Dynamical approach to synthesis of superheavy elements

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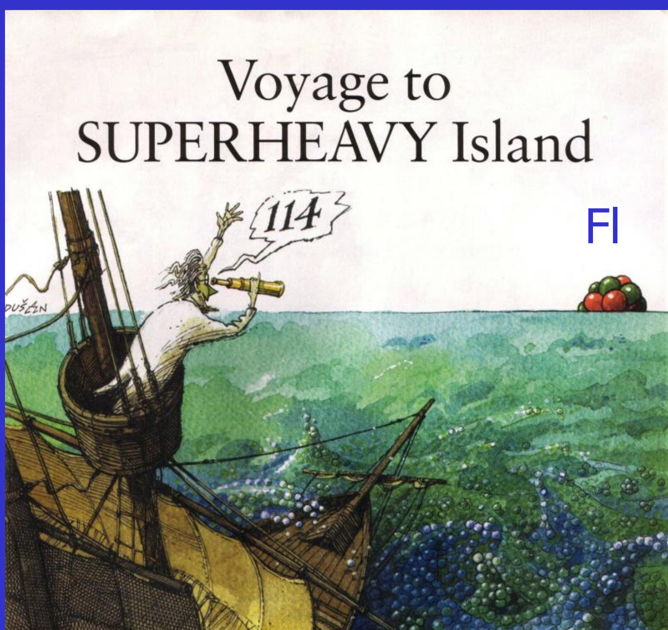


the RIBF Nuclear Physics Seminars 169th
29th October, 2013

Contains

1. Introduction
    Superheavy Elements and Theoretical approaches

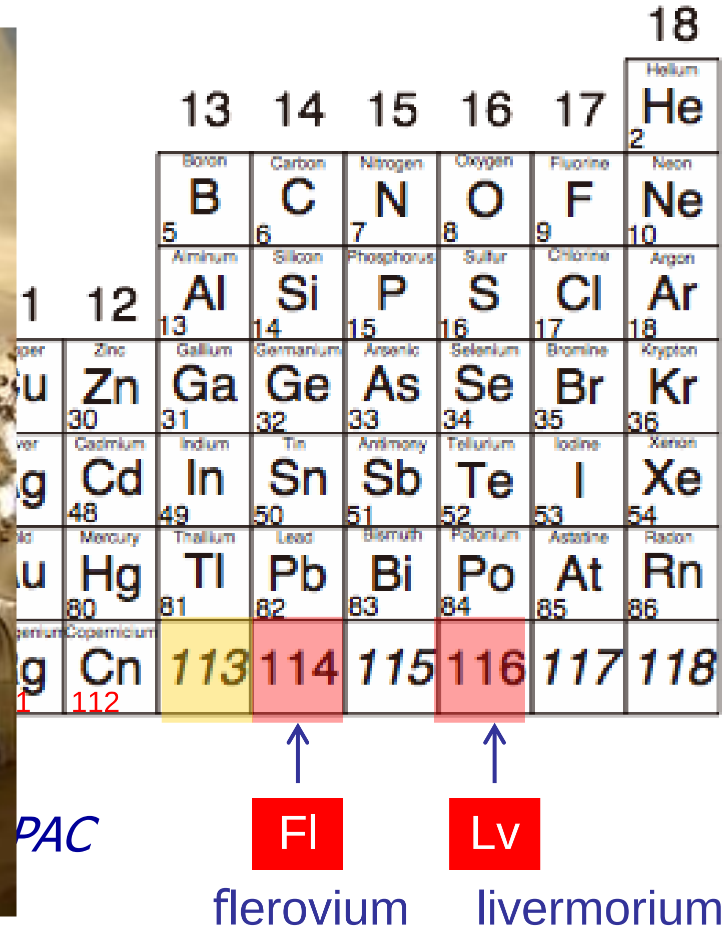
2. Model
    Dynamical model with Langevin equation
    Two center shell model

3. Results
    Evaporation residue cross section
    Mass distribution of Fission fragments

4. The way to synthesize new Superheavy elements
    by secondary beam

5. Summary

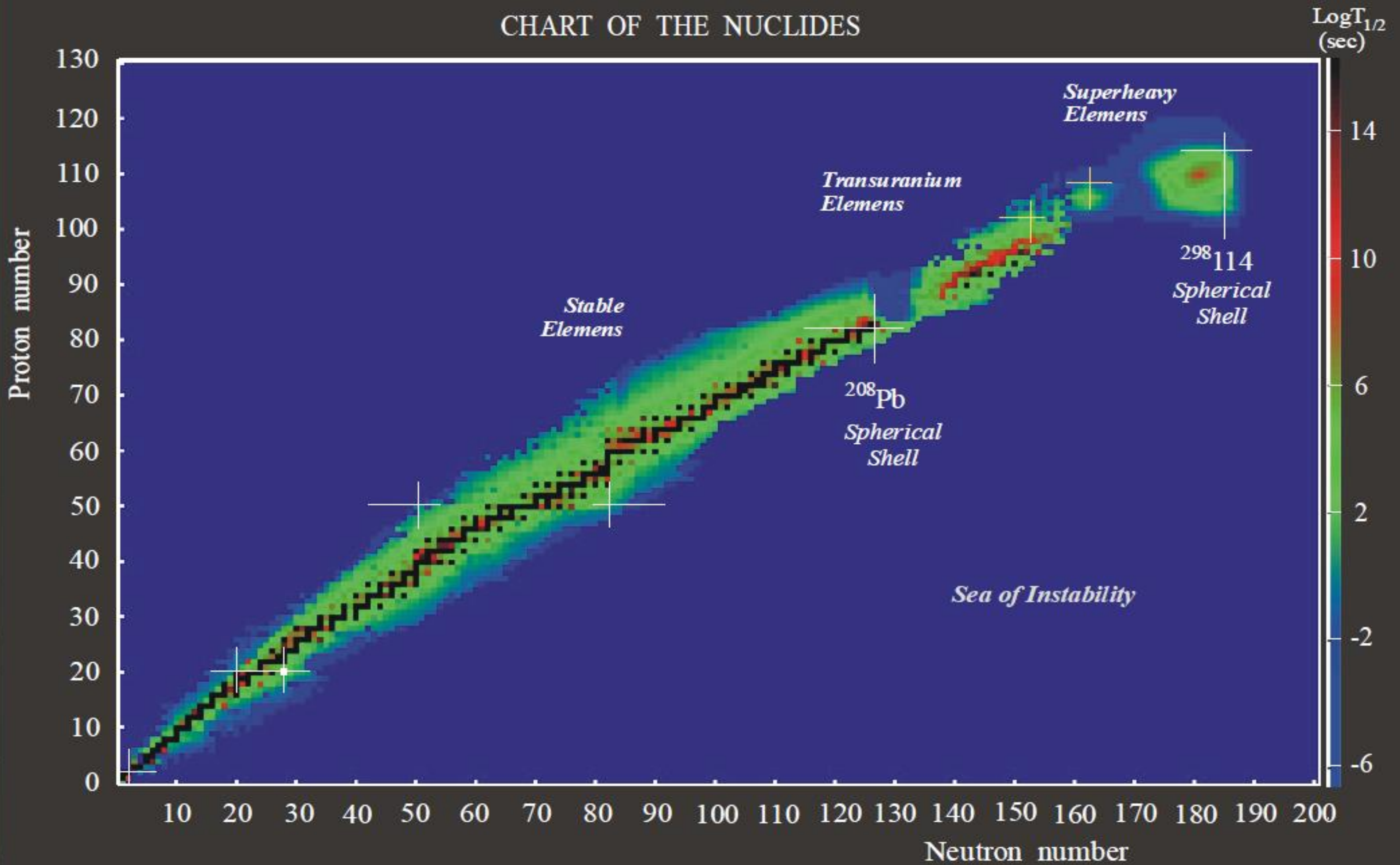
Periodic Table

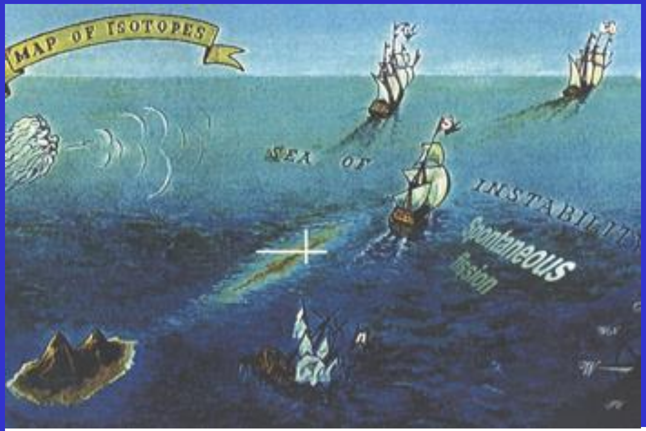


La*	Lanthanides	Lanthanum La 57	Cerium Ce 58	Praseodymium Pr 59	Neodymium Nd 60	Promethium Pm 61	Samarium Sm 62	Europium Eu 63	Gadolinium Gd 64	Terbium Tb 65	Dysprosium Dy 66	Holmium Ho 67	Erbium Er 68	Thulium Tm 69	Ytterbium Yb 70	Lutetium Lu 71
Ac**	Actinides	Actinium Ac 89	Thorium Th 90	Protactinium 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

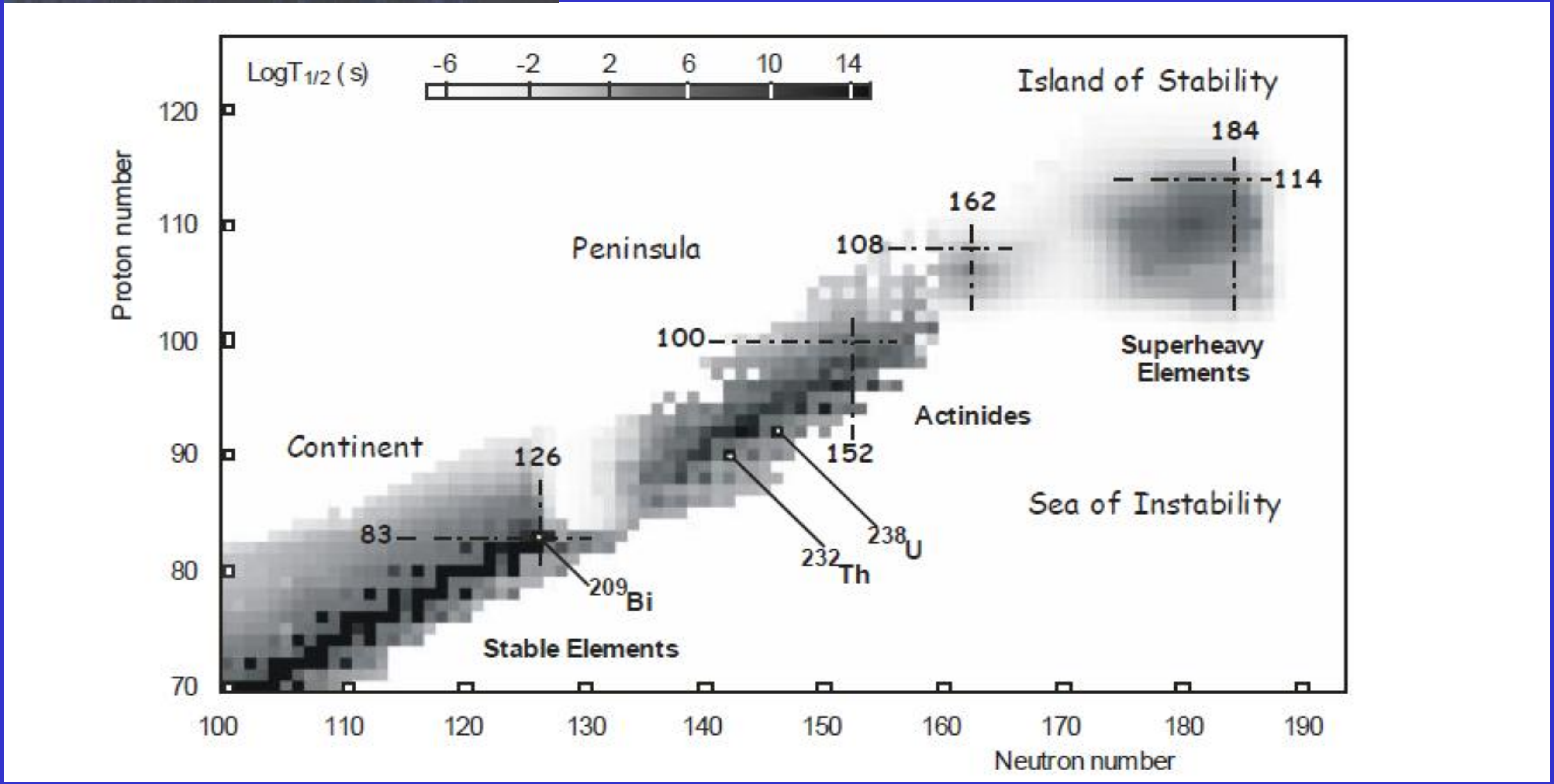
1. Introduction Nuclear Chart and Stability of Nuclei





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

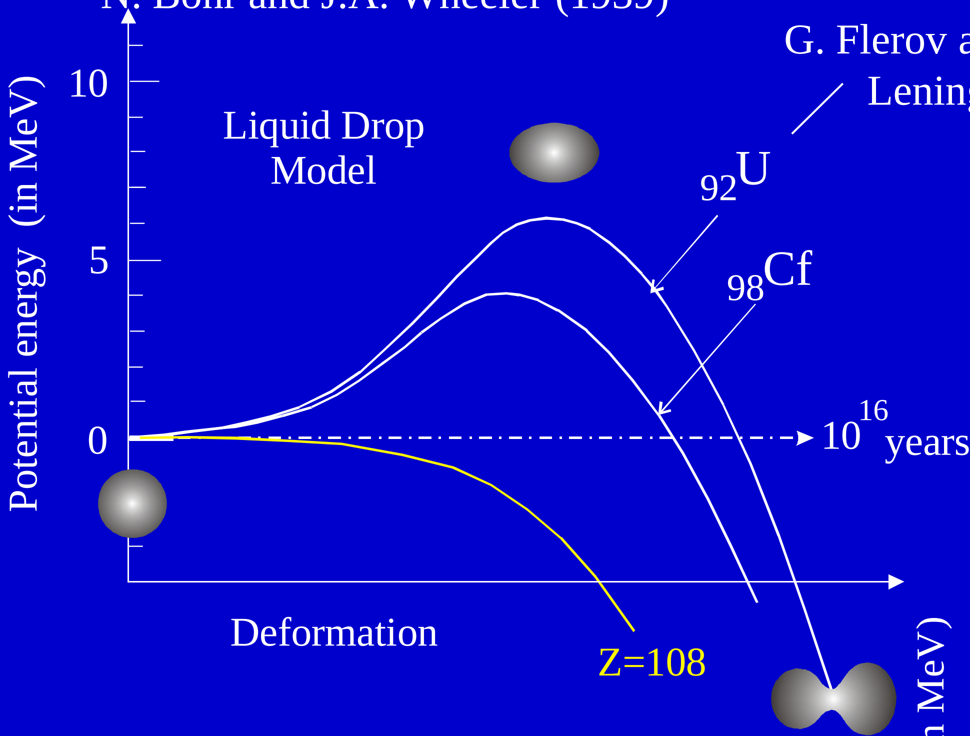


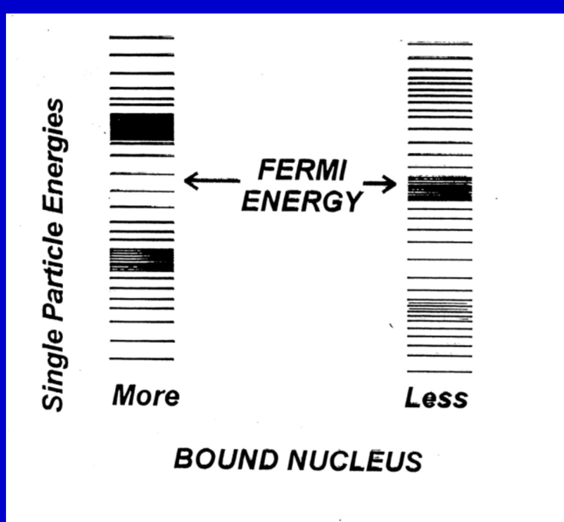
Yu.Ts.Oganessian

N. Bohr and J.A. Wheeler (1939)

G. Flerov and K. Petrjzak
Leningrad 1940

22 years later .

