11th RIBF Discussion Meeting, University of Tsukuba
Monday, March 2, 2015

# Time-dependent Hartree-Fock calculations for multinucleon transfer and quasifission processes

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In collaboration with

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Graduate School of Pure and Applied Sciences, Univ. Tsukuba
Center for Computational Sciences, Univ. Tsukuba

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TDHF theory provides us a parameter-free microscopic description for *both*

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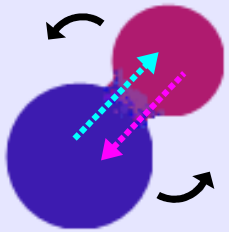
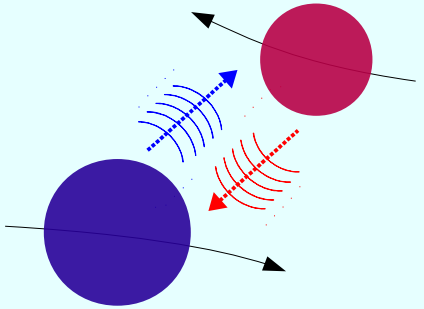
$10^{-21}$ s

*Neck formation*



Multinucleon transfer

*Quantum tunneling*



Transfer of few nucleons

Small-*b* — Impact parameter *b* — Large-*b*

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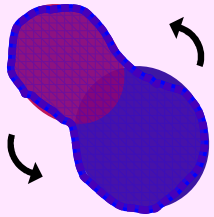

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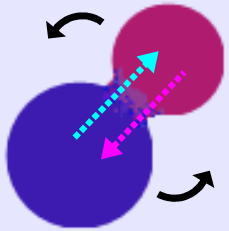

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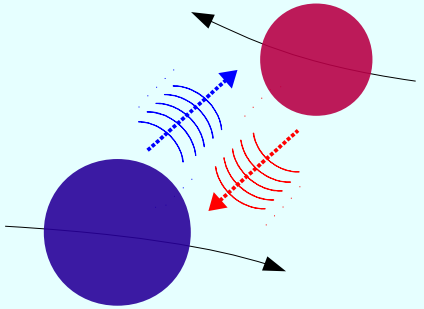

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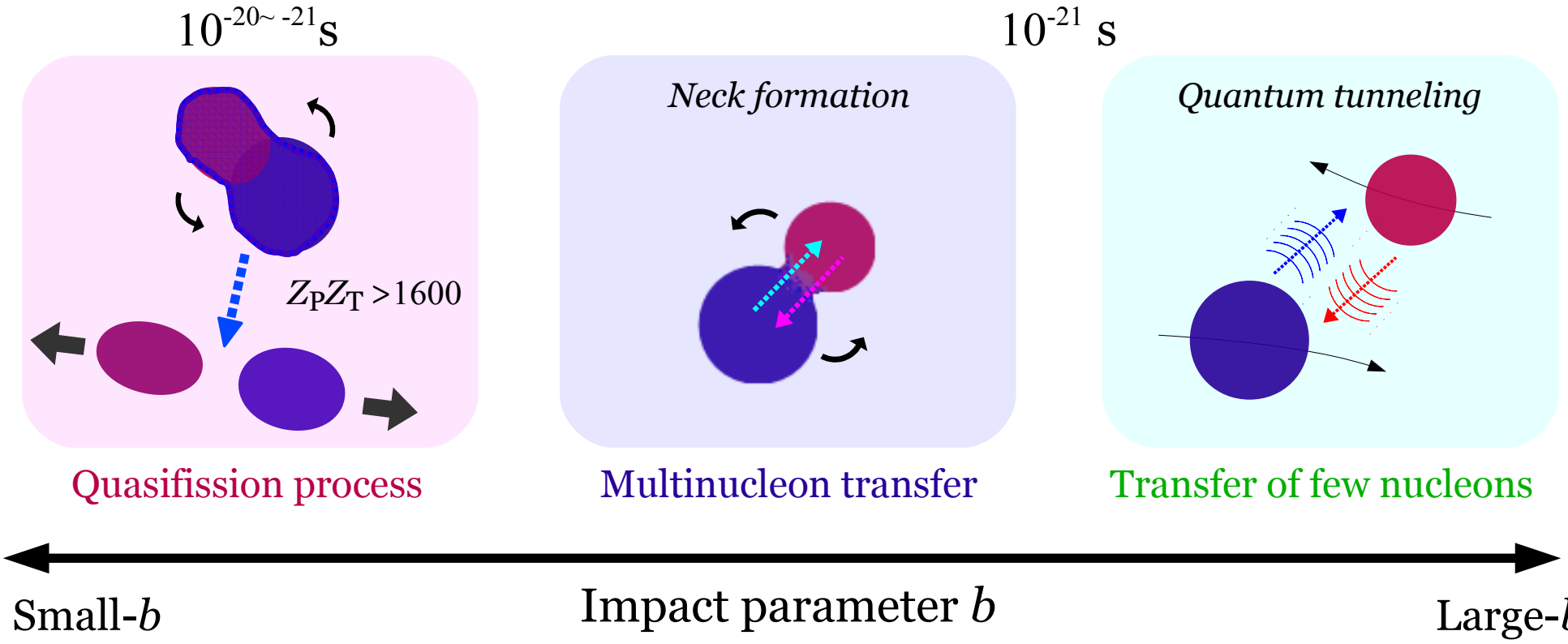

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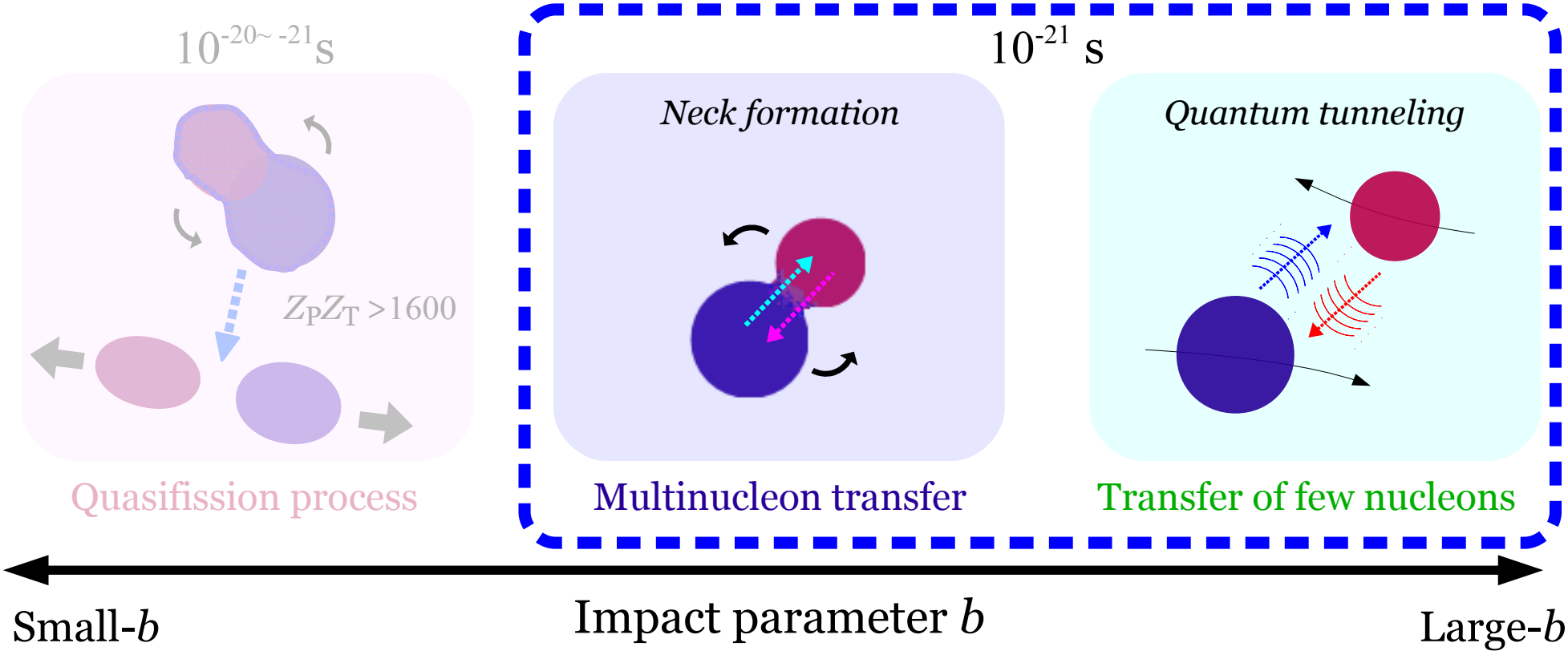

# *Illustrative example:* $^{64}_{28}Ni_{36}+^{238}_{92}U_{146}$ *at* $E_{lab}$=390 MeV

## Production cross sections for $^{64}$Ni-like fragments

Exp.: L. Corradi *et al.*, Phys. Rev. C **59**, 261 (1999)

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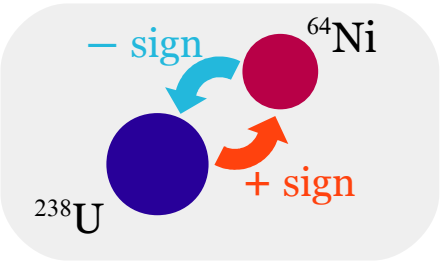


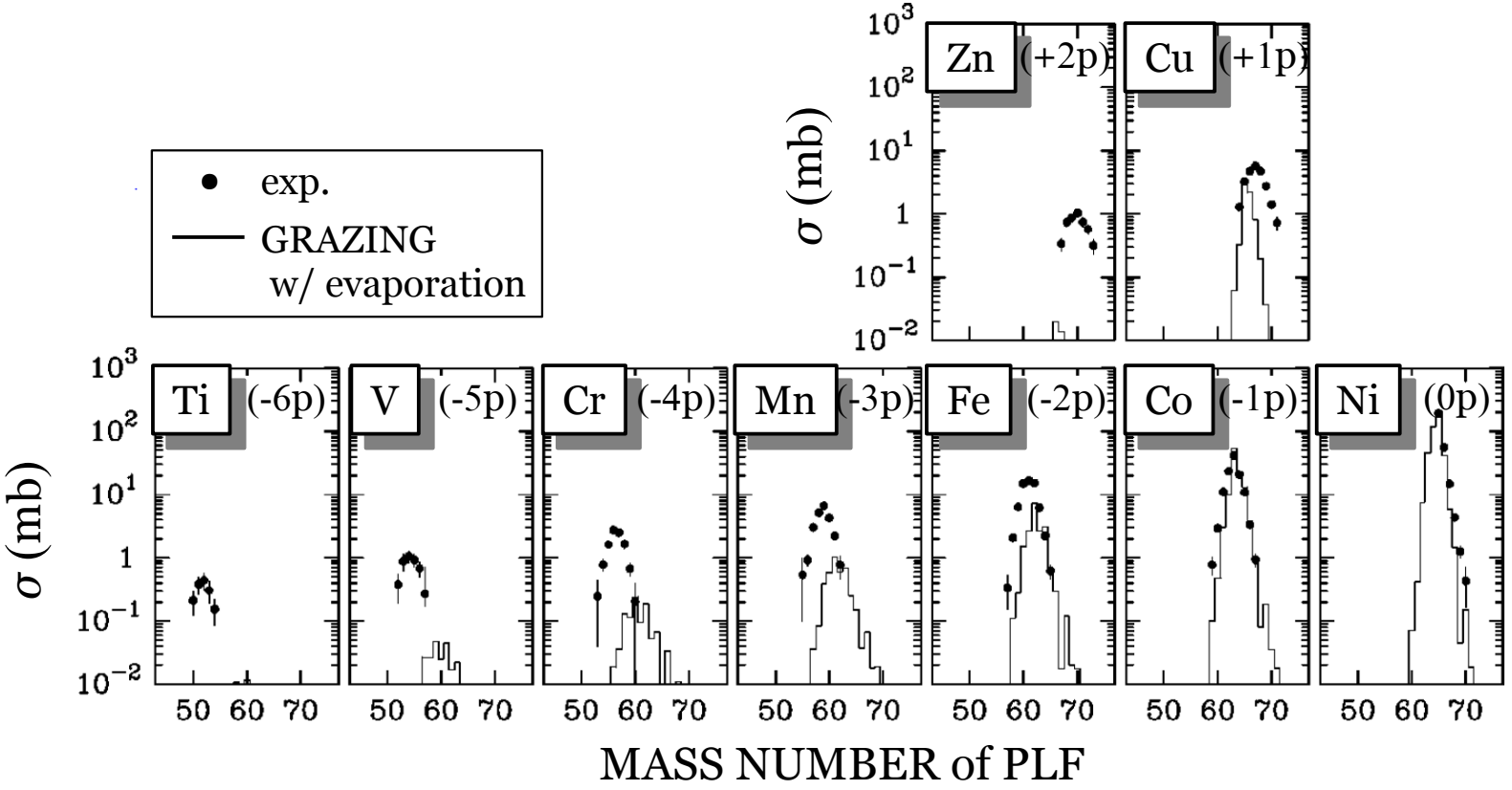

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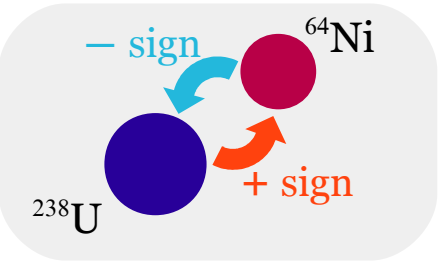


