Theoretical study on formation mechanisms of Z=120 super-heavy elements

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Key words:
Super-heavy element,
Fusion, TDMF calculation

Introduction

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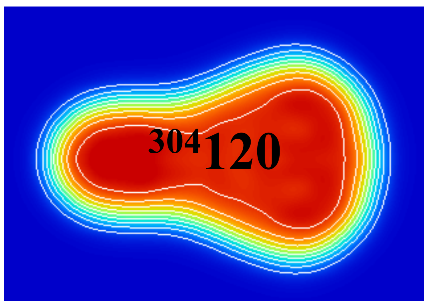
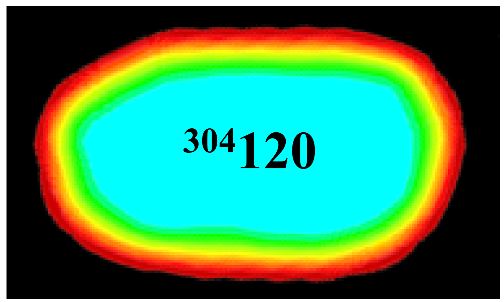
Beyond Nh (Og)!!

Motivation

- To simulate a synthesis process of the super-heavy element and to deduce the synthesis probability P_{SHE} using theoretical methods.
- In order to construct the hybrid model including suitable methods to describe the processes on **touching**, **fusion**, **compound formation** and **evaporation**, to simulate the synthesis process.

Touching process P_{touch}





Cb-TDHFB, AMD

Shape profile

Hauser-Feshbach decay P_{survive}

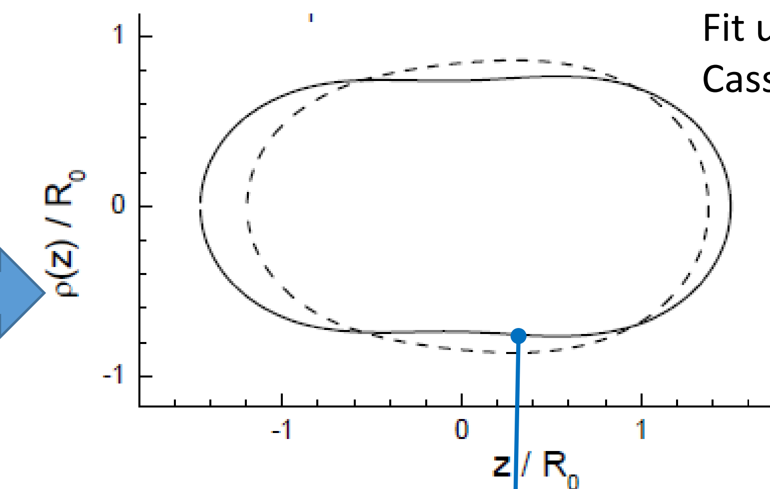
$$P_{\mathrm{survive}} = \frac{\displaystyle\sum_{D=\{n,\gamma\}:l,j} \int_0^{E_{D\max}} \rho(E^* - S_D - E_D, J^\pi) T^J_{D,l,j}(E_D) dE_D}{\displaystyle\sum_{D'=\{\cdots\}:l,j} \int_0^{E_{D'\max}} \rho(E^* - S_{D'} - E_{D'}, J^\pi) T^J_{D',l,j}(E_{D'}) dE_{D'}}$$

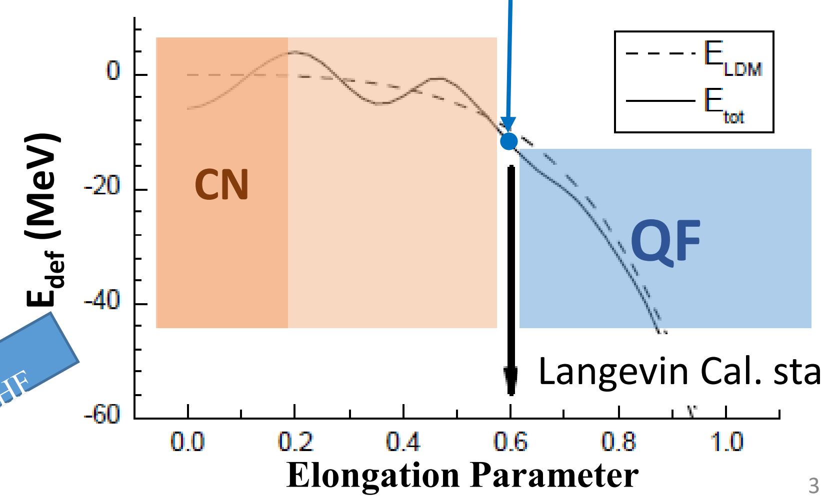
Decay mode: $D' = \{n, p, t, {}^3\mathrm{He}, \alpha, \gamma, F\}$

HFBTHO + BeoH
spin & parity

Compound & Quasi-fission P_{CNF}

4D Langevin w/ neutron evaporation





P CHF

Synthesis probability: $P_{\mathrm{SHE}} = P_{\mathrm{touch}} \cdot P_{\mathrm{survive}} \cdot P_{\mathrm{CNF}}$

Motivation

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- In order to construct the hybrid model including suitable methods to describe the processes on **touching**, **fusion**, **compound formation** and **evaporation**, to simulate the synthesis process.

> Physical quantities on **the touching process** described a microscopic method.
> We apply the time-dependent mean-field theory to ^{248}Cm+^{54}Cr, and acquire experience on the super-heavy element (Z=120) synthesis.

Purpose of this work

We show the calculations of ^{248}Cm+^{54}Cr fusion reaction using the **canonical-basis time-dependent Hartree-Fock-Bogoliubov** (**Cb-TDHFB**) theory, to check the **nucleon densities** and **energy balance** on the dynamics, for more accurate simulation, this is one of benchmark calculation.

