Tokyo Tech

Study on formation mechanisms of Z=120 elements with a hybrid model

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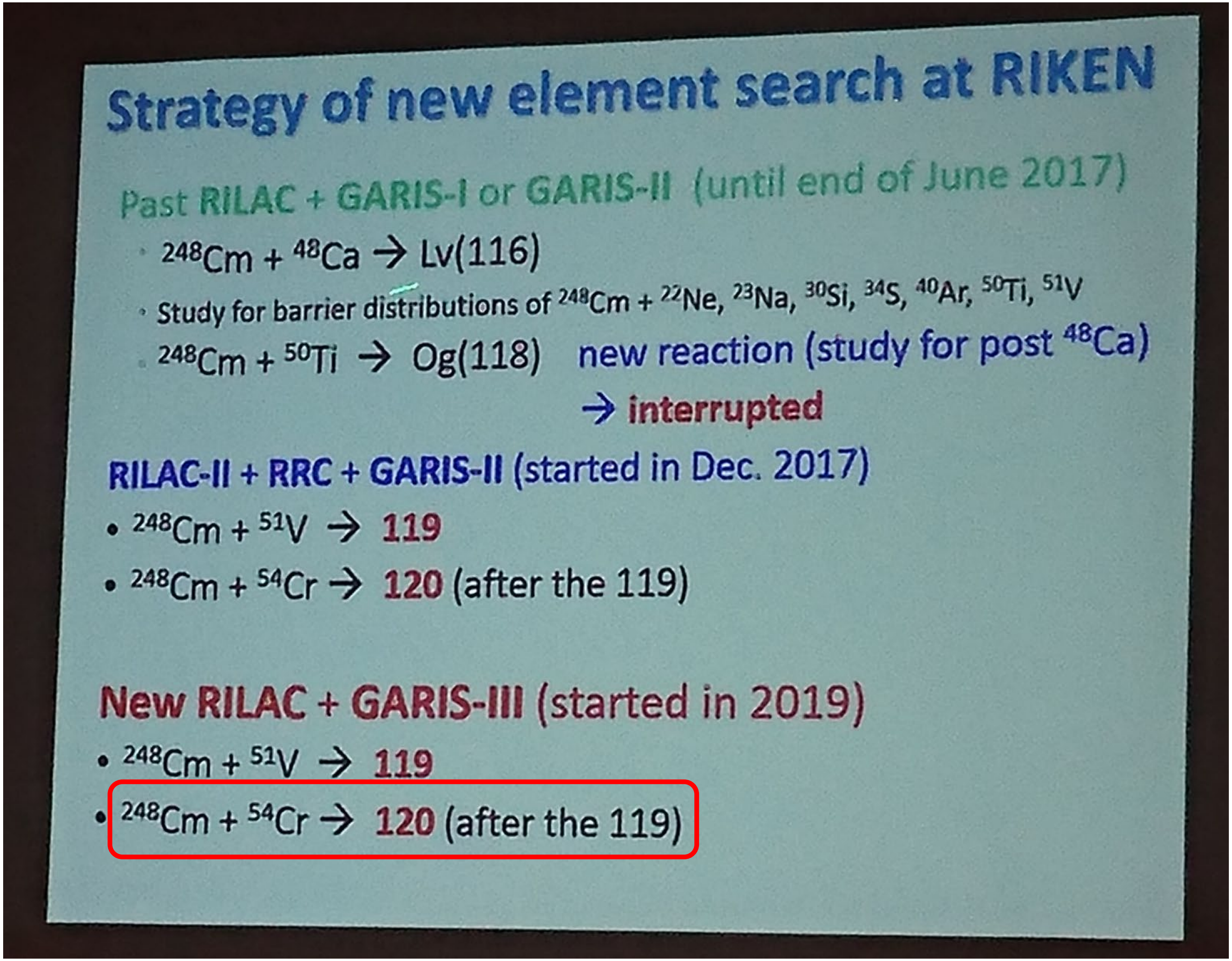
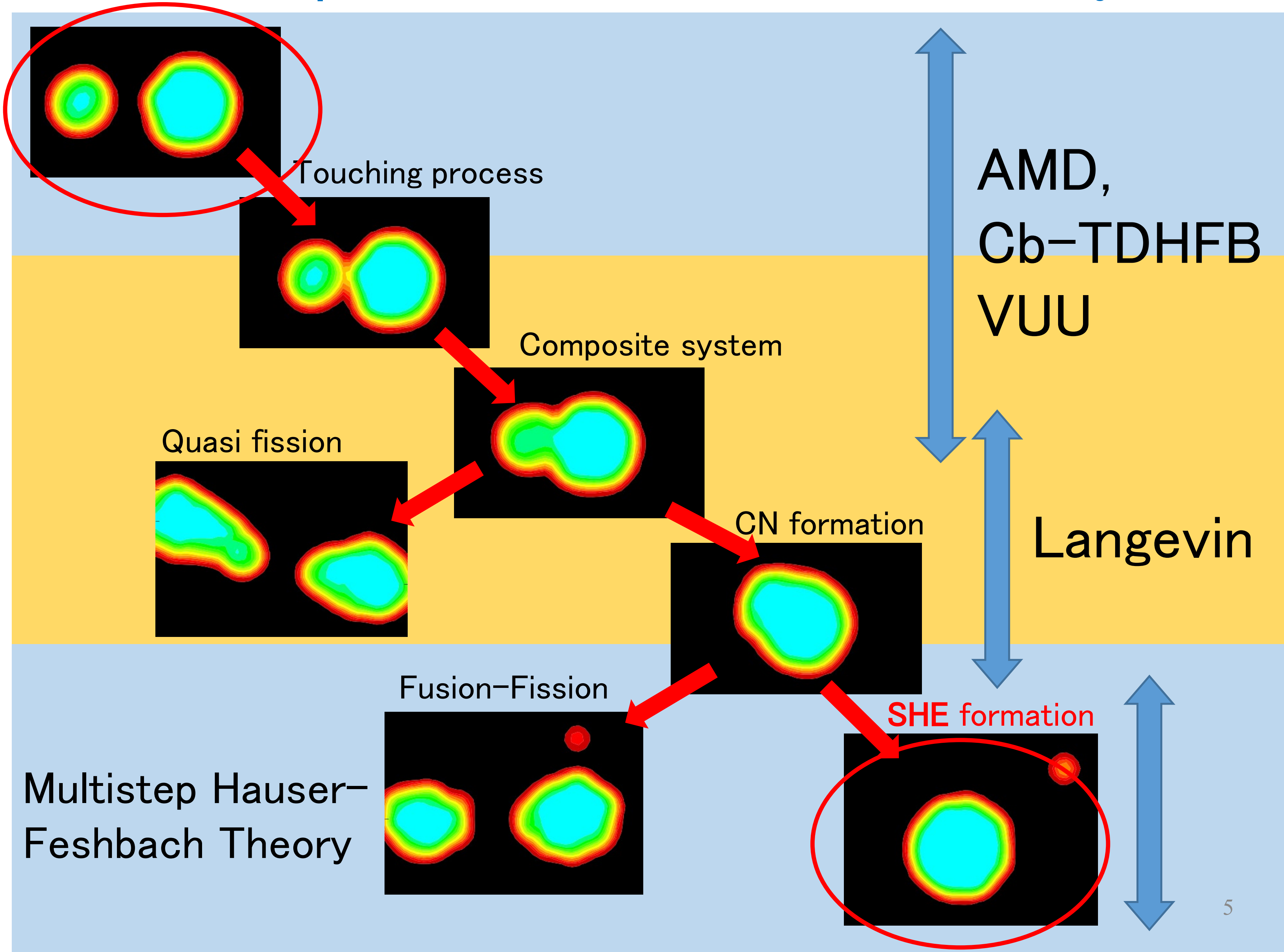
Talk by Morimoto-san in Hawaii2018