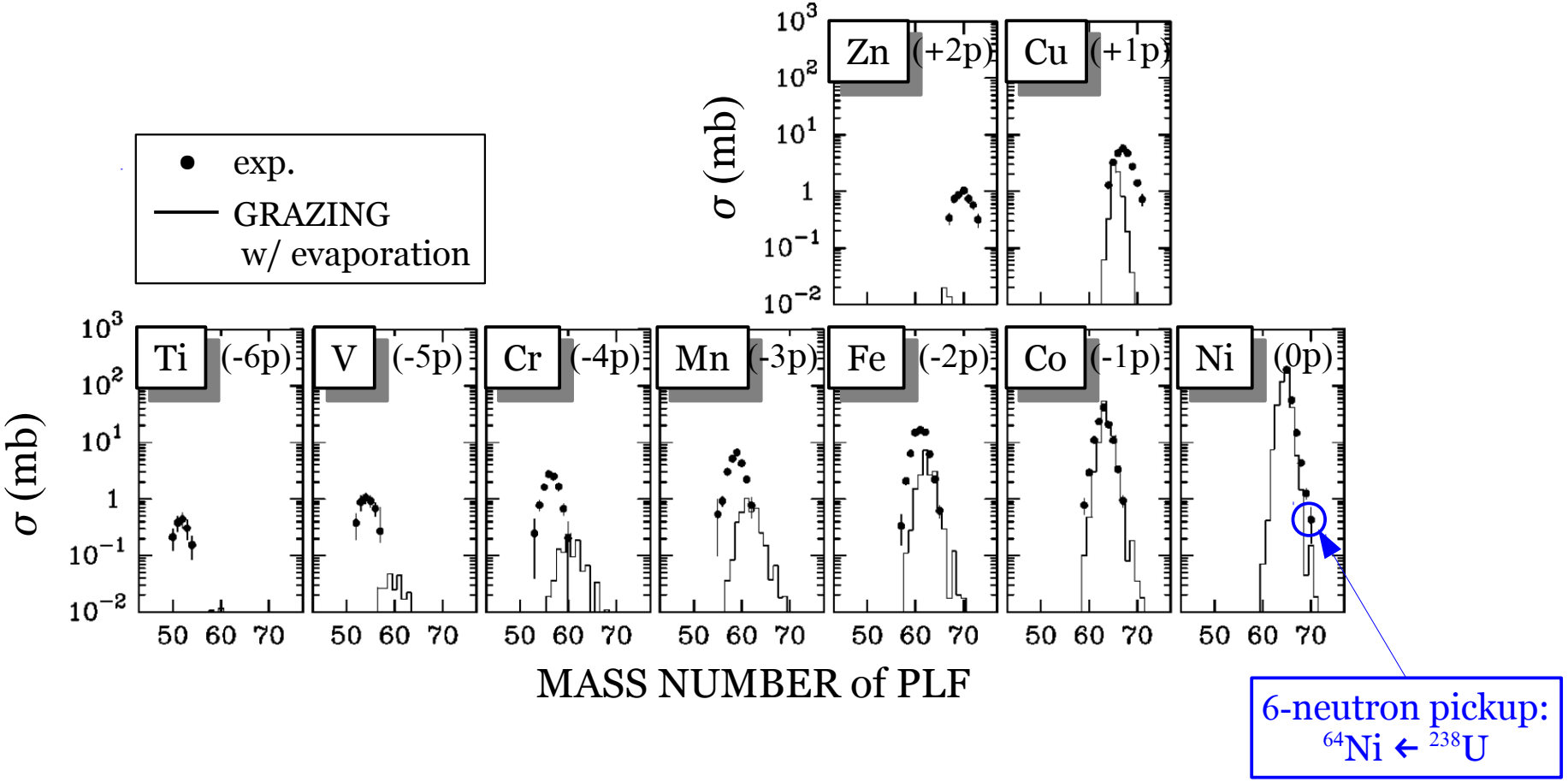

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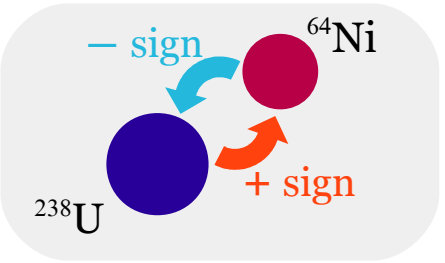


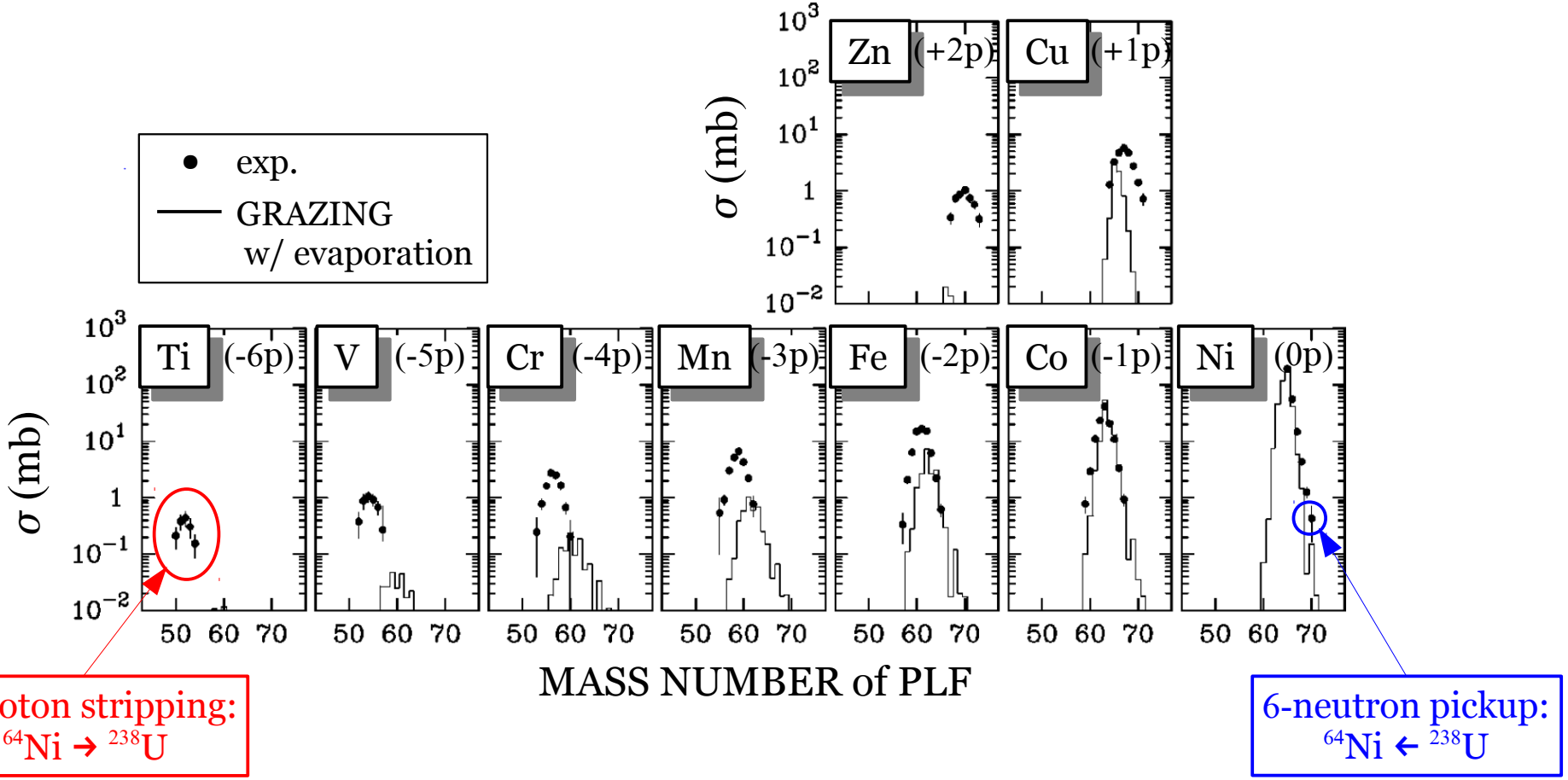

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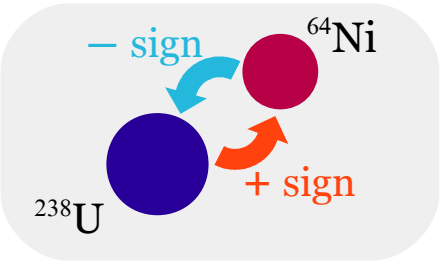