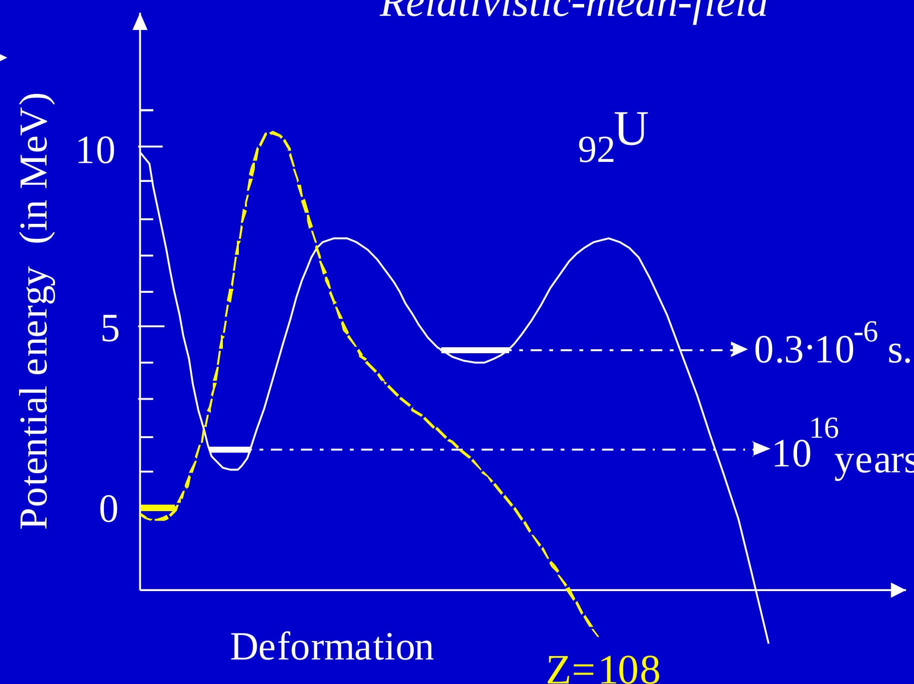




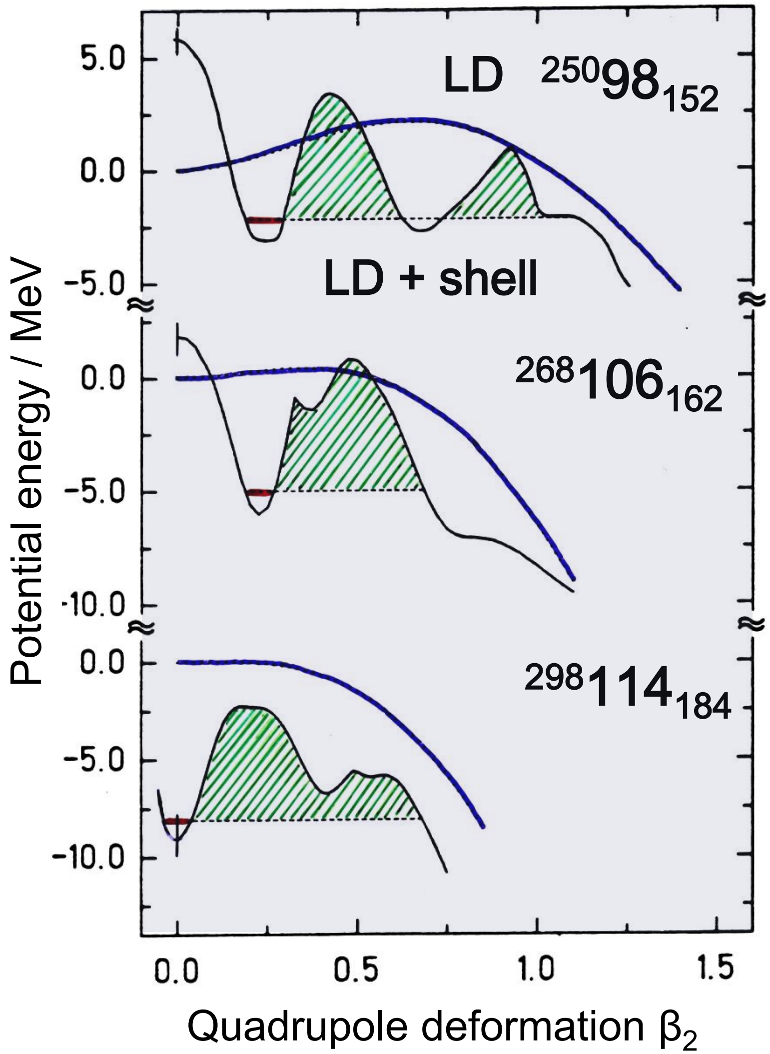
Microscopic Theory

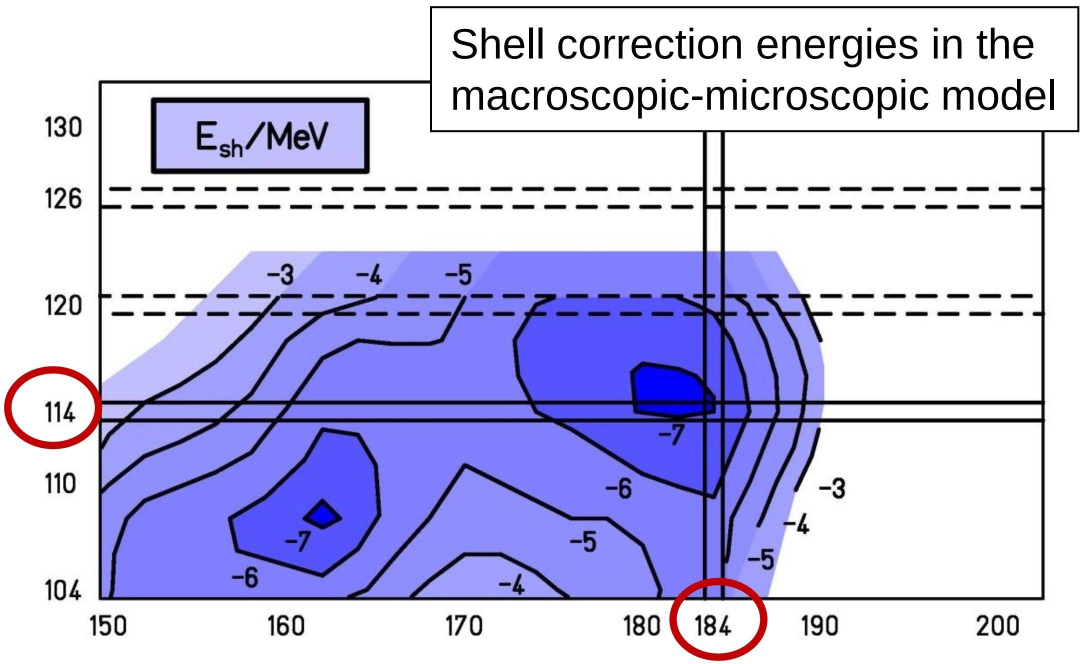
Models:

Macro-microscopic
Hartry-Fock-Bogolubov
Relativistic-mean-field

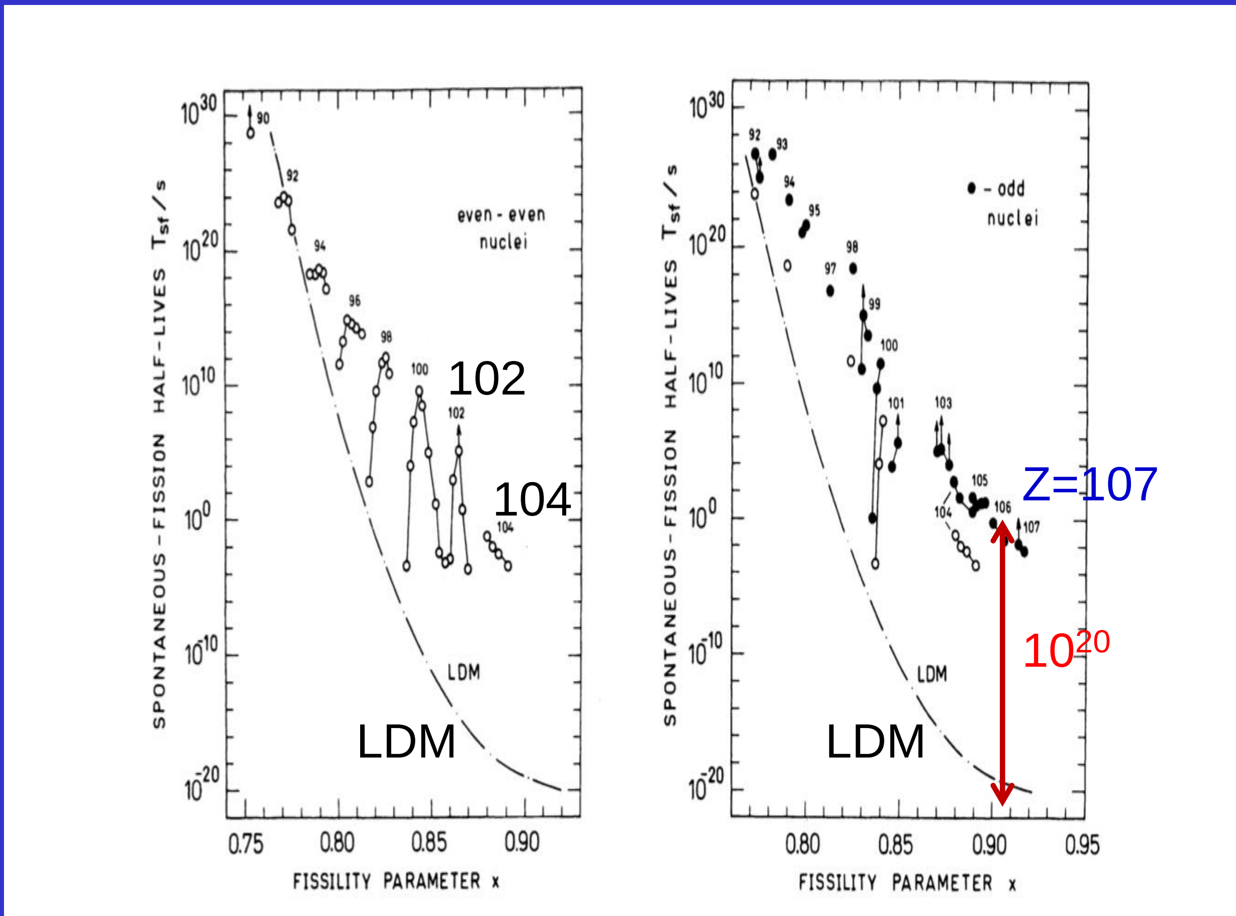


Fission barrier of Superheavy Elements





Stability of Superheavy nuclei



fissility parameter

$$x = \frac{E_C}{2E_S} = \frac{Z^2/A}{50.883\left\{1-1.7826\left[\left(N-Z\right)/A\right]^2\right\}}$$

Spherical nucleus

Surface energy

$$E_S = 4\pi r^2 A^{2/3}\gamma$$

Coulomb energy

$$E_C = \frac{3e^2}{5r_0}\frac{Z^2}{A^{1/3}}$$

Ys.Ts. Oganessian, Yu.A. Lazarev *Treatise on Heavy-Ion Science* vol.4 (1985)

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)*

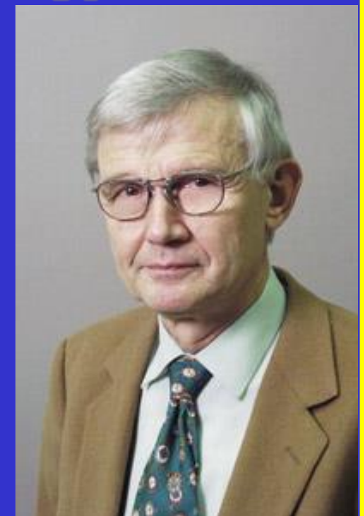
FLNR (Russia)

G.N. Flerov
(1913 -1990)

Yu.Ts. Oganessian
(1933-)

GSI (Germany)

P. Armbruster
(1931-)



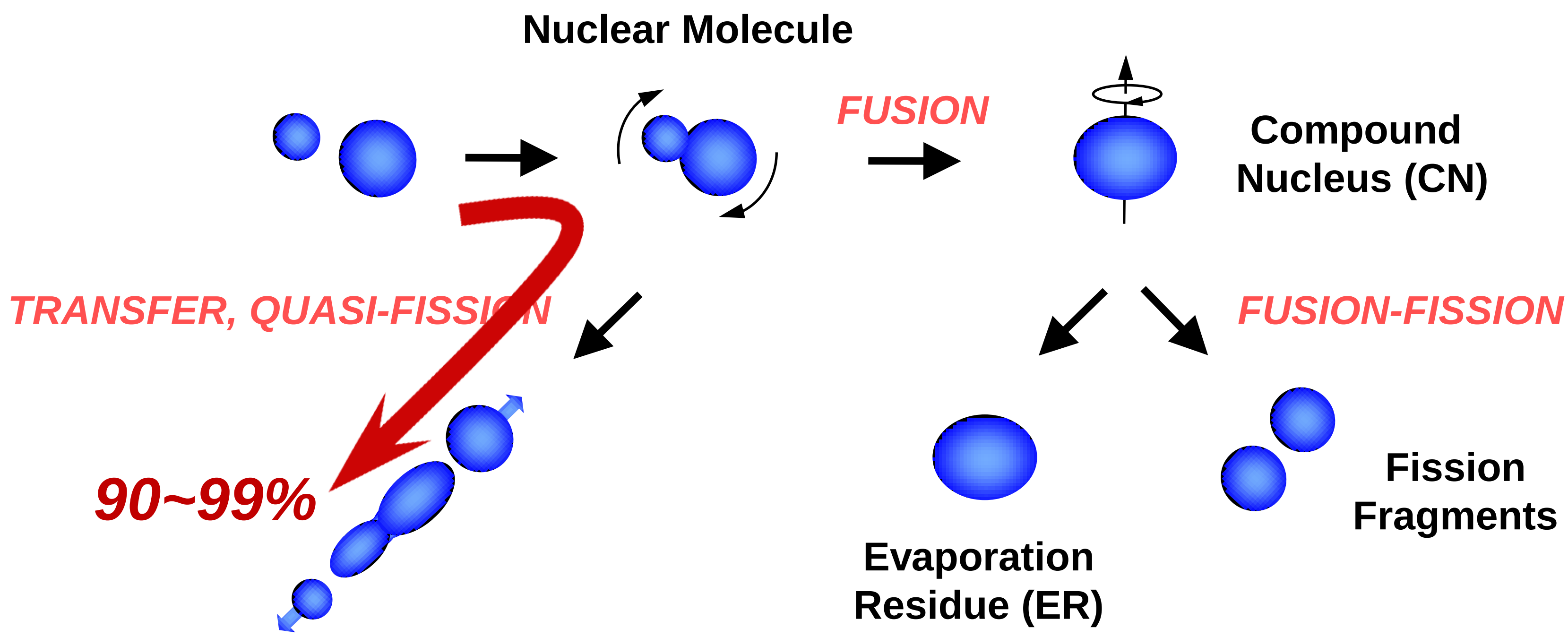
G. Muenzenberg
(1940-)

S. Hofmann
(1943-)

RIKEN (Japan)

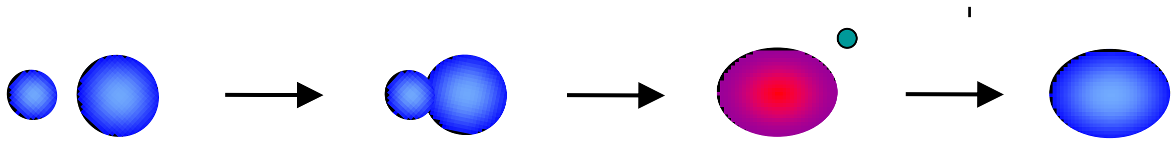
K. Morita
(1957-)

