External Review on Center for Computational Sciences, University of Tsukuba
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Multi-nucleon transfer reaction by TDHF

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In collaboration with

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OUTLINE

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What I show today

- To what extent the TDHF theory describes the MNT reaction, quantitatively.

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2. Particle number projection method
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K. Sekizawa and K. Yabana, Phys. Rev. C **88**, 014614 (2013)

3D-grid: 60×60×26 (48 fm×48 fm×20.8 fm), Mesh size: 0.8 fm

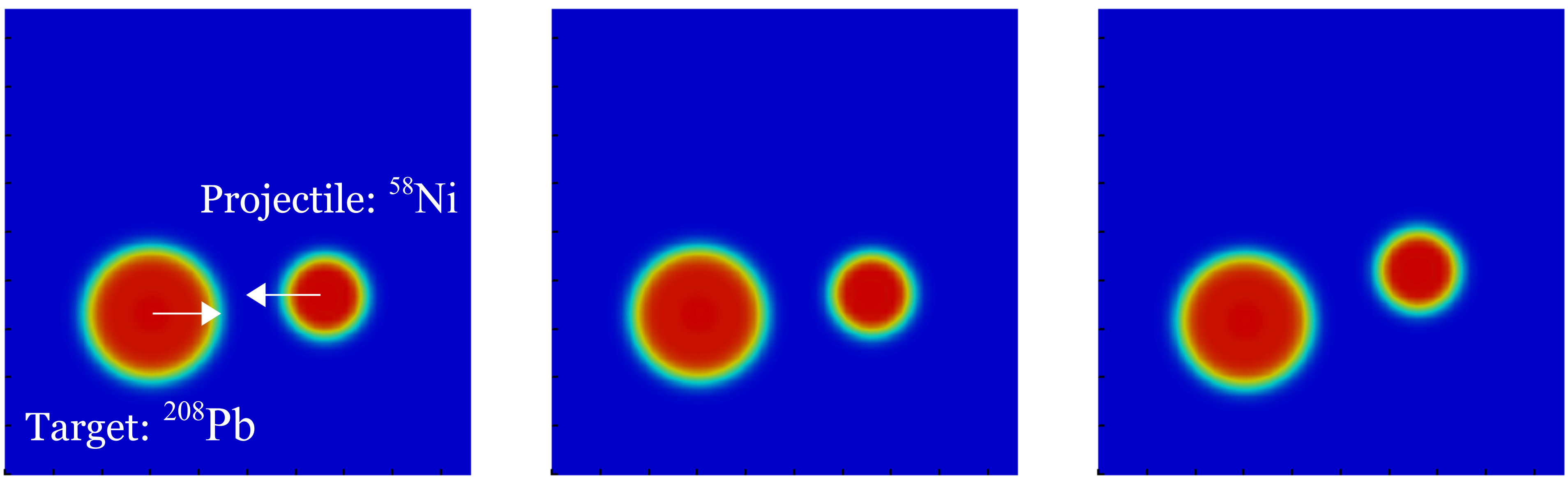
Skyrme force: SLy5, *Δt*: 0.2 fm/c, Initial separation distance: 16 fm

Calculated impact parameter: 0 ≦ *b* ≦ 10 fm

Fusion reactions (*b* ≦ 1.38 fm), Binary reactions (1.39 fm ≦ *b*)