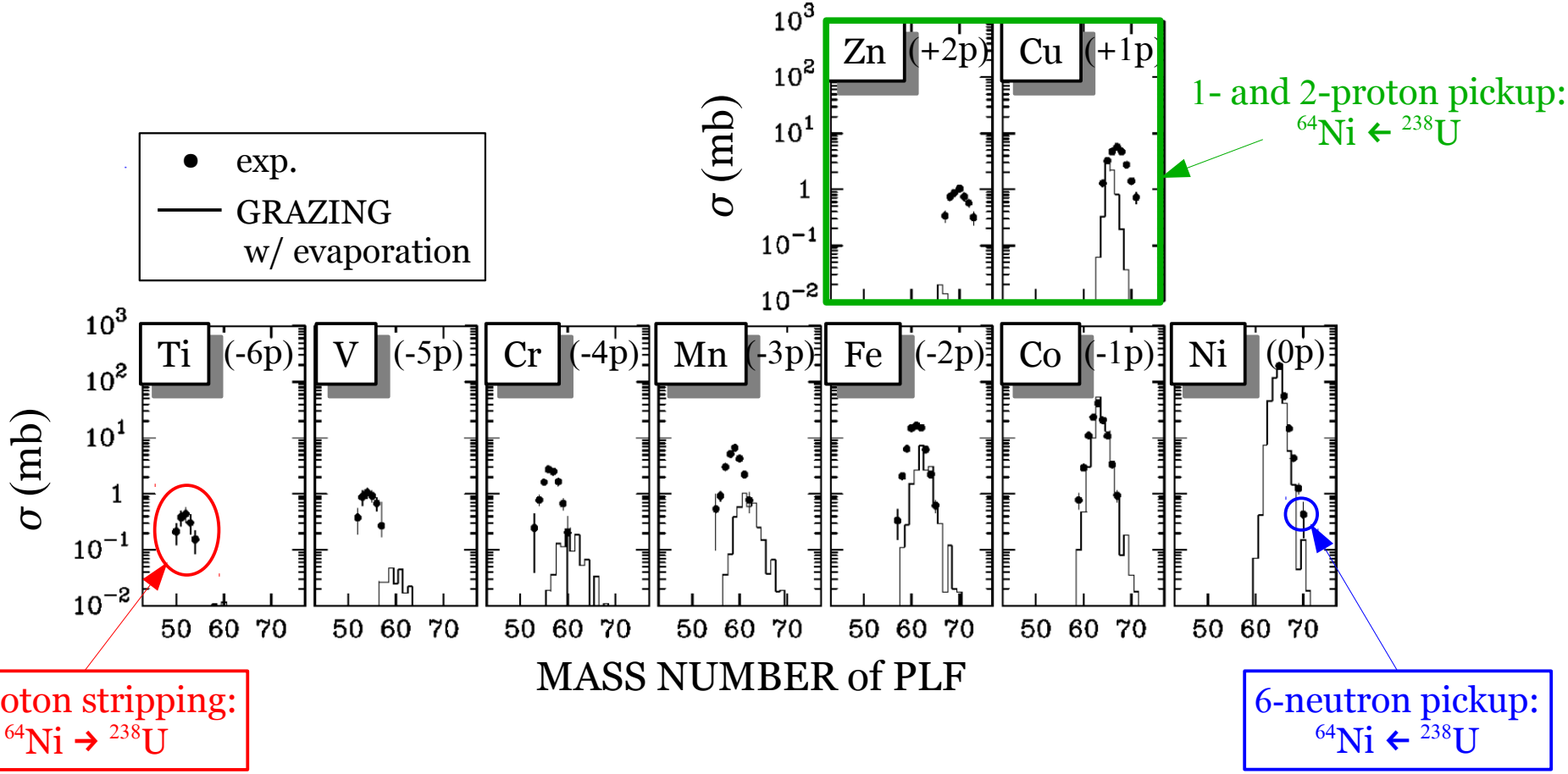

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Skyrme force: SLy5, $\Delta t$: 0.2 fm/c, Initial separation distance: 24 fm
Calculated impact parameter: $0 \leqq b \leqq 10$ fm
※ Fusion reactions have not been observed

## Density evolution obtained from the TDHF calculation

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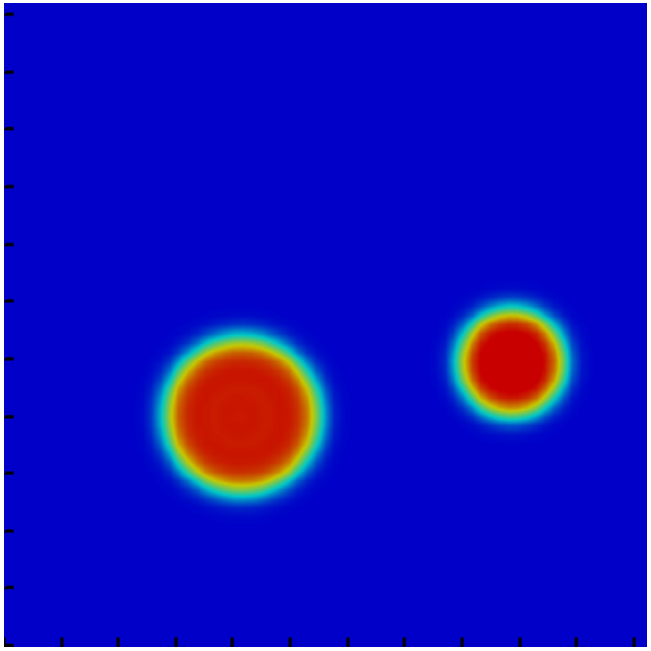

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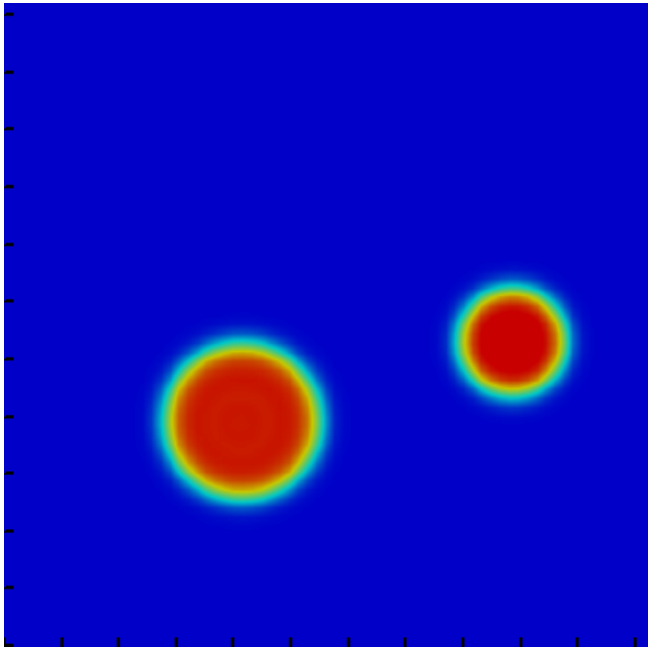

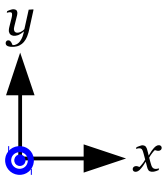


✔ symmetry axis of $^{238}$U: $z$-direction

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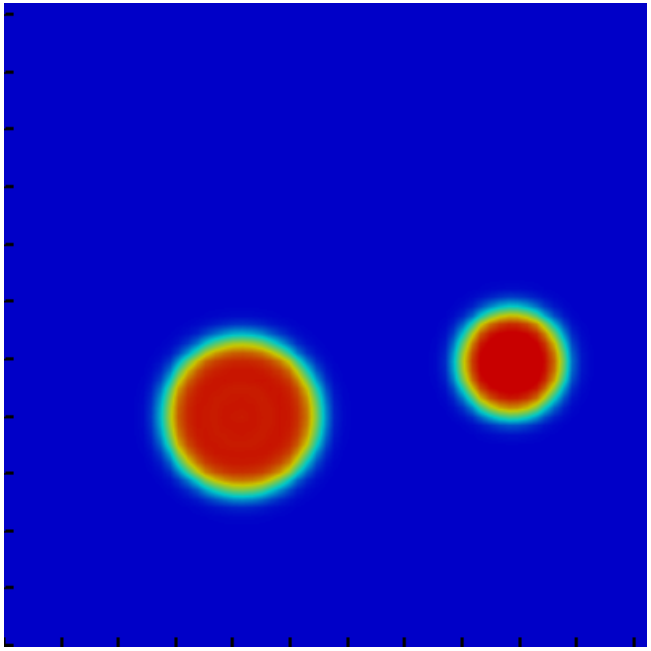

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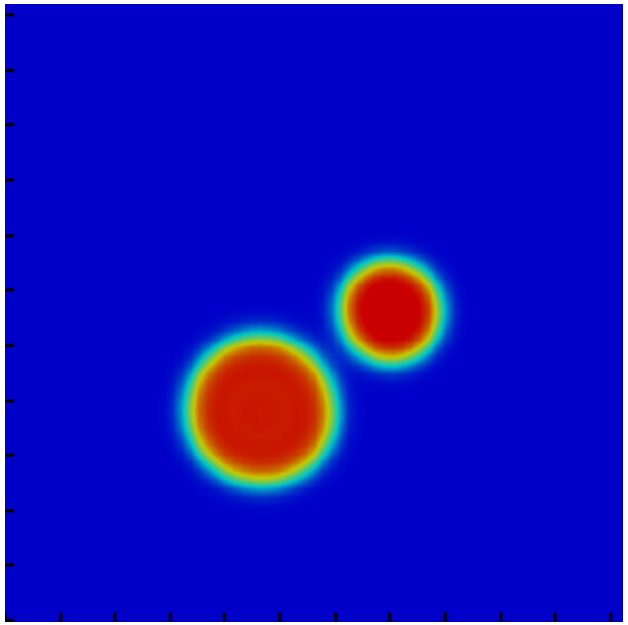

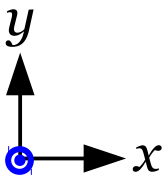


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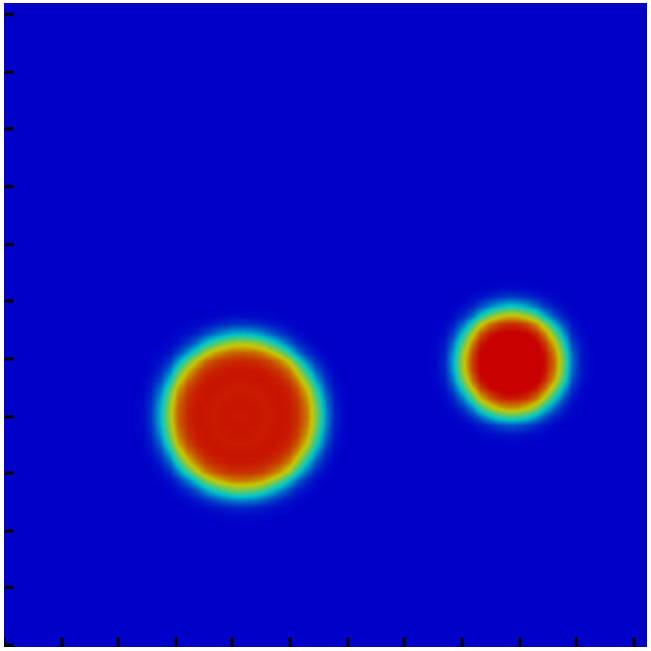

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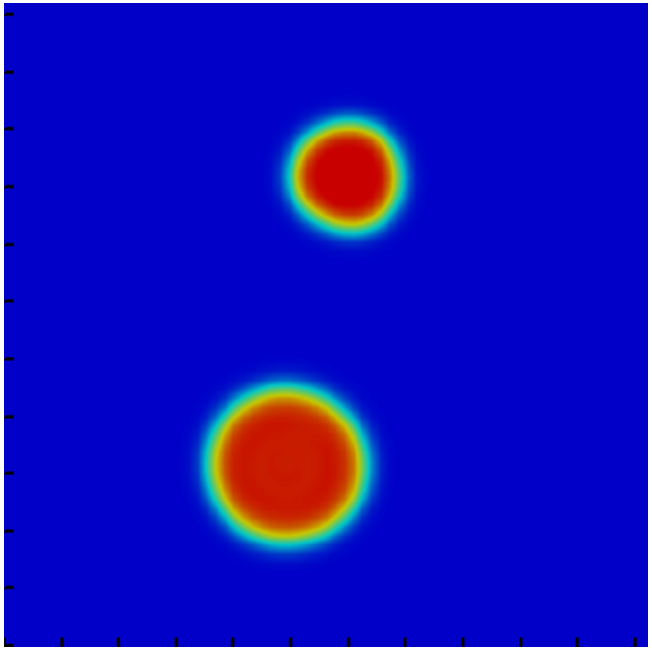