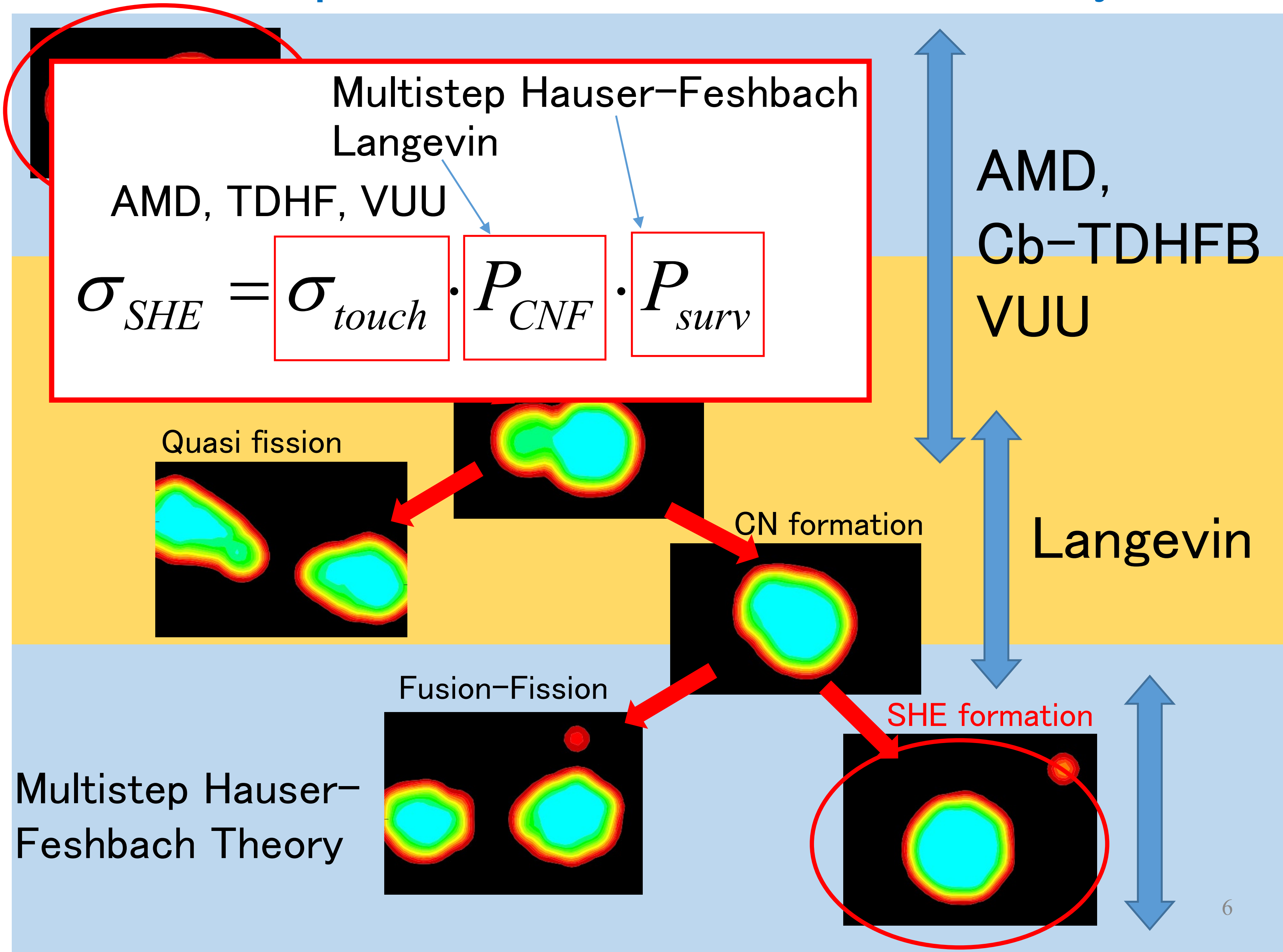
Purposes

1. Motivated by Morimoto-san's talk, we wish to understand formation mechanisms of superheavy elements (SHE)
2. As a first and naive step, we started to construct a framework to describe the whole process of SHE formation, starting from the touching process to statistical decay by eliminating free parameters as much as possible
3. We integrate models which we have developed at Tokyo Tech. with our collaborators, like antisymmetrized molecular dynamics (AMD), Cb-TDHFB, 3&4-dimensional Langevin equation, Hauser-Feshbach theory and so on, →**Hybrid model** ≠ Unified Model of Zagrebaev
4. We calculate formation probability of Z=120 element by $^{248}Cm+^{54}Cr$ reactions and hopefully we will acquire experience on the physics of SHE formation

SHE formation process and theories available at Tokyo Tech.



SHE formation process and theories available at Tokyo Tech.



$$\sigma_{SHE} = \boxed{\sigma_{touch}} \cdot \boxed{P_{CNF}} \cdot \boxed{P_{surv}}$$

Antisymmetrized Molecular Dynamics : AMD

Akira ONO et al, Prog. Theor. Phys., 87, No. 5 (1992)

Mean Field + Stochastic NN collision

Total wave function : Single Slater det. $|\Phi(r_1, r_2, \dots, r_A)\rangle = \frac{1}{\sqrt{A!}}\det[\phi_i(r_j)]$

Single particle w.f. : Gaussian coherent state: $\left\langle \vec{r} \middle| \phi_{\vec{Z}_i} \right\rangle = \left(\frac{2\nu}{\pi}\right)^{\frac{3}{4}} \exp\left[-\nu\left(\vec{r} - \frac{\vec{Z}_i}{\sqrt{\nu}}\right)^2\right]\chi_i$

$$\vec{Z} = \sqrt{\nu}\vec{D} + \frac{i}{2\hbar\sqrt{\nu}}\vec{K}, \ \chi_i = p\uparrow, p\downarrow, n\uparrow, n\downarrow$$

time-dependent
variational principle
→ Equation of motion $\boxed{i\hbar\sum_{j\tau} C_{i\sigma,j\tau}\dot{Z}_{j\tau} = \frac{\partial\mathcal{H}}{\partial Z^*_{i\sigma}}}$