Fusion process in Superheavy mass region



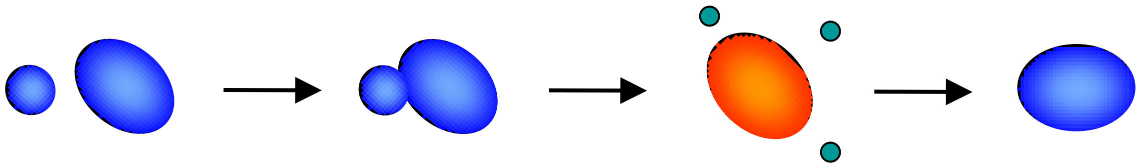
„Cold“ and „Hot“ Fusion Reactions

<u>Cold Fusion</u> → doubly magic target nuclei: Pb, Bi;
E*(CN) = 10 – 20 MeV; evaporation of 1 – 2 neutrons;
up to now successful for Z ≤ 113



reaction Q-value large

<u>Hot Fusion</u> → actinide targets (U, Cm, …) and ^{48}Ca projectiles;
E*(CN) = 30 – 40 MeV; evaporation of 3 – 4 neutrons;
up to now successful for Z ≤ 118



reaction Q-value small

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)

2012

119 $^{50}Ti + ^{249}Bk \rightarrow ^{296,295}119 + 3\text{-}4n$ (GSI- TASCA)

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

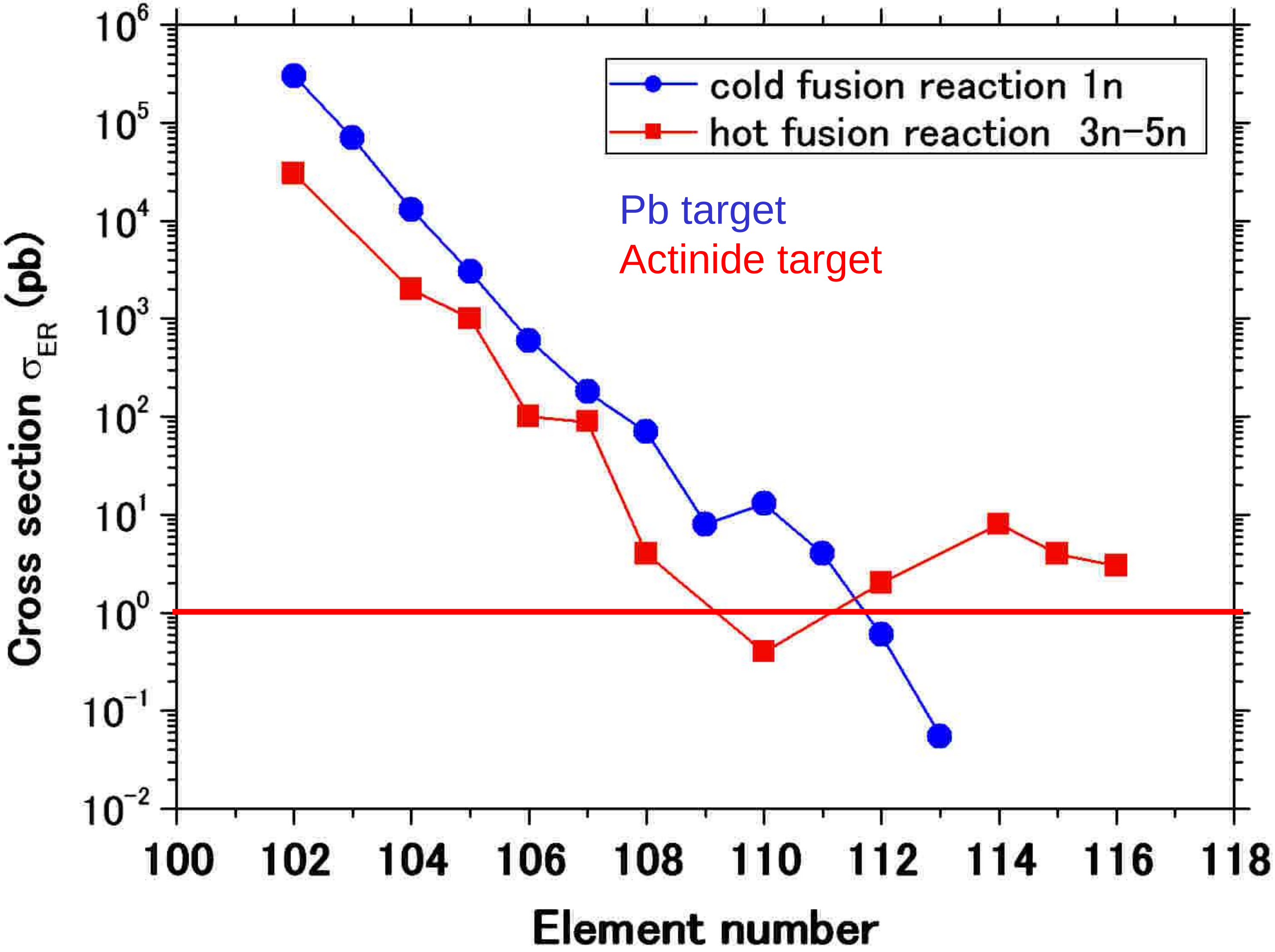
113 $^{70}Zn + ^{209}Bi \rightarrow ^{278}113 + n$ (RIKEN)

2010

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

Experimental data

Evaporation residue cross sections

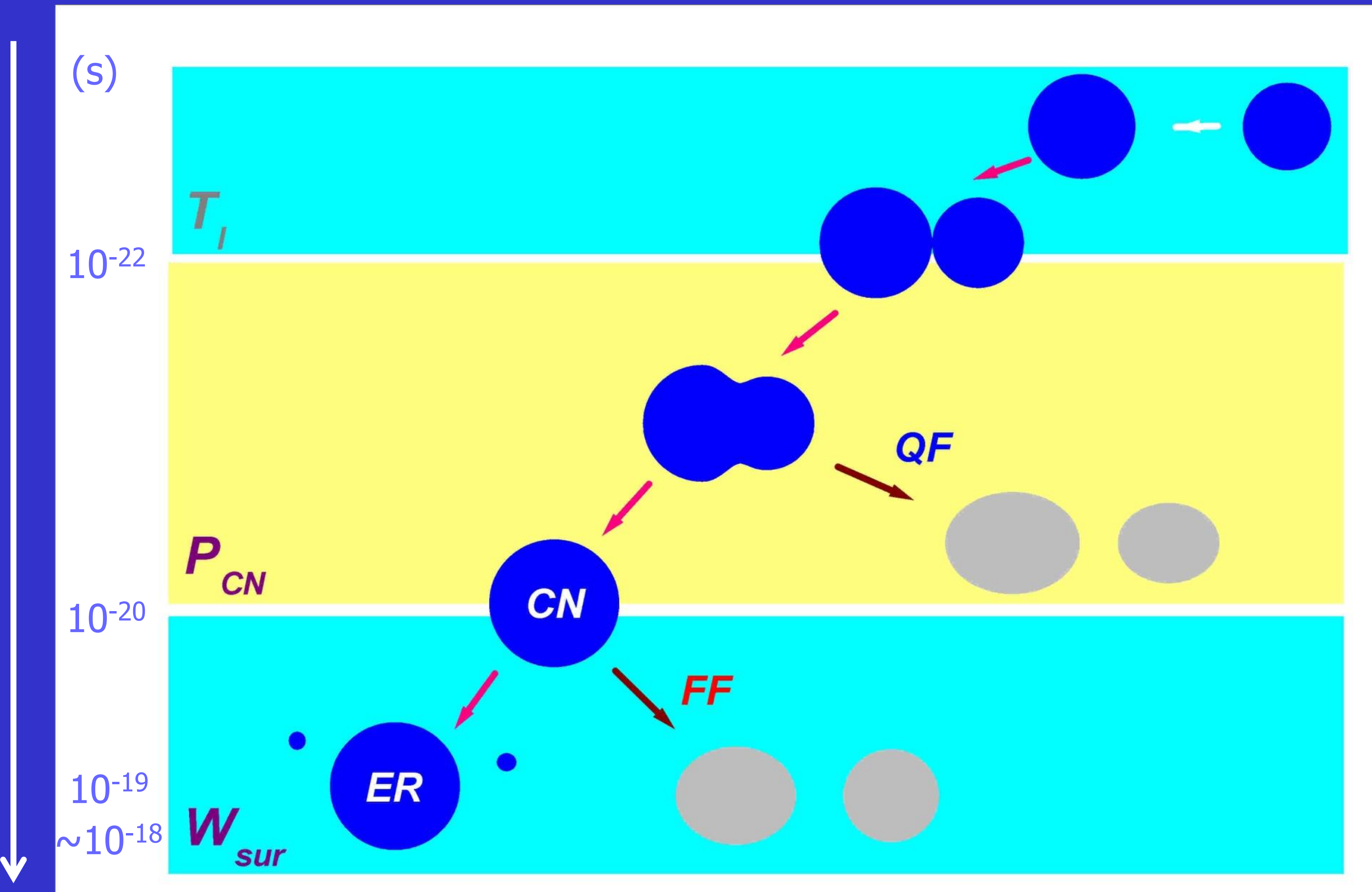


2. Model

2-1. Estimation of cross sections
2-2. Dynamical Equation

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

Reaction Time



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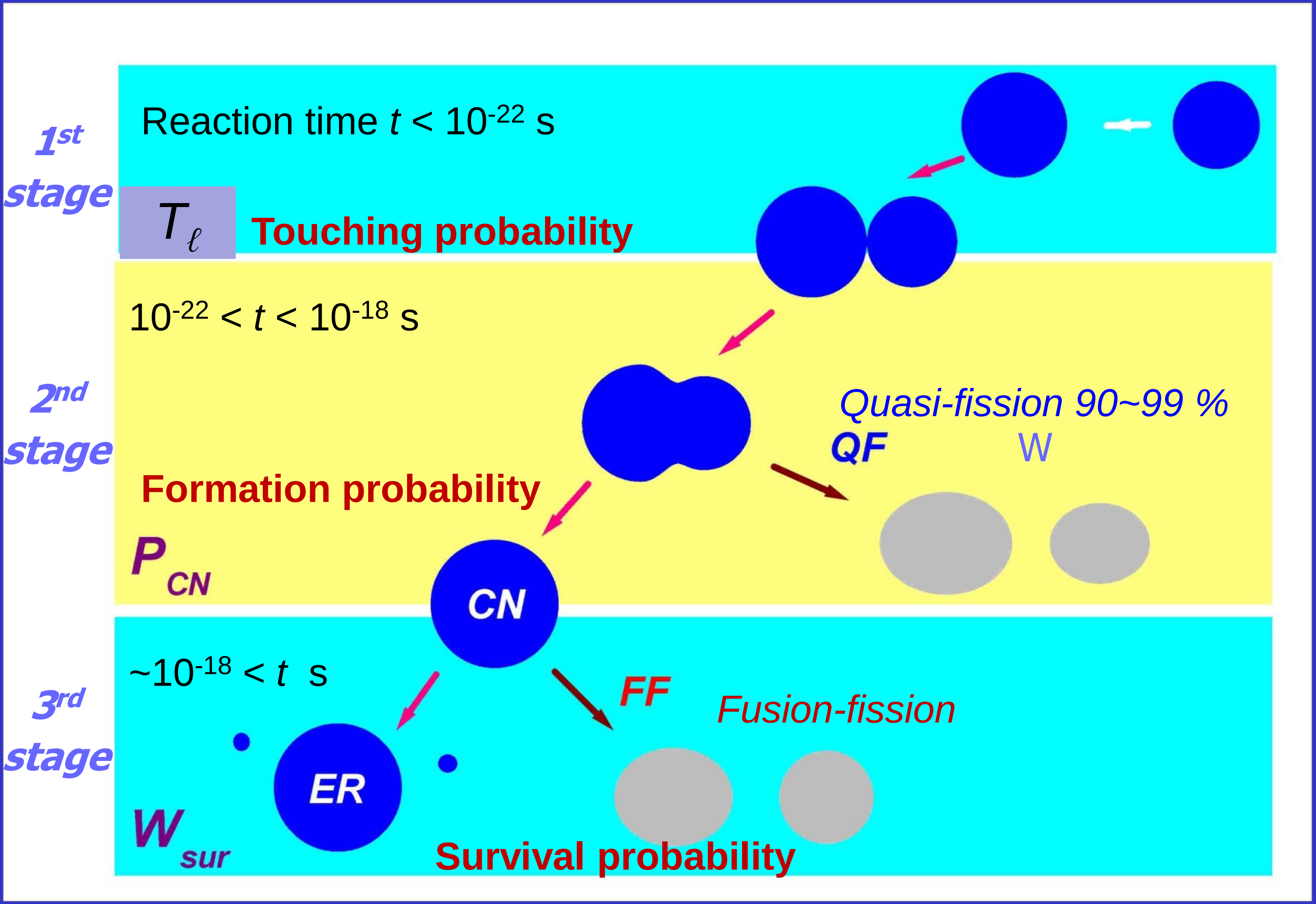
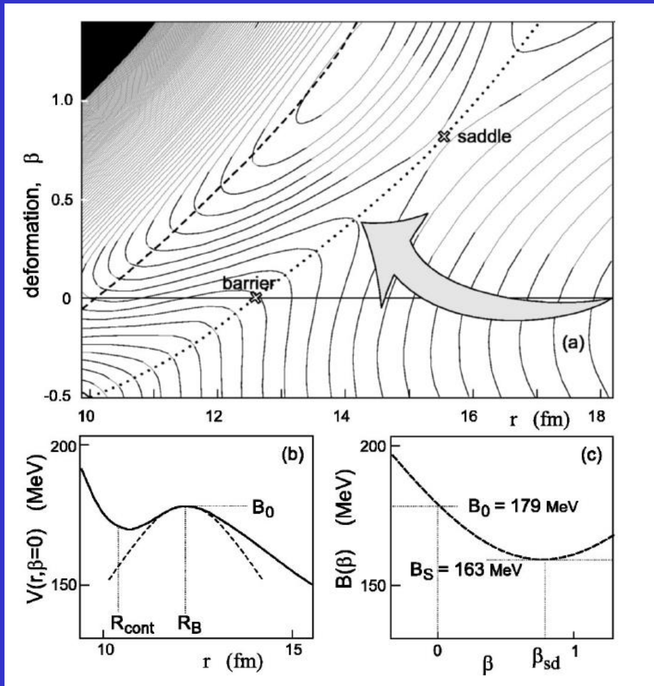


Recent Development of Theoretical Models

	T_l	P_{CN}	W_{suv}
Antonenko, Admiyan, Nasirov, Cherepanov, Volkov, Giardina, Scheid	Simple WKB	1D di-nucleus confi. Statistical method	Statistical model
Aritomo, Ohta	Experimental data, Gross-Kalinovski	3D two-center shell model 3D-Langevin eq.	Langevin with Statistical model
Bouriquet, Shen, Kosenko, Boilley, Abe	Gross-Kalinovski	2D two-center LD model 2D-Langevin eq.	Statistical model (KEWPIE)
Ohta	Simple WKB	Empirical function derived from results with 3D-Langevin	Statistical model
Zagrebaev, Greiner	Quantum (CC or empirical model)	3D two-core model Master eq.	Statistical model
Zagrebaev, Greiner, Aritomo, Karpov, Noumenko	Unified model 3D two-center shell model 3D-Langevin eq.		Statistical model
Swiatecki, Wilczynska, Wilczynski	Empirical method	1D-Diffusion model Analytical formula	Statistical model
Misicu, Gupta, Greiner	Deformation and Orientation		
Ichikawa, Iwamoto, Moller, Sierk	Deformation and Quadrupole zero-point vibrational energy		



$$T(E,l)=\int f(B)\frac{1}{1+\exp\left(\frac{2\pi}{\hbar\omega_B(l)}\left[B+\frac{\hbar^2}{2\mu R_B^2(l)}l(l+1)-E\right]\right)}dB.$$

$$f(B)=N\times\begin{cases}\exp\left[-\left(\frac{B-B_m}{\Delta_1}\right)^2\right], & B<B_m\\ \exp\left[-\left(\frac{B-B_m}{\Delta_2}\right)^2\right], & B>B_m,\end{cases}$$

V.I. Zagrebaev, et al. Phy. Rev. C. 65. (2001) 014607

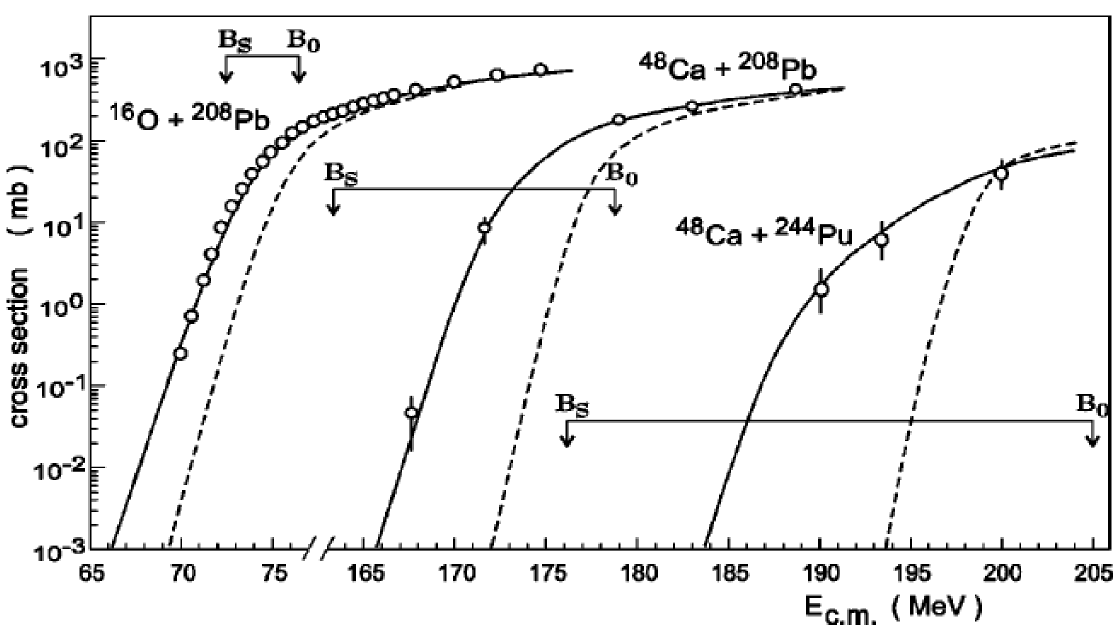


FIG. 1. Capture cross sections in the $^{16}O+^{208}Pb$ [11], $^{48}Ca+^{208}Pb$ [12], and $^{48}Ca+^{244}Pu$ [13] fusion reactions. Dashed lines represent one-dimensional barrier penetration calculations. Solid lines show the effect of dynamic deformation of nuclear surfaces (see the text). The arrows marked by B_0 and B_S show the positions of the corresponding Coulomb barrier at zero deformation and at the saddle point.