Method Time-dependent density functional theory

Cb-TDHFB S.E. et al., Phys. Rev. C**82**(2010) 034306, S.E. and T.Nakatsukasa, JPS Conf. Proc. **6**, 020056 (2015)

Interaction (*ph*) : Skyrme (SkM* w/o Center of Mass correction),

(*pp*, *hh*) : delta-function $V^\tau(\boldsymbol{r}_1,\sigma_1;\boldsymbol{r}_2,\sigma_2) = V^\tau_{pair}\frac{1-\hat{\sigma}_1\cdot\hat{\sigma}_2}{4}\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$ $\quad \Delta_l(t) = -\sum_{k>0}\kappa_k(t)V_{l\bar{l}k\bar{k}}(t)$

Cb-TDHFB equations

$$i\hbar\frac{\partial}{\partial t}|\phi_k(t)\rangle = \big(h(t)-\eta_k(t)\big)|\phi_k(t)\rangle$$

$$i\hbar\frac{\partial}{\partial t}\rho_k(t) = \kappa_k(t)\Delta^*_k(t) - \Delta_k(t)\kappa^*_k(t)$$

$$i\hbar\frac{\partial}{\partial t}\kappa_k(t) = \big(\eta_k(t)+\eta_{\bar{k}}(t)\big)\kappa_k(t) + \Delta_k(t)(2\rho_k(t)-1)$$

Properties of Cb-TDHFB

$$d/dt\langle\phi_k(t)|\phi_{k'}(t)\rangle = 0$$

$$d/dt\langle\hat{N}\rangle = 0,\ d/dtE_{\mathrm{Total}} = 0$$

In the limit of Δ=0 ➡ **TDHF**

In the static limit, ➡ **HF+BCS**

$$\eta_k(t) \equiv \langle\phi_k(t)|h(t)|\phi_k(t)\rangle + i\hbar\left\langle\frac{\partial\phi_k}{\partial t}\middle|\phi_k\right\rangle$$

Subjective reaction system: ^{248}Cm+^{54}Cr → ^{302}120 $\quad E_{in}$ = 300, 310, 320, 330, 340 [MeV]

Pairing strength V_{pair} for target and projectile
are defined to reproduce the Δ^ν, Δ^π deduced by 3-points formula.
Averaged pairing strength of nuclei is used in the Cb-TDHFB calculation.

e.g. $\Delta^\nu_3(N,Z) \equiv \frac{1}{2}(B(N-1,Z)+B(N+1,Z)-2B(N,Z))$

Method Procedure for the reaction calculation

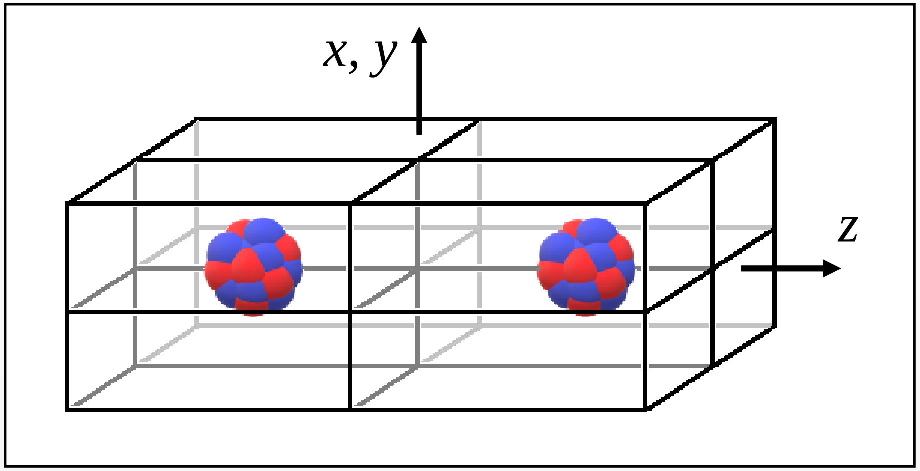
1, Calculate the ground states of ^{248}Cm, ^{54}Cr using 3D Skyrme HF+BCS self-consistently.

2, Set the ^{248}Cm, ^{54}Cr on the points with the distance working Coulomb force dominantly.

3, Boost them with an energy E_{in} considering the incidence from the infinite-point.

4, Calculate the nuclear dynamics with Cb-TDHFB.

Calculation space (3D Cartesian coordinate)



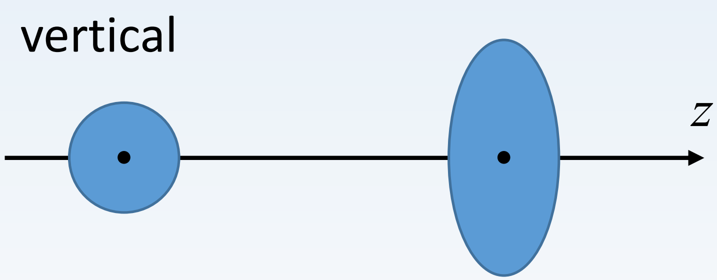
Rectangular box of 30 fm × 30 fm × 60 fm, discretized in the square mesh of Δx = Δy = Δz = 1.0 fm

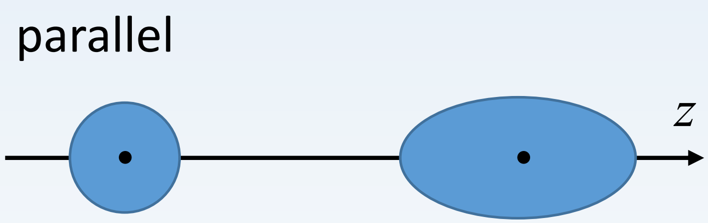
Calculate the head-on collision (*b=0*).