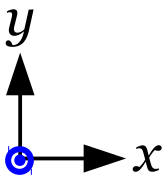


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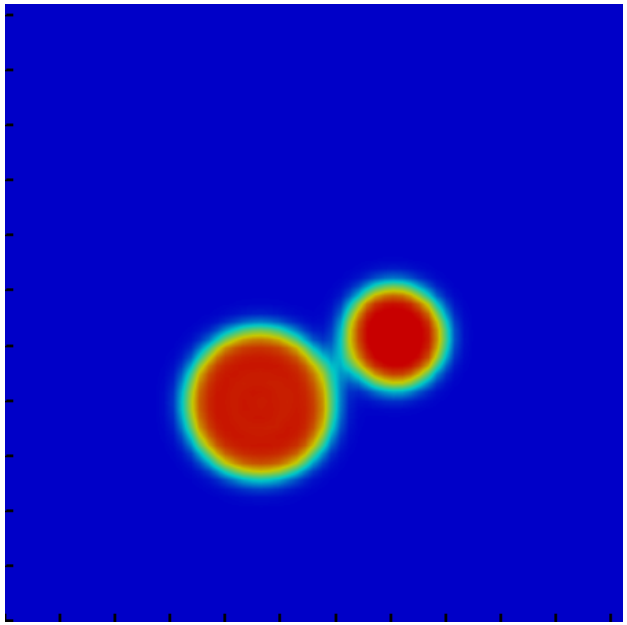

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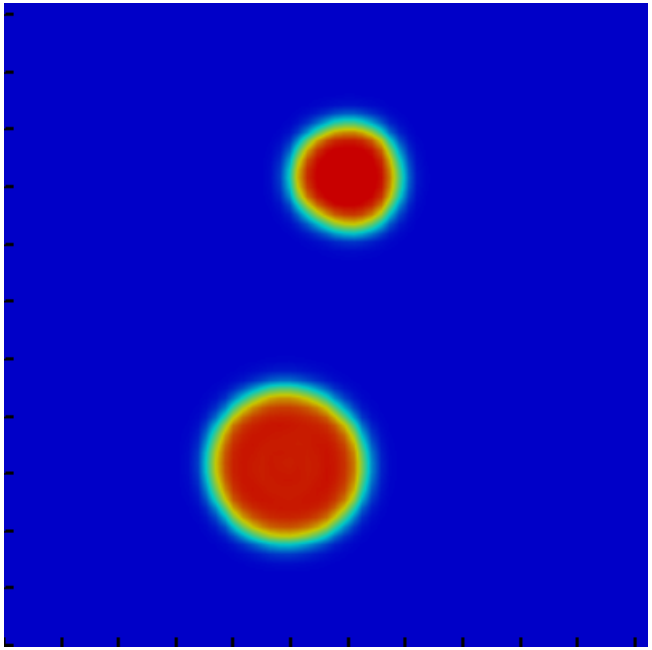

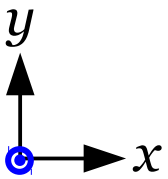


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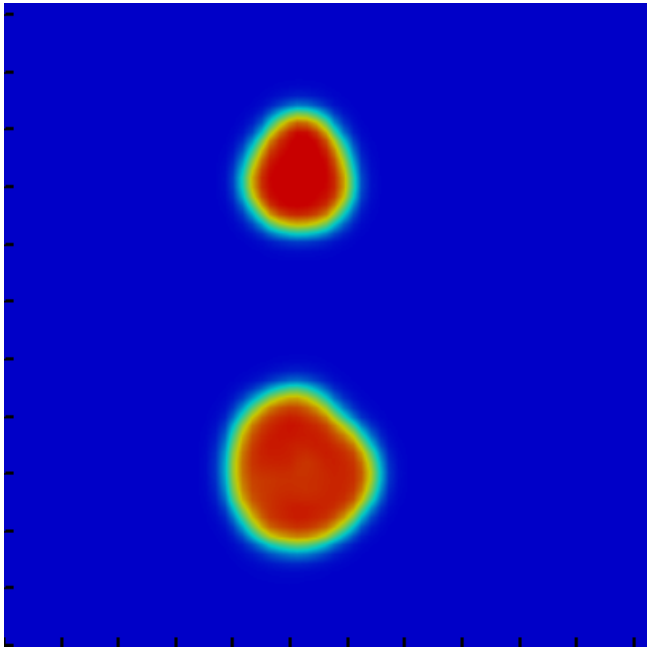

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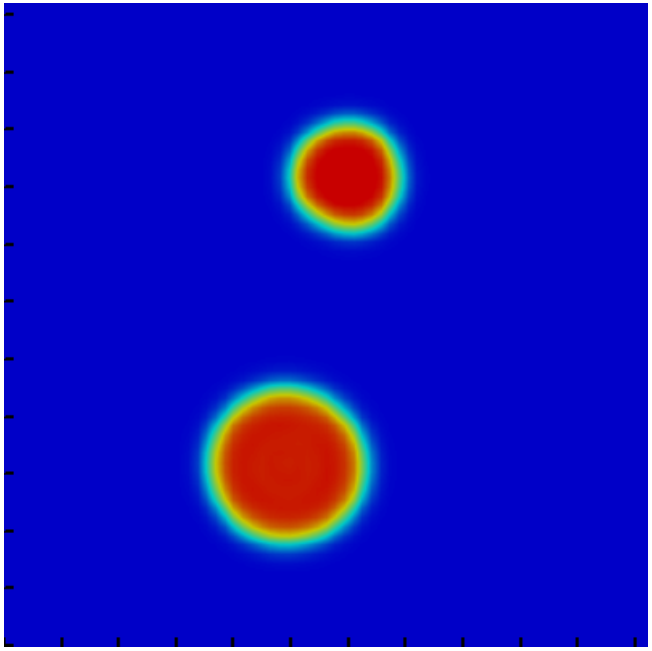

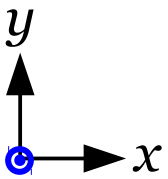


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# How to calculate the transfer probability

## Particle number projection method

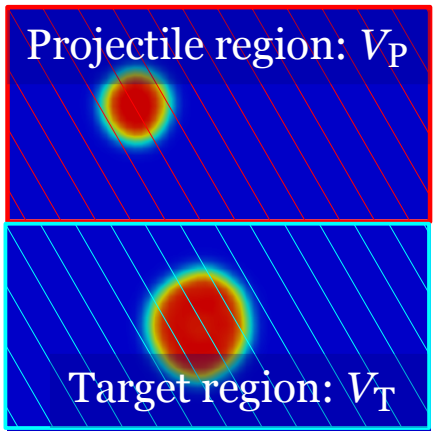
C. Simenel, Phys. Rev. Lett. **105**, 192701 (2010)

✔ 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 $V_\mathrm{P}$

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




$N$=$N_\mathrm{P}$ +$N_\mathrm{T}$: Total number of nucleons

➢ Probability $P_n$: $n$ nucleons are in the $V_\mathrm{P}$ and $N$-$n$ nucleons are in the $V_\mathrm{T}$

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

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

$$\langle\phi_i|\phi_j\rangle_\tau = \int_\tau d^3x\, \phi_i^*(\boldsymbol{x})\phi_j(\boldsymbol{x})$$
$$\tau = V_\mathrm{P} \text{ or } V_\mathrm{T}$$

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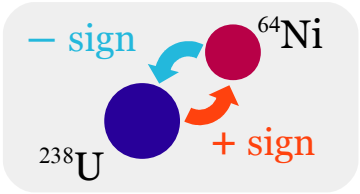
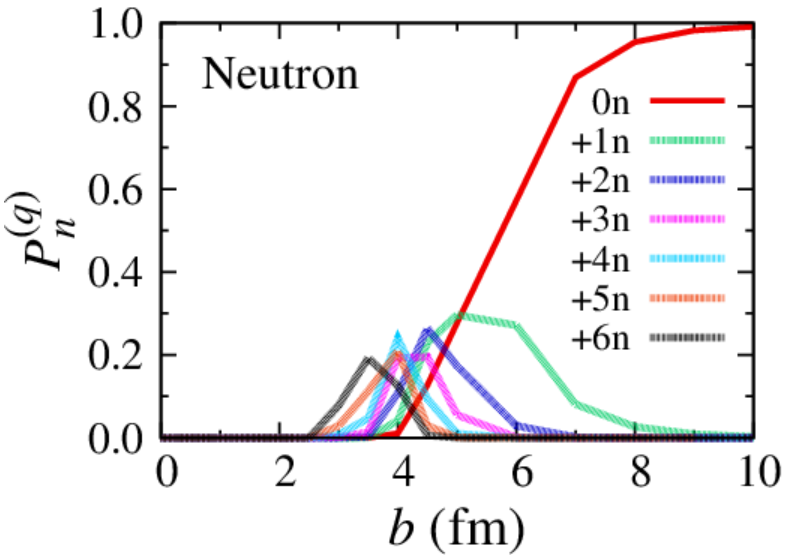
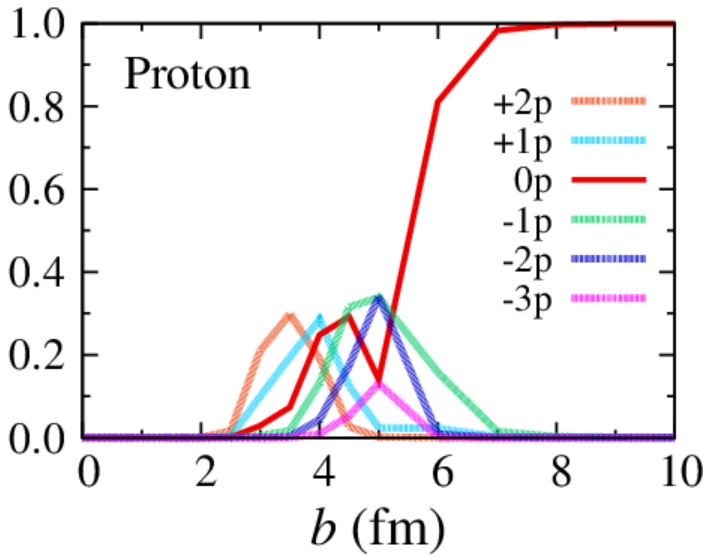
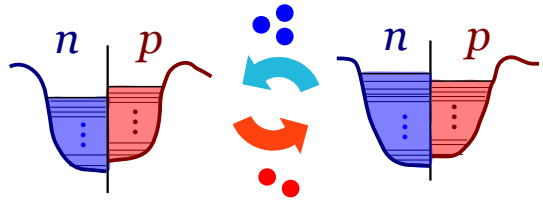
## Transfer probabilities



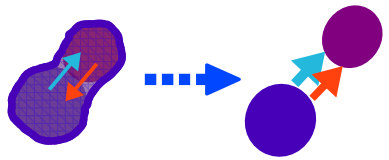




$b$>4 fm: *Charge equilibration*




$b$<4 fm: *Neck breaking*



- ✔ Nucleons are transferred toward the directions of the charge equilibrium at large-$b$ region, 4 fm < $b$.
- ✔ Probability for proton pickup channels becomes sizable at small-$b$ region, $b$ < 4 fm.

