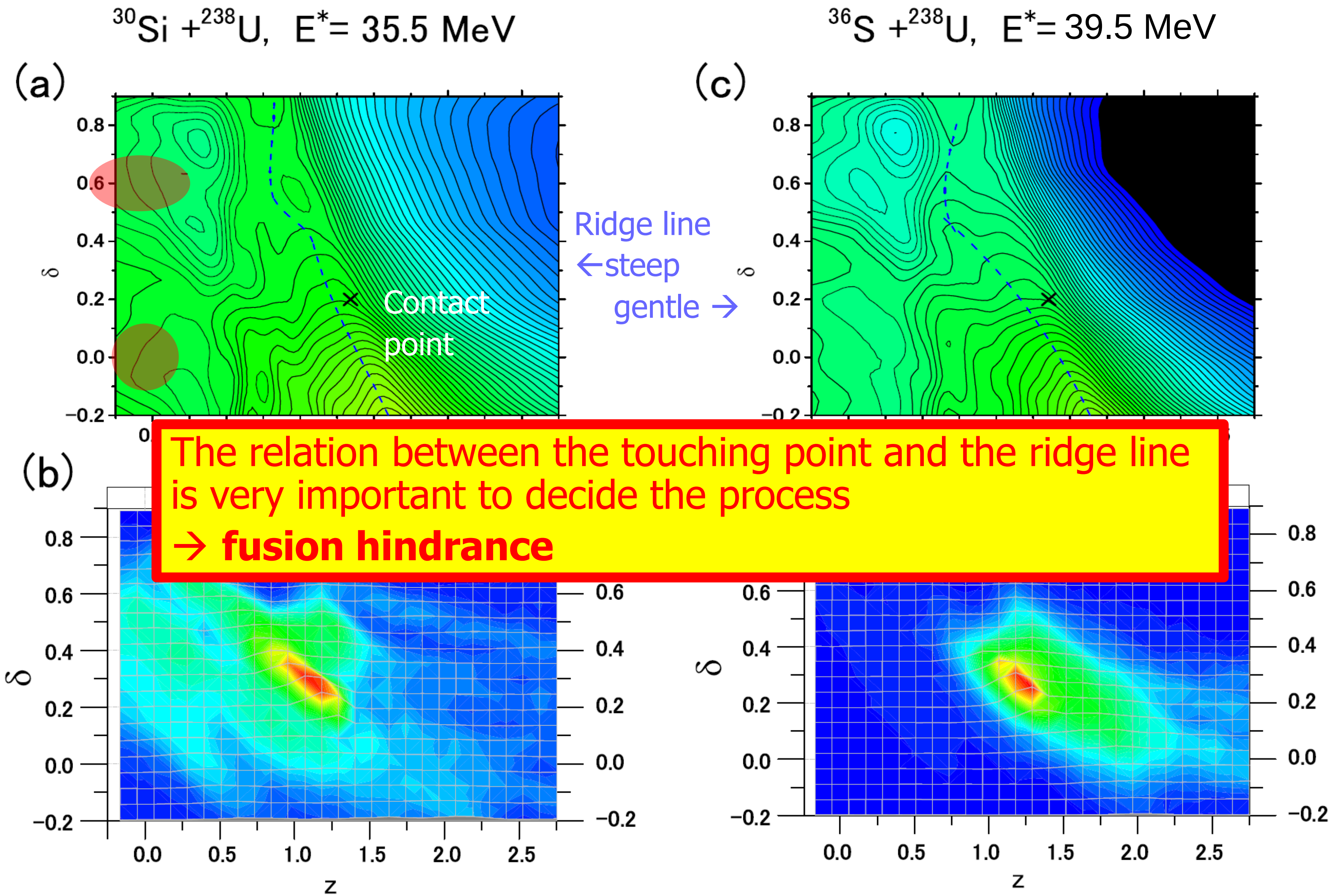


(b)