Fission width

Fission width

Bohr and Wheeler (1939)
Statistical model (transition state method)
initial state and final state

$$\Gamma_f^{BW} = \frac{1}{2\pi\rho(E^*)}\int_0^{E^*-U_B} dK\ \rho(E^*-U_B-K)$$

$$\sim \frac{T}{2\pi}\exp\left\{-\frac{U_B}{T}\right\}$$

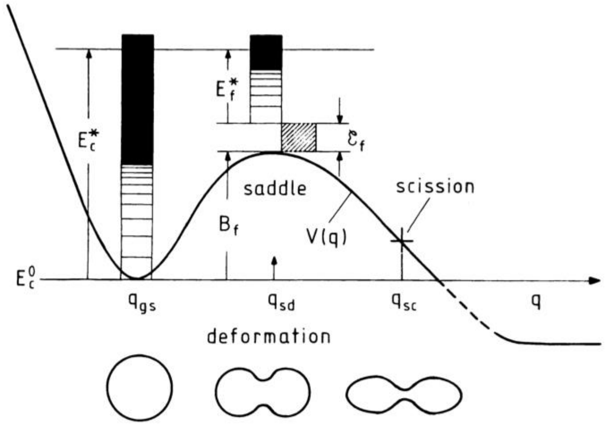


Figure 10.5 Schematic illustration of the fission mode of compound-nucleus decay. See text for a description.

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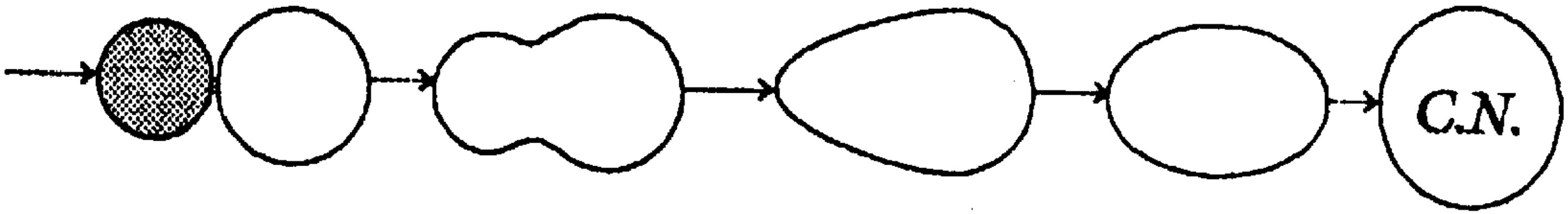
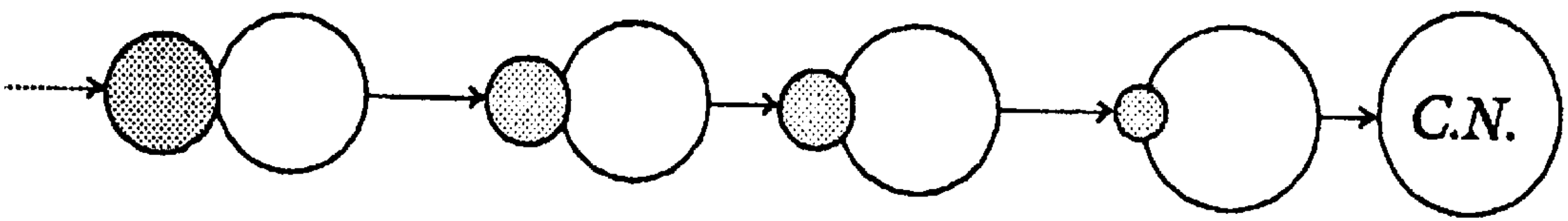
The macroscopic dynamical model.
Fusion of two nuclear liquid drops.

Nuclear shape is described by
Two center parametrozation



The dinuclear system concept.
Conservation of nuclear individualities.



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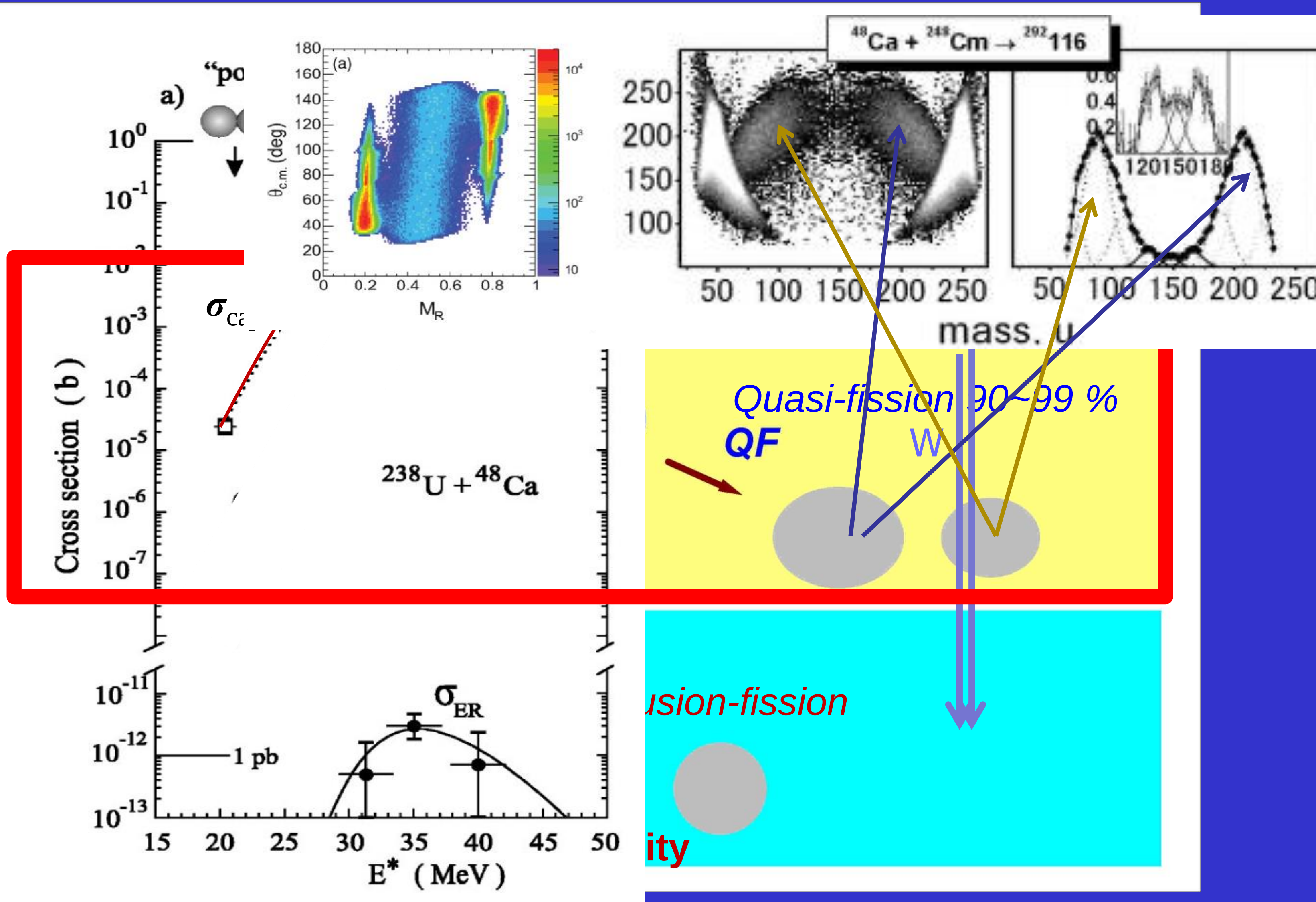
1st stag

2nd stag

3rd stag



2. Model

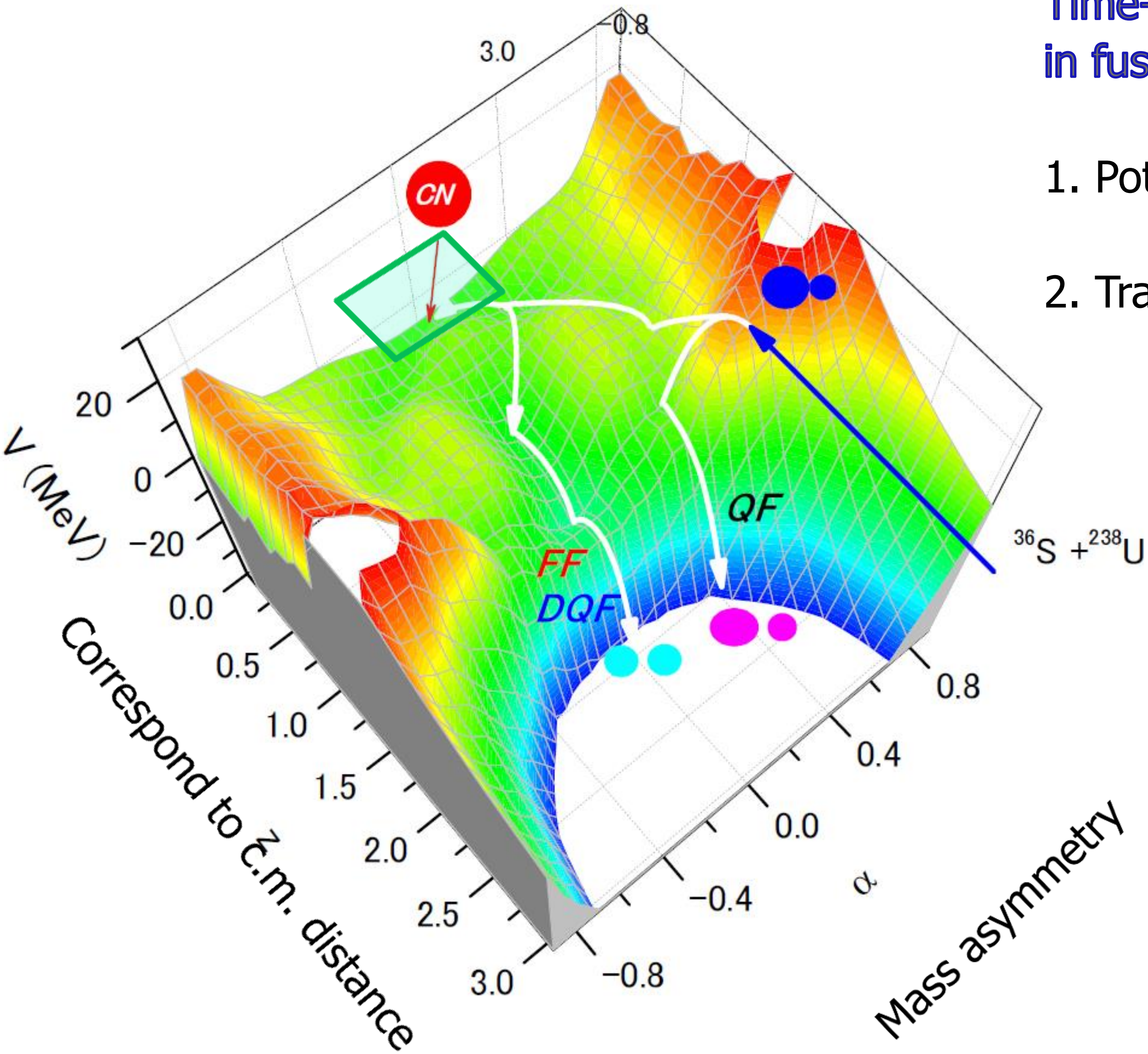
2-1. Potential

Two-center shell model (z, δ, α)

2-2. Equation

trajectory calculation

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



Time-evolution of nuclear shape in fusion-fission process

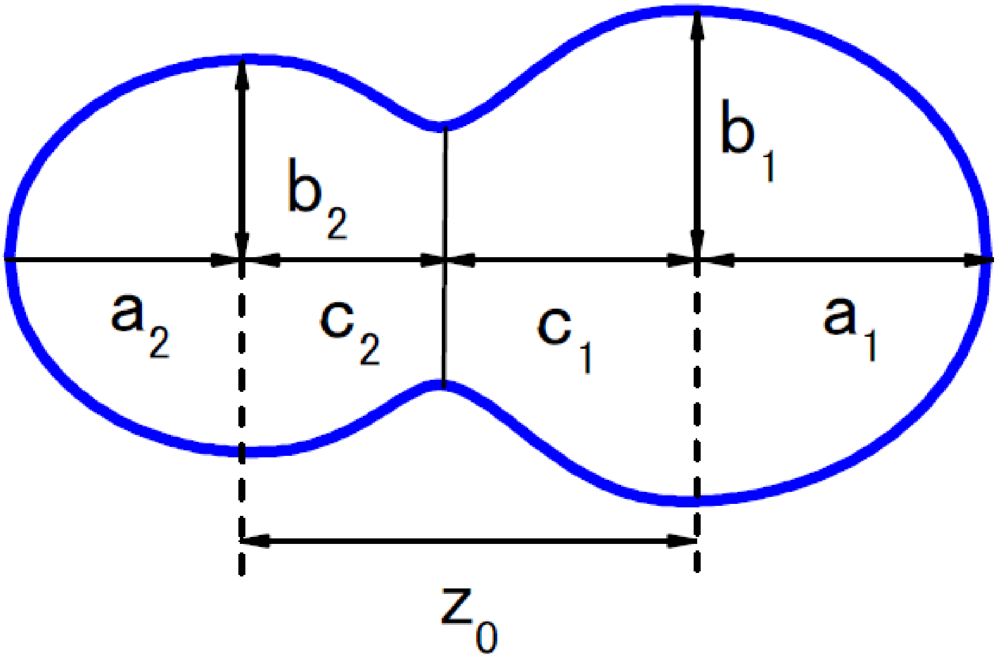
1. Potential energy surface
2. Trajectory → described by equations

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)

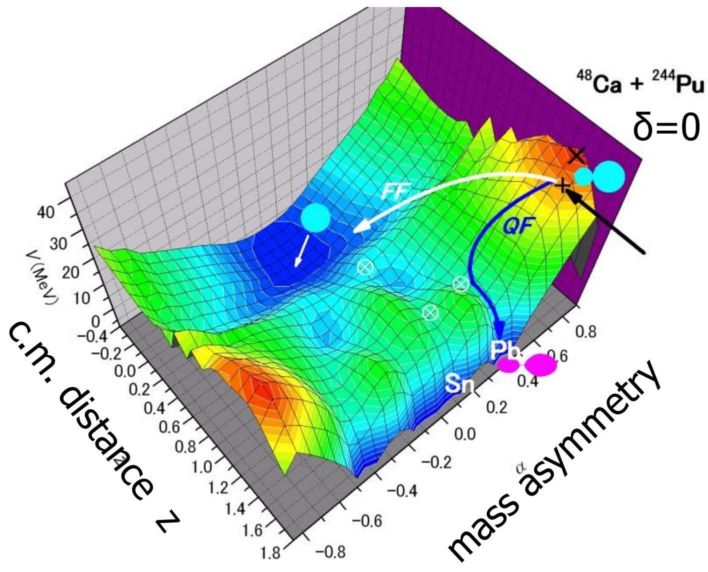
$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$