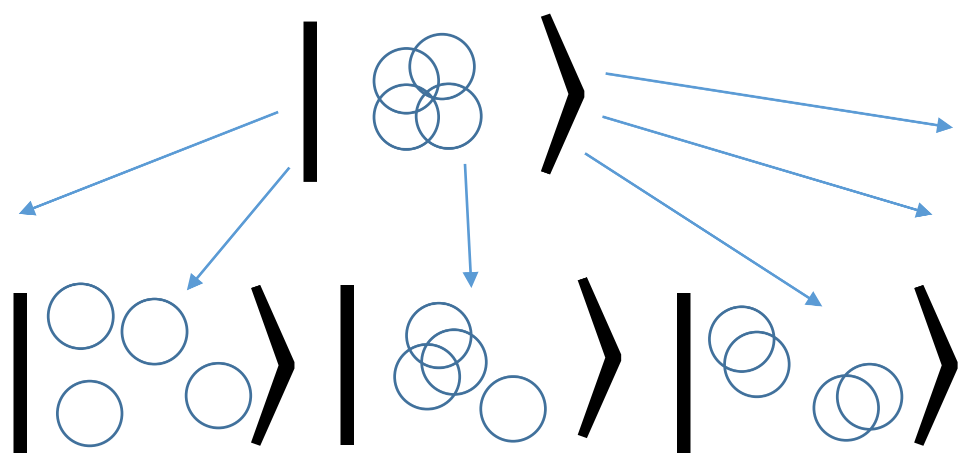
$$\mathcal{H} = \frac{\langle\Phi|\hat{H}|\Phi\rangle}{\langle\Phi|\Phi\rangle}, \ C_{i\sigma,j\tau} = \frac{\partial^2}{\partial Z^*_{i\sigma}\partial Z_{j\tau}} log\langle\phi_i|\phi_j\rangle$$

$$\sigma, \tau = \{x, y, z\}$$

Effective interaction: SLy4

Stochastic NN collision (like in cascade model)

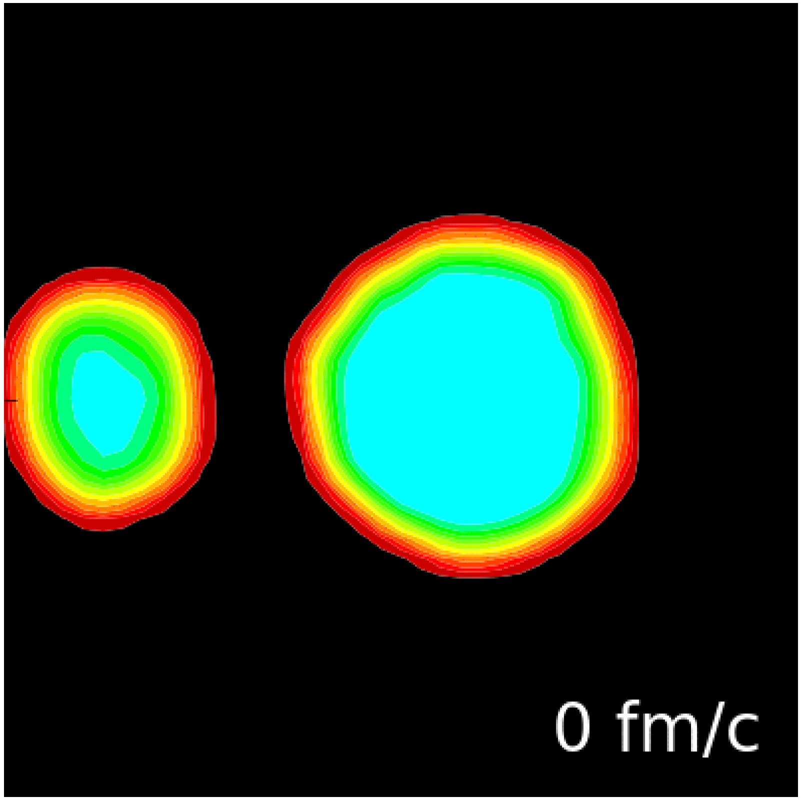
gives rise to branching of wave function→distribution