Time evolution of density obtained from the TDHF calculation

b=1.38 fm *b*=1.60 fm *b*=4.00 fm



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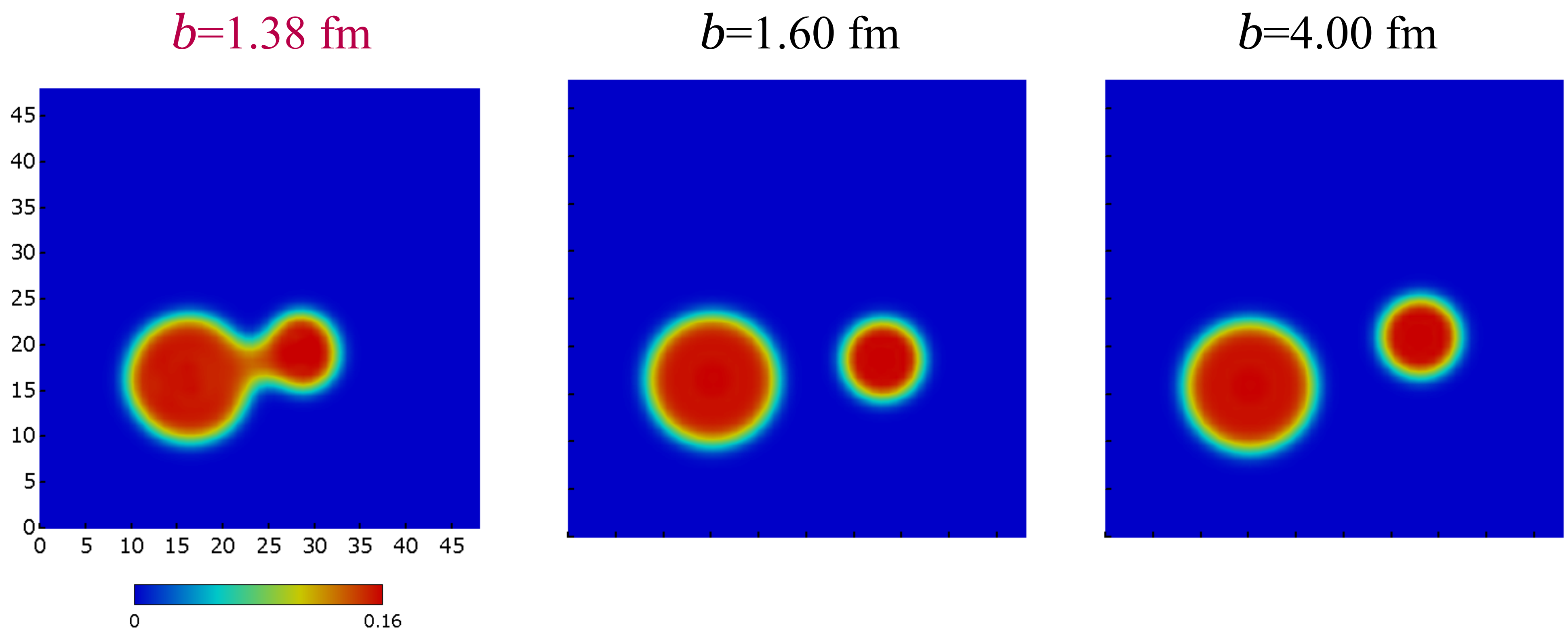

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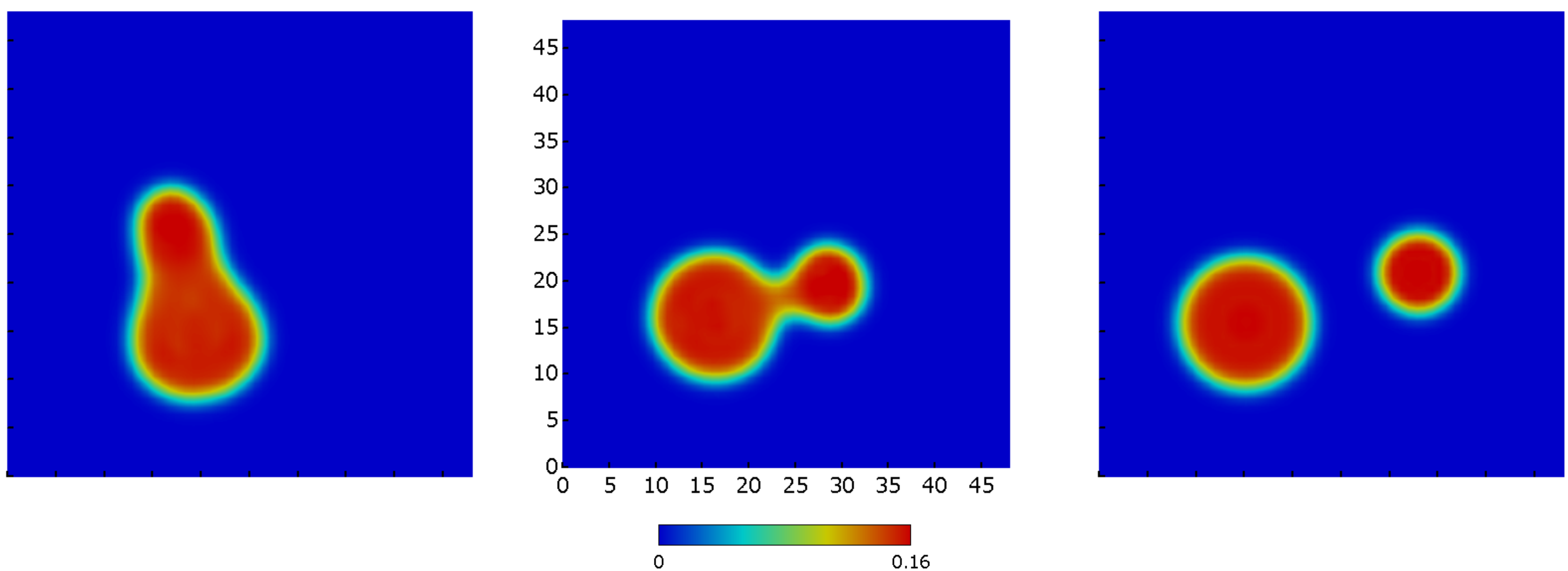