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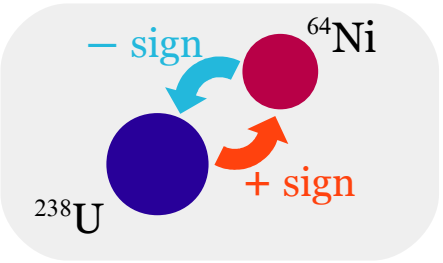
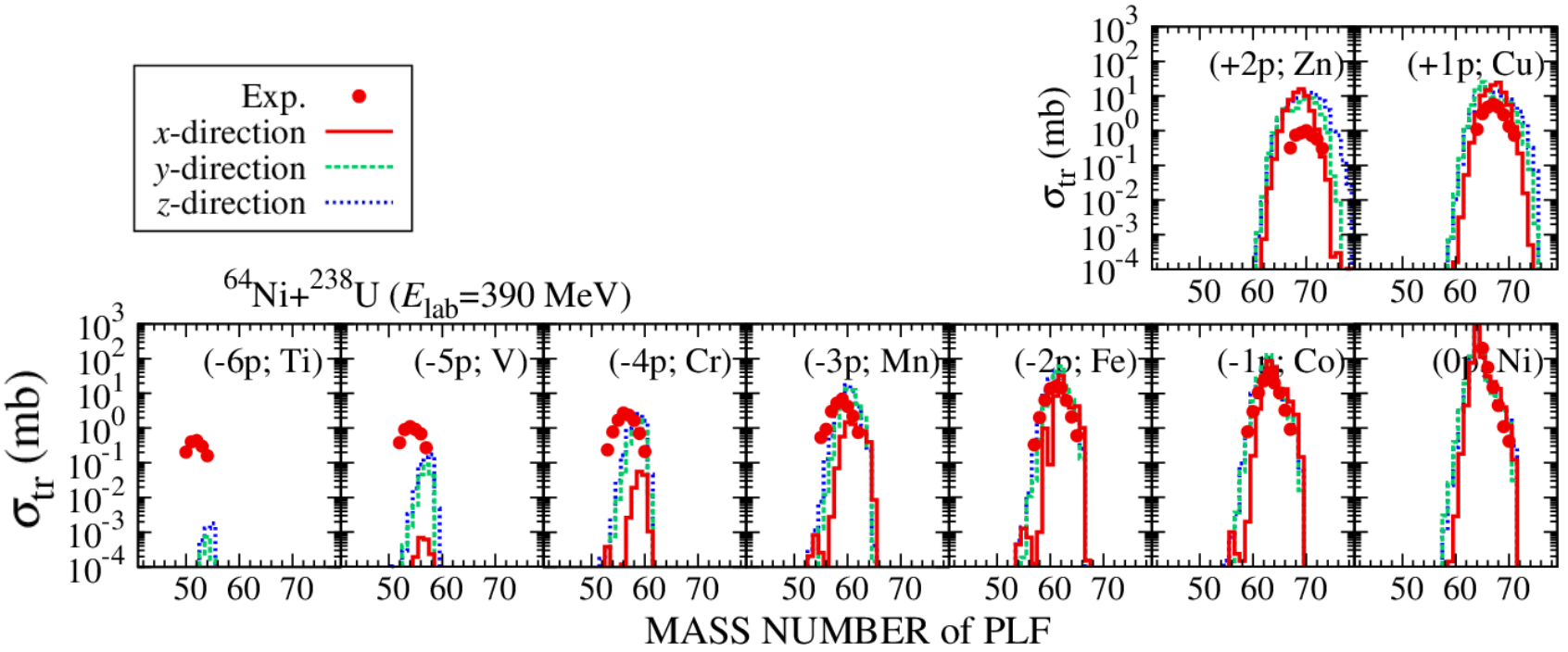
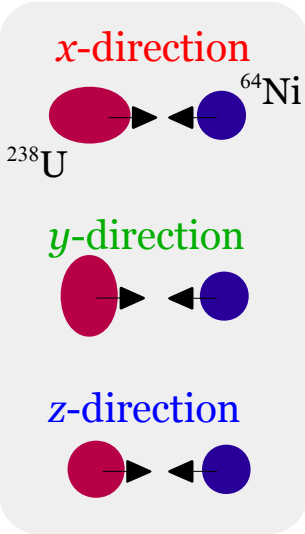
- Lines: TDHF with effects of particle evaporation




✔ TDHF reproduces measurements reasonably, both proton stripping and pickup channels.

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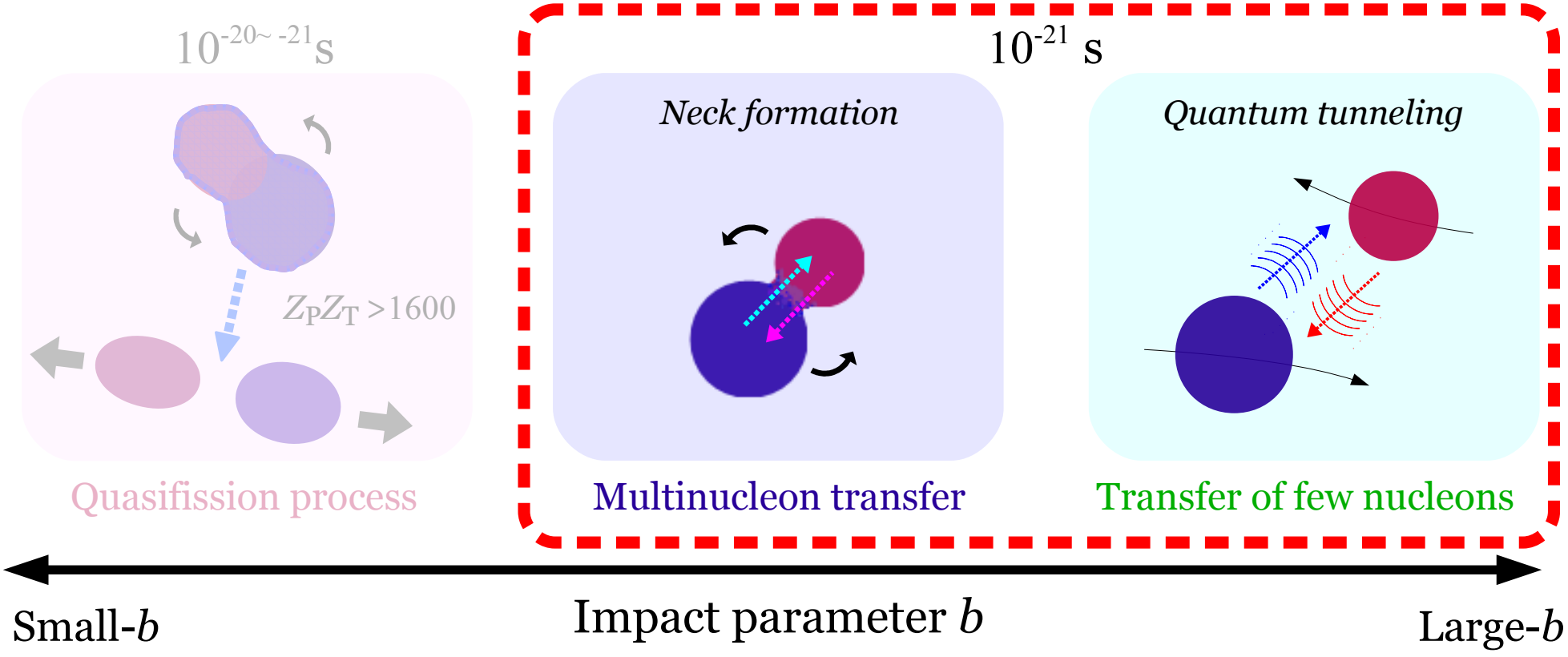

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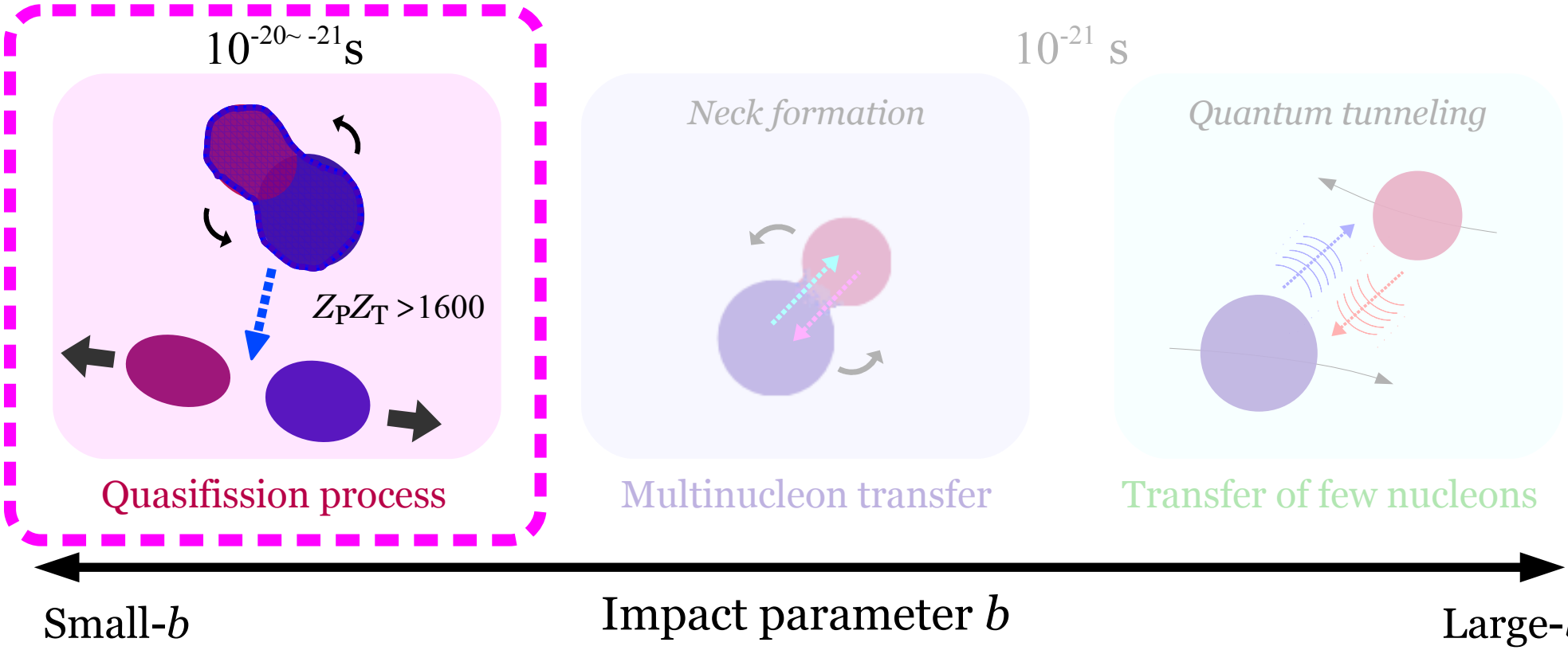

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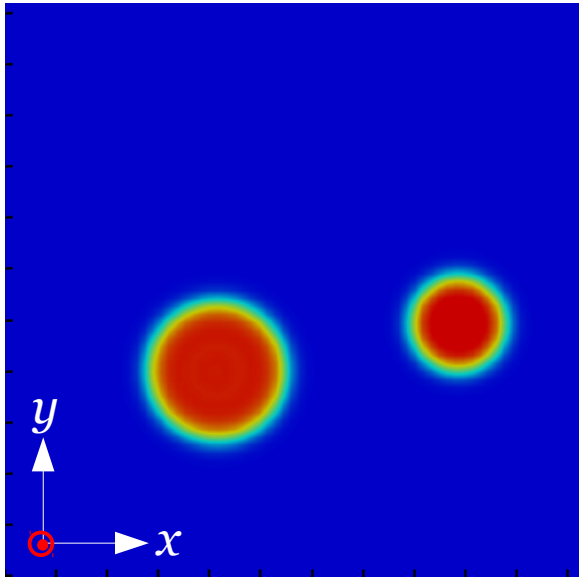
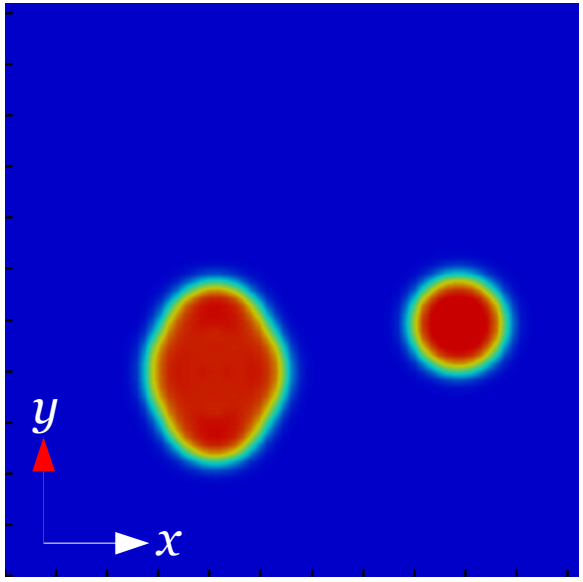
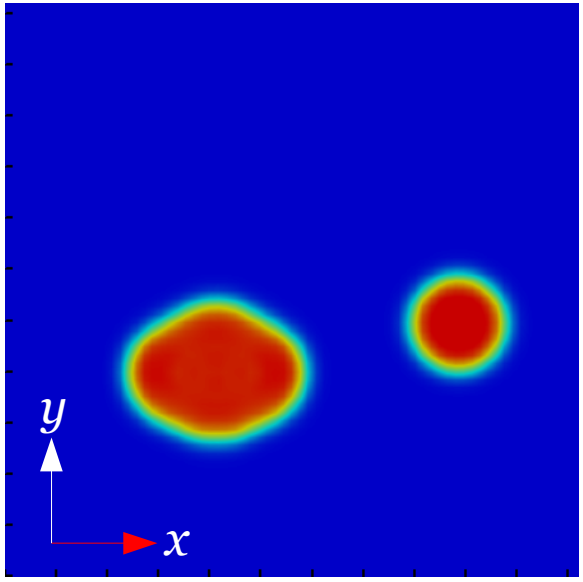



