Dynamical approach for Heavy-ion reaction and Multi-nucleon transfer

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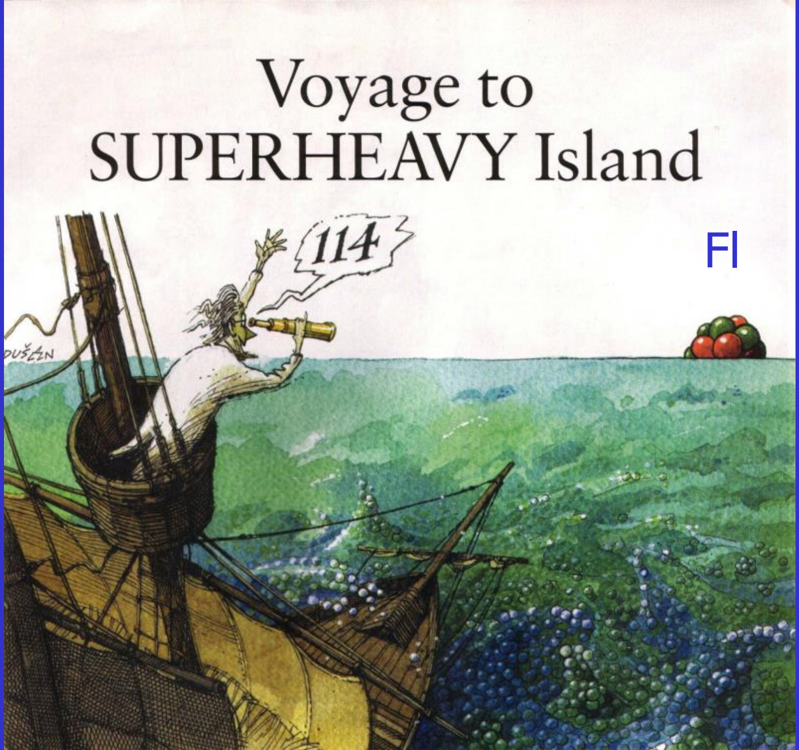


The 11th RIBF Discussion
on Heavy-ion reaction and multi-nucleon
March 2nd, 2015
University of Tsukuba

FLNR SCIENTIFIC PROGRAMME
Year 2015

Synthesis and Properties of Nuclei at the Stability Limits

Leader: M.G. Itkis

Scientific leader: Yu.Ts. Oganessian

Research of shell effects in multi-nucleon transfer reactions in order to investigate the production of superheavy neutron-rich elements in collision of actinide nuclei (238U+ 238U, 136Xe+ 248Cm, 197Au+238U).

Study of the multicluster decay of heavy nuclei.

Heavy-ion reaction
Multi-nuclear transfer reaction

- Synthesis of Superheavy elements

  Fusion-fission
  Quasi-fission
  Deep inelastic collision

  Fission

Dissipative process

Kinetic energy
→ Intrinsic energy

Friction
Dynamical model

- Multi-nuclear transfer reaction
  in Heavy mass region

Contains

1. Introduction
   Reaction in heavy mass region and superheavy elements

2. Model
   (1) Coupled-channels method (quantum) + Langevin calculation (classical)
       fusion-fission process -- Orientation effect

   (2) Full Langevin calculation (classical)
       DIS, nucleon transfer

3. Results
   $^{36}S+^{238}U$ and $^{30}Si+^{238}U$
       Capture Cross-section
       Fusion Cross-section, Evaporation residue cross section
       Mass distribution of Fission fragments

4. Multi-nucleon transfer reaction
       Surrogate reaction
       Zagrebaev

5. Summary

Periodic Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Hydrogen H 1																	Helium He 2
2	Lithium Li 3	Beryllium Be 4											Boron B 5	Carbon C 6	Nitrogen N 7	Oxygen O 8	Fluorine F 9	Neon Ne 10
3	Sodium Na 11	Magnesium Mg 12											Aluminum Al 13	Silicon Si 14	Phosphorus P 15	Sulfur S 16	Chlorine Cl 17	Argon Ar 18
4	Potassium K 19	Calcium Ca 20	Scandium Sc 21	Titanium Ti 22	Vanadium V 23	Chromium Cr 24	Manganese Mn 25	Iron Fe 26	Cobalt Co 27	Nickel Ni 28	Copper Cu 29	Zinc Zn 30	Gallium Ga 31	Germanium Ge 32	Arsenic As 33	Selenium Se 34	Bromine Br 35	Krypton Kr 36
5	Rubidium Rb 37	Strontium Sr 38	Yttrium Y 39	Zirconium Zr 40	Niobium Nb 41	Molybdenum Mo 42	Technetium Tc 43	Ruthenium Ru 44	Rhodium Rh 45	Palladium Pd 46	Silver Ag 47	Cadmium Cd 48	Indium In 49	Tin Sn 50	Antimony Sb 51	Tellurium Te 52	Iodine I 53	Xenon Xe 54
6	Cesium Cs 55	Barium Ba 56	La*	Hafnium Hf 72	Tantalum Ta 73	Tungsten W 74	Rhenium Re 75	Osmium Os 76	Iridium Ir 77	Platinum Pt 78	Gold Au 79	Mercury Hg 80	Thallium Tl 81	Lead Pb 82	Bismuth Bi 83	Polonium Po 84	Astatine At 85	Radon Rn 86
7	Francium Fr	Radium Ra	Ac**	Rutherfordium Rf 104	Dubnium Db 105	Seaborgium Sg 106	Bohrium Bh 107	Hassium Hs 108	Meitnerium Mt 109	Darmstadtium Ds 110	Roentgenium Rg 111	Copernicium Cn 112	113	114	115	116	117	118

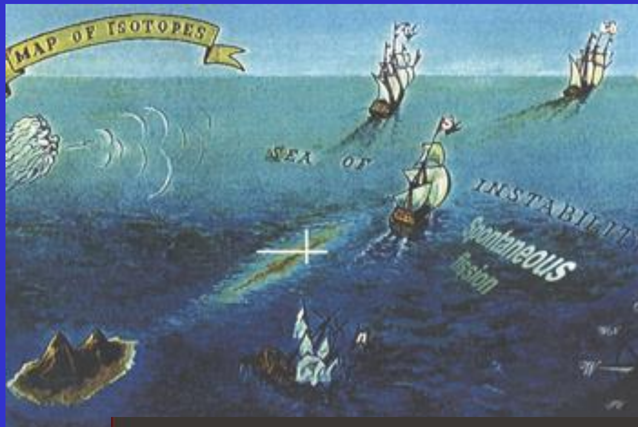
↑ 114: **Fl** flerovium
↑ 116: **Lv** livermorium

Менделеев(1834-1907)
1869

May 2012 IUPAC

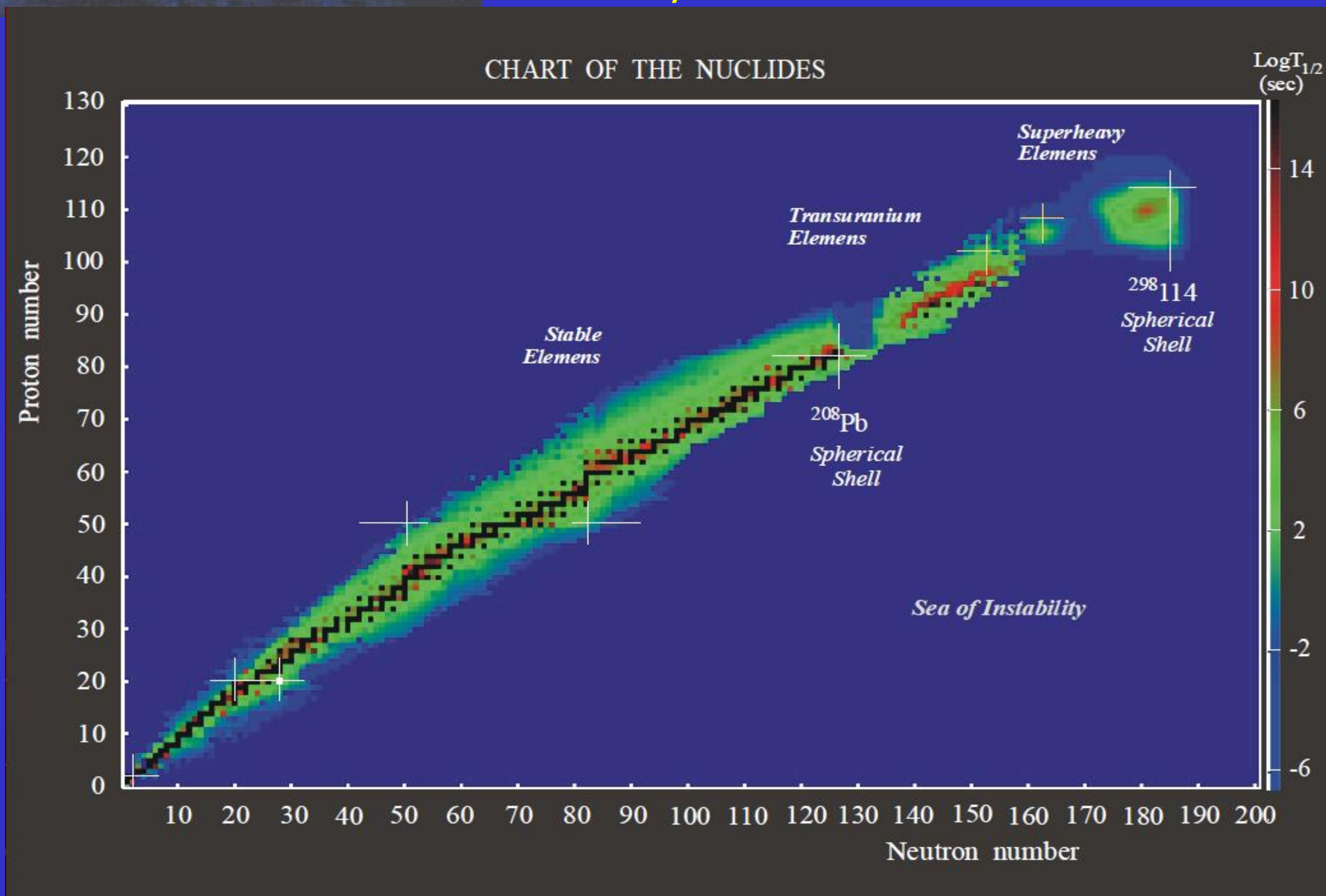
La* Lanthanides	Lanthanum La 57	Cerium Ce 58	Praseodymium Pr 59	Neodymium Nd 60	Promethium Pm 61	Samarium Sm 62	Europium Eu 63	Gadolinium Gd 64	Terbium Tb 65	Dysprosium Dy 66	Holmium Ho 67	Erbium Er 68	Thulium Tm 69	Ytterbium Yb 70	Lutetium Lu 71
Ac** Actinides	Actinium Ac 89	Thorium Th 90	Protactinium Pa 91	Uranium U 92	Neptunium Np 93	Plutonium Pu 94	Americium Am 95	Curium Cm 96	Berkelium Bk 97	Californium Cf 98	Einsteinium Es 99	Fermium Fm 100	Mendelevium Md 101	Nobelium No 102	Lawrencium Lr 103

Super Heavy Elements → less stable



Our Interests

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



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)