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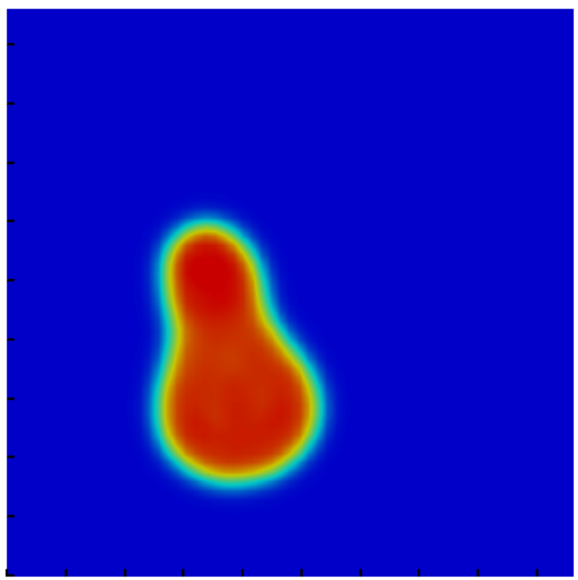
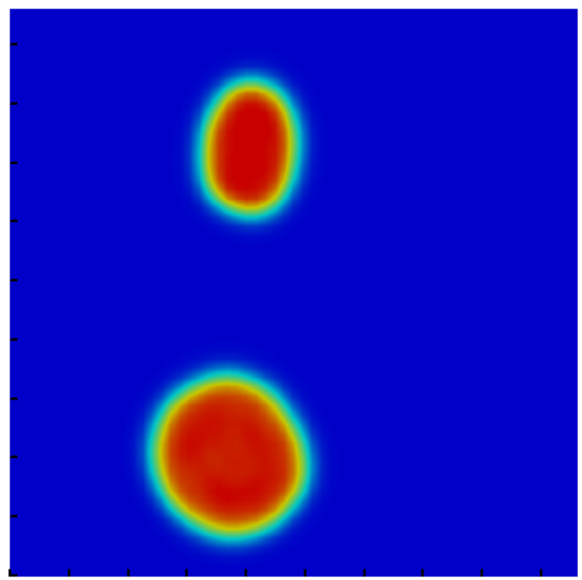
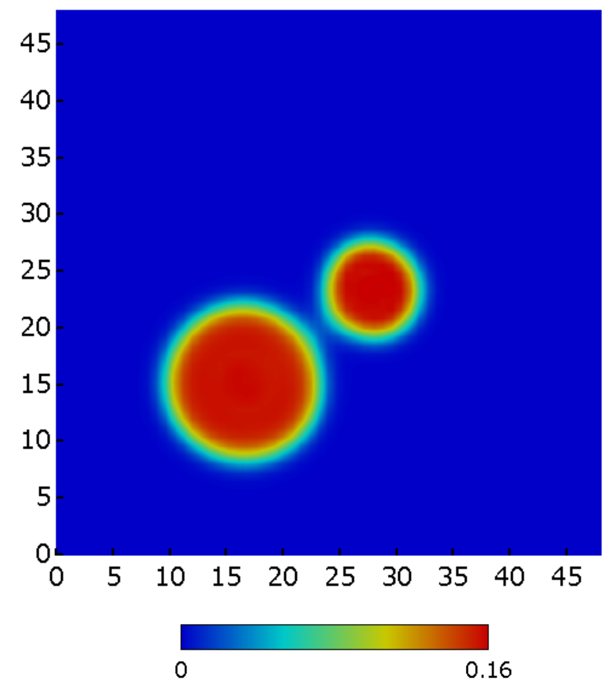