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

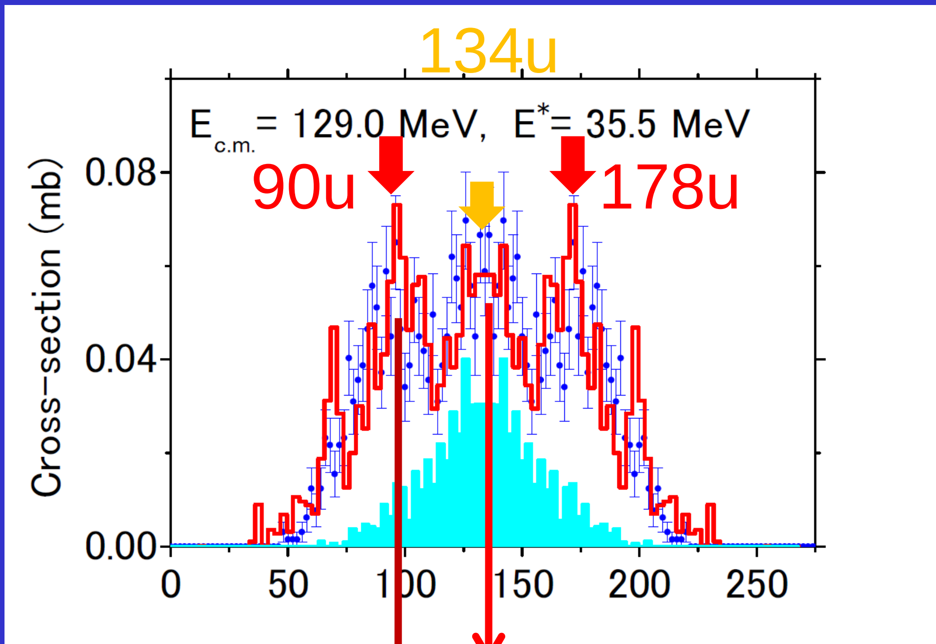
Probability distribution of total time on the z-δ plane



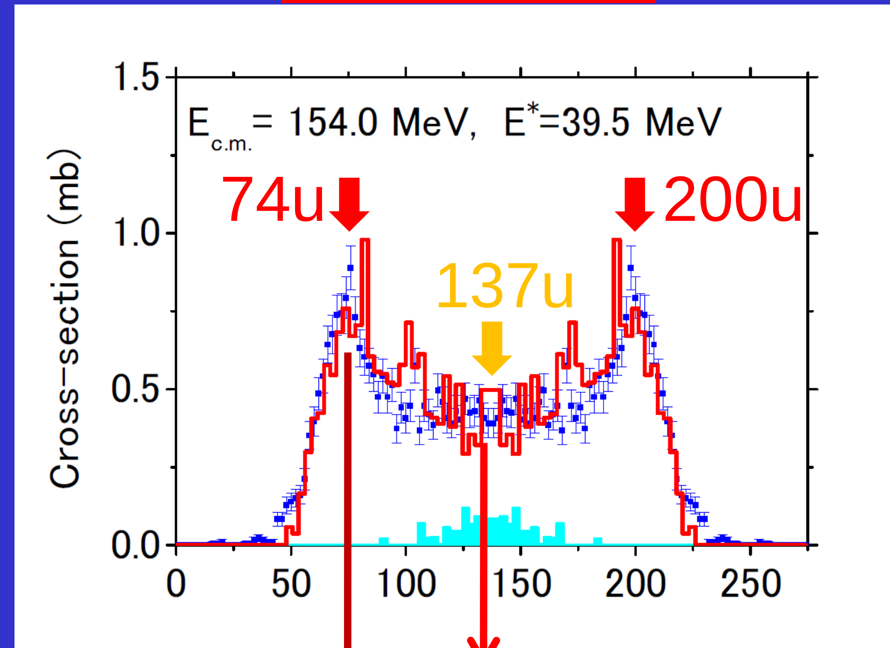
The relation between the touching point and the ridge line is very important to decide the process

→ **fusion hindrance**

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



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



FF and DQF
t > 50 x 10^{-21} sec
-0.2 < δ < 0.2 (peak 0)

QF via mono-nucleus
t < 30 x 10^{-21} sec
0.2 < δ < 0.5 (peak 0.4)