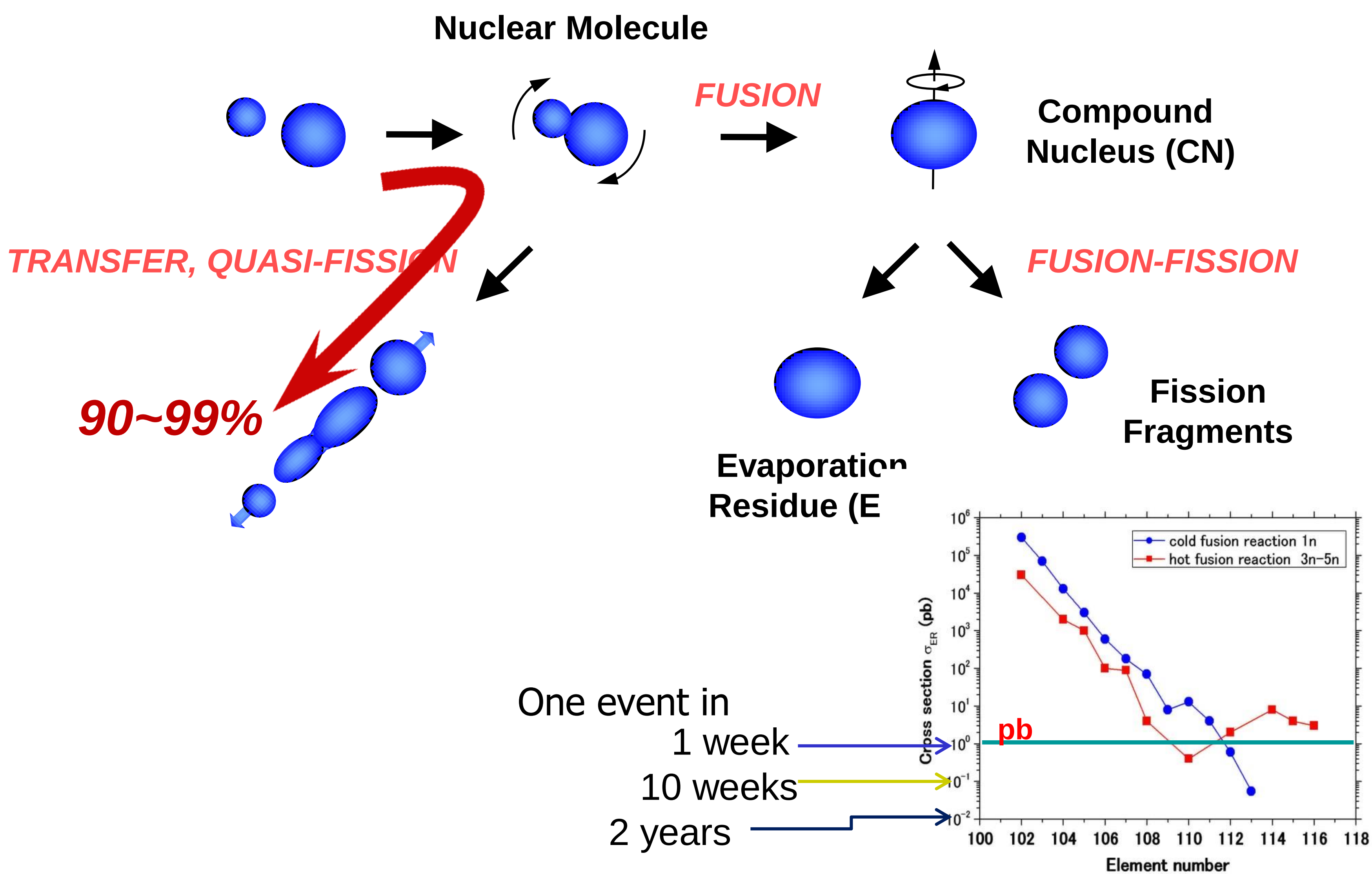
2004

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

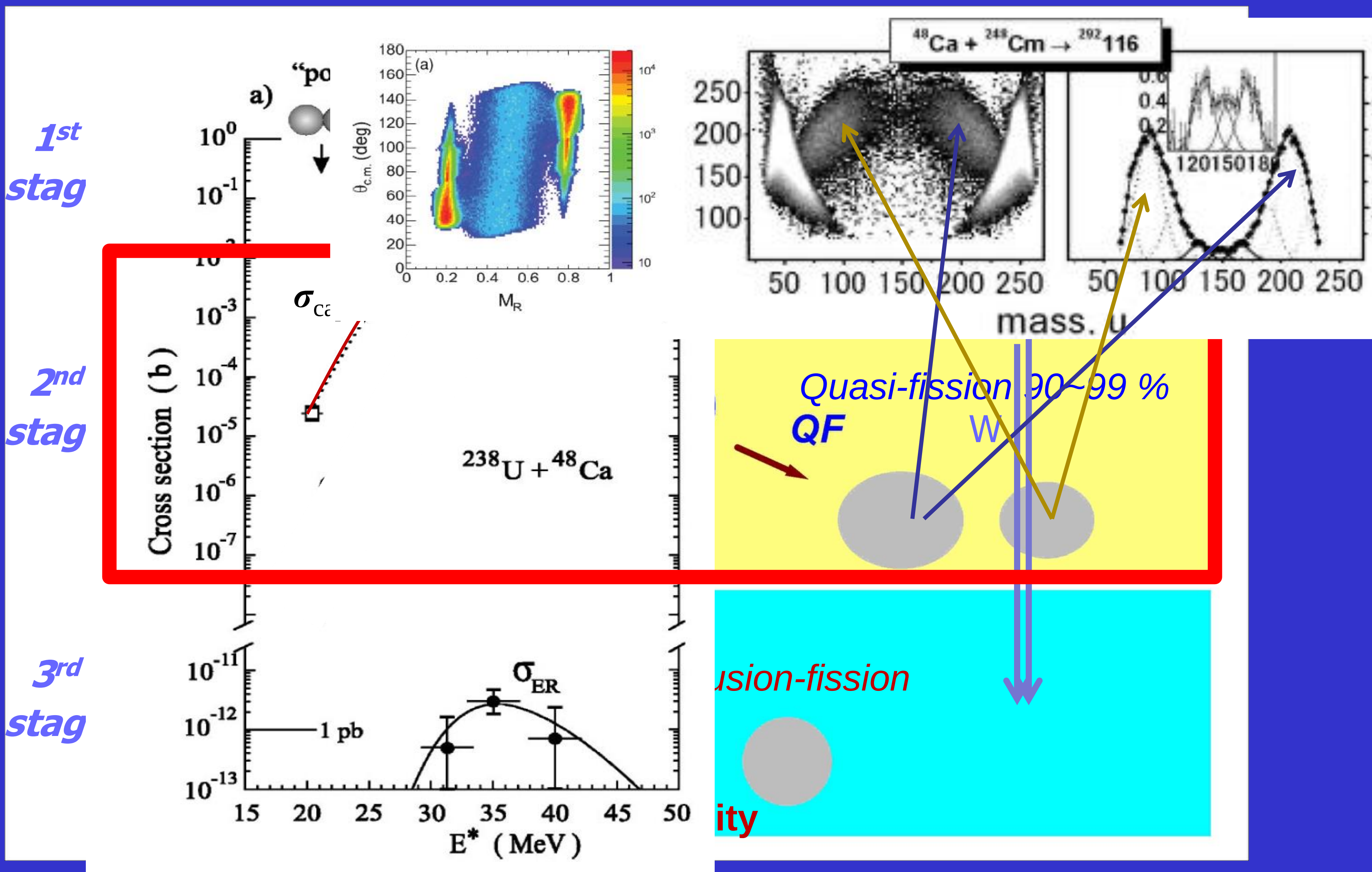
2010

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

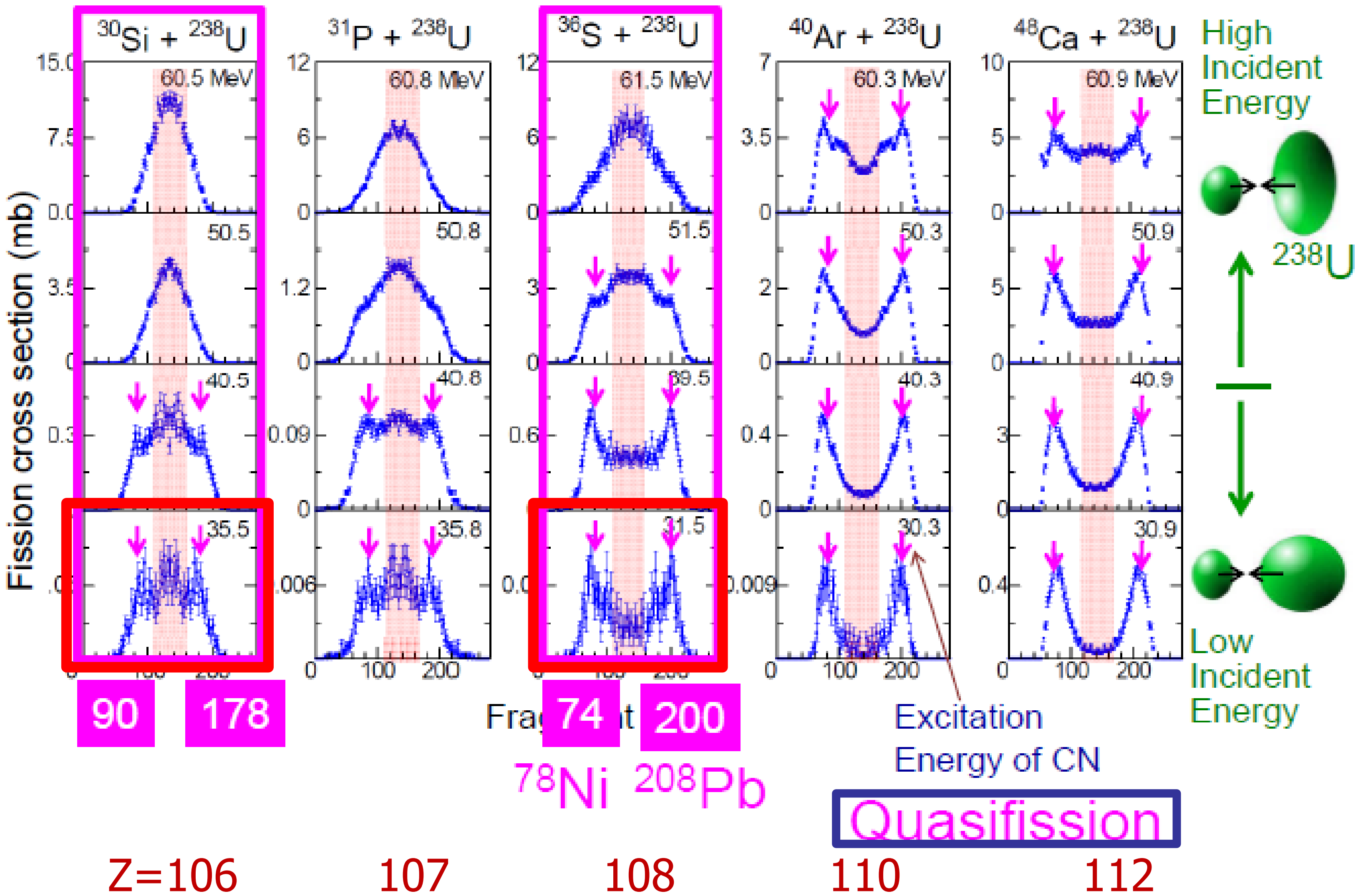
Fusion process in Superheavy mass region



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



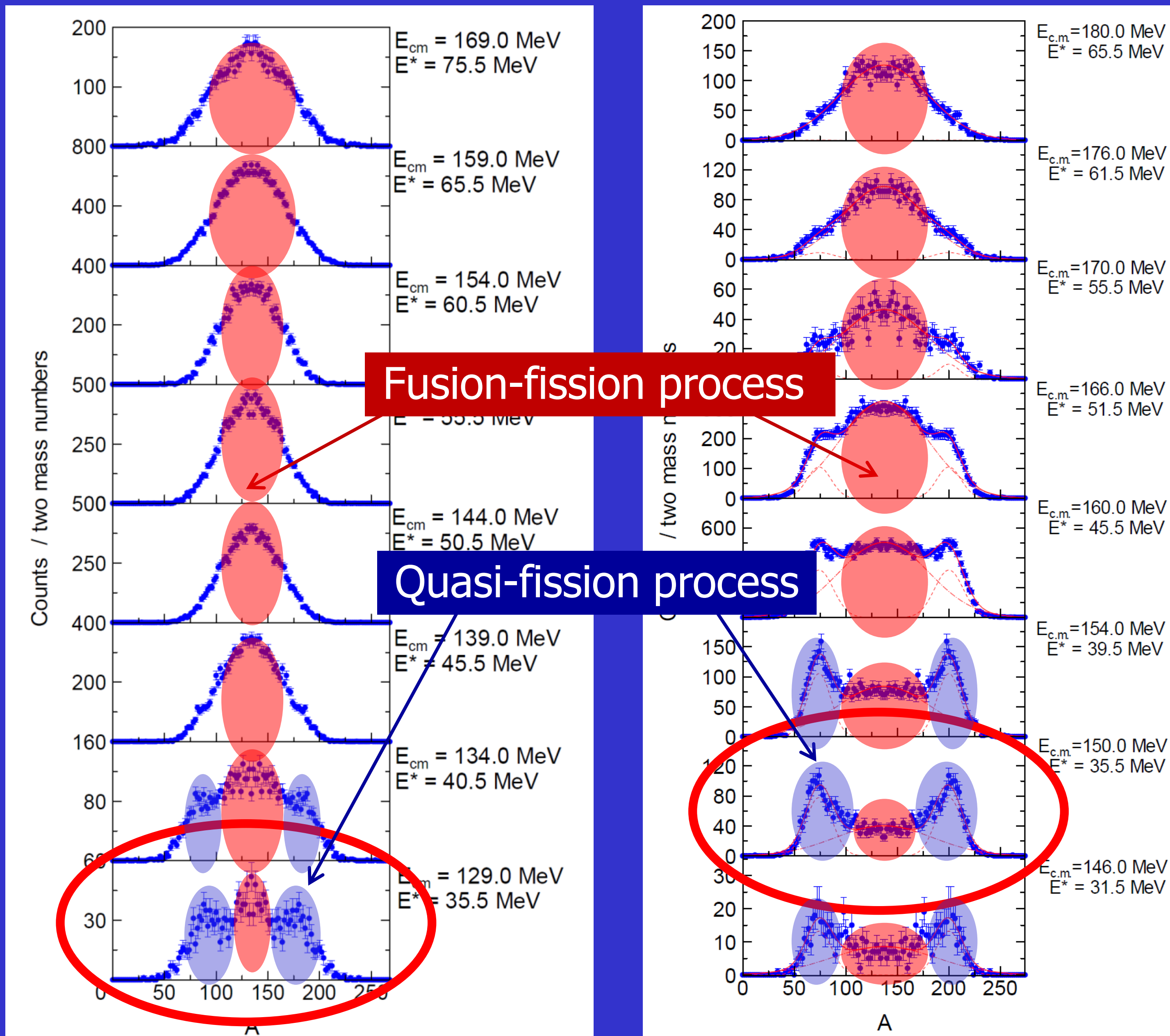
Projectile dependence of fragment mass distributions



Experiments by K. Nishio et al. (JAEA)

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

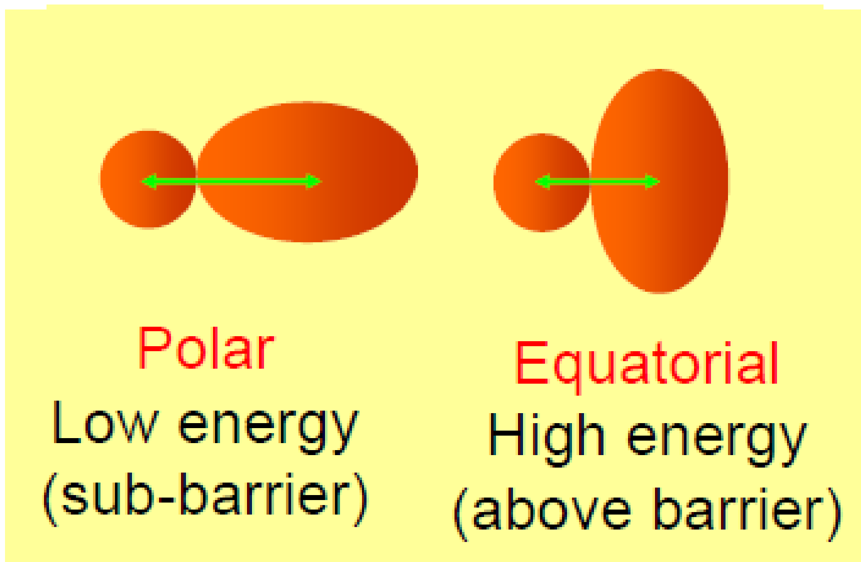
Exp. by K. Nishio *et al.* *at JAEA*

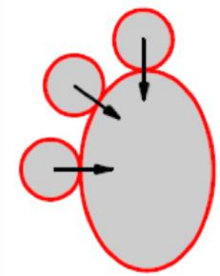


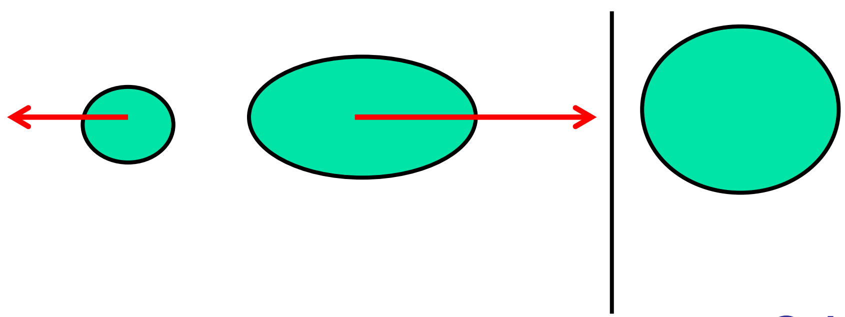
Effects of Static Nuclear-deformation on Fusion

Orientation effects of target nucleus

Coulomb repulsion







Orientation effects
→ K. Nishio (in the Symposium)

2. Model

(1) Coupled-channels method (quantum) + Langevin calculation (classical)

fusion-fission process -- Orientation effect

(2) Full Langevin calculation (classical)

DIS, nucleon transfer

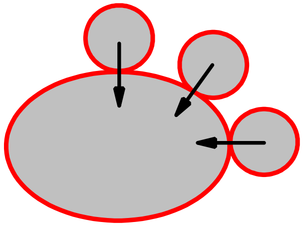
Estimation of cross sections

calculate R_{cont} for all θ
transform to the nose-nose conf. keeping R_{cont}

Capture Cross Section

1st stage

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



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

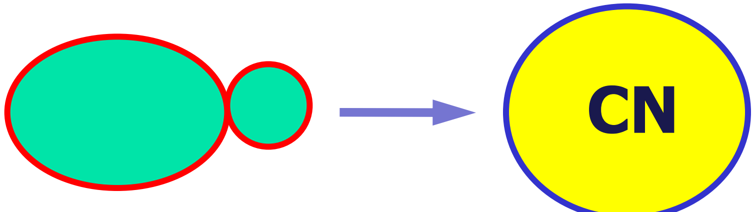
Coupled-channel method

Touching configurations for all orientations

Fusion Cross Section

2nd stage

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



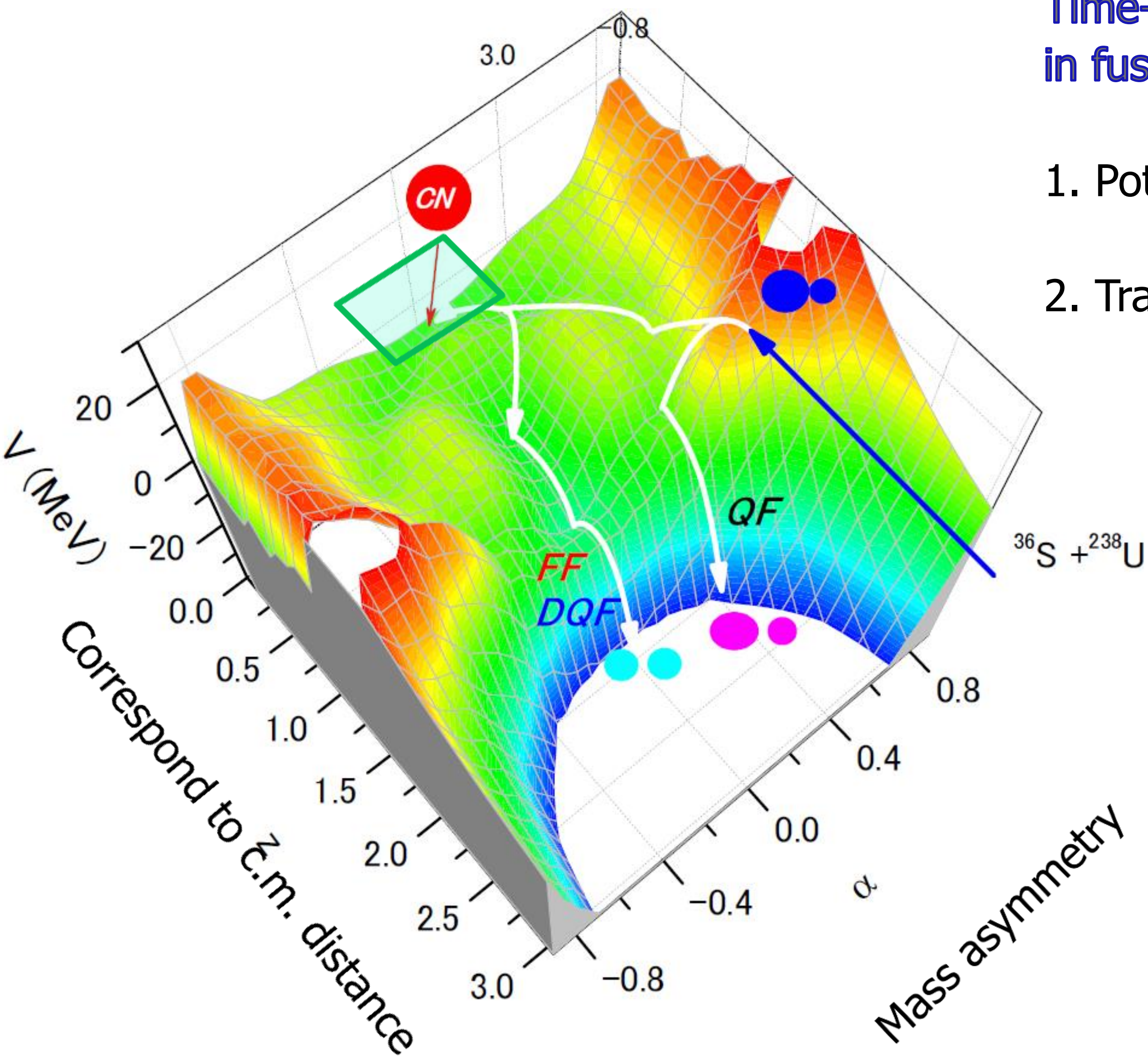
Formation probability P_{CN}

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

Dynamical calculation
Langevin eq.

Axial symmetric configuration
←start the Langevin calculation at the nose-nose configuration with each R_{cont} in 1st stage

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



Time-evolution of nuclear shape in fusion-fission process

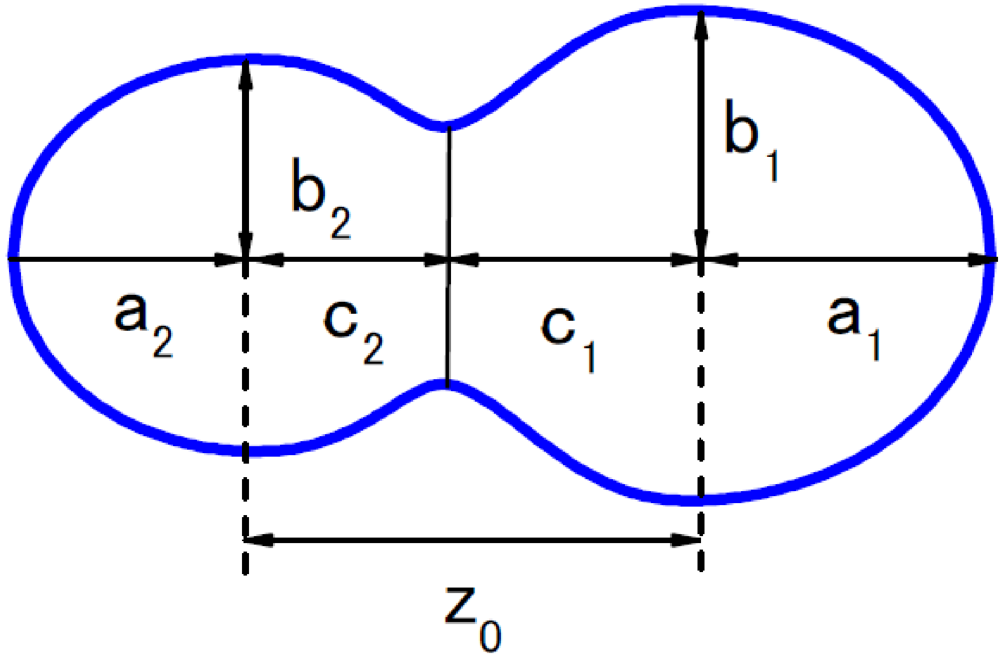
1. Potential energy surface

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)

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

Multi-dimensional Langevin Equation

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

Friction dissipation Random force fluctuation

Newton equation

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

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

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

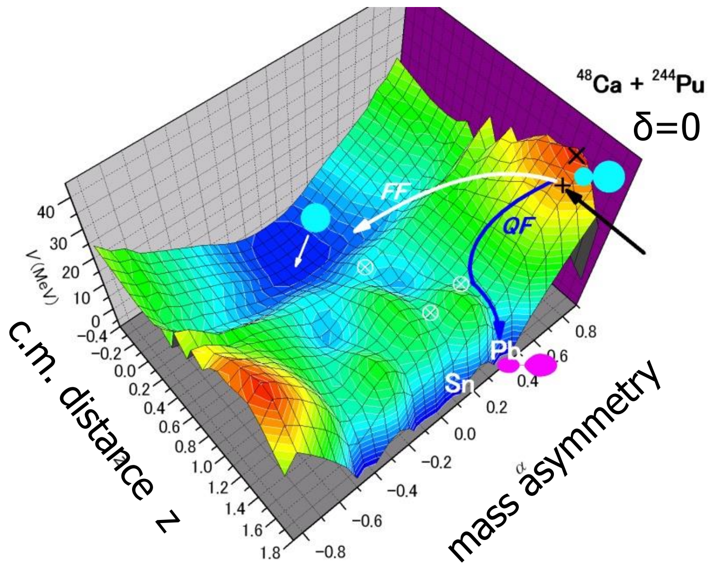
E_{int} : intrinsic energy, E^* : excitation energy