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

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

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

Potential Energy

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

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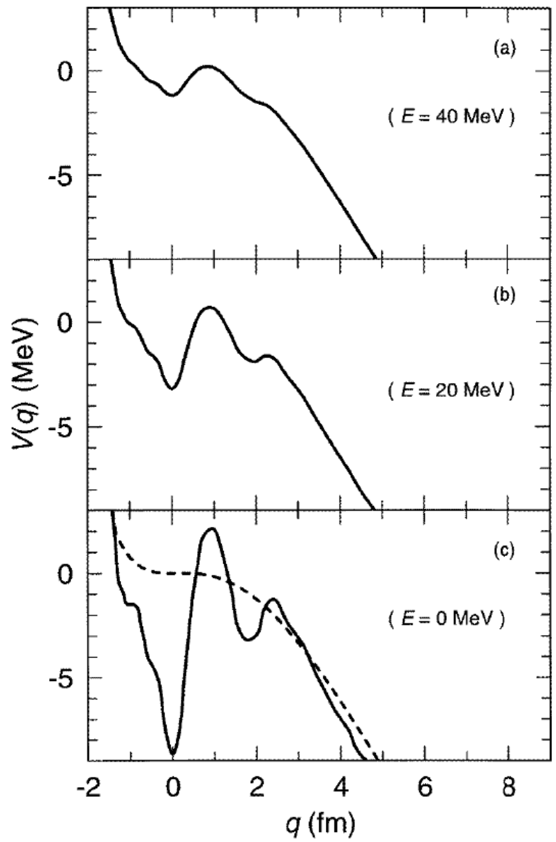
$^{298}114$



Fission barrier recovers at low excitation energy

2. Model

2-1. Potential

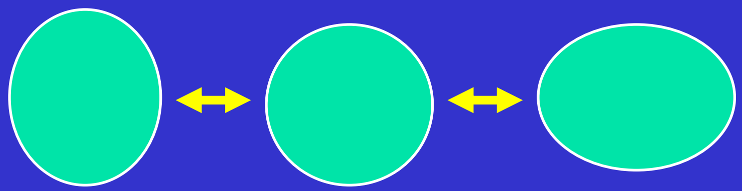
Two-center shell model (z,δ,α)

2-2. Equation

Taking into account the fluctuation around the mean trajectory

Thermal fluctuation 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

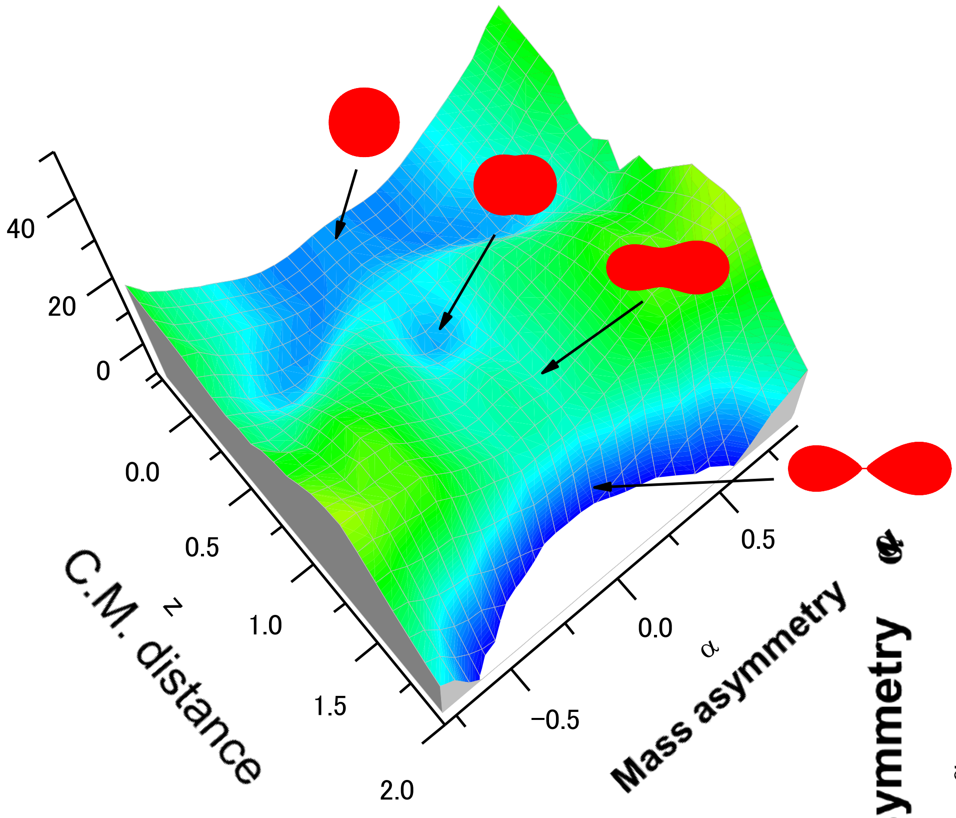
m_{ij} : Hydrodynamical mass (inertia mass)

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

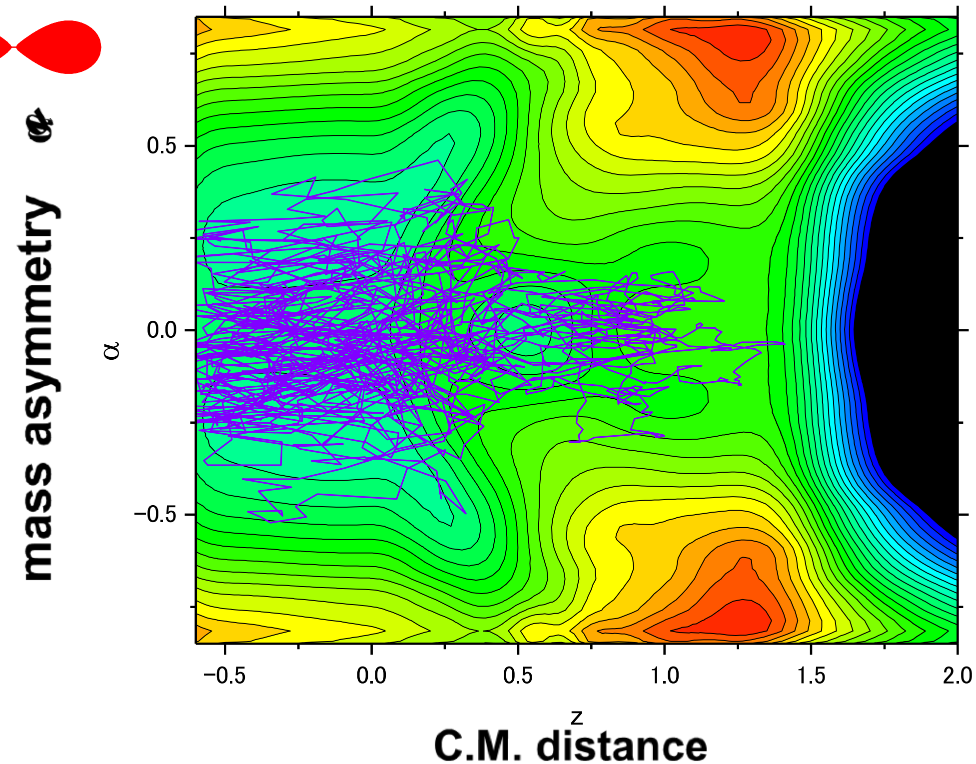
$$E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q)$$

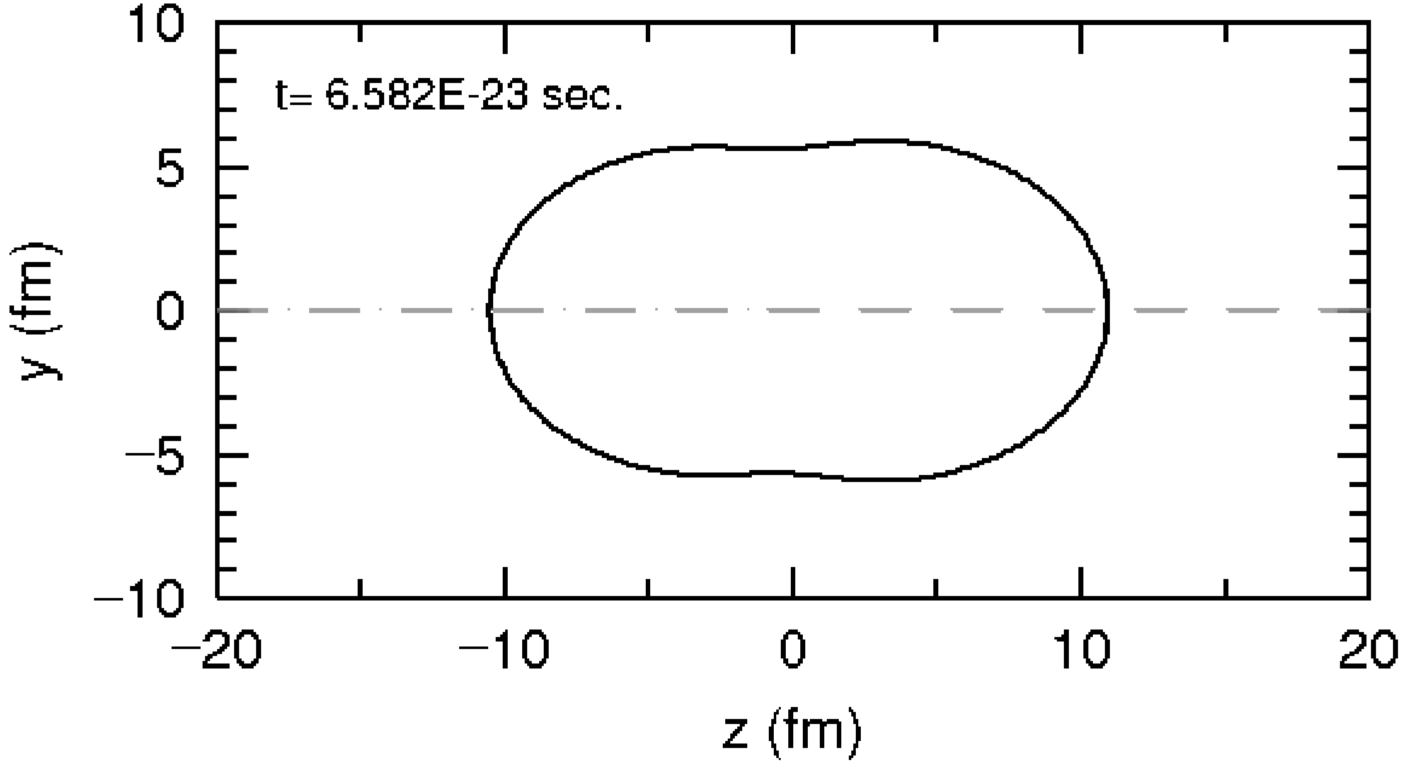
E_{int} : intrinsic energy, E^* : excitation energy

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



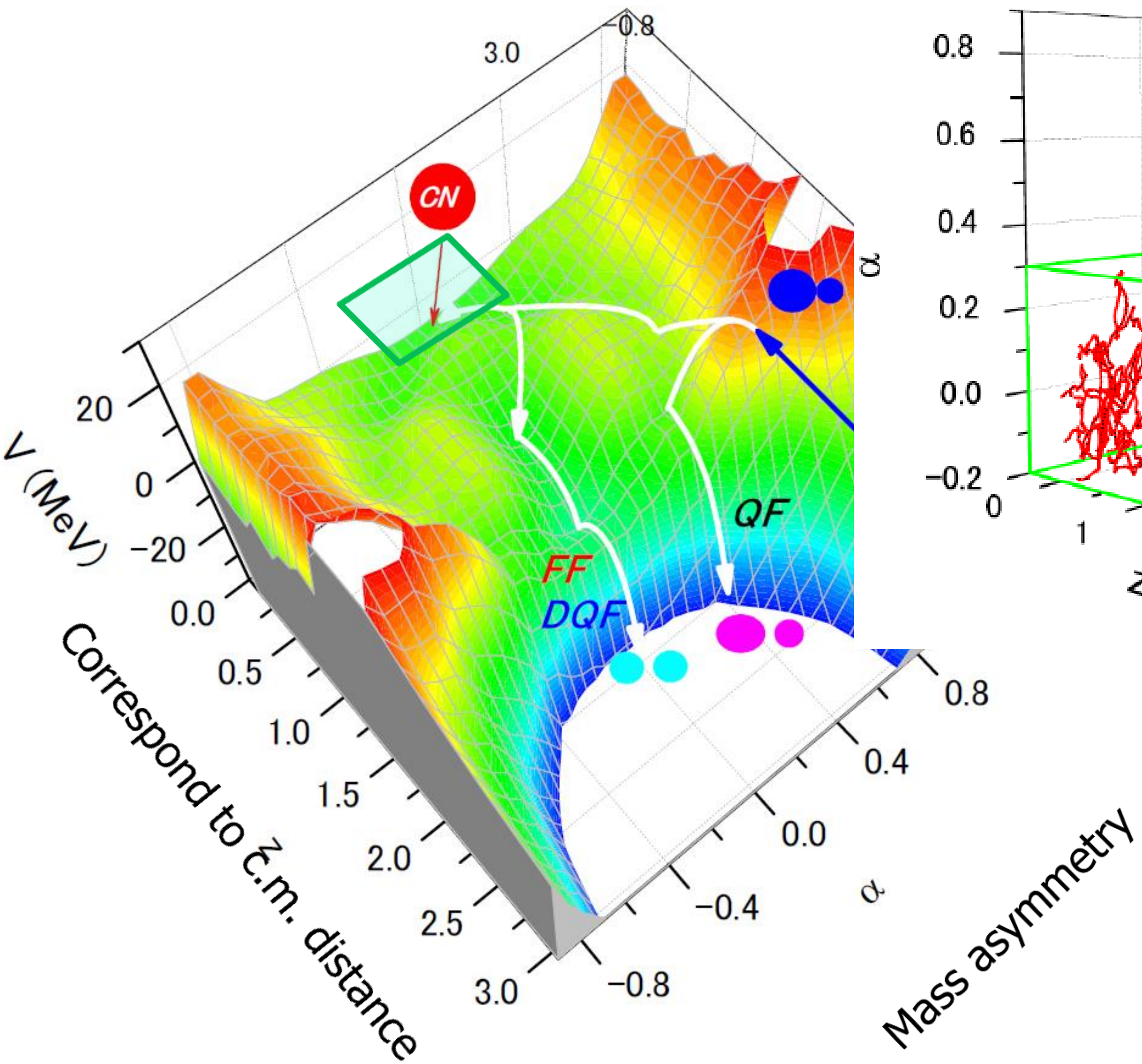
Trajectory on potential energy surface

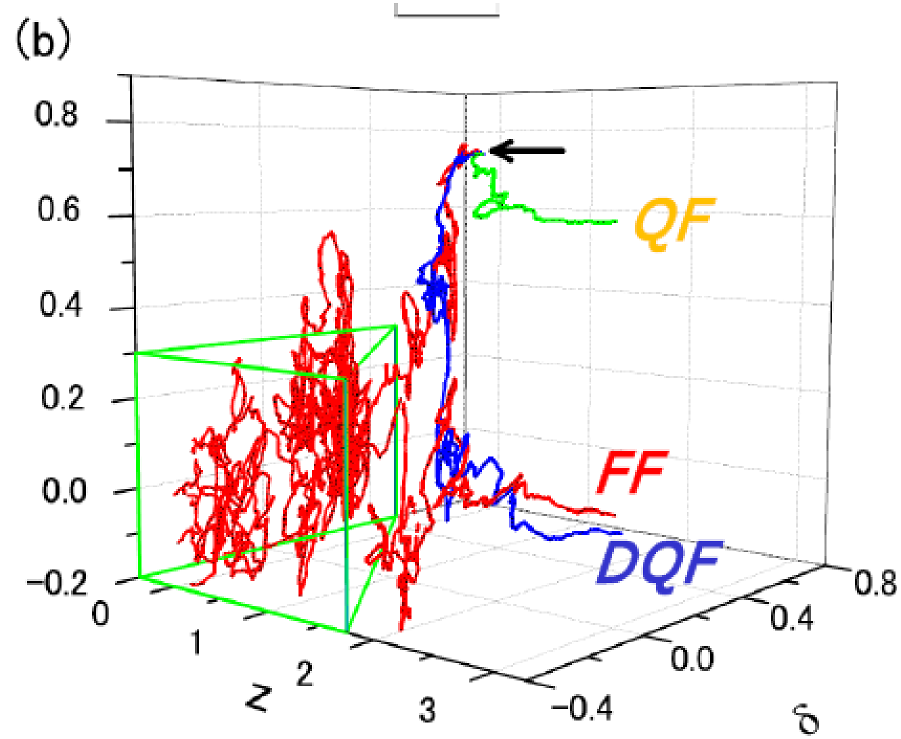




t= 6.582E-23 sec.
10
5
0
−5
−10
y (fm)
−20
−10
0
10
20
z (fm)