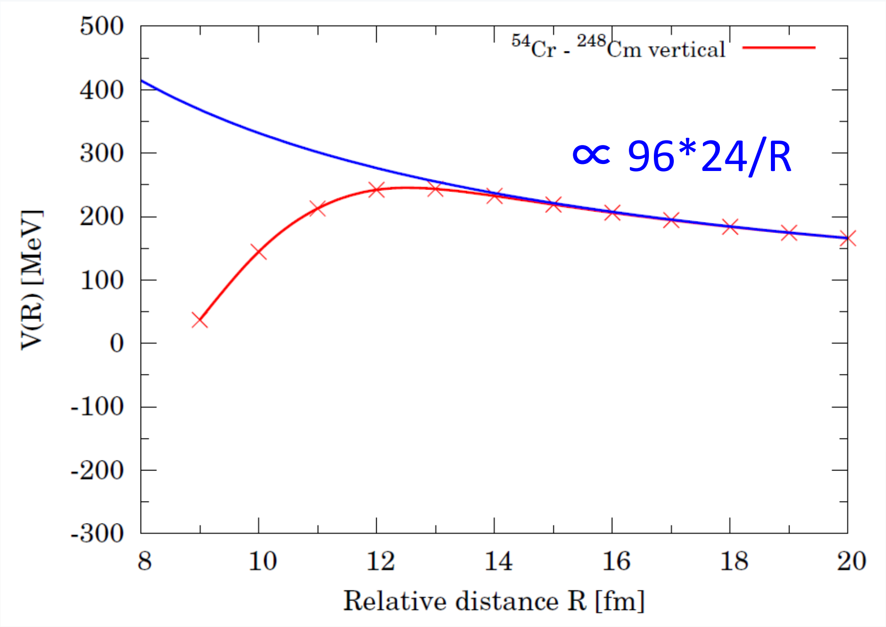
Results (Coulomb barrier height: Frozen Density Approximation)

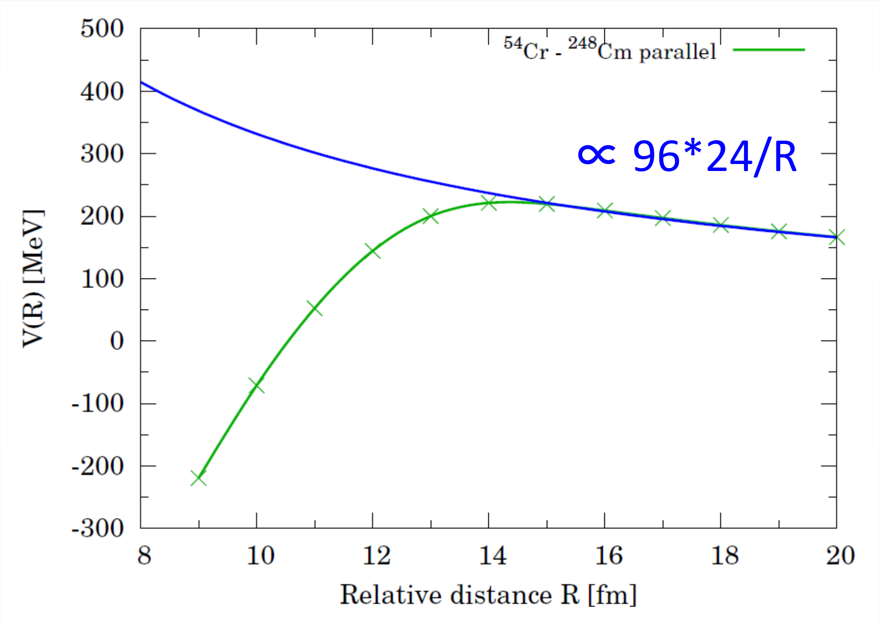
^{248}Cm has quadrupole deformed shape

→ The Coulomb barrier heights are different depending on the reaction direction.