b=1.60 fm



b=4.00 fm



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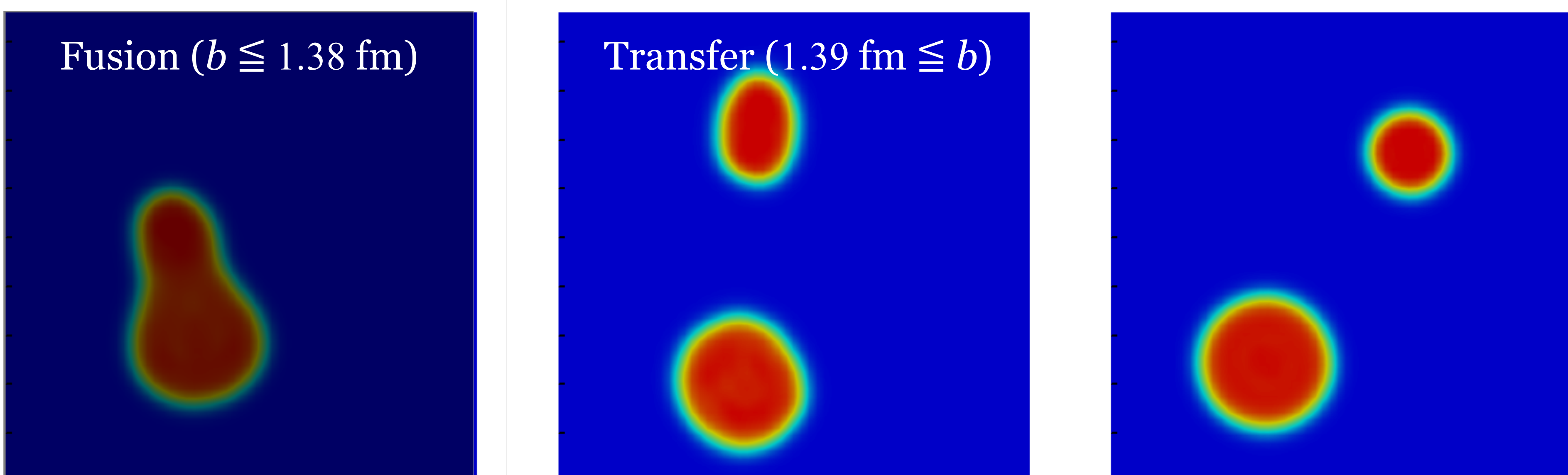

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Particle number projection method

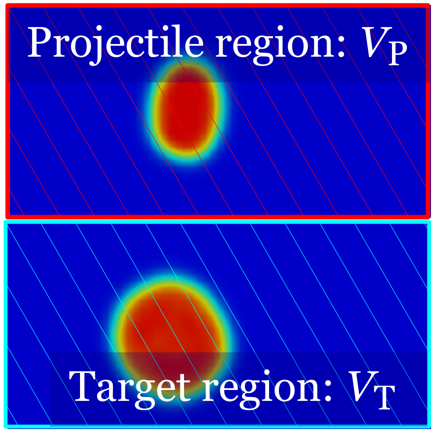
C. Simenel, Phys. Rev. Lett. **105**, 192701 (2010)

✔ Particle number projection operator

$$\hat{P}_n = \frac{1}{2\pi}\int_0^{2\pi} d\theta\, e^{i(n-\hat{N}_\mathrm{P})\theta}$$

$\hat{N}_\mathrm{P}$: Number operator of the spatial region V_P

$$\hat{N}_\mathrm{P} = \int_{\mathrm{V_P}} d^3r \sum_{i=1}^{N_\mathrm{P}+N_\mathrm{T}} \delta(\boldsymbol{r}-\boldsymbol{r}_i)$$



N=N_P +N_T: Total number of nucleons

➢ Probability P_n: n nucleons are in the V_P and N-n nucleons are in the V_T

$$\begin{aligned} P_n &= \langle \Phi | \hat{P}_n | \Phi \rangle \\ &= \frac{1}{2\pi}\int_0^{2\pi} d\theta\, e^{in\theta} \det\left\{ \langle \phi_i|\phi_j\rangle_{\mathrm{V_T}} + e^{-i\theta}\langle\phi_i|\phi_j\rangle_{\mathrm{V_P}} \right\} \end{aligned}$$

Slater determinant

$$\Phi(\boldsymbol{x}_1,\cdots,\boldsymbol{x}_N) = \frac{1}{\sqrt{N!}}\det\{\phi_i(\boldsymbol{x}_j)\}$$

Single-particle w.f.

$$\phi_i(\boldsymbol{x}) \equiv \phi_i(\boldsymbol{r},\sigma)$$

$$i = 1,\cdots,N_\mathrm{P}+N_\mathrm{T}$$

Overlap integral in respective regions

$$\langle\phi_i|\phi_j\rangle_\tau = \int_\tau d^3x\, \phi_i^*(\boldsymbol{x})\phi_j(\boldsymbol{x})$$