*y*-direction




*x*-direction



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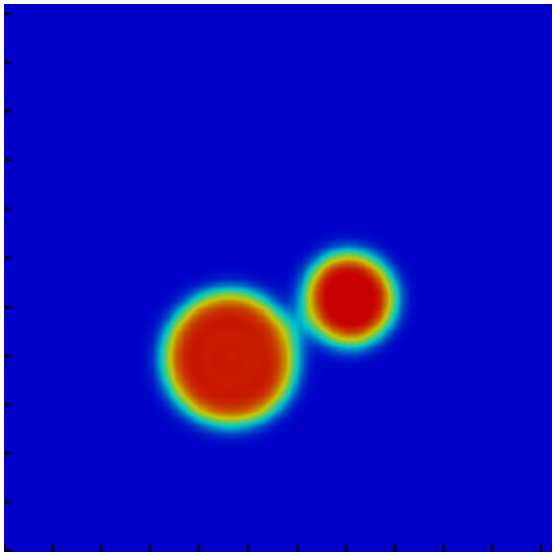

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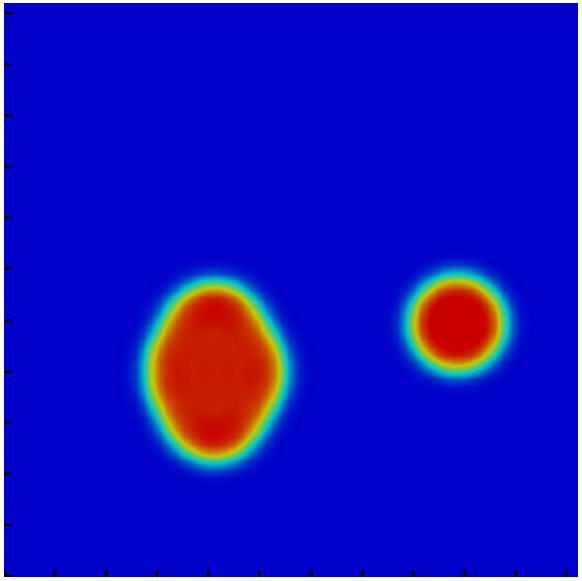
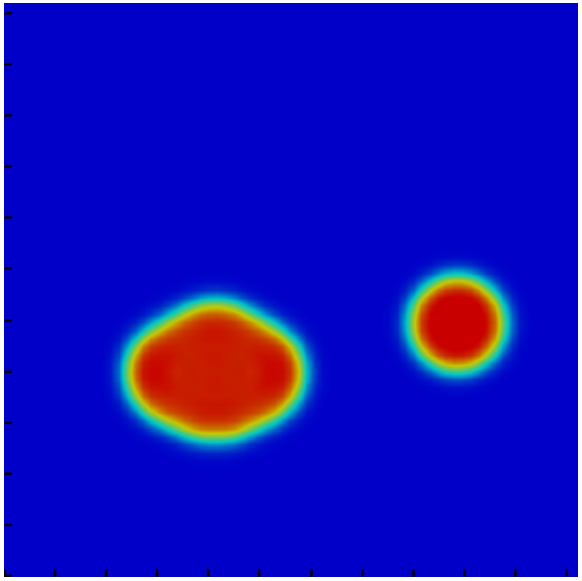


*x*-direction



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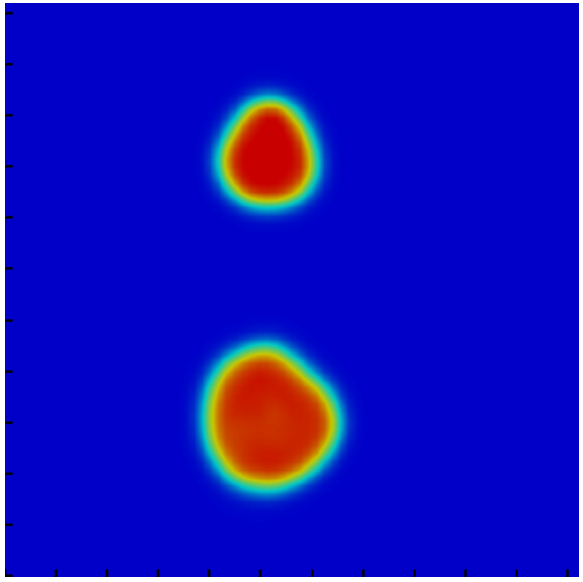

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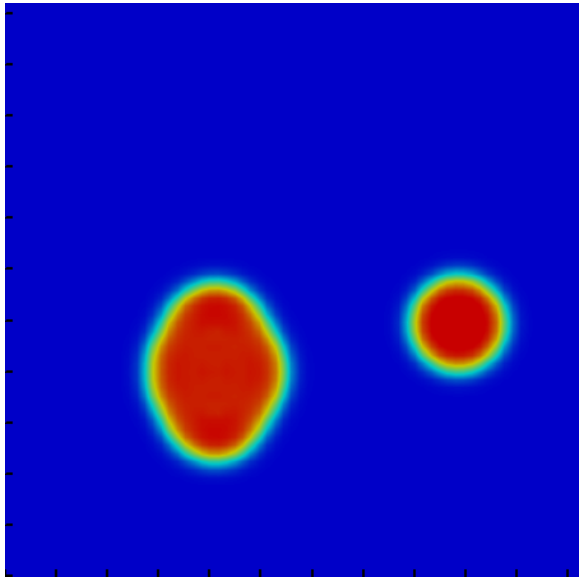

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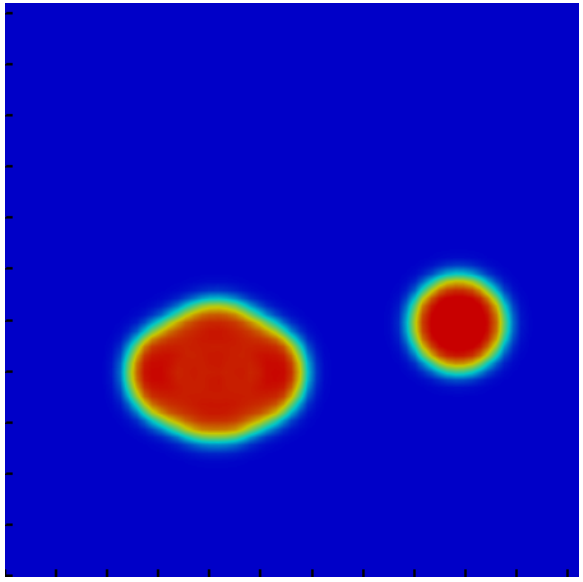

19 neutrons, 9 protons

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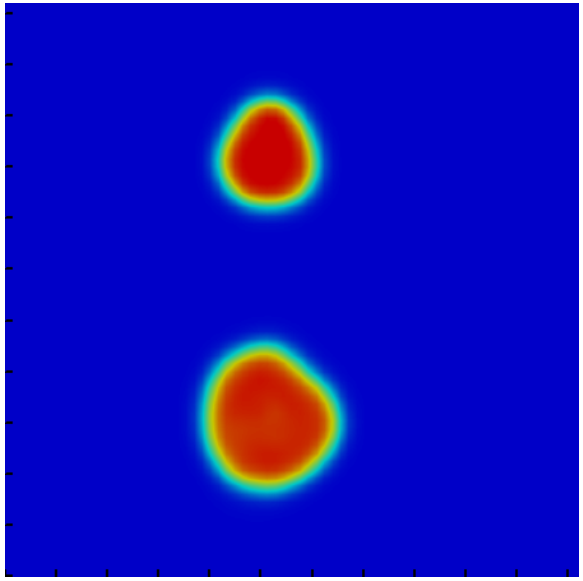

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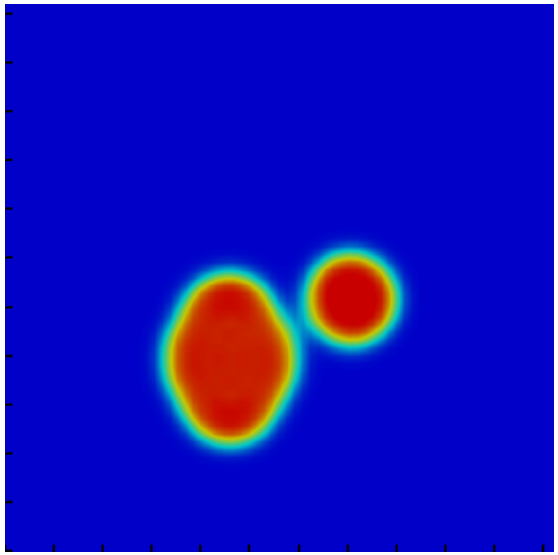

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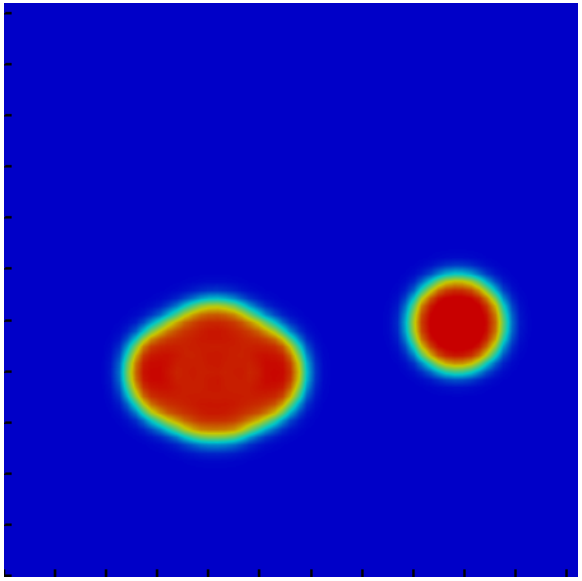

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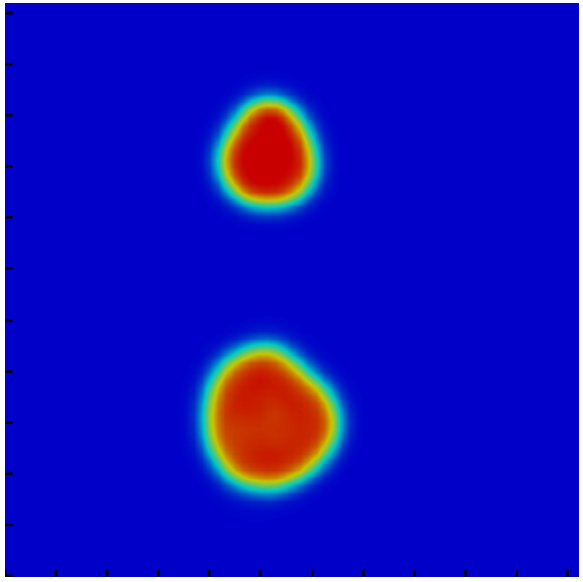