Trial calculation: ^{54}Cr (310MeV) + ^{248}Cm

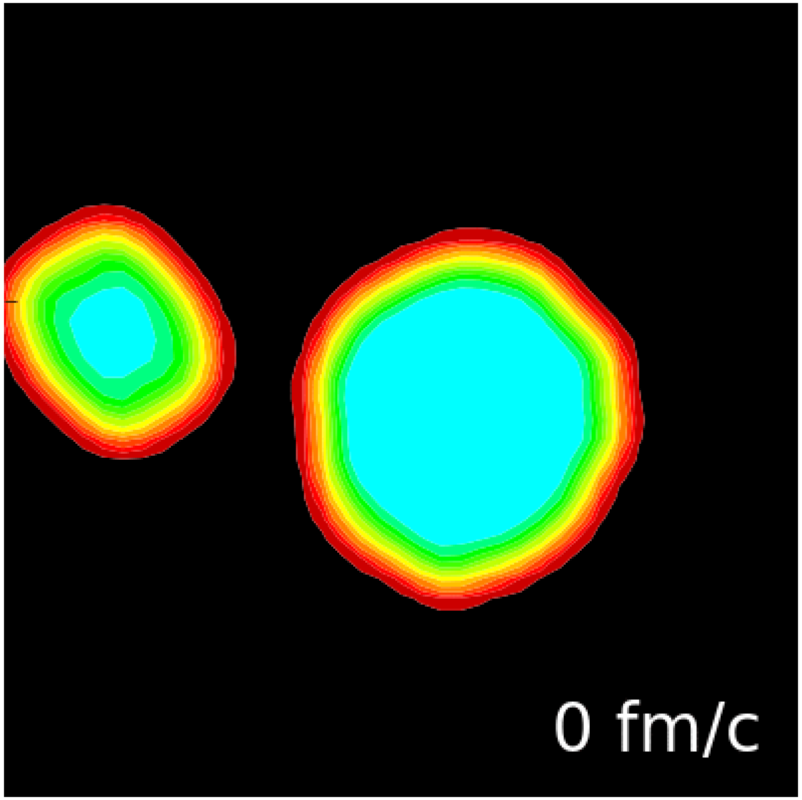
by AMD

b = 0.03 fm



^{60}Mn+^{242}Am

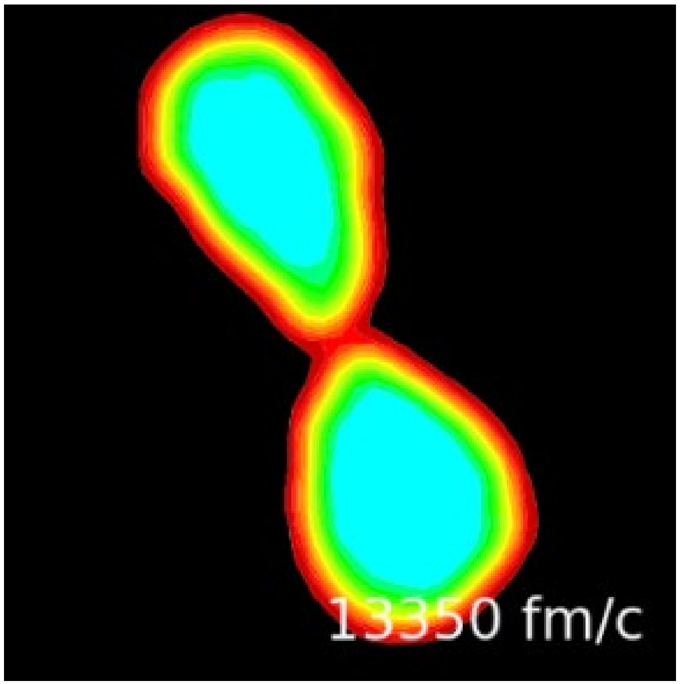
b = 3.12 fm

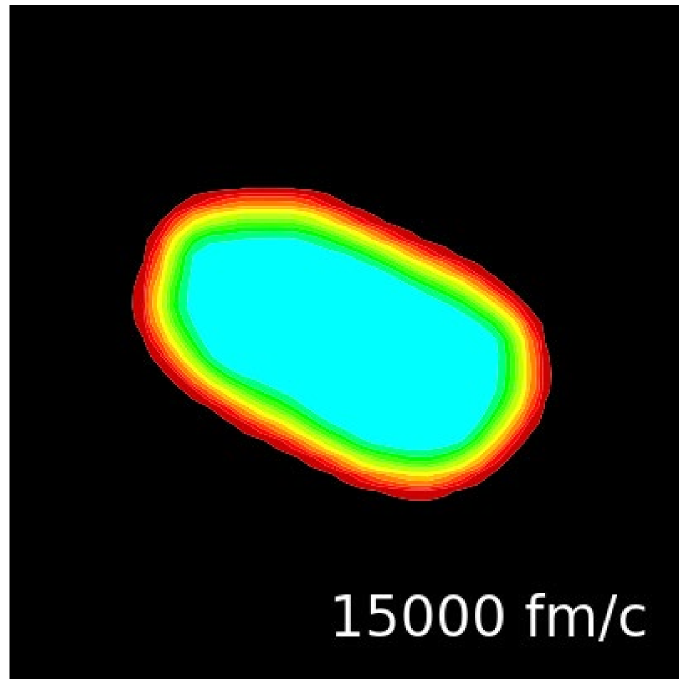


^{53}V+^{249}Bk

Touching process (b=0) by AMD

$$^{54}\mathrm{Cr}(324\mathrm{MeV})+{}^{248}\mathrm{Cm}\longrightarrow{}^{302}120$$

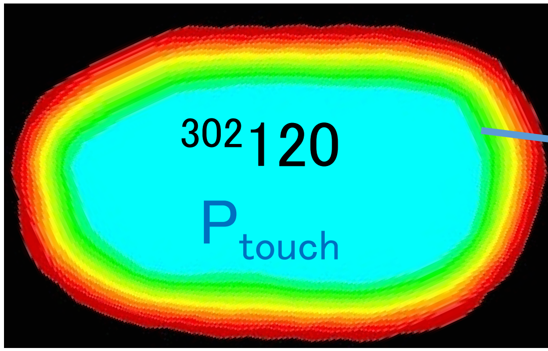




The fates of these 2 events are different due to stochasticity brought by the NN collision

Hybrid model of SHE formation of Tokyo Tech.

Touching



Shape profile
U*, L

AMD, Cb-TDHFB
VUU

Multistep Hauser-Feshbach calculation for P_{surv}

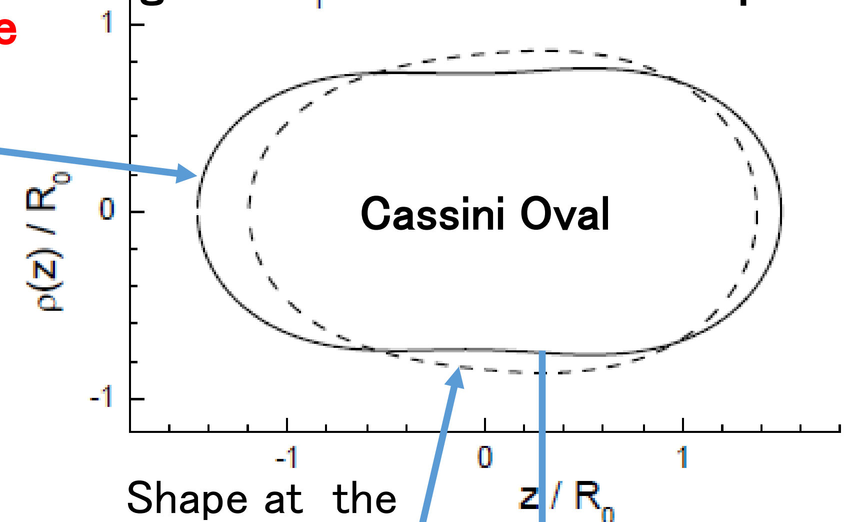
Survival probability

$$= \left[\frac{\sum_{\alpha'=\{n,\gamma\}:l'j'} \int_0^{E_{x\max}} \rho(E_{x'}, J^{\pi}) T^{J}_{\alpha' l' j'}(E_{\alpha'}) dE_{x'}}{\sum_{\alpha''=\{n,p,d,t,h,\alpha,\gamma,F\}:l''j''} \int_0^{E_{x\max}} \rho(E_{x''}, J^{\pi}) T^{J}_{\alpha'' l'' j''}(E_{\alpha''}) dE_{x''}} \right]$$