$$\tau = \mathrm{V_P} \text{ or } \mathrm{V_T}$$

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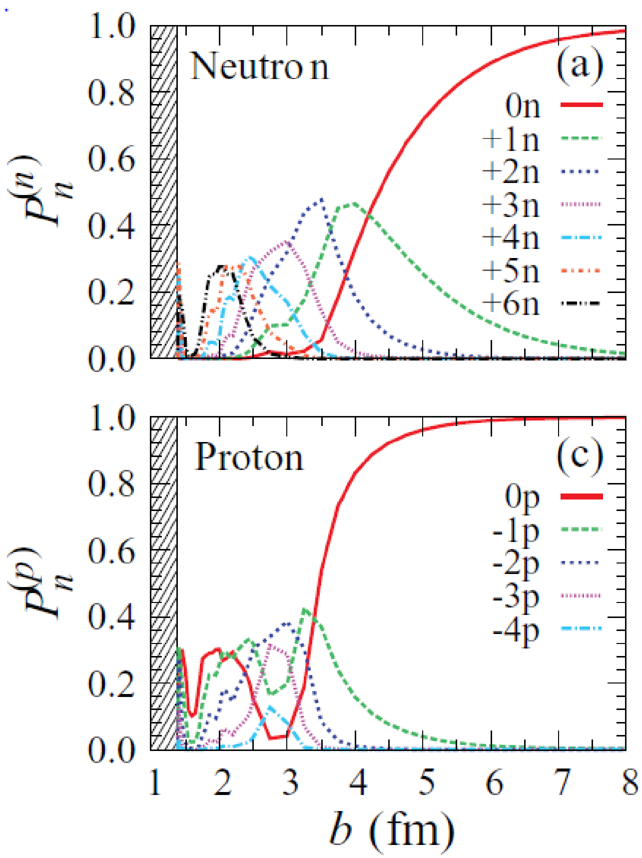
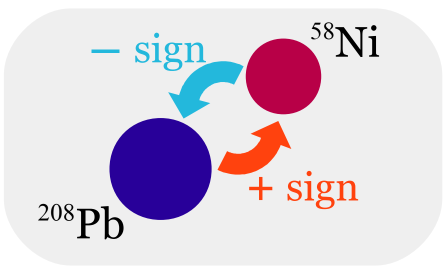
Transfer probabilities

$$P_n = \langle \Phi | \hat{P}_n | \Phi \rangle = \frac{1}{2\pi}\int_0^{2\pi} d\theta\, e^{in\theta} \det\left\{ \langle \phi_i | \phi_j \rangle_{\mathrm{V_T}} + e^{-i\theta} \langle \phi_i | \phi_j \rangle_{\mathrm{V_P}} \right\}$$: The projection method





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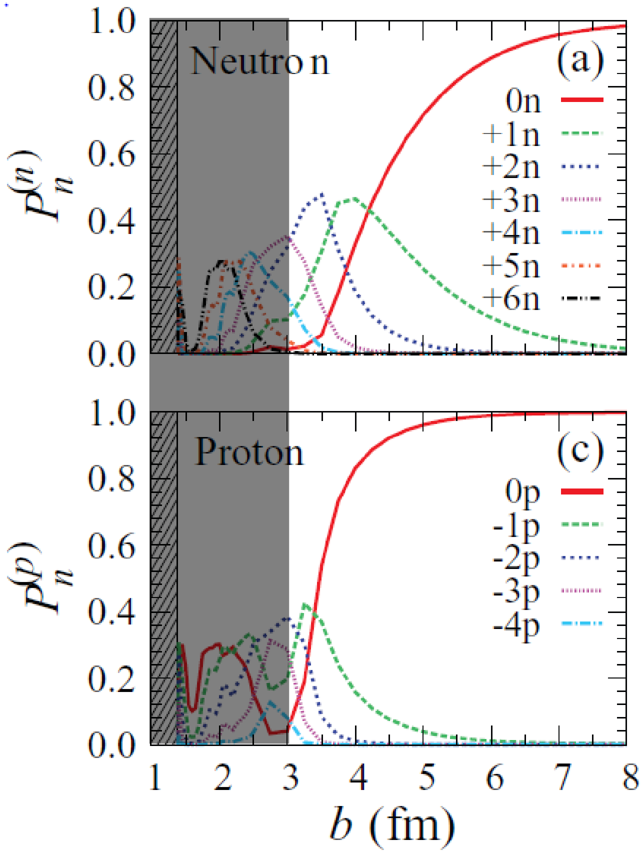

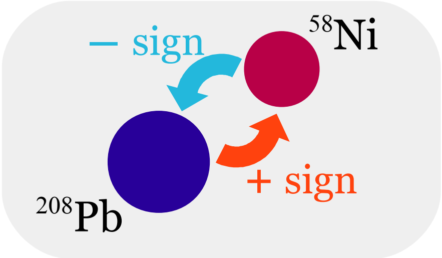

- At large impact parameter (3 fm < b)