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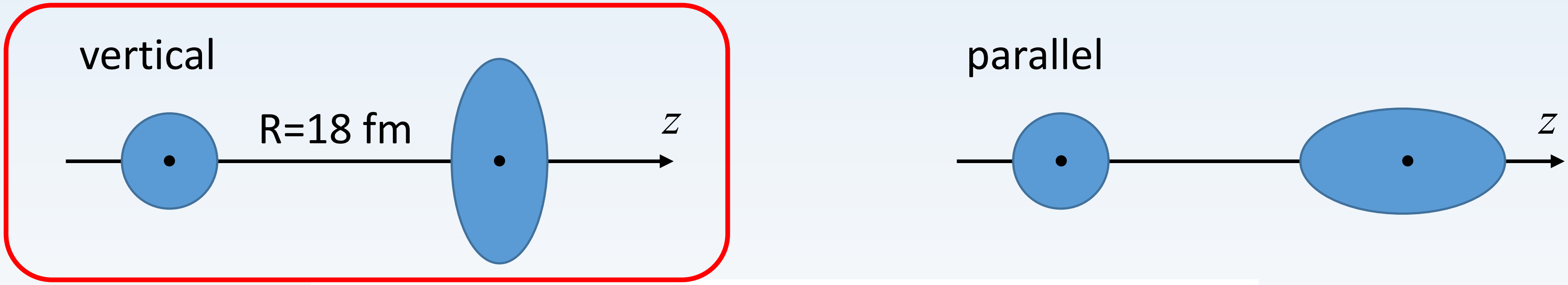
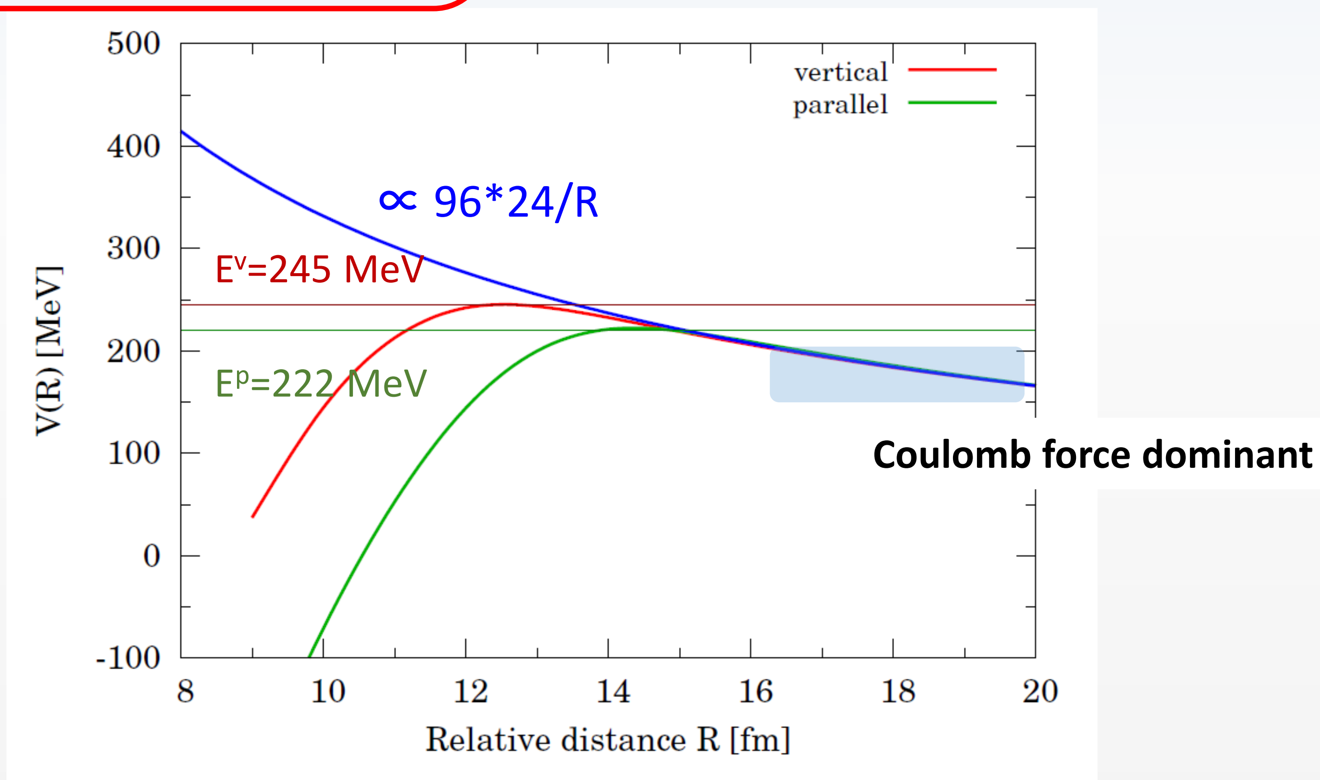
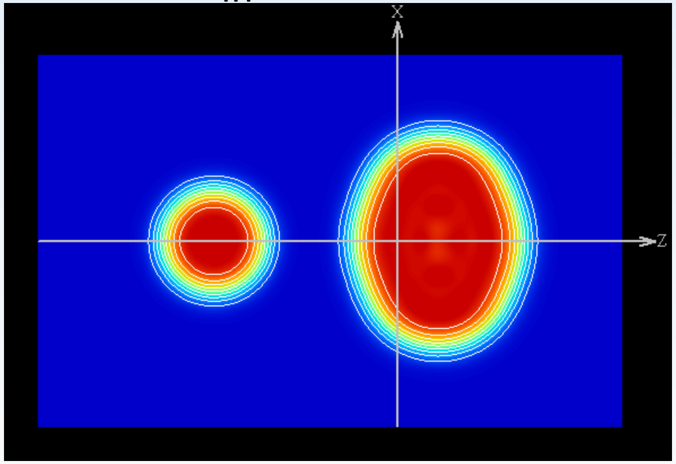


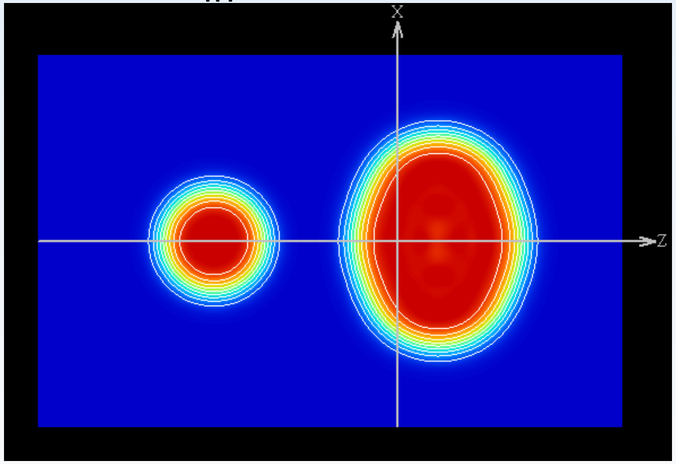


Results (TD Cal. : Neutron density distribution)