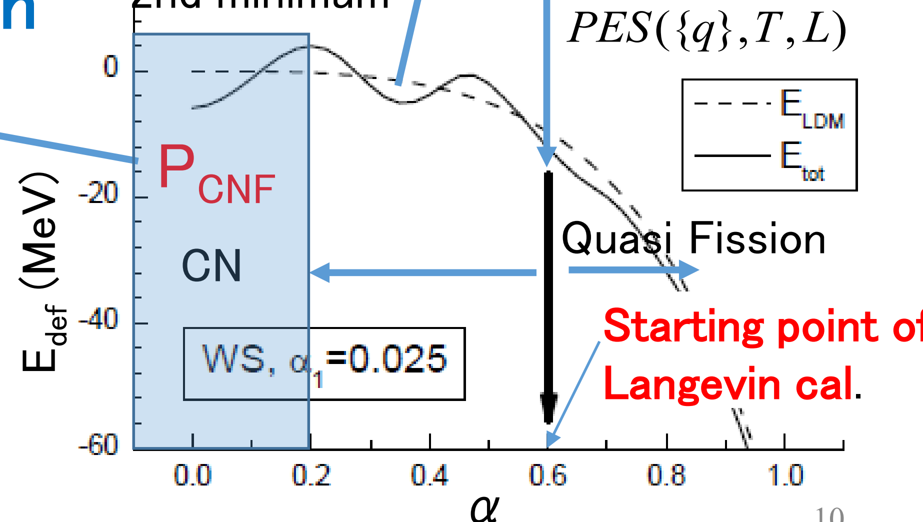
HFBTHO+BeoH

CNF or Quasi Fission

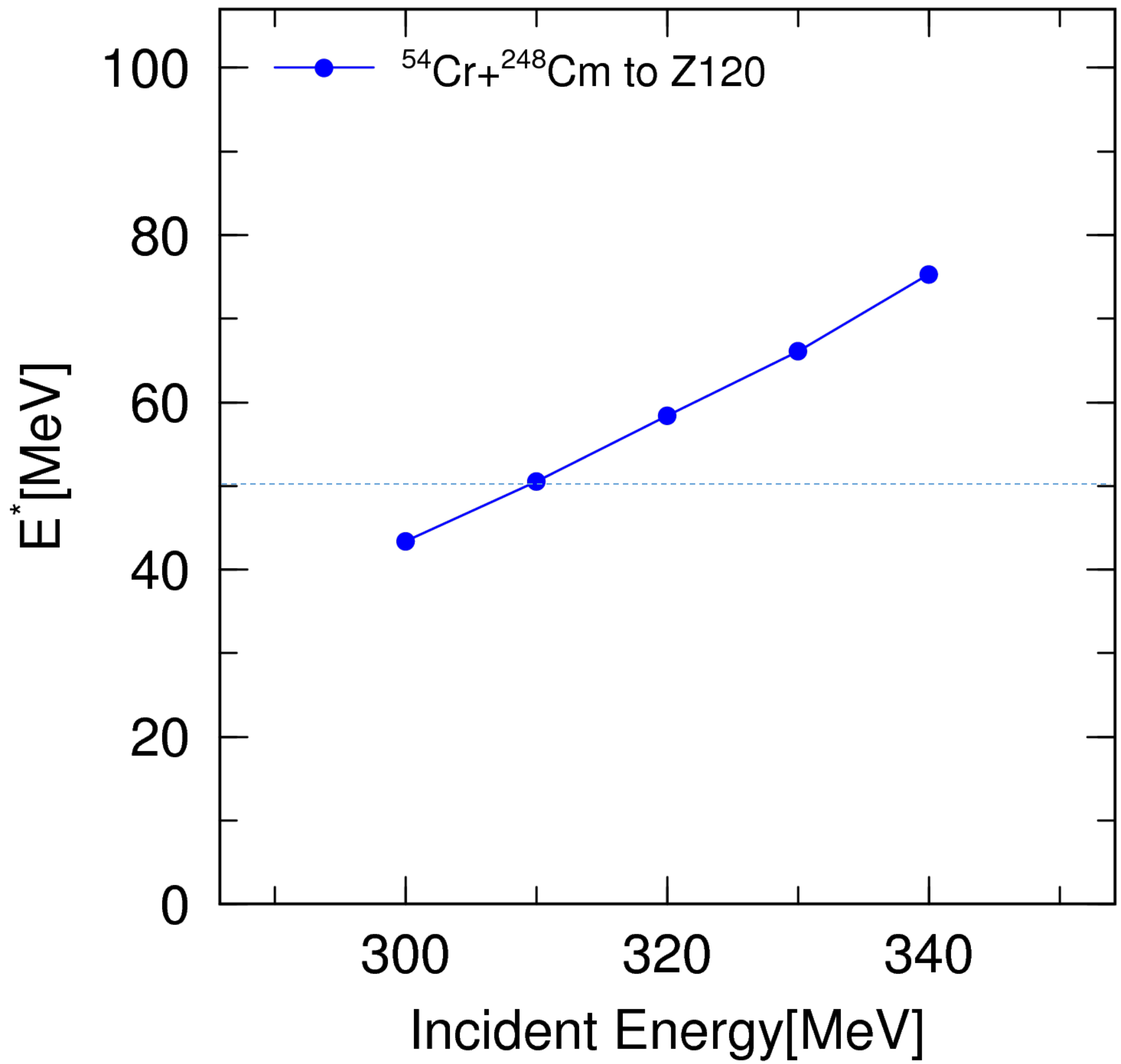
Langevin cal. with neutron evaporation



Shape at the 2nd minimum



Excitation energy of initial composite nuclei in $^{54}Cr+^{248}Cm \rightarrow ^{302}120$



Langevin calculation：E*=50MeV for $^{302}120$

- Shape parametrization : Cassini ovaloid
- Dynamical variables : 3 (α , α_1, α_4)
- Transport coefficients：Linear Response Theory （LHA)
- Free energy surface : Woods–Saxon model （Pashkevich)
- Washing out of shell effects： taken into account
- Neutron emission：Iljinov *et al.*, (Nucl. Phys. A **543**, 517 (1992))
- Rotational energy：taken into account
- Langevin equation:

$$\begin{cases} \dot{q}_\beta = \mu_{\beta\nu} p_\nu , \quad \mu \equiv M^{-1} \\ \dot{p}_\beta = -\dfrac{\partial F}{\partial q_\beta} - \dfrac{1}{2} p_\nu p_\eta \dfrac{\partial \mu_{\nu\eta}}{\partial q_\beta} - \gamma_{\beta\nu} \mu_{\nu\eta} p_\eta + \theta_{\beta\nu} \xi_\nu . \end{cases}$$

Neutron emission Width: $\Gamma_n = \dfrac{(2s_n+1)m_n}{(\pi\hbar)^2 \rho_0(U_0)} \int_0^{U_n - B_n} \sigma_{inv}(E) \rho_n(U_n - B_n - E) E dE$

Neutron emission probability at each time step: $P_n(\Delta\tau) = \dfrac{\Delta\tau}{\tau} = 2\dfrac{\Delta\tau}{\hbar}\Gamma_n$

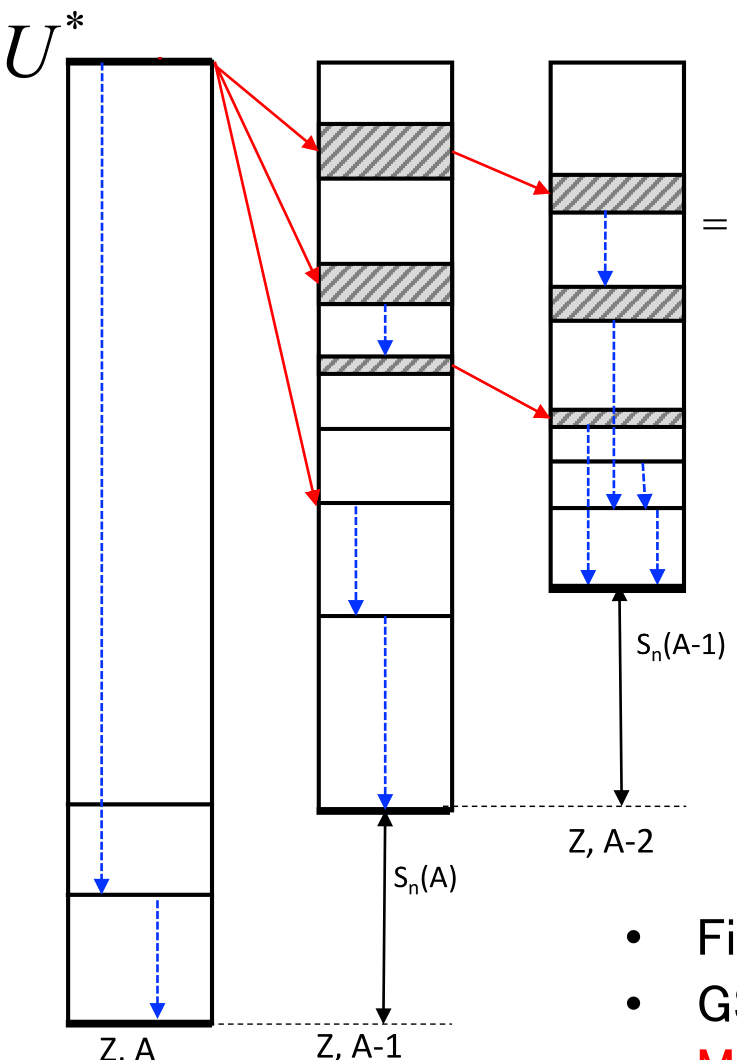
Results for AMD + Langevin（E*=50MeV)