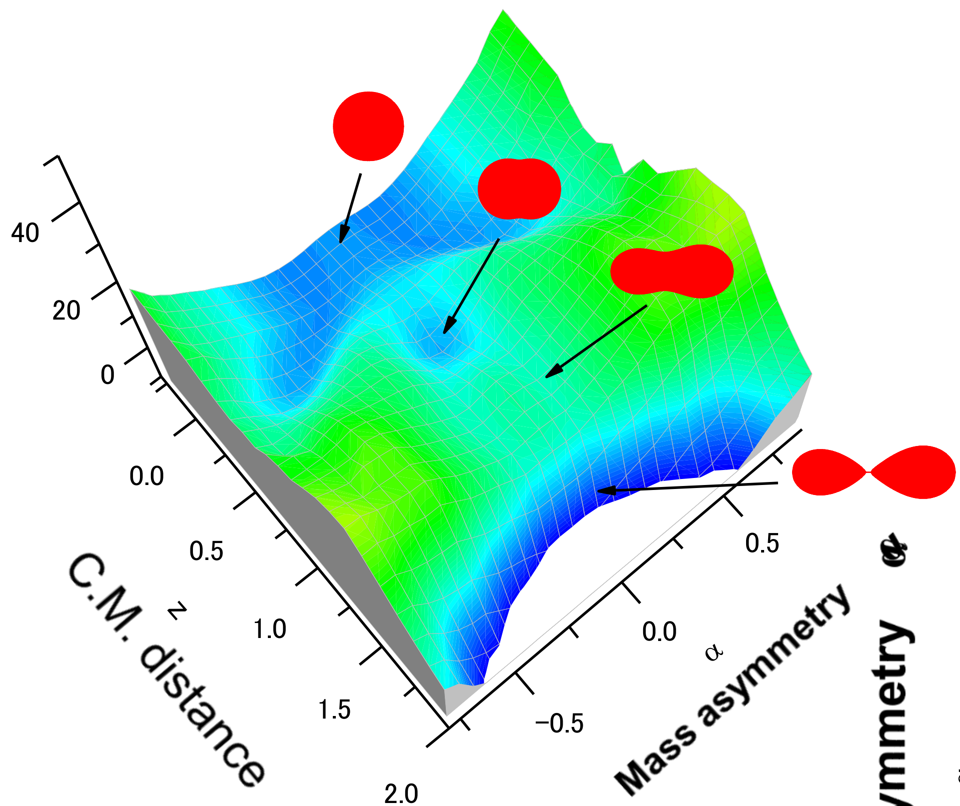
FF and **DQF**
t < 30 x 10^{-21} sec
0 < δ < 0.4 (peak 0.2)

QF
t < 10 x 10^{-21} sec
0 < δ < 0.2 (peak 0)

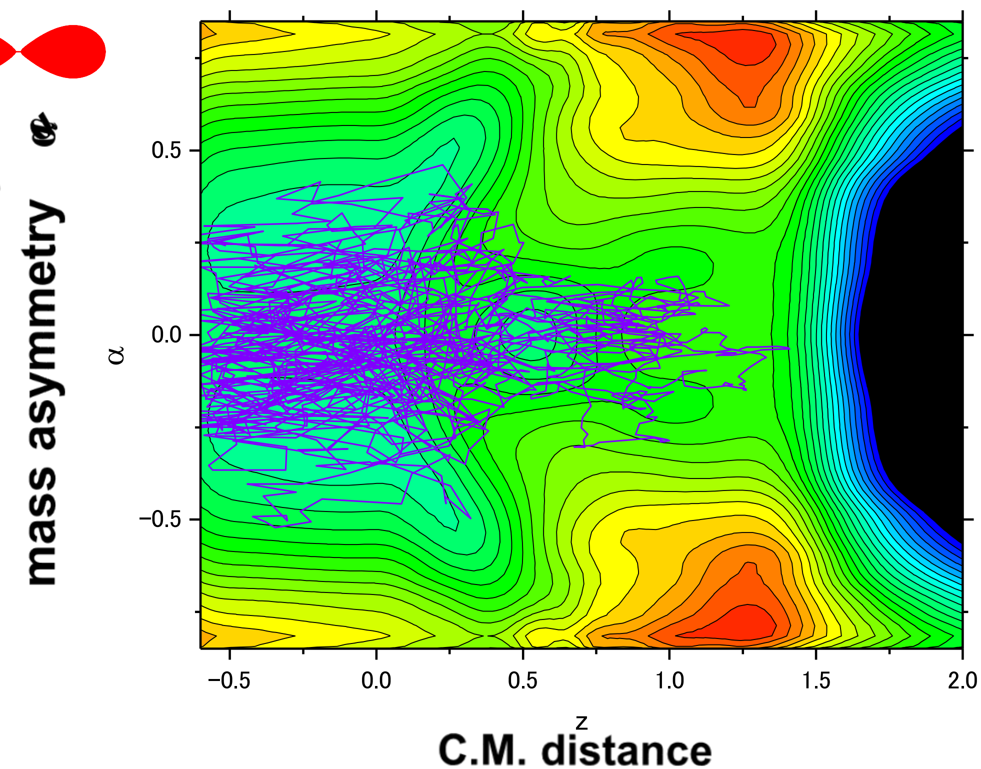
(1) Origin of the reaction process
(2) Building times
(3) Deformation of fragments