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





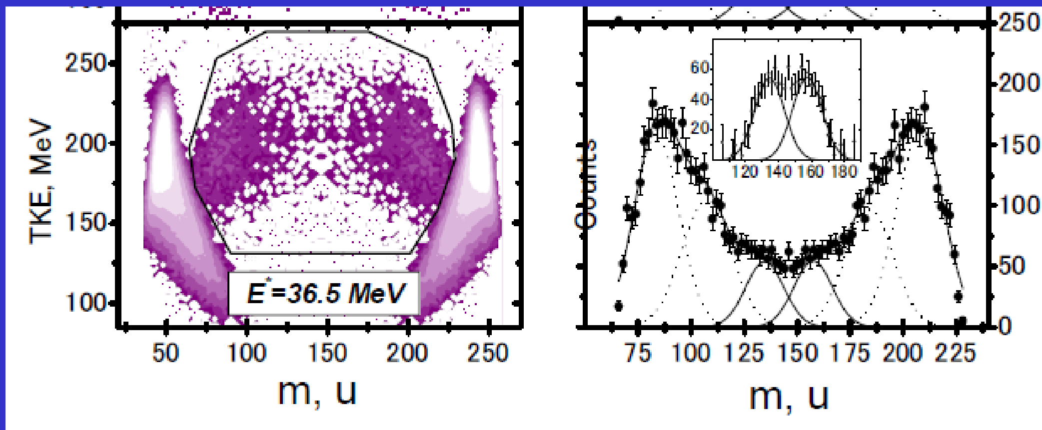
3. Results

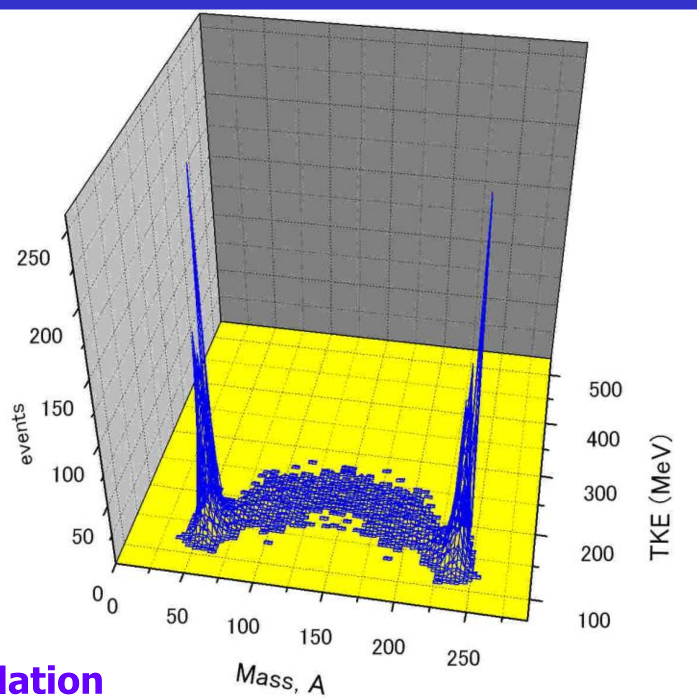
Evaporation residue cross section

Mass distribution of fission fragments

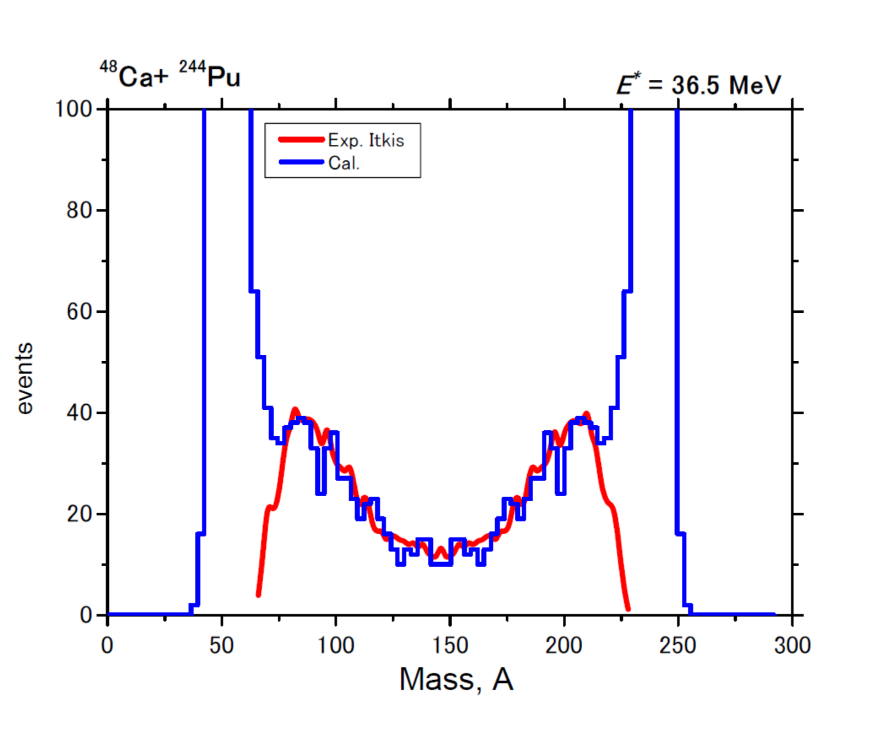
Calculation results $^{48}Ca + ^{244}Pu$

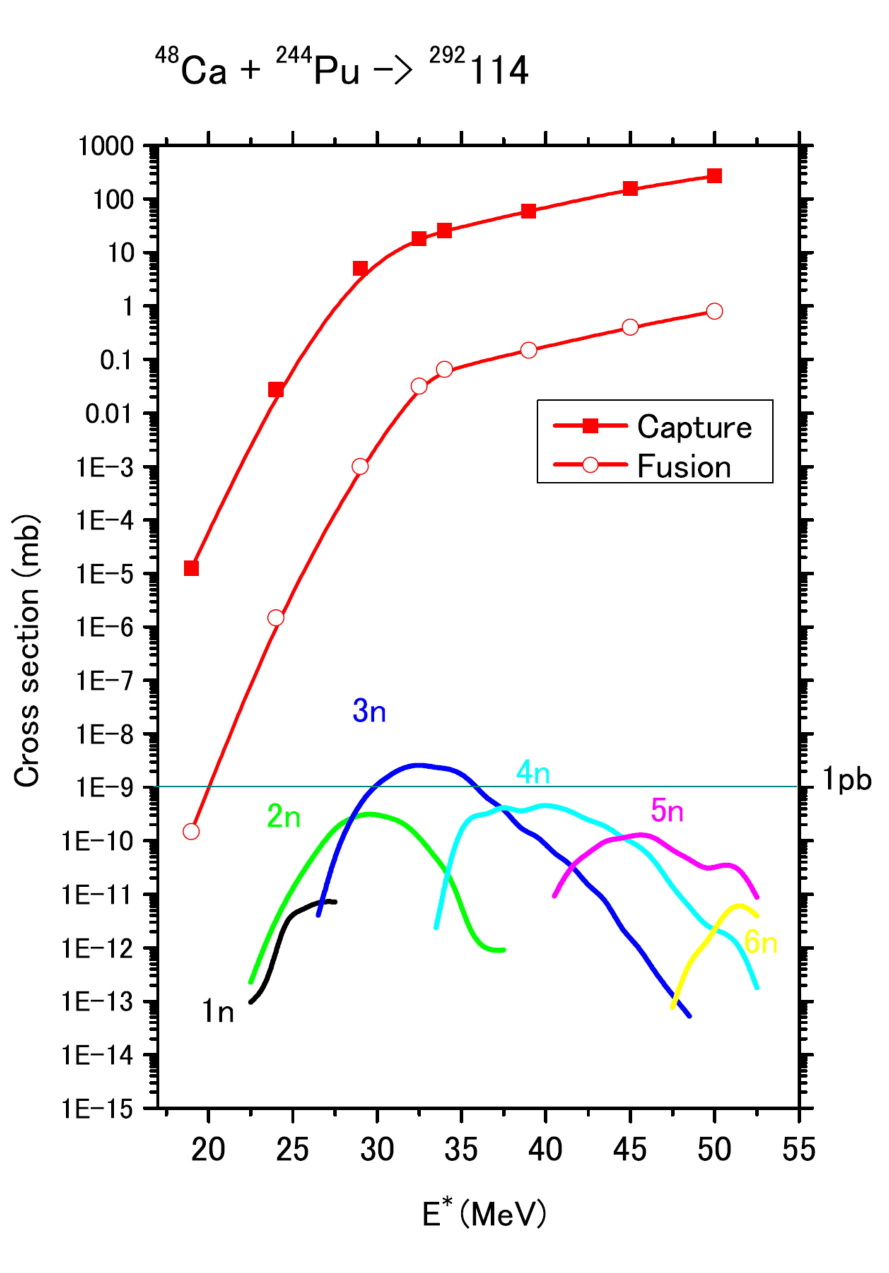
Itkis et al.



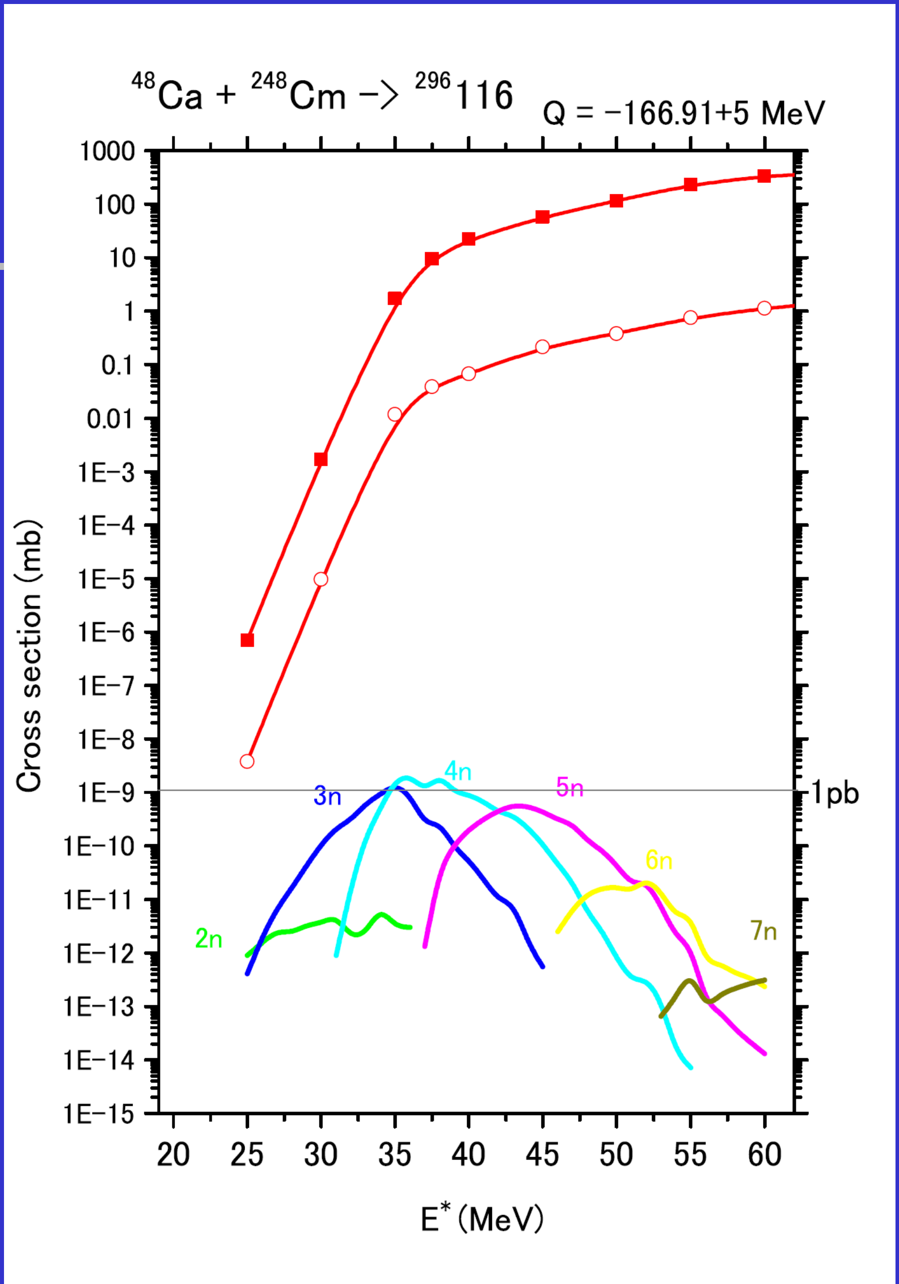


Calculation





48Ca + 244Pu -> 292114
Capture
Fusion
Cross section (mb)
E* (MeV)
1pb
1n
2n
3n
4n
5n
6n



48Ca + 248Cm -> 296116
Q = −166.91+5 MeV
Cross section (mb)
E* (MeV)
1pb
2n
3n
4n
5n
6n
7n