Initial U*=50	0n	1n	2n	3n	4n
Residue	$^{302}120$	$^{301}120$	$^{300}120$	$^{299}120$	$^{298}120$
<U*> (MeV)	50	40.0	32.1	23.5	17.1
P_{CNF}	7.54×10^{-4}	7.87×10^{-5}	3.41×10^{-5}	2.33×10^{-6}	5.79×10^{-9}

Hauser–Feshbach decay with multi-chance fission (MCF)

Multistep Hauser–Feshbach decay calculation

BeoH : Okumura, Kawano, SC. *J. Nucl. Sci. Technol.*, 55,1009–1023(2018).



$$P_{surv} = \left[\frac{\sum_{\beta'=\{n,\gamma\}:l'j'} \int_0^{E_{\beta'\max}} \rho(U^* - S_{\beta'} - E_{\beta'}, J^\pi) T^J_{\beta' l' j'}(E_{\beta'}) dE_{\beta'}}{\sum_{\beta''=\{n,p,d,t,h,\alpha,\gamma,F\}:l''j''} \int_0^{E_{\beta''\max}} \rho(U^* - S_{\beta''} - E_{\beta''}, J^\pi) T^J_{\beta'' l'' j''}(E_{\beta''}) dE_{\beta''}} \right]^n$$

ρ : Level density (Gilbert–Cameron–Ignatyuk)

T : Transmission coefficients

n～α : optical model

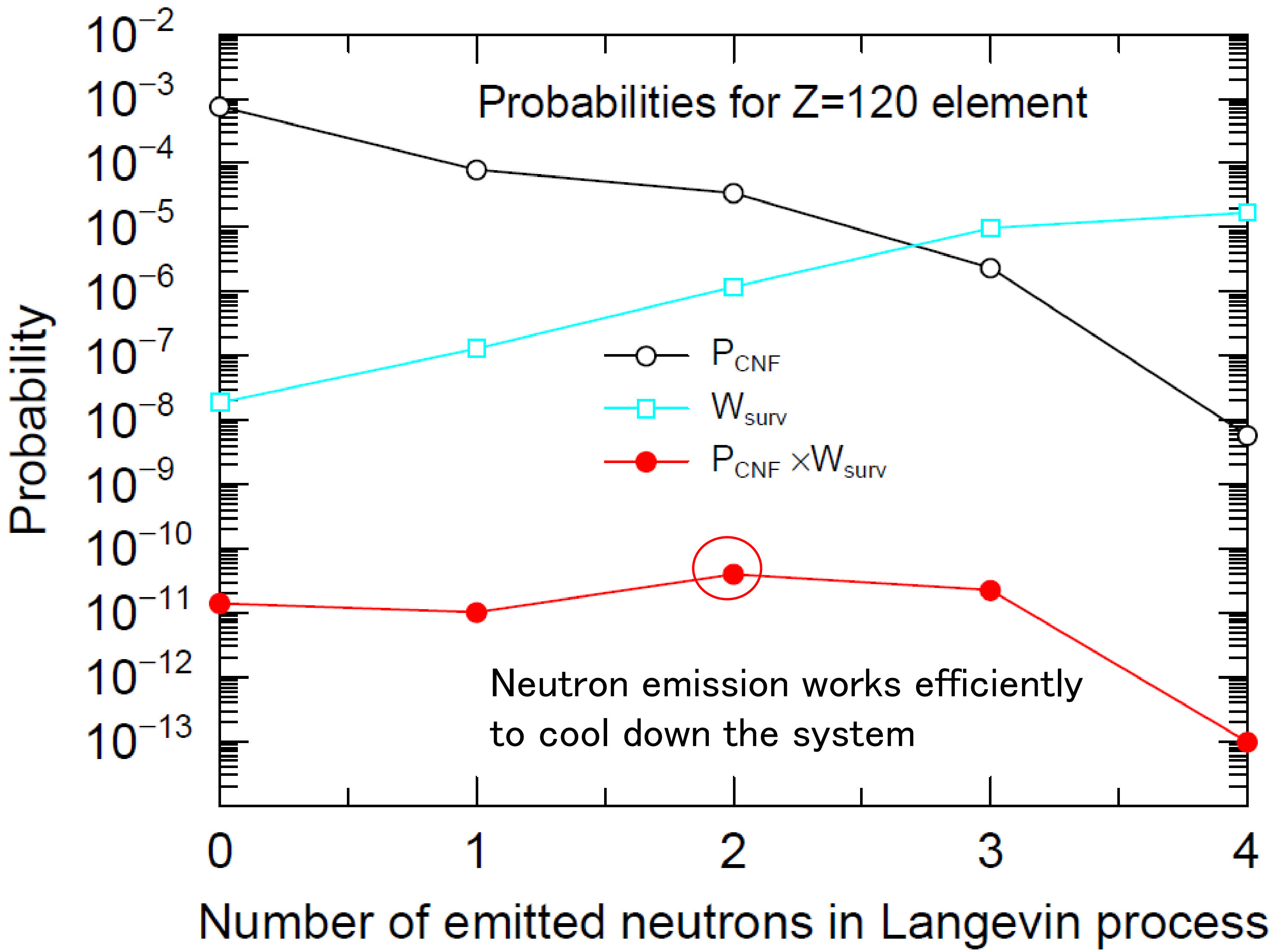
γ–decay : Kopecki–Uhl EGLO

Fission : Hill–Wheeler

- Fission barrier : Möller et al., PRC 024310(2015)
- GS spin and parity : HFBTHO code (blocking method)
- Multichance fission automatically included