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

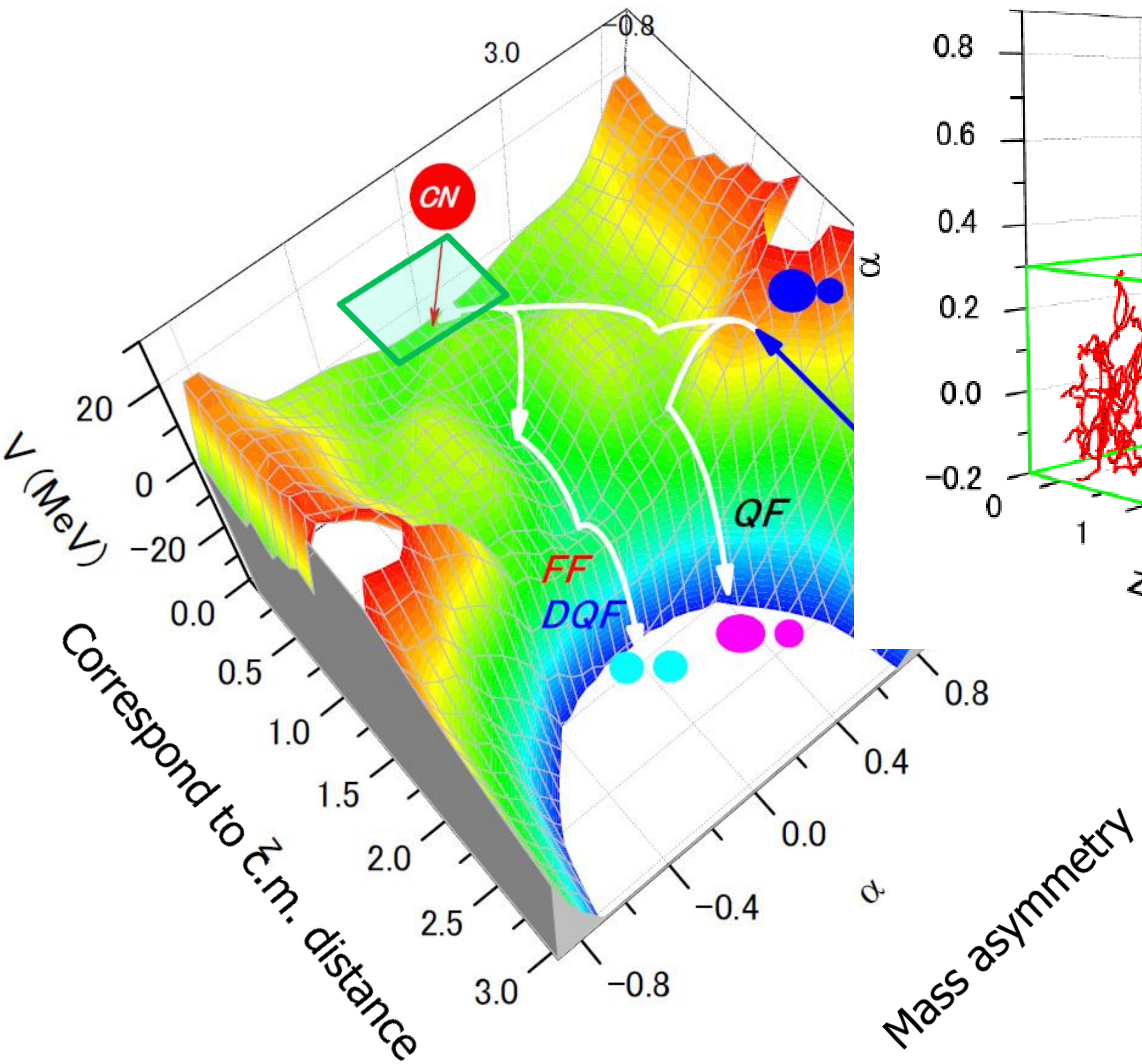
I : Moment of inertia for rigid body

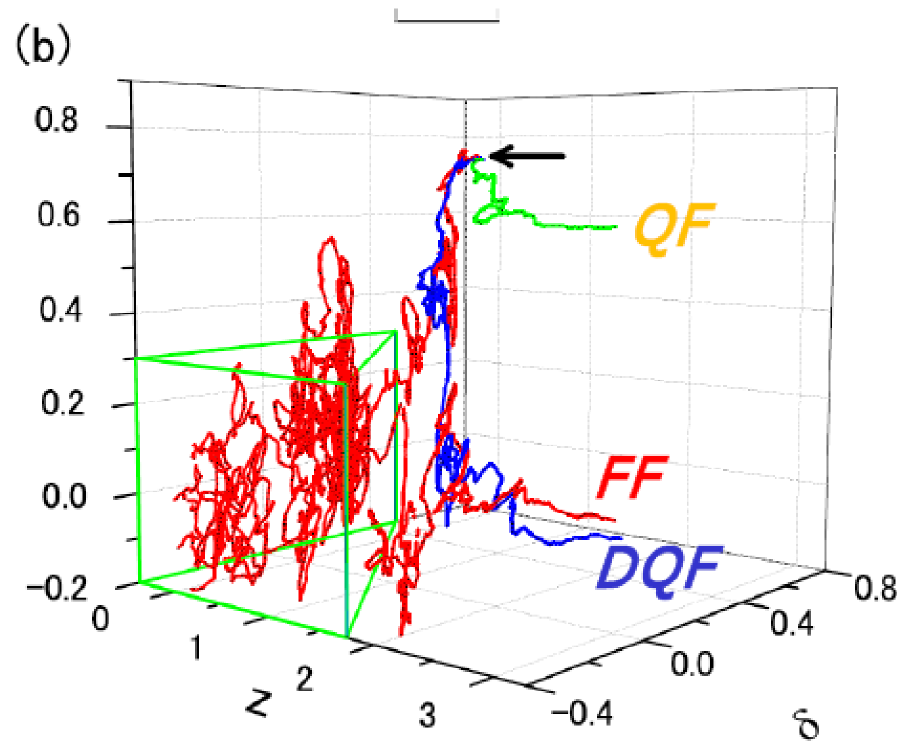
$\Phi(T)$: Temperature dependent factor

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

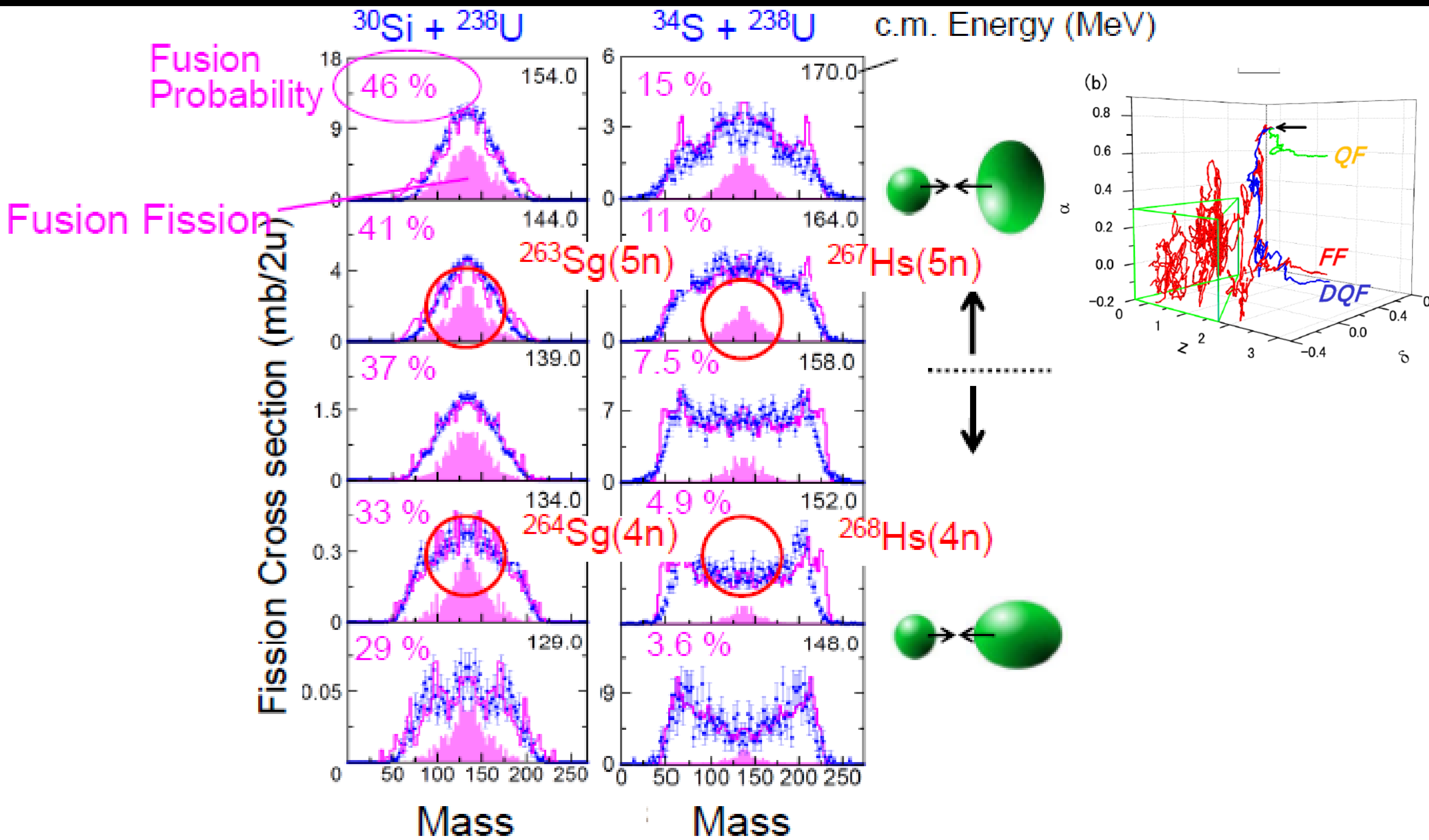
$$E_d = 20\,\mathrm{MeV}$$

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



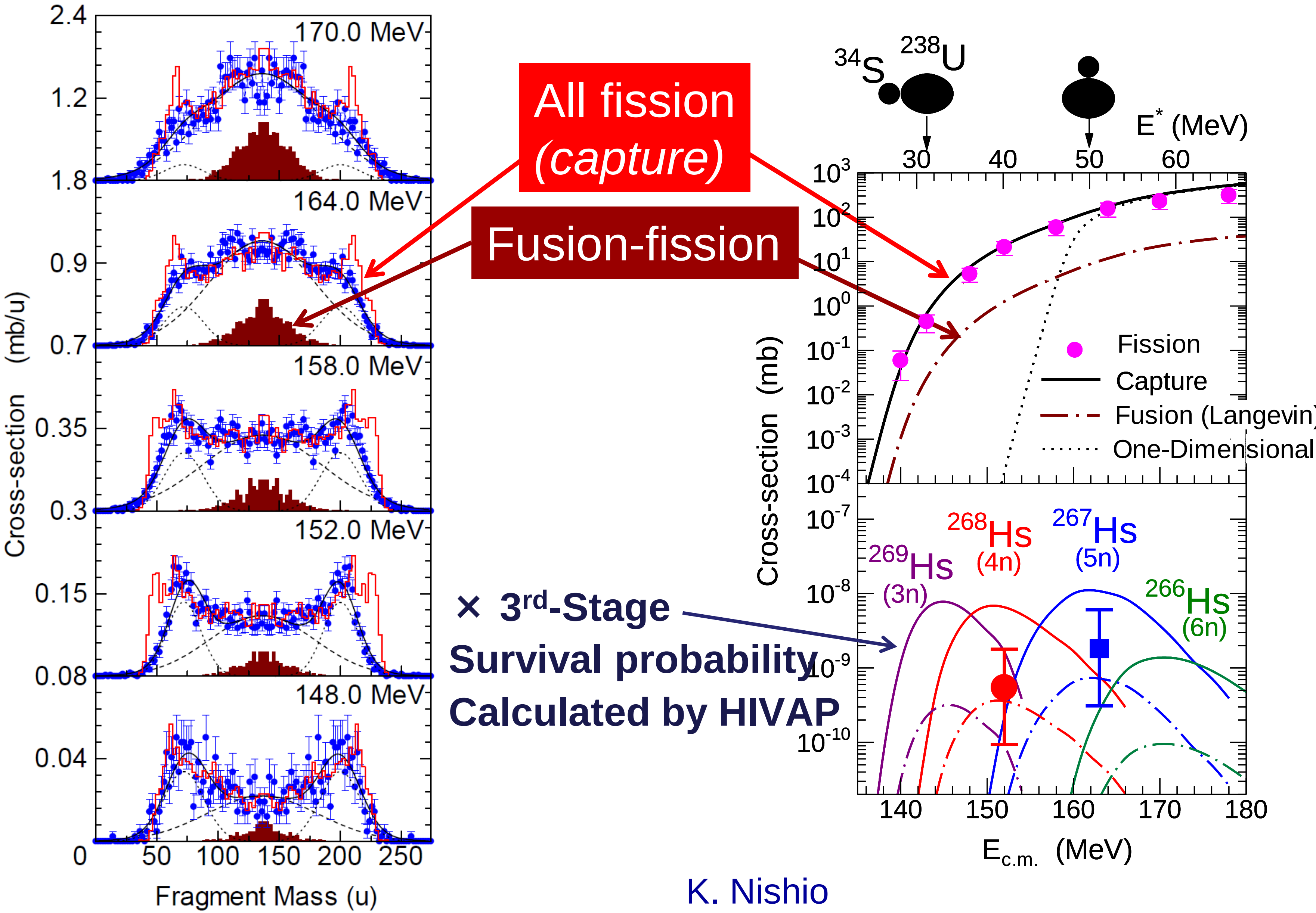


Calculated spectra for fusion-fission and quasi-fission



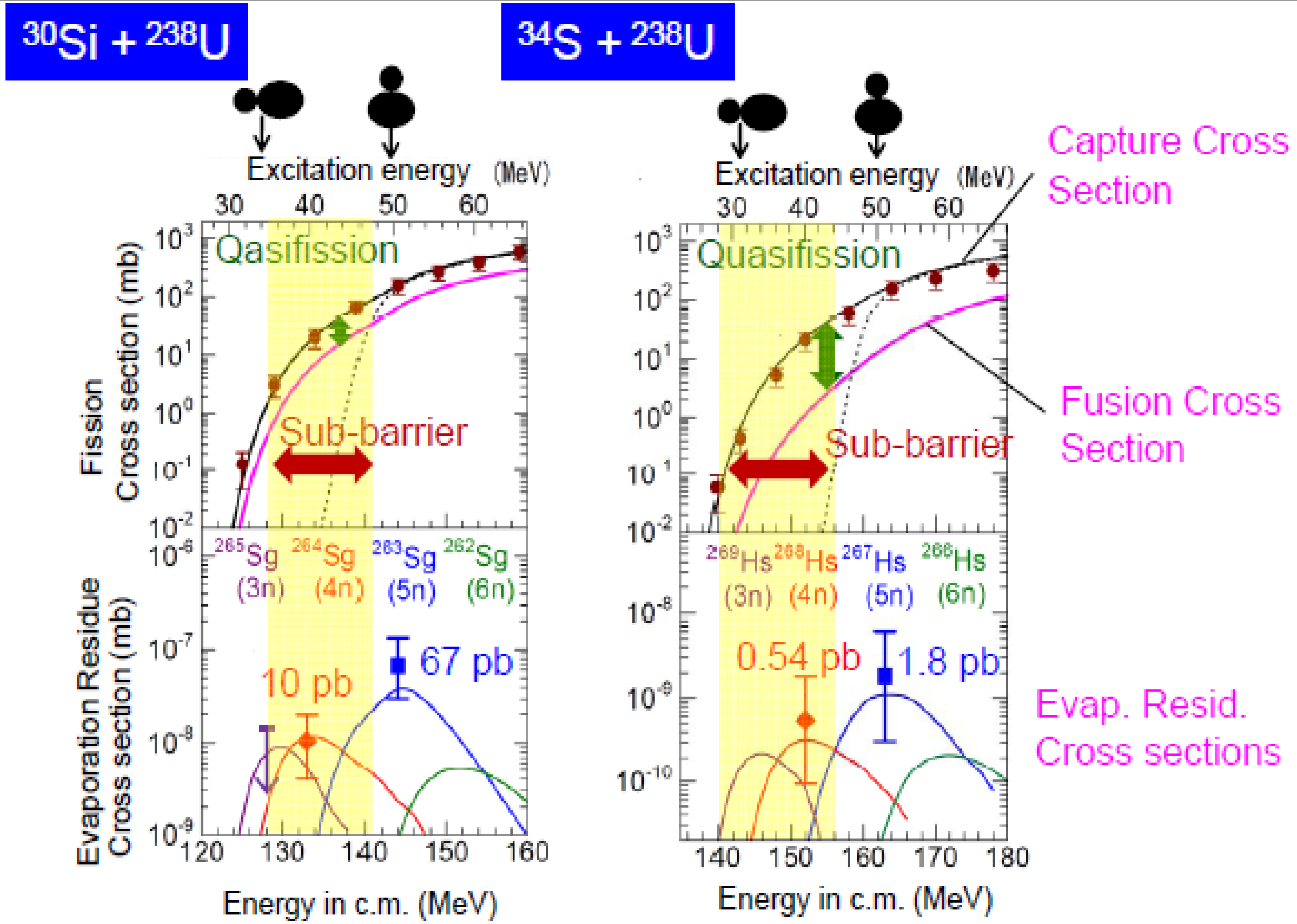
Experiments by K. Nishio et al. (JAEA)