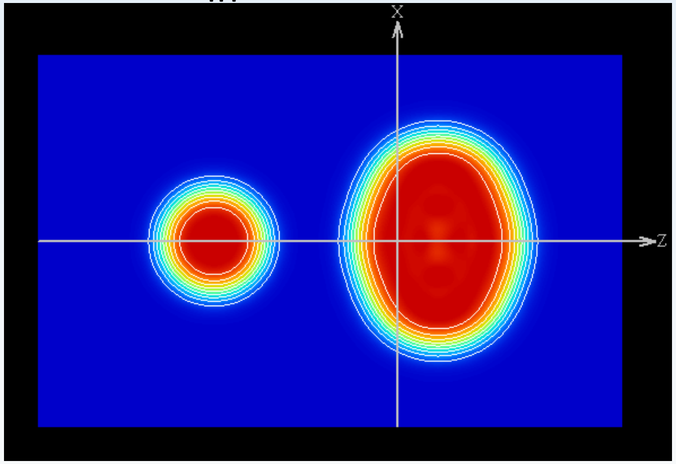
E_{in}=300 MeV



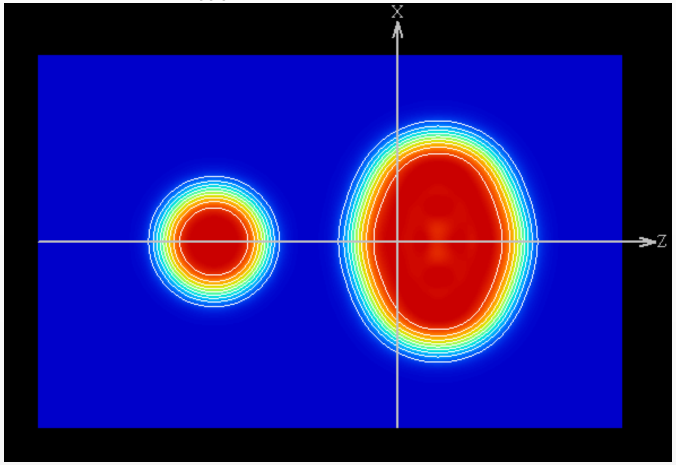
E_{in}=310 MeV



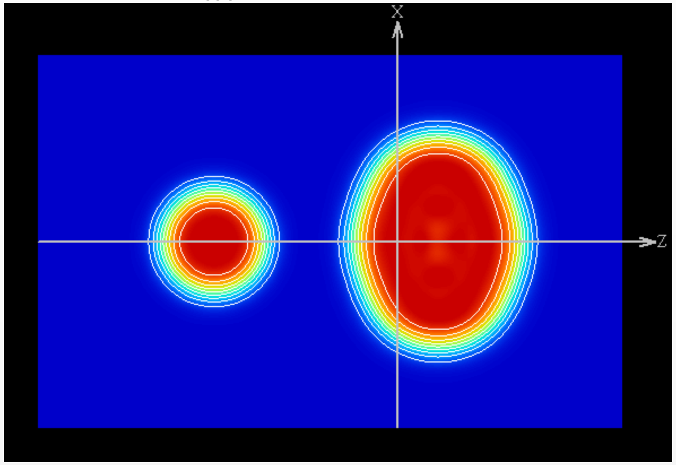
E_{in}=320 MeV



E_{in}=330 MeV



E_{in}=340 MeV



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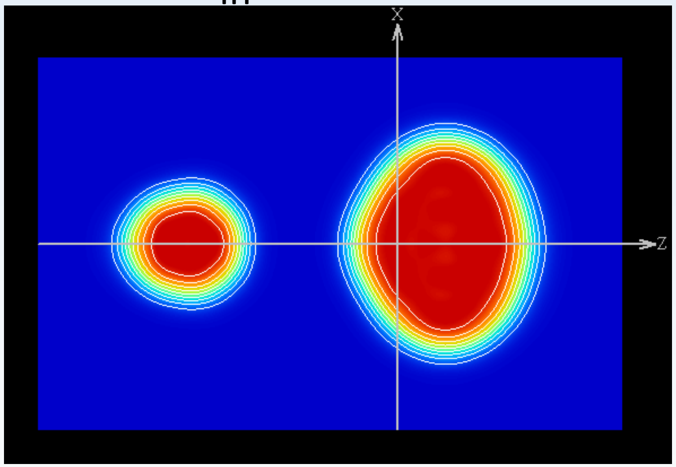

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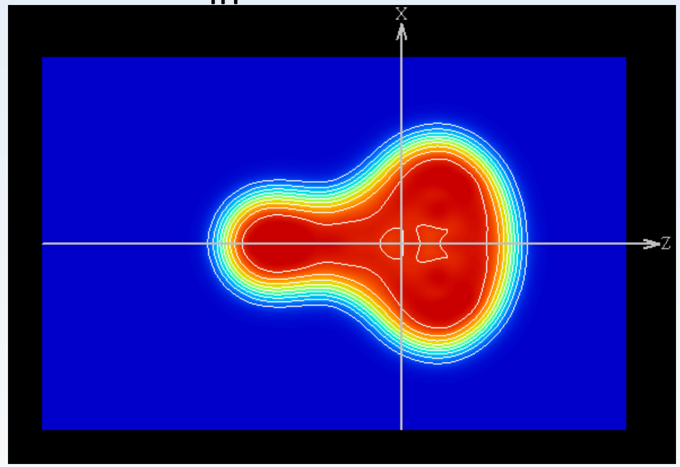

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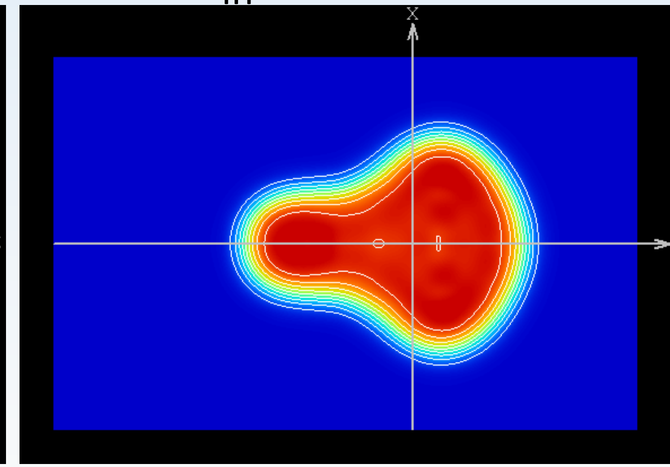

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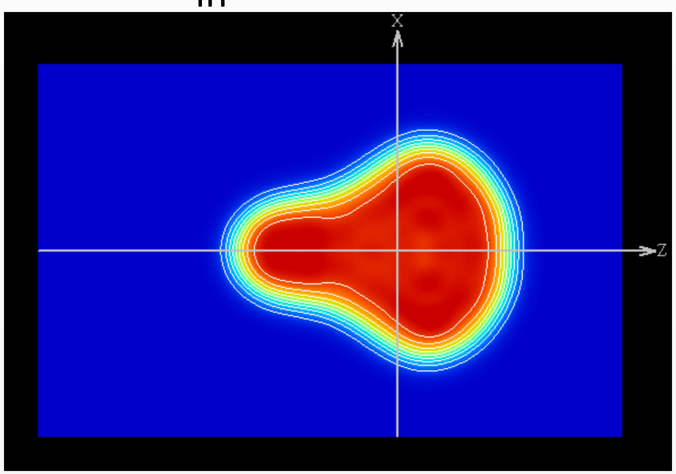