  Charge equilibration

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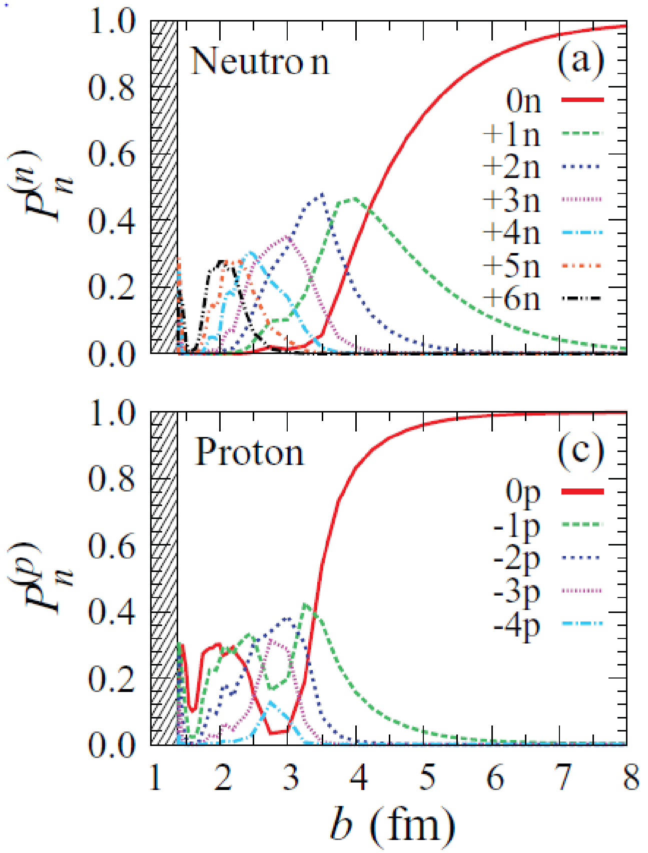

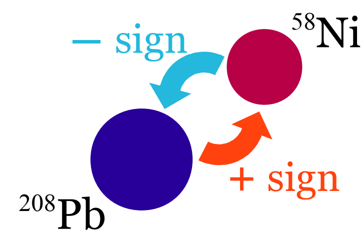

- At large impact parameter (3 fm < b)

  Charge equilibration

- At small impact parameter (b < 3 fm)

  Neck breaking

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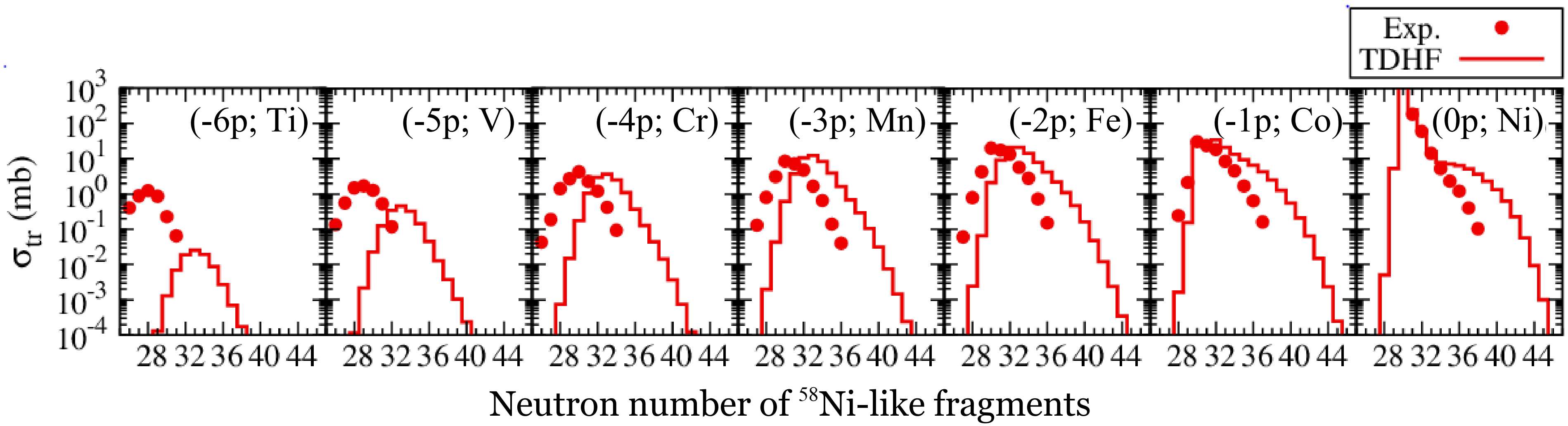
K. Sekizawa and K. Yabana, Phys. Rev. C **88**, 014614 (2013)

Production cross sections for ^{58}Ni-like fragments

Exp.: L. Corradi *et al.*, Phys. Rev. C **66**, 024606 (2002)

$$\sigma_{\mathrm{tr}}(Z,N) = 2\pi\int_{b_{\min}}^{\infty} b\, P_Z^{(p)}(b)P_N^{(n)}(b)\, db$$: Production cross section

- Horizontal axis: Number of neutrons in lighter (^{58}Ni-like) fragments
- Labels "(- *x* p)", *x*=0, ..., 6: Number of removed protons from ^{58}Ni



➢ TDHF reproduces measurement reasonably, when number of transferred nucleons is small