ER cross-sections for $^{267,268}Hs$ produced by $^{34}S + ^{238}U$



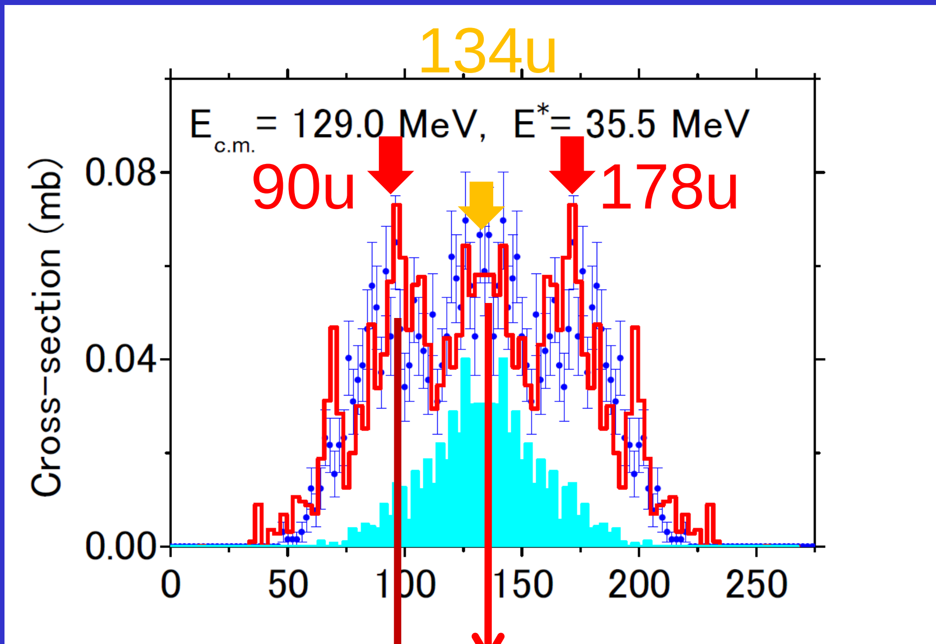
K. Nishio

Fusion and ER cross sections

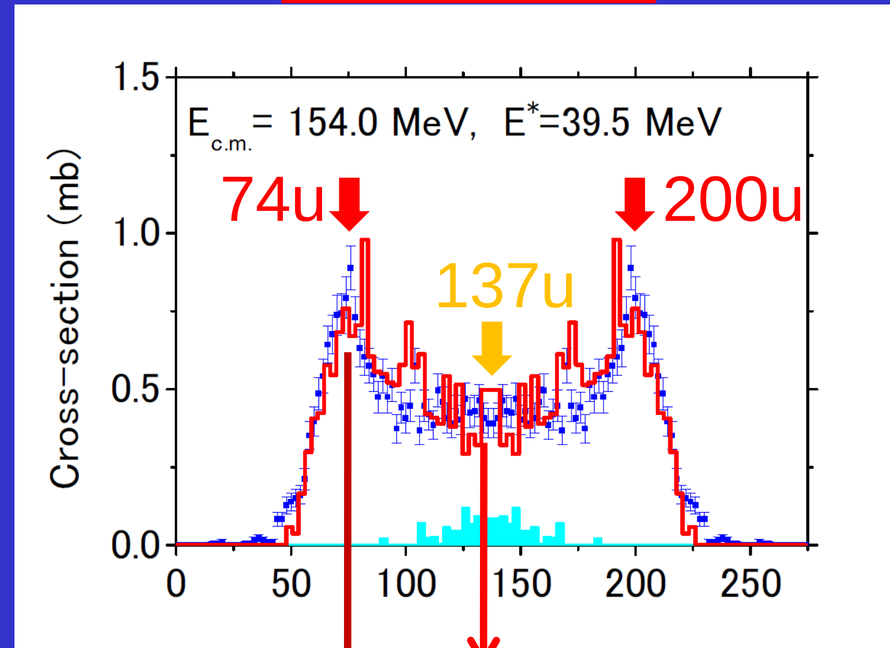


K. Nishio *et al.*, PRC **82**, 024611 (2010).
K. Nishio *et al.*, PRC **82**, 044604 (2010).

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



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



FF and DQF
$t > 50 \times 10^{-21}$ sec
$-0.2 < \delta < 0.2$ (peak 0)

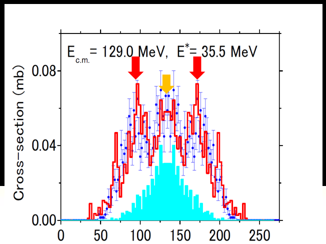
QF via mono-nucleus
$t < 30 \times 10^{-21}$ sec
$0.2 < \delta < 0.5$ (peak 0.4)

FF and **DQF**
$t < 30 \times 10^{-21}$ sec
$0 < \delta < 0.4$ (peak 0.2)

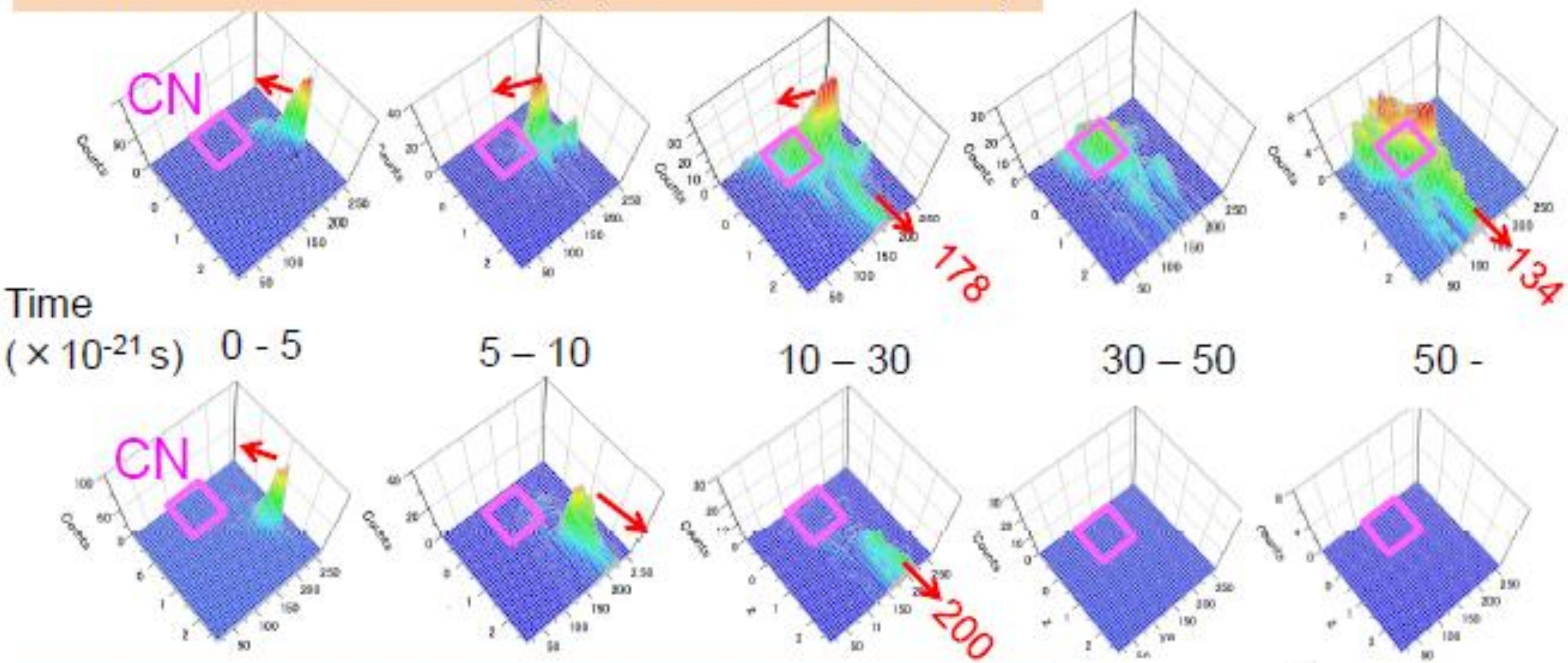
QF
$t < 10 \times 10^{-21}$ sec
$0 < \delta < 0.2$ (peak 0)

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

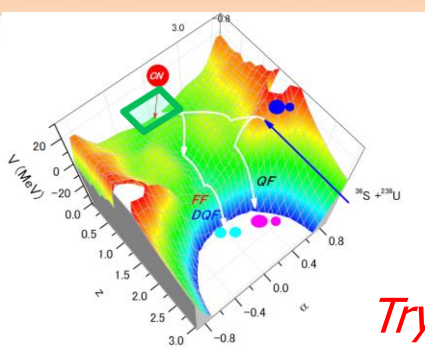
Time evolution of probability distribution

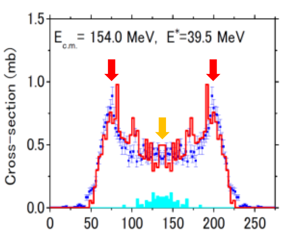


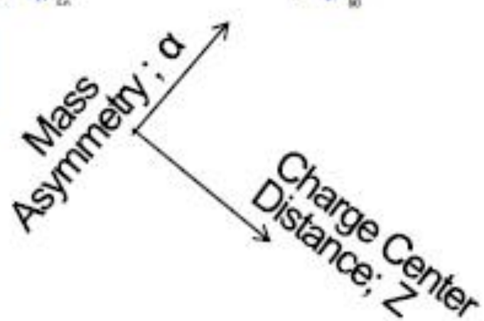
$^{30}Si + ^{238}U \rightarrow ^{268}Sg$ (E*=35.5 MeV)



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





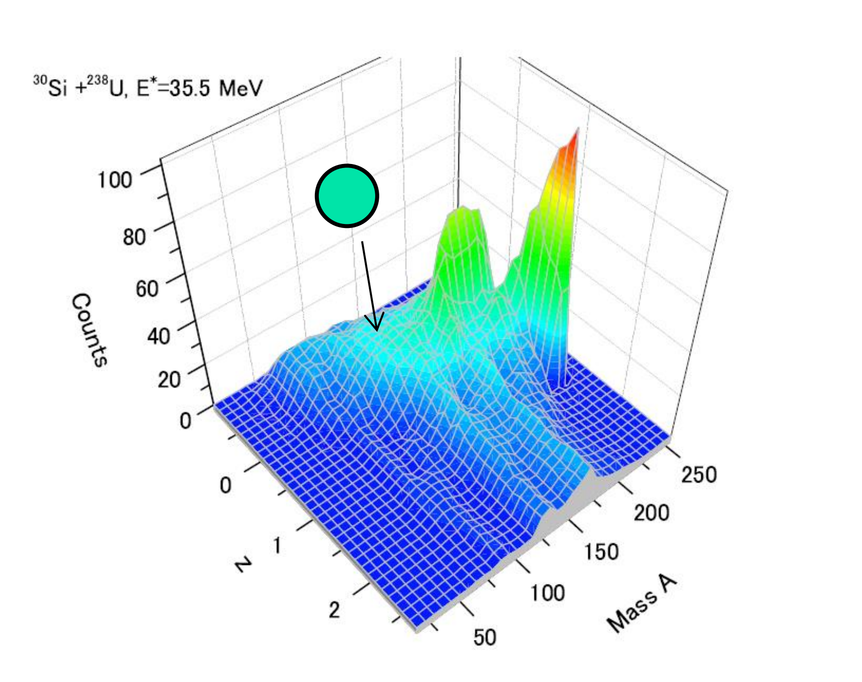


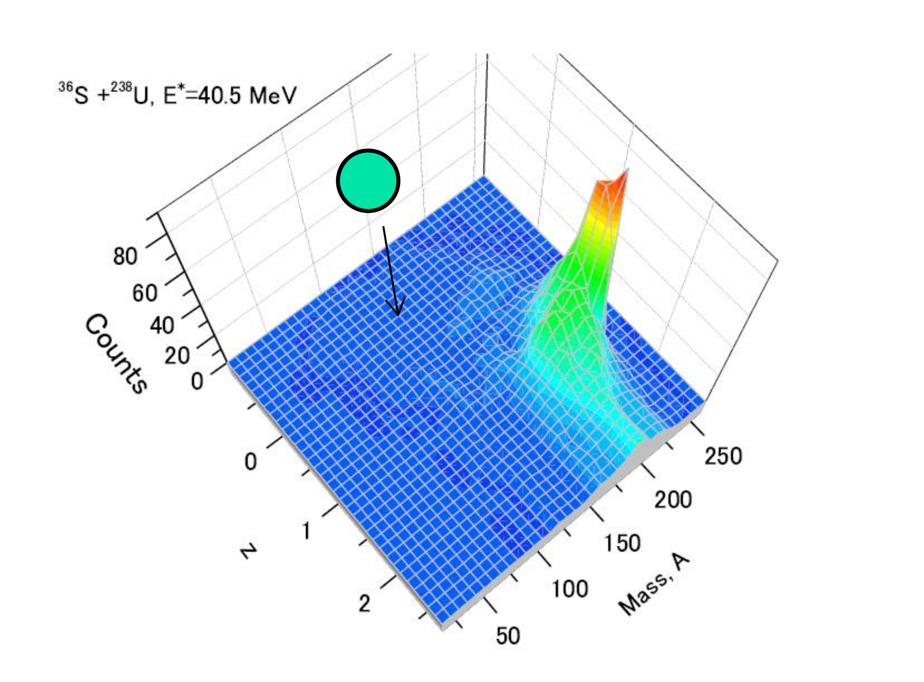
Try to clarify the origin of difference between the both cases →

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

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

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

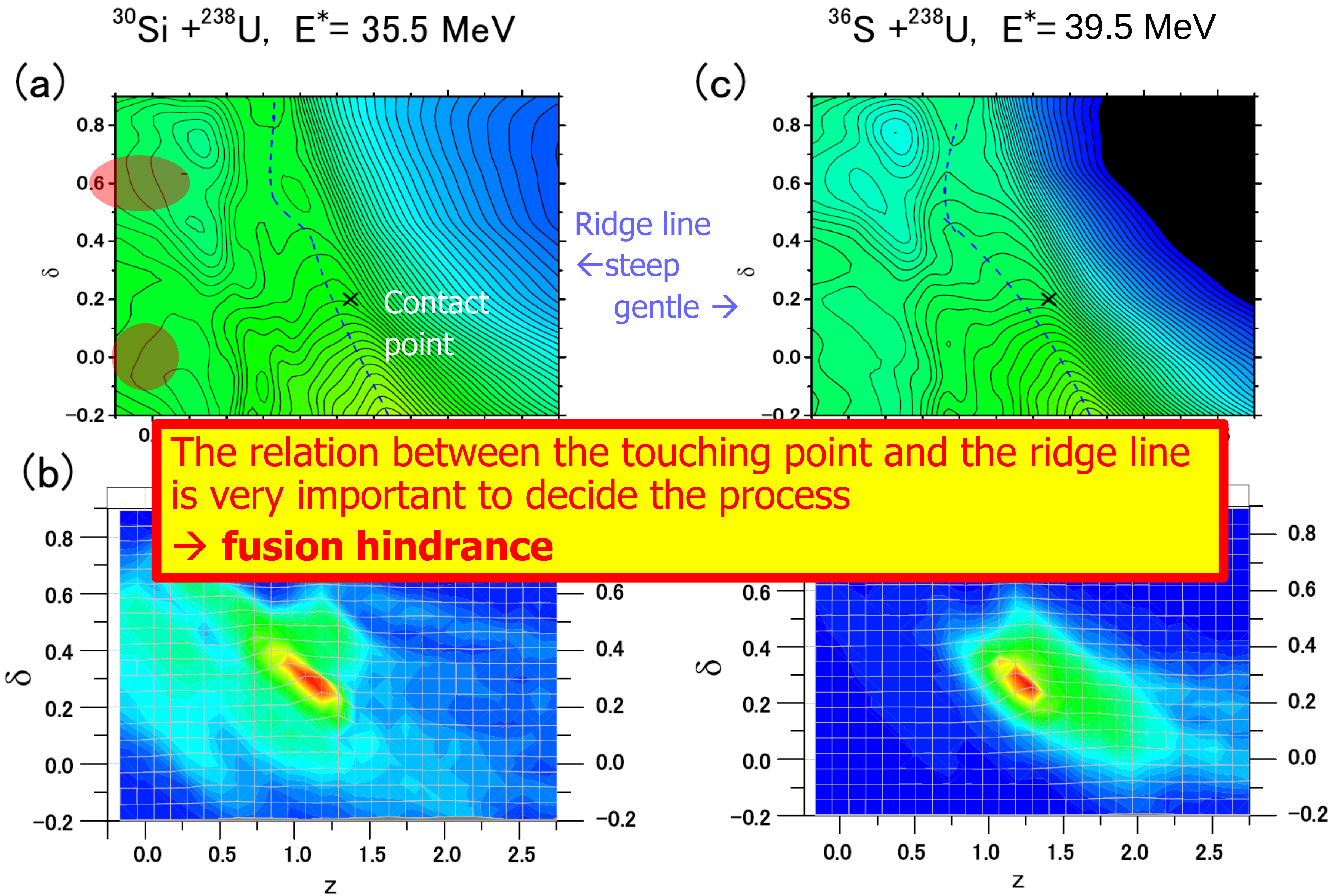




*E** =
35.5 MeV
L=0, θ=0

*E** =
39.5 MeV
L=0, θ=0

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**

2. Model

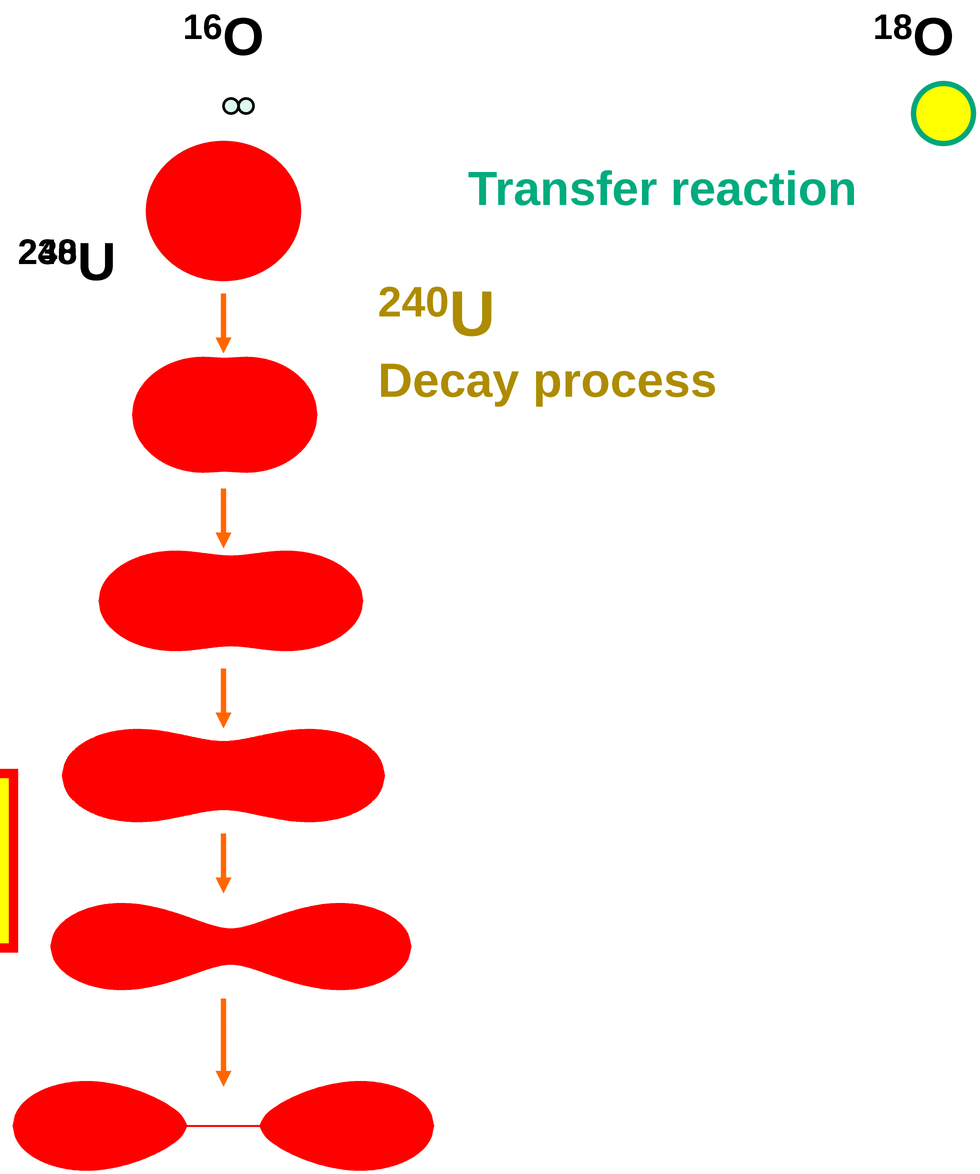
(1) Coupled-channels method (quantum) + Langevin calculation (classical)

fusion-fission process -- Orientation effect

(2) Full Langevin calculation (classical)