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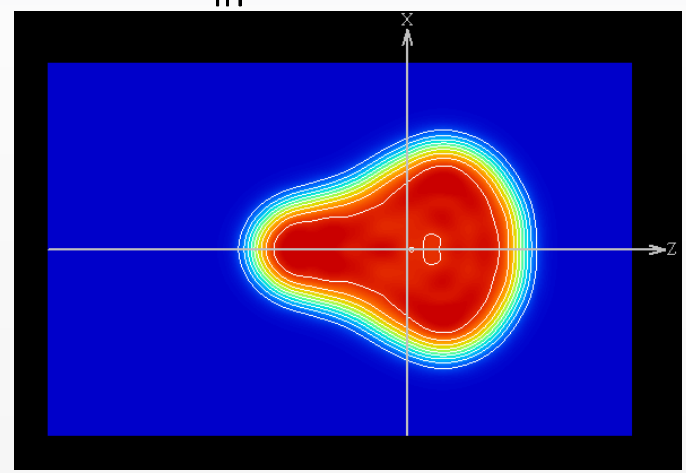
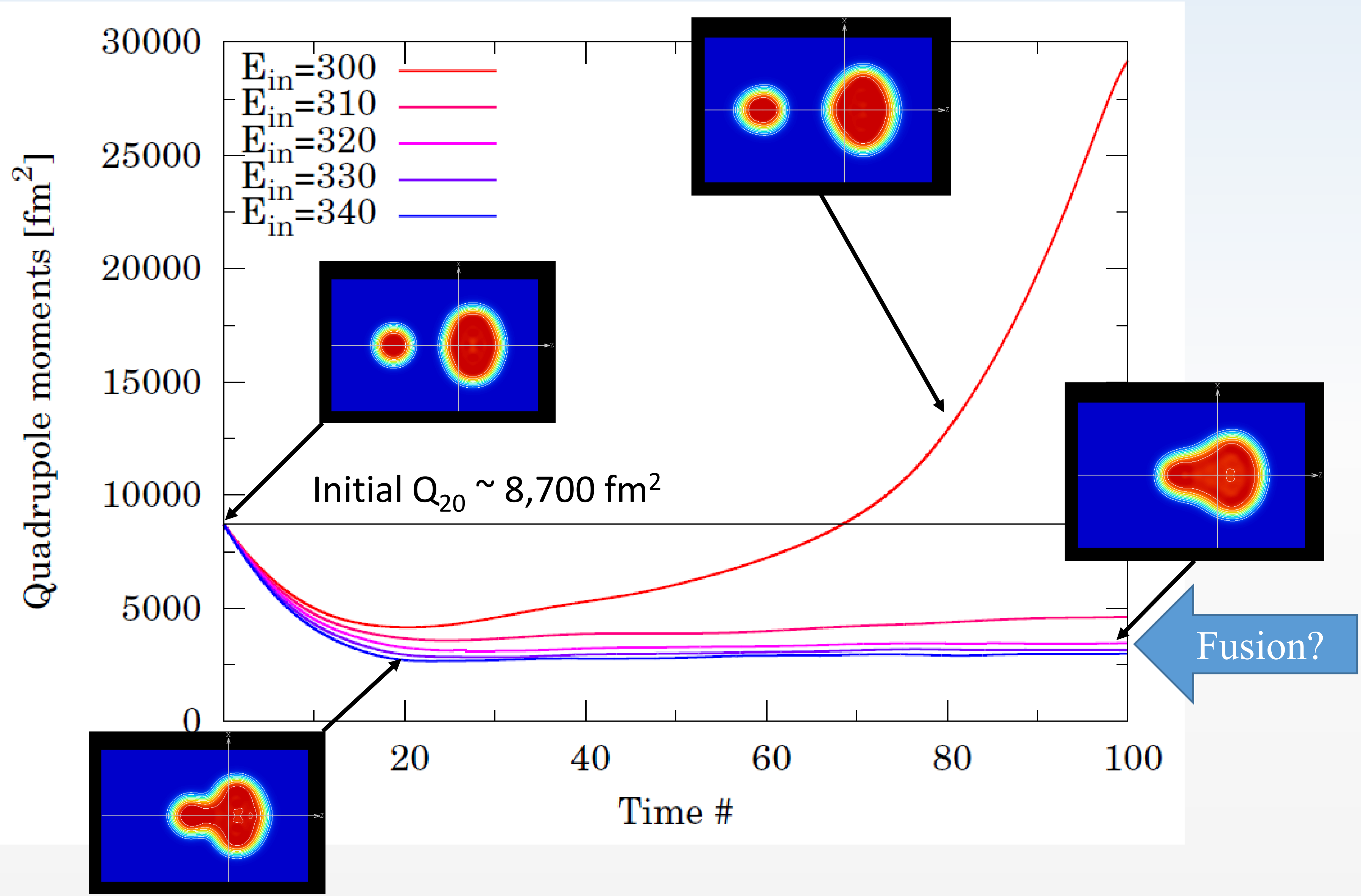


✓ For the fusion, (at least) E_{in} = 310 MeV is necessary. (Coulomb barrier E^{V}=245MeV)

Results (TD Cal. : Quadrupole momentum)