Fission Process

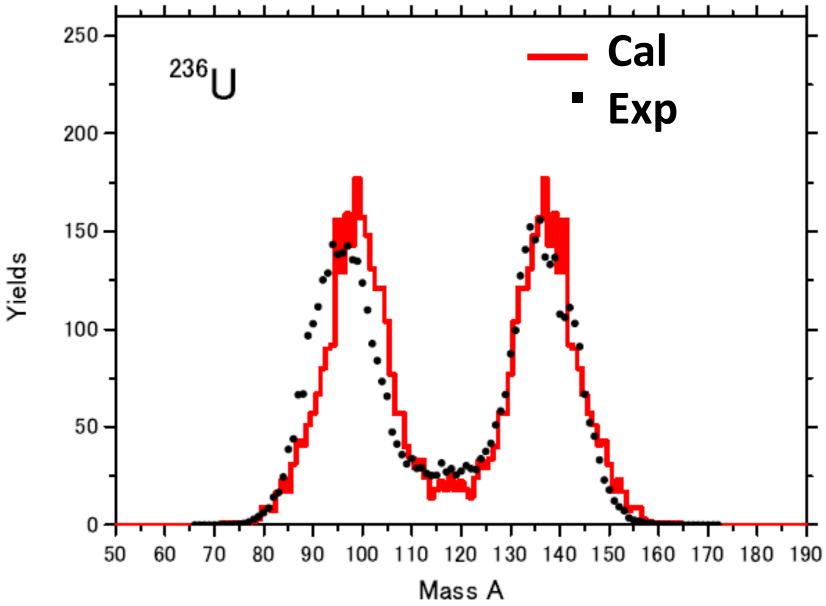
Fission process ^{240}U E* < 20 MeV

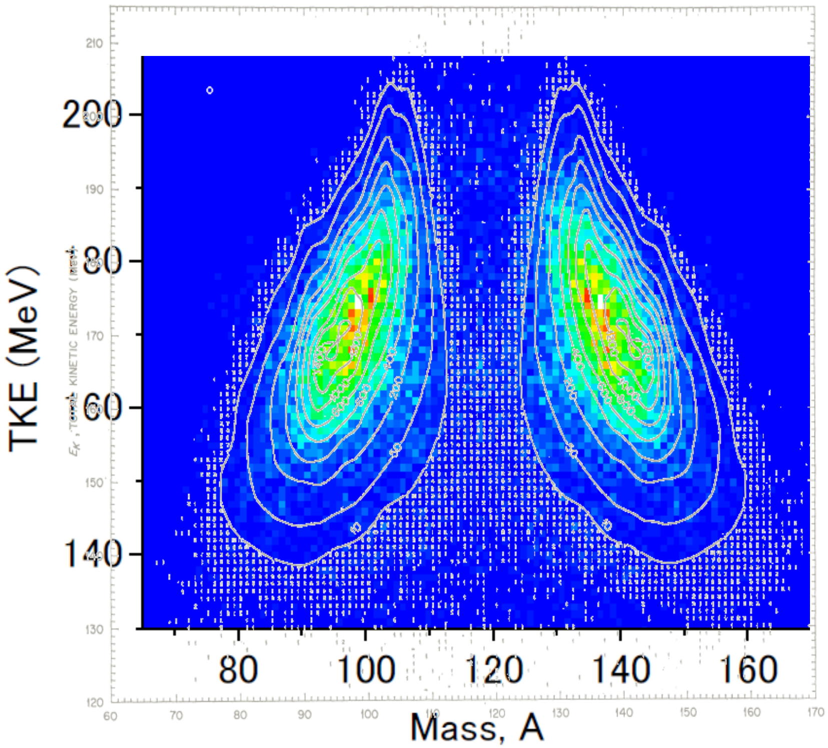


Trajectory on potential energy surface



$^{236}U^{*}$ (E^{*} = 20MeV)