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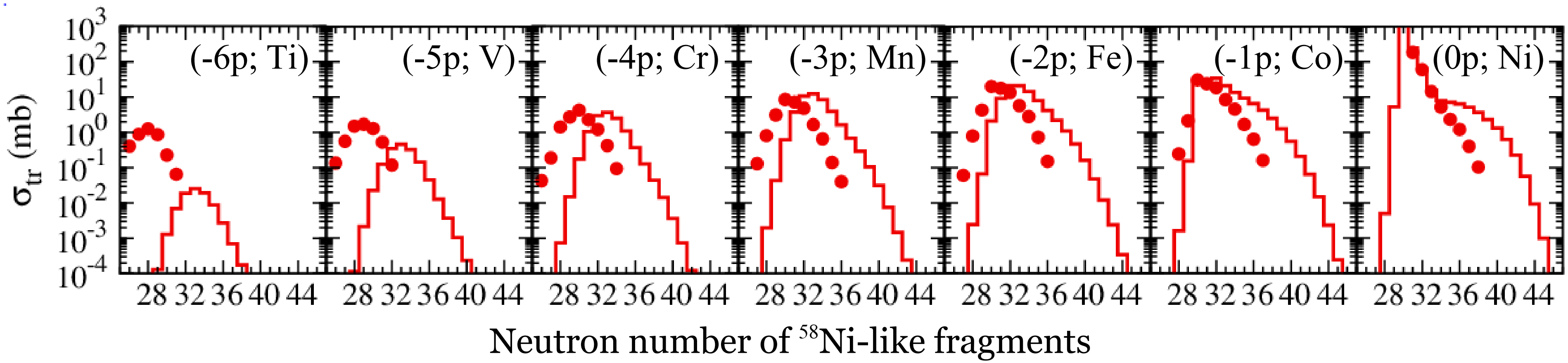
Effects of particle evaporation

✔ Deexcitation processes by particle emission



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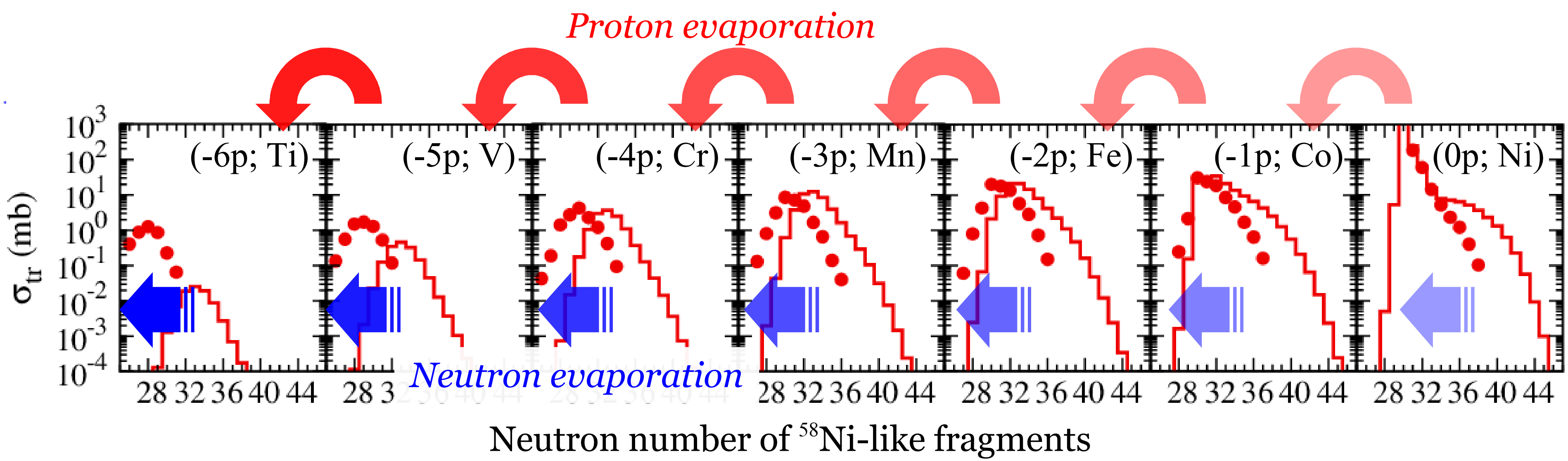