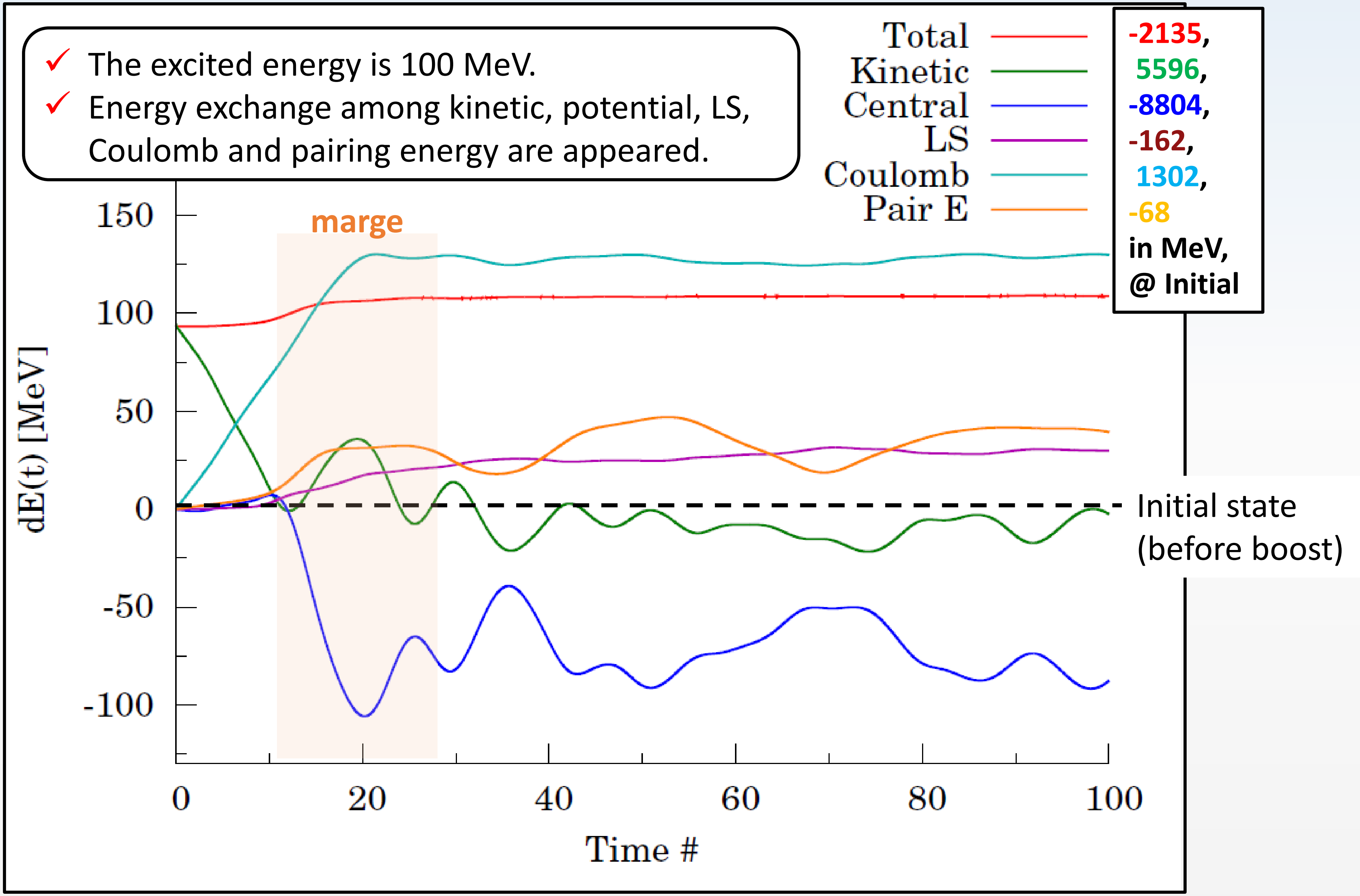


Results (TD Cal. : Energy balance on E_{in}=340MeV reaction)

Time-dependence of energy change from initial state $dE_\mu(t) = E_\mu(t) - E_\mu(0^-)$

$\mu = \{\text{Total, Kinetic, Central, LS, Coulomb, Pairing}\}$

- ✓ The excited energy is 100 MeV.
- ✓ Energy exchange among kinetic, potential, LS, Coulomb and pairing energy are appeared.



Summary

- ✓ We calculate the head-on reaction $^{248}Cm+^{54}Cr \rightarrow {}^{302}120$ using Cb-TDHFB, with $E_{in} = 300, 310, 320, 330, 340$ MeV.
    - ✓ The Coulomb barriers of $^{248}Cm+^{54}Cr$ are evaluated 245 (vertical) and 222 (parallel) MeV on the reaction direction using Frozen density approximation.
    - ✓ Over 60 MeV from Coulomb barrier is necessary for the fusion.
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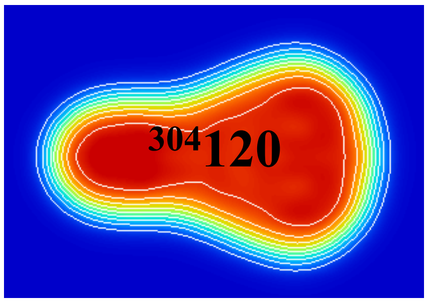
Future work

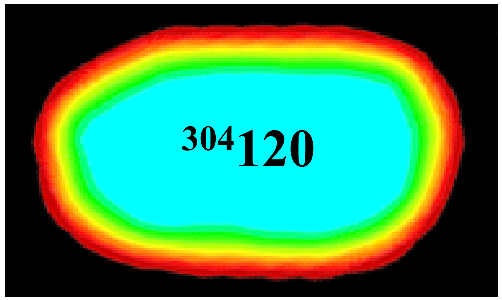
- To distinguish Quasi-fission and Fusion, more long-time calculation is necessary.
    - Optimization of the calculation space and Revision of algorithm to time-evolution
- Large-scale calculation for P_{touch} w.r.t the impact parameter, nuclear rotation
- For pairing correlation : strength, functional form, phase among target and projectile