Experiment J.Katakura, JENDL FP Decay Data File 2011 and Fission Yields

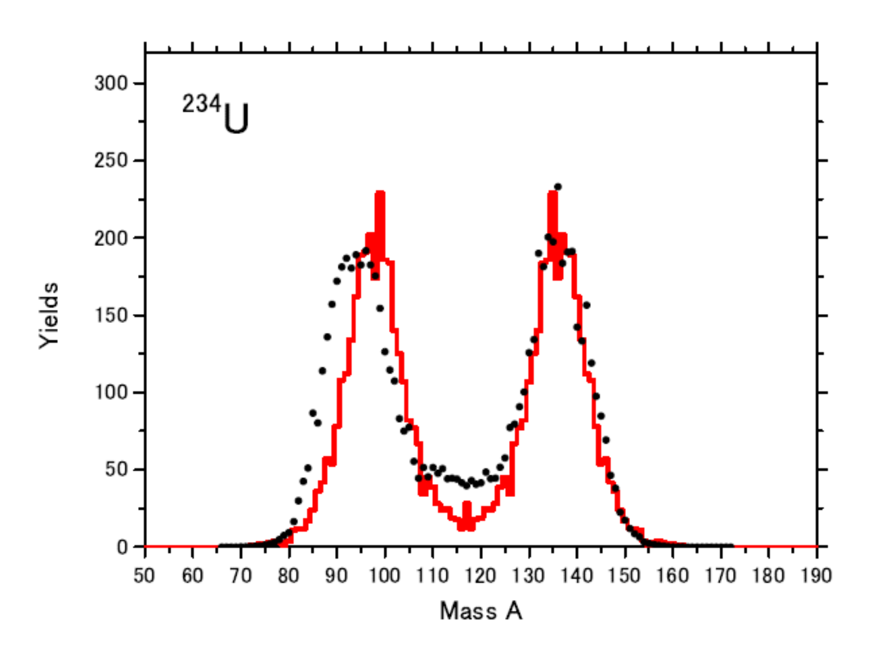
calculation Y. Aritomo and S. Chiba, PRC 88, 044614(2013)