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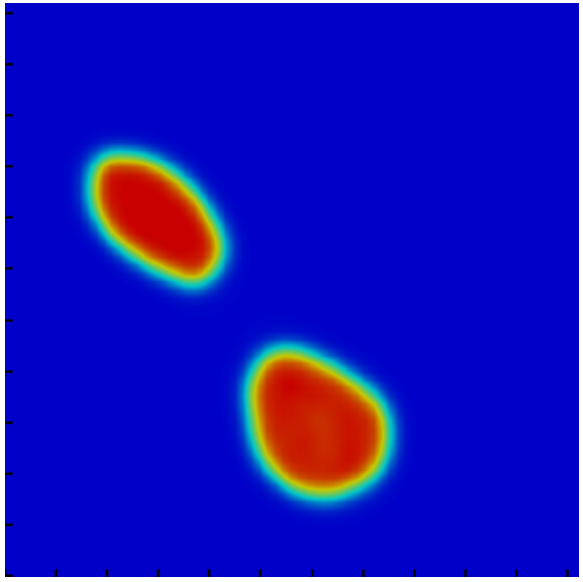

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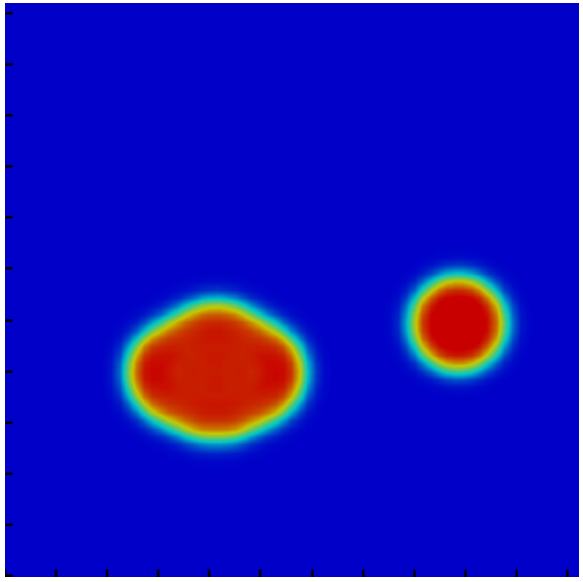

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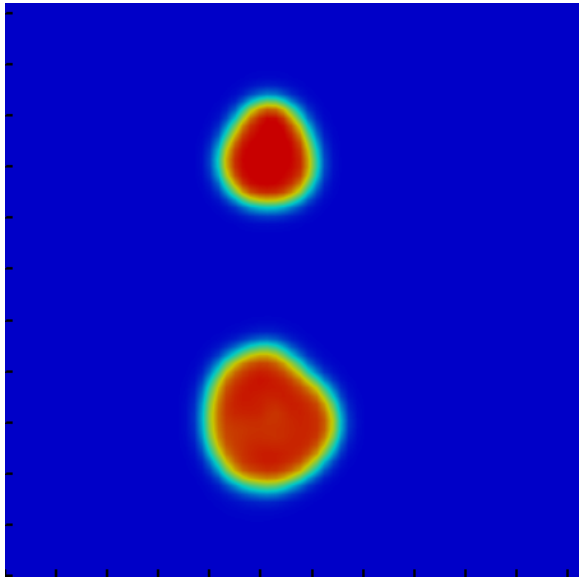

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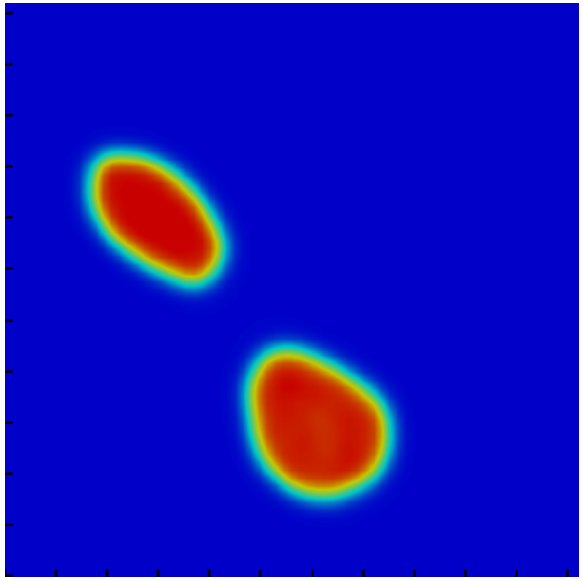

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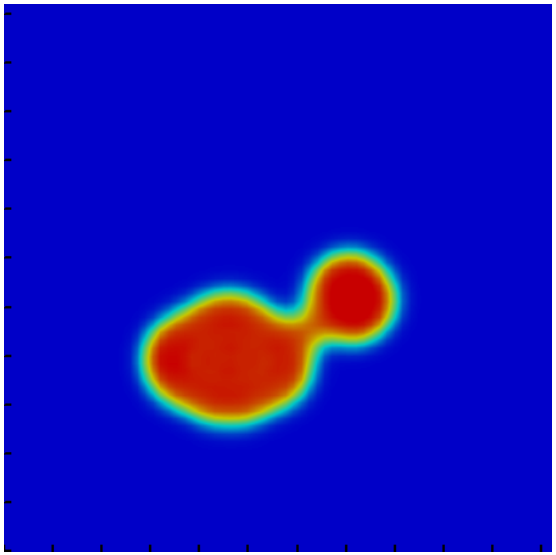

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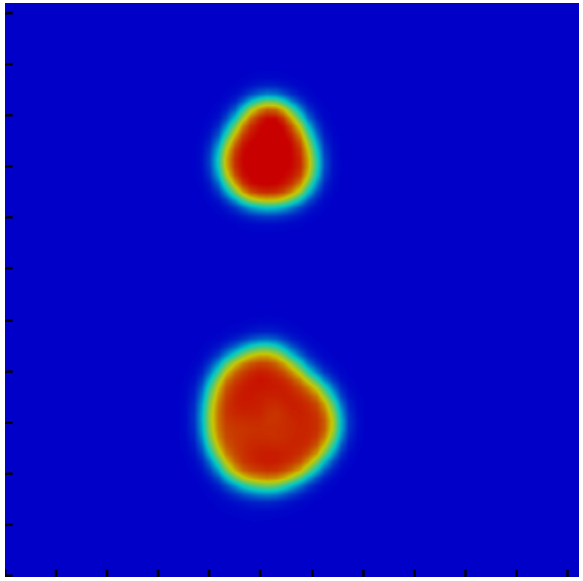

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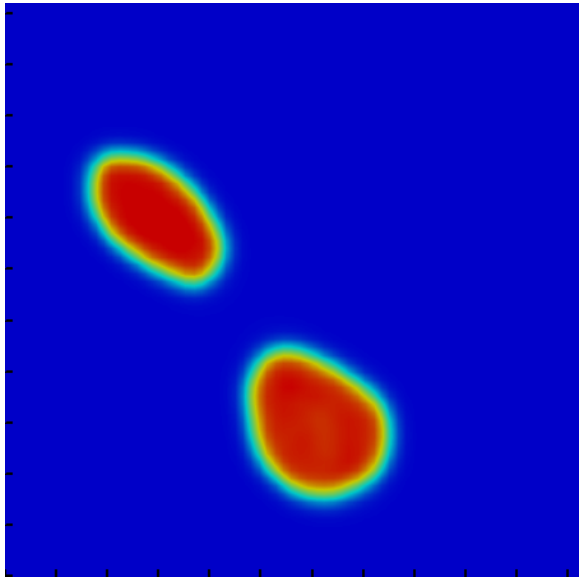

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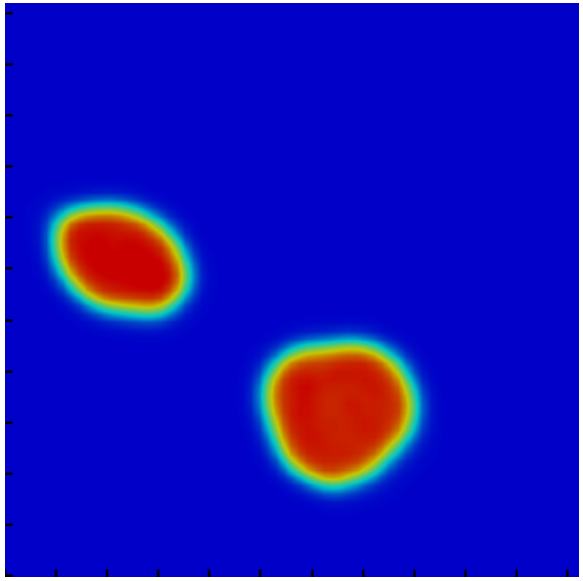

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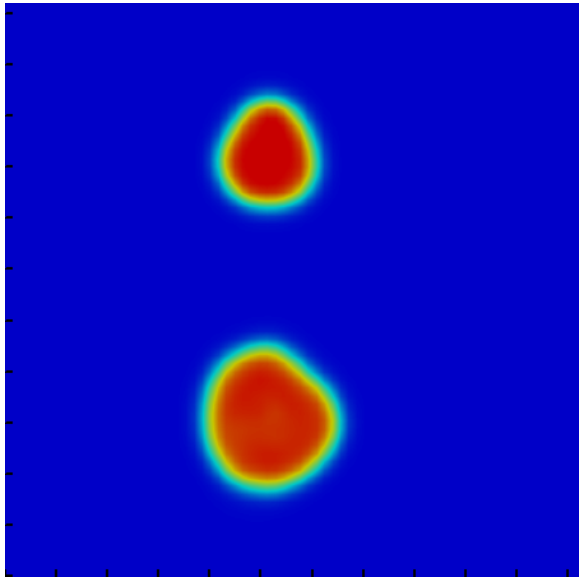

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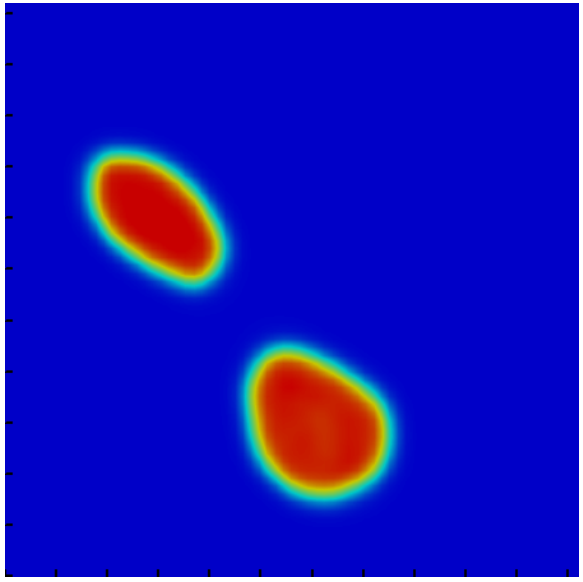

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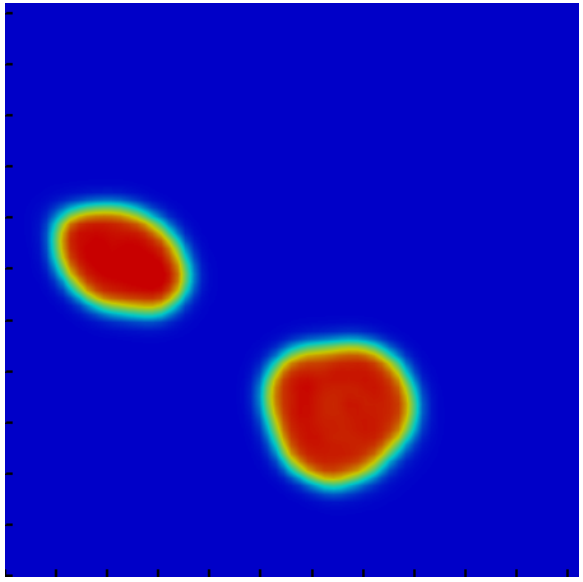