DIS, nucleon transfer

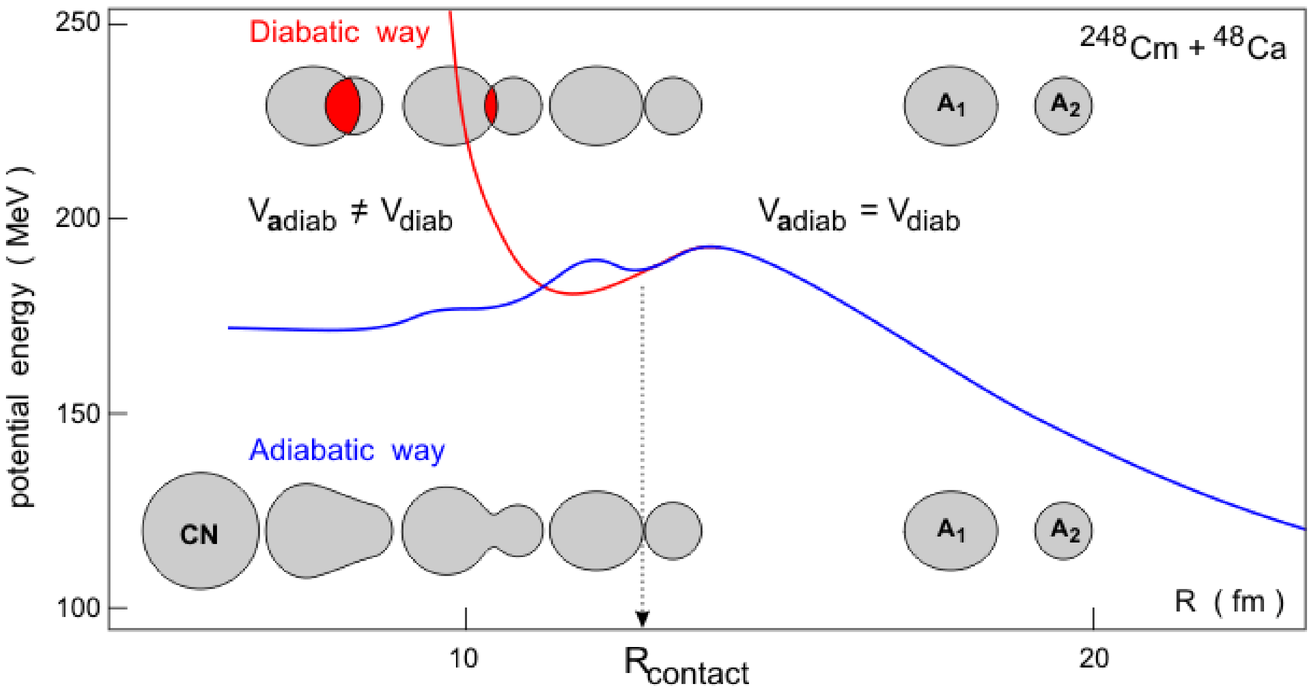
$^{18}O + ^{238}U \rightarrow ^{16}O + ^{240}U$



Evolution of nuclear shape in the whole process

Diabatic and Adiabatic Potential Energy

$$V_{diabat}(R,\beta_1,\beta_2,\alpha,\ldots) = V_{12}^{folding}(Z_1,N_1,Z_2,N_2;R,\beta_1,\beta_2,\ldots) + M(A_1) + M(A_2) - M(Proj) - M(Targ)$$



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

$$V_{adiabat}(R,\beta_1,\beta_2,\alpha,\ldots) = M_{TCSM}(R,\beta_1,\beta_2,\alpha,\ldots) - M(Proj) - M(Targ)$$

Time-dependent driving potential has to be used

$$V(t) = V_{diab}(\xi)\cdot exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-exp(-\frac{t_{int}}{\tau_{relax}})]$$

$\tau_{relax} \sim 10^{-21}$ s

the same degrees of freedom !

Time-dependent weight function

G. F. Bertsch, 1978; *W. Cassing, W. Nörenberg*, 1983. *A. Diaz-Torres*, 2004; *A. Diaz-Torres and W. Scheid*, 2005.

Langevin type equation

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

$$\frac{d\vartheta}{dt} = \frac{\ell}{\mu_R R^2}$$

$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}$$

$$\frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

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

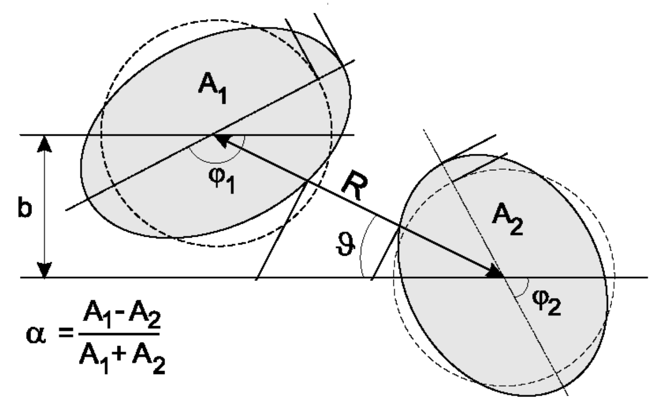
$$\frac{d\ell}{dt} = -\frac{\partial V}{\partial \vartheta} - \gamma_{\tan g}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)R + R g_{\tan g} R_{\tan g}(t)$$

$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{\tan g}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_1 - a_1 g_{\tan g} R_{\tan g}(t)$$

$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\tan g}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_2 - a_2 g_{\tan g} R_{\tan g}(t)$$

Before touching nucleon transfer

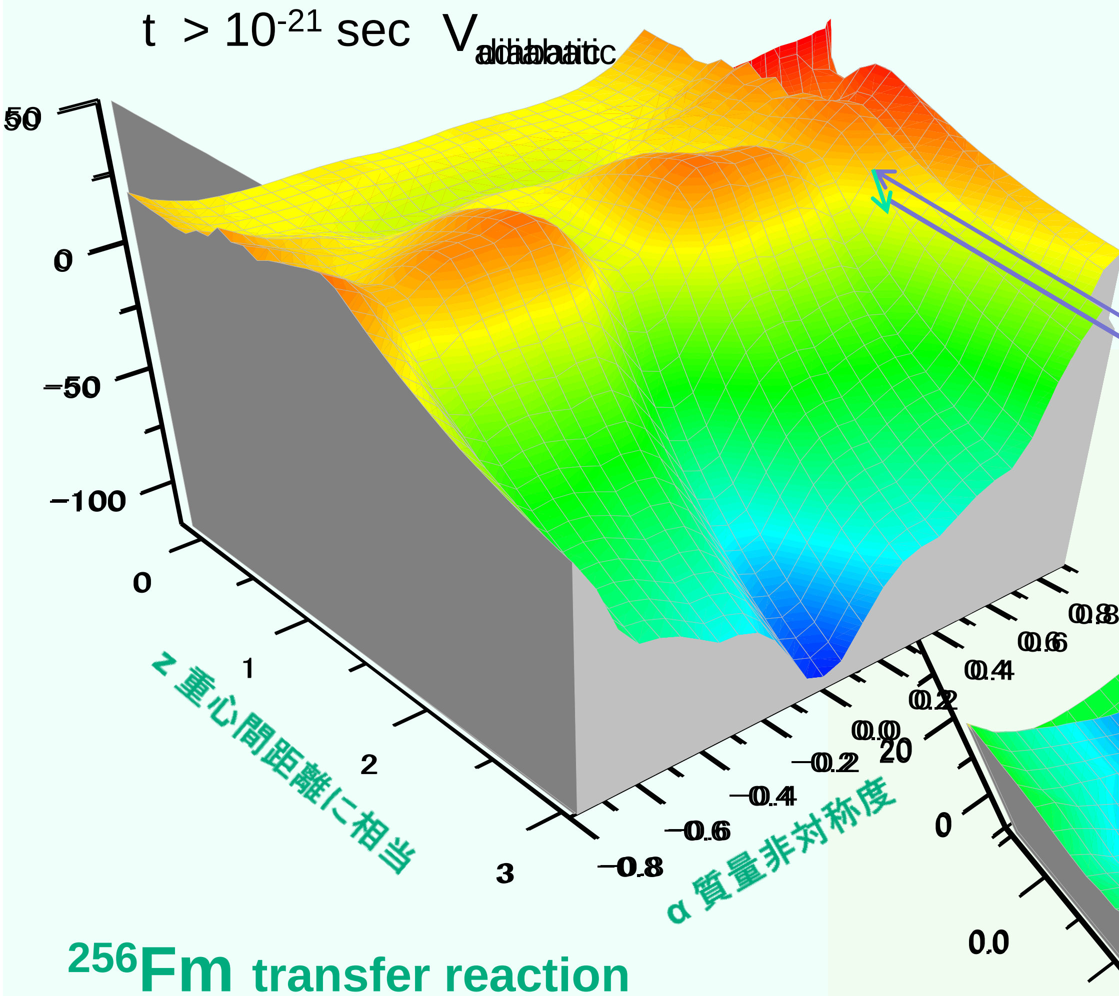
$$\frac{d\alpha}{dt} = \frac{2}{A_{CN}} D_A^{(1)}(\alpha) + \frac{2}{A_{CN}}\sqrt{D_A^{(2)}(\alpha)\Gamma_\alpha(t)}$$

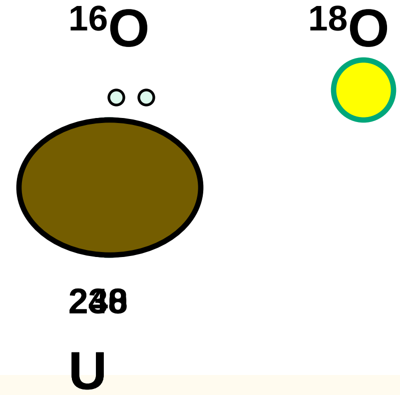


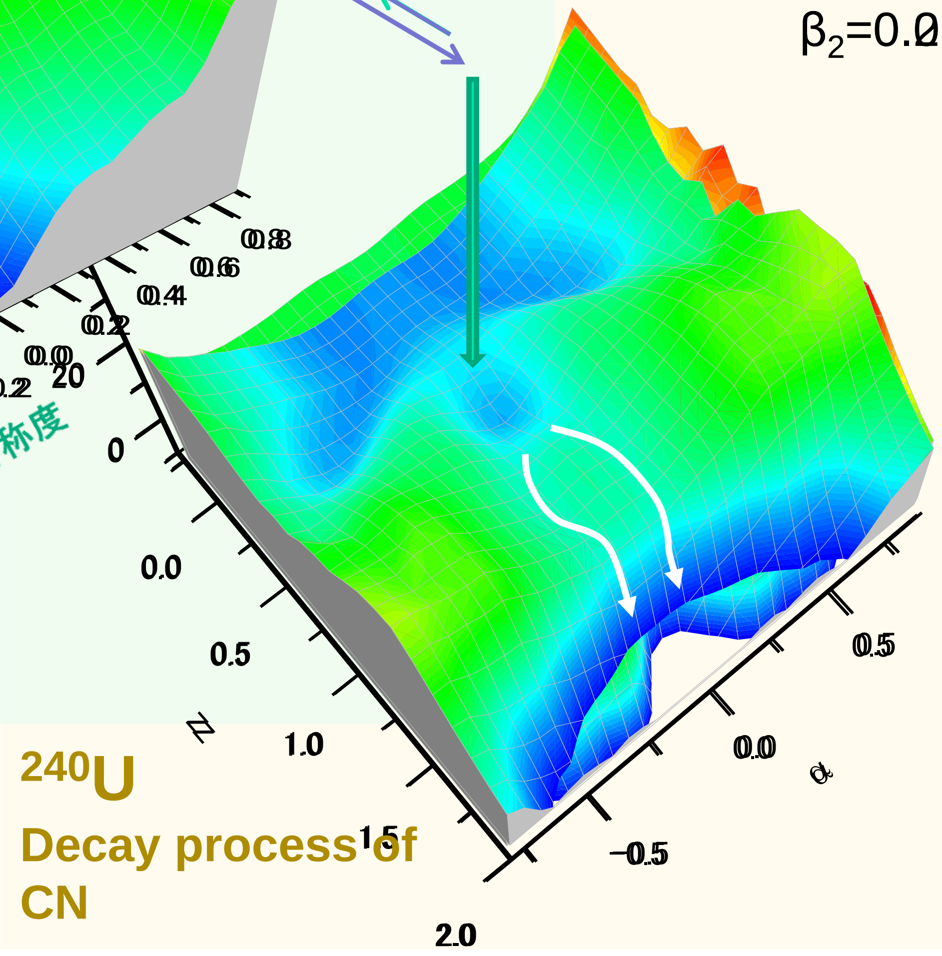
$$\alpha = \frac{A_1 - A_2}{A_1 + A_2}$$

m_{ij} : Hydrodynamical mass (mono-nucleus region), Reduced mass (separated region)