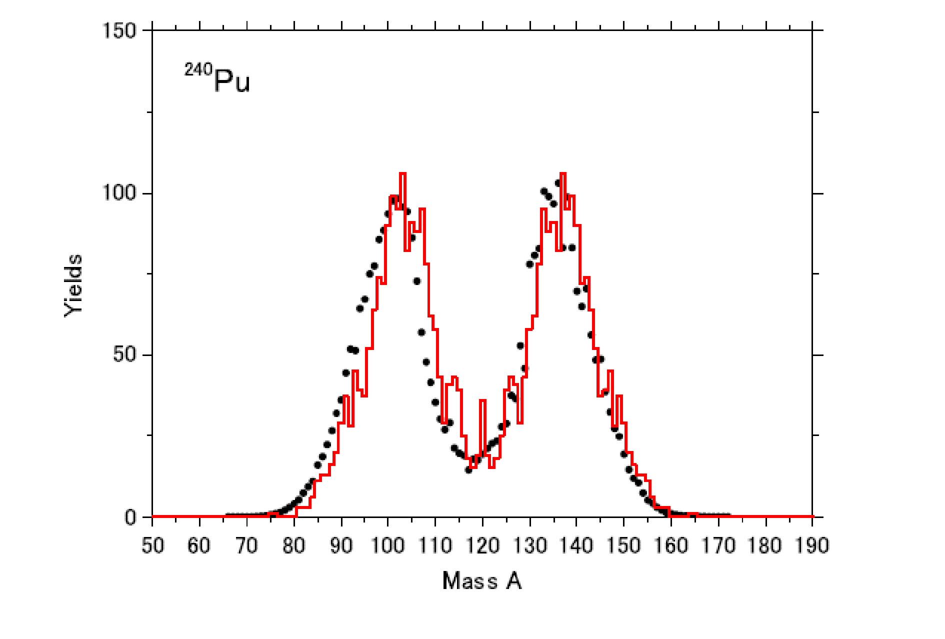
Exp. Phys.Rev. **141**(1966)1146

Mass distribution of fission fragments $E^* = 20$ MeV

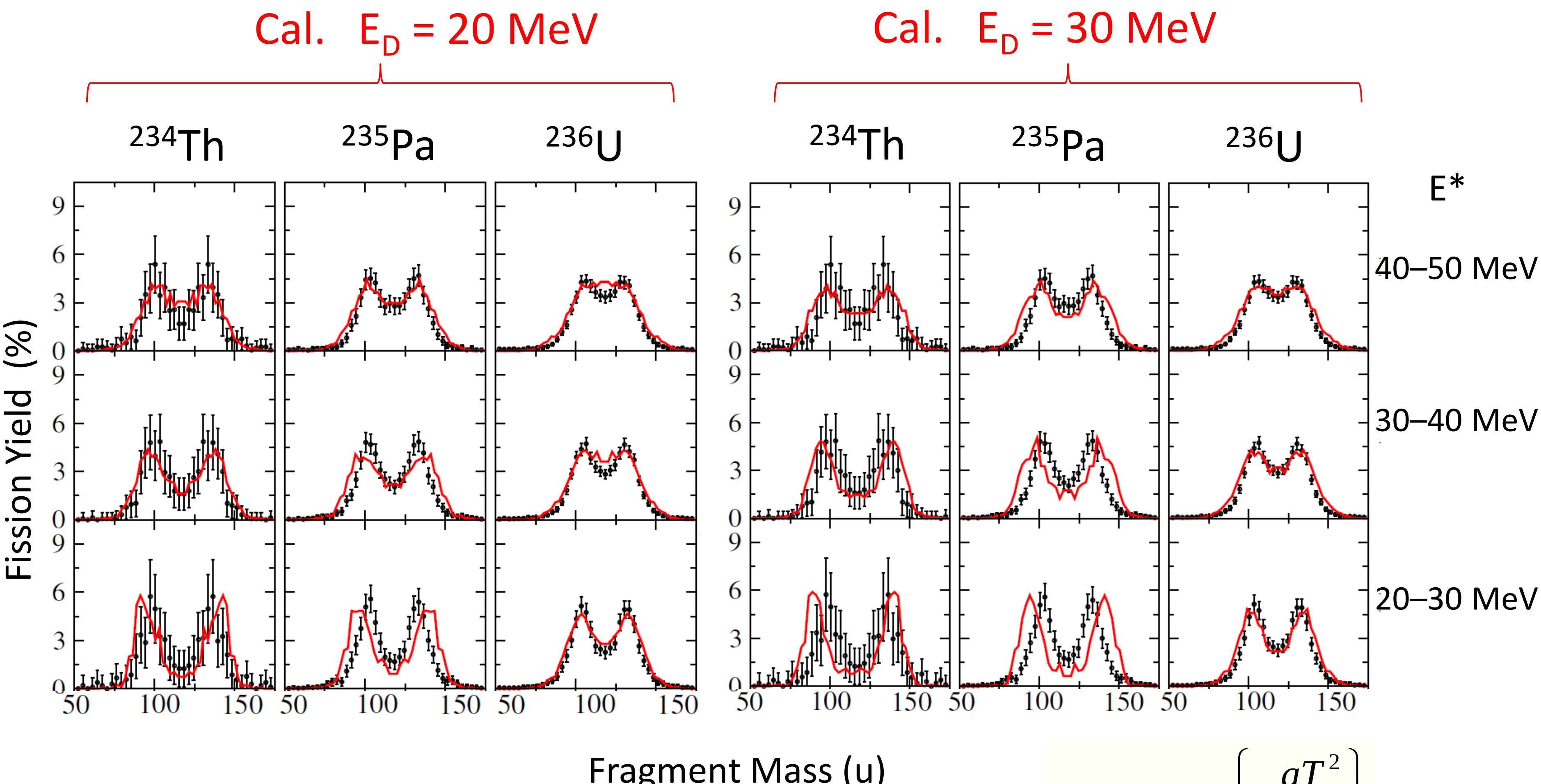
^{234}U

^{240}Pu





Comparison between Cal. and Exp.



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

Cal.

Exp.

Compiled by K. Nishio and JAEA group

5. 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 *probability distribution*

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

And….

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