4. Way to synthesize new SHE

Ti, Cr, Fe etc. beams

Transfer reaction U+Th, U+Cm

Secondary beams

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

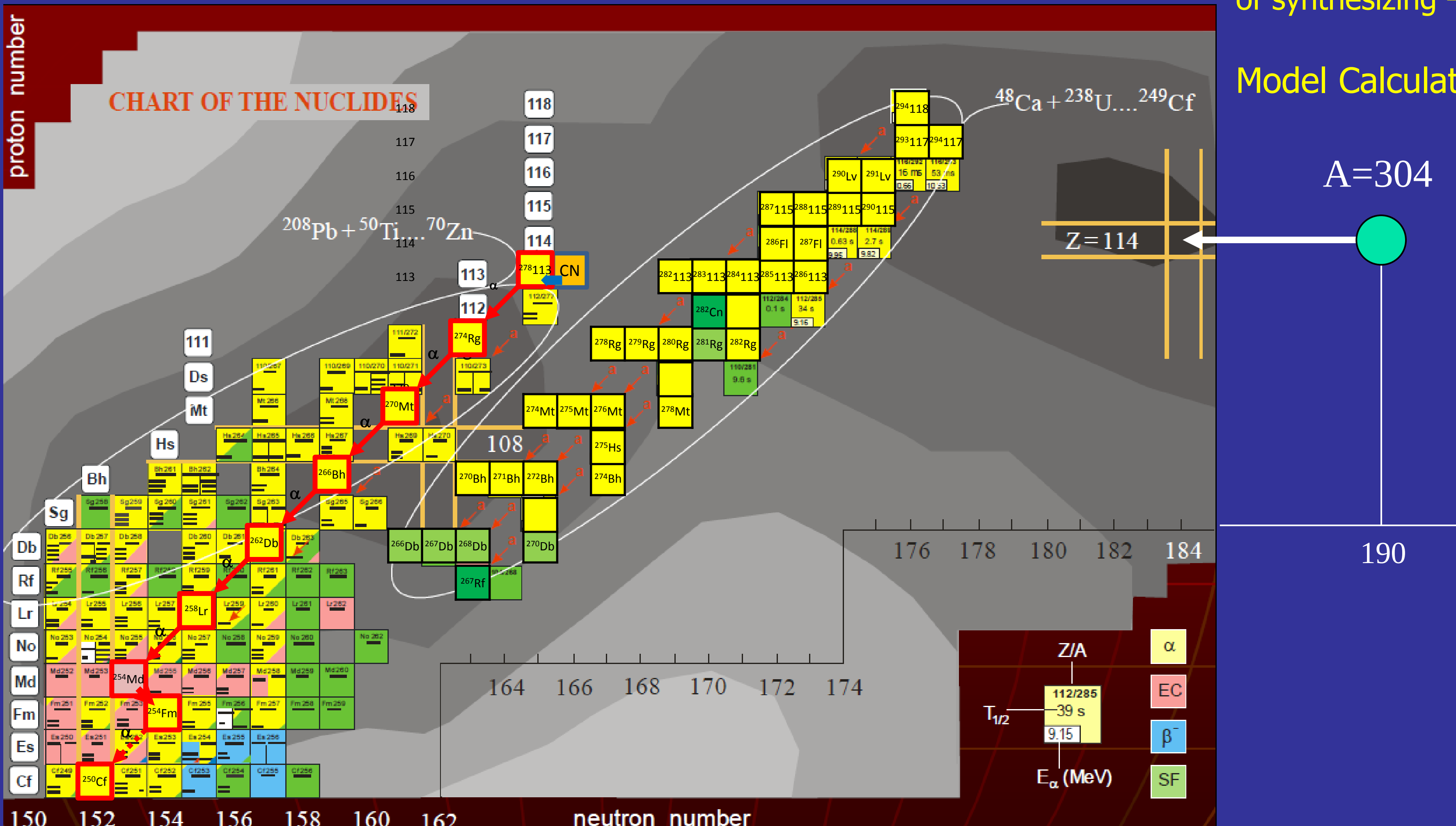
2010

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

3. Survival Process

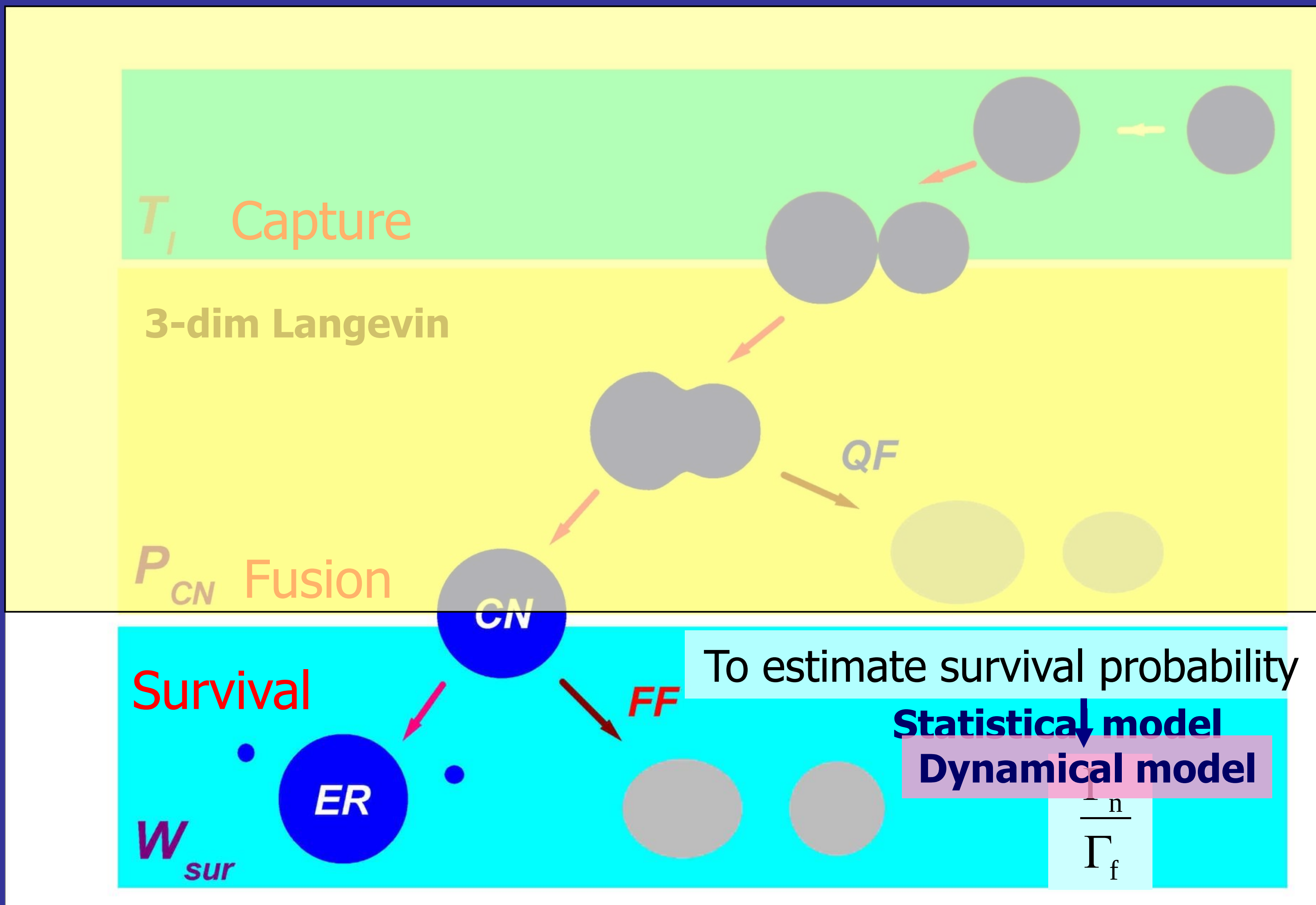
Possibility
of synthesizing $^{298}114$

Model Calculation



Yu. Ts. Oganessian and K. Morita

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



One-dimensional Smoluchowski equation

$$\frac{\partial}{\partial t}P(q,\ell;t)=\frac{1}{\mu\beta}\frac{\partial}{\partial q}\left\{\frac{\partial V(q,\ell;t)}{\partial q}P(q,\ell;t)\right\}+\frac{T}{\mu\beta}\frac{\partial^2}{\partial q^2}P(q,\ell;t)$$

statistical code

$P(q,\ell;t)$; probability distribution

μ ; inertia mass

β ; reduced friction

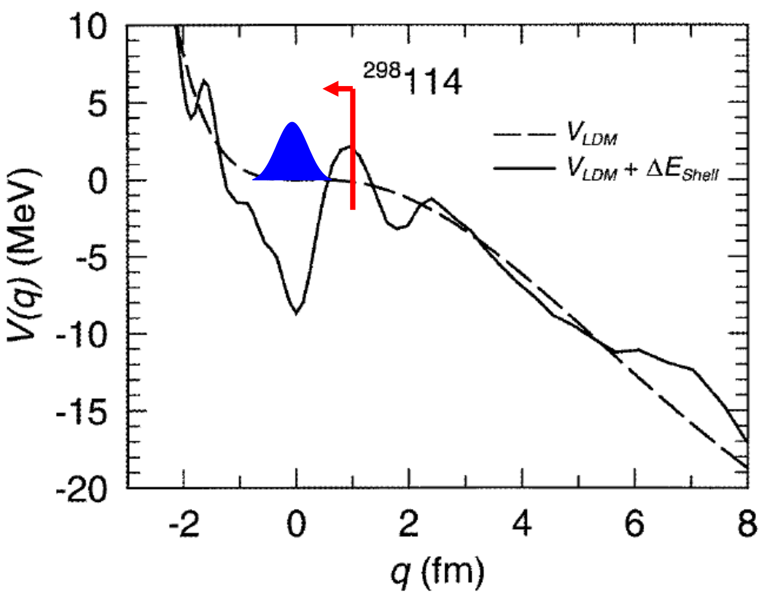
q ; separation distance

T(t) : temperature ← statistical code SIMDEC

Cooling curve

$$W(E_0^*,\ell;t)=\int_{\text{insidesaddle}}P(q,\ell;t)\,dq$$

W ; survival probability



We assume the particle emissions are limited to neutron emission in the neutron-rich heavy nuclei.

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

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

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

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

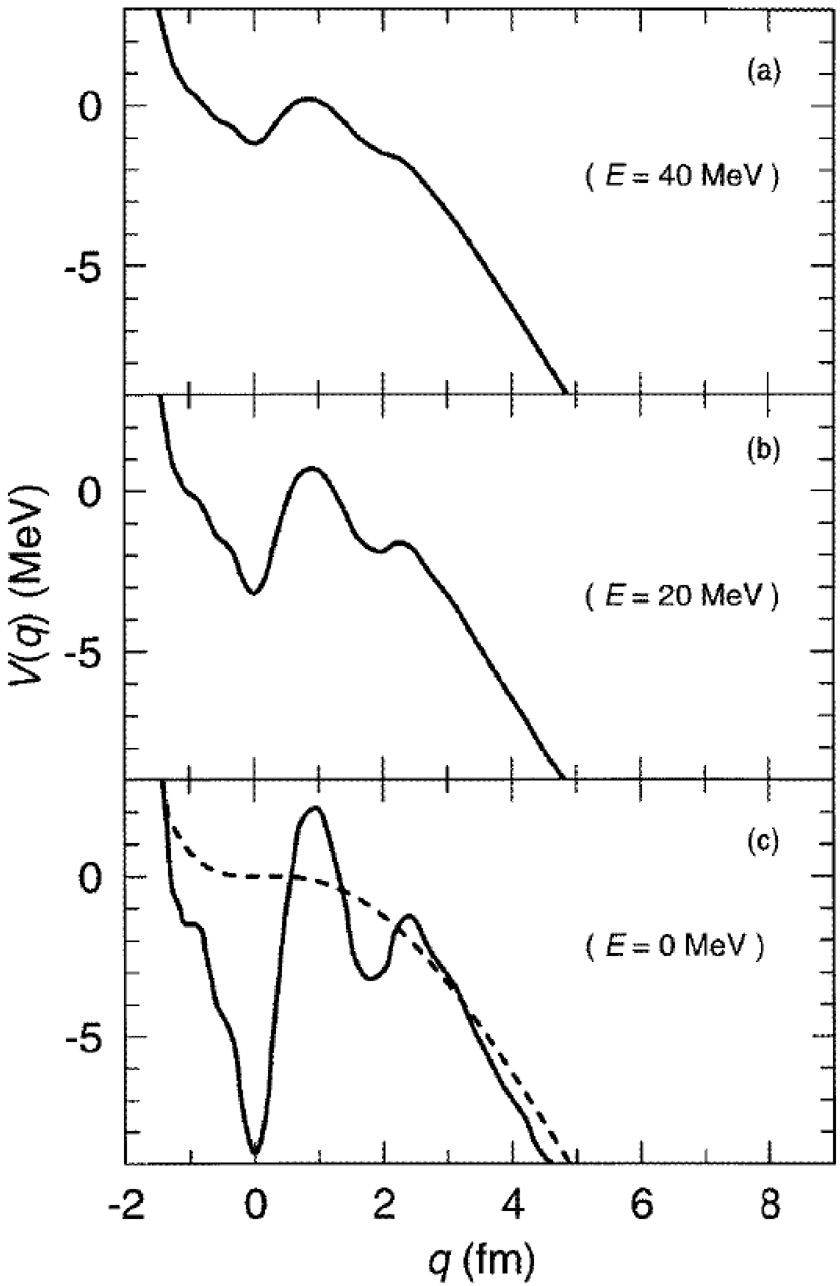
I : Moment of inertia for rigid body

$\Phi(T)$: Temperature dependent factor

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

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

$^{298}114$

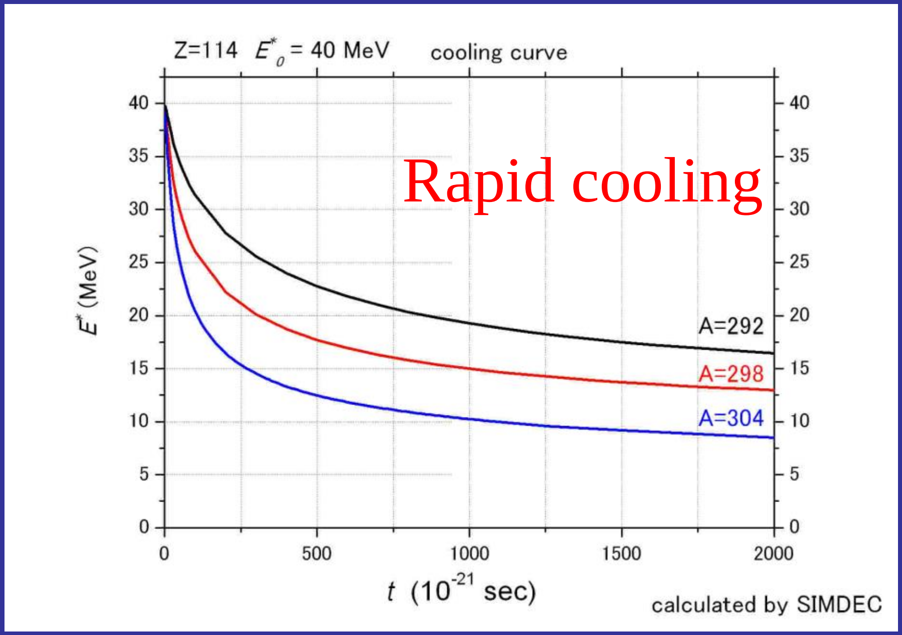


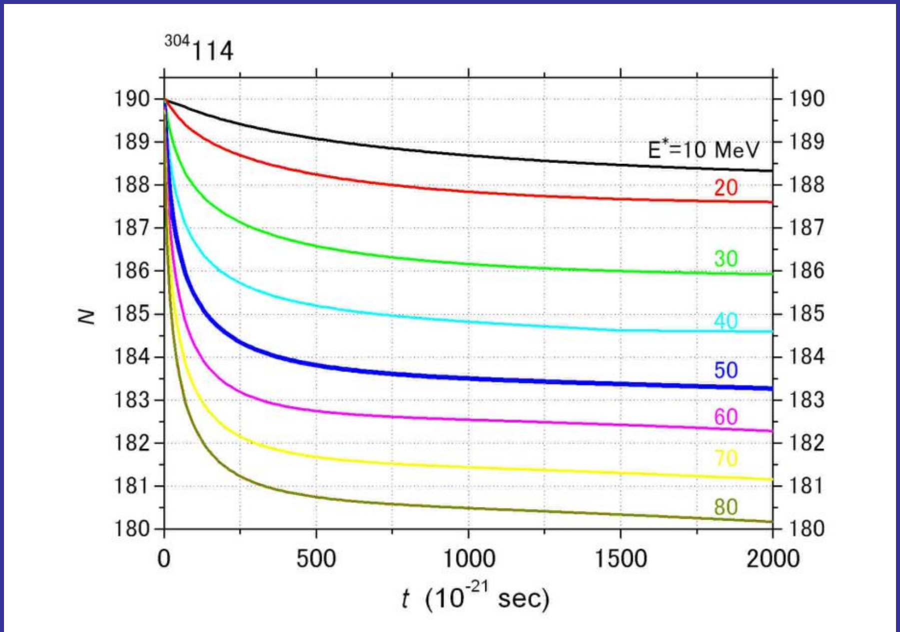
Fission barrier recovers at low excitation energy

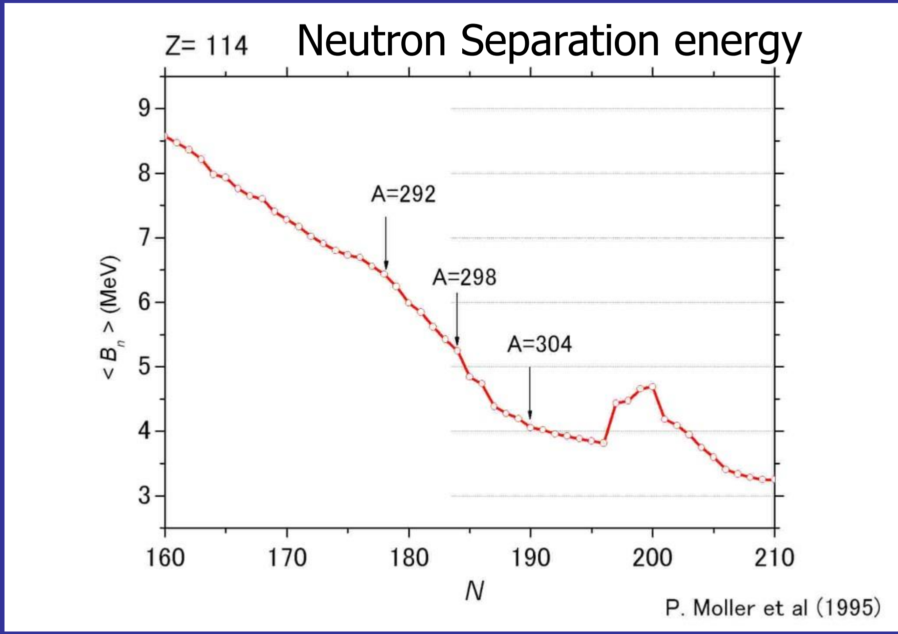
$$\Phi(T) = \exp\left(-\frac{E^*}{E_d}\right)$$