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



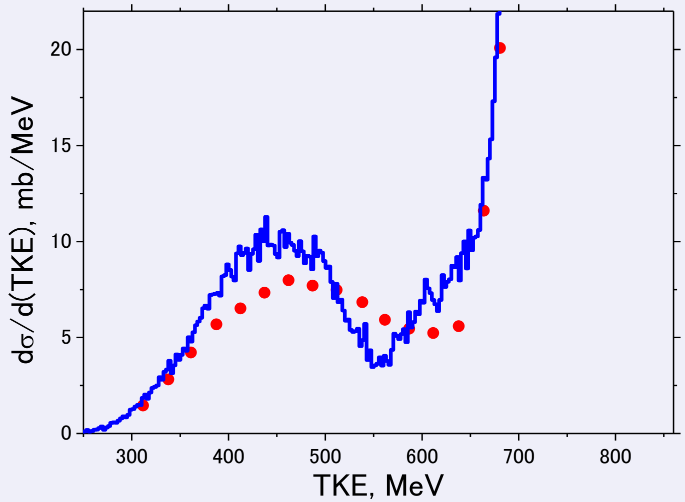


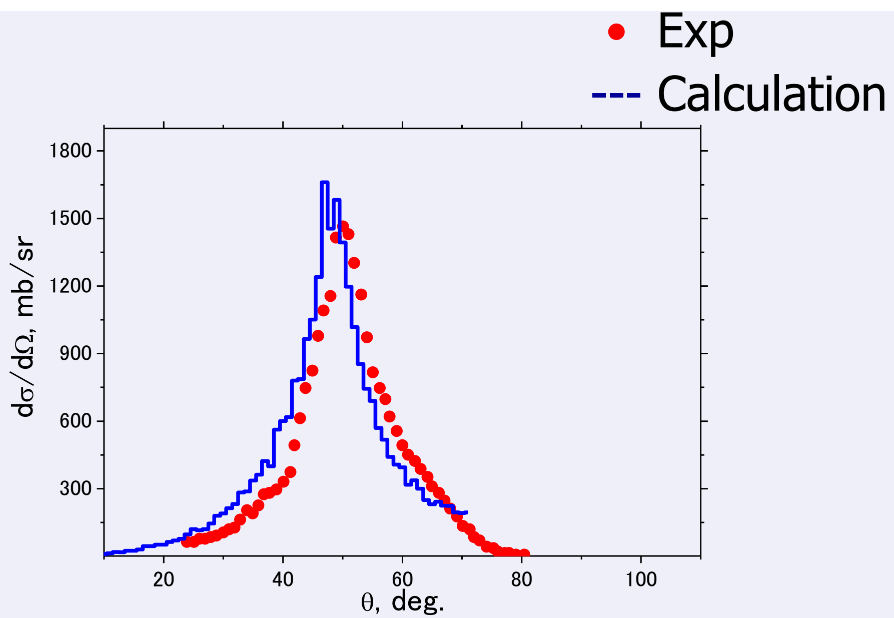


$^{18}O + ^{238}U \rightarrow ^{16}O + ^{240}U$

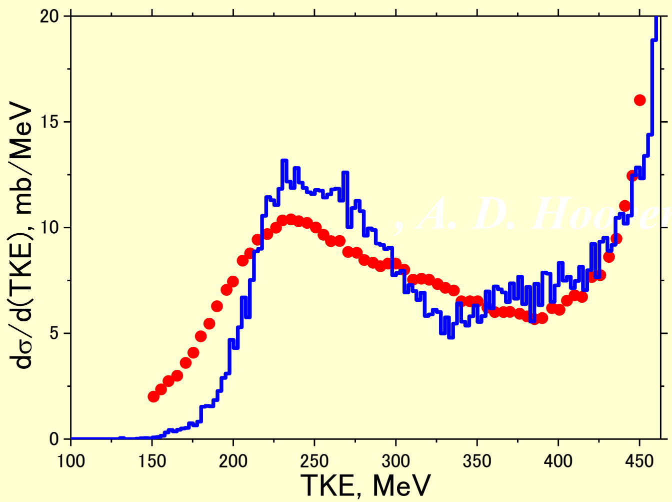
Calculation with Langevin equation DIC

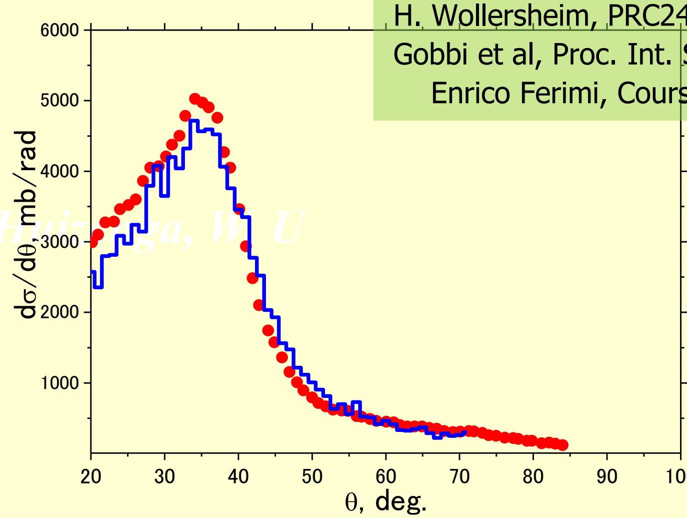
$^{136}Xe+^{209}Bi$ Ecm = 684 MeV





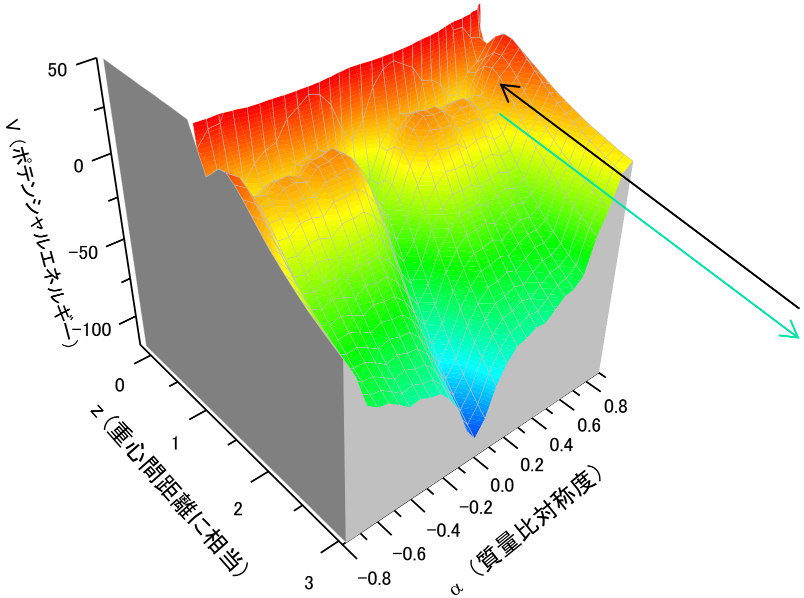
$^{86}Kr+^{166}Er$ Ecm = 464 MeV

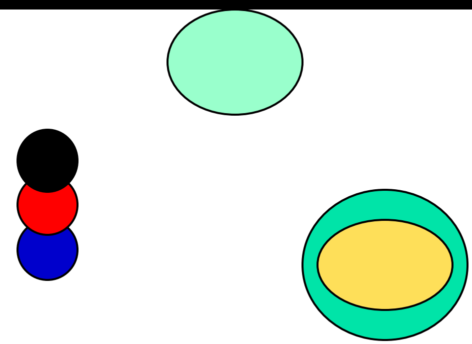


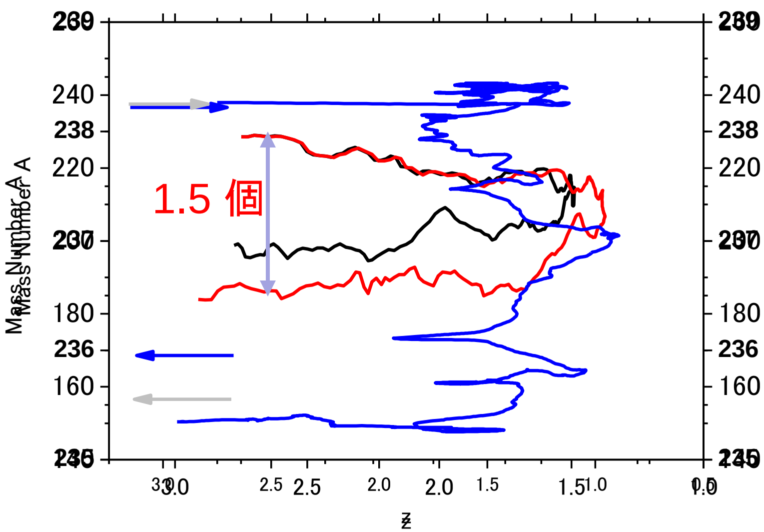


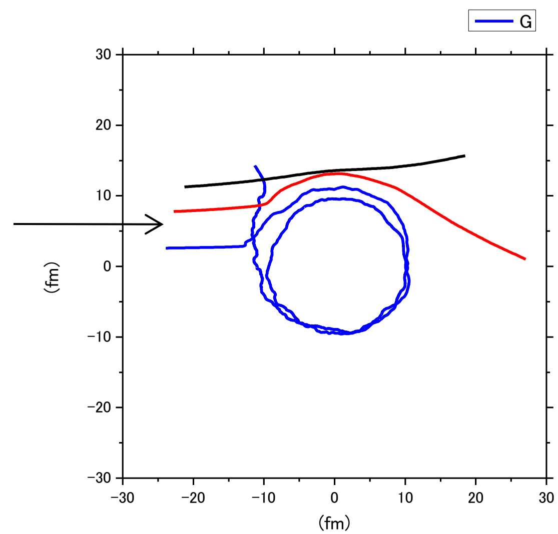
W.Wikcke et al, PRC22,128 (1980)
W.Schroder, Phys. Rep. 45, 301 (1978)
H. Wollersheim, PRC24,2114 (1981)
Gobbi et al, Proc. Int. School of Phys. Enrico Ferimi, Course LXXXVII (1979)

transfer reaction $^{18}O + ^{238}U \rightarrow ^{16}O + ^{240}U$ E_{lab}=160 MeV

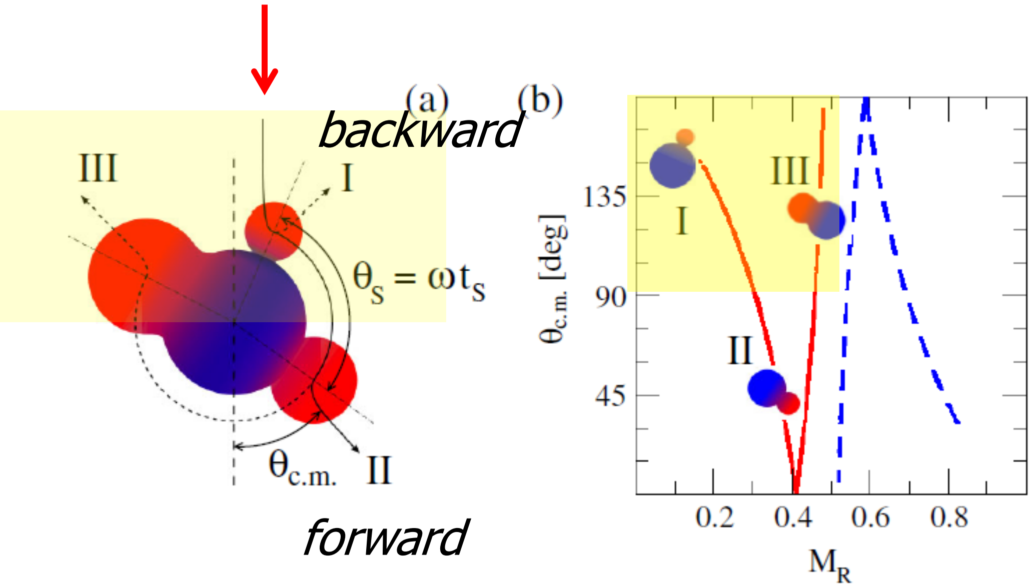




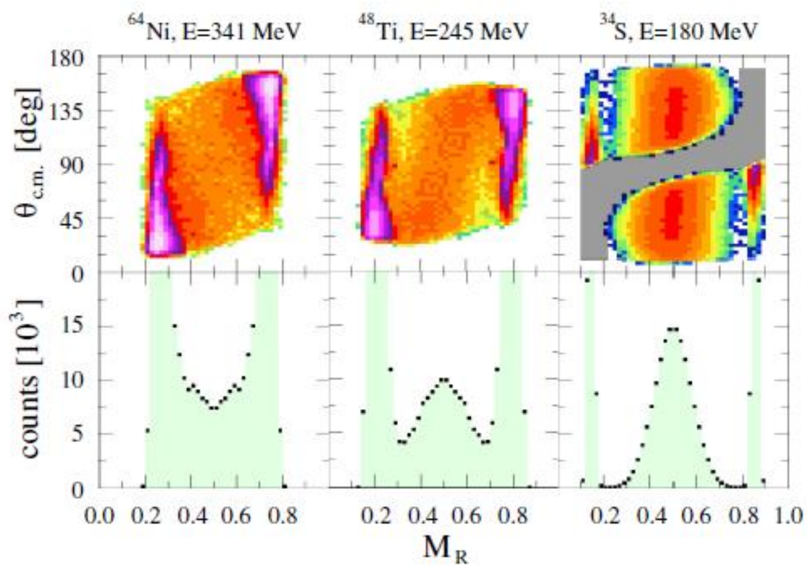




Emission angle and mass ratio of fission fragments



$^{64}Ni+^{184}W$ $^{48}Ti+^{184}W$ $^{34}S+^{184}W$



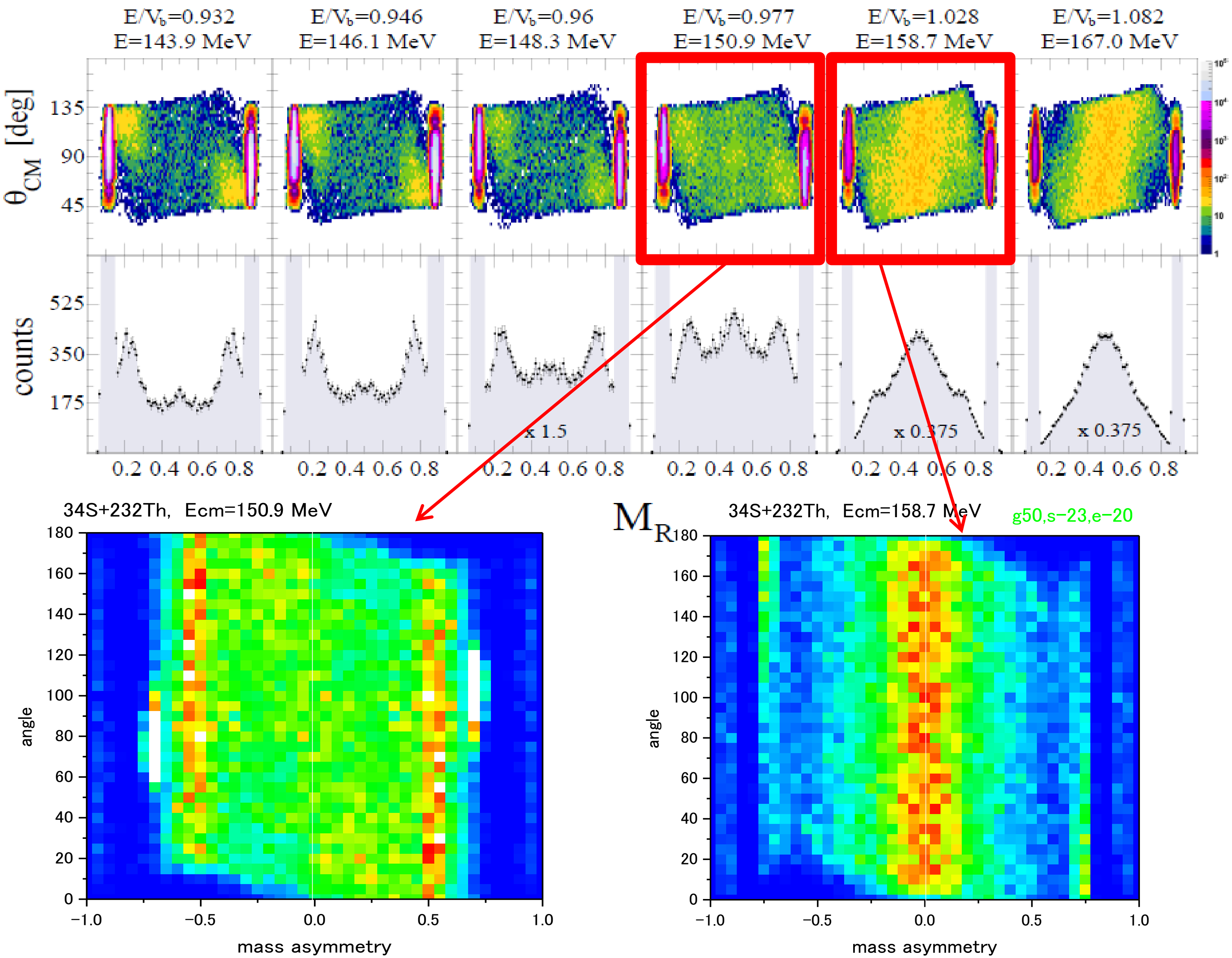
Angle distribution
→ Analyze fusion fission dynamics

A. Wakhle, D. Hinde and his group (ANU)

D.J. Hinde et al, PRL 101,092701 (2008)
R.du Rietz et al, PRL 106, 052701 (2011)

$^{34}S+^{232}Th$

Exp. A.Wakhe, D. Hinde et al (ANU)



Way to synthesize new SHE

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

2) Secondary beams

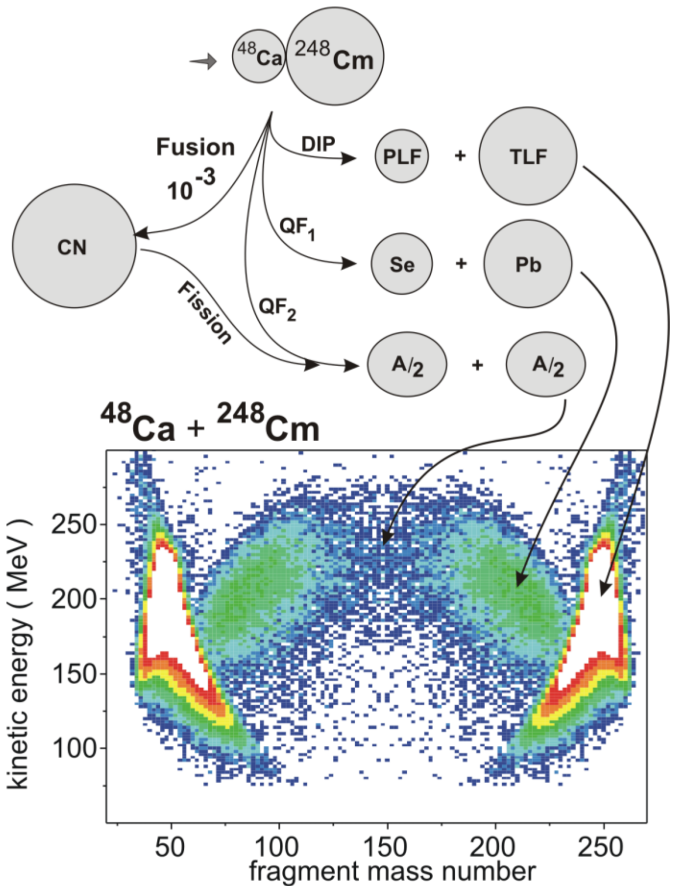
3) Transfer reaction U+Th, U+Cm

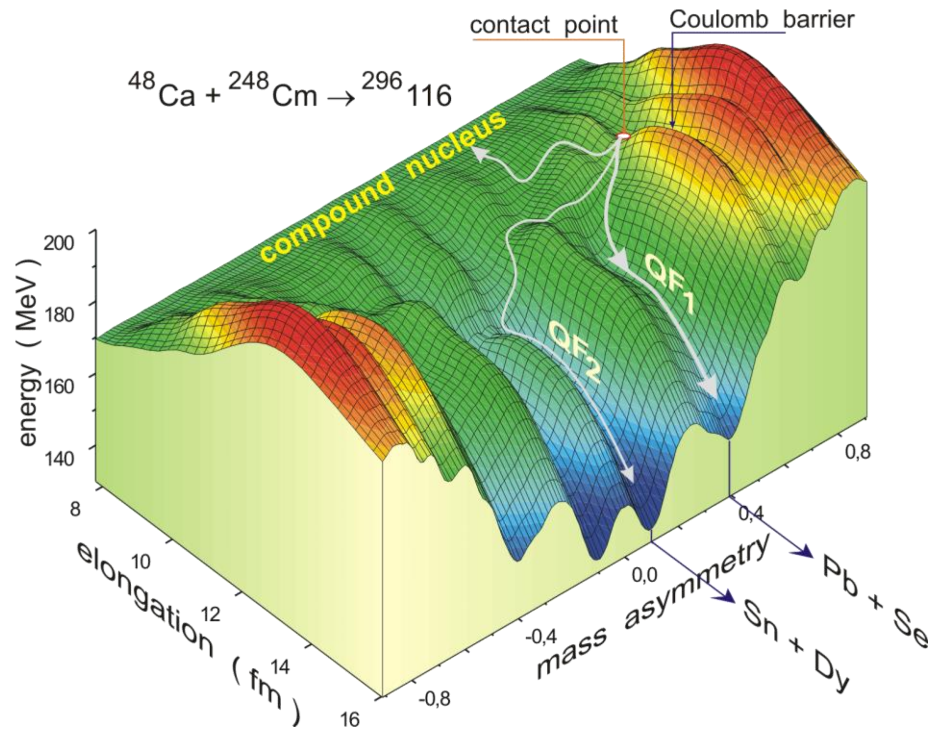
Valery Ivanovich Zagrebaev

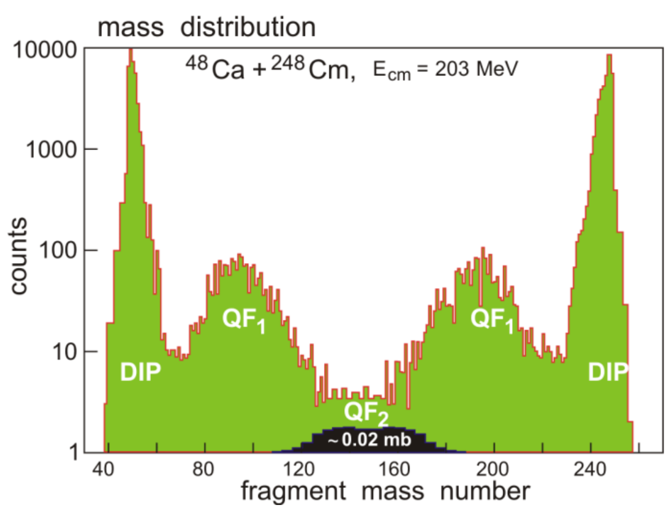
(1950-2015)