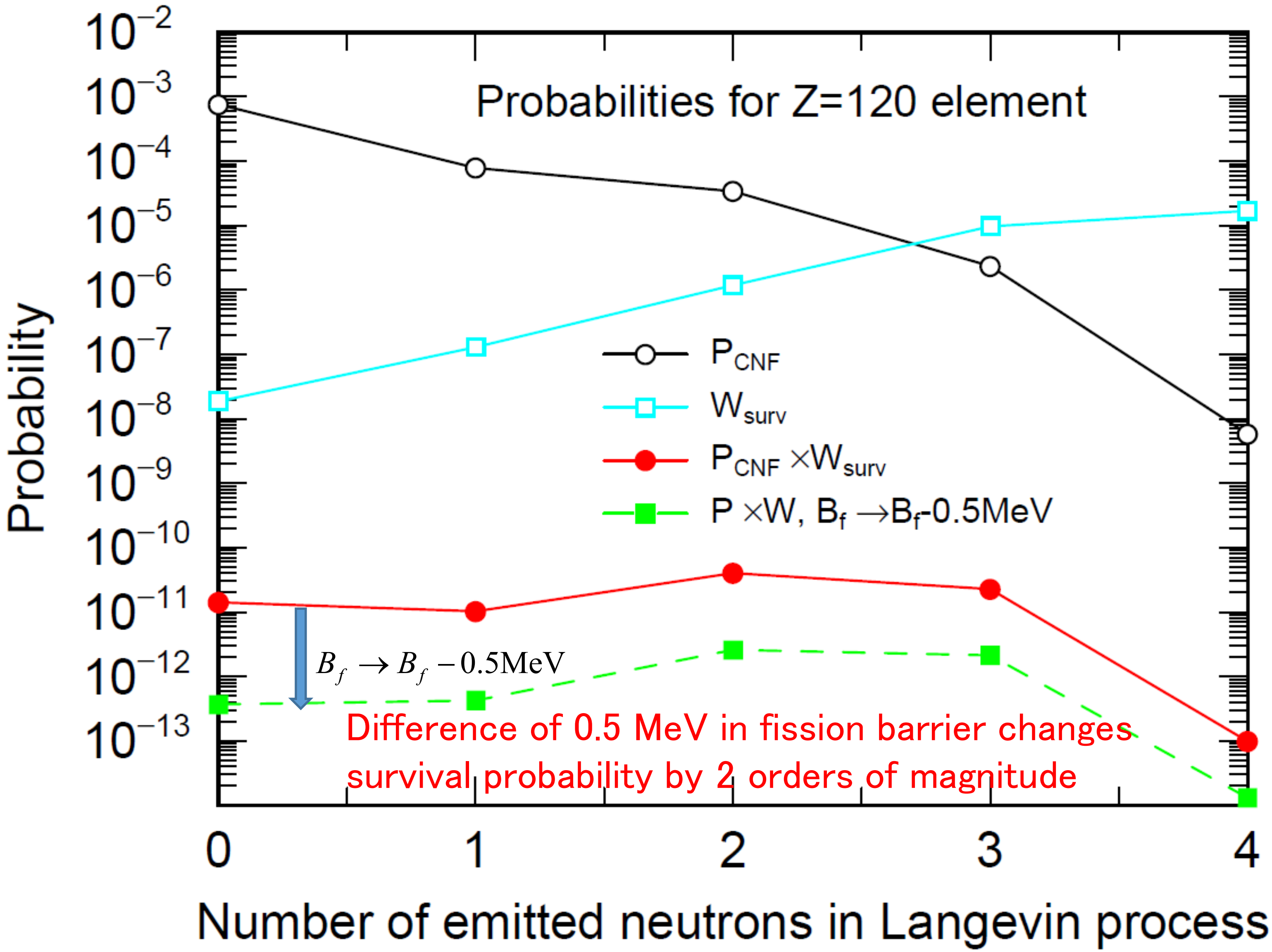
Results from AMD+Langevin＋HF

# of emitted neutrons	0n	1n	2n	3n	4n
Residue	$^{302}120$	$^{301}120$	$^{300}120$	$^{299}120$	$^{298}120$
⟨U*⟩ (MeV)	50	39.7	32.3	23.6	17.1
① P_{CNF}	7.54×10^{-4}	7.87×10^{-5}	3.41×10^{-5}	2.33×10^{-6}	5.79×10^{-9}
Bf (MeV)	3.12	3.61	4.02	4.61	6.92
②W_{surv}	1.87×10^{-8}	1.30×10^{-7}	1.18×10^{-6}	9.71×10^{-6}	1.70×10^{-5}
$P_{CNF} \times W_{surv}$	1.41×10^{-11}	1.02×10^{-11}	4.02×10^{-11}	2.26×10^{-11}	9.84×10^{-14}



Probabilities for Z=120 element
P_{CNF}
W_{surv}
$P_{CNF} \times W_{surv}$
Neutron emission works efficiently
to cool down the system
Probability
Number of emitted neutrons in Langevin process