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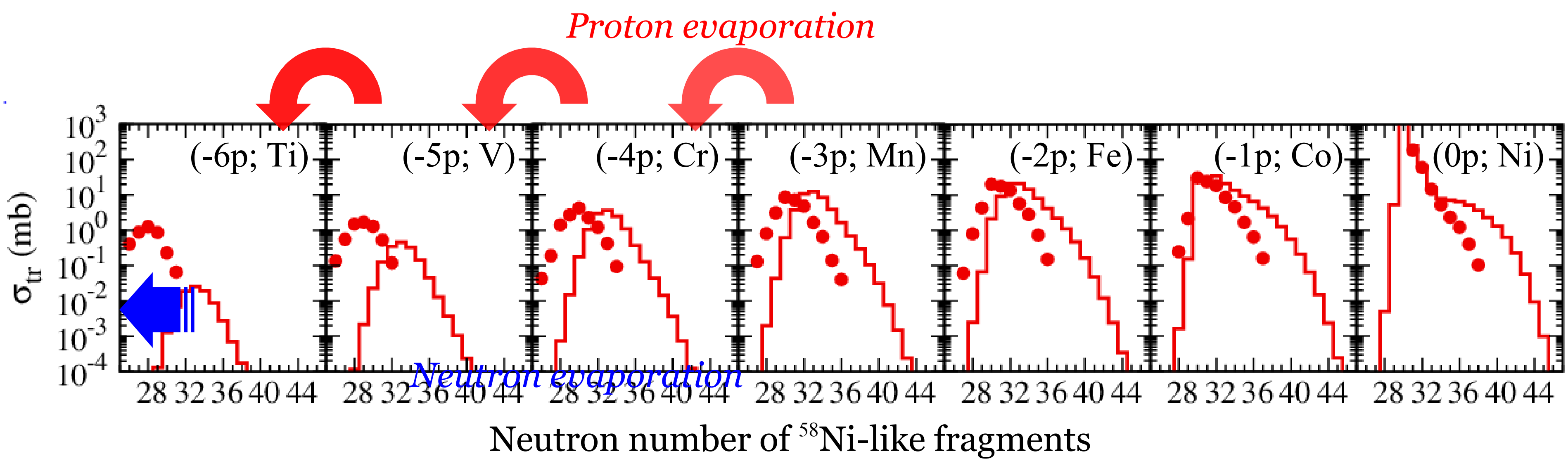

➢ Our approach to include the effects of particle evaporation

(1) Evaluate internal energy	(2) Subtract the g.s. energy	(3) Put $E^*_{N,Z}$ into a statistical model
$E_{N,Z}$	$E^*_{N,Z} = E_{N,Z} - E_{\rm g.s.}$	$P^{\rm evap.}_{n,z}$
Projection method	Excitation energy	Evaporation probabilities

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K. Sekizawa and K. Yabana, In preparation.

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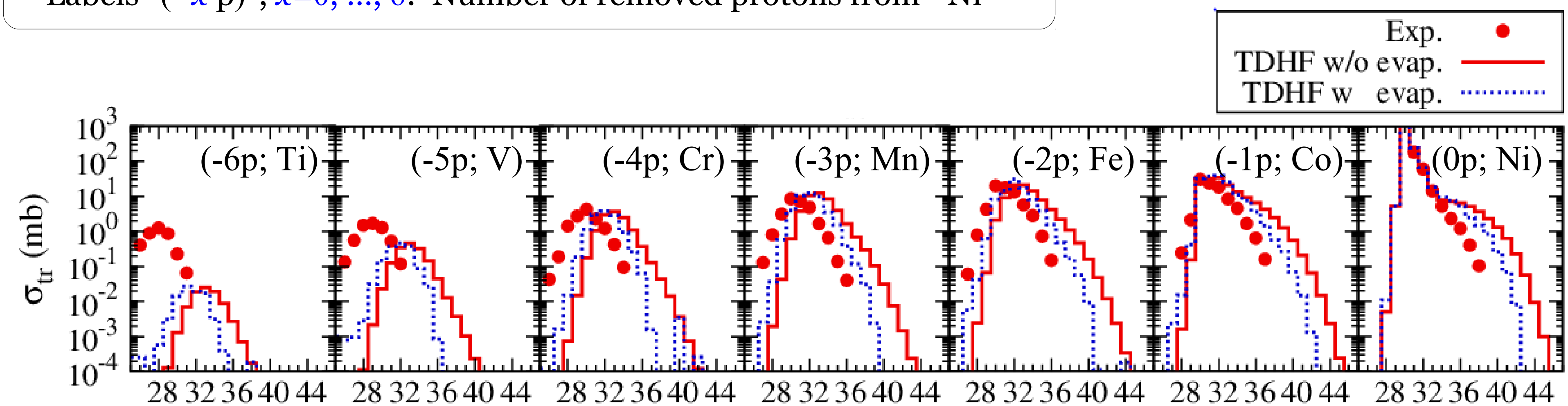
(*Preliminary*)



➢ The discrepancy is somewhat remedied, but not enough.

It may indicate the importance of correlation effects beyond the mean-field level.

Summary and Perspective

Summary

- ✔ I showed how to calculate nucleon transfer probabilities from the TDHF wave function.
  (Projection method: C. Simenel, PRL**105**(2010)192701)

- ✔ I presented results of the TDHF calculation for $^{58}Ni+^{208}Pb$ reaction.
  (K. Sekizawa and K. Yabana, PRC**88**(2013)014614)

- ✔ I discussed how to include effects of particle evaporation.

Perspective

➢ We try to find a preferable condition to produce *N*-rich unstable nuclei.