FLNR, JINR, Dubna Russioa

Quasi-fission and fusion-fission processes

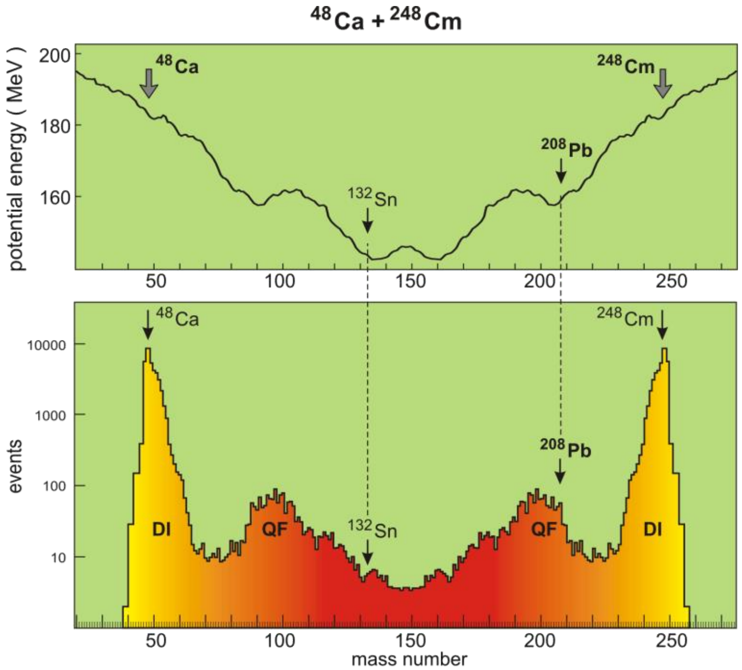




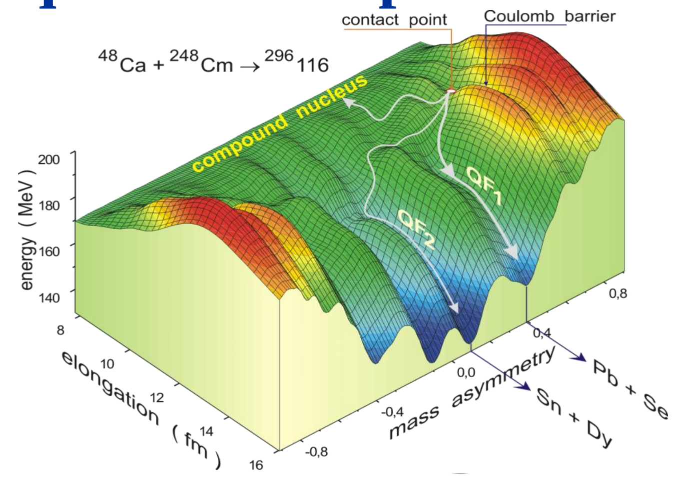


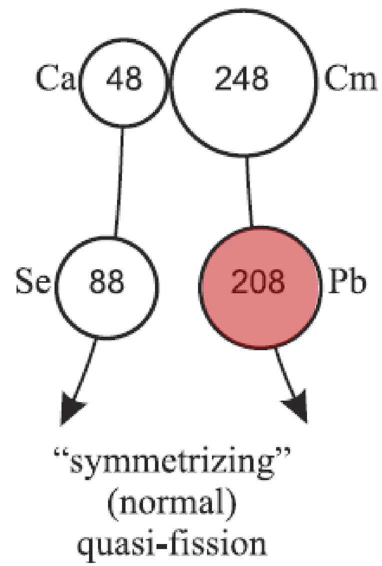
V.I. Zagrebaev

Inverse (antisymmetrizing) quasi-fission process



normal (symmetrizing) quasi-fission





V.I. Zagrebaev

System of coupled Langevin type Equations of Motion

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta\}$

$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

$$\frac{d\vartheta}{dt} = \frac{\ell}{\mu_R R^2}$$

$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}, \quad \frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta 1}}{\mu_{\beta 1}}$$

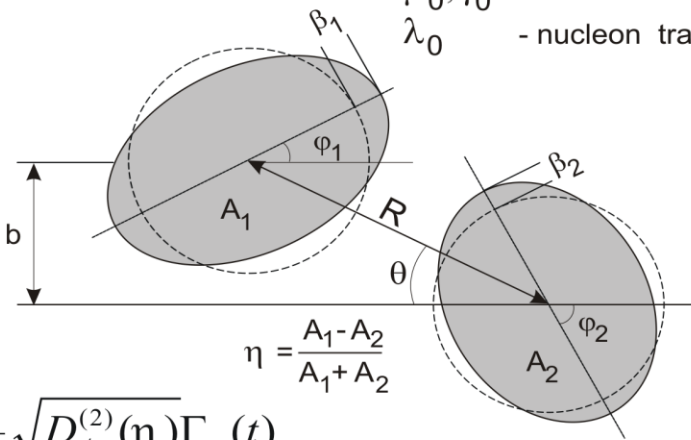
$$\frac{d\beta_2}{dt} = \frac{p_{\beta 2}}{\mu_{\beta 2}}$$

$$\frac{d\eta}{dt} = \frac{2}{A_{CN}} D_A^{(1)}(\eta) + \frac{2}{A_{CN}} \sqrt{D_A^{(2)}(\eta)}\,\Gamma_\eta(t)$$

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate



$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\ell^2}{\mu_R R^3} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial R} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\,\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{\partial V}{\partial \vartheta} - \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) R + \sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

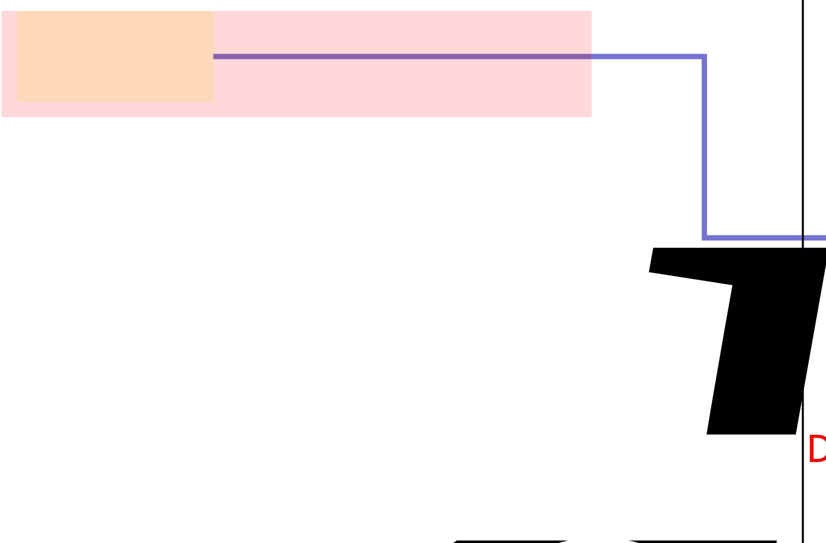
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\text{tan}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_\beta \frac{p_{\beta 1}}{\mu_{\beta 1}} + \sqrt{\gamma_{\beta 1} T}\,\Gamma_{\beta 1}(t)$$

$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_\beta \frac{p_{\beta 2}}{\mu_{\beta 2}} + \sqrt{\gamma_{\beta 2} T}\,\Gamma_{\beta 2}(t)$$

Nucleon transfer

Mass transfer



Neutron and proton transfer

$$\frac{d\alpha_N}{dt} = \frac{2}{N_{CN}} D_N^{(1)}(\alpha_N) + \frac{2}{N_{CN}} \sqrt{D_N^{(2)}} \Gamma(t),$$

$$\frac{d\alpha_Z}{dt} = \frac{2}{Z_{CN}} D_Z^{(1)}(\alpha_Z) + \frac{2}{Z_{CN}} \sqrt{D_Z^{(2)}} \Gamma(t),$$

$$\alpha_N = \frac{2N - N_{CN}}{N_{CN}},$$

$$\alpha_Z = \frac{2Z - Z_{CN}}{Z_{CN}},$$

Drift $$D_{N,Z}^{(1)} = \lambda_{N,Z}(A \to A+1) - \lambda_{N,Z}(A \to A-1),$$

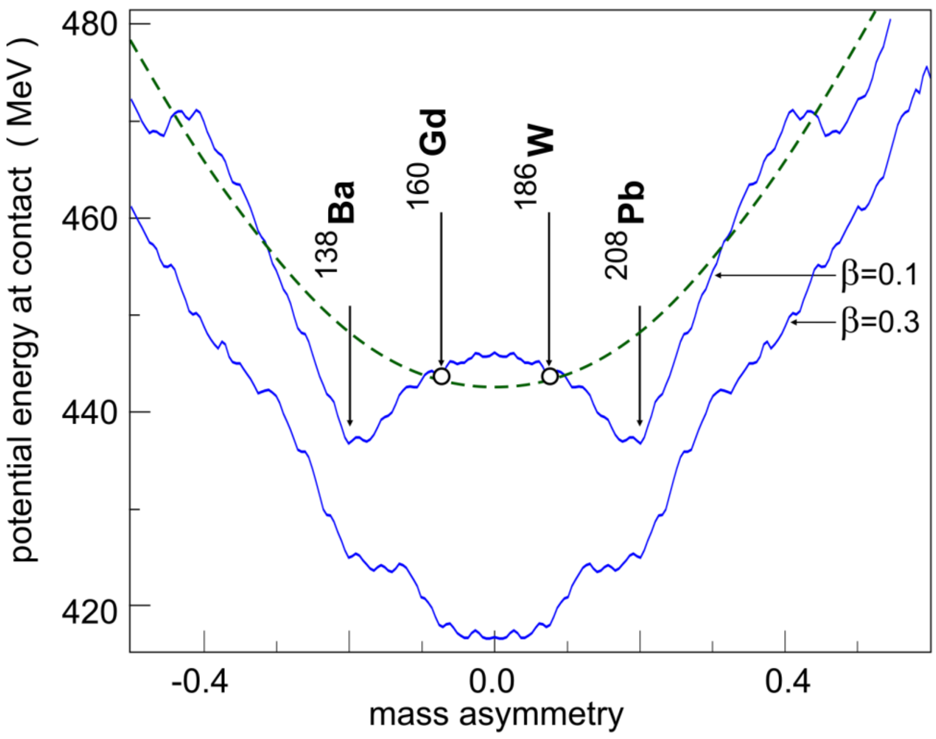
Diffusion $$D_{N,Z}^{(2)} = \frac{1}{2}\{\lambda_{N,Z}(A \to A+1) + \lambda_{N,Z}(A \to A-1)\}.$$

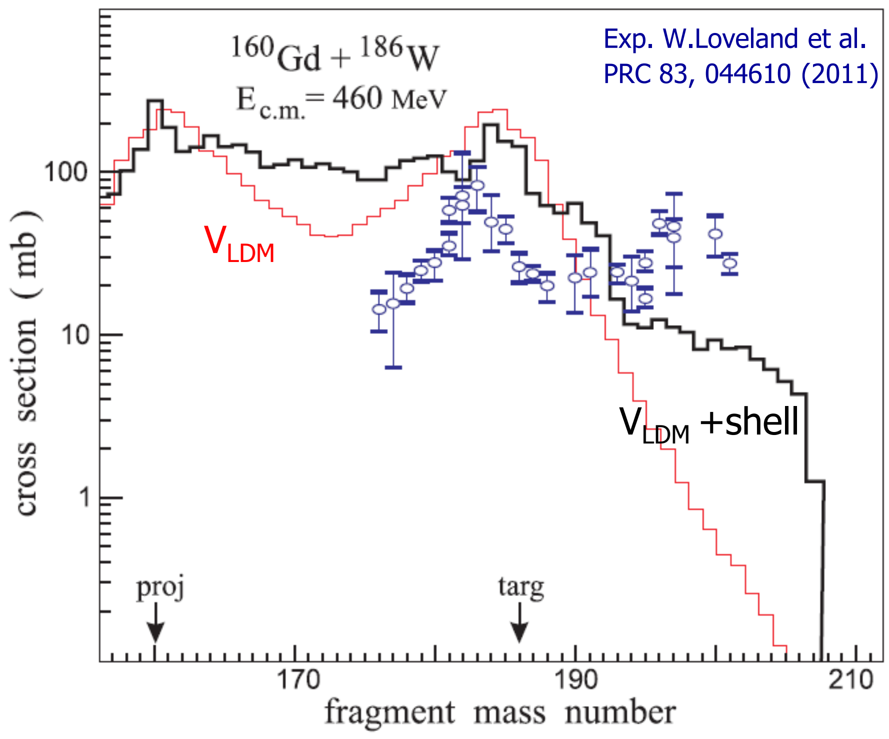
$$\lambda_{N,Z}^{(\pm)} = \lambda_{N,Z}^{0} \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{N,Z}^{tr}(z, \delta, A \to A \pm 1),$$

Nucleon Transfer rate

$$\lambda_0^N = \lambda_Z^0 = \frac{\lambda^0}{2}.$$

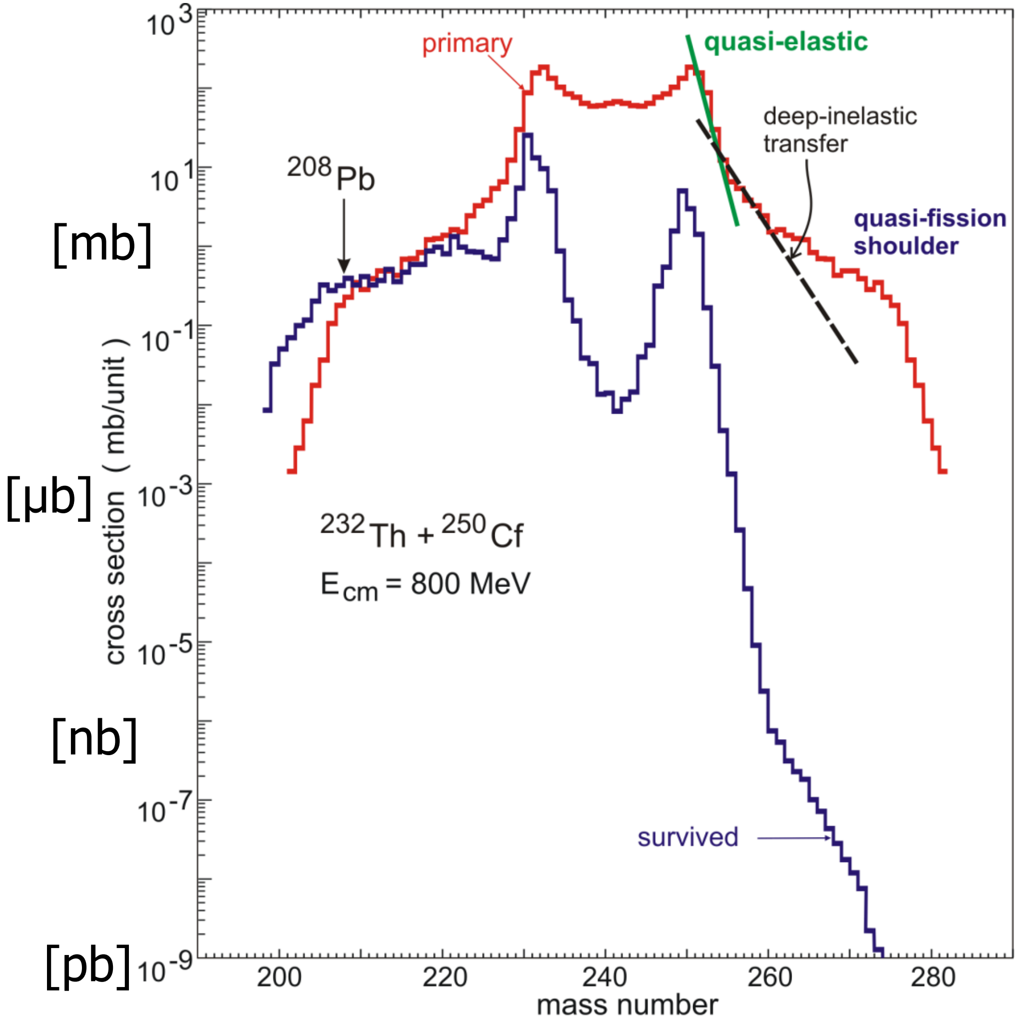
Shell effects in damped collisions
$^{160}Gd + ^{186}W$