Again …

Touching process P_{touch}



Cb-TDHFB,



AMD

Shape profile

Hauser-Feshbach decay $P_{survive}$

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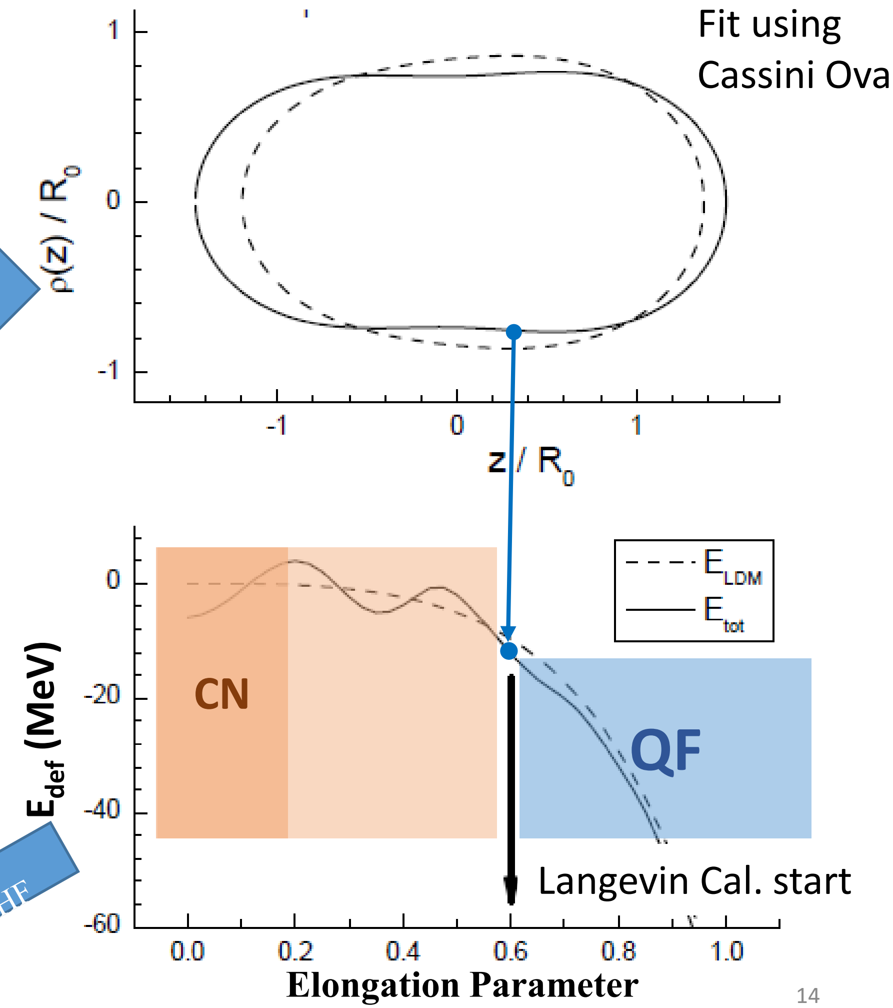
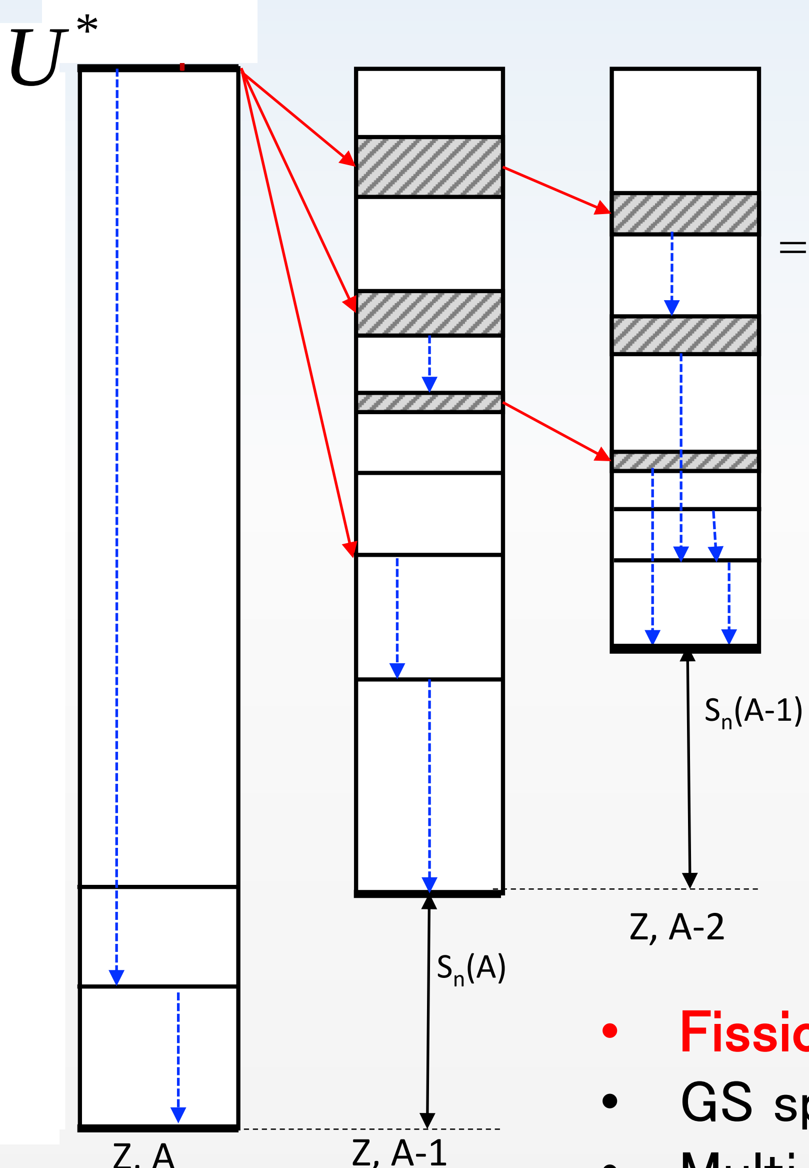


P_{CHF}

Synthesis probability: $P_{SHE} = P_{touch} \cdot P_{survive} \cdot P_{CNF}$

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 : Kopecki–Uhl EGLO(up to E3)

Fission : Hill–Wheeler

- Fission barrier : Litnevsky et al., PRC 89, 034626(2014)
- GS spin and parity : HFBTHO code (blocking method)
- Multi-chance fission automatically included

Results from AMD+Langevin＋HF

Initial U^*=50	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}
②P_{surv}	1.87×10^{-8}	1.30×10^{-7}	1.18×10^{-6}	9.71×10^{-6}	1.70×10^{-5}
$P_{CNF} \times P_{surv}$ ①×②	1.41×10^{-11}	1.02×10^{-11}	4.02×10^{-11}	2.26×10^{-11}	9.84×10^{-14}

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