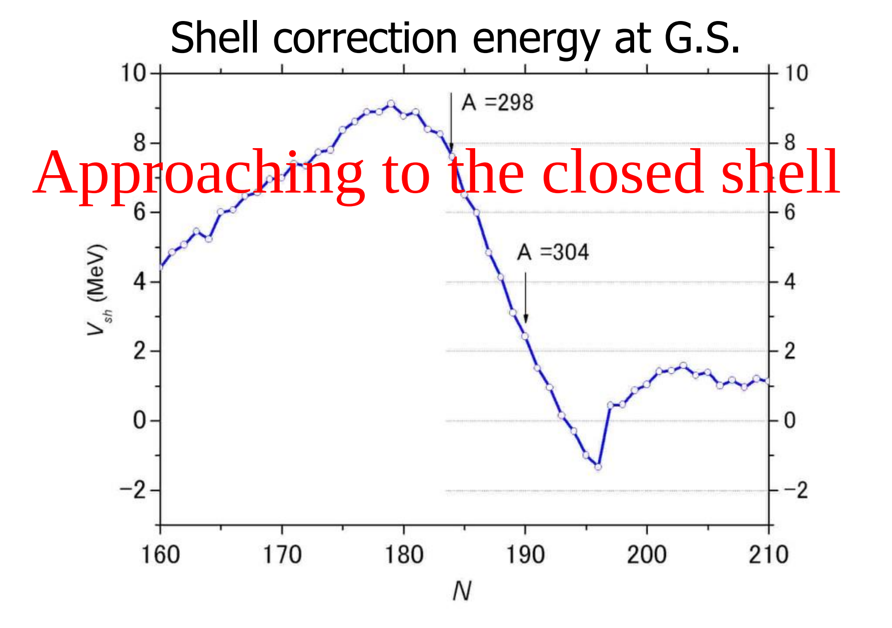
$$E_d = 20\,\mathrm{MeV}$$

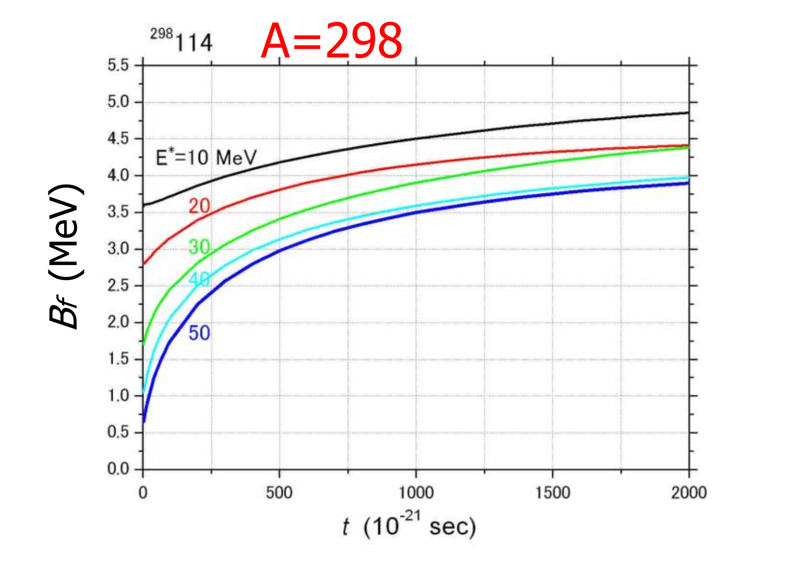
3. Survival process



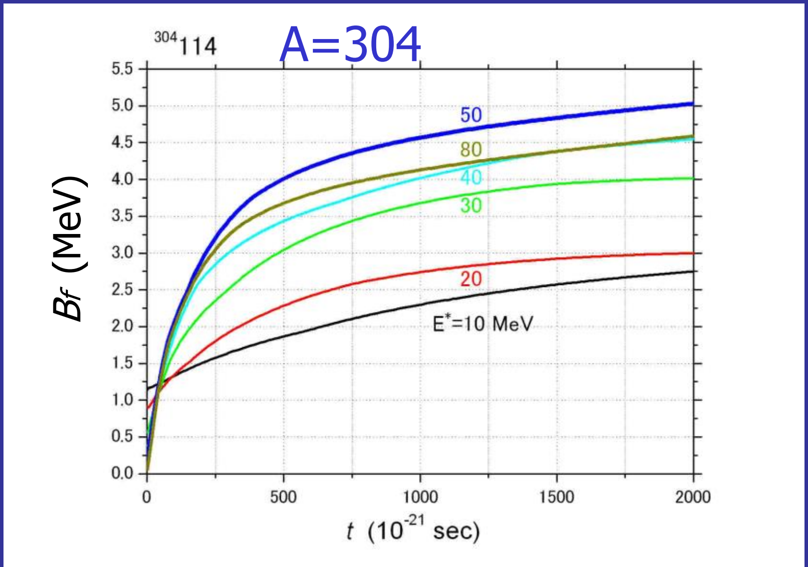




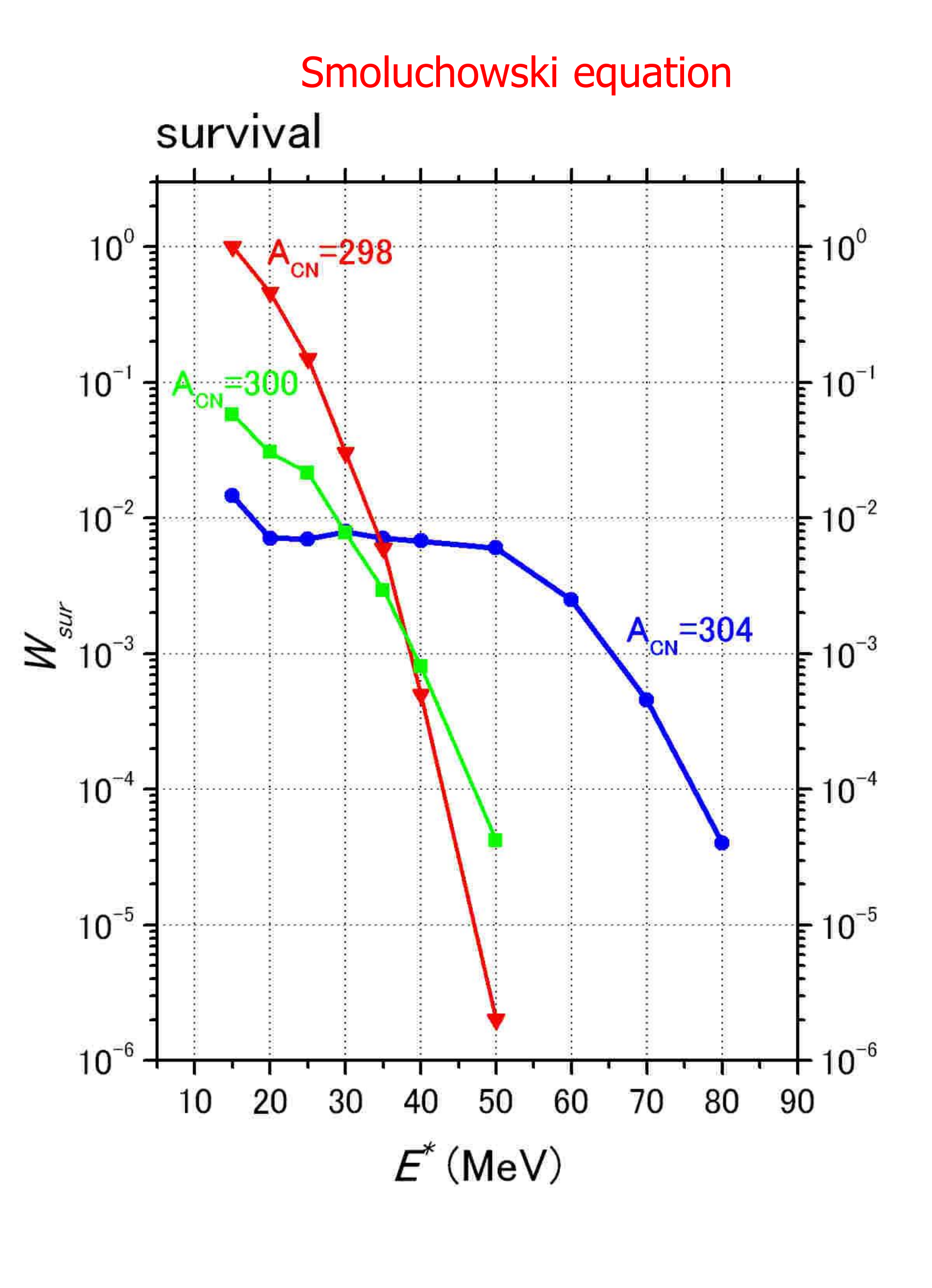




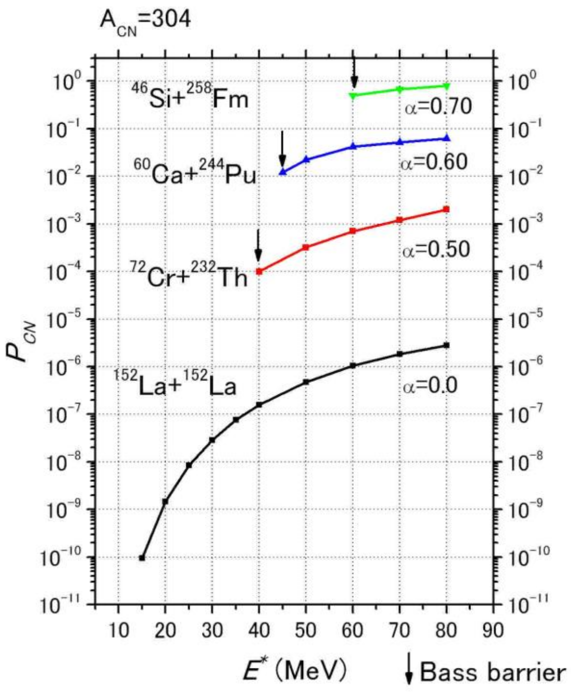
A=298
$^{298}114$
E*=10 MeV
20
30
40
50
B_f (MeV)
t (10^{-21} sec)



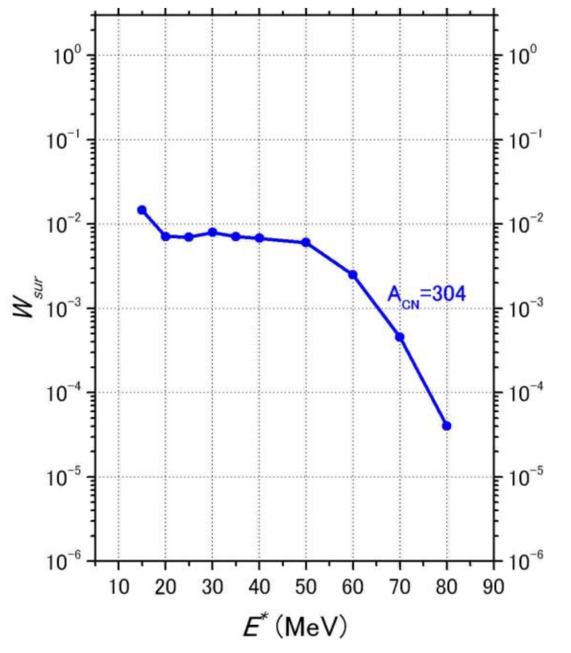
A=304
$^{304}114$
50
80
40
30
20
E*=10 MeV
B_f (MeV)
t (10^{-21} sec)



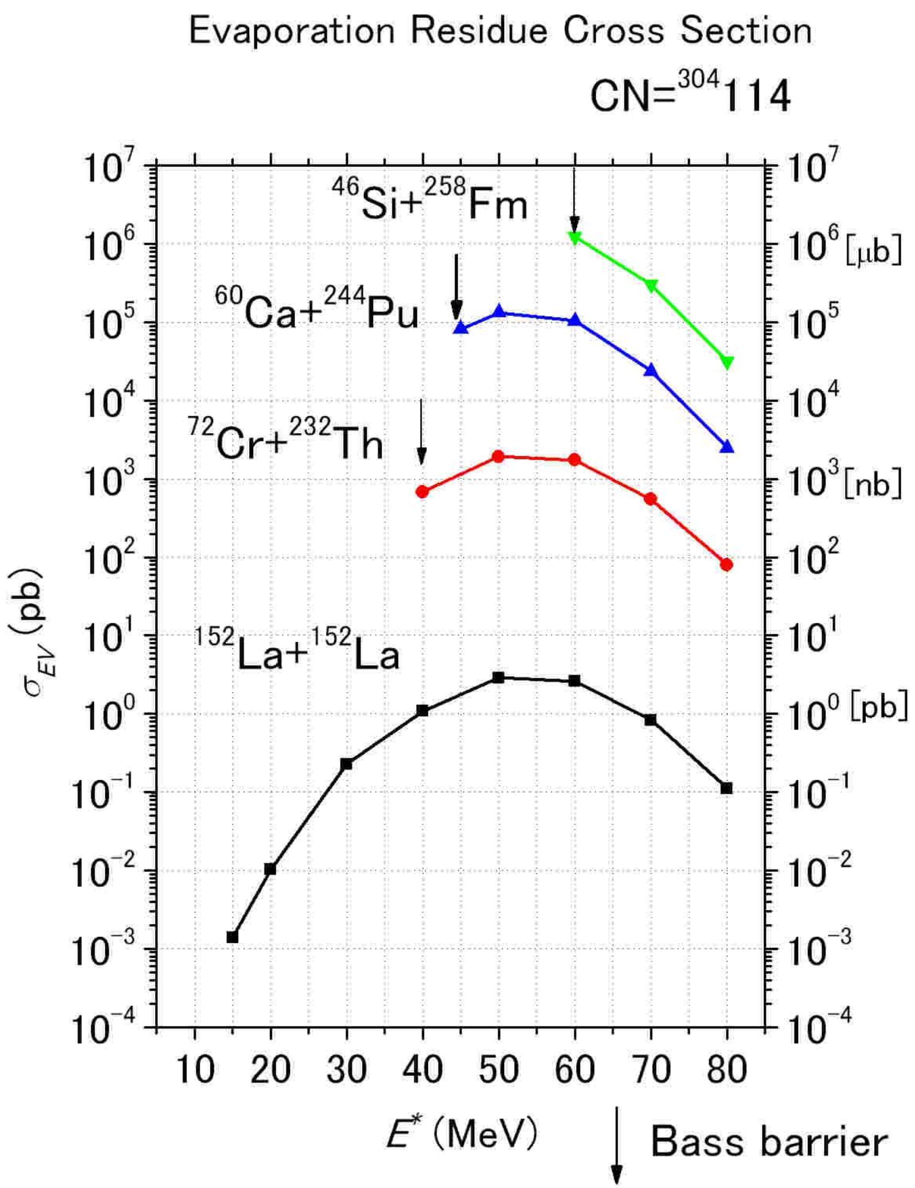
Smoluchowski equation
survival
A_{CN}=298
A_{CN}=300
A_{CN}=304
W_{sur}
E^* (MeV)



A_CN=304
46Si+258Fm
60Ca+244Pu
72Cr+232Th
152La+152La
α=0.70
α=0.60
α=0.50
α=0.0
P_CN
E* (MeV)
Bass barrier



W_sur
A_CN=304
E* (MeV)



Evaporation Residue Cross Section
CN=304114
46Si+258Fm
60Ca+244Pu
72Cr+232Th
152La+152La
σ_EV (pb)
[μb]
[nb]
[pb]
E* (MeV)
Bass barrier

4. Summary

1. The possibility of synthesizing a doubly magic superheavy nucleus, $^{298}114_{184}$, was investigated on the basis of fluctuation dissipation dynamics.

2. Owing to the neutron emissions, we must generate more neutron-rich compound nuclei.

3. To calculate the survival probability, we employ the dynamical model.

4. $^{304}114$ has two advantages to achieving a high survival probability.

1) small neutron separation energy and rapid cooling

2) the neutron number of the nucleus approaches that of the double closed shell

→ obtain a large fission barrier

5. The systematical investigation compared with the statistical model and dynamical one is necessary. We must apply the dynamical model for known systems.

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)

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