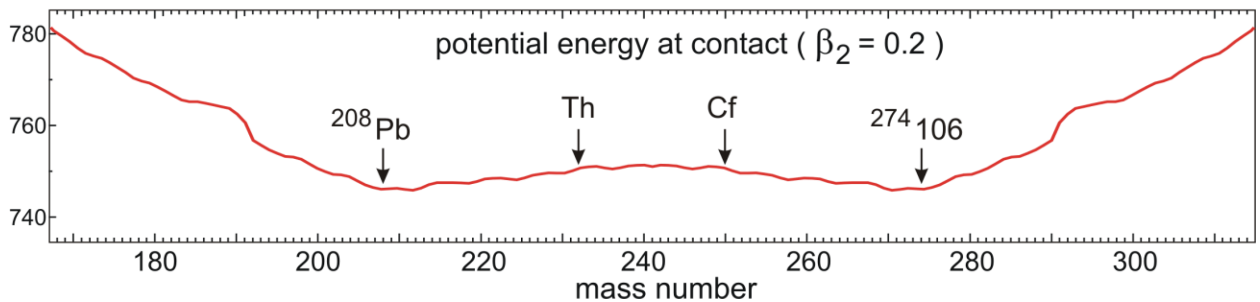




V.I. Zagrebaev

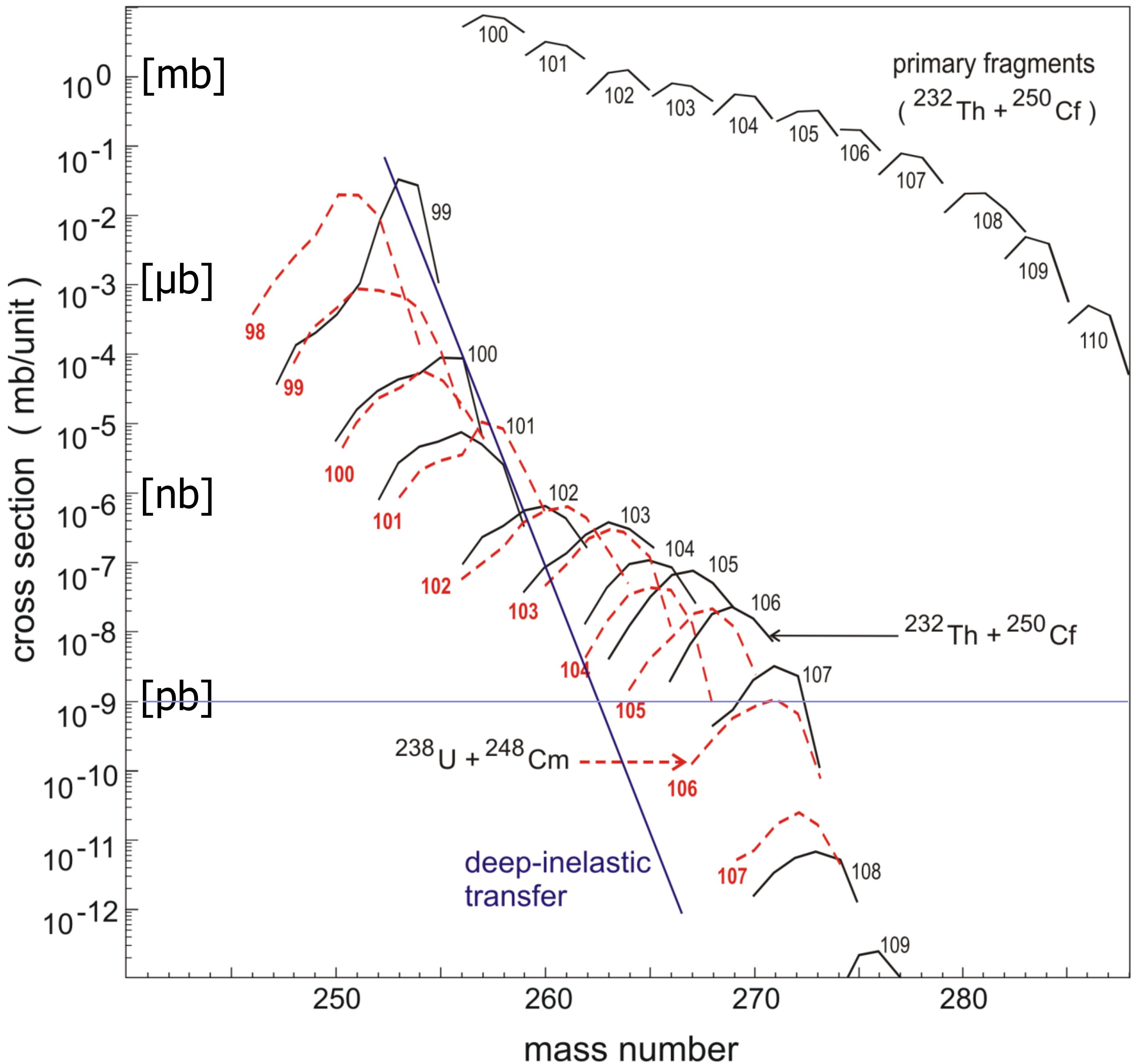
Shell effects in damped collisions of transactinides. New way to superheavies





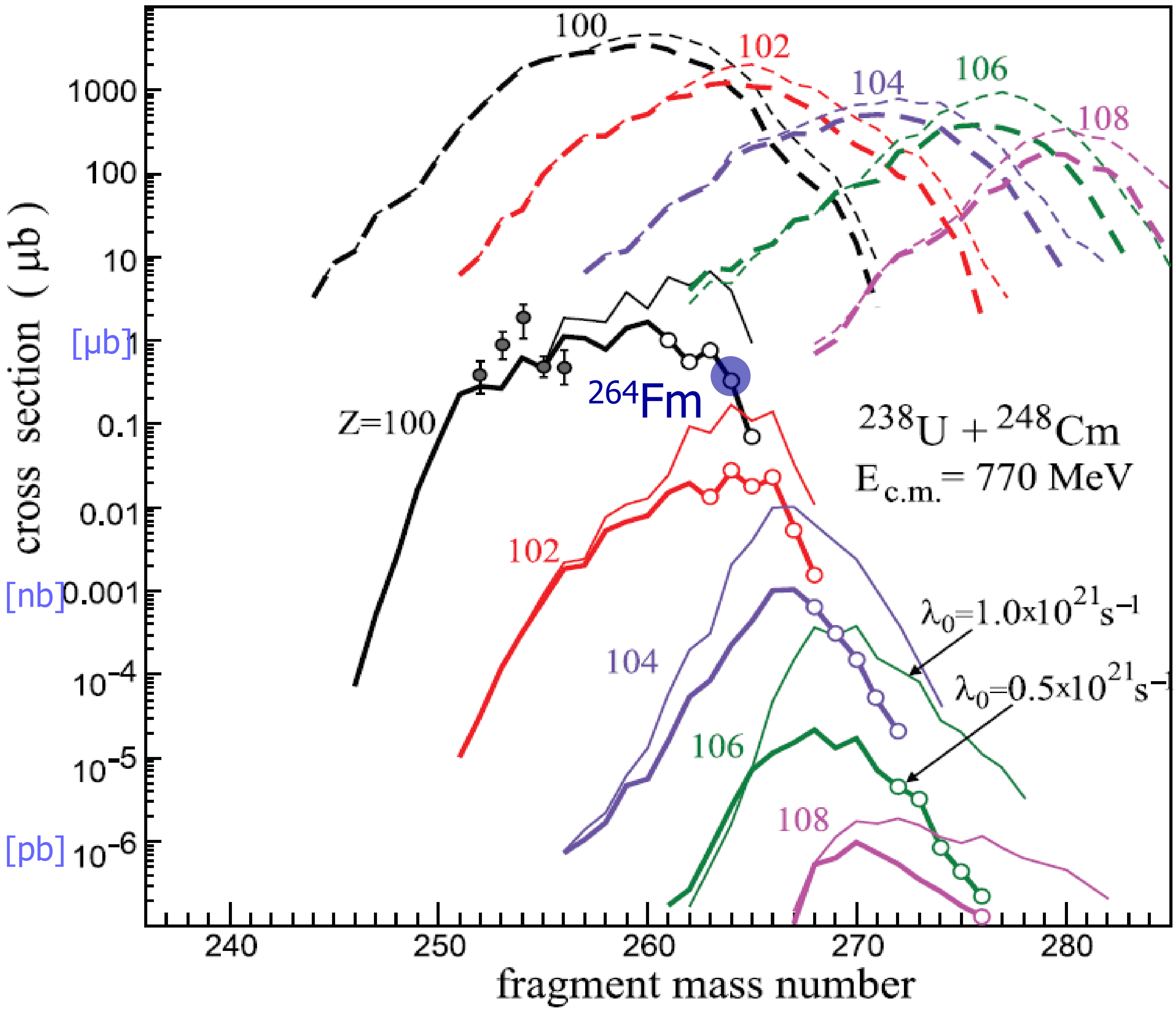
V.I. Zagrebaev

Isotopic yield of SHE in collisions of transactinides



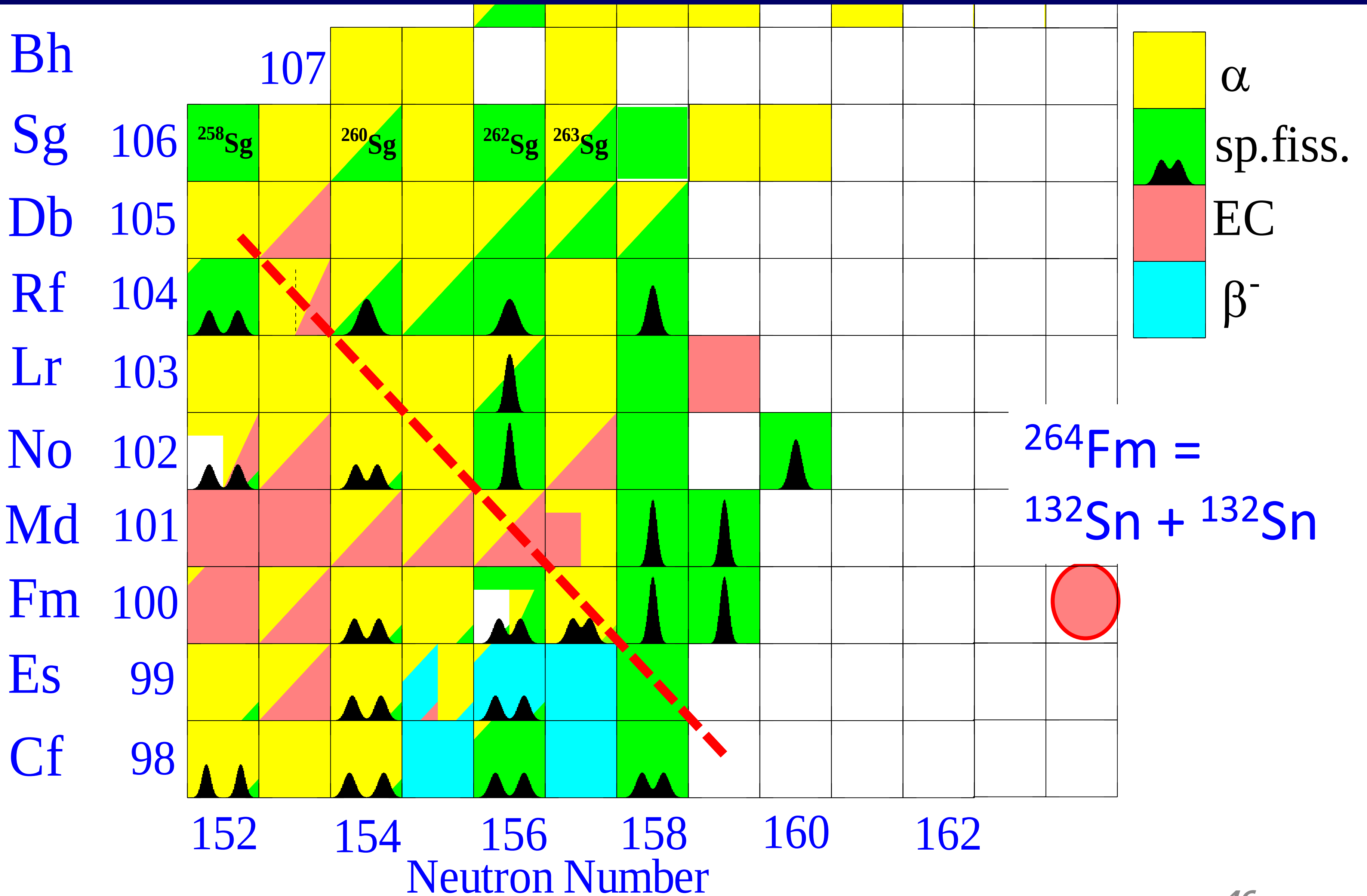
V.I. Zagrebaev

Isotopic yield of SHE in collisions of transactinides

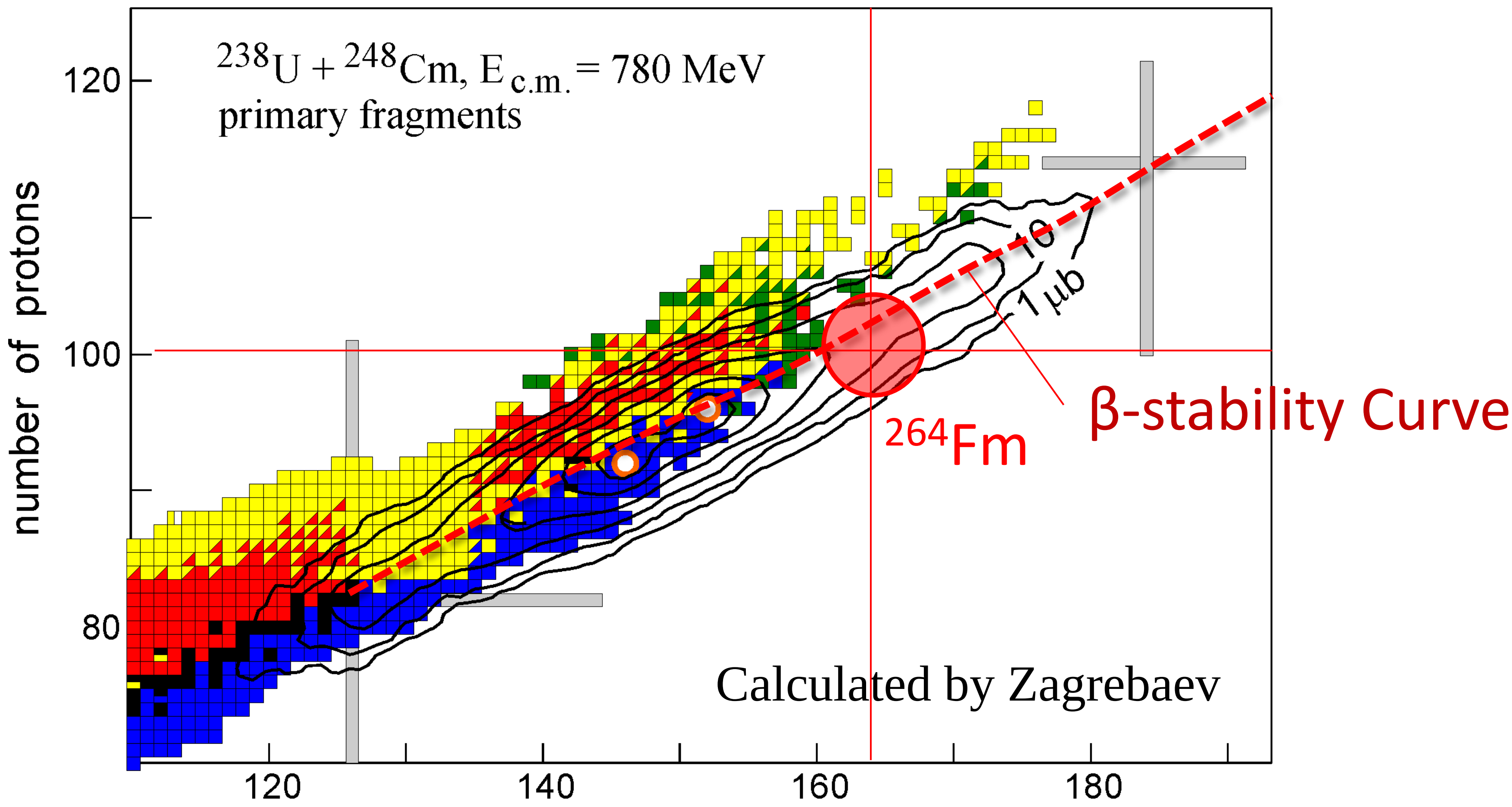


V.I. Zagrebaev and W. Greiner, PRC 87, 034608 (2013)

Spontaneous Fission (Fragment Mass Yield)



Nuclei produced in ^{238}U and ^{248}Cm

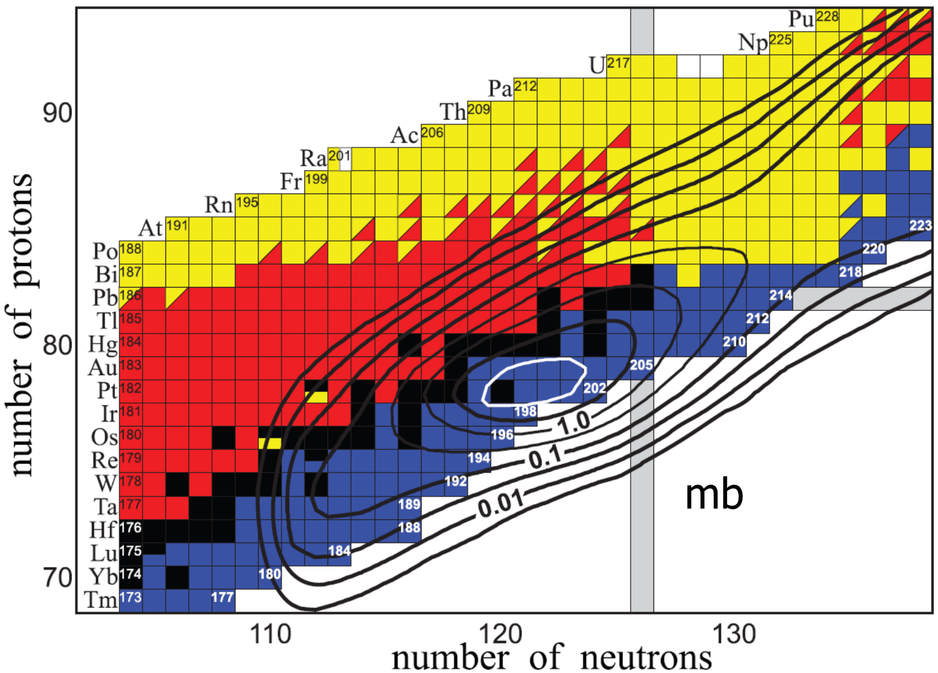


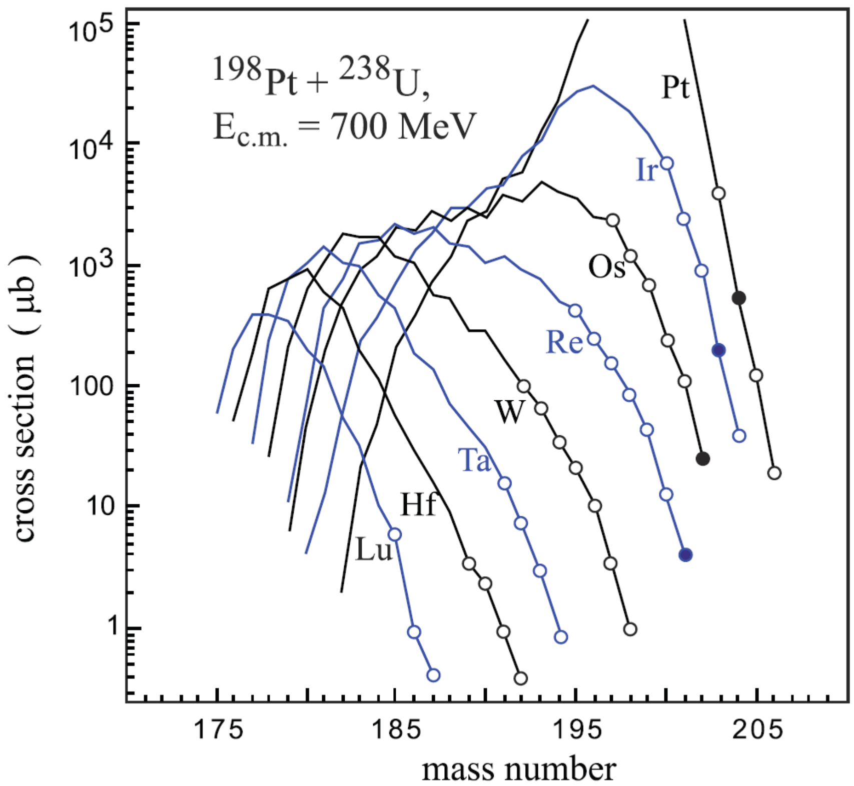
Number of neutrons

Isotopic yield of SHE in collisions of transactinides

$^{198}Pt + ^{238}U$

$E_{c.m.} = 700$ MeV





V.I. Zagrebaev and W. Greiner, PRC 87, 034608 (2013)

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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