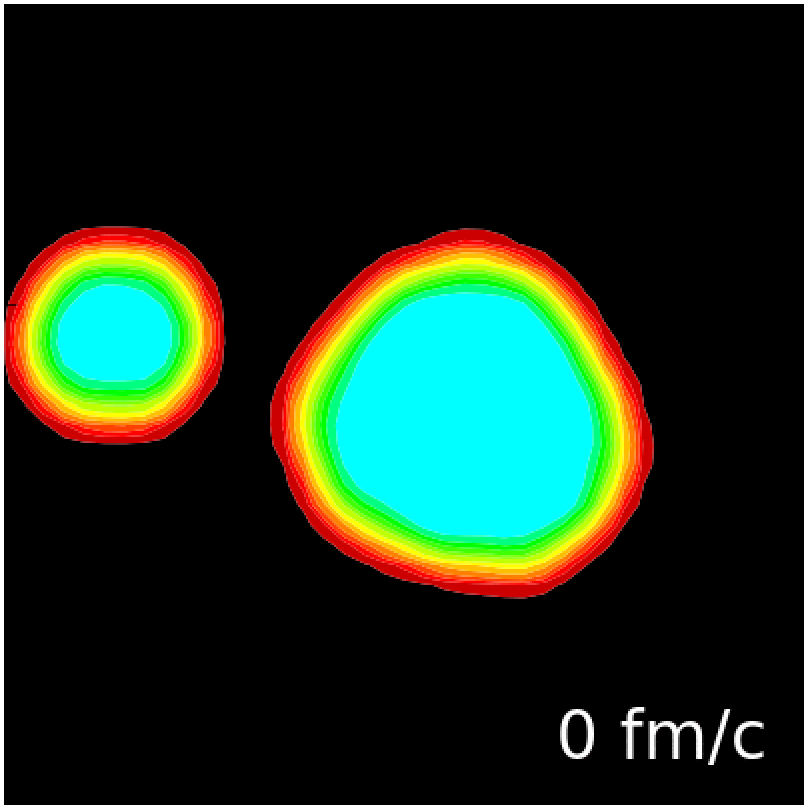
Results from AMD+Langevin＋HF



^{54}Cr(324MeV) + ^{248}Cm by AMD

b = 3.29 fm

^{54}Cr+^{248}Cm→^{126}Sn+^{176}Yb

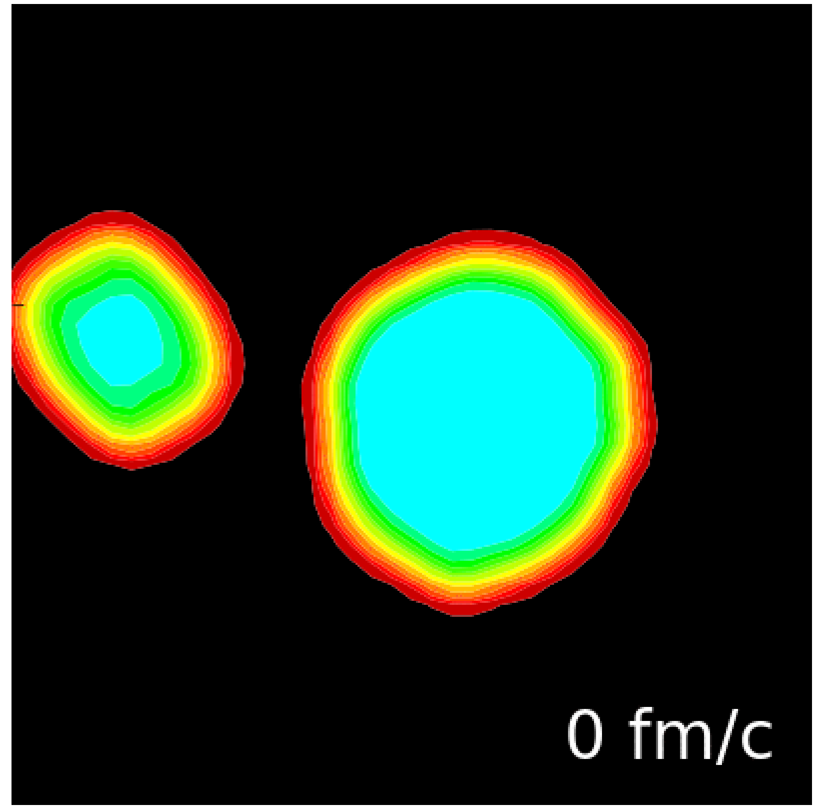


^{126}Sn : L=9.52 $\hbar$

^{176}Yb : L=5.86 $\hbar$

b = 3.05 fm

^{54}Cr+^{248}Cm→^{302}102

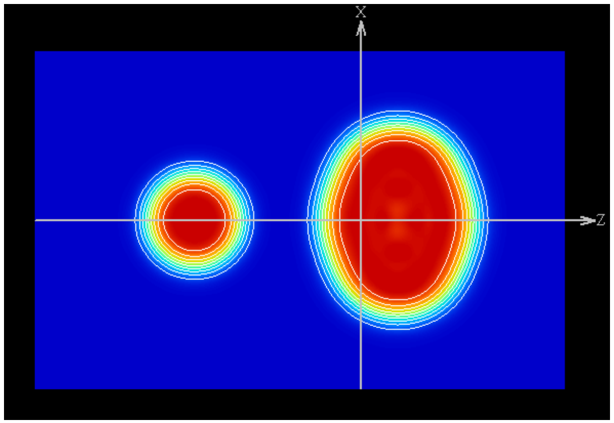


^{302}X : L=76.95 $\hbar$

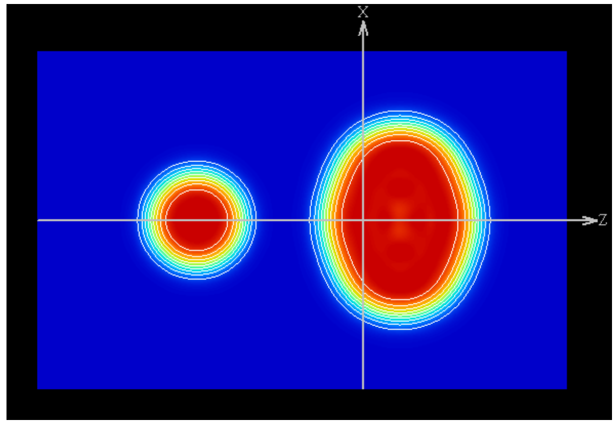
Off-center fusion seems to be strongly hindered

Another approach (Cb-TDHFB Cal. : Neutron density distribution), talk by S. Ebata tomorrow

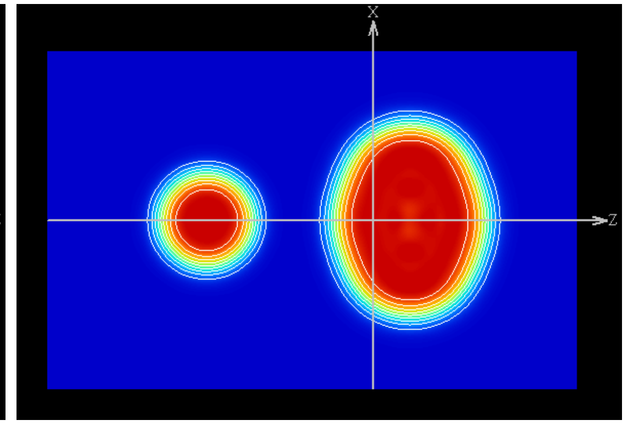
E_{in}=300 MeV



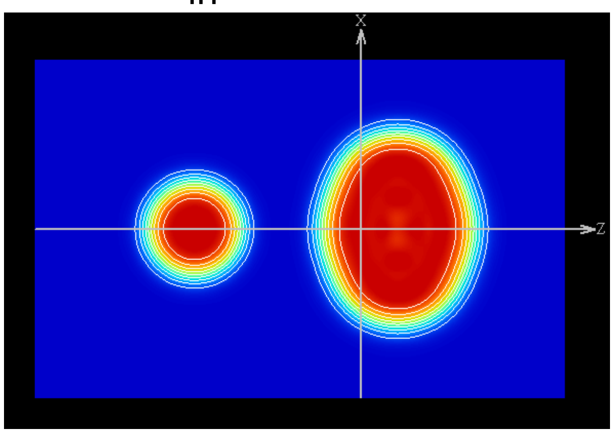
E_{in}=310 MeV



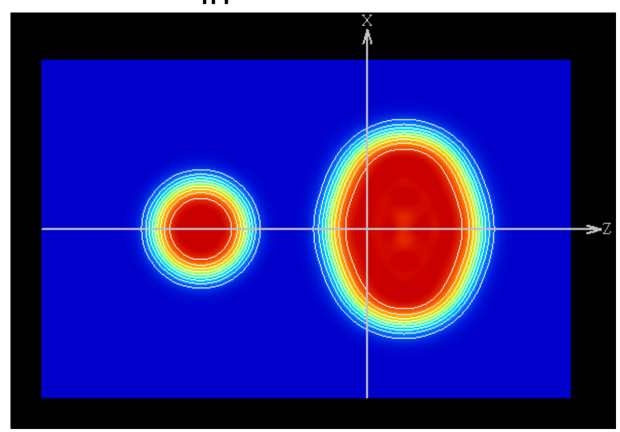
E_{in}=320 MeV



E_{in}=330 MeV



E_{in}=340 MeV



Summary-1

1. We have integrated theoretical tools developed or prepared at Tokyo Tech. to give a description of formation of SHE including Z=120 elements: AMD, Cb-TDHFB, VUU, Langevin equation, multistep Hauser-Feshbach theory and HFBTHO
2. By performing calculations at the touching phase with microscopic theories like AMD or TDHFB, we can eliminate all free parameters which are present in conventional semi-classical approaches
3. We applied our method for the system of $^{54}Cr+^{248}Cm$ at energy of hot fusion, and have verified that we can indeed describe the whole process starting from touching phase to formation of compound nuclei
4. It was found that the most compact shape we could produce is still more elongated compared to shape of the 2^{nd} saddle calculated by the 3D Cassini-Woods-Saxon model

Summary–2

5. It was found that populated composite system has excitation energy more than 40 MeV, so fission barrier is almost washed out. It leads to a very small survival probability, and it is the bottleneck of SHE formation with this reaction
6. Survival probability also depends strongly on spin values of the CN so they must be specified (by experiment, hopefully)
7. The survival probability is sensitive to excitation energy, so we must consider distribution of the excitation energy in the future work.
8. If cooling of populated nuclei by neutron emission works efficiently, the fission barrier revives, and there is a possibility that the survival probability may gets several orders larger
9. We have also started Cb–TDHFB calculation for the touching process (talk by S. Ebata)
10. If this kind of calculation makes sense, we would further refine our model and acquire knowledge on formation of SHE


Thank you very much!!