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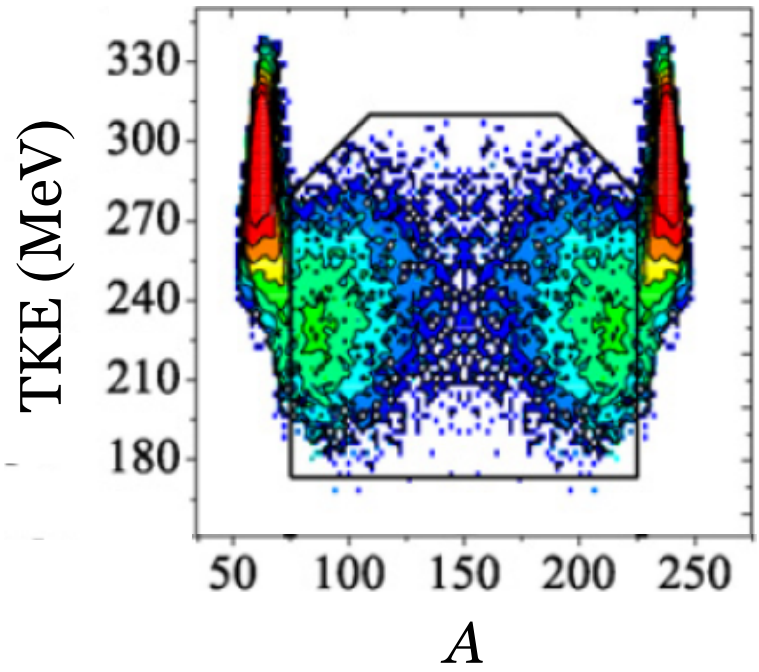
## Total kinetic energy (TKE) *vs.* fragment mass ($A$) plot

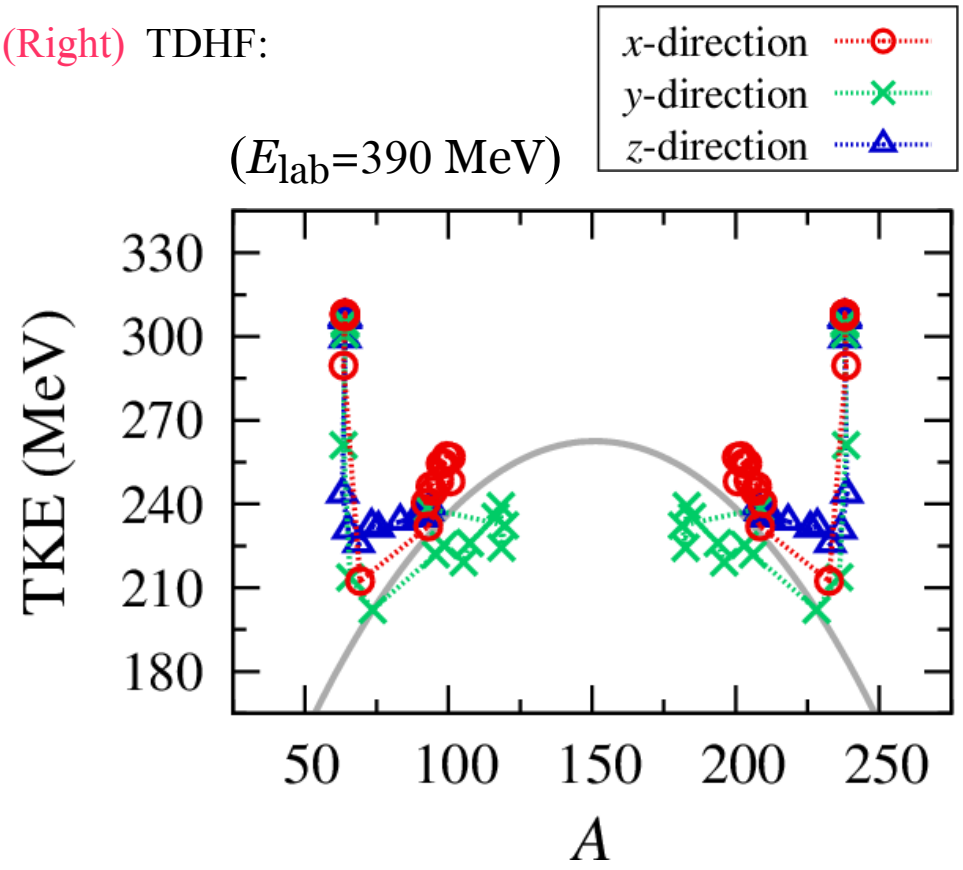
(Left) Exp.: E.M. Kozulin *et al.*, PL**B686**(2010)227

($E_{lab}$=382 MeV)




(Right) TDHF:

($E_{lab}$=390 MeV)

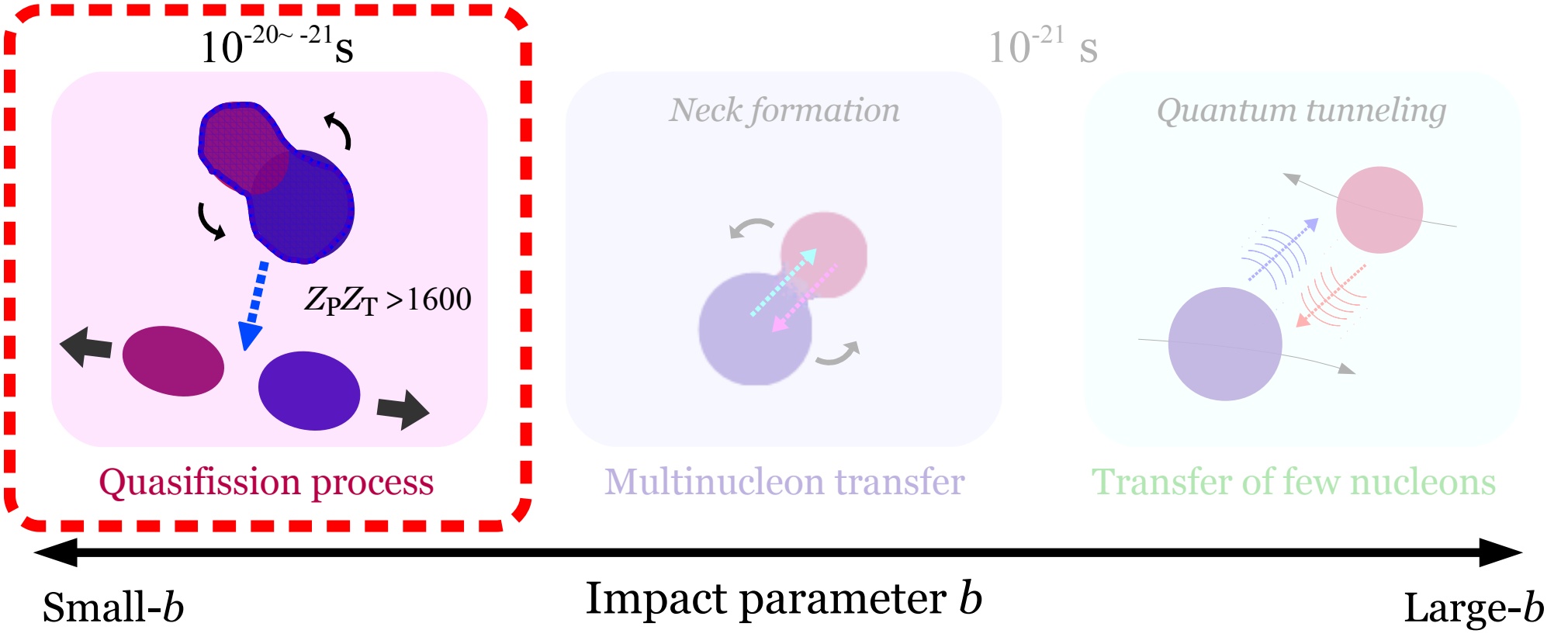



✔ The TKE-$A$ distribution for the quasifission processes reasonably agrees with the experimental data.

# *Take-away message*

TDHF theory provides us a parameter-free microscopic description for *both*

- ✔ multinucleon transfer processes in peripheral collisions *and*
- ✔ <u>quasifission processes in central collisions.</u>



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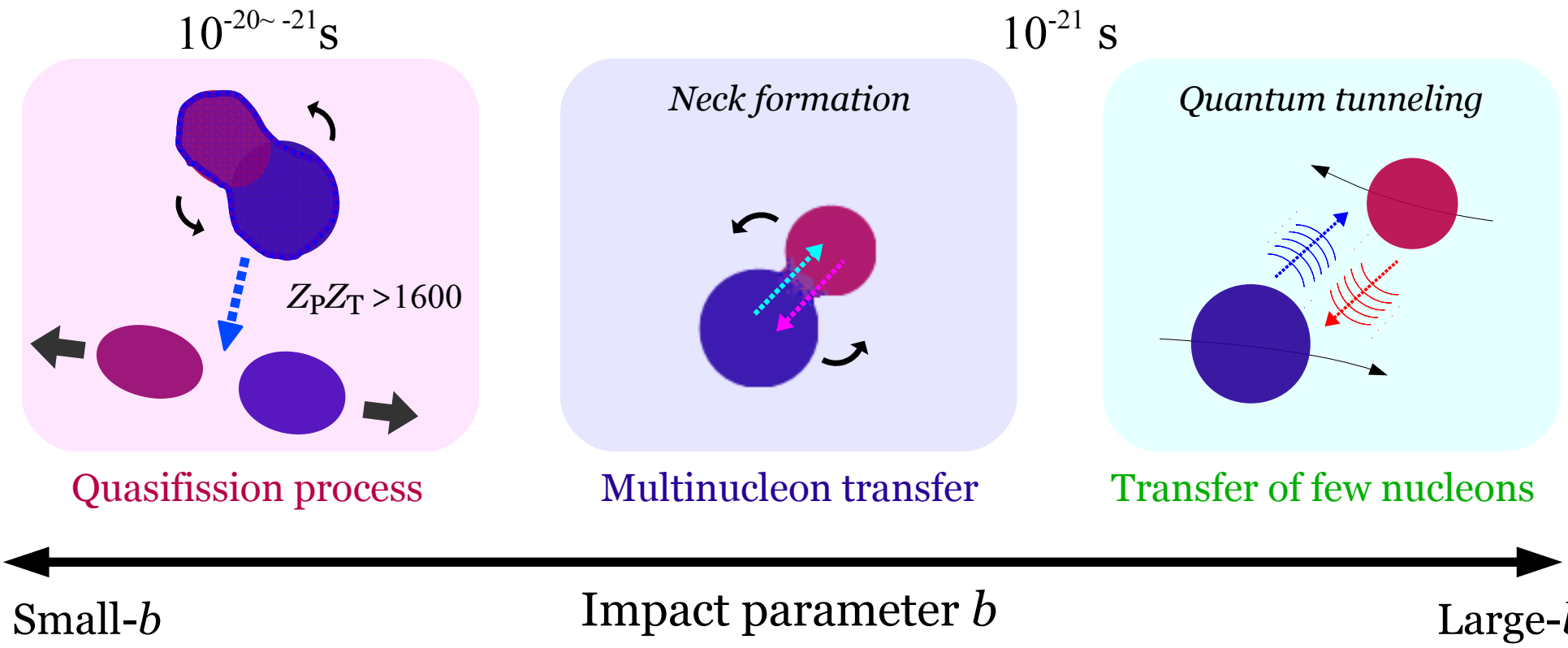

*About me:*

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*References:*

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*K. Sekizawa and K. Yabana, to appear in JPS Conference Proceedings, arXiv.1409.8612 [nucl-th].*

*Thank you for your attention.*